



Institut für Schichten und Grenzflächen
Institut 2: Bio- und Chemosensoren

***Defect modes in electromagnetic bandgap
structures for micro- and millimetre waves***

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Abstract

In the previous decades, the investigation of the optical properties of materials has led to a number of important developments like the laser, optical fibre cables and high precision spectrometers. In 1987, Yablonovich and John suggested a possibility to tailor the optical properties of a periodic dielectric material so that the flow of electromagnetic waves could be controlled by the creation of a band structure for allowed and forbidden states, the so called “electromagnetic bandgap”. It was found out that such structures could exhibit improved properties that could not be achieved with conventional treatment of light waves, for example higher quality factors, low radiation losses in sharp bends in waveguides, low dispersion waveguiding and frequency selective substrates. Another feature of these so-called “electromagnetic bandgap” (EBG) materials was that their properties could be scaled to an arbitrary frequency range by rescaling the lattice constant of the dielectric lattice. This scalability makes them interesting for possible applications in the frequency range in between the microwave and optical ranges, the so called “Terahertz gap”. In the frame of this work, the suitability of electromagnetic bandgap structures for possible applications as integrated passive element in circuits from the microwave up to the millimetre wave range has been investigated. It has been taken advantage from the scalability of the EBG properties, which makes it possible to investigate structures at low frequencies where fabrication, assembly and measurement are relatively easy and to scale up the results that have been found.

In the first part of this work, a theoretical description of the behavior of electromagnetic waves in periodic dielectric media is given, and the basic properties of EBG structures are derived from the appropriate solutions of Maxwell’s equations. Several different EBG lattice structures are presented, and described by band structure calculations. Furthermore the behavior of point and line defects in the lattice is investigated, and a slab structure that can provide a three dimensional confinement is presented. In the second part, a number of fabrication schemes for EBG structures from the microwave range up to millimetre wave frequencies are presented, which have been investigated in the frame of this work, in collaboration with partners. Here different ways of fabrication have been investigated such as mechanical treatment, moulding techniques and microfabrication techniques (laser machining and Silicon etching) and different material systems are employed. In the third part of this work the simulated and fabricated structures have been investigated experimentally at frequencies of 10, 20, 30 and 100 GHz with respect to a possible application as passive transmission line elements and high quality factor resonant structures. For frequencies of 10 GHz, it has been shown that in a 2D EBG structure for TM waves the strength of the coupling to a defect resonance could be tuned and optimised by size variation of adjacent lattice elements to yield low insertion loss. Furthermore, a broadband waveguiding with little reflection by line defects with a width of one and three lattice periods could be shown. A three dimensional confinement of modes has been demonstrated in both simulation and experiment for a 3D EBG structure with a band gap at 20 GHz. For frequencies around 30 GHz, the creation of a band gap in a 2D EBG structure that was prepared by a ceramic moulding technique with a band gap for TM waves has been demonstrated and a resonant cavity mode with moderate quality factor could be observed. Two different structures with band gaps at frequencies around 100 GHz were investigated and it was shown that a 2D interconnected structure could exhibit a band gap for TM waves and provide a high mechanical stability without the need for a backfilling material. A 2D slab structure could provide a three dimensional confinement of defect modes by a combination of both band gap guiding and index guiding. A broadband waveguiding by a line defect mode in this slab structure was shown, and it was demonstrated that a localised mode in a point defect could act as a high quality factor cavity in both band pass and band reject configuration.

Zusammenfassung

Die Erforschung der optischen Eigenschaften von Materialien hat in den letzten Jahren und Jahrzehnten eine Reihe wichtiger Entwicklungen hervorgebracht, beispielsweise den Laser, optische Glasfaserkabel und hochpräzise Spektrometer. Im Jahr 1987 schlugen Yablonovich und John eine neue Möglichkeit vor, die optischen Eigenschaften von Materialien zu beeinflussen, wonach die Ausbreitung elektromagnetischer Wellen in dielektrischen Materialien durch eine periodische Strukturierung kontrolliert werden könnte, die eine Bandstruktur für erlaubte und verbotene elektromagnetische Zustände entstehen lässt, die sogenannte „elektromagnetische Bandlücke“. Man fand heraus, dass solche Strukturen neue, verbesserte Eigenschaften besitzen konnten, welche mit herkömmlicher Behandlung von Lichtwellen nicht erreichbar waren, so beispielsweise höhere Gütefaktoren, niedrigere Strahlungsverluste in Wellenleitern, dispersionsfreie Wellenleitung und frequenzselektive Substrate. Eine weitere Eigenschaft dieser sogenannten „electromagnetic bandgap“ (EBG) Materialien ist, dass Ihre Eigenschaften in beliebige Frequenzbereiche skaliert werden können in dem die Periodizität der Strukturierung des Materials entsprechend verändert wird. Diese Skalierbarkeit macht sie interessant für mögliche Anwendungen im Frequenzbereich zwischen Mikrowellen- und optischen Frequenzen, der sogenannten „Terahertz-Lücke“. Im Rahmen dieser Arbeit wird die Eignung von EBG-Materialien für mögliche Anwendungen als integrierte passive Elemente in Schaltkreisen von Mikrowellen- bis hinauf zu Millimeterwellenfrequenzen untersucht. Dabei wurde die Skalierbarkeit der EBG Eigenschaften ausgenutzt, die es möglich macht, Strukturen bei niedrigen Frequenzen zu untersuchen wo Herstellung, Zusammenbau und Messung relativ leicht sind, und die Ergebnisse in höhere Frequenzbereiche hinaufzuskalieren.

Im ersten Teil dieser Arbeit wird eine theoretische Beschreibung des Verhaltens elektromagnetischer Wellen in periodischen Dielektrika gegeben und die Grundlagen von elektromagnetischen Bandgap Strukturen werden aus den entsprechenden Lösungen der Maxwell'schen Gleichungen abgeleitet. Eine Reihe von EBG Strukturen wird vorgestellt und durch Berechnung Ihrer Bandstruktureigenschaften beschrieben. Weiterhin wird das Verhalten von Punkt- und Liniendefekten im dielektrischen Gitter untersucht und eine Schichtstruktur wird vorgestellt, in der ein dreidimensionaler Einschluss der Feldenergie möglich ist. Im zweiten Teil der Arbeit wird eine Reihe von Herstellungsverfahren für EBG Strukturen im Bereich von Mikro- bis Millimeterwellen vorgestellt, die im Rahmen der Arbeit, in Zusammenarbeit mit Partnern hergestellt wurden. Verschiedene Herstellungsmethoden wie mechanische Behandlung, keramische Formtechniken und Mikrofabrikationstechniken (Laserbearbeitung und chemisches Ätzen) werden untersucht und verschiedene Materialsysteme benutzt (Oxidkeramiken, Silizium). Im dritten Teil der Arbeit werden die simulierten und hergestellten Strukturen bei Frequenzen von 10 bis 100 GHz experimentell untersucht. Dabei werden zwei und dreidimensionaler Einschluss von Moden, einstellbare Ankopplungsstärke an Defektmoden sowie reflektionsarme Wellenleitung untersucht.

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Introduction

In the previous decades, the investigation of the properties of materials and material systems has lead to a number of breakthroughs, some of which have influenced strongly the daily life. The most prominent of these developments certainly is the so called semiconductor revolution, where a deeper understanding of the electronical properties of materials has lead to significant advances in technology. There are many more examples like the discovery of high temperature superconductors, magnetic materials or, more recently, the investigation of the physical properties of biomaterials.

One of these fields is the investigation of the optical properties of materials, which has so far lead to a number of important developments like the laser, optical fibre cables and high precision spectrometers. In 1987, Yablonovich and John suggested a possibility to tailor the optical properties of a material in a way very similar to how it has been done in semiconductor physics for a long time[1][2]: They proposed that in a periodically arranged dielectric material, the flow of electromagnetic waves could be controlled by the creation of a band structure for allowed and forbidden states: the material could exhibit a so called “electromagnetic bandgap”. Many researchers all over the world have since then investigated these “electromagnetic bandgap (EBG) materials” or “photonic crystals”, as they were originally called. It has been found that it is possible to create band gaps that prohibit light propagation through the material[3][4][5], confine light at defects in the material[6][7], or guide it along defect lines[8][9]. Furthermore, it was found out that these structures could exhibit improved properties that could not be achieved with conventional treatment of light waves, for example higher quality factors[10], low radiation losses in sharp bends in waveguides[8][9], low dispersion waveguiding over a large frequency band[11] and frequency selective substrates for high directivity antennas[12][13]. Another feature of EBG materials was that their properties could be scaled to an arbitrary frequency range by rescaling the lattice constant of the dielectric lattice. Since their discovery, electromagnetic bandgap materials have been investigated in a large frequency range from the low microwave range with wavelengths of several centimetres up to optical frequencies with wavelengths in the micrometre range.

When the spectrum of electromagnetic waves as mentioned above is observed, it is obvious that technology for both the microwave range and the optical frequencies has undergone a strong development in the last decades. Nevertheless, there has been relatively little investigation devoted to the frequency range in between them, the so called “Terahertz gap”, and Terahertz spectroscopy has emerged as an important research topic only in the recent years. Even though material properties in this frequency range and the possible application of Terahertz waves especially in imaging and detection systems are very promising, there is a lack in high power signal sources, passive structures and detectors that makes an advancement

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in technology for the Terahertz range difficult. In recent times, the development of time domain spectroscopy setups has made the Terahertz range accessible by providing both broadband sources and detectors, and the ongoing progress in the development of semiconductor high frequency devices has made it possible to multiply microwave sources up to frequencies approaching the region of one Terahertz. So far, passive elements like transmission lines, high quality resonator structures or filters are either based on monolithic micromachined integrated circuits (MMIC) or metal waveguides. These devices suffer from increased losses at high frequencies. For even higher frequencies, quasioptical devices can be used, which have the drawback that they are extremely bulky. For the realisation of possible integrated oscillator circuits at millimetre wave frequencies, the properties of EBG structures could provide a suitable technology for the design of passive structures: Due to the scalability of their properties, EBG structures are suited for an application in an arbitrary frequency range and could therefore be tailored to act as a passive element at these frequencies. Due to the possibility of fabrication from low loss materials, EBG structures have the potential to have a performance superior to standard transmission lines for Terahertz frequencies in terms of both losses and integration capability.

In the frame of this work, the suitability of electromagnetic bandgap structures for possible applications as integrated passive element in circuits from the microwave up to the millimetre wave range has been investigated. It has been taken advantage from the scalability of the EBG properties, which makes it possible to investigate structures at low frequencies where fabrication, assembly and measurement are relatively easy and to scale up the results that have been found. A number of structures have been investigated starting from the microwave range around 10 GHz up to millimetre wave frequencies around 100 GHz.

The investigation of electromagnetic bandgap structures involves a number of different tasks: Simulation, fabrication and experimental measurement. Due to the increasing power of simulation tools, it has become possible to calculate the high frequency properties of the dielectric lattice and gain information about its behavior in terms of band structure, transmission spectra, eigenfrequencies and eigenmode field distributions. From a fabrication point of view, both the dielectric material and the method for the patterning of the dielectric lattice must be investigated with respect to the size of the structures and the dielectric properties at different frequency ranges. The measurement at different frequency bands must be carried out with a number of different experimental setups.

This work is mainly separated into three parts:

In the first part, a theoretical description of the behavior of electromagnetic waves in periodic dielectric media is given, and thus the basic properties of EBG structures are derived from the appropriate solutions of Maxwell's equations. A number of EBG lattice structures are presented, and by calculations of their band structure, the conditions under which the periodic dielectric lattices exhibit an electromagnetic band gap are explained. In the frame of these calculations, optimized lattice structures and their parameters for a large band gap are investigated for the structures that were under consideration for fabrication and measurement. Furthermore the behavior of point and line defects in the lattice is investigated and a situation is addressed, where a three dimensional confinement of a defect mode by a combination of bandgap guiding and index guiding is possible.

In the second part, a number of fabrication schemes for EBG structures are presented, that have been investigated in the frame of this work, in collaboration with partners. For the different frequency ranges of interest, different ways of fabricating the dielectric lattice and

different material systems are investigated. The fabrication methods include mechanical treatment, moulding techniques and microfabrication techniques such as laser machining and Silicon etching.

In the third part of this work, the simulated and fabricated structures are investigated experimentally. Here, experiments around 10, 20, 30 and 100 GHz are presented. These experiments were aimed towards the investigation of electromagnetic bandgap structures as passive transmission line elements and high quality factor resonant structures as parts of integrated circuits at micro- and millimetre wave frequencies. Therefore, resonant cavities and their quality factors were measured, the transmission properties of line defect waveguides and the possibility of coupling from external sources into the EBG lattice as well as coupling of waves between different defect structures inside the EBG lattice were investigated.

Finally, the most important results are summarized, and a perspective for further work towards the application of EBG structures in millimetre wave circuits will be given.

Chapter 1: Maxwell's equations in media

The description of classical electric and magnetic phenomena is based on Maxwell's equations, introduced by J.C. Maxwell in 1873. These equations treat the behavior of space and time dependent electromagnetic fields in arbitrary media on a macroscopic basis. All properties of classical electromagnetic waves in media can be derived from these equations, using appropriate boundary conditions and material parameters. Therefore, the treatment of Maxwell's equation does not only provide the basics for the analysis of electromagnetic bandgap structures, but also for the measurement methods that are used in the characterisation of devices at microwave and millimetre wave frequencies. In this chapter we will introduce Maxwell's equations in their differential form and deduce a wave equation for the simple case of an electromagnetic wave propagating in a homogenous medium. Furthermore we will treat the influence of a medium on the propagation of a wave, especially in the case of lossy media.

1.1 - Maxwell's equations

In their differential form, the Maxwell equations are given by:

$$\operatorname{div} \vec{D} = \rho \quad (1.1) \qquad \nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \quad (1.3)$$

$$\operatorname{div} \vec{B} = 0 \quad (1.2) \qquad \nabla \times \vec{H} = \vec{j} + \frac{\partial \vec{D}}{\partial t} \quad (1.4)$$

Here we introduce the dielectric displacement $\vec{D}$, electric field $\vec{E}$, magnetic induction $\vec{H}$ and magnetic field $\vec{B}$. These quantities are space (x,y,z) and time (t) dependent vector fields. The dielectric displacement $\vec{D}$ is related to the response of a material upon an external electric field $\vec{E}$, and its components D_i can be expressed in a power series

$$D_i = \sum_j \varepsilon_{ij} E_j + \sum_{j,k} \chi_{ijk} E_j E_k + O(e^3) \quad (1.5)$$

We will restrict our considerations to the case of small electric fields, where only the first addend will come into play. In this case the fields are related to the properties of the material in which they propagate by the macroscopic material parameters ε (dielectric permittivity), μ (magnetic permeability) and σ (conductivity). The relation can be written in a set of linear material equations:

$$\vec{D} = \epsilon \vec{E} \quad (1.6a)$$

$$\vec{B} = \mu \vec{H} \quad (1.6b)$$

$$\vec{j} = \sigma \vec{E} \quad (1.6c)$$

The material parameters describe the macroscopic effects of the microscopic interactions of electric and magnetic waves with a medium. They are generally 2nd order tensors, but in homogenous isotropic media they can be simplified to be scalar. In the general form they will have a real and an imaginary part

$$\epsilon = \epsilon_r + i\epsilon_{ri}$$

$$\mu = \mu_r + i\mu_{ri}$$

$$\sigma = \sigma_r + i\sigma_{ri} \quad (1.6d)$$

In the following we restrict the magnetic permeability to be unity ($\mu=1$).

1.2 - The wave equation

We will assume the case of a non-conducting ($\sigma_r = \sigma_{ri} = 0$), non-dissipative ($\epsilon_{ri} = 0$) and uncharged ($\rho = 0$, $\vec{j} = 0$) medium. Furthermore, the medium is homogenous and isotropic, so the dielectric constant can be written as a scalar. In this case Maxwell's equations can be rewritten, and a homogenous wave equation for electric and magnetic field is obtained:

$$\left[\nabla^2 - \frac{1}{c_{med}^2} \frac{\partial^2}{\partial t^2} \right] \begin{pmatrix} \vec{E} \\ \vec{H} \end{pmatrix} = 0 \quad (1.7)$$

The constant c_{med} denotes the speed of light in the medium. It is given by $c_{med} = c_0 / \sqrt{\epsilon\mu}$ with the vacuum light speed $c_0 = c$. The increment $\sqrt{\epsilon\mu} = n$ is called refractive index and is equal to the ratio of light speed in vacuum and in the medium $n = c_{med} / c_0$. We assume a harmonic time dependence of the fields

$$E_x(z, t) \propto e^{i\omega t}, H_y(z, t) \propto e^{i\omega t} \quad (1.8)$$

($\omega = 2\pi f$, angular frequency), and introduce a linear dispersion relation

$$\omega^2 = c_{med}^2 \vec{k}^2 \quad (1.9)$$

In this case, the wave equation can be written as the so called **Helmholtz-equation**

$$\nabla^2 \begin{pmatrix} \vec{E} \\ \vec{H} \end{pmatrix} + \vec{k}^2 \begin{pmatrix} \vec{E} \\ \vec{H} \end{pmatrix} = \left(\frac{d^2}{dx^2} + \frac{d^2}{dy^2} + \frac{d^2}{dz^2} \right) \begin{pmatrix} \vec{E} \\ \vec{H} \end{pmatrix} = 0 \quad (1.10)$$

The vector $\vec{k}$ is called wave vector and describes the direction of propagation of the wave. It is related to the wavelength by $\lambda = 2\pi / |\vec{k}|$. A special set of solutions of this wave equation are so called plane waves. Their electric and magnetic fields can be written in the form

$$\vec{E}(\vec{r}, t) = \vec{E}_0 e^{i(\vec{k}\vec{r} - \omega t)}, \vec{H}(\vec{r}, t) = \vec{H}_0 e^{i(\vec{k}\vec{r} - \omega t)} \quad (1.11)$$

These solutions are transversal waves, i.e. they obey the conditions:

$$\vec{k} \cdot \vec{E} = 0 \quad (1.12a)$$

$$\vec{k} \cdot \vec{H}_0 = 0 \quad (1.12b)$$

$$\vec{k} \times \vec{H} = -\frac{\omega}{c_{med}} \vec{E}_0 \quad (1.12c)$$

Electric and magnetic field are perpendicular to each other and to the wave vector $\vec{k}$ at any time.

1.3 - Lossy materials

If electromagnetic waves propagate in a medium, there will be an interaction between the electric and magnetic fields and the microscopic structure of the medium. This interaction can be described in a macroscopic approach by the material parameters ϵ, μ, σ that were introduced before. An electric field will cause the polarization of atomic or molecular dipole moments, enhancing the effective local field, and a magnetic field will align magnetic dipoles that produce an additional magnetization.

The treatment of loss mechanisms in materials for high frequency electromagnetic fields is an important issue in the field of electromagnetic bandgap materials, because modes will always be concentrated in regions of dielectric material to some extent, resembled by a dielectric filling factor that will be introduced later, and therefore will suffer from losses in that material. These losses degrade the performance of a device in which an EBG structure is integrated. The most important loss contributions arise from dielectric losses due to an imaginary component of the dielectric function of a material, and from conduction losses due to a finite conductivity of a material. In this part of the chapter, we will derive the effect of lossy media on the solutions of Maxwell's equations.

Dielectric loss tangent

Let us assume a semi infinite space extended in the direction of $z \geq 0$ filled with an uncharged medium ($\rho=0, \vec{j}=0$), and an electromagnetic wave with a wave vector $\vec{k}$ that is oriented normal to the boundary of this space $\vec{k} = k \cdot \vec{e}_z$. The electric field of the wave is oriented parallel to the x-axis ($\vec{E} = E_x \vec{e}_x$) and the magnetic field is oriented parallel to the y-axis ($\vec{H} = H_y \vec{e}_y$). We will furthermore assume a harmonic time dependence for the fields according to equation (1.8), and a scalar dielectric constant ϵ . In this case we receive from the Maxwell equations and the material equations (1.6):

$$\nabla \times \vec{H} = (\sigma - i\omega\epsilon) \vec{E} \quad (1.16a) \quad \text{or} \quad \nabla \times \vec{H} = -i\omega(\epsilon + i\frac{\sigma}{\omega}) \vec{E} \quad (1.16b)$$

It is obvious that we can define either a frequency dependent conductivity or a frequency dependent dielectric constant to describe the influence of the material parameters on the waves.

$$\tilde{\sigma} = \sigma - i\epsilon\omega \quad (1.17a) \quad \tilde{\epsilon} = \epsilon + i\frac{\sigma}{\omega} \quad (1.17b)$$

CHAPTER 1: MAXWELL'S EQUATIONS IN MEDIA

This ambiguity represents a situation, where the frequency of the oscillation of the electric field is high compared with the time of flight for the electrons in the material. It resembles the impossibility to distinguish between oscillating bound charges (dipoles) and free charge carriers at high frequencies. The electric field will be of the form

$$E(z, t) = E_0 \cdot e^{i(\gamma z - \omega t)} \quad (1.18)$$

with a propagation constant

$$\gamma = i\omega\mu_0(\sigma - i\omega\varepsilon) \quad (1.19)$$

that has both a real and an imaginary part. The imaginary part describes the damping of the propagating wave by dissipation of energy in the material. Taking into account the real and imaginary part of both ε and σ , we receive

$$\gamma = \omega\mu_0(\omega\varepsilon'' - \sigma)\left(1 + i\frac{\omega\varepsilon'' + \sigma}{\omega\varepsilon' - \sigma}\right) \quad (1.20)$$

From this term we must take into account four contributions to absorption:

- a term σE related to the current of free charge carriers due to the electric field
- a term $\omega\varepsilon'' E$ related to the dissipative part of the displacement current due to the oscillation of bound carriers in the electric field
- two terms $i\sigma E$ and $-i\omega\varepsilon' E$

In the contributions $i\sigma E$ and $-i\omega\varepsilon' E$ current and electric field are out of phase by 90° and therefore do not contribute to the losses. The relation of the imaginary and real part of the displacement current is called the loss tangent $\tan \delta$.

$$\tan \delta = \frac{\omega\varepsilon'' + \sigma}{\omega\varepsilon'} \quad (1.21)$$

In the microwave range, the conductivity current σE can be neglected compared to the displacement current $\omega\varepsilon'' E$ and the loss tangent is given by the ratio of complex and real part of the dielectric function:

$$\tan \delta = \frac{\varepsilon''}{\varepsilon'} \quad (1.22)$$

For lower frequencies, however, the influence of the conductivity will come into play, so that in the case of $\omega \ll \sigma/\varepsilon'$ the damping must be written as

$$\tan \delta = \frac{\sigma}{\omega\varepsilon'} \quad (1.23)$$

Conduction losses – the skin effect

Let us assume a volume with ideally conducting walls. Here the electric field will be oriented normal to the wall surface while the magnetic field is completely tangential to it. In case of a metal with finite conductivity, the magnetic field can penetrate into the metal to some extent. If this penetration depth is small compared to the bending radius of the wall, which is true in microwave resonators, we can derive a relation between the electric and magnetic field at the metal walls:

$$\vec{E}(z=0) = Z_s (\vec{n} \times \vec{H}(z=0)) \quad (1.24)$$

Here, $\vec{n}$ is a vector normal to the metal wall. Z_s is called surface impedance, its real part $R_s = \Re(Z_s)$ is called surface resistance, the imaginary part $X_s = \Im(Z_s)$ is called surface reactance. In the range of Ohm's law, the so called "normal skin-effect" can be observed. The magnetic field will penetrate into the metal with a penetration depth λ given by

$$\Im(Z_s) = \omega\mu_0\lambda, \quad \lambda = \Re\left(\int_{0 \rightarrow \infty} \frac{H(z)}{H(z=0)} dz\right) \quad (1.25)$$

In this case the surface impedance Z_s is

$$Z_s = (1+i)\sqrt{\frac{\omega\mu_0}{2\sigma}} \quad (1.26)$$

leading to a surface resistance given by

$$R_s = \Re(Z_s) = \sqrt{\frac{\omega\mu_0}{2\sigma}} \quad (1.27)$$

The propagation of a wave in the metal can be described by a propagation constant

$$\beta = (1+i)\sqrt{\frac{\omega\mu_0\sigma}{2}} \quad (1.28)$$

and the length scale of penetration into the metal is given by the skin depth δ_s

$$\delta_s = \sqrt{\frac{2}{\omega\mu_0\sigma}} \quad (1.29)$$

Chapter 2: Periodic dielectric materials

In a solid material, the behavior of electrons is described in the non-relativistic case by the well known Schrödinger equation for electron wave functions $\Psi(\vec{r})$

$$\left[-\frac{\hbar^2}{2m} \nabla^2 + V(\vec{r}) \right] \Psi(\vec{r}) = E \Psi(\vec{r}) \quad (2.1)$$

In solid, crystalline materials, the atoms are arranged in a periodic lattice. The crystal lattice is characterised by the periodic Coulomb potential of the atoms $V(\vec{r})$. This periodic potential imposes conditions for the valid eigensolutions of the Schrödinger equation in the lattice and leads to an arrangement of the spectrum of allowed eigenvalues (the electron energies) in bands and band gaps, the so called band structure. The band structure description of materials gives an explanation for the electronic properties of different solid materials, such as isolators, metals, and semiconductors. The exploitation of these properties has made it possible to tailor the electronic behavior of a material in an extremely flexible way, and especially the utilisation of semiconducting materials has given rise to a huge number of developments in technology. These technical developments are nowadays known as the “semiconductor revolution”.

In 1992, Yablonovich and John suggested[1][2], that in a medium with a spatially periodic dielectric constant, the allowed solutions for Maxwell’s equations could display a very similar behavior. He pointed out that an arrangement of the allowed eigenvalues (in this case: mode frequencies) for electromagnetic waves in periodic dielectric media in bands and band gaps could lead to a new class of materials and devices with properties not achievable by common microelectronics. Shortly thereafter, it was shown in calculations and experiments, mostly done at microwave frequencies[4][5][15][16][17], that indeed the solutions of Maxwell’s equations for a periodic dielectric medium are arranged in bands and band gaps of allowed and forbidden frequencies, and that for modes with a frequency inside the band gap a propagation was forbidden.

The new materials were initially called photonic crystals[18], due to their similarity to solid state crystal structures, and their properties, which were extremely promising for the application in optics and optoelectronics. Later on, the term “Electromagnetic BandGap (EBG) structures” was introduced, to pay respect to the much broader field of application for these structures and the fact, that a strict periodicity is not always necessary. The investigation of EBG materials has since then lead to high hopes for a possibility to tailor the optical properties of materials.

In this chapter we will present the wave equation for electromagnetic waves in a periodic dielectric medium and we will derive the properties of the equation and its solutions. From these properties we will derive a scheme for the description of electromagnetic bandgap structures and introduce the most important parameters that are used in this description. Finally, we will present numerical methods, that are utilized in the calculation of the behavior of electromagnetic waves that propagate in periodic dielectric materials.

2.1 - Maxwell's equations in periodic media

In a periodic dielectric medium the dielectric displacement must be written in the form

$$\vec{D} = \epsilon_o \epsilon_r(\vec{r}) \vec{E} \quad (2.2)$$

with a spatially varying dielectric constant $\epsilon_r(\vec{r})$. For the description of electromagnetic bandgap materials, we want to treat a simplified case that allows the following assumptions to be made for the periodic dielectric material:

- there are no free charges $\rho = 0$
- there are no free currents $\vec{j} = 0$
- the material is non-magnetic: $\mu_r = 1$, $\vec{H}(\vec{r}, t) = 1/\mu_0 \vec{B}(\vec{r}, t)$
- the dielectric material is macroscopic and isotropic: $\epsilon_r(\vec{r})$ is a scalar
- the dielectric material is lossless: the imaginary part of $\epsilon_r(\vec{r})$ vanishes

Furthermore, we assume a harmonic time dependence of electric and magnetic field

$$\begin{aligned} \vec{E}(\vec{r}, t) &= \vec{E}(\vec{r}) \cdot e^{i\omega t} \\ \vec{D}(\vec{r}, t) &= \vec{D}(\vec{r}) \cdot e^{i\omega t} \end{aligned} \quad (2.3)$$

We can now treat Maxwell's equations under these conditions[18] and receive two constituting equations (wave equations) for the description of electric and magnetic fields in a periodic dielectric medium:

$$\Phi_H \vec{H}(\vec{r}) = \nabla \times \left[\frac{1}{\epsilon(\vec{r})} \nabla \times \vec{H}(\vec{r}) \right] = \frac{\omega^2}{c^2} \vec{H}(\vec{r}) \quad (2.4)$$

$$\Phi_E \vec{E}(\vec{r}) = \frac{1}{\epsilon(\vec{r})} \nabla \times [\nabla \times \vec{E}(\vec{r})] = \frac{\omega^2}{c^2} \vec{E}(\vec{r}) \quad (2.5)$$

These two equations are vector eigenvalue equations for electric field $\vec{E}(\vec{r})$ and magnetic field $\vec{H}(\vec{r})$ with the operators Φ_H, Φ_E and the eigenvalues ω . They are determining for the behavior of electromagnetic waves in media with a space dependent dielectric constant $\epsilon(\vec{r})$. The analysis of the properties of these equations and their solutions leads to an understanding of the behavior of electromagnetic waves travelling in a periodic dielectric medium, and thus an explanation for the properties of electromagnetic bandgap materials. In the following we will list the properties of the equations and draw conclusions for the valid solutions.

2.2 - Properties of solutions

Φ_H is a linear, hermitian operator

Φ_H is a linear, hermitian operator, therefore its eigensolutions have various useful properties. This is well known from the Schrödinger equation, as the Hamilton operator is a hermitian operator, too.

- **Superposition:**

From the linearity of equation (2.4) it follows, that the superposition of its solutions will again be a solution. Therefore we can conclude that modes, that differ only by a constant factor, can be assumed as the same mode.

- **Orthogonality:**

Different solutions of equation (2.4) will be orthogonal to each other. Due to system symmetries it can happen that two modes have identical frequencies. These modes are called degenerate. On the other hand, if the frequency of two modes is different, they will be orthogonal to each other. Due to the linearity of (2.4) it is always possible to find a basic system of orthogonal modes, so that we can generally say that two modes with different frequencies will be orthogonal to each other

- **Real eigenvalues:**

The eigenvalues of a hermitian operators are always real. As the eigenvalues in (2.4) and (2.5) are the eigenfrequencies of the modes, it is assured that the mode frequencies will always positive and therefore physically meaningful.

Contrary to Φ_H , the operator Φ_E is not hermitian, therefore we will restrict our considerations to Φ_H only. However, it is also possible to hermitize equation (2.5) by a redefinition of the field $\vec{E}(\vec{r})$, but as this will only result in a more complicated formulation and reveal no new physical insights, we will focus on an analysis of (2.4).

The electric field energy

The electromagnetic energy functional, which describes the variation of the energy of an eigenmode of the operator Φ_H due to a change in field distribution $\vec{H}(\vec{r})$, is given by:

$$E_F(\vec{H}) = \frac{1}{2} \frac{(\vec{H}, \Phi_H \vec{H})}{(\vec{H}, \vec{H})} \quad (2.6)$$

If we enter the wave equation (2.4) into this equation and assume a time harmonic behavior of the fields, we will receive an expression for the electric field energy

$$E_D = \left(\frac{1}{8\pi} \right) \int d^3r \frac{1}{\varepsilon(r)} |\vec{D}(\vec{r})|^2 \quad (2.7)$$

From this term we can draw two conclusions for modes that are located in regions with different permittivity $\varepsilon(\vec{r})$:

- If the dielectric constant of the material is not homogenous, but distributed in regions of high dielectric constant $\epsilon_h(\vec{r})$ and low dielectric constant $\epsilon_l(\vec{r})$, then a fundamental mode will have its electric field located in regions of high dielectric constant in order to minimize its field energy. The band, where these mode are located is called “dielectric band”
- A second solution of the wave equation must obey the orthogonality to the first mode and must therefore have a part of their electric field concentrated in regions of low dielectric constant. Therefore its frequency ω will be increased compared to a lower order mode with the same wave vector $\vec{k}$. This will result in a frequency difference for different order modes with identical wave vectors. This is the origin of the phenomenon known as electromagnetic band gap. The band where modes with increased frequency are located is called “air band”.

It has been pointed out that the descriptions of electron wave functions in the periodic Coulomb potential of atoms in a solid material and the description of electromagnetic waves in a periodic dielectric material exhibit some similarities. Nevertheless, in certain aspects those two system also exhibit significant differences. In this part of the chapter, these similarities and differences will be explained, and it will be shown what properties can be deduced for the special forms of solutions of Maxwell’s equations in EBG materials.

Vector character of the fields

The electron wave functions that are solutions of the Schrödinger equation are scalar functions. In the case of electromagnetic bandgap structures, we have to treat electric and magnetic fields, which have a vector character. We can therefore expect that the behavior of waves propagating in EBG structures will depend on the orientation of the electric and magnetic field of the wave. For example, in a two dimensionally periodic dielectric lattice we will expect to observe a different behavior for waves with their electric field inside the plane of periodicity, and for waves with the electric field perpendicular to this plane. In analogy to the treatment of electromagnetic modes in resonators, we will distinguish between two different types of modes:

- A mode with an electric field in the plane of periodicity is called transverse electric (TE)
- A mode with the electric field oriented perpendicular to the plane of periodicity is called transverse magnetic(TM).

It will be shown later that in two dimensionally periodic EBG structures the existence and size of an electromagnetic band gap is strongly dependent on the polarisation of the mode, and we will try to explain which features of the lattice structure are responsible for the creation of a band gap for these two polarisations.

2.3 - Scalability of solutions

When we look at the Coulomb potential of atoms in a solid material, we will always observe a periodicity, that is in an order of magnitude given by the size of the atoms, for example Bohr’s radius. Therefore, band gaps for electron eigenenergies will always be located in a certain energy region, typically in the order of several electron volt (eV). In the case of electromagnetic bandgap materials, such a length scale is not given, and the periodicity of the

dielectric lattice can be chosen arbitrarily. The only limiting factor would be the feasibility of machining the structure. Therefore, the frequency bands of electromagnetic band gaps can be chosen accordingly, determined only by the chosen periodicity of the dielectric lattice. EBG materials can be designed to work for frequencies from the low microwave region at several gigahertz, corresponding to a wavelength of several centimetres up to optical frequencies with wavelengths of the order of a micrometre or below. Due to this independence from a fixed length scale, it makes sense to express the parameters of an EBG material in a dimensionless form that is normalized to the lattice constant. This notation pays respect to the scalability of the solutions, which makes it possible to rescale the properties of a given EBG lattice to make it work at a different frequency range.

Rescaling properties

An electromagnetic bandgap material is characterized by the periodic dielectric constant $\epsilon(\vec{r})$. For a given $\epsilon(\vec{r})$, we obtain solutions of the wave equation $\vec{H}(\vec{r})$ with eigenfrequencies ω . If the space dependence (periodicity) of the dielectric constant of an EBG system is rescaled by a factor s , a new wave equation is obtained:

$$\nabla \times \left[\frac{1}{\epsilon(\vec{r}/s)} \nabla \times \vec{H}(\vec{r}/s) \right] = \frac{\omega^2}{c^2 s^2} \vec{H}(\vec{r}/s) \quad (2.8)$$

with $\epsilon(\vec{r}) = \epsilon(\vec{r}/s)$, $\vec{r} = \vec{r} \cdot s$, $\nabla = \nabla/s$.

The new wave equation corresponds to (2.4), with a rescaled mode pattern and a rescaled frequency. It can be seen that rescaling the periodicity of the dielectric lattice will rescale the frequency region of the band gaps, but will leave all other properties of the solutions unchanged. If the absolute value of the periodic dielectric constant is scaled by a factor s , we will obtain

$$\nabla \times \left[\frac{1}{\epsilon(\vec{r})} \nabla \times \vec{H}(\vec{r}) \right] = \frac{s^2 \omega^2}{c^2} \vec{H}(\vec{r}) \quad (2.9)$$

A rescaling of the absolute value of the dielectric constant will result in an unchanged mode pattern, but will scale the eigenfrequencies of the modes, and thus the frequency region of the band gap, by the same factor.

Dimensionless variables

The scalability of EBG materials makes it reasonable to describe their properties with variables, that are not bound to a length scale, either. We will therefore introduce dimensionless parameters most of which are defined relative to the lattice constant. Therefore an overall change in the length scales of an EBG structure will keep these parameters constant and the EBG properties can be easily transferred to another length scale.

1) Gap-midgap-ratio

The frequency band, in which an EBG structure will exhibit a bandgap, is dependent on its periodicity and absolute value of the dielectric constant. However, the size of the band gap is related to the particular lattice parameters that are used, as will be explained later. A

dimensionless variable to describe the size of the band gap is the so called gap-midgap ratio given by the ratio of gap width $\Delta\omega$ to gap mid-frequency ω_0

$$\Gamma = \frac{\Delta\omega}{\omega_0} \quad (2.10)$$

II) Dielectric contrast

The dielectric lattice will in most cases consist of two materials, one with a low dielectric constant ε_l , and another one with a higher dielectric constant ε_h . A dimensionless variable to describe the influence of these two dielectric materials on the EBG properties is the so called dielectric contrast given by the ratio of the two dielectric constants of the materials

$$E = \frac{\varepsilon_h}{\varepsilon_l} \quad (2.11)$$

III) Dielectric filling factor

It has been pointed out earlier, that the electric field energy will tend to concentrate in the low and high index materials by different amounts, according to the mode order. A dimensionless variable to describe the difference between modes with the same wave vector but different mode frequencies is the so-called dielectric filling factor κ_{diel} , given by the space integral of the electric field in the high dielectric region, divided by the total space integral of the electric field in the EBG structure.

$$\kappa_{diel} = \frac{\int_{\varepsilon_h} \vec{E}^*(\vec{r}) \vec{D}(\vec{r}) d^3r}{\int \vec{E}^*(\vec{r}) \vec{D}(\vec{r}) d^3r} \quad (2.12)$$

IV) Normalization to the lattice constant

The order of magnitude of the periodicity of the EBG lattice, given by its lattice constant a is mainly determining the frequency band where the band gaps can be found in. Therefore it makes sense to normalise all parameters that are necessary to describe the EBG lattice to this lattice constant:

- normalized frequencies $\frac{\omega a}{2\pi c} = \frac{f a}{c} = \frac{a}{\lambda}$
- size of the structural features in the lattice unit cell x/a (in most cases, radius of cylindrical elements r/a or height of the structure h/a)

2.4 - Solving Maxwell's equations for periodic media

A periodic dielectric material can be a rather complicated system, so that an analytical solution of Maxwell's equations is in most cases impossible. Especially for finite structures, only numerical approaches can yield insights into the properties of the solutions and the band structure. Nevertheless, the periodicity of EBG structures makes it possible, to approach the system in a way that is common from the treatment of electron wave functions in the periodic atom lattice: we can describe the dielectric structure by a repetition of a unit cell with a well defined shape and a lattice, in which the contents of the unit cell are arranged repeatedly. Thus we will be able to use the same terms and formulations that have been successfully used

in the treatment of solid state materials for a long time: Bloch waves, reciprocal space, band structure and density of states.

The Bloch-Floquet theorem

In this part of the chapter we will explain a way to deal with a periodic dielectric structure numerically. We will focus on the special case of transverse magnetic (TM) modes in a two dimensionally periodic dielectric lattice. The dielectric material will be periodic in the x-y-plane, and therefore the electric field will have a component in the z-direction only: $\vec{E}(\vec{r}) = \vec{E}_z(\vec{r}) \cdot \vec{e}_z$.

In this case the wave equation will be reduced to

$$\frac{1}{\varepsilon(\vec{r})} (\partial_x^2 + \partial_y^2) E_z(\vec{r}) + \frac{\omega^2}{c^2} E_z(\vec{r}) = 0 \quad (2.13)$$

The vector $\vec{r} = (x, y)$ denotes a 2D vector that defines the lattice point of interest. The space dependence of the material is described by $\varepsilon = \varepsilon(\vec{r})$.

As the material we want to look at is periodic in two dimensions, the dielectric constant can be written as $\varepsilon(\vec{r}) = \varepsilon(\vec{r} + \vec{R})$ where the two dimensional vector $\vec{R}$ is an element of the set $\mathfrak{R} = \{n_1 \vec{a}_1 + n_2 \vec{a}_2; (n_1, n_2) \in \mathbb{Z}^2\}$ generated by the primitive translations $\vec{a}_i$, ($i = 1, 2$) that serve as a basis for the EBG lattice. In such a case, where the wave equation of the system is a differential equation with periodic coefficients, its solutions must obey the Bloch-Floquet theorem[19]. The solutions can be labeled with a wave vector $\vec{k}$, that has values within the so-called first Brillouin zone (BZ) of the reciprocal lattice. The folding back of solutions with larger wave vector into the first BZ makes it possible to introduce a band index n . According to the Bloch-Floquet theorem, the solutions of the wave equation corresponding to an eigenfrequency $\omega_n(\vec{k})$ have the form of plane waves

$$\vec{E}(\vec{r}) = \vec{E}_{n, \vec{k}}(\vec{r}) = e^{i\vec{k}\vec{r}} u_{n, \vec{k}}(\vec{r}) \quad (2.14)$$

with $u_{n, \vec{k}}(\vec{r}) = u_{n, \vec{k}}(\vec{r} + \vec{R})$, i.e. the plane waves have the same periodicity as the underlying lattice. To solve the equation, the periodic functions can be expanded in a Fourier series over the reciprocal lattice vectors $\vec{\Gamma}$ of our EBG lattice. The electric and magnetic field are expanded into a series of plane waves. This approach is utilized in the so called Plane Wave Expansion (PWE) method that will be discussed later.

$$\frac{1}{\varepsilon(\vec{r})} = \sum_{\vec{\Gamma}} \eta_{\vec{\Gamma}} e^{i\vec{\Gamma}\vec{r}} \quad (2.15a)$$

$$E_{\vec{k}}(\vec{r}) = \sum_{\vec{\Gamma}} a_{\vec{k} + \vec{\Gamma}} e^{i(\vec{k} + \vec{\Gamma})\vec{r}} \quad (2.15b)$$

Here, the Fourier coefficients are given by

$$\eta_{\vec{\Gamma}} = \frac{1}{V_{WSC}} \int_{V_{WSC}} d^2\vec{r} \frac{1}{\varepsilon(\vec{r})} e^{-i\vec{\Gamma}\vec{r}} \quad (2.16)$$

with the volume V_{WSC} of the Wigner-Seitz-Cell (WSC). With this ansatz we can transform the differential eigenequation (2.13) into an infinite matrix eigenequation with coefficients $b^{\vec{k}+\vec{\Gamma}} = |\vec{k} + \vec{\Gamma}| a^{\vec{k}+\vec{\Gamma}}$:

$$\sum_{\vec{\Gamma}} |\vec{k} + \vec{\Gamma}| |\vec{k} + \vec{\Gamma}| \eta_{\vec{\Gamma}-\vec{\Gamma}'} b^{\vec{k}+\vec{\Gamma}} = \frac{\omega_{\vec{k}}^2}{c^2} b^{\vec{k}+\vec{\Gamma}} \quad (2.17)$$

With a suitable truncation, this eigenvalue problem can be solved numerically[20]. From the solutions of this equation it is possible to calculate the full information about the dispersion of the given EBG lattice, the density of states, the group velocity and the dispersion of modes. Additionally, mode patterns and mode eigenfrequencies can be calculated.

2.5 - Simulation techniques

Electromagnetic bandgap structures have a complicated space dependence of the dielectric constant. Due to their special properties, that require the existence of a number of lattice periods, these structures must be described in an extension that is much larger than one unit cell, and therefore, much larger than the wavelengths for which they exhibit an electromagnetic band gap. While the solution of Maxwell's equations for other, conventional high frequency devices, can be achieved by semi analytical approaches (mode matching technique) or even, in simple cases like a cavity resonator, analytically, this simple treatment will not lead to a result in the case of electromagnetic bandgap materials. For the computation of EBG material properties special techniques have to be applied that allow to numerically solve Maxwell's equations for a complicated periodical geometry. The results that are of interest are the band structure of the periodic lattice, its density of states, transmission properties and field distributions of defect modes. There have been several approaches to the computation of EBG systems reported in the literature:

1. The expansion of the fields into a complete basis with subsequent numerical solving of the truncated matrix eigenvalue problem as given by (2.17) [3][21][22]. As a complete basis in most cases plane waves have been used[23][24], but also spherical functions[25][26][27].
2. Direct solving of the Maxwell equations on a discrete grid by Fourier transformation of the time varying response of the system to an input signal (FDTD method)[4][28][29][30].
3. Establishment of a relation of the electromagnetic fields on two sides of an unit cell and subsequent calculation of a transfer matrix (transfer matrix method)[31][32][33][34].

In this part of the chapter we will present two simulation techniques, that have been used in the frame of this work to simulate the properties of electromagnetic bandgap materials: a code based on the Finite Difference Time Domain (FDTD) method and a code based on the Plane Wave Expansion (PWE) method.

Finite difference time domain method

In the frame of this work, a commercially available solver has been used (CST Microwave Studio). This code is based on the Finite Integration Technique (FIT). It can be applied for

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many types of electromagnetic problems, from static field calculations to high frequency applications in both time and frequency domain[35]. In an FIT solver, the Maxwell's equations are solved on a grid in their integral form

$$\oint_{\partial A} \vec{E} d\vec{s} = - \int_A \frac{\partial \vec{B}}{\partial t} d\vec{A} \quad (2.18a)$$

$$\oint_{\partial A} \vec{H} d\vec{s} = \int_A \frac{\partial \vec{B}}{\partial t} d\vec{A} \quad (2.18b)$$

$$\oint_{\partial V} \vec{D} d\vec{A} = \int_V \rho dV \quad (2.18c)$$

$$\oint_{\partial V} \vec{B} d\vec{A} = 0 \quad (2.18d)$$

In order to solve these equations numerically, a finite calculation domain is defined, enclosing the problem under consideration. State of the art FDTD codes use a 3D computer aided design (CAD) interface to create a three dimensional model of the calculation domain. By creating a suitable mesh system, the domain is split up into several small cuboids, the so-called grid cells. Then a second mesh is set up, orthogonal to the first one. The spatial discretization of the Maxwell's equations is then performed on these two orthogonal mesh systems. The electric grid voltages and magnetic facet fluxes are allocated on the primary grid, the dielectric facet fluxes and the magnetic grid voltages are allocated on the dual grid (see figure 2.1).

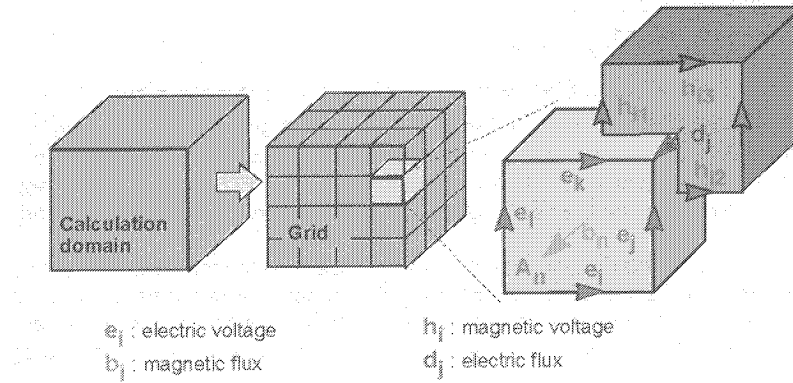


Figure 2.1: Discretization of the calculation domain on a rectangular grid and a second orthogonal grid.

Now Maxwell's equations are formulated for each of the cell facets separately. By a suitable application of Faraday's law and Ampere's law on the voltages and fluxes in the facets, a set of so called Maxwell's Grid Equations (MGE) is obtained. They represent a discretized form of the Maxwell's equations, taking into account the topological information of the grid describing the electromagnetic problem that is under consideration[36]. Finally, the material equations are introduced with discretized material parameters that are summarized in matrices

$$\begin{aligned} \vec{D} &= \epsilon \vec{E} \\ \vec{B} &= \mu \vec{H} \\ \vec{J} &= \vec{E} + \alpha \vec{J}_s \end{aligned} \quad (2.19a-c) \quad \Rightarrow \quad \begin{aligned} \tilde{d} &= \tilde{M}_\epsilon \tilde{e} \\ \tilde{b} &= \tilde{M}_\mu \tilde{h} \\ \tilde{j} &= \tilde{M}_\sigma \tilde{e} + \tilde{j}_s \end{aligned} \quad (2.20a-c)$$

The FIT formulation is a very general method and can be applied to all frequency ranges from DC to high frequencies. The formulations of the FIT can also be rewritten in time domain to yield a standard Finite Difference Time Domain (FDTD) method.

For the creation of the mesh, the so called Perfect Boundary Approximation (PBA) is used. The PBA method is a combination of the Finite Element Method (FEM) and Transmission Line Matrix (TLM) method (see figure 2.2)[37].

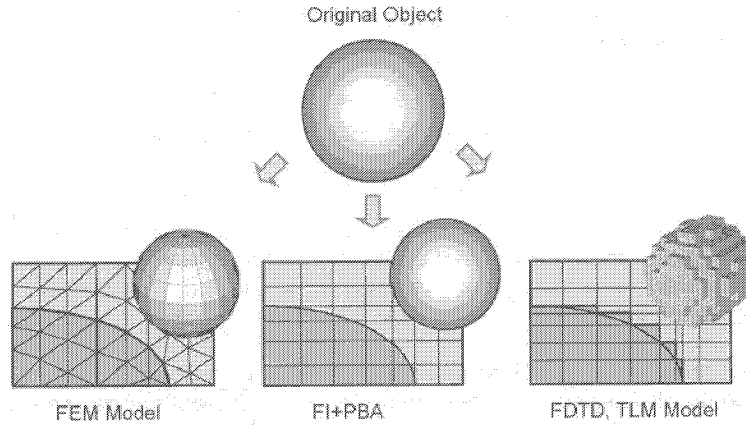


Figure 2.2: Comparison of the modeling techniques FEM (finite element method) and TLM (transmission line method) and their combination, the PBA (perfect boundary approximation) method.

In the simulations that were performed in the frame of this work, two different solvers were applied to tackle different problems:

Transient solver

The transient solver is particularly suitable, if large or open structures and structures with an excitation port for a high frequency signal have to be investigated over a large frequency range. In the frame of this work, it was mainly used for the computation of S parameters and field distributions. It is based on the solution of the space discretized set of Maxwell's Grid Equations, in which the time derivatives are substituted by central differences yielding the explicit update formulation for the loss-free case. The calculation variables are given by the electric voltages and fluxes. Both unknowns are located alternatively in time, well known as the frog-leap scheme[38]. For example, the magnetic flux at $t=(n+1) \cdot \Delta t$ is computed from the magnetic flux at $t=n \cdot \Delta t$ and from the electric voltage at half time step before, at $t=(n+1/2) \cdot \Delta t$.

Eigenmode solver

The eigenmode solver allows the computation of the structure's eigenmodes and the corresponding eigenvalues. It is especially suited for closed structures and structures that work at low mode orders (filters, resonators). It is based on the eigenvalue equation for non-driven and loss-free harmonic problems, whose solution is achieved through a Krylov-subspace method[39]. For the calculation of high resonant structures, it can be utilised to calculate corresponding S parameters by the use of modal analysis.

Plane wave expansion method

For the calculation of eigenmodes of a periodic system, the Plane Wave Expansion (PWE) method is a suitable choice. Therefore it is a very valuable tool for the calculation of band structures, mode frequencies and mode patterns in EBG structures. But also for non periodic structures, for example a point or line defect in an EBG lattice, the PWE solver can be used.

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In this case, a new unit cell is defined that includes the defect and a sufficient number of surrounding unit cells, the new unit cell is called supercell. The calculation is then performed using the supercell as a unitcell, taking into account the band folding that will occur when the Wigner-Seitz cell of the system is enlarged. We have found the wave equation for the case of a periodic dielectric material to be

$$\nabla \times \left[\frac{1}{\varepsilon(\vec{r})} \nabla \times \vec{H}(\vec{r}) \right] = \frac{\omega^2}{c^2} \vec{H}(\vec{r}) \quad (2.21)$$

With Bloch's theorem, we can write the magnetic field in case of a periodic dielectric material as $\vec{H}(\vec{r}) = \vec{H}_{n,\vec{k}}(\vec{r}) = e^{i\vec{k}\vec{r}} u_{n,\vec{k}}(\vec{r})$, with $u_{n,\vec{k}}(\vec{r}) = u_{n,\vec{k}}(\vec{r} + \vec{R})$ with the periodicity of the lattice.

When we enter the Bloch ansatz into the wave equation, we obtain

$$\hat{\mathcal{E}} u_{n,\vec{k}}(\vec{r}) = (i\vec{k} + \nabla) \times \left(\frac{1}{\varepsilon(\vec{r})} (i\vec{k} + \nabla) \times u_{n,\vec{k}}(\vec{r}) \right) = \bar{\omega}^2 \cdot u_{n,\vec{k}}(\vec{r}) \quad (2.22)$$

where we defined a hermitian operator $\hat{\mathcal{E}}$ and a normalised frequency $\bar{\omega} = \omega/c$.

Since $\hat{\mathcal{E}}$ is hermitian, the functional

$$E[u_{n,\vec{k}}(\vec{r})] = \frac{\int d^3r u_{n,\vec{k}}^*(\vec{r}) [\hat{\mathcal{E}} u_{n,\vec{k}}(\vec{r})]}{\int d^3r u_{n,\vec{k}}^*(\vec{r}) u_{n,\vec{k}}(\vec{r})} \quad (2.23)$$

is real and positive for any choice of $u_{n,\vec{k}}(\vec{r})$. It can be shown that the function that minimizes $E[u_{n,\vec{k}}(\vec{r})]$ is eigenvector of $\hat{\mathcal{E}}$ with the minimum frequency $\bar{\omega}$. The next lowest mode is the function which also minimizes $E[u_{n,\vec{k}}(\vec{r})]$ and is orthogonal to the first mode. Thus we can find all required modes by minimization of $E[u_{n,\vec{k}}(\vec{r})]$ and subsequent orthogonalisation. The minimisation is performed by the expansion of the periodic function $u_{n,\vec{k}}(\vec{r})$ in a series

$$u_{\vec{k}}(\vec{r}) = \sum_{\vec{\Gamma}} a_{\vec{\Gamma}} e^{i(\vec{k} + \vec{\Gamma})\vec{r}} \quad (2.24)$$

When the sum is truncated at a reasonable value, the matrix eigenvalue problem can be solved numerically. The PWE method is a very fast and efficient method for the solution of eigenvalue problems. Nevertheless, it has some disadvantages:

- in can be applied to periodic problems only which will drastically increase calculation times for nonperiodic structures due to the employing of a supercell.
- Lossy materials cannot be treated because $\hat{\mathcal{E}}$ is hermitian for the lossless case only.
- The distribution of $\varepsilon(\vec{r})$ must be kept constant during the simulation. Therefore a frequency dependence of $\varepsilon(\vec{r})$ can not be taken into account.

Chapter 3: Simulations of Electromagnetic Bandgap structures

Electromagnetic bandgap structures are artificially created materials with a periodic dielectric constant. Their spatial extension will always be in all three dimensions. Nevertheless, they are not necessarily periodic in all three space dimensions. As the periodicity is the main feature of EBG materials that defines their properties, a terminology has been created that pays respect to this situation, and the terms one-, two- and three-dimensional EBG structures represent the number of space directions in which the structure is periodic. In this chapter we will present the most common types of one-, two- and three dimensional EBG lattice structures and show, under which conditions they exhibit a band gap for certain types of electromagnetic waves. Advantages and disadvantages of the three types of EBG lattices will be compared. Also the dependence of the size of these band gaps on the structural features of the EBG lattice is explained and simulations are performed to find out, which EBG structures yield the largest band gap for a specific application.

We will begin with a treatment of the simple case of one dimensional (1D) EBG structures where the creation of a band gap can be explained for a simple case of periodicity. Afterwards, we will focus on different kinds of two dimensional (2D) EBG structures, as they are the main topic of this work. We will present calculations that were made in the frame of this work to find out, which kinds of 2D EBG structures yield large band gaps for electromagnetic waves with special orientations of electric and magnetic field, as they were introduced in chapter 2. Then the effect of defects in periodic dielectric structures will be explained and the behavior of defect modes for various types of point and line defects will be discussed, as well as a potential confinement of a defect mode in all three space dimensions by the utilization of a slab structure. Finally, a short introduction to 3D EBG structures, that have also been investigated in this work, will be given.

It has to be pointed out that due to the great advances in simulation techniques, also related to the growing computational power that is available, simulations play an important role in the description of EBG structures. By simulation of their properties it is very often possible to make assumptions on their behavior without actually fabricating the structure. Therefore, one focus of this work has been put on the simulation of EBG structure properties. The simulation results that are presented in this chapter have been achieved in the frame of this work.

3.1 - One dimensional EBG structures

One dimensional (1D) EBG structures have been known for a long time under the name „Bragg mirrors“. They are a very simple structure in both description and fabrication, as they consist of a periodic stack of dielectric slabs with thicknesses d_1 and d_2 and dielectric constants ε_1 and ε_2 (see figure 3.1) [31][40][41] [42].

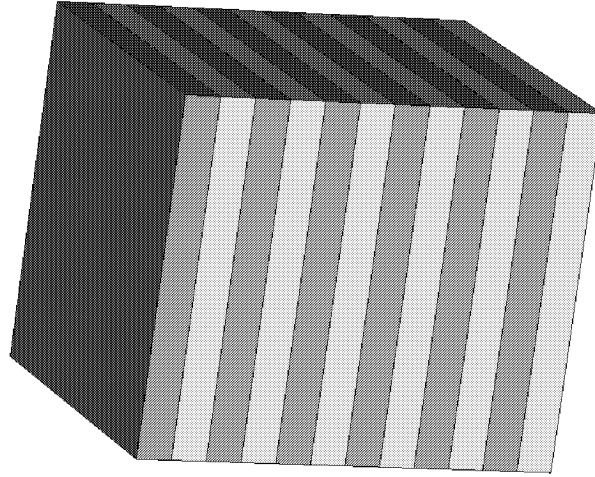


Figure 3.1: Periodical stack of layers made from two different dielectric materials. The layers have thickness $d_1=d_2$ and dielectric constants ε_1 and ε_2 . This structure is called one dimensional electromagnetic bandgap material, or Bragg stack.

However, due to their simplicity, the 1D EBG structures do not possess a complete bandgap. It can be shown that for any arbitrary wavelength, there is always an angle of incidence for which a propagating mode is allowed to exist in the lattice[43]. Nevertheless, a 1D EBG structure can be tailored to make a perfect mirror. This means, that even though propagation can not be forbidden for a given frequency range, the 1D EBG material can be designed so, that for a wave with a frequency out of this range incident onto the 1D EBG structure from a lower index material, it will be reflected for an arbitrary angle of incidence. In this case a wave can not enter the 1D lattice, even if it would be allowed to propagate[44][45] [46][47].

We will take advantage from the simplicity of 1D EBG structures and explain from a practical example, why an electromagnetic band gap can be created in a periodic dielectric material. Let us discuss a plane wave with a wavelength λ propagating in a homogenous medium with a dielectric constant $\varepsilon=1$ (vacuum). In this case the wave will have a frequency $f=c_0/\lambda$ and a related dispersion $\omega(\vec{k})=c_{med} \cdot |\vec{k}|$ with the light speed c_{med} in the medium. The band structure for this simple system is shown in figure 3.2.

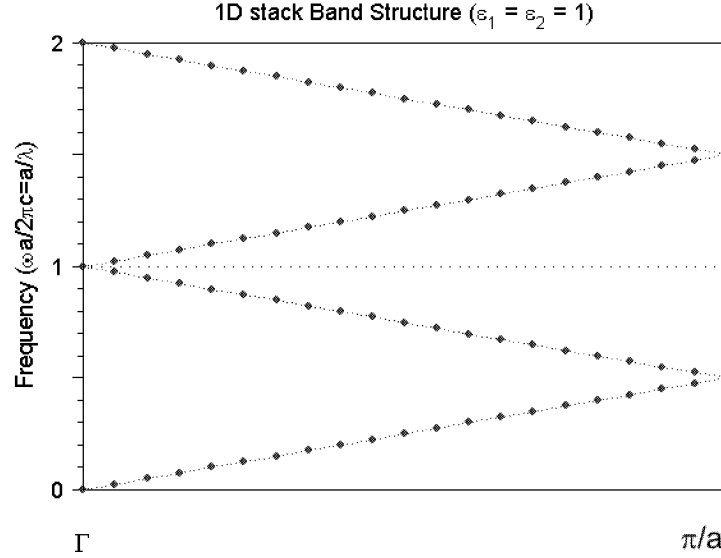


Figure 3.2: Linear dispersion relation of a wave propagating in a homogenous medium with a dielectric constant $\varepsilon=1$.

When the slabs have different dielectric constants ε_1 and ε_2 and are arranged with a periodicity that corresponds to the half wavelength $a=\lambda/2$, we will observe a changed behavior. For a wave vector $k=\pi/a$, there will be two degenerate modes with identical wave vector, but for the one mode, the electric field will have a maximum in the material with dielectric constant ε_1 , while the other mode will have a maximum electric field in the material with dielectric constant ε_2 in order to maintain its orthogonality to the lower order mode. The electric field density for these two modes is depicted in figure 3.3.

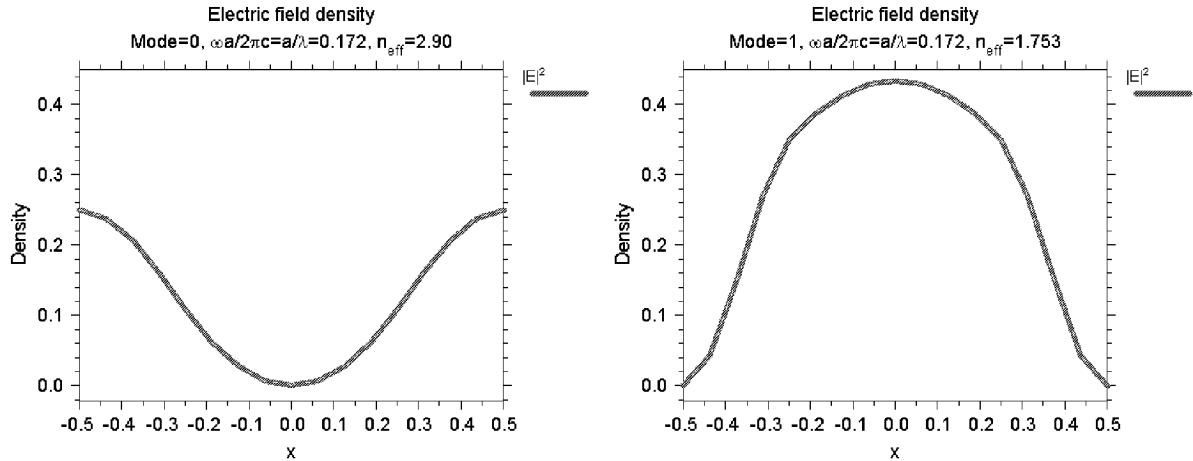


Figure 3.3: Distribution of electric field density for a k vector at the edge of the Brillouin zone and for modes 0 (below the band gap) and 1 (above the band gap). The effective index for mode 0 is higher, therefore the frequencies of the modes are split.

The non uniformity of the space distribution of the dielectric constant will lift the degeneracy of the two modes. At the corresponding point in the dispersion curve, we will therefore observe a splitting of the dispersion into a lower and a higher band, creating a band gap in between, as shown in figure 3.4. This splitting gives rise to a region of frequencies, that can not be an eigensolution of the wave equation in the periodic slab system. This is the origin of the electromagnetic bandgap in the simple case of a 1D structure.

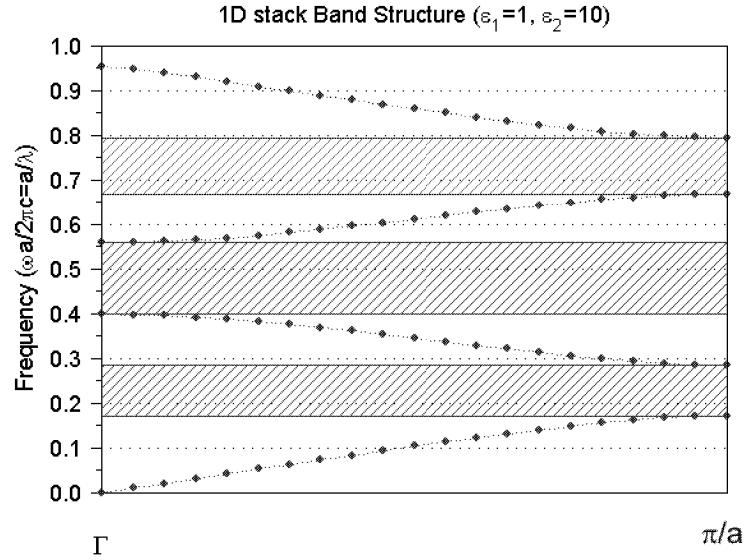


Figure 3.4: Stack of slabs with dielectric constants $\varepsilon_1=1$ and $\varepsilon_2=10$. The degeneracy of the two modes at the edge of the Brillouin zone with wave vector $k=\pi/a$ is lifted and they exhibit different frequencies, giving rise to a region of frequencies with no corresponding wave vector, the band gap.

As generally an EBG structure will be made from a periodic arrangement of high dielectric material in an air background or vice versa, we can name the bands after the material, in which the majority of the field of a mode is located in. Therefore we will call a band below a band gap dielectric band, and a band above a band gap will be called air band.

The existence of electromagnetic band gaps in two and three dimensionally periodic media can be understood in a very similar way. Nevertheless, in those cases the structures are more complicated and the lifting of the degeneracy is not so obvious. Still there are some rules, according to which it can be decided, whether or not a specific EBG structure will exhibit a band gap. In the second part of this chapter we will try to deduce some basic rules for the existence of an electromagnetic band gap in two dimensionally periodic dielectric materials.

3.2 - Two dimensional EBG structures

In the previous chapter we have discussed 1D periodic electromagnetic bandgap structures. They represent a class of EBG structures that is relatively simple to handle in both theory and experiment, but has limited band gap potential. Nevertheless, their simple structure makes it possible to explain the mechanism of the creation of a band gap nicely. In this chapter we will focus on two dimensionally periodic (2D) EBG structures. They consist of a dielectric material periodic in one plane and homogenous in the direction normal to the plane. This class of EBG materials has been treated extensively in the literature[16][17] [15] [48]. We will begin with the explanation of a feature very special to 2D EBG structures: the separation of electromagnetic waves into different polarisations with respect to the plane of periodicity. Afterwards we will discuss the band gap properties of two different 2D EBG structures with respect to the propagation direction and polarisation of a propagating electromagnetic wave: the square lattice and the hexagonal lattice.

Finally, we will discuss the behavior of defect modes in localized (point-) and extended (line-) defects in 2D EBG structures and the possibility of the 3D confinement of a line defect mode by the employment of a 2D EBG lattice with finite height (2D EBG slab) surrounded by a lower index cladding material (index guiding).

Polarisation dependence of the band gap

In a dielectric structure that is homogenous in one direction (we choose the z-direction here) and periodic in the perpendicular plane, we can write the dielectric constant as $\varepsilon(\vec{r}) = \varepsilon(\vec{\rho}) = \varepsilon(\vec{\rho} + \vec{R})$ where $\vec{\rho}$ is a vector in the plane of periodicity $\vec{\rho} = \rho_x \cdot \vec{e}_x + \rho_y \cdot \vec{e}_y$ and $\vec{R}$ is an arbitrary linear combination of the primitive vectors of the dielectric lattice $\vec{R} = a_x \cdot \vec{e}_x + a_y \cdot \vec{e}_y$. From our previous considerations we know that in the case of a periodic material the wave vector $\vec{k}$ of a propagating wave is a vector from the first Brillouin zone. In our example this condition can be applied for the component of the vector $\vec{k}$ in the x-y-plane $\vec{k}_{xy}$, while there is no restriction on the component of the wave vector in the direction normal to the plane, $\vec{k}_z$. In this case, the solutions of the wave equation for periodic dielectric media will be of the form

$$\vec{E}(\vec{r}) = \vec{E}_{n,\vec{k}}(\vec{r}) = e^{i\vec{k}\vec{r}} u_{n,\vec{k}}(\vec{r}) \quad (3.1)$$

with $u_{n,\vec{k}}(\vec{r}) = u_{n,\vec{k}}(\vec{r} + \vec{R})$ for all lattice vectors $\vec{R}$ of the dielectric lattice.

If we assume that the wave is propagating in the plane of periodicity only, then $k_z = 0$ and due to the symmetry of the structure we can separate a solution of the wave equation into two different polarisations.

- **TE polarisation:**
Waves with TE polarisation will have an electric field completely in the plane of periodicity, $\vec{E}_\rho \cdot \vec{e}_z = 0$, and a magnetic field perpendicular to this plane, $\vec{H} = H_z \cdot \vec{e}_z$.
- **TM polarisation:**
Waves with TM polarisation will have an electric field perpendicular to the plane of periodicity, $\vec{E} = E_z \cdot \vec{e}_z$, and a magnetic field perpendicular to this plane, $\vec{H}_\rho \cdot \vec{e}_z = 0$.

It must be noted at this point that the nomenclature TE and TM that is use here is different from the one commonly used in optics, where the polarisations are just named vice versa. The reason is that we are looking at the field orientation with respect to the direction of uniformity of the material, rather than the direction of propagation of the wave. The considerations concerning the polarisation of propagating waves enlighten one of the major differences in the description of electromagnetic waves in periodic dielectric media in comparison with the treatment of electron wave functions in the periodic Coulomb potential: the vector character of the electromagnetic fields makes the band structure of the periodic dielectric lattice strongly dependent on the polarisation of the propagating wave with respect to the plane of periodicity.

The 2D square lattice

The most simple 2D periodic structure is the square lattice characterised by a set of two lattice vectors $\vec{a}_1 = a \cdot \vec{e}_x$; $\vec{a}_2 = a \cdot \vec{e}_y$ (see figure 3.5a). The Brillouin zone of this lattice is also square, and the irreducible Brillouin zone has a triangular shape between the major symmetry points Γ , M and X. These points of symmetry correspond to the lattice vectors $\vec{k}_\Gamma = 0$, $\vec{k}_X = \pi/a \cdot \vec{e}_x$, $\vec{k}_M = \pi/a \cdot \vec{e}_x + \pi/a \cdot \vec{e}_y$ (see figure 3.5b).

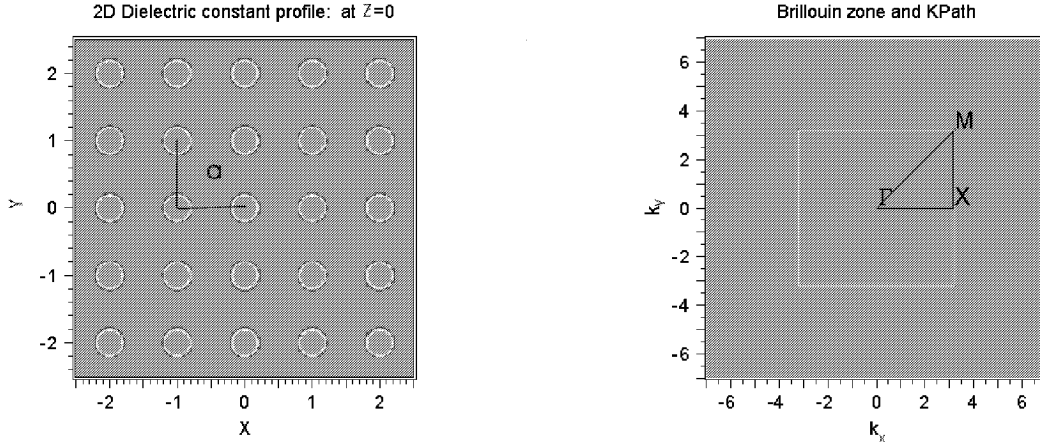


Figure 3.5: Left side: Distribution of the dielectric material in a square lattice. The lattice elements have a circular shape and are separated by the lattice constant a . Right side: First Brillouin zone of the square lattice. The main symmetry points are denoted by Γ , M and X.

The lattice symmetry is completely defined by the above primitive vectors. However, the EBG properties of the lattice are dependent on the distribution of the dielectric material in the unit cell. In general there will be a region of high dielectric material ϵ_{high} surrounded by a background of low dielectric material ϵ_{low} , or vice versa. We shall see what the band structure of the lattice looks like in these two different cases.

Dielectric rods in air background

Let us assume that the unit cell has a circular shaped region of high dielectric material ϵ_{high} that is surrounded by a material with low dielectric constant ϵ_{low} . This structure would be realised by a square lattice of dielectric rods placed in a vacuum or air background as already shown in Figure 3.5a. In this simple case, the distribution of the dielectric material can be easily described by the ratio of the rods' radius $r' = r/a$. As we have learned in Chapter 2, it makes sense to normalize all structural parameters of the dielectric lattice to the lattice constant and use dimensionless variables. Therefore the square lattice of dielectric rods would

be described by the relative rod radius r' , and the dielectric contrast $E = \frac{\epsilon_{high}}{\epsilon_{low}}$. We will look at

the band structure of such a square lattice for the dielectric constants $\epsilon_{high}=10$ and $\epsilon_{low}=1$, and for a relative radius $r'=0.3$ (see Figure 3.6). It can be seen that this structure exhibits a number of band gaps for TM modes (modes with their electric field oriented along the axis of the rods), while there is no band gap for TE modes.

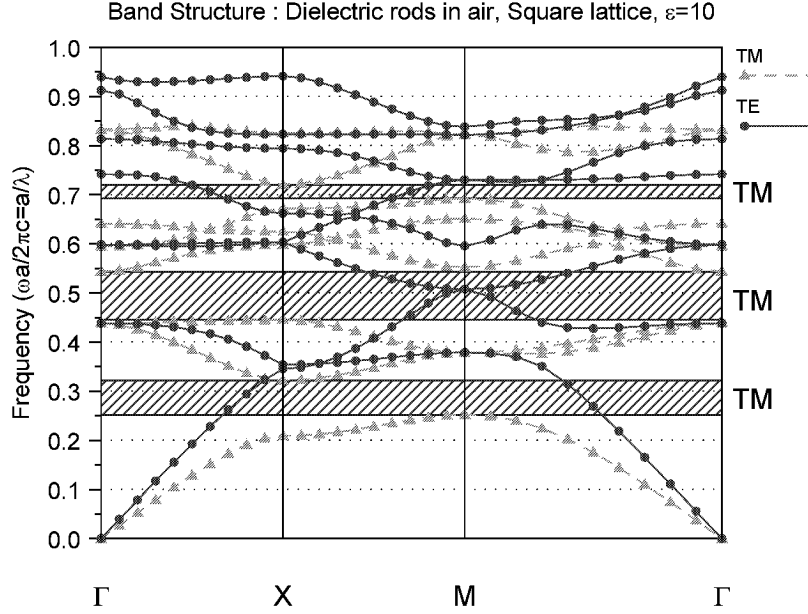


Figure 3.6: Band structure of the square lattice of dielectric rods of relative radius $r'=0.3$ with $\epsilon_{high}=10$ in a background material with $\epsilon_{low}=1$. The structure exhibits three band gaps for TM modes and no band gap for TE modes

Figure 3.7 shows the dependence of the band gaps on the relative rod radius. From this picture we can learn an interesting fact about the behavior of the band gaps for TM waves in this structure: With increasing relative rod radius, the size of the band gaps shrinks. At a value of $r'=0.45$, where the dielectric rods almost touch each other, all gaps are vanished. This behavior suggests that band gaps for TM modes are only possible in periodic lattices of dielectric material where the regions of high dielectric constant material do not touch each other.

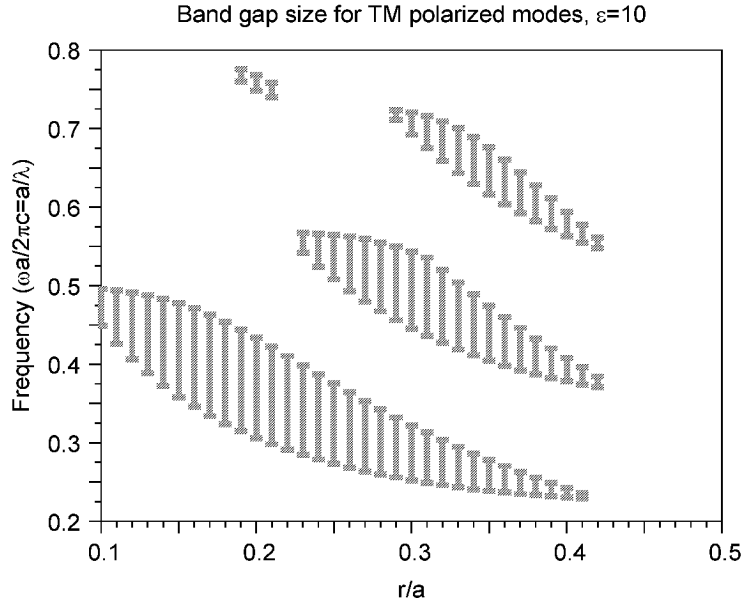


Figure 3.7: Dependence of the band gap size for TM polarized modes on the radius of the dielectric rods. There are several band gaps for TM modes and no band gap for TE modes. With increasing rod radius the gaps shrink and vanish when the rods almost touch each other.

Air holes in dielectric background

As a second case we will investigate the inverted form of the above lattice, where a region of low dielectric material ϵ_{low} is surrounded by a background of high dielectric material ϵ_{high} . This structure would be realised by a square lattice of air holes drilled in a block of dielectric material. In figure 3.8 we have plotted the band structure for a relative hole radius of $r/r=0.45$, and we can notice some differences from the previous example:

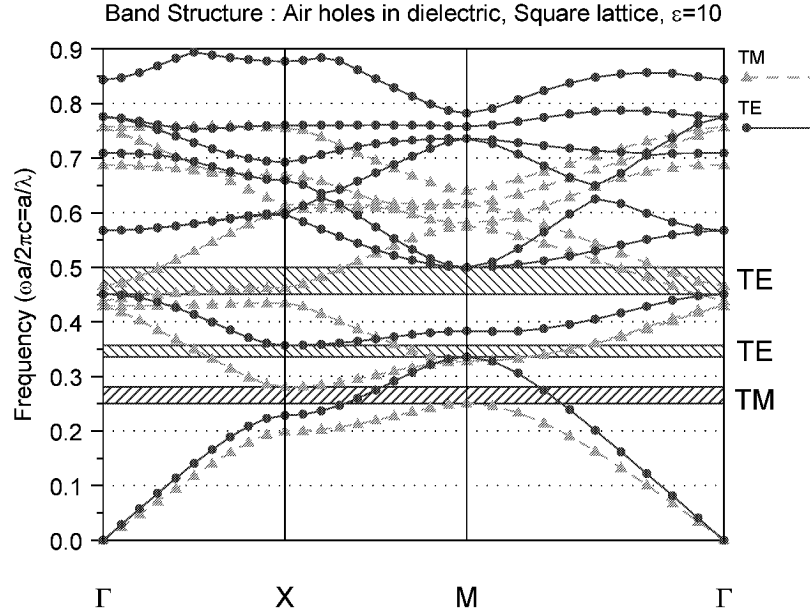


Figure 3.8: Band structure of the square lattice of air holes with $\epsilon_{low}=1$ in a background dielectric background material with $\epsilon_{high}=10$. The structure exhibits two band gaps for TE modes and a small band gap for TM modes.

In this case we can observe band gaps for both TE and TM waves. Nevertheless, we can still observe a similar behavior as observed in our first example: band gaps for TM waves exist only when the relative radius of the holes reaches the value of 0.5, where the air regions are overlapping and isolated regions of dielectric material begin to form. As long as the relative radius is below 0.5, the high dielectric material forms connecting structures that separate the low dielectric regions from each other, and we can conclude that the existence of a band gap for TE waves is due to these interconnections.

Contrary to the previous case, the frequency of the band gaps increases with increasing relative radius r' . This is due to the fact that in the case of patterned holes, with increasing relative radius, the amount of air increases. Thus, the average dielectric constant over the unit cell decreases and the modes are increased in frequency in order to keep their amount of electromagnetic energy constant.

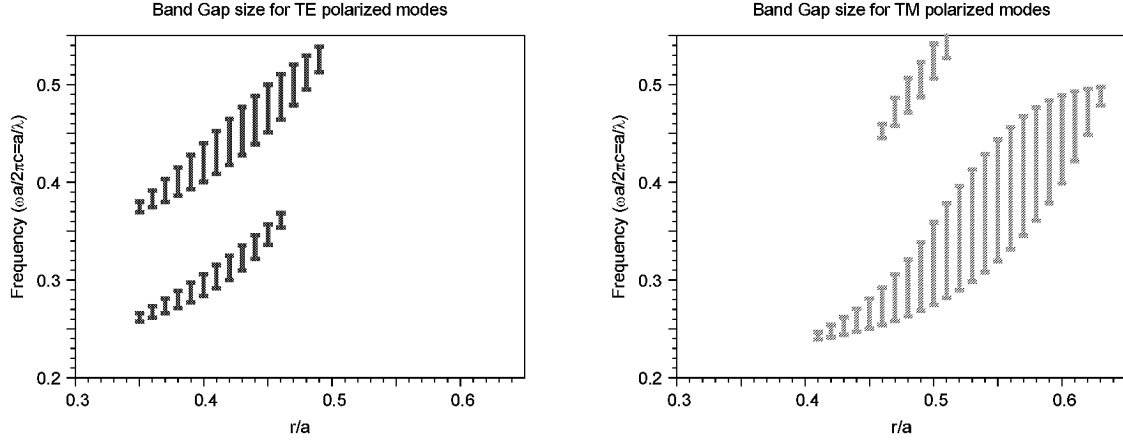


Figure 3.9: Dependence of the band gap size on the radius of the air holes. Several band gaps for both TE and TM modes can be observed. For small hole radii band gaps for TE modes are dominating, while for overlapping holes band gaps for TM modes are dominating.

Altogether we can note for the general behavior of 2D EBG lattices:

- Isolated regions of high dielectric material in a background of low dielectric material lead to band gaps for TM modes.
- Connected regions of high dielectric material between islands of low dielectric material lead to a band gap for TE modes.

Keeping this in mind, we can suppose that a 2D lattice structure that can support a band gap for both TE and TM modes simultaneously must consist of both interconnected and isolated regions of high dielectric material. It has been reported in the literature that a hexagonal arrangement of air or dielectric rods nearly meets these requirements[15] [18][48]. The dielectric regions between 3 lattice elements act as isolated spots, while the dielectric regions between two lattice elements act as interconnecting structures. As this structure seems promising for a large band gap for both polarisations, we will examine the hexagonal lattice structure closer.

The 2D hexagonal lattice

The hexagonal lattice is characterised by the two primitive vectors $\vec{a}_1 = a \cdot \vec{e}_x$, $\vec{a}_2 = a \cdot \vec{e}_x \cdot \sin 60^\circ + a \cdot \vec{e}_y \cdot \cos 60^\circ$. The Brillouin zone of this lattice is also hexagonal, and the irreducible Brillouin zone is characterized by a triangular shape between the major symmetry points Γ , K and M. These symmetry points correspond to the lattice vectors $\vec{k}_\Gamma = 0$, $\vec{k}_K = \pi / (a \cdot \sin(60^\circ) \cdot \vec{e}_x) + \pi / (a \cdot \cos(60^\circ) \cdot \vec{e}_y)$, $\vec{k}_M = \pi / a \cdot \vec{e}_y$ (see figure 3.10a).

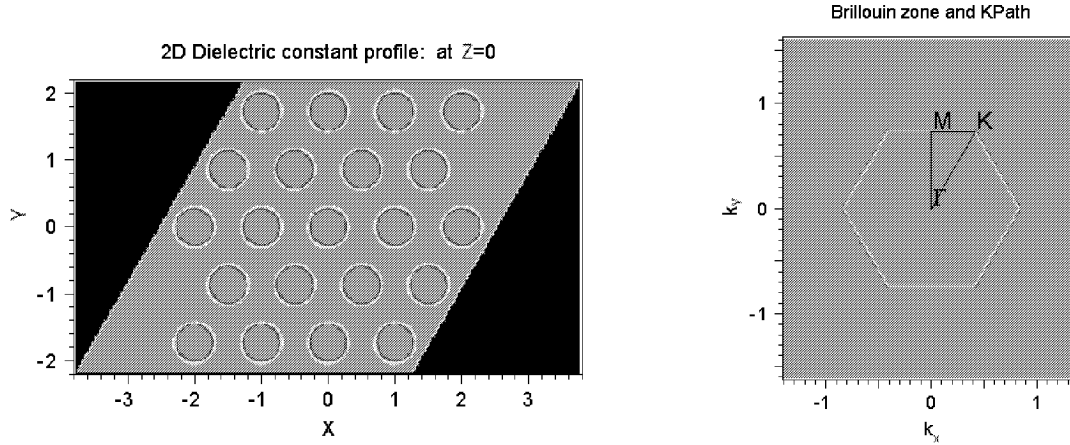


Figure 3.10: a) Distribution of the dielectric material in a hexagonal lattice. The lattice elements have a circular shape and are separated by a lattice constant a . b) First Brillouin zone of the hexagonal lattice. The main symmetry points are denoted by Γ , M and K .

Again, we will study the band structure and the dependence of band gap position and size on relative radii for both a dielectric rods structure in air background and an air holes structure in dielectric background.

Dielectric rods in air background

We will start with the investigation of a structure of dielectric rods of infinite length along the z direction, that are arranged in a hexagonal lattice in the x - y plane. In Figure 3.11 the band structure for TE and TM waves propagating in such a lattice is displayed, for a relative radius of $r/r=0.3$. We can observe that there are only two band gaps for TM waves, which look very similar to the band gaps in the case of a square lattice. Additionally, there is a small band gap for TE waves.

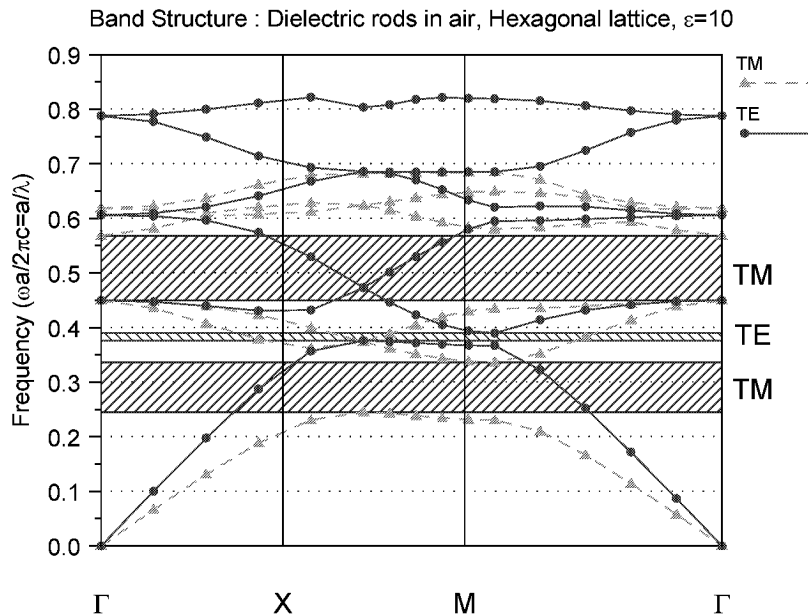


Figure 3.11: Band structure of the hexagonal lattice of dielectric rods with $\epsilon_{high}=10$ in a background material with $\epsilon_{low}=1$. Two large band gaps for TM modes can be seen, while there is only a small band gap for TE modes.

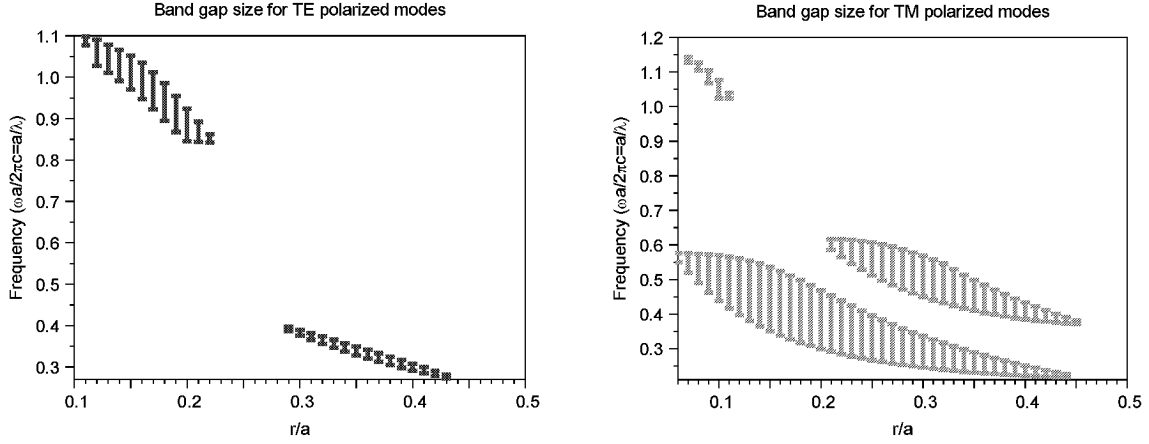


Figure 3.12: Dependence of the band gap size on the radius of the dielectric rods. Several band gaps for both TE and TM modes can be observed, but the band gaps for TM modes are dominant.

The dependence of the band gap width and position on the rods radius as shown in figure 3.12 shows that even though band gaps for both polarisations can exist simultaneously for relative radii below $r\tau=0.22$ and above $r\tau=0.28$, these band gaps do not overlap, so a complete band gap for both polarisations does not exist. As the origin of the band gap is due to the different dielectric constants in the lattice, it is an important question how the size of the existing band gaps is dependent on the dielectric constant of the rods, and whether a complete band gap can exist for a higher dielectric constant. Figure 3.13 shows the dependence of the band gap widths on the dielectric constant of the rods for a relative radius of $r\tau=0.35$. It can be observed that generally for an increasing dielectric constant the size of the band gap grows. Even though the band gaps for TE and TM waves come very close and almost touch each other, there is no overlapping and a complete band gap does not exist.

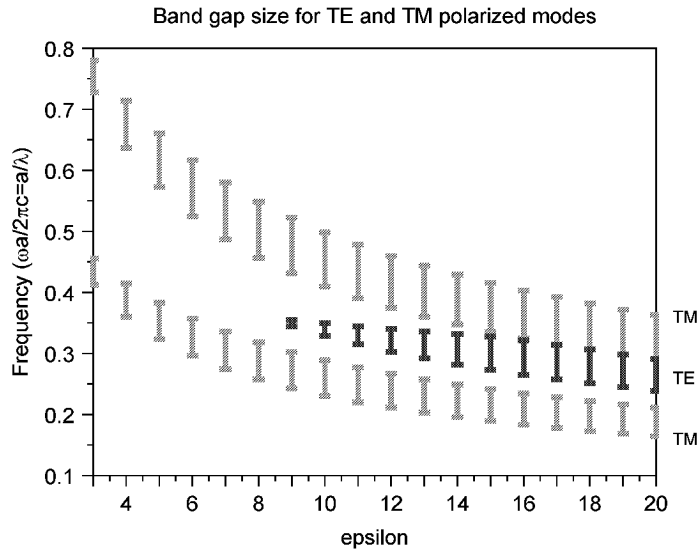


Figure 3.13: Dependence of the existence of band gaps for TE and TM waves on the dielectric constant of the rods for a rod radius $r\tau=0.35$. It can be seen that there is no overlapping band gap region, even though the both gaps come very close for high dielectric constants above 15.

In the case of a square lattice, the inverse structure of periodically patterned holes had already yielded a small complete band gap. Therefore it can be expected, that the inverse hexagonal lattice of air holes in dielectric background will also possess a band gap for both polarisations simultaneously.

Air holes in dielectric background

Fig 3.14 shows the band structure for TE and TM waves propagating in a hexagonal lattice of holes with relative radius $r/r=0.45$.

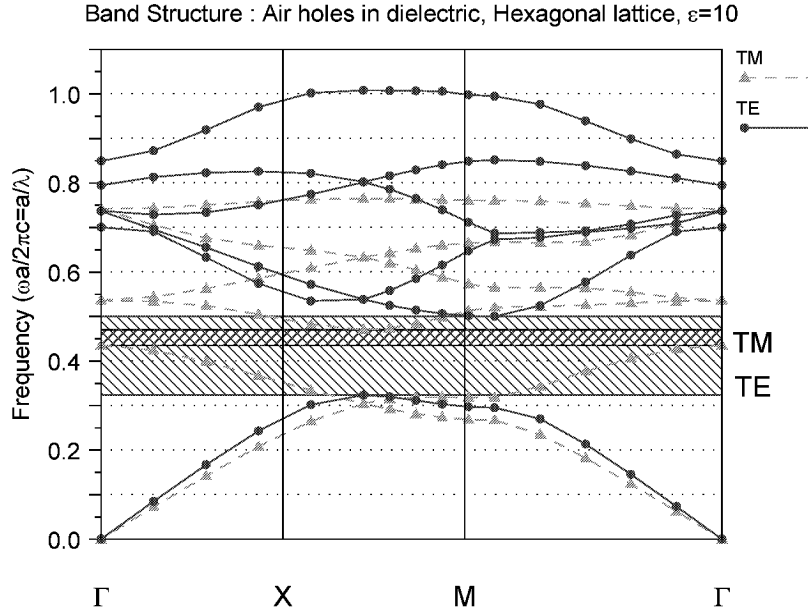


Figure 3.14: Band structure of the hexagonal lattice of air holes with $\epsilon_{low}=1$ in a background dielectric background material with $\epsilon_{high}=10$ and relative radius $r/r=0.45$. The structure exhibits a large band gap for TE modes and a small band gap for TM modes

Contrary to the case of a square lattice we can observe only one band gap for TE waves, but this band gap is much larger, with a gap-midgap ratio of $\frac{\Delta\omega}{\omega_0}=0.43$. Also there is an

overlapping band gap for TM waves. From Figure 3.15 it can be seen that there is a complete band gap for both TE and TM waves for a range of relative radii from 0.41 up to 0.5, with a maximum of $\frac{\Delta\omega}{\omega_0}=0.78$ at a relative radius of $r_{max}/r=0.48$ (see Figure 3.16 for the band

structure of the lattice in this case). In this case we can even observe a second smaller complete band gap opening up at higher relative frequencies of about 0.8.

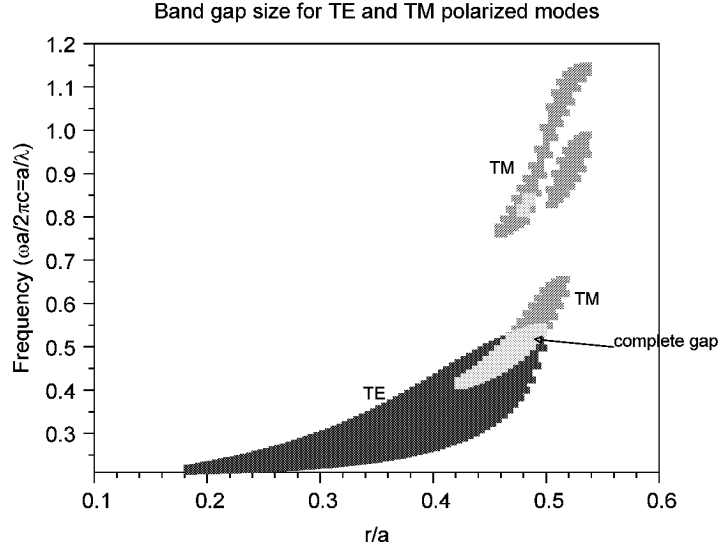


Figure 3.15: Dependence of the band gap size on the radius of the high dielectric rods. There are several band gaps for both TE and TM modes, but the TM band gaps are dominant. There is a region of overlapping band gaps for relative hole radii of more than 0.41.

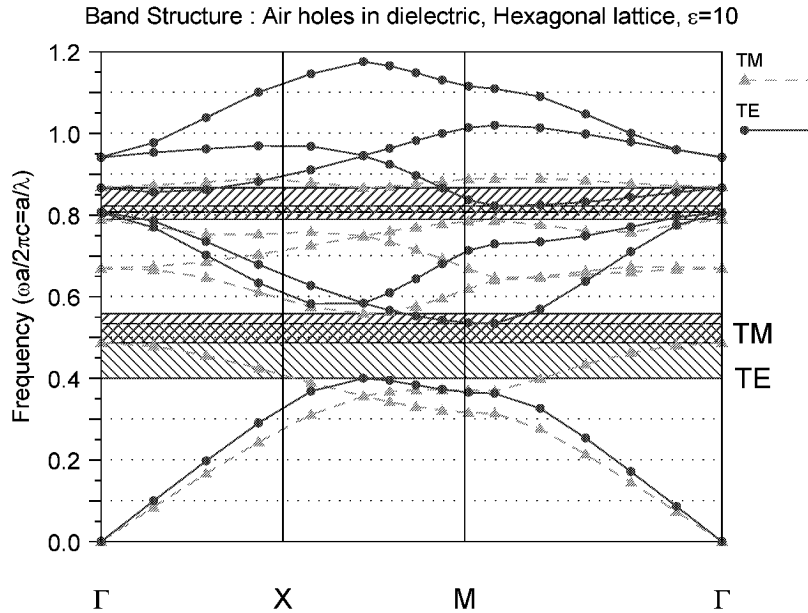


Figure 3.16: Band structure for the hexagonal lattice of holes in dielectric background material for a relative hole radius of $r_{\max} r=0.48$. The structure exhibits two overlapping areas with complete band gaps for both TE and TM modes simultaneously.

Again, the dependence of the band gap size on the dielectric constant will be investigated for the case of a relative rod radius of $r r=0.48$. In figure 3.17, the dependence of the band gap size for TE and TM polarisation, as well as the size of the complete band gap is plotted for a varying dielectric constant of the background material.

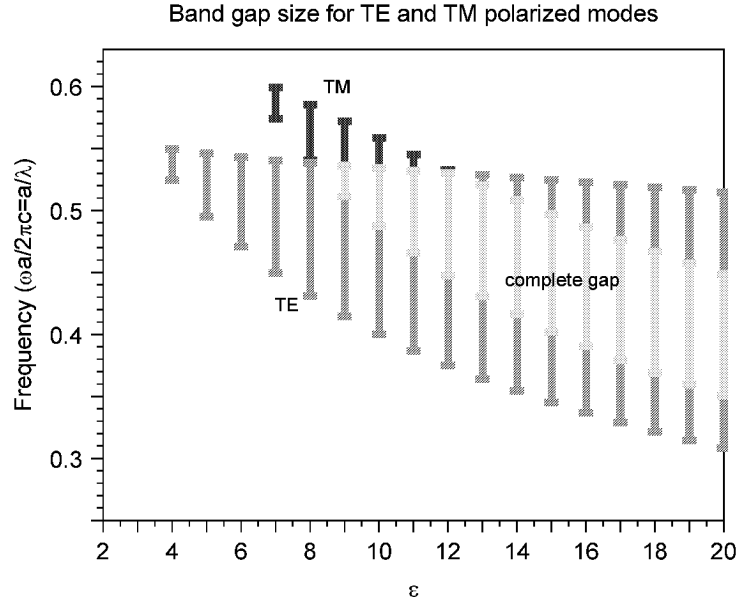


Figure 3.17: Dependence of the existence of band gaps for TE and TM waves on the dielectric constant of the background material for a holes radius $r=0.48$. With increasing dielectric constant both gaps grow and there is a large region, where both gaps overlap and a complete band gap exists.

In conclusion it can be said that in a 2D EBG lattice, a hexagonal arrangement of lattice elements can yield a large band gap for TE or TM polarised waves if holes or rods are used, respectively. Also it is possible to create a relatively large complete band gap if the hexagonal array of holes in dielectric is used and the dielectric contrast is sufficiently large (greater than 8). For a microwave application that can utilize TE polarised modes, the hexagonal hole array is therefore the lattice structure of choice, while for an application where TM modes have to be used, an array of dielectric rods should be employed.

3.4 - Point defects in EBG structures

So far we have discussed periodic dielectric materials, that exhibit a band structure for their allowed electromagnetic mode frequencies, with regions of zero density of states, the so-called band gaps. The description of such a system is based on the Bloch-Floquet-description of eigenmodes and the definition of a reciprocal lattice (see chapter 2). However, the definition of a reciprocal space and the band structure considerations that follow from it are valid only for a system with perfect translation symmetry. If the symmetry of the system is locally broken, the band structure description of the electromagnetic mode spectrum will not be at this point, and an electromagnetic state with a frequency in the band gap of the surrounding lattice can be excited. This defect state will be confined to the position of the defect and may not propagate into the surrounding lattice [7][49][50] [51]. In this part of the chapter we will present an approach for the mathematical description of EBG defect modes and discuss the frequencies and mode patterns of point defect modes for a varying shape of the defect. Furthermore we will investigate the properties of line defect modes and describe a defect waveguide in an EBG lattice.

Theoretical description of EBG defect states

In a periodic dielectric lattice the electromagnetic fields will be of the form of Bloch waves $\vec{E}_{n,\vec{k}}(\vec{r})$ and $\vec{H}_{n,\vec{k}}(\vec{r})$ [18] [19] [20]. A description of a localized defect mode at the lattice position $\vec{R}$ can be achieved by a development of the electromagnetic field into a set of localised basis functions that also contain all the information about the surrounding periodic lattice. These functions are called Wannier functions and they are created by a Fourier transform of the extended Bloch functions $\vec{E}_{n,\vec{k}}(\vec{r})$, associated to a frequency range covered by the band n , and centered around the lattice point $\vec{R}$ [19][20] [52].

$$W_{n,\vec{R}-\vec{R}'}(\vec{r}) = \frac{V_{WSC}}{(2\pi)^2} \int_{BZ} d^2\vec{k} \cdot e^{-i\vec{k}(\vec{R}-\vec{R}')} \vec{E}_{n,\vec{k}}(\vec{r}) \quad (3.2)$$

The electric field $\vec{E}(\vec{r})$ that is a solution of the wave equation in the frequency domain form

$$\nabla^2 \vec{E}(\vec{r}) + \left(\frac{\omega}{c}\right)^2 \{\epsilon_p(\vec{r}) + \delta\epsilon(\vec{r})\} \vec{E}(\vec{r}) = 0 \quad (3.3)$$

can then be expanded into a series

$$\vec{E}(\vec{r}) = \sum_{n,\vec{R}} \vec{E}_{n,\vec{R}} W_{n,\vec{R}}(\vec{r}) \quad (3.4)$$

Inserting this equation into the wave equation leads to a matrix equation

$$\sum_{m,\vec{R}'} \{\delta_{n,m} \delta_{\vec{R},\vec{R}'} + D_{\vec{R}\vec{R}'}^{nm}\} E_{m\vec{R}'} = \left(\frac{c}{\omega}\right)^2 \sum_{m,\vec{R}'} A_{\vec{R},\vec{R}'}^{n,m} E_{m,\vec{R}'} \quad (3.5)$$

which can be solved by numerical means as described in the previous chapter. The localisation of the solutions is given by the exponential term in the Wannier functions (3.2) that decays with increasing distance $(\vec{R} - \vec{R}')$.

In the following chapter we will distinguish between two types of defects:

-Localised point defects:

In a localised defect, the dielectric lattice is disturbed at a single point or an area of the order of not more than a few lattice periods (zero dimensional defect). We will expect a defect state in the band structure of such a system, that has a frequency in the band gap of the surrounding lattice. It is interesting to investigate the dependence of the defect mode frequency on the shape of the defect and its dielectric constant relative to the regular lattice element it replaces. Furthermore, it is interesting to investigate the mode patterns of such a defect mode and the strength of their confinement by the surrounding lattice. Also, the amount of energy of the defect mode stored in the dielectric material, is of importance, as it determines the material quality factor of the defect mode (see chapters 1,5).

-Extended defects:

In an extended defect, the periodic lattice is disturbed in one or two dimensions, which will lead to a line defect (one dimensional defect) or a plane defect (two dimensional defect). We expect that there will be the possibility for a mode to propagate along such a defect. It is interesting to investigate the dispersion of such defect modes dependent on the shape of the defect and its dielectric constant relative to the surrounding lattice.

Zero dimensional defects (point defects) in EBG lattices

Zero dimensional defects or point defects in EBG structures can be utilised in a number of ways: a defect mode can act as a resonator, a combination of several defect modes can act as a filter. Furthermore, a linear arrangement of point defect modes can also act as a waveguiding structure, very similar to a one dimensional (line) defect. For the description of point defect modes there are two parameters that describe their behavior: The frequency of a defect mode and its mode pattern (field distribution of electric and magnetic fields in the defect). In this chapter we will investigate how these parameters change depending on the shape of the defect. In our considerations we will focus on the case of a point defect in a two dimensionally periodic EBG structure made from a hexagonal arrangement of dielectric rods.

Variation of single lattice elements

Let us assume that at some point in the lattice one of the dielectric rods is changed. This change can be either a change in the size of the rod, keeping its dielectric constant equal to that of the surrounding rods, or a change in the dielectric constant of the rod material, keeping its shape constant. The situation for a defect created by an increased rod radius is displayed in Figure 3.18.

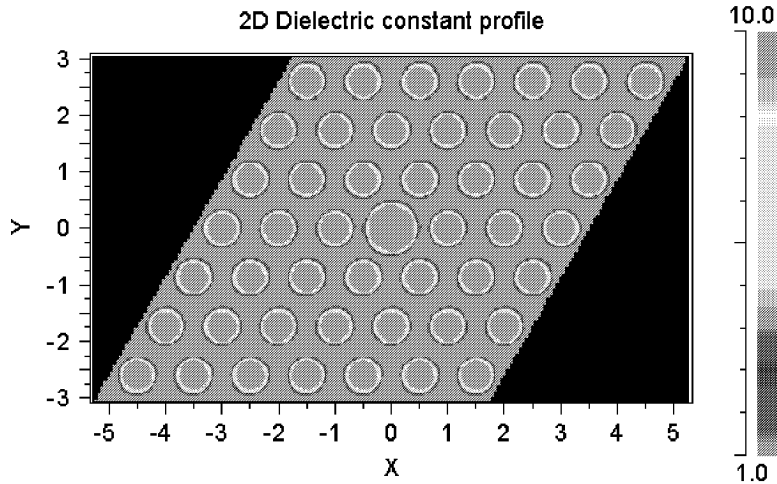


Figure 3.18: Distribution of the dielectric material in a hexagonal lattice. At one lattice point the size of a lattice element is changed to create a point defect.

First we will calculate the band structure of such a defect lattice for a varying shape (radius) of the defect rod given by the ratio of defect rod radius r_{defect} to nominal rod radius r_0

$$\Delta_r = \frac{r_{defect}}{r_0} \quad (3.6)$$

In figure 3.19 we plot the frequency of a defect mode within the first band gap for TM waves in dependence on the radius of the defect rod. For $r_{\text{defect}} = 0$ (no rod at all) we can observe a defect mode with a frequency very close to the upper band edge (air band). When r_{defect} is increased, the defect state out of the air band is being pulled down into the band gap. When the r_{defect} approaches r_0 (no defect anymore), the defect modes vanishes in the dielectric band. The non existence of a defect mode for radii $r_{\text{defect}} \approx r_0$ is due to the finite resolution of our simulation tool, a plane wave expansion solver as explained in chapter 2.5, which in these settings can not resolve the small difference between the defect rod and the surrounding rods.

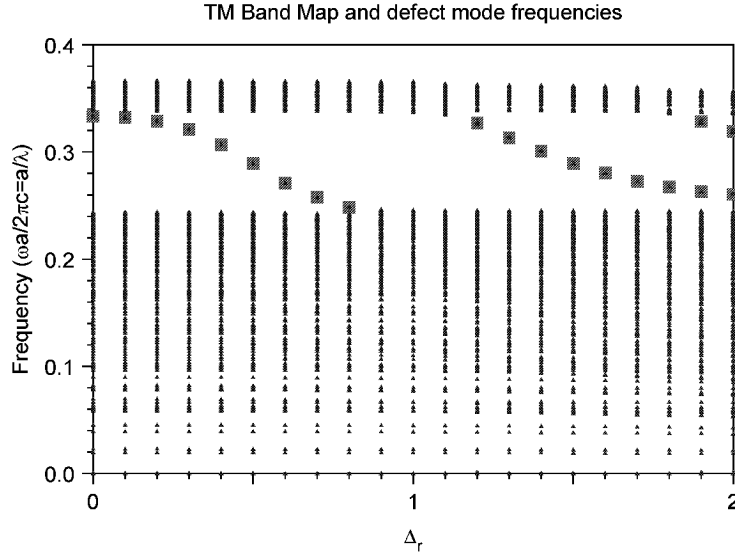


Figure 3.19: Frequency of a point defect mode in the 2D hexagonal EBG lattice. The defect mode is pulled down from the air band for an increasing defect radius and when $r_{\text{defect}} \approx r_0$ it vanishes into the dielectric band. For further increased radius, a second mode is pulled down from the air band.

When r_{defect} is further increased to be larger than r_0 , second order defect modes are pulled out of the air band. These modes show the same behavior for increasing rod radius: their frequencies go down and finally the modes vanish into the dielectric band.

We can conclude, that the removal of high dielectric material from the lattice will lift a mode out of the dielectric band into the band gap towards the air band, while the adding of additional high dielectric material will pull a mode out of the air band into the band gap towards the dielectric band. From this conclusion we can already guess, what the behavior of a defect mode frequency will be, when the dielectric constant is varied from the one of the surrounding lattice. We can expect that an increase of the dielectric constant will act very similar to an increase of the volume of the dielectric material, i.e. an increase of the defect rod radius. Figure 3.20 shows the frequency of the defect modes dependent on the dielectric constant of the defect rod, given by the ratio

$$\Delta_\varepsilon = \frac{\varepsilon_{\text{defect}}}{\varepsilon} \quad (3.7)$$

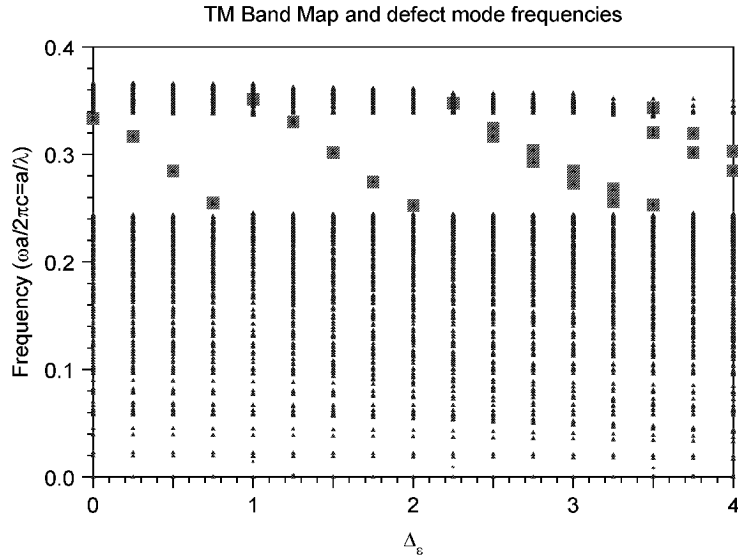


Figure 3.20: Dependence of the defect mode frequency on the dielectric constant of the defect rod. The same behavior as for an increased radius can be found. For high Δ_ϵ there is more than one defect mode related to the defect rod.

It can be noted that an increase of the dielectric constant at a defect has a similar effect as observed for an increase of the volume of dielectric material: an increasing of ϵ_{defect} pulls a mode down from the air band into the band gap. A difference occurs for larger Δ_ϵ : there is more than one mode being pulled down from the air band. A calculation of the defect mode field pattern can reveal the difference between those modes.

Defect mode patterns

We have mentioned before that in addition to the frequency of a defect mode, the mode pattern is of interest. In case of non fundamental, higher order defect modes (in above example the modes for $r_{\text{defect}} > r_0$ or $\epsilon_{\text{defect}} > \epsilon$), we can see that there is more than one mode being pulled down from the air band.

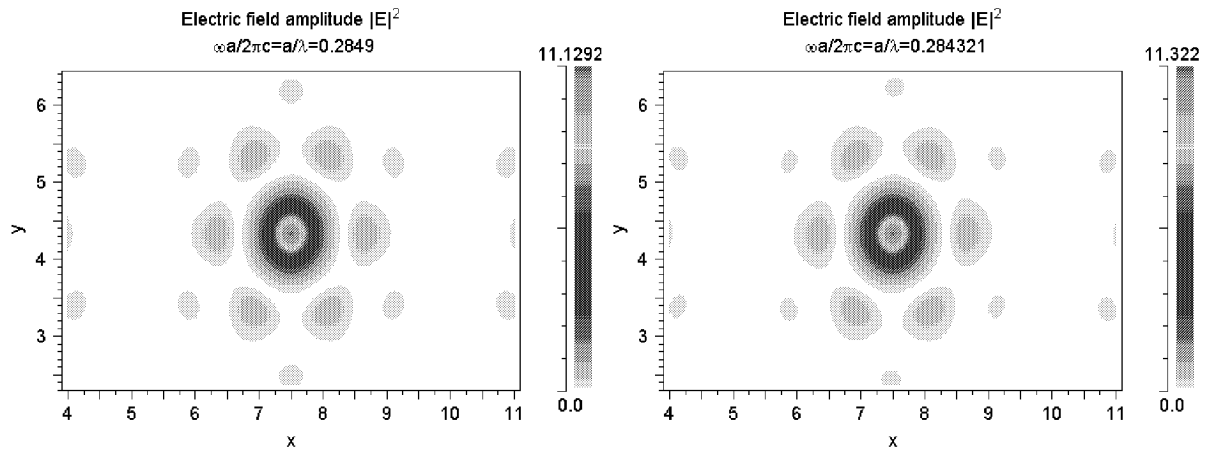


Figure 3.21: Electric field amplitude of the defect mode for left side: $\epsilon_{\text{defect}} = 0.5 \cdot \epsilon$, Right side: $r_{\text{defect}} = 0.5 \cdot r_0$. For both decreased size and decreased dielectric constant of the defect the mode pattern is almost identical.

We can calculate the defect mode patterns for $\varepsilon_{\text{defect}} < \varepsilon$ or $r_{\text{defect}} < r_0$ (“small” defect) as well as for $\varepsilon_{\text{defect}} > \varepsilon$ or $r_{\text{defect}} > r_0$ (“large” defect) in order to see what the difference between lower and higher order modes is. In Figure 3.21 the mode pattern of a defect mode is displayed for the case of $\varepsilon_{\text{defect}} < \varepsilon$ or $r_{\text{defect}} < r_0$. It can be seen that in case of a lower order defect mode the mode pattern is a monopole with zero field minima in the angular direction. The mode pattern is identical for both a smaller dielectric constant and smaller rod radius at the defect. Also the relative defect mode frequency given by $\frac{\omega a}{2\pi c}$ is almost identical.

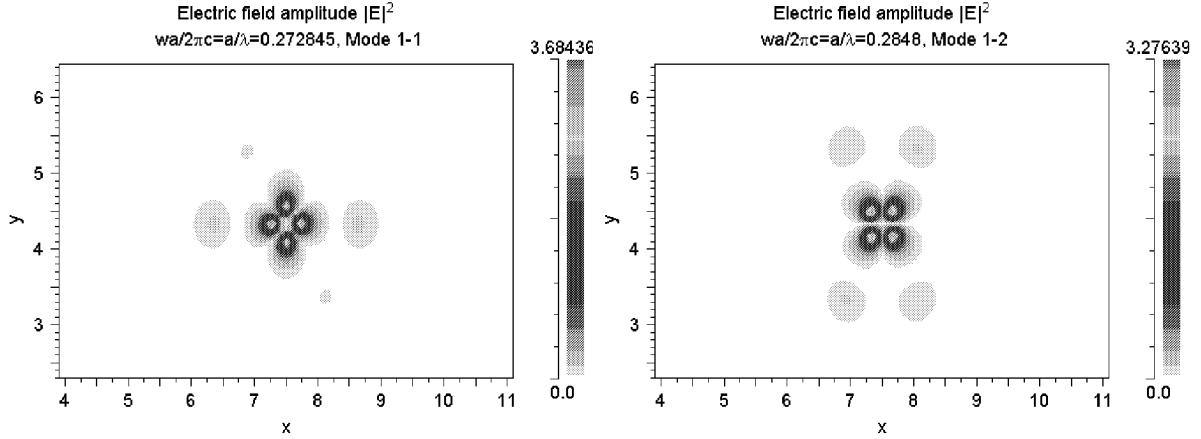
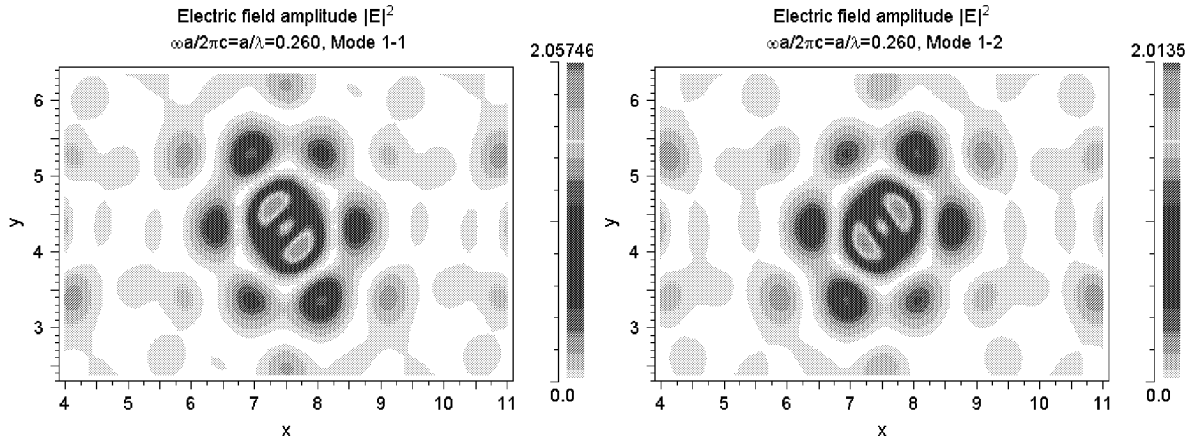


Figure 3.22: Electric field amplitude of the higher order defect modes for $\varepsilon_{\text{defect}} = 3 \cdot \varepsilon$. There are two modes with a higher order field pattern (four nodes of the field distribution in angular direction). Due to the fact that the surrounding lattice does not possess a 90° symmetry, the frequencies of the modes are not degenerate.

Figures 3.22 and 3.23 show the field patterns of the higher order defect modes for increased dielectric constant or radius of the defect rod. The higher order defect modes exhibit a number of nodes in their field distribution. For $\varepsilon_{\text{defect}} > \varepsilon$ there are two modes with four nodes in the angular direction, and for $r_{\text{defect}} > r_0$ there are two modes with four nodes in the angular direction and two nodes in radial direction and two nodes in angular direction.



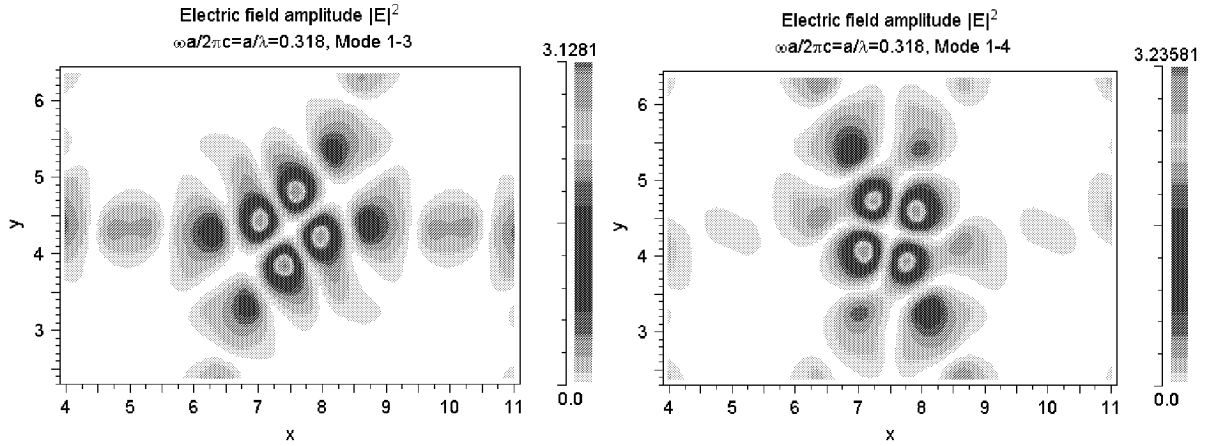


Figure 3.23: Electric field amplitude of the higher order defect modes for $r_{\text{defect}} = 2 \cdot r_0$

In summary we can conclude that the effect of a defect on the spectrum of allowed and forbidden modes is determined by both its spatial deviation from the lattice standard, given by Δ_r , and its deviation in dielectric constant from the lattice standard, given by Δ_ϵ . We can therefore conclude, that the “size” of a point defect in an EBG material is not given by either of these two values, but by their product

$$\Delta_{\text{tot}} = \Delta_r \cdot \Delta_\epsilon \quad (3.8)$$

With increasing Δ_{tot} we can observe defect modes with higher mode indices in the band gap. For defects where the defect “size” is increased a mode is pulled down from the air band, while for defects where the defect “size” is decreased, a mode is lifted from the dielectric band.

Large one dimensional defects

We have seen that in the case of a defect, where either the lattice element size or the material of the defect vary strongly from the surrounding lattice elements, there will be higher order modes that can exist at the defect position. To further investigate this situation, we simulate a large point defect in a 2D EBG structure, where not only one rod has been removed from the lattice, but also its six surrounding rods. The band gaps for this lattice structure have been found to be

$$\Gamma_1 = 10.06 \text{ GHz} \rightarrow 14.22 \text{ GHz}$$

$$\Gamma_2 = 19.12 \text{ GHz} \rightarrow 23.78 \text{ GHz}$$

$$\Gamma_3 = 28.73 \text{ GHz} \rightarrow 32.72 \text{ GHz}$$

It can be observed, that additionally to the monopole and dipole modes already shown in the previous part of the chapter, there are other, higher order modes with frequencies in the band gaps of the structure. In figure 3.24, the field distributions of the modes are shown.

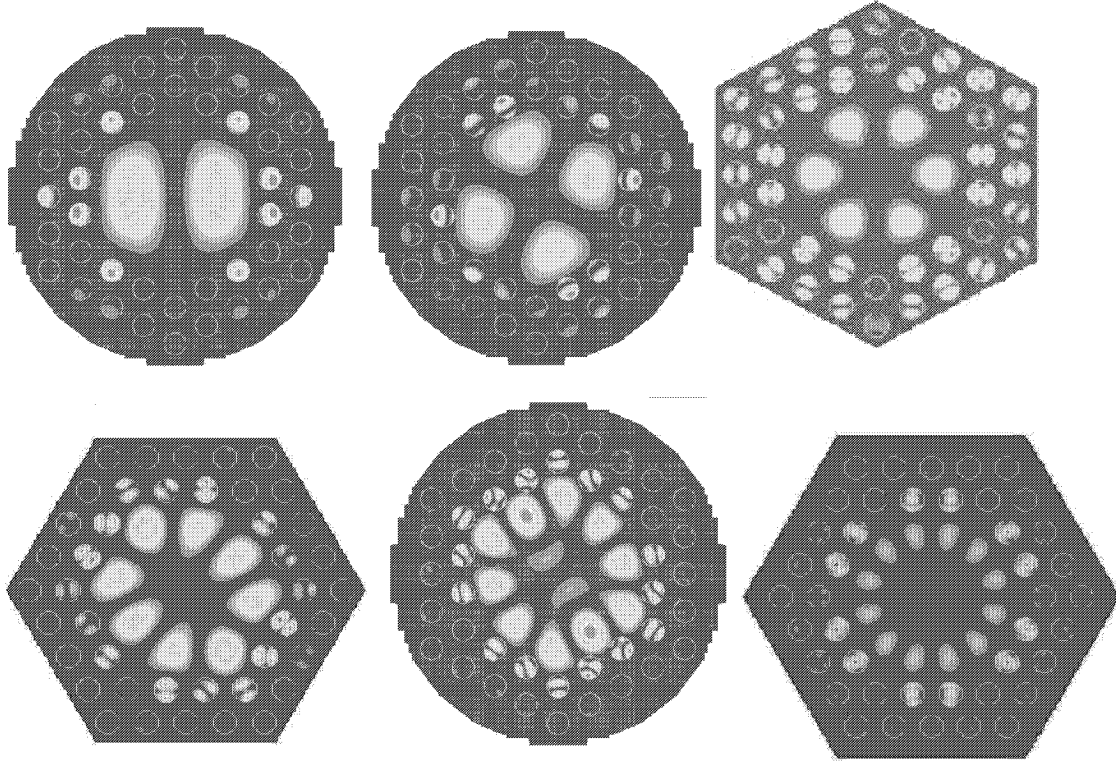


Figure 3.24: Distribution of the electric field density for various defect modes in a large point defect in a 2D hexagonal EBG lattice. For higher mode frequencies and corresponding higher band gaps of the lattice the order of the modes increases.

It can be seen clearly, that the mode patterns are very similar to cavity resonator TM modes. In table 3.1 we have put together the mode pattern, the mode frequency, the dielectric filling factor κ_{diel} and the distance of mode frequencies of EBG defect modes and corresponding cavity resonator mode frequencies. The according cavity resonator size was fitted from the frequency of the lowest order mode, so that in this case the defect mode frequency and the cavity resonator mode frequency coincide[53][54].

Mode Nr.	Mode pattern	Frequency (GHz)	κ_{diel}	Δf (GHz)
1	TM 110	10.36	0.37	0
2	TM 210	12.68	0.28	-1.21
3	TM 310	12.71	0.69	-4.54
4	TM 410	20.04	0.31	-0.48
5	TM 510	22.08	0.28	-1.64
6	TM 710	28.21	0.56	1.35

Table 3.1: Summary of mode pattern, defect mode frequency, dielectric filling factor and frequency distance from the corresponding cavity mode

In figure 3.25, the mode frequencies for the EBG and cavity resonator modes are plotted in a diagram. The error bars that are attached to the EBG defect mode frequencies resemble the dielectric filling factors κ_{diel} .

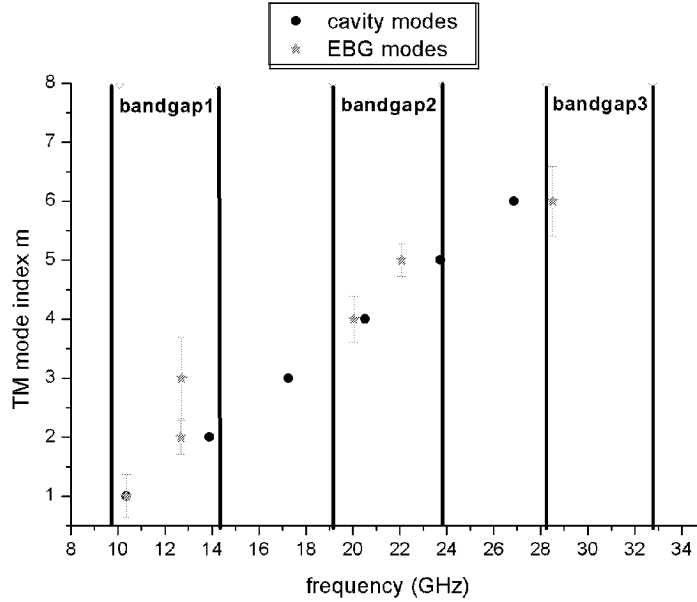


Figure 3.25: Comparison of mode frequencies for EBG defect modes in a large point defect and cavity resonator modes for a cylindrical cavity resonator with corresponding radius. The error bars indicate the dielectric filling factor κ_{diel} of the mode.

Two things can be observed:

- The mode frequencies of the EBG defect modes are always located in the band gaps, even if the corresponding cavity mode frequency is not.
- When a cavity mode frequency is outside the band gaps, the EBG defect mode frequency will differ strongly from it. For such defect modes, the dielectric filling factor is generally higher, as they need to extend into the dielectric lattice. These modes are forced to have frequencies in the band gap, even though their “natural” frequencies were outside. Therefore they do not fit into the defect very well and are less strongly localized than others. This delocalisation is then expressed in the dielectric filling factor κ_{diel} of the mode, which is large for a large frequency shift Δf .

3.5 - Line defects in EBG structures

When a number of neighbouring lattice elements is removed from the EBG lattice, a one dimensional defect (line) defect or a two dimensional defect (plane defect) is formed. In both cases, there is not only the possibility of the excitation of a defect mode with a frequency in the band gap of the EBG lattice, but also the mode can propagate along the defect. Such kinds of defects can act as passive transmission line elements (waveguides[8] [9][55][56][57], beam splitters[58][59] and couplers[60][61][62]). In this part of the chapter we will investigate the effect of a line defect on the band structure of an EBG lattice. We will focus on the case of a hexagonal lattice of both air holes in dielectric material and dielectric rods in air background, as these lattice types have been found to yield the largest band gaps for TE and TM modes, respectively. The line defect has in both cases been created by changing the size of a line of lattice elements along the $\Gamma - K$ direction of symmetry. As we have seen in the previous part of the chapter, the introduction of a point defect gives rise to a localised state with a frequency in the band gap. The defect mode can not propagate through the lattice and has therefore zero group velocity. It will appear in the band gap as a flat line inside the gap. In the case of a line

defect, a mode can travel along the defect. We can expect that such a defect mode will also exhibit a dispersion. In the following we will show the dispersion curves of various line defect modes for different defect types and deduce the waveguiding properties of the defect from these curves.

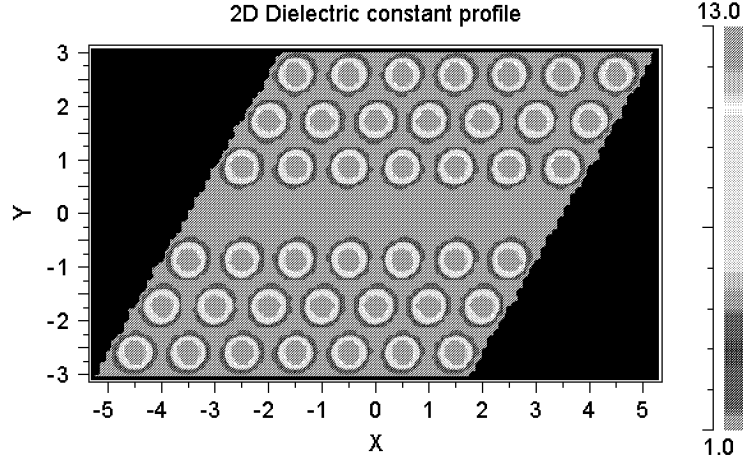
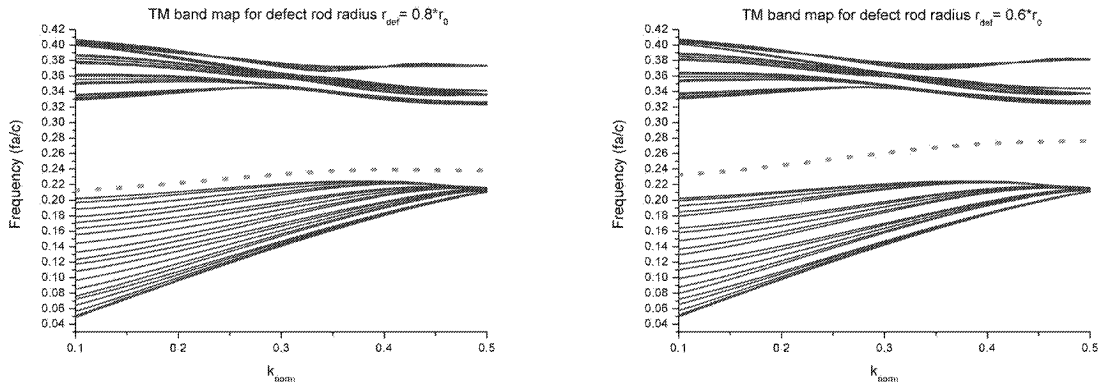


Figure 3.26: Distribution of the dielectric material in a 2D hexagonal EBG structure with a line defect, where one line of lattice elements has been removed.

When one line of dielectric rods is removed from the lattice, a line defect is created. This type of defect is called W1 defect[20], and the distribution of the dielectric material in this case is shown in figure 3.26. In the following figure 3.27, the reduced band structure of this array, where only wave vectors for the propagation of a mode along the defect have been taken into account, are shown for different radii of the rods forming the defect. The lattice rods had a relative radius of $r/r_0=0.3$ and a dielectric constant of 11.4. We can observe that when the radius of the defect rods is reduced, the behavior of the defect mode is very similar to the case of a point defect discussed before where a single dielectric rod was changed in size. A mode is lifted from the dielectric band and travels through the band gap when the size of the rods is further decreased. For zero defect radius the defect mode is already very close to the air gap.



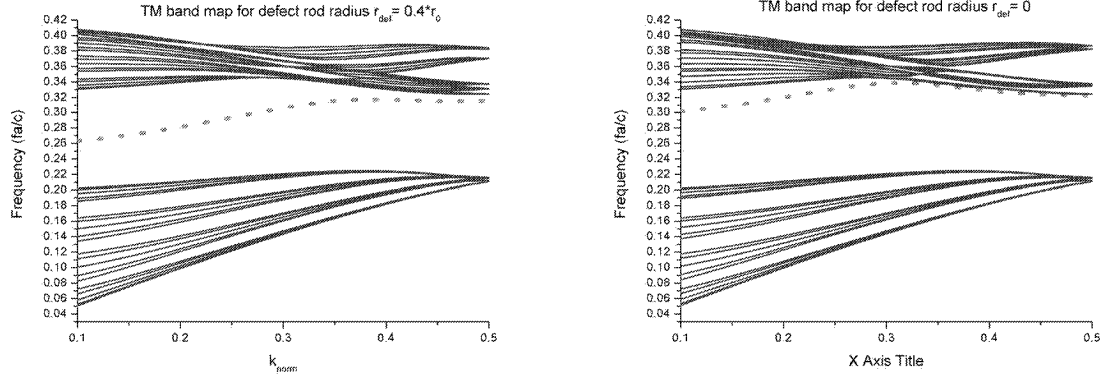
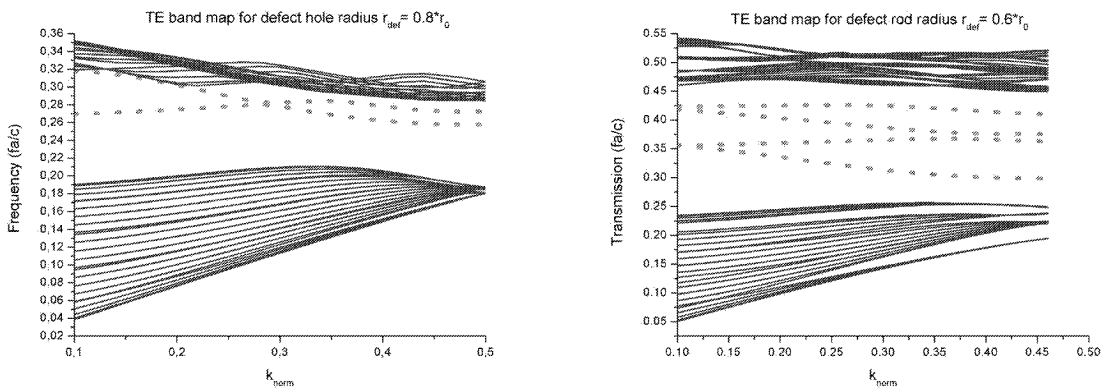


Figure 3.27: Reduced band structures for a line defect in a hexagonal lattice of dielectric rods. The lattice rods had a relative radius of $r_r=0.3$ and a dielectric constant of 11.4. For decreasing rod radius the defect mode given by the dotted line travels from the dielectric band to the air band. For all values of r' , only a single mode is observed.

This type of waveguide shows a single mode behavior: There is only one dispersion curve in the band gap. We can see that a W1 line defect can act as a single mode waveguide. The dispersion curve of the defect mode is very flat, in none of the cases does it cover the complete band gap. A waveguiding by this defect mode can therefore be expected only for a frequency range of the band gap and not for the total band gap.

In the previous part of the chapter we have observed, that if the radius of holes in the hexagonal lattice of air holes in dielectric background is changed to form a defect, a similar defect mode appears. However the defect mode was this time pulled down from the air band and was much more likely to support second order modes. We have investigated the line defect made from a changed radius of a line of air holes in dielectric. The holes had a relative radius of $r_r=0.45$ and the dielectric constant of the background material was 11.4.



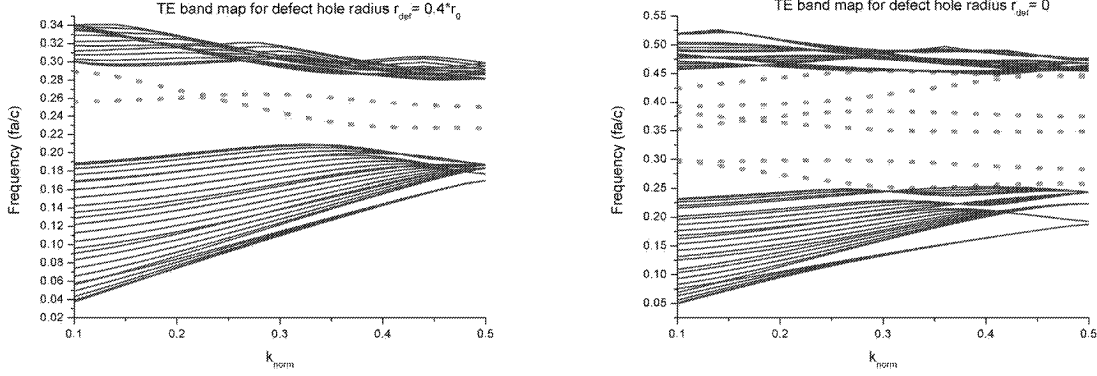


Figure 3.28: Reduced band structures for a line defect in a hexagonal lattice of air holes. The holes had a relative radius of $r/r=0.45$ and the background material had a dielectric constant of 11.4. For decreasing hole radius a number of defect modes given by the dotted lines travel from the air band to the dielectric band.

Reduced band structures for this defect type are shown in figure 3.28. It can be observed that, contrary to the rods defect, the holes defect exhibits a number of defect modes. A single mode behavior can not be observed. If the radius of the holes is further increased, the dispersion curves of the modes begin to overlap and the waveguide will become multimode. Another difference is, that the mode bands cover a much larger range of the band gap, and, for vanishing holes, the complete band gap is covered. It must be noticed here that by the introduction of this defect, the band gap of the surrounding lattice is not destroyed, as we have examined only a propagation along the direction of the defect. For other directions the band gap will still be existent. More work on this topic is shown in Chapter 6, where also the problem of an in-gap cutoff frequency is further addressed.

3.6 - 2D EBG slab structures

Total internal reflection

In the previous chapters it has been discussed, that a confinement of electromagnetic waves by Bragg reflection in a periodic dielectric medium is possible for an arbitrary direction of propagation, if the medium is three dimensionally periodic. Unfortunately, due to their complicated periodic structure, these 3D EBG structures are hard to fabricate, especially at higher frequencies where the structural elements approach the micrometre range and complex fabrication schemes have to be employed[6][63] [64]. A number of these fabrication schemes will be presented in chapter 4. Nevertheless, it is obvious that Bragg reflection is not the only way to confine electromagnetic waves. From the classical theory of electromagnetic waves at boundaries of material with different dielectric constants it is well known, that under certain conditions, the wave can be totally reflected at the boundary between the materials[40].

Let us assume a situation where a plane wave travelling in a medium with refractive index n_1 is incident on the boundary to a medium with another, larger refractive index n_2 under an angle θ_1 .

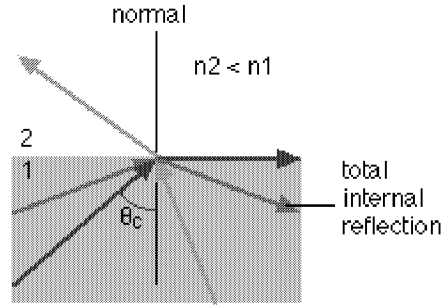


Figure 3.29: Reflection of a wave at an interface between two dielectric materials with refractive indices n_1, n_2 . For an incidence angle greater than the critical angle θ_c , the wave is completely reflected at the interface.

The angle, under which the outgoing beam travels into medium 2 is given by Snell's law:

$$n_1 \sin \theta_1 = n_2 \sin \theta_2 \quad (3.9)$$

$$\theta_2 = \arcsin \left(\sin \theta_1 \frac{n_1}{n_2} \right) \quad (3.10)$$

From this equation we can see, that when a wave is travelling from a medium with high dielectric constant into a medium with lower dielectric constant, there is a critical value for the angle of incidence above which the argument of the arc sin becomes greater than unity:

$$\sin \theta_c = \frac{n_2}{n_1} \quad (3.11)$$

When the angle of incidence is larger than θ_c , the wave is completely reflected at the boundary. This phenomenon is called total internal reflection.

2D dielectric slab modes

In chapter 1, it was shown that the solution of the wave equation for a homogenous medium with a fixed dielectric constant $\varepsilon(\vec{r}) = \varepsilon$ had the form of plane waves

$$H(\vec{r}) = H_{\vec{k}}(\vec{r}) = \vec{H}_0 \cdot e^{(i\vec{k}\vec{r})} \quad (3.12)$$

where $\vec{H}_0$ is a constant vector that denotes the orientation of the magnetic field and the translational symmetry of the homogenous space is described by the wave vector $\vec{k}$ that denotes how the wave behaves under an arbitrary translation. These waves have a transversal form ($\vec{k} \cdot \vec{H}_0 = 0$). The eigensolutions of the wave equation have eigenvalues (eigenfrequencies) that obey $(\omega/c_{med})^2 = k^2$. Let us now discuss a dielectric slab that consists of a plane with thickness a , infinitely extended in x and y direction and a dielectric constant ε_{slab} , surrounded by a cladding material with $\varepsilon_{cladding} = 1$. In this system the dielectric constant is invariant under a translation in the x-y-plane, but it varies in the z-direction. The x- and y component of the fields in this system must again have the form of a plane wave, but in the z

direction the wave cannot be determined by a wave vector k_z , since a translational symmetry in this direction is not given. We can write the magnetic field in the form

$$H(\vec{r}) = H_{\vec{k}}(\vec{r}) = e^{(i\vec{k}\vec{\rho})} \vec{h}(z) \quad (3.13)$$

with a vector $\vec{\rho} = \rho_x \cdot \vec{e}_x + \rho_y \cdot \vec{e}_y$ in the homogenous plane. In this description, the form of $\vec{h}(z)$ is still unclear, however, different modes with a given wave vector $\vec{k}$ can be lined up in order of increasing mode frequency, so that we can define a band number n . Let us assume that the orientation of the magnetic field is in the x direction and the wave is travelling along the y direction:

$$\vec{H}_{k_y,n}(\vec{r}) = e^{(ik_y y)} \phi_n(z) \vec{e}_x \quad (3.14)$$

If we insert this wave form into the wave equation (2.4), we obtain

$$\nabla \cdot \left(\frac{1}{\varepsilon(\vec{r})} \nabla \phi \right) = \frac{d}{dz} \left(\frac{1}{\varepsilon(z)} \frac{d\phi}{dz} \right) = \left(\frac{k_y^2}{\varepsilon(z)} - \frac{\omega^2}{c^2} \right) \phi \quad (3.15)$$

The term on the right hand side of the equation lets us make some assumptions on the behavior of modes in this kind of dielectric slab. If $\omega > c_{med} k_y$ then the z dependence of the modes will show an oscillatory behavior $\phi(z) \propto e^{(ik_z z)}$. In this case there will be a continuum of states that are extended both in the slab and the cladding region. If $\omega < c_{med} k_y$, the states of the slab will decay into the cladding with $\phi(z) \propto e^{(-\kappa z)}$.

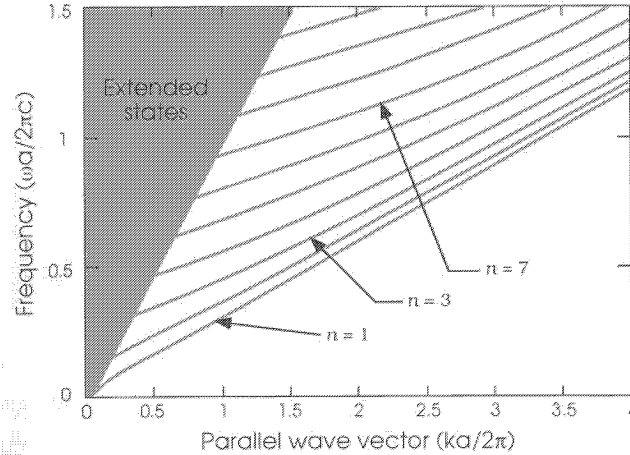


Figure 3.30: Confined and extended modes of a slab structure. Modes that are above the dispersion of the surrounding medium given by the light line will not be confined to the slab (from [18]).

These modes will be confined to the dielectric slab and they are arranged into bands that can be indexed by the previously introduced n . The band structure of such a slab system is shown in figure 3.30, where the straight line in the middle of the band diagram denotes the dispersion of the cladding material, the so called “light line”.

In an EBG slab, the situation will be very similar, however, due to the non uniformity of the dielectric material distribution in the x-y plane, the waves travelling in the plane will not have the shape of a plane wave, but there will be additional conditions for their field distribution, and the shape of the bands below the light line. In this region the band structure of the EBG material will become visible. The behavior of waves that travel in this kind of slab will be explained in the next part of this chapter.

2D EBG slab structures

In the previous part of the chapter we have studied 2D EBG lattices that had infinite extension in the direction perpendicular to the plane of periodicity. Contrary to this situation, a 2D EBG slab structure has a finite height h and is surrounded by a material with low dielectric constant (low index cladding) as seen schematically in figure 3.31[65][66][67][68][69][70][71].

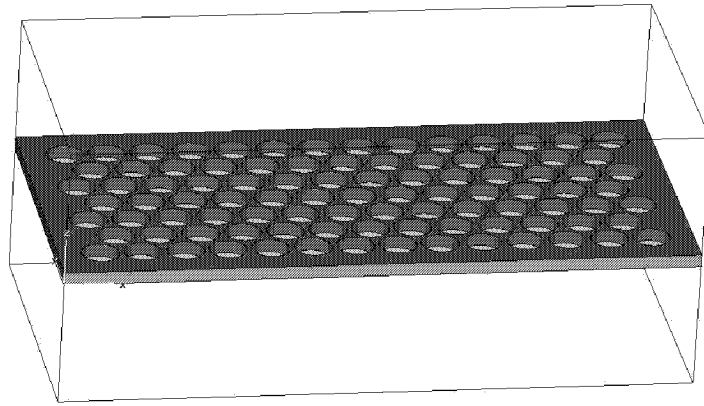


Figure 3.31: Schematic drawing of a 2D hexagonal EBG slab that is surrounded by a low index cladding material (air).

In the case of a slab structure, there is an additional parameter, the relative height of the slab, which is given by the ratio of the height of the dielectric holes h and the lattice constant a . The boundary conditions for propagating electromagnetic waves are different. A 2D slab structure is not uniform along the direction perpendicular to the 2D lattice. Therefore, modes will not be completely polarized and a distinction into TE and TM modes is not possible. However, we can classify the modes in the slab structure with respect to the x-y-plane of symmetry. We can distinguish between TE-type (even) and TM-type (odd) modes[72].

In analogy to the perfect 2D case we expect that a structure of air holes in dielectric background material will exhibit a large band gap for TE-type (even) modes and a structure of dielectric rods in air background will support a band gap for TM-type (odd) modes. A calculation of the band structure for a hexagonal lattice of air holes is shown in figure 3.32.

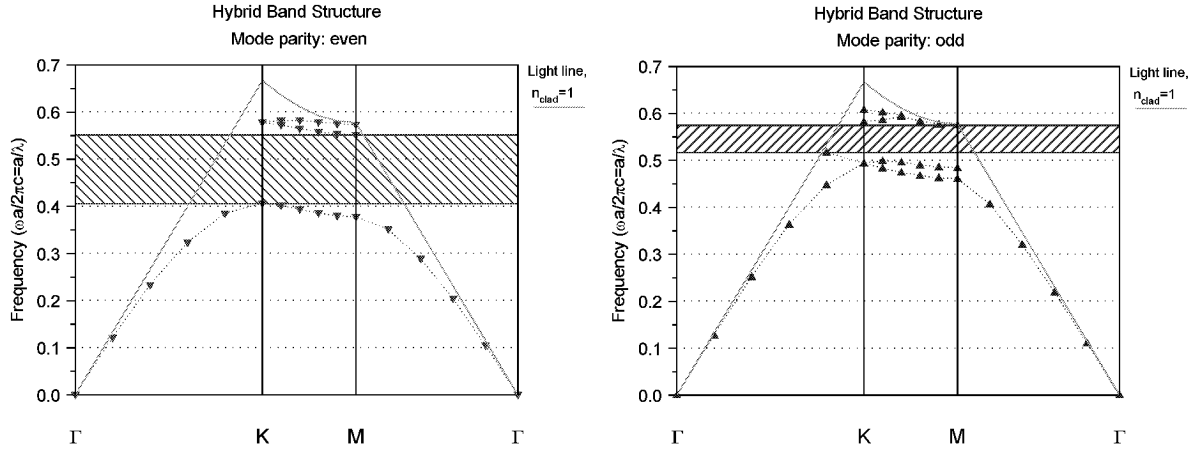


Figure 3.32: Reduced band structure of the hexagonal 2D EBG slab system as seen in figure 3.31 for even and odd modes. Only the region of the band gap below the “light line”, representing the continuum of modes above and below the slab, can be taken into account.

Compared with the previously calculated band structure for the 2D lattice, we observe a different behavior. Previously, we assumed the structure to be extended infinitely in the direction perpendicular to the 2D plane, or we assumed, that a propagation out of this plane was not existent. Now, we have to deal with a system, where a volume above and below the 2D EBG structure is present, in which a continuum of modes can exist. These modes are located above the so called light line, which is depicted in figure 3.38. The band structure of a slab system will therefore be influenced by the dispersion of the space above and below given by the light line. Only modes that are located below this light cone will be confined in the 2D EBG plane. Modes with a frequency inside the band gap of the slab, but above the light cone, will be able to couple to the continuum of modes and thus possess a field distribution that is evanescent in the direction perpendicular to the slab, i.e. strong radiation will occur. The finite thickness of the EBG slab will influence the existence of a band gap in such structures. A calculation of the dependence of the band gap size of a holes structure as depicted in figure 3.32 on the relative height of the slab is shown in figure 3.33.

It can be seen that the band gap has a maximum for a relative slab height of $h'=0.5 \rightarrow 0.8$. When the slab is chosen too thick, there will always be the possibility of creation of higher order modes by adding additional nodal planes in the plane of periodicity with little additional energy cost, which makes a band gap between these modes impossible. If the slab is too thin, it will only display a weak perturbation in the low index cladding material, and modes will be very weakly guided. Therefore, an optimum height for the slab is necessary to support a large band gap.

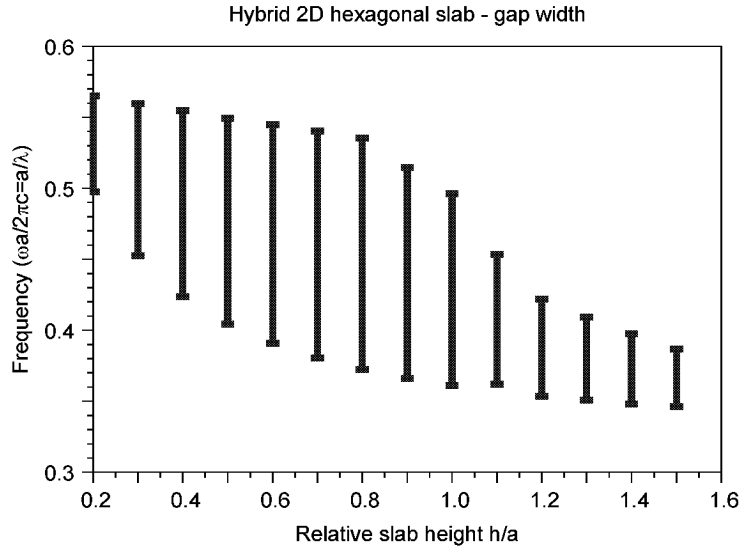


Figure 3.33: Dependence of the width of the band gap in a hexagonal slab structure of holes in dielectric background on the relative height of the slab h/a . With both increasing and decreasing height, the band gap shrinks and for relative heights of $h/a=0.5 \rightarrow 0.8$ a maximal value is reached.

Line defects in 2D EBG slabs

In the previous chapter we looked at two different cases for the creation of a line defect in a 2D EBG lattice: a lattice of low index (air) holes in dielectric background material and a lattice of high dielectric elements in an air background. It was shown that for both types of lattice a mode can travel along a line defect and there is an allowed band inside the band gap of the perfect structure, the size of which depends on the size of the lattice elements that form the defect. In this part of the chapter however, we will face a different situation: the linear waveguide is surrounded by low index material at its top and bottom and an index guiding is only possible, when the average dielectric constant is not too low in the region of the slab line defect. In analogy to the line defect in 2D EBG structures, we can create two different types of line defects in the EBG slab [72]:

1. Reduced-index defects that are made by an increased radius of holes in a high dielectric background material or by a reduced size of dielectric rods in an air background material
2. Increased-index defects that are made by a decreased radius of holes in a high dielectric background material or by an increased size of dielectric rods in an air background material

Generally, the first type of line defect is more suitable, as it originates from modes that are lifted into the band gap from the dielectric band. This has been found for the point defect case in the previous part of this chapter. These defect waveguides are of single mode character without a degeneracy of the defect modes. On the other hand, the necessary minimum dielectric contrast between the slab waveguide and the cladding material imposes a condition on the size of the lattice elements in the defect: if too much dielectric material is removed, there will still be an EBG defect mode, but an index guiding will not be possible anymore. It has to be pointed out that in this case of defects also the guiding in the horizontal direction is a genuine feature of EBG defect slabs. In a classical dielectric waveguide a mode can not be guided in a material that has an average dielectric constant that is lower than the one of the

surrounding material. Dispersion curves for both cases of reduced-index guides are shown in figure 3.34. The symmetry of the modes is even (TE-type) for the holes structure and odd (TM-type) for the rods structure.

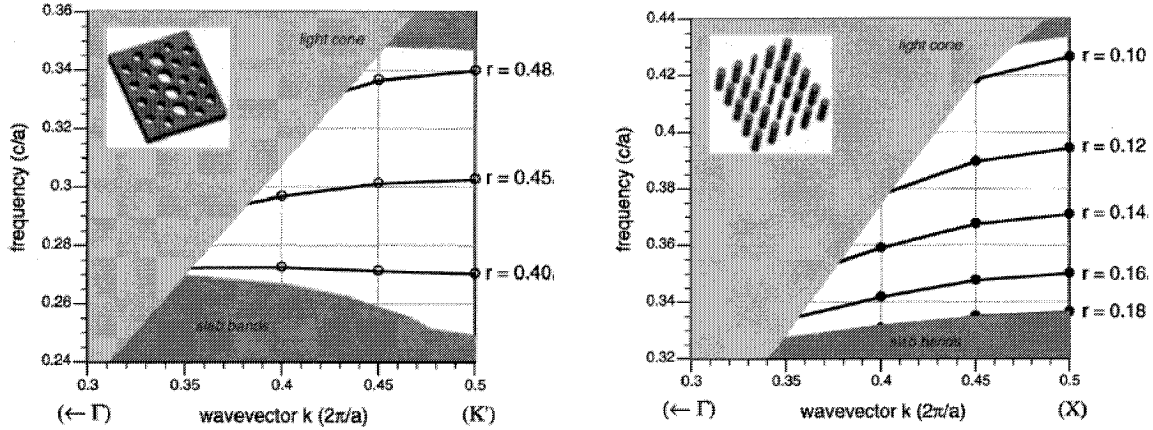


Figure 3.34: Reduced-index line defect slab waveguides: In both cases the waveguide will be single mode. The relative radius of the surrounding holes is $r=0.3$ and the relative radius of the surrounding rods was $r=0.2$, respectively (from [72]).

It should be noticed that all defect waveguides are single mode and the guiding does only exist for a narrow range of defect radii. Furthermore it must be noticed that in the case when too much dielectric material is removed, the in gap defect mode vanishes. The Bragg reflection in the plane of periodicity is still present, but there is no index guiding in the perpendicular direction anymore.

The second type of line defects supports defect modes that are pulled down into the band gap from the air band. In any case a guided mode will be supported, and therefore the increased index defects are more suitable to act as a EBG slab defect waveguide. Additionally, the fabrication of holes structures with different hole radii is much easier than the fabrication of freestanding dielectric rod structures. However, it is more likely in this type of line defects, that there is more than one mode pulled down from the air band and the line defect waveguide will be of multimode character. Additionally, there will be modes that are index guided in the plane of periodicity. As their guiding is not related to the bandgap properties of the lattice, we will not take them into account.

The reduced band structure of defect waveguides in increased-index slabs is shown in figure 3.35. It can be seen that in the case of increased-index waveguides there are two defect modes with different field symmetry, however, if the defect radius is not chosen too large (in case of rods) or small (in case of holes), the waveguide will still be single mode.

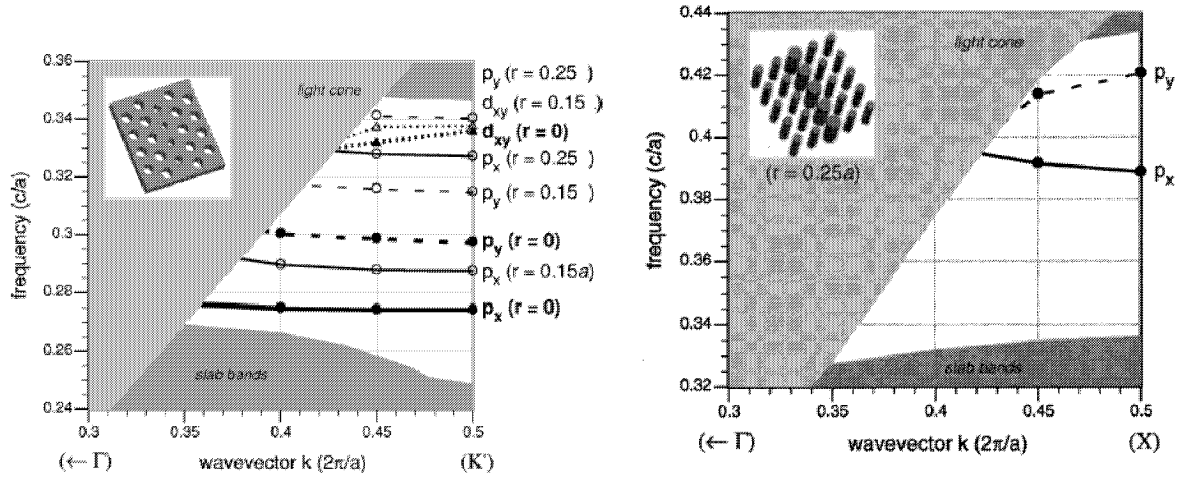


Figure 3.35: Increased-index line defect slab waveguides: The reduced-hole-radius waveguide will very likely be multimode while the waveguide with the increased radius of dielectric rods will be single mode (from [72]).

In summary, one can conclude that a slab structure can act as a single mode waveguide for a relatively broad frequency range, if the polarisation of the incident wave and the structural parameters of the EBG lattice are chosen wisely. In the experimental chapter of this work, we will present experiments that confirm the bandgap in a 2D EBG slab and the existence of resonances and travelling waves at point and line defects in such a slab system.

3.3 - 3D EBG structures

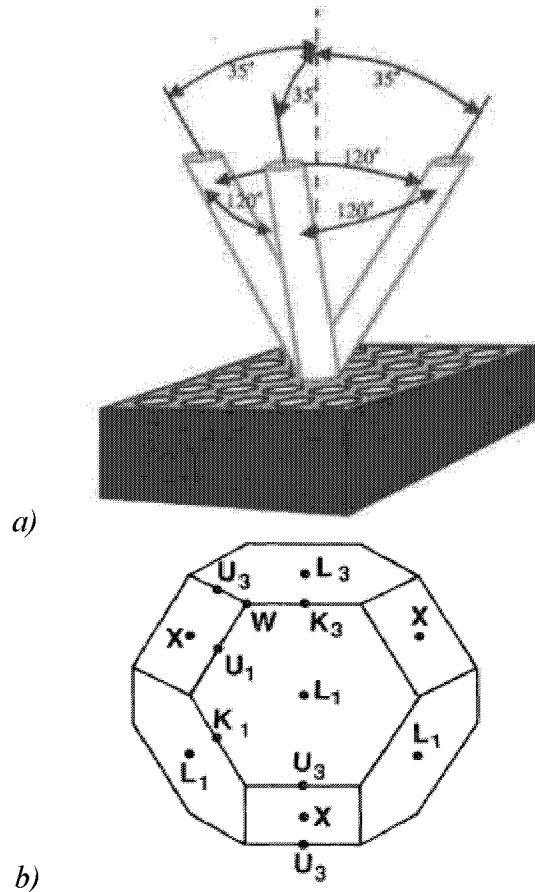
After the principle of electromagnetic bandgap structures was first discovered, a lot of work has been devoted to the ideal case of EBG materials: a 3 dimensionally periodic arrangement of dielectric material, that was supposed to have a "complete" band gap. In this material, the propagation of electromagnetic waves would be forbidden for a given frequency range for all directions of propagation and all orientations of the electric field. However, it was not obvious in which way the dielectric lattice should be built up to exhibit these properties. A large number of 3D periodic lattices has been investigated in the microwave range, mostly by Yablonovitch and Gmitter[73], but it took over 2 years to find at least one appropriate lattice symmetry that showed such a complete band gap. The structure was made from overlapping spheres of dielectric material, that had been arranged in a face centered cubic (fcc) lattice, where the dielectric regions occupied 86% of the unit cell volume. It was found that, if the dielectric contrast was large enough (typically greater than 2), a complete band gap could exist[73]. After the first discovery of a structure with a complete band gap, there was a huge stimulus for both experimentalists and theorists to discover more structures with complete band gap. Calculations of a number of different structures have been performed, and, surprisingly, it turned out that the "complete gap" fcc structure, did indeed not have a complete band gap for all wave vectors, but only a so called "pseudo gap" with a very small density of states (DOS) for a region of wave vectors[74][75]. After this discovery it was doubted whether an EBG structure with a full 3D gap would exist at all. However, it took only a small time until finally the first lattice structure with a "real" full 3D gap was discovered. Ho et al. proposed in 1990 that a modified version of the fcc lattice, the diamond lattice structure could possess a full 3D band gap[3]. It was shown that for a minimum dielectric contrast, both a structure of dielectric spheres in air background and air spheres in dielectric

background would exhibit a complete band gap. After finally an EBG structure with a complete band gap had been found, many experiments have been conducted. Still, all of these experiments were made in the microwave range, where the spheres had sizes of the order of several millimetres up to several centimetres. But the aim was to create a 3D full gap structure for visible light at wavelengths of a few micrometres and maybe even below. Having these frequency ranges in mind, the problem of fabricating the 3D periodic structures was obvious. It was therefore necessary to modify the 3D lattice, to make it possible to apply microfabrication techniques to achieve periodic structures with feature sizes in the submillimetre and micrometre range.

In this chapter we will briefly discuss the most relevant 3D periodic dielectric structures with complete band gap that have been successfully calculated, fabricated and measured, hand in hand with some methods of fabrication. It is necessary to mix these two different topics, as in most cases, fabrication methods can only be applied to a very special lattice structure, and therefore the choices of lattice structure and fabrication method are very closely connected and can not be discussed separately. At the end of the chapter we will discuss one of the structures in more detail, as some work within this thesis has been devoted to it.

The Yablonovite

Shortly after it had been found out that the 3D periodic lattice of spheres with the diamond lattice structure would exhibit a large band gap[3], it was discovered by Yablonovitch in 1991, that there was a relatively easy way to fabricate a structure with very similar lattice geometry[6].



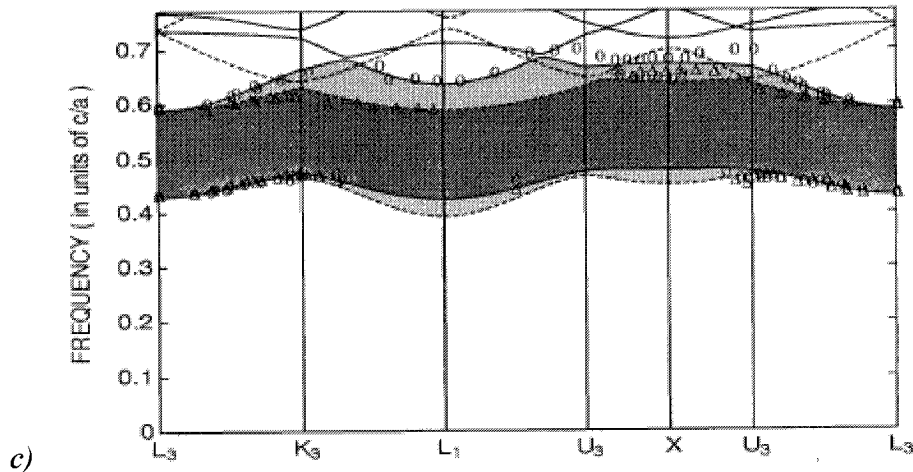


Figure 3.36: a) Possible fabrication method for the Yablonovite: holes are drilled into a dielectric slab with angles of 35° and 120° , respectively. b) First Brillouin zone of the Yablonovite. c) Calculated band structure for the Yablonovite exhibiting a complete band gap for relative frequencies around 0.5

A closer inspection of the diamond lattice structure reveals that its main structural feature is the existence of channels of low dielectric material along the $[110]$ direction. Yablonovitch suggested that drilling of holes into a block of dielectric material with an angle of 35.25° relative to the $[111]$ surface of the dielectric would yield a structure very close to the diamond lattice structure. This structure was found to have a complete band gap, too, and it was called "Yablonovite" after its inventor. Band structure calculations show that this structure exhibits a complete band gap for dielectric contrasts as low as 1.45 [6]. The structure has been successfully fabricated by a number of groups that etched holes into blocks of dielectric material [76][77]. However, even if a scheme for fabrication is found, the fabrication of the structure is relatively complicated and therefore not especially suitable for an application. Figure 3.36a shows a schematic way of fabrication by drilling or etching, the Brillouin zone of the Yablonovite and a band structure calculation.

Self-organized photonic crystals - inverted Opals

A convenient way to arrange material in a certain lattice symmetry is to utilize the process of self-organization [20][51][78][79]. Small beads of silica (SiO_2) or polymers have been used to fabricate a 3D periodic lattice with fcc symmetry, which could theoretically possess a 3D band gap. The high material filling factor of these structures require a high dielectric constant to make the band gap complete. The materials commonly used in these techniques generally have low dielectric constants around 2, thus they can not provide the dielectric contrasts required and a full gap is not possible. However, it was found out that an inversion of the lattice elements could produce a complete band gap. Here the 3D lattice of low-index-material spheres is infiltrated with a high index material, in many cases Si or Ge will invert the lattice structure [79][80], turning the former high index regions into low index regions and therefore make it much more easy to accomplish the needs for a complete band gap regarding dielectric contrast and filling factor. To go even one step further, a chemical removal of the silica or polymeric parts of the structure will further increase the index contrast, making the structure exhibit an even larger complete band gap. Figure 3.37 shows a band structure calculation and the density of states for a Si infiltrated fcc lattice where the low index material was removed chemically, as well as a micrograph of an inverted opal structure (figure 3.38).

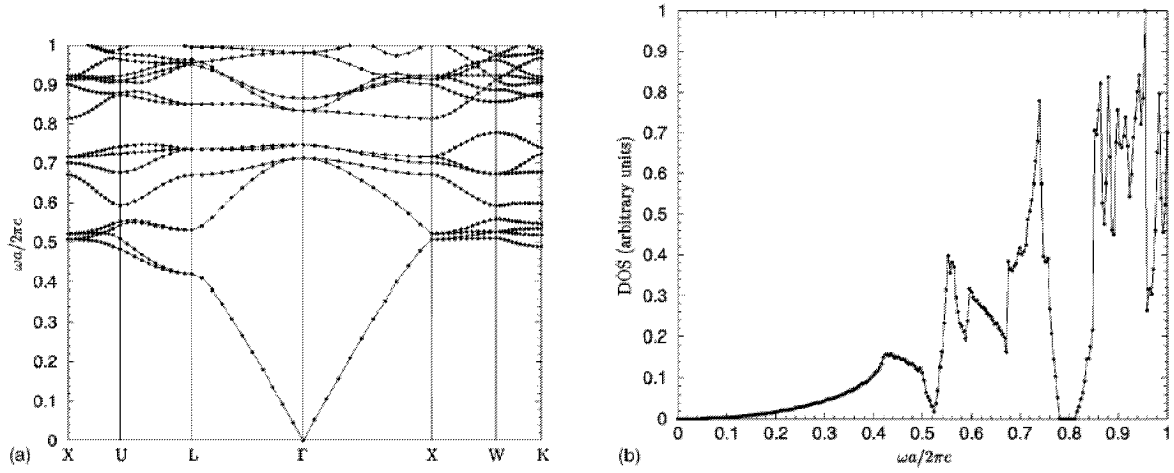


Figure 3.37: a) Band structure of a self-assembled 3D EBG material made from a Silicon infiltrated inverted opal with fcc lattice symmetry, where the low index material was removed chemically (inverted opal structure). b) Calculation of the density of electromagnetic states in the structure as described in figure a) (from [51])

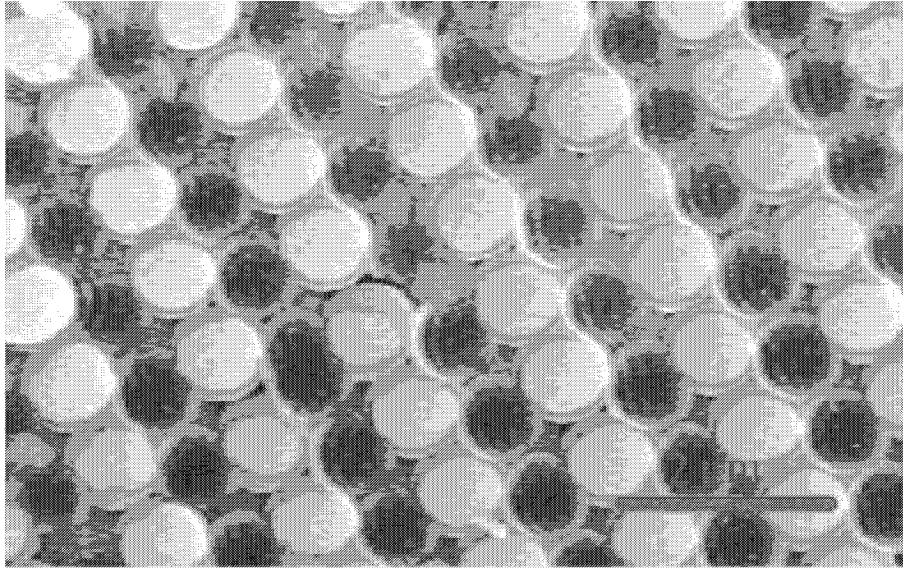


Figure 3.38: Micrograph of the inverted opal structure of Silicon spheres arranged in an fcc lattice (from [80]).

A stacked 2D hexagonal structure

In 2000, Johnson and Joannopoulos proposed a structure with a large complete band gap for dielectric contrasts as low as 2, as it would be the case in a Si/SiO₂ system[81][82]. The structure consists of an alternating layered structure of two dimensionally periodic lattices with large and small hole diameters (see figure 3.39 for a schematic view of the structure and a band structure computation). This structure has the advantage, that within its layers, it closely mimics the behavior of 2D EBG materials, that are much easier to treat both experimentally and theoretically, but it also exhibits a confinement of waves in the third dimension due to its layered nature[83][84]. The only drawback, again, is the relatively complicated way of fabrication for this structure, due to which no reliable fabrication scheme has been found so far.

Typical parameters, for an undistorted fcc lattice of air cylinders in a dielectric constant of 12 (Si), are: $d=a/\sqrt{3}$, $x=a/\sqrt{2}$, $r=0.293 \cdot a$, and $h=0.93 \cdot a$, where a is the fcc lattice constant. This results in a 21% complete three-dimensional band gap, centered at a frequency of $0.569 c/a$.

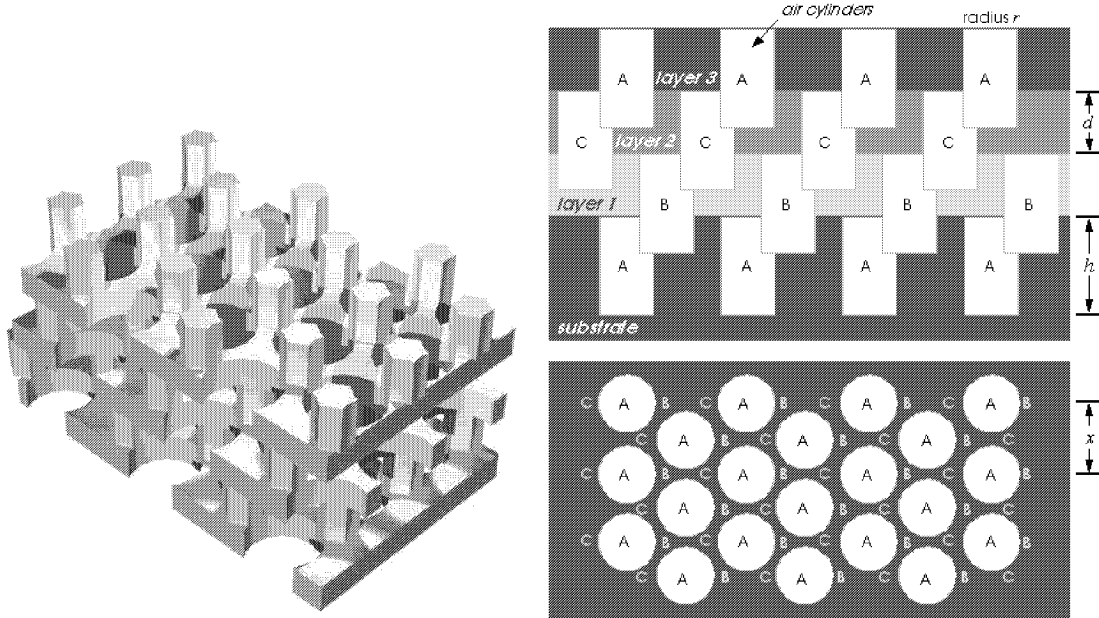


Figure 3.39: a) A schematic view of the 3D EBG structure made from stacking of 2D hexagonal EBG layers. A rod layer and a holes layer are alternately stacked. Here the rod layer is fabricated by drilling overlapping holes into the bulk dielectric so that a rod lattice remains. b) Top and side view of the 3D stacked structure. The position and size of the holes in the dielectric material can be seen[81].

A 3D layer by layer structure

In 1994, Ho et. al. proposed a structure that can support a complete band gap and is made from a stack of layers of one dimensional rods[85]. In this structure the first layer consists of rods arranged parallel to each other separated by the lattice constant a , the second layer is a copy of the first one, but rotated by 90° . The rods in the third layer are parallel to the ones in the first but shifted along the lattice constant by half a period. Layer four is made from rods parallel to those in layer two, but again shifted by half a period. After 4 layers, the structure is repeated starting with layer 1. This means that the structure is sequenced in a repetition of four layers with a repetition length c . This structure was realised shortly after its discovery by Ozbay et al. [86][87][88] and due to its appearance it was called "Lincoln-log" or "woodpile" structure. Experiments were performed in the microwave region[89], for Terahertz[87][88][90][91], and, later on, for optical frequencies[9][92][93]. The structure can be fabricated relatively easy by wafer bonding or stacking of wafers that are etched from both sides to create two layers at the same time. It is advantageous for a possible application not only due to the fact that it can be fabricated relatively easy, but it also has a high mechanical stability. In the following we will describe a woodpile structure of rods with a square cross section, i.e. width b , height c , and a length l . In the case of cylindrical rods, the width and height would be replaced by a rod radius, r .

The rods are stacked in the $\langle 001 \rangle$ direction, and rods from two adjacent layers are oriented in the $\langle 110 \rangle$ and $\langle 1\bar{1}0 \rangle$ direction. The Brillouin Zone of the structure has the shape of a clinched dodecahedron. The woodpile structures exhibits an fct (face centered tetragonal) lattice, except from the special case of $c/a=1/2\sqrt{2}$, where the lattice symmetry is fcc (face centered cubic).

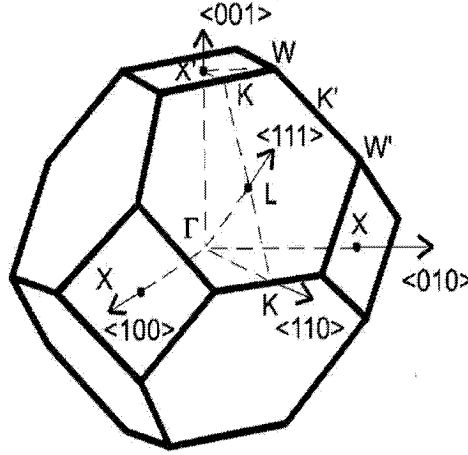


Figure 3.40: Brillouin zone of the clinched dodecahedron woodpile structure with the main symmetry points.

The woodpile structure can be derived from the diamond structure, if the (110) chains of atoms are replaced by the dielectric rods. The Brillouin zone of the structure is shown in Figure 3.40.

We can find a parametrization of the structure with the introduction of two variables:

1. Its material filling factor f , defined as the ratio of dielectric material in the unit cell and total volume of the unit cell: $f=b/a$
2. Its aberration from the fcc symmetry, described by the ratio of lattice constants $k=c/a$.

Assuming a fixed dielectric constant of the rod material, the size and position of the structure's band gap are completely defined by these two parameters. The dependence of the complete band gap width for the fcc lattice on the material filling factor, as well as the aberration is shown in figures 3.41 and 3.42. We can observe the largest band gap for a material filling factor of about $f=0.25$ and an aberration of $k=0.25$, where the band gap ranges from relative frequencies of 0.403 up to 0.469, which corresponds to a gap-midgap ratio of $\Gamma = \frac{\Delta\omega}{\omega_0} = 15.29\%$.

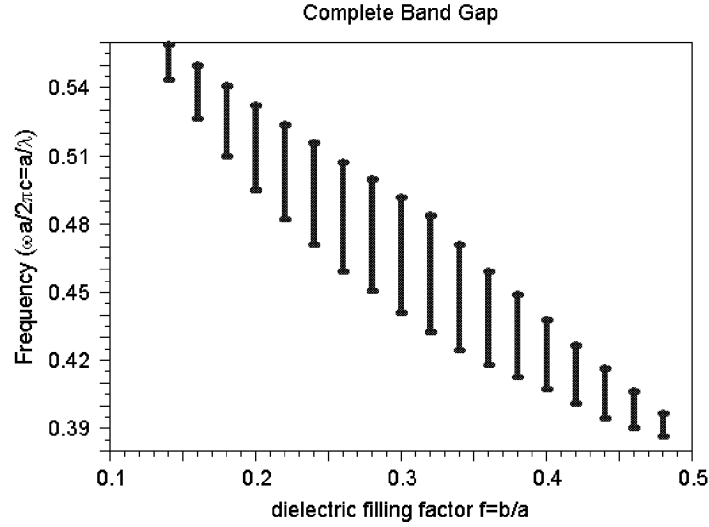


Figure 3.41: Dependence of the size of the complete band gap of the woodpile structure on the dielectric filling factor f , given by the ratio of rod width and lattice constant for a fixed rod height corresponding to an aberration $k=1/2\sqrt{2}$ (fcc lattice). It can be seen that the maximum band gap width is reached for $f=0.23$ where the gap is between relative frequencies of 0.441 and 0.492, and the gap-midgap ratio is $\Gamma=9.14\%$

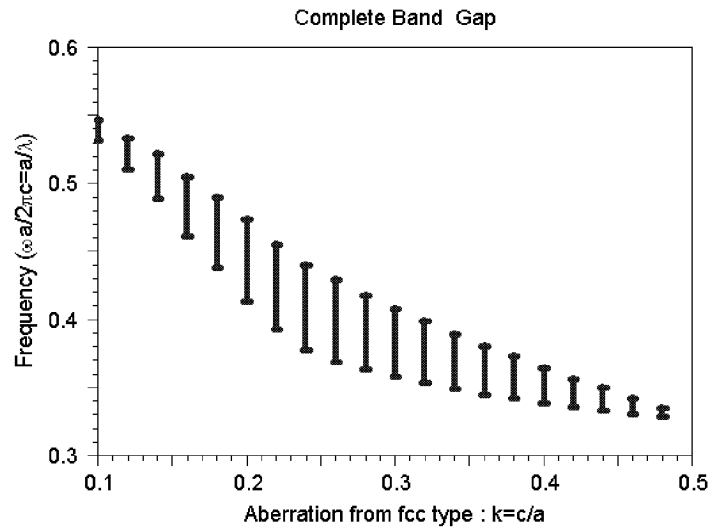


Figure 3.42: Dependence of the complete band gap width of the woodpile structure on the aberration of the lattice from the fcc structure for a dielectric filling factor of $f=0.25$. The maximum size of the band gap is reached for an aberration of $k=0.26$

To further increase the effective size of the band gap that can be utilized, it is useful to take a look at the band structure of the woodpile structure. The complete band structure is depicted in figure 3.43 for a filling factor of $f=0.2$ and an aberration of $k=0.2$.

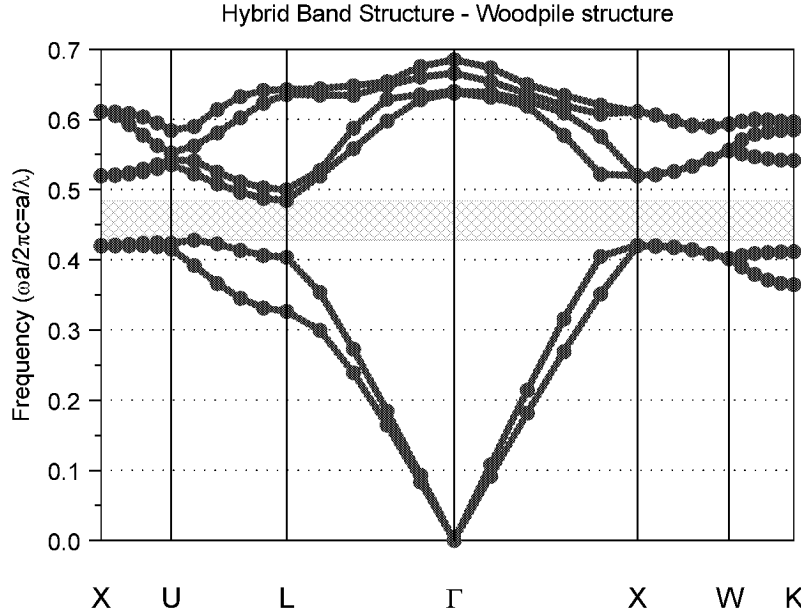


Figure 3.43: Complete band structure of the woodpile lattice for a material filling factor of $f=0.2$ and an aberration of $k=0.8$. The 2nd and 3rd band at the lattice symmetry point X (propagation along the stacking direction of the layers) are degenerate.

When the width of the complete band gap is determined, it can be seen that its upper edge frequency is mostly influenced by a low frequency of the mode from the second band at the symmetry point L . A mode propagating in $\Gamma - L$ direction will travel inside the plane of the rod layers. There will be two modes in bands 2 and 3 with perpendicular orientations of the electric field, one of which will be in the plane, and the other one will be perpendicular to this plane. The mode with the field in the plane will see the interconnected regions of high dielectric material from the rods and will therefore have a relatively low frequency, but the other mode will see a different distribution, because these interconnected regions do not exist in the direction perpendicular to the plane. Its frequency will therefore be much lower, effectively diminishing the size of the band gap. This situation is related to the left branch of the band structure in figure 3.24. However, when a mode is investigated that travels perpendicular to this plane, there will be two possible orientations of the electric field again, which will both see the interconnected regions of the dielectric rods, due to their arrangement in 90° to each other. These modes will therefore be degenerate, making a large band gap possible. For a wave travelling perpendicular to the plane of the dielectric rods, the band gap will range from relative frequencies of 0.403 up to 0.52, yielding a gap-midgap ratio of $\Gamma = 25.3\%$. This situation is related to the right branch of the band structure in figure 3.24.

In a later chapter we will present the experimental investigation of the 3D woodpile structure.

Other 3D EBG structures

Apart from the structures that were mentioned here, there is a large number of other fabrication techniques and lattice structures for the realisation of 3D periodic structures (wafer fusion bonding[94], holographic lithography[95][96][97], micromanipulation[98], glancing-angle deposition[99] and, recently, autocloning[100]). As this is not one of the main topics of this work, there is no space to discuss them all in detail here.

Overall, one can conclude that basically for an application as a passive element in micro- and millimetre wave circuits, both 2D and 3D EBG structures can be employed. Due to their higher flexibility, easier fabrication and the possibility of three dimensional confinement by index guiding, the 2D structures are more advantageous. It is obvious that for the different types of 2D EBG structures the 2D hexagonal lattice is superior because it can exhibit large band gaps for both TM and TE polarisation of the waves, if dielectric rods or air holes are used, respectively. In case of a lattice made from dielectric rods in air, a TM polarised wave can be used conveniently as the TM mode is the fundamental mode in a rectangular waveguide. To fulfil the appropriate boundary conditions for TM modes, the rods lattice can be limited at the top and bottom with metal plates. If a TE polarised mode is employed, the hexagonal hole array should be used, as it can produce a large band gap for this polarisation. In this case it might become difficult to find appropriate boundary conditions for the TE mode atop and below the EBG material, but as we have seen a three dimensional confinement of a defect mode by index guiding is possible.

Chapter 4: Fabrication of electromagnetic bandgap structures

For electromagnetic bandgap materials, the fabrication of the periodic structure is one of the most important issues. Due to the scalability of the properties of an EBG material, a lattice structure can be tailored to work in an arbitrary frequency band by rescaling the lattice constant and thus the lattice parameters that are defined relative to it (chapter 2). EBG structures have been utilized from the microwave range, where length scales are in the order of several millimetres or centimetres up to optical frequencies, with length scales of the order of few micrometres or several hundred nanometres. However, the periodicity of the dielectric material must always be in the order of magnitude of the wavelength corresponding to the desired target frequency. Therefore, for different frequency bands, different fabrication schemes must be employed to fabricate the periodic dielectric structures. The materials that are used in the fabrication of EBG structures also vary over the frequency spectrum. On the one hand, the material must be chosen according to the fabrication scheme (mainly in case of micro- or nanoscale fabrication techniques for EBG structures that work at optical frequencies), on the other hand, the absorption properties of most dielectric and semiconducting materials have a frequency dependence, which makes them suitable only for a limited frequency range. In the scope of this work, a number of different fabrication methods and materials for periodic dielectric structures have been used. The topic of this chapter is the discussion of the fabrication methods and materials that were chosen. Here we will combine the discussion of the applied fabrication scheme with an introduction of the fabricated structures. We will start with the description of a fabrication scheme for EBG structures in the microwave range around 10 GHz, afterwards a method of fabrication for EBG structures around 30 GHz will be presented. Finally, we will discuss two methods for the fabrication of EBG structures at frequencies around 100 GHz.

4.1 - Fabrication and material issues

Fabrication issues

EBG structures for the microwave range are commonly realized by manual assembly[17][101] or mechanical treatment of bulk dielectrics like drilling[102][103] (mechanical, high pressure water beam), dicing[91] and grinding, as well as laser machining[88]. Due to the large size of the structures, the assembly can be done by manual placement of the lattice elements in most cases. For higher frequencies up to several 10 GHz, the structural parameters shrink down to sizes in the order of several hundred micrometres up to several millimetres (size and distance of the discrete lattice elements), so that conventional

mechanical fabrication schemes will approach their limits in terms of tolerances and fabrication cost. In this range laser machining is a valuable tool with high precision and speed[88], nevertheless it can cause a strong degradation of the microwave properties of the dielectric material due to the formation of amorphous regions in crystalline or polycrystalline materials caused by overheating. These regions will exhibit high microwave losses, which will decrease quality factors in the EBG device. Here ceramic moulding techniques can play an important role in fabrication, because they can provide a non-destructive way to machine complex structures from a broad choice of materials. In the submillimetre and optical frequency range, EBG structures are fabricated by chemical[87] and physical[105][106][107] etching processes, electrochemical processes [108][109][110], rapid prototyping[111], self organisation[78][79], and recently autocloning[112][113].

Material issues

Materials that are commonly used in the microwave range of several GHz are low loss oxide ceramics like Al_2O_3 [101][88], single crystals (Sapphire) as well as Teflon or other ceramic polymers[102][103][114]. For submillimetre and optical frequencies, dielectric and semiconductor materials that are commonly used in state of the art microfabrication and lithography can be employed, such as high resistive Silicon[105], Si/SiO₂[115], high resistive Al_2O_3 [88], GaAs[92][93], InGaAsP[116] and many more. Microwave absorption in dielectric materials increases proportional to the frequency, while the absorption in semiconducting materials decreases with increasing frequency. The two curves cross at approximately 100 GHz, where the losses in Sapphire and Silicon are of the same order. At these frequencies, the loss contribution from the material is a major issue, therefore the optimisation of material properties for a given frequency range is of high importance for the design of an EBG material.

4.2 - Microwave EBG structure for 10 and 20 GHz

In the frame of this work, a 2D EBG structure made from dielectric rods in an air background was designed.

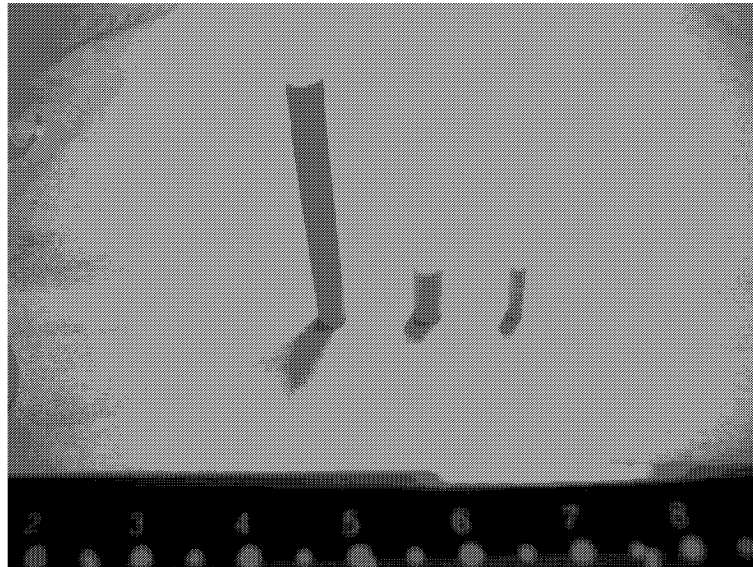


Figure 4.1: Dielectric rods of different size and radius made from polycrystalline Al_2O_3 .

The rods had a diameter of 4.3 mm and a height of 70 mm. They were fabricated by an external company (Kyocera) by pressing of ceramic powder and subsequent sintering. Further changes to the rods parameters have been performed with mechanical tools (length cutting, radius thinning). A picture of these ceramic rods with different lengths and radii is shown in figure 4.1. The rods were manually arranged into a hexagonal EBG lattice. To achieve a better accuracy of the rod positions, a thin mask was used, that was made by drilling holes in a hexagonal pattern into a thin slab made from a low loss, low dielectric material (teflon). The mask fits the shape of the microwave resonator, in which the measurement was performed. The rods were then placed in the holes of the teflon mask (see figure 4.2).

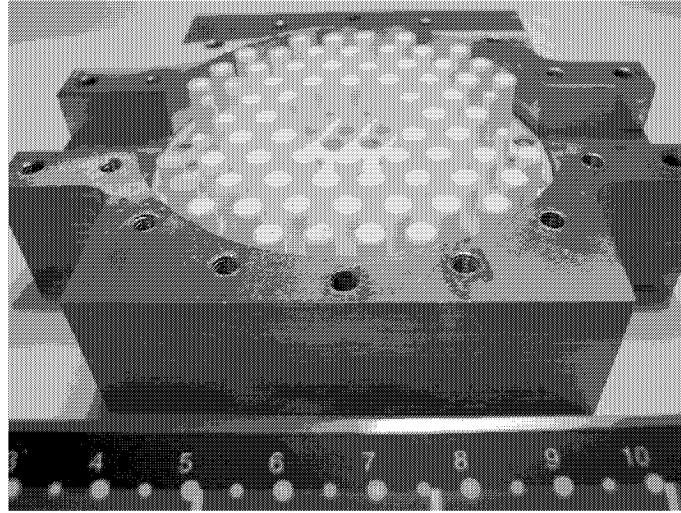


Figure 4.2: Photograph of the experimental setup for a 2D EBG structure at 10 GHz: The dielectric rods were placed onto a thin Teflon mask inside the resonator.

For the frequency of 20 GHz, a 3D EBG structure was designed. The lattice elements were dielectric bars with a square profile.

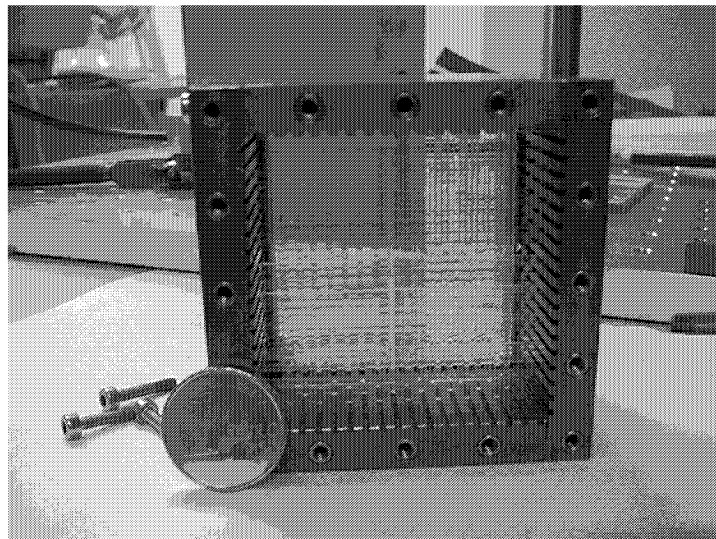


Figure 4.3: Experimental arrangement for a 3D EBG structure at 20 GHz: The dielectric bars were cut from single crystal sapphire and manually arranged in the metallic housing.

The bars were cut from single crystal Al_2O_3 (Sapphire) with subsequent optical polishing. The rods were arranged into the EBG structure manually, by stacking them along guiding slits in the housing of the resonator that was used for the measurement (see figure 4.3).

4.3 - Microwave EBG structures for 30 GHz made by moulding techniques

In the frame of this work two 2D EBG structures for a frequency of 30 GHz have been fabricated in cooperation with partners. Both structures were made by ceramic moulding techniques, that promise advantages compared with standard machining processes for ceramics in the microwave frequency range. These advantages, the principle of ceramic moulding and the methods that were investigated in this work will be explained in the following.

Ceramic materials have a very high mechanical stability, which makes the periodic patterning from a bulk material, especially at submillimetre length scales, difficult due to a number of reasons: A mechanical treatment is in most cases extremely lengthy and expensive (mechanical drilling, ultrasonic drilling, high pressure water beam drilling), or will degrade the microwave properties of the material due to the forming of amorphous regions (laser machining). In recent years, moulding techniques have been employed to overcome these difficulties[117][118][119]. In ceramic moulding processes, the final ceramic structure is patterned into a soft mould. This has been done by a number of ways like mechanical methods, but also, at smaller length scales, plasma etching[120][121] and x-ray lithography (LIGA)[122]. Subsequently, the ceramic material is being prepared in form of a liquid slurry, which is cast[123], injected[124] or pressed[122] [125] into the mould. After a stabilizing process (oven drying) the mould is then removed mechanically, thermically, chemically or by laser ablation. There is a number of problems, that must be solved to find an optimised moulding procedure, and a number of conditions for an optimal choice of materials or material systems for both mould and slurry. In the following the most important of these issues will be listed.

Sufficient density of the green body

The ceramic structure that is gained after the filling of the mould with the slurry and prior to sintering (green body) must have a sufficient density. This density is determined mainly by the volume fraction of solid material in the slurry. However, there is always a trade off between positive and negative effects related to the density of the slurry.

- The slurry must contain a high volume fraction of solid material to give the ceramic structures a sufficient stability to survive the processes of removal of the mould and subsequent sintering. A low density of the green body will cause cracks and deformations of the structure
- The dielectric constant and loss tangent of the final ceramic structure will be influenced by the density of the green body. A low density can lead to a porous ceramic with a dielectric constant lower than desired. Additionally, the creation of inhomogenities and grain boundaries can increase the loss tangent of the material.
- When the volume fraction of solid material is low in the slurry, not only porosity can appear, but also the shrinking rate of the material during the sintering process is highly increased, making the overall structure smaller than intended. This shrinking may be

extremely inhomogeneous over the volume of the structure and is therefore hard to take into account during the designing of the structure prior to the fabrication.

- The viscosity of the slurry has a negative impact on the filling of the mould. Low viscous structures need a higher pressure to fill the mould sufficiently, which will either lead to an incompletely filled mould or to a higher stress applied to the mould material when the slurry is pressed into it.

A higher density can be achieved by careful selection of the binding material/ceramic powder system, as well as the application of high pressure during the mould filling process, which, again, makes a wise choice of the mould material necessary.

Chemical and mechanical stability of the mould

When the ceramic slurry is pressed into the mould, high pressure is of advantage, because it will lead to a more stable green body with higher volume fraction of ceramic powder as opposed to the binding system. The mould material must be stable enough to keep its shape during the application of this pressure. Nevertheless, the mould material should not be too brittle, otherwise, the patterning can lead to damage to the mould like cracking. Additionally, the mould material must be chemically inert with respect to the binding system to prevent chemical reactions between mould and slurry during the filling process, as well as physically inert, especially while removing the mould, to prevent contamination of the green body. Finally, the mould material must be machinable in the temperature range of choice, which is given by the parameters of the slurry, typically below 100 °C.

Simple mould removal

While the possibility of a non destructive removal of the mould is in some cases given, more often the ceramic green body will be separated from the mould by destruction of the mould. In this process a number of difficulties can arise and the mould material must be carefully chosen to avoid them.

- In case of mechanical peeling the mould is stripped off the green body mechanically. This method is very well suited for mould removal, as it does not create any destructive effects on the green body. However, it is only applicable for flat structures with low aspect ratios.
- In case of laser ablation of the mould, local overheating of the green body can lead to recrystallization effects that will strongly degrade the microwave properties of the ceramic material. Additionally, thermal expansion leads to mechanical stress.
- Thermal removal of the mould (burning) will lead to a strong creation of gas in the mould, that can lead to damage or even destruction of the green body, especially in case of small scale structures. Additionally, thermal expansion of green body and mould material can lead to distortion of the green body material, or a deviation from the desired lattice parameters.
- Etching processes apply little thermal stress on the green body, on the other hand a contamination of the green body by residual anorganic components of the etchant is possible which will lead to a degradation of the microwave properties of the ceramic, or a destruction of the ceramic surface.
- The “soft” dissolution of the mould material is a non destructive way to remove the mould. Nevertheless, in this case problems can be caused by a partial dissolution of the binding material in the green body which will degrade its stability, and volume

changes of mould and green body during the dissolution process can be harmful to the structure. The material systems for both green body and mould must be extremely carefully chosen in this case.

An embossing/lost mould method

The process of fabrication of ceramic microstructures with an embossing/lost mould technique is shown schematically in figure 4.4. The ceramic material is made from a mixture of the ceramic powder (Al_2O_3 in our case) and an aqueous polyvinyl alcohol (PVA) binder system. It is then pressed in to the form of a thin sheet, the so-called viscous polymer processed (VPP) ceramic tape by calendering.

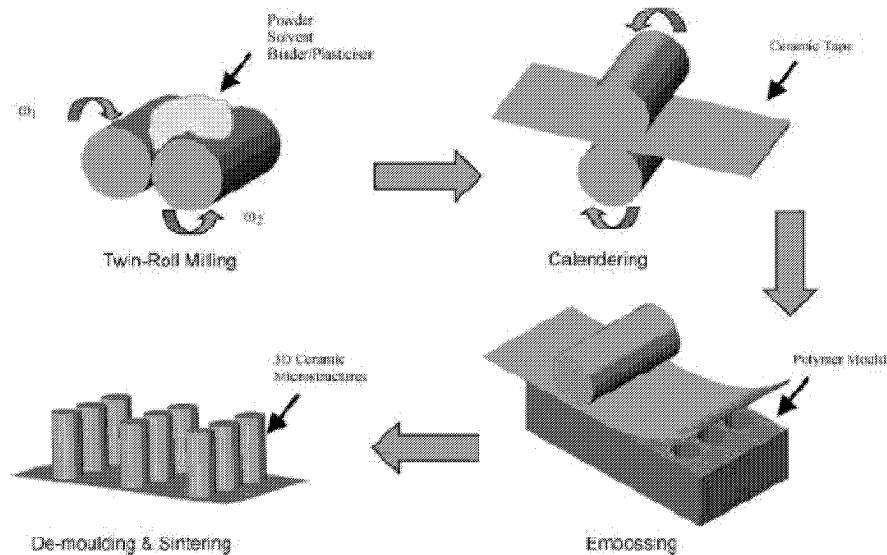


Figure 4.4: Fabrication scheme of the fabrication process for ceramic mould structures. The VPP tape is calendered and pressed into the patterned mould, which is removed subsequently (from [125]).

The structure to be fabricated is then patterned as a negative form into a polymeric mould made from polymethyl methacrylate (PMMA) with a CNC controlled mechanical drilling machine. At a high pressure of 10 MPa and room temperature, the VPP tape is embossed into the mould. After the system is dried for several hours at a medium temperature (80°C) to remove the binding system, the mould is removed chemically by a solvent such as acetone or chloroform. The remaining ceramic structure is then sintered at high temperatures (>1200°C)[125].

In our case the ceramic structure consisted of isolated dielectric rods. Therefore, a removal of the mould would mean that the structure falls apart. To avoid this, a thin bottom layer was added to the structure by some sheets of VPP tape across the whole mould. After the sintering process, the structure was backfilled with a low dielectric constant, low loss stabilizing material (paraffin) to increase mechanical stability of the lattice of rods. The stabilizing bottom layer was subsequently removed from the structure by cutting or polishing. The fabricated structure is shown in figure 4.5.

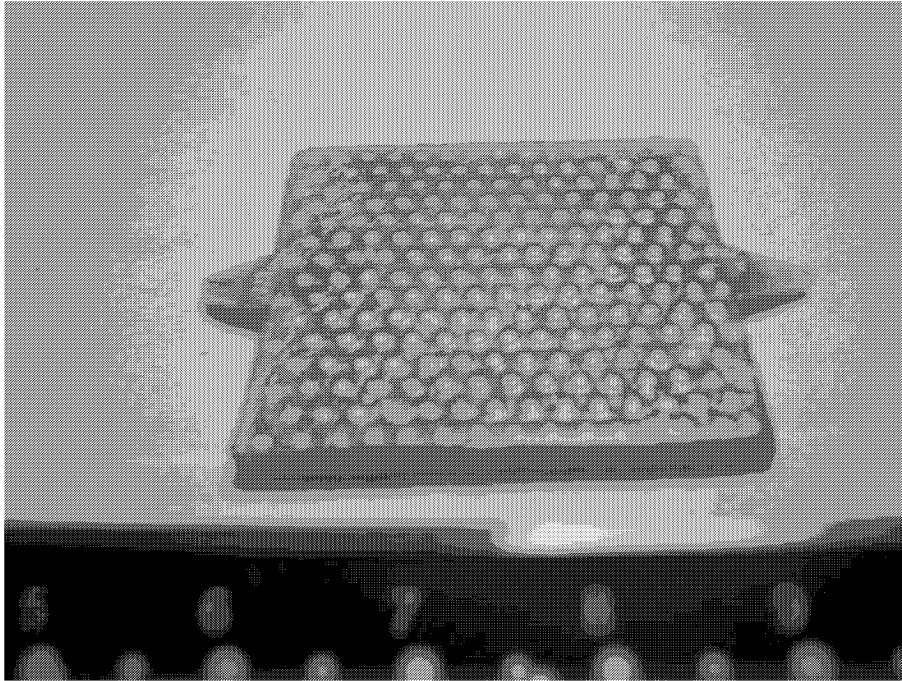


Figure 4.5: 2D EBG structure made from the moulding technique described above. The dielectric rods lattice was backfilled with paraffin wax to form a compact 2D slab.

Fabrication issues:

There is a number of issues to be solved for a proper application of this fabrication method. Unfortunately, these problems could not be tackled in the frame of this work and must be left for further investigation. Nevertheless, they will be listed here, and the possible reasons will be explained.

Non-uniformity of rod positions

There are two issues related to non-uniformity in the fabricated EBG structures. On the one hand, the position of the Alumina rods does not always match the hexagonal lattice, but the rods are shifted in their positions by up to 0.5 mm. On the other hand, the rods are not uniformly distributed in the position along their axis. This situation can be seen in figure 4.6. Both issues are related to the same source: During the sintering process, thermal and mechanical stress is applied to the structure. Therefore, its original shape can be distorted, and the position of the rods can change. Also, the flatness of the green body can be distorted, which will then lead to a situation where some rods are located higher than others. When backfilling the structure with the paraffin, it can happen, as seen in figure 4.6, that some rods are still standing free, while others are already completely covered. This issue will also give rise to difficulties when polishing the structure, because the polishing process might shift the position of the rods even more, due to the applied mechanical forces. In the experiment, this issue can lead to a decreased band gap size, possibly a shift of the band gap frequency, and the wax layer on the surface of the structure can give rise to unwanted surface modes, as in this area there is no EBG structure and therefore no band gap present.

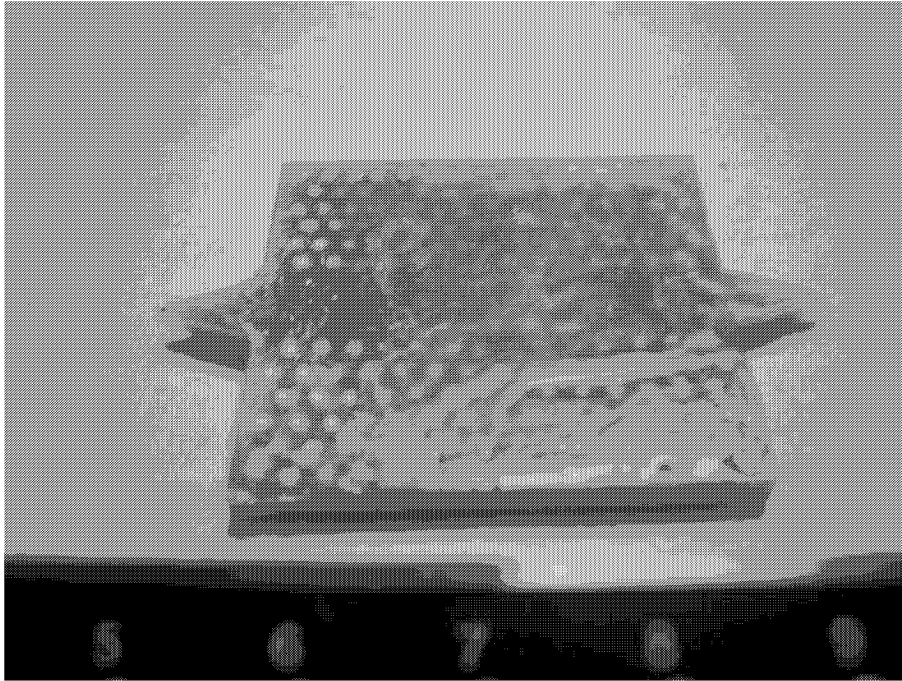


Figure 4.6: The distribution of the backfilling material is not uniform over the sample. At some places the dielectric rods are exposed, while at others they are completely covered under a layer of wax. Additionally, the position of the dielectric rods is distorted from the hexagonal lattice structure slightly.

Surface roughness

The backfilling of the material with wax makes it necessary to polish the structure, and the wax layer covering the rods must be removed. This removal can lead to surface roughness and even scratches in the surface, as seen in figure 4.7.

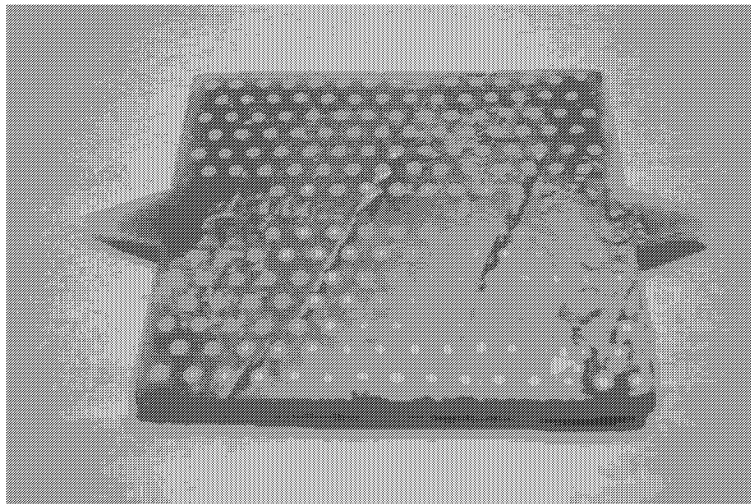


Figure 4.7: The surface of the structure is partially destroyed by scratches and roughness. This is caused by the polishing of the structure when removing additional backfilling material

Overall change in lattice parameters

Overall changes in the lattice parameters include two derivations from the originally designed structure: a change in the size of the dielectric rods and a change in the lattice constant that separates them. Both changes are caused by the shrinking of the structure during the sintering process. It can be avoided when the shrinking rate is known precisely. In this case the design of the structure can be made by that factor larger to compensate the shrinking. Nevertheless, if the shrinking factor is unknown, inhomogenous over the structure or the green body structure is not optimised (as explained before), the shrinkage can lead to unwanted results for the finished structure in terms of smaller band gap or shift of its frequency.

A Sodium Chloride Moulding technique

The moulding technique presented in the following text comprises the possibility of creation of high aspect ratio ceramic structures by combination of a special, low viscosity slurry and a very gentle mould removing process. We have tried to work with a number of different mould materials: Polycarbonate, Polymethyl methacrylat (PMMA), Polyethylen, and sodium chloride.

Polycarbonate:

The mould made from Polycarbonate can be machined nicely (see figure 4.8). However, the removing of the mould bears a lot of problems: The material is very viscous, which means that high mechanical stress is applied to the fine ceramic structure of the green body while the thermal removal of the mould.

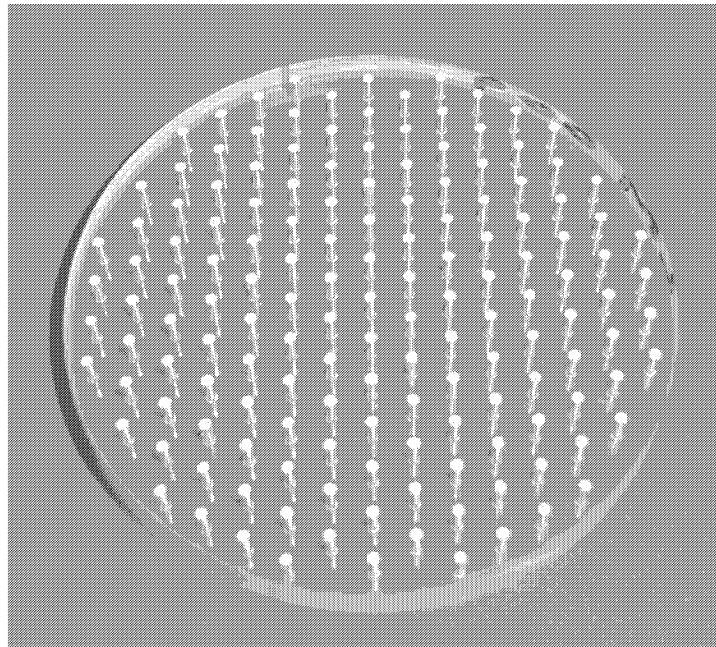


Figure 4.8: Photograph of a polycarbonate mould, patterned with small holes with a diameter of 0.7 millimetres.

Additionally, the burning of the polycarbonate will create lots of gases that will also be able to destroy the shape of the ceramic structure.

Polymethyl Methacrylate (PMMA):

This mould material can be removed chemically. It exhibits the same problems during mould removal as Polycarbonate due to its viscosity. Additionally, before chemical dissolution, the structure will absorb a lot of the solvent, which blows up its volume and thus mechanical stress is again applied to the ceramic structure.

Polyethylen:

A Polyethylen (wax) system is a very good choice for a mould material. It can be relatively nicely machined (see figure 4.9) and the removal of the mould can be done thermally at temperatures below 100°C. Therefore, low stress is applied to the green body. Still there will be some stress applied to the ceramic structure during the heating, and additionally when melting the mould material can stick to the ceramic rods and distort them from their lattice positions.

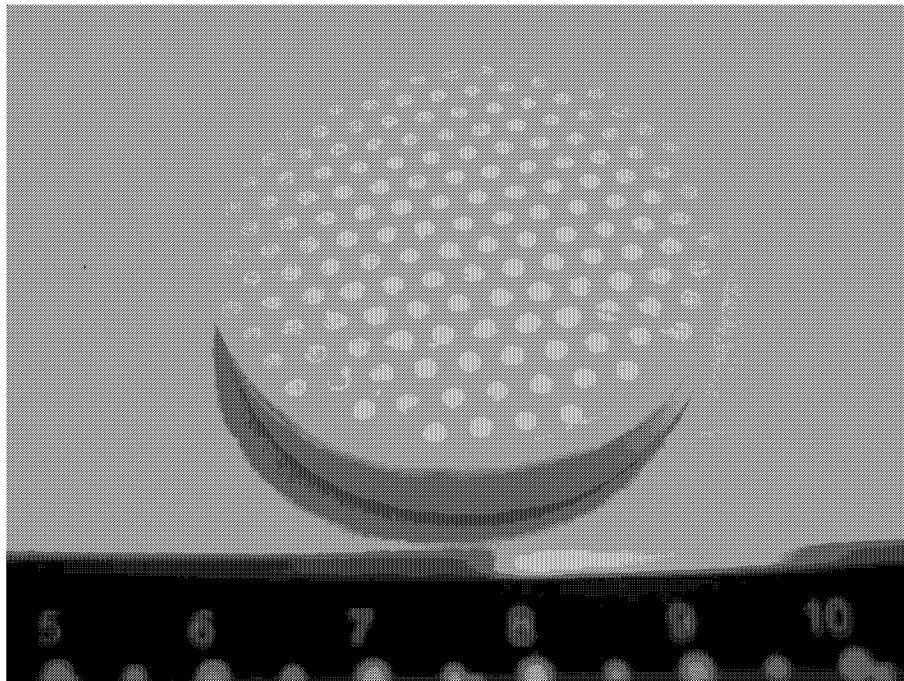


Figure 4.9: Ceramic green body of the alumina rods structure that was pressed into a Polyethylen mould, prior to mould removal. The rods are uniformly arranged into the hexagonal lattice structure and the thick substrate underneath plate can be seen that was used for stabilisation.

In conclusion it can be said that the wax mould system can be used to fabricate EBG structures, only for the highest aspect ratio structures it is not the optimal choice.

NaCl:

A sodium chloride mould has been found to be the best material for a mould so far. Even though it is relatively brittle and some problems can arise during the periodical patterning of the mould due to the creation of cracks in the material, it can still be used as a mould system in the region around 30 GHz, with millimetre sized lattice elements. The removal of the mould can be done by dissolution in water at room temperatures for about one hour, which is by far the best way of mould removing, as it does not do any harm to the green body at all. The mould was made by mechanical drilling of single crystalline sodium chloride (NaCl) slabs with a thickness of 10 millimetres (see figure 4.10).

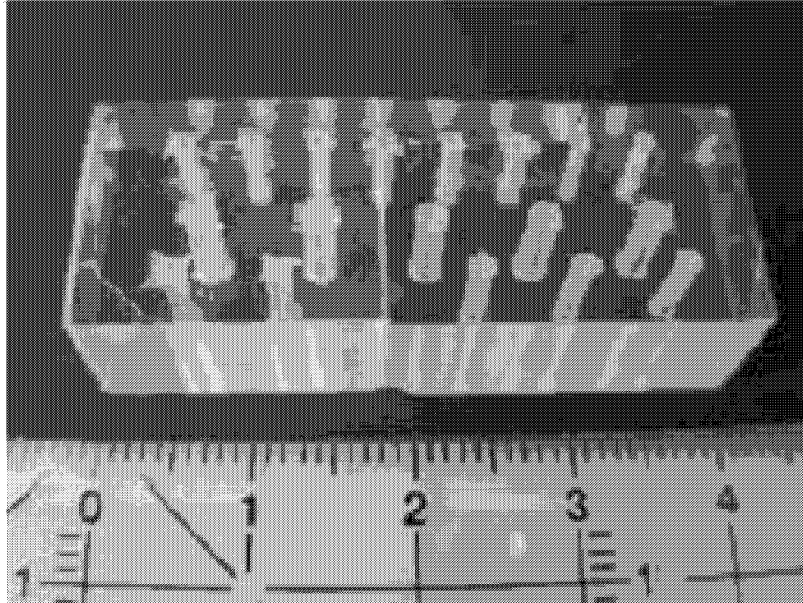


Figure 4.10: Sodium Chloride mould that was patterned with thin holes to test its stability. The small cracks are due to the brittleness of the NaCl material, but overall the mould material can be suitably machined.

We have fabricated EBG structures for a frequency range around 30 GHz by filling the NaCl mould with a ceramic slurry. After the periodical patterning of the mould by mechanical drilling, the mould was placed into a holder and the slurry was filled atop. The low vacuum from a water pump was used to pump the slurry into the holes of the mould. A distance has been left between the mould and the bottom of the holder to create a substrate plate of several millimetre thickness, which should provide stability of the isolated rods system after the mould was removed. The ingredients of the ceramic slurry that was used for filling the mould were pre-dried alumina powder (CT3000SG, Alcoa) and a thermoplastic low viscosity paraffin wax (Siliplast, Zschimmer & Schwarz) plus a dispersant (Stearic acid, Merck). The mixture was prepared at temperatures of 85°C. After the solidification of the slurry by drying in an oven at moderate temperatures, the mould was removed from the green body by simple dissolution in water. The green body of the ceramic rods structure can be seen in figure 4.11.

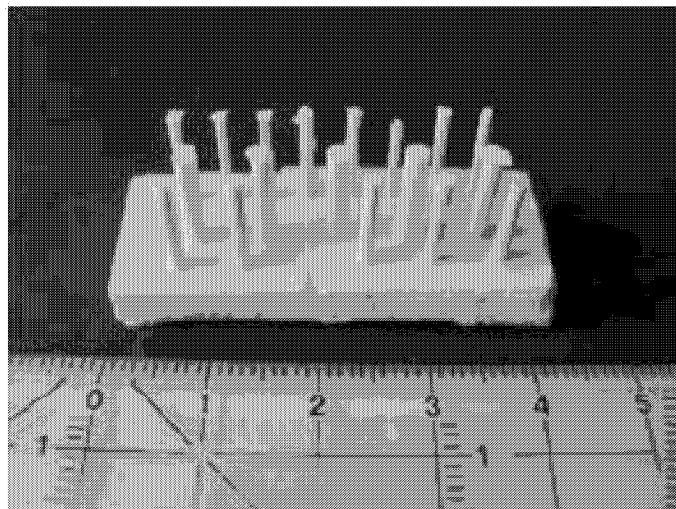


Figure 4.11: Green body of high aspect ratio dielectric rods made with a NaCl mould.

CHAPTER 4: FABRICATION OF ELECTROMAGNETIC BANDGAP STRUCTURES

Subsequently the organic components of the slurry were burned out for one hour at 600°C in air. The resulting ceramic structure (brown body) was then sintered to the final ceramic structure for five hours at 1500°C in air (see figure 4.12 for photographs of the brown body).

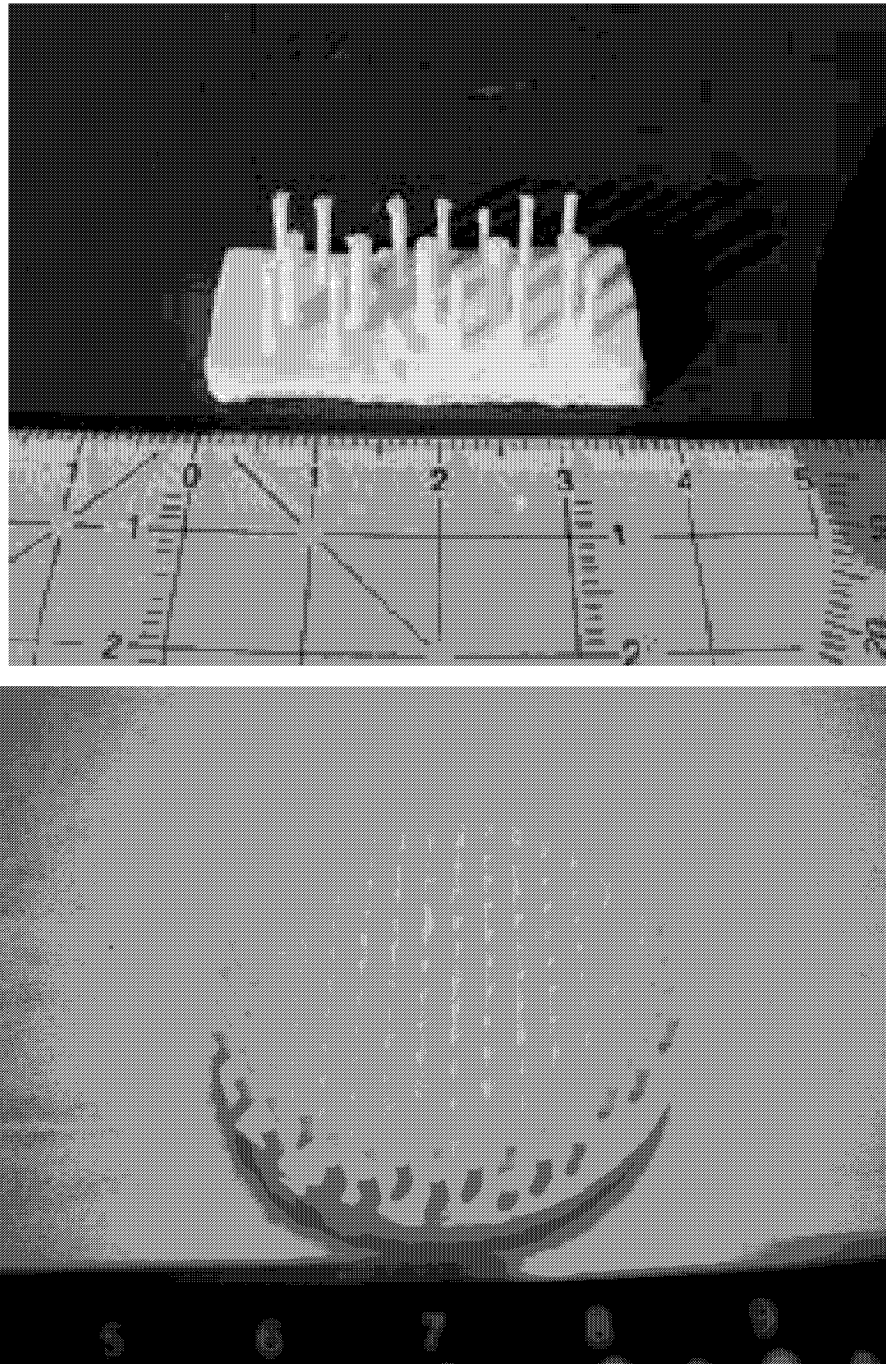


Figure 4.12: Brown bodies of the sintered dielectric rods structures that were fabricated with a NaCl mould. The rods are uniformly arranged into the lattice structure.

The density of the green body after removal of the mould was found to be 65 % of the theoretical density of Alumina, after the sintering process a density of 97-98 % of the theoretical density was achieved.

A scanning electron microscope (SEM) analysis of the surface morphology of the ceramic rods shows a smooth and dense surface (see figure 4.13). The sintered ceramic grain size was found to be between one and five micrometres.

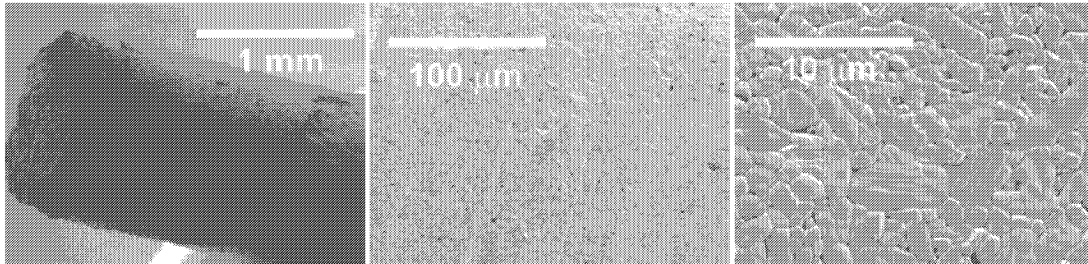


Figure 4.13: SEM micrograph of the dielectric rods fabricated with the NaCl moulding method (left side). The relatively smooth surface is only disturbed by little scratches (middle image) that arise from the pressing of the slurry into the mould. The size of the grains is between 1 and 5 micrometres (right side).

Overall, the ceramic moulding method proved to provide a relatively uncomplicated fabrication scheme for high aspect ratio ceramic structures for a frequency range of about 30 GHz, once the right slurry/mould system is found.

4.4 - 2D EBG structures made by reactive ion etching

For a target frequency of 100 GHz, the lattice parameters of EBG structures will be on the order of several hundred micrometres. While for mechanical and laser machining the limits of feasibility will already be approached due to the small scale of the structures, conventional etching processes are still not easy to apply, especially because the structure height is still quite large.

There are two major problems in the application of etching processes for EBG structures in the millimetre and low submillimetre range:

1. High aspect ratio structures are required, where a realisation requires highly anisotropic etching processes.
2. The material thickness will be of the order of several hundred micrometres, which will require extremely long etching times or very high etching rates.

In recent years, the so-called “Advanced Silicon Etching” (ASE) or Bosch-process[126] has proven to be the method of choice for etching of high aspect ratio structures. The Bosch process has been applied in a number of ways, for example in the realisation of Polysilicon structures for acceleration meters, microelectromechanical structures (MEMS) based on “Silicon-on-insulator” (SOI) materials[127][128] or the fabrication of microneedles for medical applications of small doses of agents[129]. In the following part of the chapter we will present a fabrication scheme for 2D EBG structures for frequencies around 100 GHz, that was developed at the Institute für Mikrosystemtechnik (IMTEK) in Freiburg according to a design that was developed in the frame of this work. In figure 4.14 the fabrication process is shown schematically.

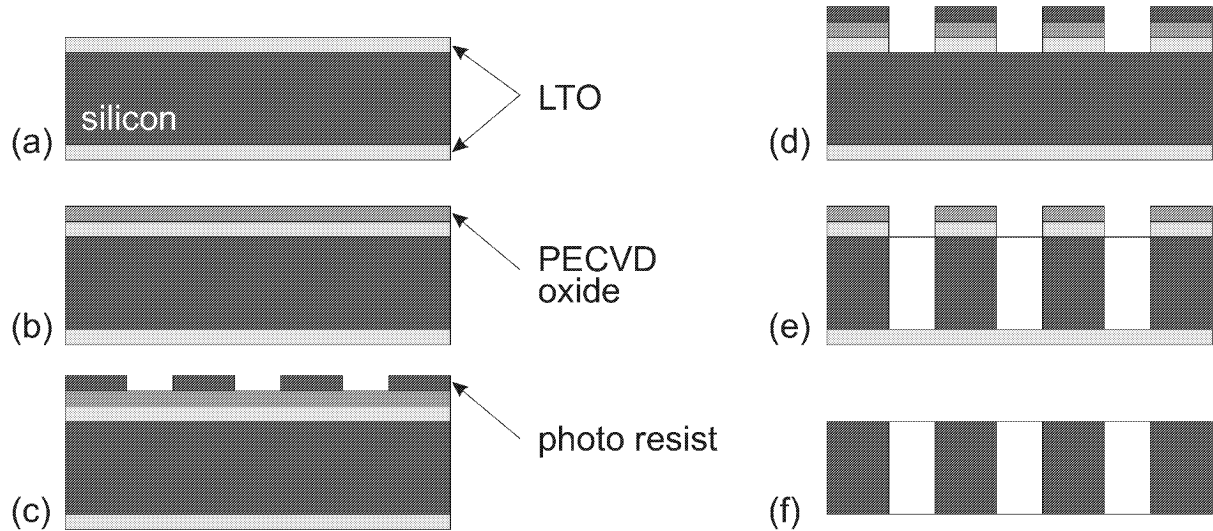


Figure 4.14: Fabrication process using deep reactive ion etching; (a) deposition of low temperature oxide (LTO) used as etch stop layer, (b) deposition of PECVD Silicon oxide on wafer front side (masking layer), (c, d) oxide patterning, (e) deep reactive ion etching, (f) removal of oxide layers.

In a first process step, a $1\mu\text{m}$ thick low temperature Silicon oxide (LTO) layer is deposited on both sides of the 4 inch wafer by chemical vapour deposition (CVD). This layer is annealed at 650°C for one hour to reduce intrinsic mechanical stress. Then, a $3.5\mu\text{m}$ thick oxide layer is deposited by plasma enhanced CVD (PECVD) onto the front side of the wafer. While the oxide layer sandwich on the front side of the wafer serves as etch mask, the $1\mu\text{m}$ thick LTO layer on the wafer rear is used as etch stop layer. The front Silicon oxide layers are patterned using photolithography and reactive ion etching (RIE). As a next step, the oxide mask pattern is transferred into the material with an inductively coupled plasma (ICP) etching process. At this point the Bosch process is applied, which consists of time periodic intervals of alternating steps: one anisotropic etching process and a second passivating process. During the anisotropic etching process the substrate material is etched mainly in the desired direction, but some etching at the sidewalls into the unwanted direction can also occur. In the passivation step the sidewalls of the etch holes are passivated to minimize the etching rate at these surfaces. After etching through the entire wafer (thickness $525\mu\text{m}$), the etch process stops automatically at the rear oxide. In a final process step, the Silicon oxide layers on both sides of the wafer are removed by 50 % hydrofluoric acid (HF) solution.

For the patterning of the EBG lattice on the wafer, a mask printed with a standard laser printer has been used. The small corrugation of the shape of the structures arises from this limited resolution of the etch mask and can be avoided, if other, expensive mask writing techniques are used (see figure 4.15 for closeup micrographs of the structure).

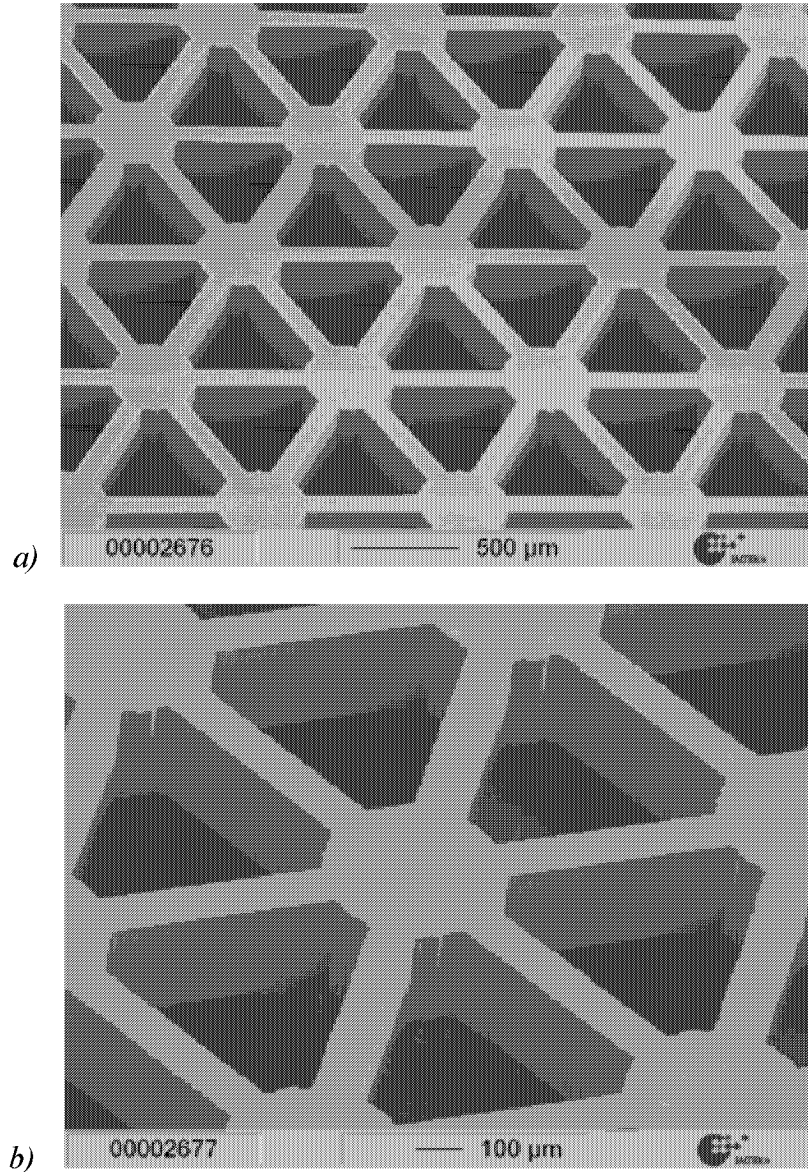


Figure 4.15 a: Overview of several lattice periods of the machined structure, the uniformity of the lattice elements is obvious. Fig. 4.15 b: Close up of the structure, the small corrugation arises from the limited etch mask resolution.

4.5 - 2D EBG structures made by laser machining

It has been mentioned before that laser machining is another method of choice for the fabrication of 2D EBG structures. It has its advantages in high fabrication speed and high precision. Structures down to sizes of several 10 μm can be fabricated, depending on the radius of the laser beam. A major drawback, however, are the high temperatures that are applied to the material, because it is evaporated by the energy of the laser beam. Therefore, laser machined areas of the material will, especially in the case of single- or polycrystalline material, be degraded in their high frequency properties and exhibit larger losses. A 2D EBG structure that was made from laser machining of a Silicon wafer was investigated. The wafer had a thickness of 525 μm and was made from high resistive Silicon. A structure of hexagonally arranged circular holes was drilled into the wafer by the laser beam. The laser

that was used in the process was a pulsed Nd:YAG solid state laser with a power of 150W, pulse length of 0.2-2 μs and a wavelength of $\lambda=1024\text{nm}$.

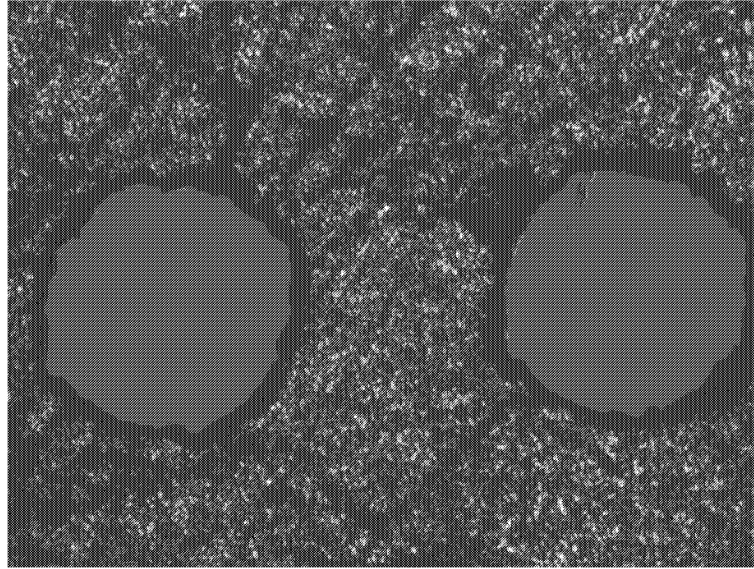


Figure 4.16: Micrograph of two adjacent holes of the 2D EBG structure made by laser machining. The shape of the holes is approximately circular. Distortions from the circular shape arise from the limited step size of the laser stepper motor.

It was observed that the drilled holes had a nicely circular shape (see figure 4.16). The small steps that can be seen at the edge of the drilled holes are due to the limited step size of the stepper x-y-motor of the laser carrier. Nevertheless, the shape of the holes is satisfying.

Unfortunately, the extremely strong heat production due to the melting of the material has a very bad impact on the surface of the wafer. At the bottom side there is molten material that flows out of the holes and creates small hills at the edges of the holes. Heat bubbles below the surface of the waves will also cause a creation of small hills (see figure 4.17).

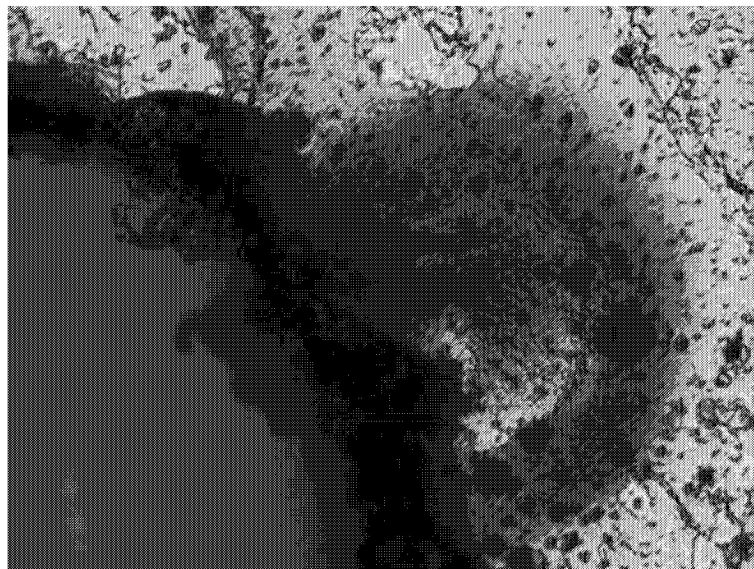


Figure 4.17: Heat bulge at the edge of a drilled hole

Additionally, parts of the molten and blown out material condense over the whole surface of the wafer. A comparison between front and back side of a wafer is shown in figure 4.18.

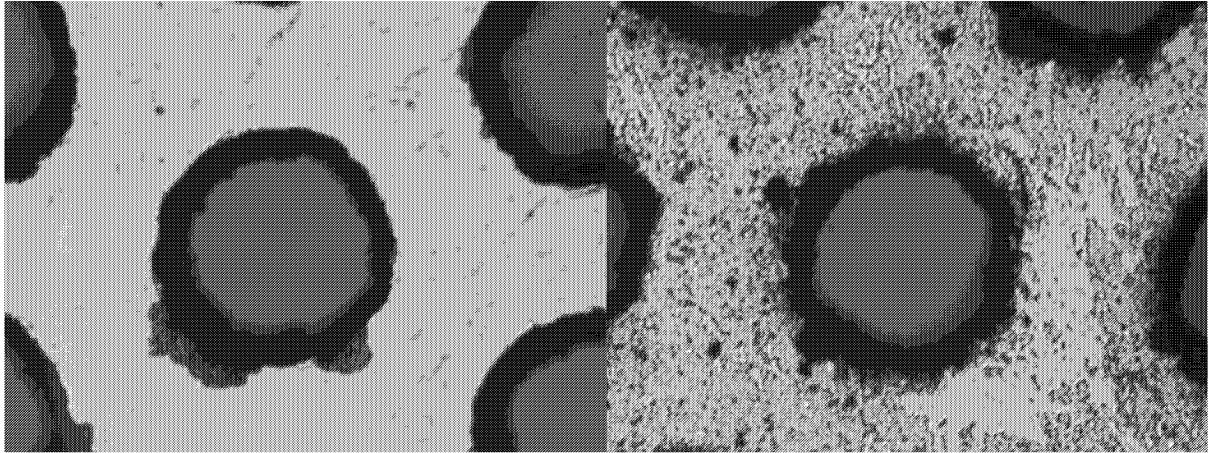


Figure 4.18: Comparison of front and back side of the Silicon wafer. The front side of the wafer is still relatively clean while the back side is severely corrugated due to the thermal stress during the fabrication process and the deposition of molten material on this surface.

It is possible to remove the dirt on the back side of the wafer by polishing (see figure 4.19). During this process, large parts of the condensed material will be removed, but there will be a dense network of scratches covering the whole surface of the wafer. Experiments to determine the influence of these scratches on the EBG properties of the materials must be undertaken, unfortunately, this could not be done in the frame of this work. Additionally, alternative polishing methods that include chemical polishing must be investigated.

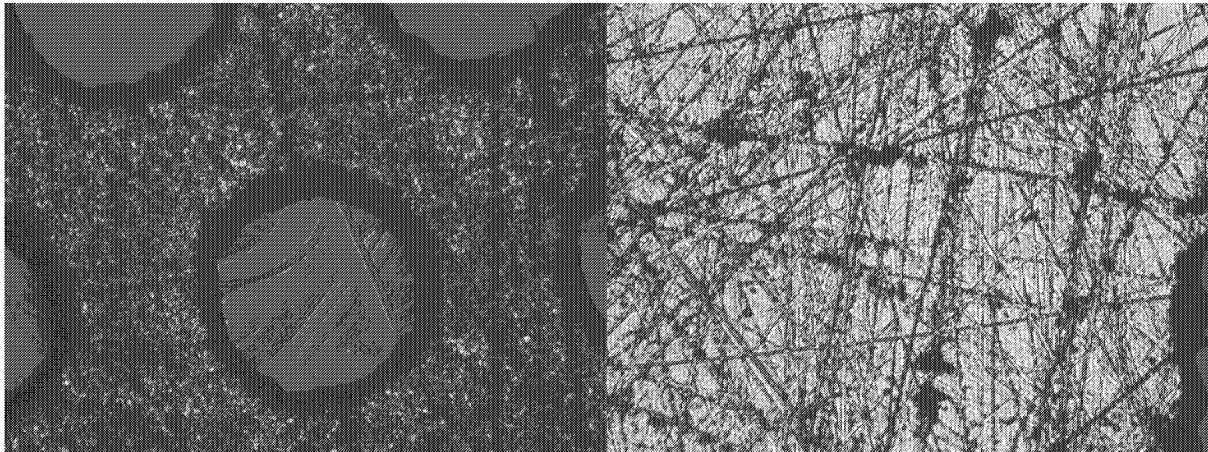


Figure 4.19: Micrograph of the polished Silicon surface. The structure is now more regular than before. However, the front side does not look as plain as before, and in a closer view it can be seen that there is a dense network of scratches over the whole surface of the wafer.

In conclusion, it seems that the machining of dielectric EBG structures with a laser is a very convenient and precise method of fabrication. Nevertheless, it seems to have a very strong impact on the quality, especially the surface roughness of the structures. The influence of this roughness must be investigated in order to judge whether the laser drilling is a suitable method. Alternate methods of drilling that do not include a strong heating of the material, for example drilling with an extremely high pressure water beam or ultrasonic methods, should also be investigated.

Chapter 5: Experimental techniques

In the frame of this work, a number of electromagnetic bandgap structures has been investigated experimentally to verify the results that were gained from the simulation and to investigate the quality of the used fabrication methods. The experiments have been conducted in the microwave range up to 40 GHz and in the millimetre wave range around 100 GHz. Transmission parameters as well as quality factors have been measured. Due to the fact that electromagnetic bandgap structures can be tailored to operate in different frequency regimes, it is also necessary to use different experimental techniques to measure their properties. In this chapter, the experimental techniques that were used in the frame of this work will be presented and to some extent also an overview of the physics behind them will be given.

5.1 - S parameter measurements and passive microwave devices

In this part of the chapter, the basics of measurements at microwave frequencies will be summarized. We will explain the concept of S parameters measurements and the most important variables for the characterisation of resonators and waveguides. Most of the results from this part of the chapter can be found in standard microwave device textbooks[130][131][132][133]

S parameter measurements

The frequency behavior of a microwave device is characterized by its transmission and reflection properties. Figure 5.1 shows schematically a device with two gates. At each gate there is an incoming signal described by a_1, a_2 and an outgoing signal b_1, b_2 . The symbols a_1, a_2, b_1, b_2 represent the amplitude of the signal given by the voltage of the incoming and outgoing signal (U^i, U^o) at port n of the device, divided by the wave impedance

$$a_n = \frac{U_n^i}{\sqrt{Z_L}} \quad b_n = \frac{U_n^o}{\sqrt{Z_L}} \quad (5.1)$$

The transmission properties of the device can be described, when the incoming and outgoing waves are set into relation:

$$\begin{pmatrix} b_1 \\ b_2 \end{pmatrix} = \begin{pmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{pmatrix} \begin{pmatrix} a_1 \\ a_2 \end{pmatrix} \quad (5.2)$$

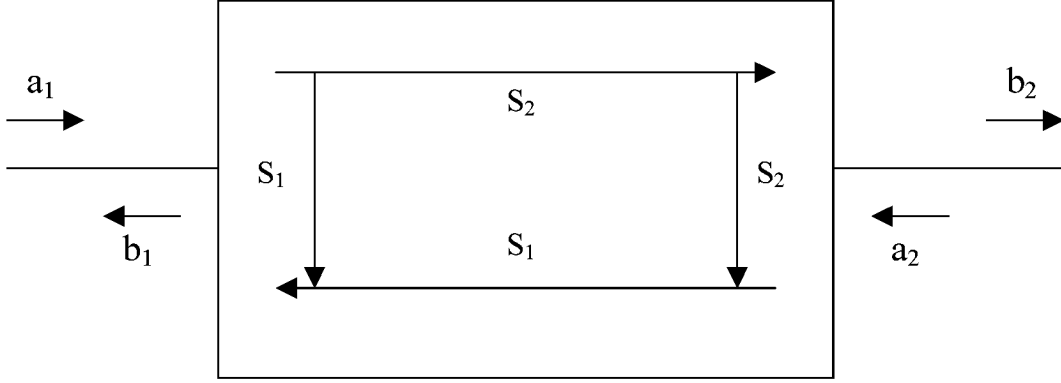


Figure 5.1: Schematic drawing of a two-port device with incoming signals a_1, a_2 and outgoing signals b_1, b_2 . The reflection and transmission of the signals through the device are characterized by the S parameters S_{ij} .

For devices with more than two gates, the S parameter matrix is replaced by a matrix of the corresponding size. Due to the formulation of the a_n and b_n with a normalization on the wave impedance, the S parameters are only determined by the frequency dependence of the device under test, and are independent from the high frequency power of the incoming signal. The S_{ij} parameters describe the reflection of a signal at port i for $i = j$ and the transmission of a signal from port j to port i for $i \neq j$. Their absolute square $|S_{ij}|^2$ denotes the ratio of the high frequency power for the incoming and outgoing signal:

$$|S_{ij}|^2 = \frac{P_{in,j}}{P_{out,i}} = \left(\frac{I_{in,j}}{I_{out,i}} \right)^2 = \left(\frac{U_{out,i}}{U_{in,j}} \right)^2 \quad (5.3)$$

The S parameters are given in dimensionless units of decibel (dB)

$$S_{ij} [dB] = 10 \cdot \log(S_{ij}) \quad (5.4)$$

Resonators

A resonator is a volume in which electromagnetic energy can be stored in one of its eigenmodes. In this chapter we will focus on cavity resonators where the electromagnetic energy is stored in a resonator volume that is filled with air or a dielectric material. The mode spectrum of the cavity resonator is given by its shape and size. When an eigenmode of the resonator with a mode pattern $\vec{H}(\vec{r})$ and a frequency ω (the mode eigenfrequency) is excited, it will contain an amount of electromagnetic energy W given by

$$W = \frac{1}{2} \mu_0 \int d^3r |\vec{H}(\vec{r})|^2 \quad (5.5)$$

This energy will be stored in the resonator, but due to a number of mechanisms, in every oscillation period of the mode a part of the energy will be lost. This leakage can be due to radiative losses in case of an open or partially open resonator, or losses in the material of the resonator. The mode will decay on a time scale τ given by

$$\tau = \frac{Q_0}{\omega} \quad (5.6)$$

Here Q_0 is the unloaded quality factor of the resonator and is defined by the ratio of total stored energy W and energy loss P_0 , normalized to an oscillation period ω :

$$Q_0 = \frac{\omega W}{P_0} \quad (5.7)$$

If we neglect radiation losses, which is a good approximation for most microwave resonators, the losses of energy in the resonator will be caused by the interaction of the electromagnetic fields with the material in the resonator. We can observe two contributions: One contribution from dielectric materials due to their loss tangent $\tan \delta$, and a second contribution from the metallic walls of the resonator due to their surface resistance R_s . Loss tangent and surface resistance have been introduced in chapter 2.

The dielectric quality factor Q_{diel} is given by

$$\frac{1}{Q_{\text{diel}}} = \sum_i \kappa_i \tan \delta_i \quad (5.8)$$

where the $\tan \delta_i$ are the loss tangents of the dielectric materials present in the resonator volume and the κ_i are the dielectric filling factors, given by the ratio of the electric energy in the dielectric i and the total electric energy of the mode

$$\kappa_i = \frac{E_{\text{diel},i}}{E_{\text{tot}}} \quad (5.9)$$

The metallic quality factor Q_m is given by the sum of the loss contributions from the metallic surfaces of the resonator with surface resistance $R_{s,j}$ and a geometric factor, representing the field strength of the magnetic field at the metal surface A_j related to the total magnetic field in the resonator volume.

$$\frac{1}{Q_m} = \sum_j \frac{R_{s,j}}{G_j} \quad (5.10)$$

Here the geometric factor G_j is given by

$$G_j = \omega \mu_0 \frac{\int d^3 r |\vec{H}(\vec{r})|^2}{\int dA_j |\vec{H}(\vec{r})|^2} \quad (5.11)$$

The total unloaded quality factor of a resonator will be the sum of the single contributions:

$$\frac{1}{Q_0} = \frac{1}{Q_{diel}} + \frac{1}{Q_m} = \sum_i \kappa_i \tan \delta_i + \sum_j \frac{R_{s,j}}{G_j} \quad (5.12)$$

In an experiment, the high frequency signal must always be coupled from an external source into the resonator, in order to measure its resonant modes. This coupling will introduce additional losses due to leakage of energy back into the coupling antennae. The measured quality factor is called loaded quality factor and it will always be lower than the unloaded quality factor. The influence of the antennas is described by coupling quality factors Q_1 and Q_2 . Overall, the loaded quality factor of the resonator for a mode with field distribution $\vec{H}(\vec{r}), \vec{E}(\vec{r})$ will be given by

$$\frac{1}{Q_l} = \frac{1}{Q_0} + \frac{1}{Q_1} + \frac{1}{Q_2} \quad (5.13)$$

The loaded quality factor can be measured in the experiment. It is related to the frequency of a resonant mode ω_0 and its half width $\Delta\omega$ by

$$Q_l = \frac{\omega_0}{\Delta\omega} \quad (5.14)$$

There is a special case of transmission resonators, where the resonant cavity is placed at the side of a transmission line. In this case, the transmission spectrum would exhibit a dip at the resonance frequencies of the cavity. The situation is displayed in figure 5.2. For the lossless cavity the transmission in the dip will be zero. The loaded quality factor of the cavity is described by the halfwidth of the dip in linear scale, while the strength of the coupling is related to its depth. The unloaded quality factor Q_0 can be calculated by

$$Q_0 = \frac{f_0}{\Delta f} \frac{1}{|S_{21}|^2} \quad (5.15)$$

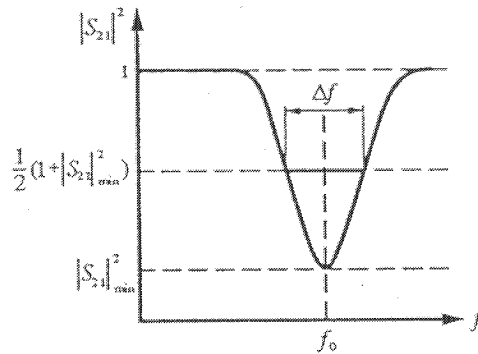


Figure 5.2: Frequency of a band reject transmission filter with losses

Cavity resonators

The cavity resonator is a commonly used device in microwave measurements. In this work, defect resonances in EBG materials are investigated, that are expected to show similarities to

cavity resonator modes. Therefore, in this part of the chapter we will summarize the properties of cavity resonator eigenmodes and their field distributions for the special case of the cylindrical cavity resonator. We assume, that the cavity resonator is made from a cylindrical volume, enclosed by perfectly conducting electric walls. The volume is filled with a homogenous medium ($\sigma=0, \mu=1, \epsilon$). The cavity has a diameter d and a length l . This system has rotational symmetry along the length of the resonator. The Helmholtz equation can in this case be separated into an axial and a radial part:

$$\nabla_t^2 \begin{pmatrix} \bar{E}(\bar{r}) \\ \bar{H}(\bar{r}) \end{pmatrix} + k^2 \begin{pmatrix} \bar{E}(\bar{r}) \\ \bar{H}(\bar{r}) \end{pmatrix} = 0 \quad \text{with} \quad \nabla_t^2 = \frac{\partial^2}{\partial r^2} + \frac{1}{r} \frac{\partial}{\partial r} + \frac{1}{r^2} \frac{\partial^2}{\partial \phi^2} \quad (5.15)$$

This case is very simple and can be solved analytically. The complete mode pattern can be calculated from the z-component of electric and magnetic field (E_z, H_z). We will therefore distinguish modes with $E_z=0$ and modes with $H_z=0$:

1. Transverse electric modes. These modes have $E_z=0$ but $H_z \neq 0$
2. Transverse magnetic modes. These modes have $H_z=0$, but $E_z \neq 0$

The z-components of the fields are given by the Bessel functions J_m :

$$\begin{aligned} H_z(mnp) &= J_m \left(\frac{2\chi_{mn}r}{d} \right) [A \cdot \cos(m\phi) + B \cdot \sin(m\phi)] \sin \left(\frac{p\pi z}{l} \right) \\ E_z(mnp) &= J_m \left(\frac{2\chi_{mn}r}{d} \right) [A \cdot \cos(m\phi) + B \cdot \sin(m\phi)] \cos \left(\frac{p\pi z}{l} \right) \end{aligned} \quad (5.16)$$

with the mode indices m, n, p describing the nodes of the field distribution in azimuthal, radial and axial direction. The χ_{mn} and χ'_{mn} are the nodes of the Bessel functions and its derivative.

The eigenfrequencies of these modes are given by

$$f_{mnp} = \frac{c}{2} \sqrt{\left(\frac{\chi_{mn}}{d} \right)^2 + \left(\frac{p}{l} \right)^2} \quad (TM \text{ modes}) \quad (5.17 a)$$

$$f_{mnp} = \frac{c}{2} \sqrt{\left(\frac{\chi'_{mn}}{d} \right)^2 + \left(\frac{p}{l} \right)^2} \quad (TE \text{ modes}) \quad (5.17 b)$$

In this simple case, the geometric factors of the modes can also be calculated analytically.

Rectangular waveguides

Rectangular waveguides are commonly used for the transport of the electromagnetic modes in the microwave range. They are made from a metal tube with a rectangular cross section. Waves propagating in this tube will travel longitudinally along the tube, being reflected back and forth at the side walls of the tube in x and y direction. They will consist of a standing wave (plane wave) in the direction normal to the reflecting walls of the guide and one travelling wave parallel to these walls. Due to this guiding process, a pure transverse

electromagnetic (TEM) mode will not exist, but we can distinguish modes into transverse electric (TE) and transverse magnetic (TM) modes, where either the electric (TE) or the magnetic (TM) field has no component along the direction of propagation. The solutions of the wave equation in the rectangular waveguide are given in the form

$$\begin{aligned}\nabla^2 \vec{E} &= \gamma_g^2 \vec{E} \\ \nabla^2 \vec{H} &= \gamma_g^2 \vec{H}\end{aligned}\quad (5.18)$$

with a propagation constant γ_g that is given by the propagation along the guide and the influence of the reflecting walls on the standing wave pattern normal to the propagation direction

$$\gamma_g^2 = \gamma_0^2 + k_c^2 \quad (5.19)$$

with $\gamma_0^2 = -\omega^2 \epsilon \mu$ determined by the material in the guide (usually $\epsilon \cdot \mu = 1$) and the so called cutoff wavenumber $k_c^2 = k_x^2 + k_y^2$. A propagation of waves below the cutoff frequency

$$k_c^2 = -\omega^2 \epsilon \mu \Rightarrow f_c = \frac{1}{2\pi\sqrt{\epsilon\mu}} \sqrt{k_x^2 + k_y^2} \quad (5.20)$$

is not possible. The modes that can propagate in the waveguide are characterized by mode indices m, n that describe the mode pattern in the direction normal to the propagation. Generally, the lowest order mode with a frequency above the cutoff frequency is the dominant mode in a rectangular waveguide.

Let us assume a rectangular shaped metal tube filled with air ($\epsilon = \mu = 1$) with side lengths a and b, and wave propagating in z-direction.

TE and TM modes in rectangular waveguides

The cutoff wavenumber k_c and the correlated cutoff frequency f_c for TE and TM modes are given by

$$k_c = \sqrt{\frac{m\pi^2}{a^2} + \frac{n\pi^2}{b^2}} \quad f_c = \frac{1}{2\sqrt{\epsilon\mu}} \sqrt{\frac{m^2}{a^2} + \frac{n^2}{b^2}} \quad (5.21)$$

The propagation constant of a TE wave with frequency f is then given by

$$\gamma_g = \omega\sqrt{\epsilon\mu} \sqrt{1 - \left(\frac{f_c}{f}\right)^2} \quad (5.22)$$

In rectangular guides, modes with the same order m, n always share the same cutoff frequency, they are therefore called “degenerate modes”. For a guide with $a > b$, the TE_{01} mode is dominant. Basically, in a waveguide, all modes are present, but the non-propagating modes decay fast enough to neglect their influence. Nevertheless, in an application the waveguide dimensions for a given frequency range should always be chosen so that there is a minimum number of propagating modes.

5.2 - Frequency domain submillimetre wave spectroscopy

When frequencies approach 100 GHz, the dimensions of conventional metallic waveguides become very small, and the surface resistance of the metal increases, so that Ohmic losses in the waveguide walls become problematic and fabrication tolerances become significant. Therefore, millimetre and submillimetre waves are in most cases guided in free space by dielectric lenses, metallized mirrors and wire grid polarisators. The dimensions of these devices are in the order of several centimetres, as compared to a wavelength in the millimetre range. Therefore, the rules of geometrical optics cannot be applied. The treatment of waves in such a system is called “quasioptical”. For the quasioptical regime, diffraction effects do not play a role, but we cannot assume an infinitely small wavelength. A solution of the wave equation has to be found that is an approximation to the plane wave for a finite wavelength. This solution is called the “Gaussian beam” and in cylindrical coordinates it is of the form[40][134]

$$E(r, z) = E_0 \frac{w_0}{w(z)} e\left(-\frac{r^2}{w(z)^2}\right) e^{(-i\{\phi_0 - \Psi_T(r, z) - \Psi_L(z)\})} \quad (5.23)$$

For the propagation of a Gaussian beam through optical devices, it is possible to find a transfer matrix formulation, when suitable parameters for the beam description are introduced. As this is not one of the main topics of this work, it will be left out.

Backward wave oscillators

In a backward wave oscillator (BWO), electrons are generated by thermal heating of a cathode, and are accelerated towards the anode (collector) by a high voltage. The electrons from the source are focussed to a beam by a high external magnetic field. The electron beam is directed to many times cross a meandering transmission line or waveguide, in which a radio frequency (RF) signal will be coupled in (see figure 5.3).

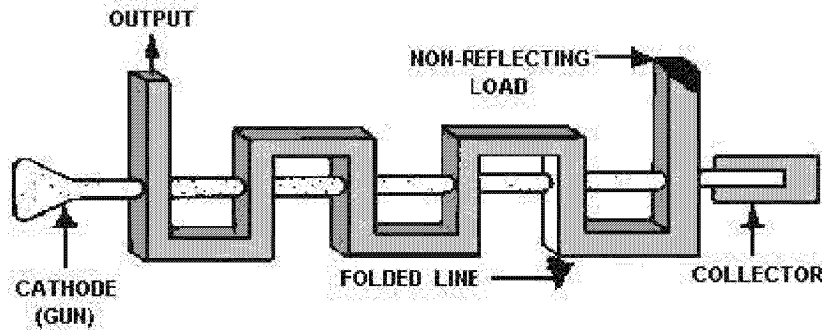


Figure 5.3: Schematic drawing of the meandering slow wave structure along which the electrons are bunched and energy from the electron beam is transferred to the wave

The meandering line acts as a slow wave structure for the RF signal, so its velocity in the direction of the electron beam is approximately equal to that of the electrons accelerated by the high voltage. The electric field of the RF signal will velocity modulate the electrons and a bunching of the electrons in the beam will occur. The bunching leads to an even stronger interaction between the RF signal and the electron beam, and thus the signal is amplified. The output frequency of the device is controlled by the transit time of the electron beam. It can therefore be controlled over the potential of the collector, i.e. the acceleration voltage of the electron beam. BWOs typically work in the frequency regime above 80 GHz and up to more

than one Terahertz. Their advantage lies in the very high output power even at Terahertz frequencies (typically several tens of milliwatts)

Golay cell detector

A Golay cell is a broadband, high sensitive optoacoustical detector. An air volume is enclosed with a thin foil that is transparent for millimetre wave radiation (polyethylene). The foil window bulges slightly when heat is received by it. The bulging tilts a small mirror, which, in turn, varies the amount of light proceeding from a lamp to a photocell. The radiation is measured by sensing the increase in pressure in a gas chamber as the temperature rises when radiation is absorbed. Golay cells have a very high sensitivity ($10^{-10} - 10^{-11} \text{ W}/\sqrt{\text{Hz}}$) and a linear response over a wide range of input intensities (40 dB). The Golay cell is operated in a chopped mode, and the measurement of its output signal must be performed with a lock-in amplifier.

5.3 - Time domain terahertz spectroscopy

In a Time Domain Terahertz Spectroscopy (TDS) setup, the high frequency signal is composed of spectral components typically in the range from 60 GHz up to a few Terahertz. The signal is generated by either biased semiconductor emitters or rectification of an optical pulse by nonlinear effects in electro optical crystals. Emission spectra of various emitters are shown in figure 5.4.

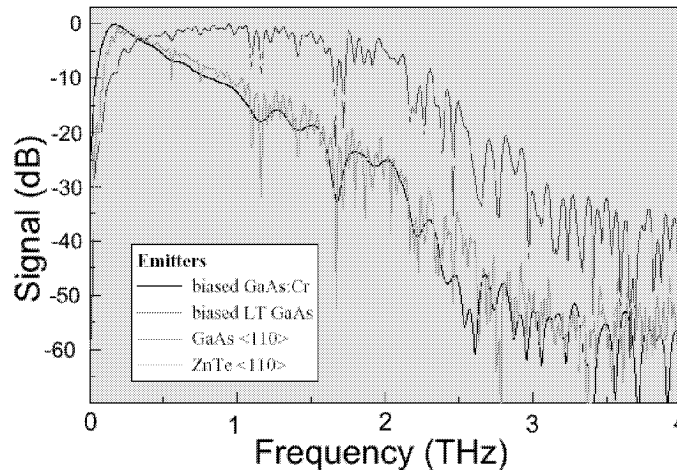


Figure 5.4: Typical emission spectra of various Terahertz emitters such as biased semiconductor devices or electro optical crystals

In the frame of this work, Terahertz generation by optical rectification was used, therefore the basics of signal generation and detection will be shortly explained[135][136][137]. A pulsed laser with a wavelength of 800 nm and a pulse length of 50-80 femtosecond (fs) (Coherent MIRA) seeds a multipass femtosecond amplifier (Quantronix ODIN) that is pumped by a Nd:YLF laser with an output power of 5 Watt. The amplifier emits laser pulses with a length of 40 fs, a peak electric field of 5 kV/cm and a peak power of 2.3 kW. To measure a sample, the beam is split into two parts. One part of the beam is used as a sampling beam and is guided along a variable delay line that has a typical length of a few centimetres, according to a delay of a few hundred picoseconds. The other part of the beam, which is called the probe beam, is focused onto a non-centrosymmetric electro optical crystal (in our case ZnTe) that is cut in <110> direction. The optical pulse induces a second order non-linear polarisation,

which will be proportional to the envelope of the pulse. The radiated field of this polarisation will then consist of frequencies according to the fourier transform of the pulse shape, ranging from several ten GHz up to several THz.

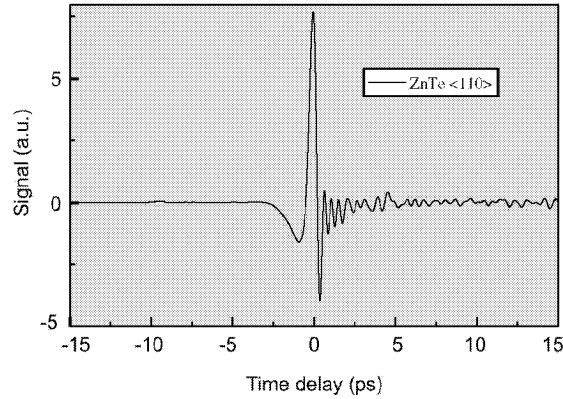


Figure 5.5: Typical shape of a terahertz pulse that is propagated through a sample: The original pulse at a delay of zero picoseconds is expanded due to the frequency dependent transmission of the sample.

The probe pulse propagates through the sample, where its shape and time position relative to its reference pulse in the sampling beam is changed due to the complex refractive index N of the sample. A typical pulse shape after the transition through a sample is shown in figure 5.5. After the probe beam has propagated through the sample, it is brought together with the sampling beam and both pulses are incident on the detector, another nonlinear electrooptical crystal (ZnTe). At this point it has to be kept in mind that the length of the sampling pulse is much shorter than the length of the probe pulse. The relative time delay between the two pulses can be varied by the delay line. The optical pulse of the sampling beam will influence the properties of the detector crystal, so that the polarisation of the electric field of the probe beam will be rotated. This change in polarisation can be measured with two subsequent polarizers and photodiodes. With a scanning of the sample pulse delay, the shape of the probe pulse in time can be measured. A schematic view of the measurement setup is shown in figure 5.6:

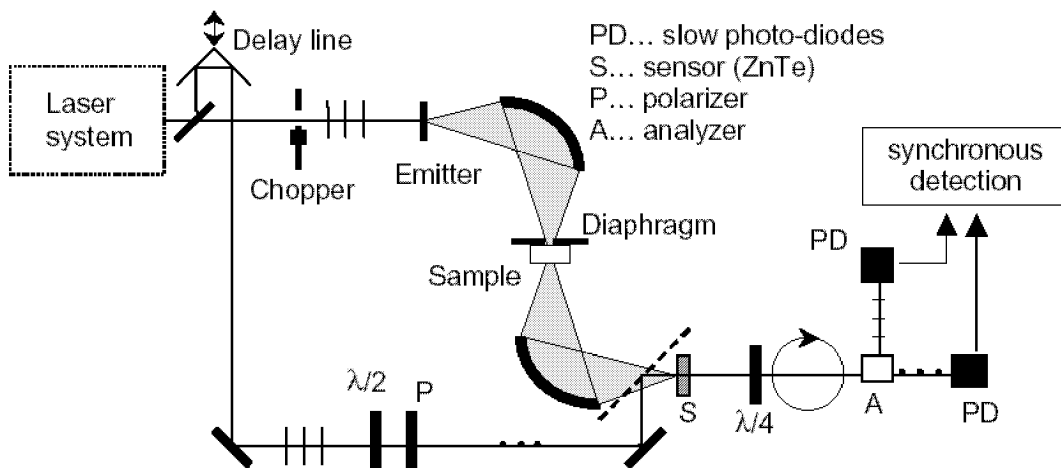


Figure 5.6: Schematic drawing of a TDS experimental setup. The optical pulse from the laser system is split into a probe beam and a sampling beam. The probe beam is propagated through a Terahertz emitter and passes through the sample. It is combined with the sampling beam before the detector. The polarisation of the signal is rotated to determine the strength of the probe pulse that has passed the sample for different delays of the sampling beam.

When the measured pulse is divided by a reference pulse signal from a measurement without a sample, the influence of the sample can be determined and expressed in the transmission coefficient $t(\omega)$.

Chapter 6: Experimental investigation of electromagnetic bandgap structures

In the previous chapters of this work, the properties of a number of electromagnetic bandgap structures have been investigated in simulation. For the realisation of these structures, different fabrication processes have been investigated and EBG structures for frequencies from 10 GHz up to 100 GHz have been fabricated. For the investigation of EBG structures, the experimental measurement is important for two different reasons: on the one hand, findings from simulation must be confirmed in the experiment, and on the other hand, the properties of the fabricated structures must be measured in order to judge whether the applied fabrication method is suitable. In this part of the chapter we will present experimental investigations of EBG structures at frequencies of 10, 20, 30, 90 and 100 GHz. One of the goals of this work was the investigation of electromagnetic bandgap structures with respect to a possible application in future millimetre and submillimetre wave circuits. To achieve this goal, it must be demonstrated that EBG structures can act as passive elements in such circuits. With the experiments that are presented in this chapter we have tried to show that EBG structures can be used to create high quality factor resonant structures and low loss broadband waveguiding elements for the micro- and millimetre wave range.

6.1- Excitation of line and point defect modes in a 2D EBG lattice for 10 GHz

In a previous chapter we have already discussed the behavior of line and point defect modes in 2D EBG materials. Nevertheless, we did not take into account that the lattice has a finite extension and the excitation of a mode must come from outside. Also we have not studied a situation where there is more than one defect structure in the lattice. For a successful application of an EBG material in a high frequency circuit, it is not only necessary that the EBG lattice has a suitable band gap and thus a possibility to store or guide a mode in a point or line defect. It is equally important to find efficient schemes for a coupling of the electromagnetic energy from external microwave circuitry into the EBG lattice. Additionally, the coupling between different defect structures inside the EBG lattice must be optimised to make sure that the single components can effectively be combined.

In this chapter we will show and explain how the coupling from an external metal waveguide into a line defect in a 2D EBG structure can be optimised by a variation of the line defect size by investigation of dispersion curves of defect modes and field distributions in both waveguide and line defect. Furthermore, we will demonstrate that a tuning of the coupling strength from a line defect in an EBG lattice into a resonant cavity made from a point defect

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created by the removal of several lattice elements is possible, when appropriate lattice elements are modified.

For these investigations we have employed a 2D hexagonal lattice of dielectric rods with air as a background material. The rods were fully enclosed in a metal housing made from oxygen free high conductive (OFHC) copper. We have cut the rods to a length of 10 mm, which corresponds to one third of the wavelength at the target frequency. Thus it was ensured that only TM modes with their electric field along the rod axis and without nodes in that direction would propagate. The metal housing containing the EBG elements was equipped with two standard X-band waveguide ports with a width of 19.05 mm and a height of 9.525 mm. Each waveguide port was terminated with a standard waveguide-to-coaxial transition to provide the connection to the measurement setup. The waveguide was operated in its fundamental mode that has its electric field in our desired direction along the rods' axis, parallel to the smaller edge of the metal waveguide with no nodes along that direction. This type of mode has the lowest cutoff frequency in rectangular waveguides and is therefore dominant, which makes it very suitable for our setup. An operation in a mode with different polarisation is not suitable, due to the relatively small height of the metal housing, which will enforce an electric field along the y direction. A photograph of the resonator can be seen in figure 6.1.

The experiments have been performed using an HP 8510 network analyser and a full 2 port S parameter test set. We will show comparisons between simulation and experimental results for the transmission parameter S_{12} of the described 2D photonic crystal structure including various defect structures and deduce the coupling properties of the EBG structures thereof.

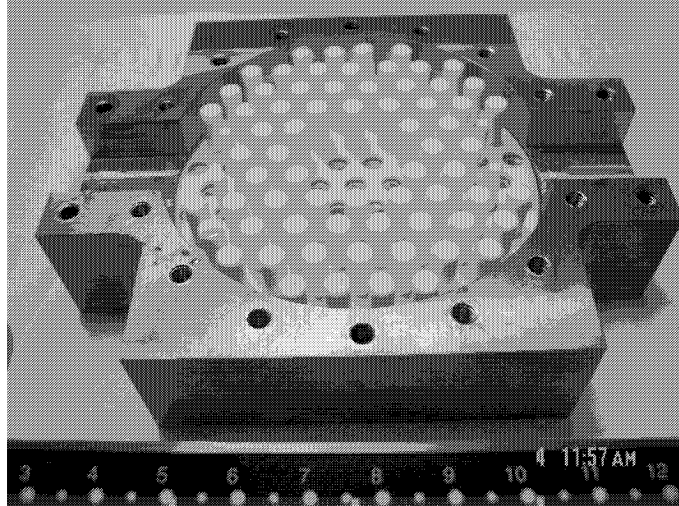


Figure 6.1: Experimental arrangement of the dielectric rods in the metal cavity. The hexagonal lattice was formed by placing the rods in places that were determined by a thin Teflon mask that was aligned with the resonator bottom.

The 2D photonic crystal lattice has been formed out of ceramic rods made from polycrystalline aluminium oxide (Al_2O_3) with an isotropic dielectric constant of $\epsilon_r = 9.6$, loss tangent $\tan \delta = 5.8 \cdot 10^{-5}$ at 10 GHz, a radius of 2.16 mm and a length of 11 mm. The ratio between rod radius r and lattice constant a was chosen to be 0.3, thus yielding three photonic band gaps for TM waves. As our target frequency range was in the microwave region, we chose an absolute lattice constant of 7.2 mm, and the resulting band gaps were located in the X and Ku band from 10 to 14.2 GHz, in the K band from 19.1 to 23.8 GHz and in the Ka band from 28.3 to 32.7 GHz. We will focus on the first band gap around 12 GHz, by

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investigating a frequency span from 8 GHz to 16 GHz. The axis along the metal waveguide will be referred to as x-axis, the one along the dielectric rods as z-axis and the one perpendicular to both as y-axis. For each structure under investigation we will compare our results from simulation and experiment and explain its behavior in three frequency regions separately: below the bandgap, in the bandgap and above the bandgap.

Band structure and transmission behavior

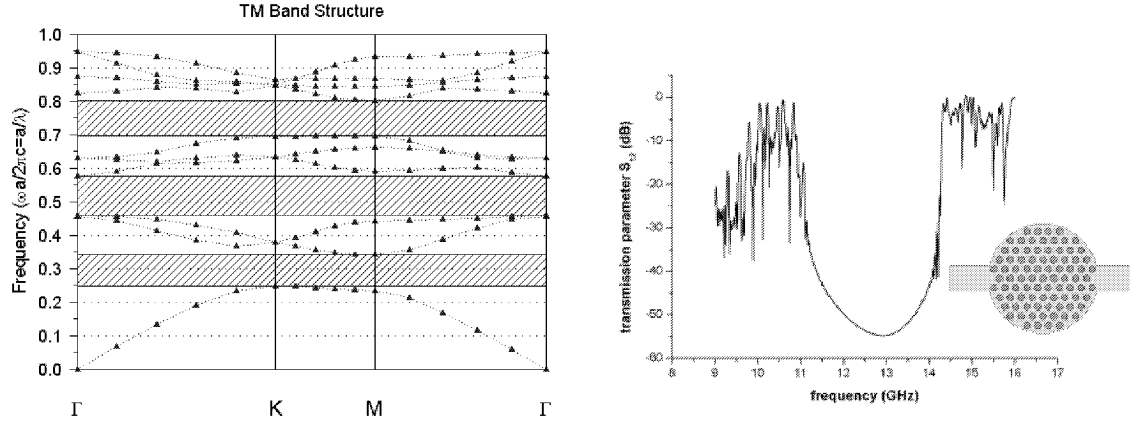


Figure 6.2: Left side) Band structure of the hexagonal lattice of dielectric rods for modes with TM polarisation. Three band gaps can be observed that are located at relative frequencies around 0.29, 0.52 and 0.75 GHz. Right side) Simulated transmission curve for the structure assembled into the metal resonator.

To emphasize the effect of the introduction of a defect into the EBG lattice, we have as a first step calculated and measured the behavior of the photonic crystal without any defect. The simulation of the band structure as well as the transmission parameter S_{21} of this structure is shown in figure 6.2. The structure itself is shown in the inset of figure 6.2, right side.

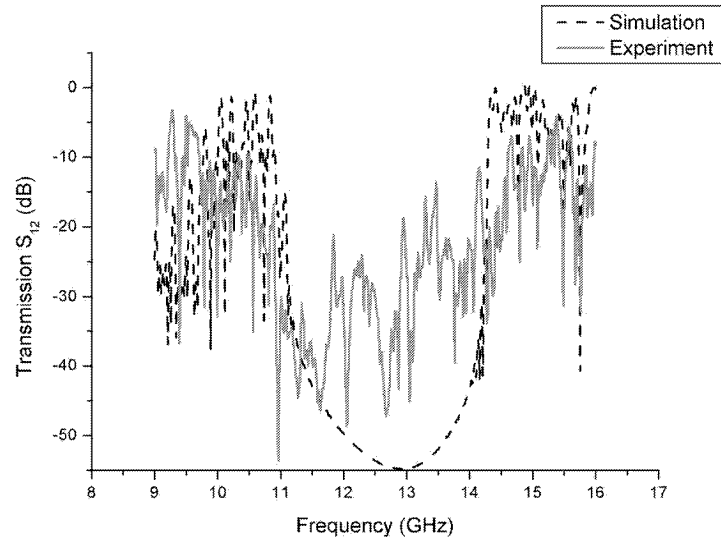


Figure 6.3: Comparison of simulation and experimental result for the transmission of the 2D EBG lattice. The structure exhibits a drop in transmission of about 20 dB for frequencies from 11 to 14.5 GHz, corresponding to the first band gap of the lattice.

In figure 6.3 a comparison between the experimentally measured transmission curve and the curve gained from simulation is given. The basic features of the structure can be found in both curves, with only a slight shift in frequency. This shift was found to be caused by some error in our simulation related to the influence of the waveguide ports and is present in all simulation results. At frequencies below the lower band edge, the transmission exhibits an extremely high density of structures, with an average value of around -10 dB. Those structures are related to the uncontrolled excitation of modes in the metal housing surrounding the EBG lattice. Above the lower edge of the photonic band gap around 10 GHz the transmission drops to around -40 dB. The excitation of housing modes is strongly suppressed because their existence is forbidden due to the EBG properties of the lattice. As it can be seen from a number of small peaks inside the bandgap, this suppression is not complete due to the finite-sized EBG lattice, but there is no significant transmission for frequencies inside the band gap supported by those housing modes. For frequencies corresponding to the first band gap of the structure between 11 and 14 GHz we can observe an average transmission drop of more than 20 dB.

Waveguiding - line defect matching

The first defect structure to be investigated is the same EBG lattice where one line of rods has been completely removed to form a line defect (W1 defect). This structure has already been investigated in chapter 3 and it was found that the line defect gives rise to a defect band with a frequency in the band gap. We can therefore expect that for frequencies above this cutoff frequency a transmission through the line defect will be possible. A comparison between simulation and experiment of S_{21} is shown in figure 6.4, the structure itself is shown in the inset.

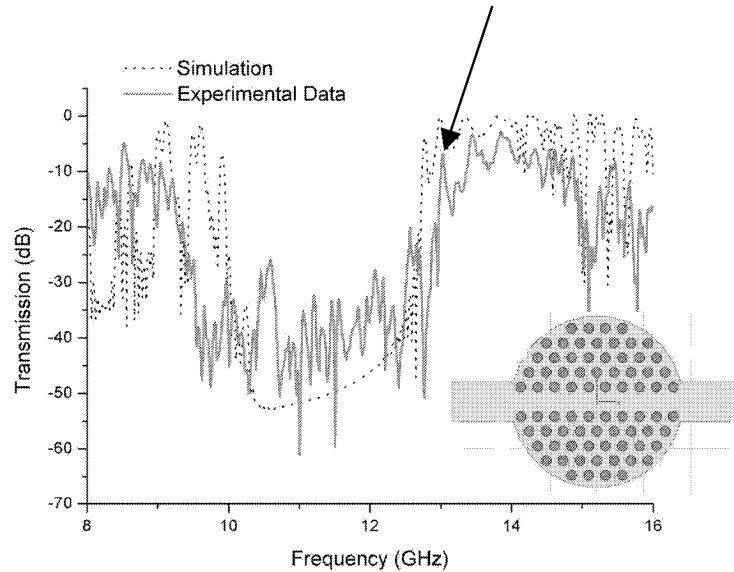


Figure 6.4: W1 line defect in a 2D hexagonal photonic crystal: comparison between simulation results and experimental measurement in the microwave range from 8 to 16 GHz. The graph shows the transmission parameter S_{12} . The structure under investigation is shown in the inset. We can observe a high mode density below and above the band gap, a drop in transmission due to the band gap and several transmission peaks of line defect modes starting around 13 GHz. The first of these modes, with an experimentally observed frequency of 13.02 GHz, is marked with an arrow.

According to our expectation, with the beginning of the band gap the transmission is very low, similar to the perfect lattice case. However, with increasing frequency in the band gap

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we observe that above a certain in-gap frequency a number of transmission peaks appears. These peaks are located at frequencies of $f_{1,\text{exp}}=13.02$ GHz (marked with an arrow in figure 6.4), $f_{2,\text{sim}}=13.25$ GHz, $f_{3,\text{sim}}=13.46$ GHz and $f_{4,\text{sim}}=13.86$ GHz. They are related to the excitation of standing waves in the line defect with a different number of field maxima along the defect (1-4 maxima), as shown by the simulated field distribution displayed in figure 6.5.

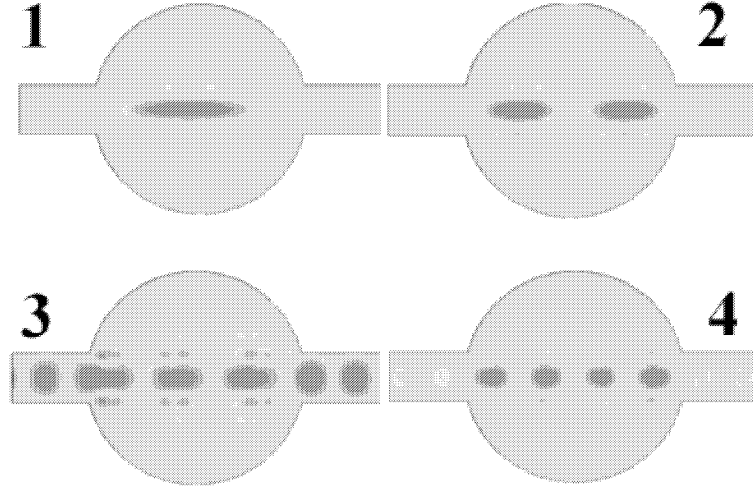


Figure 6.5: Line defect modes of a W1 line defect in a 2D hexagonal photonic crystal. The shown electric field distributions (absolute values) are related to the in-gap transmission peaks shown in figure 6.4. The calculated resonant frequencies are: $f_{1,\text{sim}}=12.77$ GHz, $f_{2,\text{sim}}=12.98$ GHz, $f_{3,\text{sim}}=13.34$ GHz, $f_{4,\text{sim}}=13.84$ GHz

In accordance with a conventional metal waveguide the mode frequencies f_n were found to be determined by the cutoff frequency of the lowest order mode and the mode index n (number of maxima) along the propagation direction by the equation:

$$f_n = \sqrt{f_c^2 + \left(\frac{cn}{2L}\right)^2} \quad (6.1)$$

From a fit of equation 6.1, taking into account the experimentally determined values for the line defect mode frequencies, the cutoff frequency of the W1 line defect waveguide can be calculated to be 12.85 GHz. The existence of a cut-off frequency within the bandgap is consistent with the flat dispersion curves of similar line defect waveguides reported in the literature[57][138][139] and the in gap cutoff frequency determined by our band structure calculations. For a clarification, in figure 6.6 the reduced band structure for modes propagating along the defect is shown again, and we observe the existence of a defect mode inside the band gap above a certain cutoff frequency (dotted line in figure 6.6).

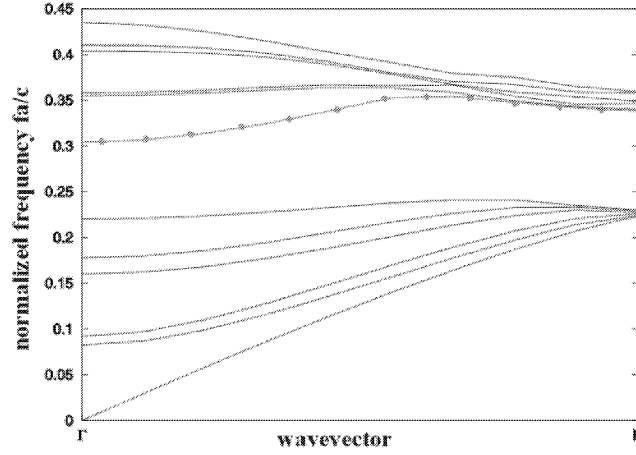


Figure 6.6: Calculated band structure of the investigated 2D EBG with the W1 line defect for certain wave vectors. The dotted line displays the frequencies of the propagating defect modes with frequencies inside the band gap. The solid lines mark the continuum of modes in the bands.

It can be seen clearly that there is no broadband matching between traveling modes in the metal waveguide and the W1 EBG line defect. This lack of matching can be explained from a geometrical point of view, if the transverse field distributions of traveling waves in the metal and defect is observed. In y-direction, the electric fields in the metal waveguide have to be zero at the metal surfaces to obey the boundary conditions. At the corresponding position in the defect waveguide, the electric fields should have their first zero in order to achieve a good matching. In contrast, the field turns from a maximum in the middle of the defect to a minimum in the first line of dielectric rods. The results of the simulation addressing this field distribution can be seen in figure 6.7.

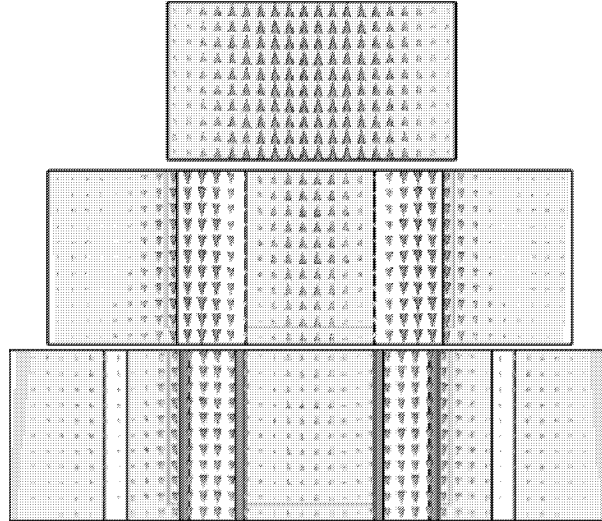


Figure 6.7: View of the electric field distribution in top: metal waveguide, middle: transition region between metal and defect waveguide, bottom: W1 defect waveguide. The figure shows a cut through the structure perpendicular to the x-axis. We can clearly see that the electric field has to undergo a change from zero field to maximum field in the transition area, which leads to a bad coupling behavior.

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There is a transition from vanishing electric field in the metal waveguide to a maximum of negative electric field at the y-value of the metal waveguide/defect waveguide boundary, which prohibits a good coupling between these two guiding parts. Reflection becomes significant and the transmission drops, as it is seen in our results. To overcome this problem of mismatching we tried to find a line defect structure, where a matching between the waveguide parts is supported by geometrical considerations. A structure where three rows of rods have been removed from the EBG structure (W3 defect) has been investigated.

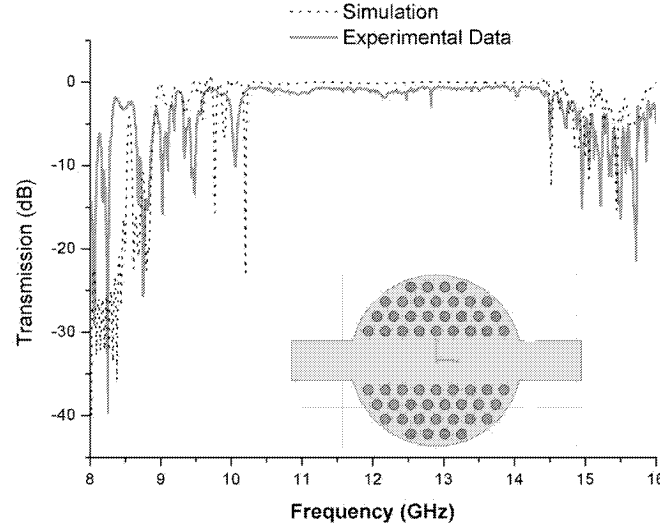


Figure 6.8: W3 line defect in a 2D hexagonal EBG structure: comparison between simulation and experimental result for the transmission parameter S_{12} . The structure under investigation is shown in the inset.

The transmission curve in the same frequency band as above is shown in figure 6.8, the structure is shown in the inset. Below and above the band gap we can again observe the highly structured transmission behavior related to the excitation of housing modes. However, compared with the case where only one line had been removed, the transmission curve shows a completely different behavior for frequencies within the band gap. We observe a broadband guiding of waves throughout the photonic bandgap. Between 10.5 GHz and 14.5 GHz the average transmission loss is -0.07 dB and, apart from two minor dips in the transmission curve, the transmission loss never falls below -1 dB, which is a sign for a very good matching between both waveguide parts. From the analysis of the reflection coefficient, the return loss was found to be around -20 dB over this frequency range.

The discrepancy of coupling behavior between the W3 and the W1 line defect can be explained once again geometrically by examining the electric field of the traveling mode. The field distribution found in the simulation is shown in figure 6.9. Because of the larger defect width, the nodes of the metal waveguide mode are not in mismatch with defect geometry anymore. The defect mode may have a minimum at the position of the first rods while additionally having a node at about the same y-position as the mode in the metal waveguide. The field can transit properly between those two waveguide types and a good coupling is achieved.

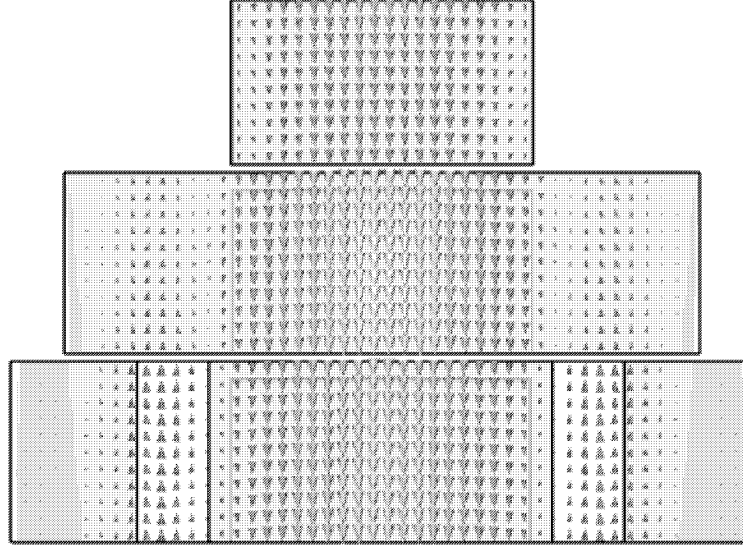


Figure 6.9: Transverse view of the electric field distribution in a) metal waveguide part, b) transition area between metal and defect waveguide, c) W3 defect waveguide in the EBG structure. The figure shows a cut through the structure perpendicular to the x-axis. We can observe that the change the electric field has to undergo between metal waveguide part and line defect part is much smoother than for the W1 line defect shown in figure 6.7.

A broadband guidance of waves over the whole frequency range of the electromagnetic bandgap is possible. A corresponding band structure calculation for the W3 line defect can be seen in figure 6.10. A defect mode can be observed for any frequency inside the band gap (dotted lines in figure 6.10).

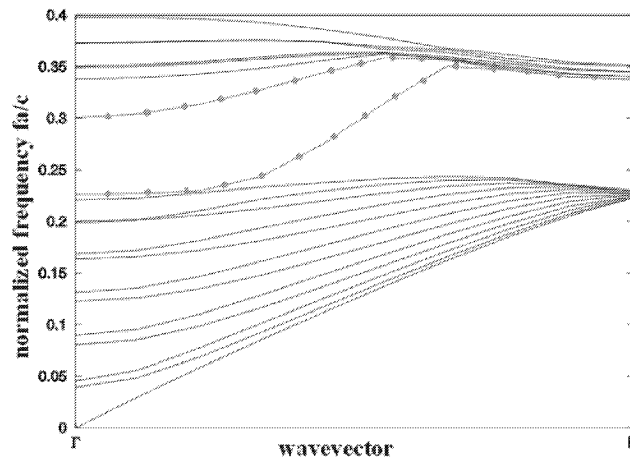


Figure 6.10: Reduced band structure of the investigated 2D EBG structure with the W3 line defect for wave vectors along the defect. The dotted lines display the frequencies of the propagating defect modes with frequencies inside the band gap. The solid lines mark the continuum of modes in the bands.

Point defect mode excitation

To extend the problem of controlled excitation of line defect modes to point defect modes, we have investigated an extended point defect in the photonic crystal. The resonant modes of

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such extended defects have already been discussed in chapter 2. The structure can be seen in figure 6.11.

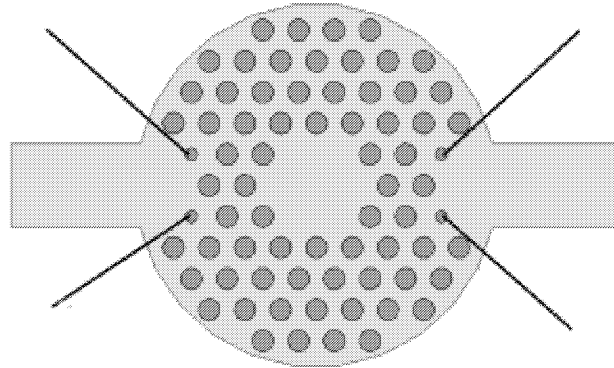


Figure 6.11: By removing a number of rods in the middle of the EBG lattice, an extended defect was created. The marked rods have been varied between $r=0$ mm and $r=2.16$ mm to change the strength of the coupling to the defect resonance.

We have removed a number of rods in the middle of the photonic crystal structure to provide the defect. The coupling between the metal waveguide and the photonic crystal was provided by a line defect where three rows of rods have been left out (W3 defect). This structure allows for a good coupling to the metal waveguide, as it was explained before. The defect cavity was separated from the defect waveguide by two periods of the photonic crystal to allow for a localized mode.

According to conventional resonators, we expect that the strength of the coupling to the resonance will affect two parameters of the resonance peak: its height, describing the insertion loss at resonance, and its width, describing the loaded quality factor. For a strong coupling and without losses, we expect the peak maximum to approach zero dB and a low loaded quality factor Q_l , while for a weak coupling the resonance peak should be little above the background noise and Q_l should be nearly equal to the unloaded quality factor Q_u . The value of Q_u should be the same for every coupling strength, since it is determined only by the losses in the metal and dielectric parts of the resonator.

We started varying the photonic crystal lattice elements that connect the W3 defect waveguide with the photonic crystal parts surrounding the defect and recorded the transmission curves, loaded and unloaded quality factors of the resonances, and transmission peak heights. We found out that the coupling strength was highly sensitive to the radius of four particular rods (marked rods in figure 6.11).

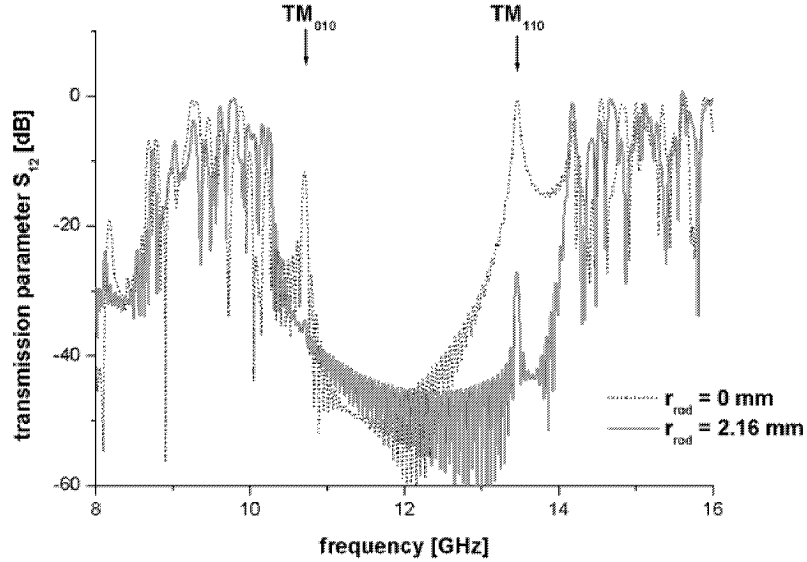
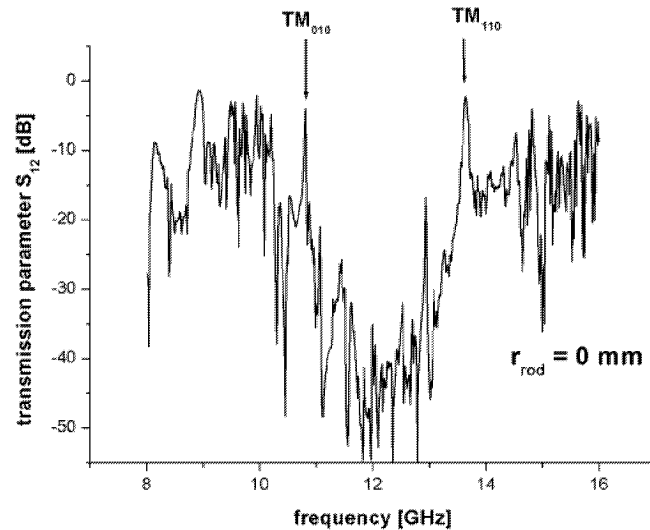


Figure 6.12: Simulation of the behavior of the transmission peaks related to localized modes of the extended defect in our 2D photonic crystal for a varied radius of certain lattice elements (coupling rods).

Those rods will be named “coupling rods”. We have varied the radius of the coupling rods and recorded the S parameters for each of the rod radii both in simulation (figure 6.12) and experiment (figure 6.13). We have varied the rod radius in five steps between zero radius and normal radius. Apart from the high density of modes outside the band gap that was explained before, the transmission curve exhibits two major resonant peaks with frequencies inside the band gap. Those peaks can be assigned to localized resonant modes with a field distribution that can be identified from the field simulation. The peak at 10.7 GHz can be identified as the TM_{010} mode while the peak at 13.45 GHz can be identified as the TM_{110} mode of the extended defect (see field distribution depicted in figure 6.14). Both resonances show the expected behavior when the radii of the coupling rods are varied.



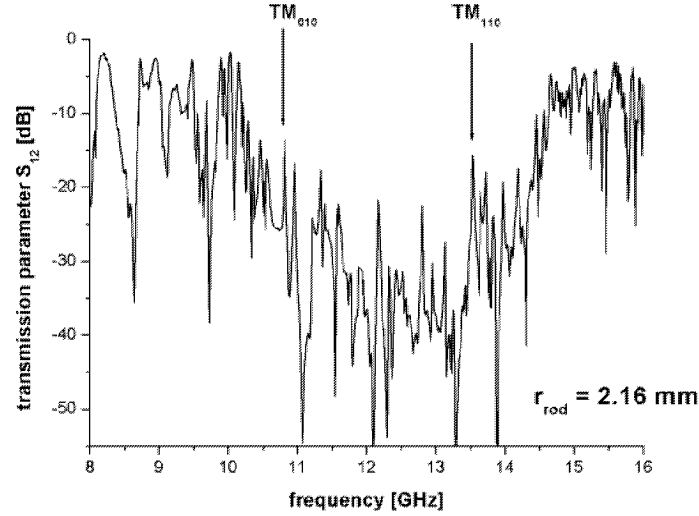


Figure 6.13: Experimental results for the behavior of the transmission peaks related to the localized modes of the defect for different coupling rod radii.

For a small rod radius we observe a strong coupling to the resonance. The maximum S_{12} value approaches 0 dB, and we observe a very broad resonance peak for both modes. With an increasing rod radius the maximum transmission value in the resonance decreases, and the resonance peak almost vanishes in the background of housing modes, when the rod radius has its normal value. Its frequency however remains constant, and the corresponding peaks can therefore be identified even while they are very little above the background noise. The loaded quality factor of the resonances increases with rod radius, although the overall losses in metal and dielectric do not change. This increase in Q_l must therefore arise from a weakened coupling strength.

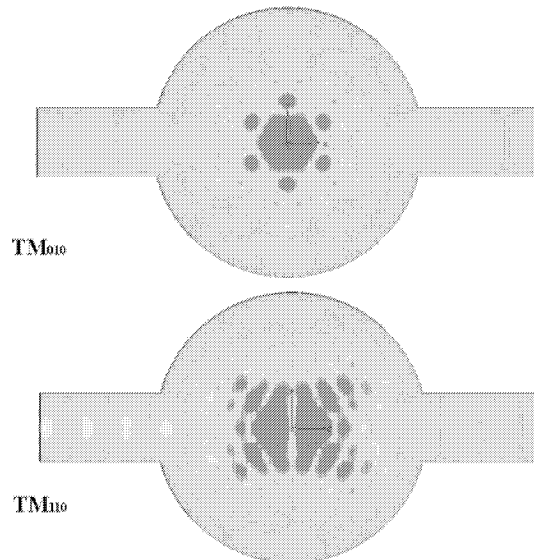


Figure 6.14: Simulated electric field distribution (absolute value) of the resonant modes related to the observed transmission peaks. Mode frequencies are $f_{TM_{010}} = 10.7 \text{ GHz}$ and $f_{TM_{110}} = 13.45 \text{ GHz}$. Dielectric filling factors are $\kappa_{TM_{010}} = 0.59$ and $\kappa_{TM_{110}} = 0.52$ for a coupling rod radius $r = 0 \text{ mm}$.

The unloaded Q factor due to metal losses in the cavity endplates for a TM_{nm0} ($n \geq 0, m \geq 1$) resonant mode with angular frequency ω can be calculated for a resonator with height h and metal boundaries with a given surface resistance R_s from the following equation:

$$Q_{TM} = \frac{G}{R_s} \quad \text{with} \quad G = \omega \mu_0 h / 2 \quad (6.2)$$

The surface resistance of copper was calculated by

$$R_s = \sqrt{\frac{\omega \mu}{2\sigma}} \quad (6.3)$$

assuming a dc conductivity of $\sigma = 5.8 \cdot 10^7$ 1/(Ωm) for copper. For the resonant modes that we have investigated, we received $Q_{TM010}(Exp) = 17,200$ and $Q_{TM110}(Exp) = 19,300$ from this formula. If we neglect the losses in the dielectric, our 3D simulation yields unloaded quality factors of $Q_{TM010}(Sim) = 16,000$ for the TM_{010} mode and $Q_{TM110}(Sim) = 21,500$ for the TM_{110} mode. We believe that the experimental and simulation values coincide within the error of our numerical simulation. The dielectric loss contribution to the unloaded quality factor was calculated by

$$\frac{1}{Q_u^d} = \kappa \tan \delta \quad (6.4)$$

with κ being determined to be 0.59 for the TM_{010} and 0.52 for the TM_{110} mode from our simulation. Taking into account dielectric losses, we received an overall unloaded Q factor of 10.300 for the TM_{010} mode and 13.000 for the TM_{110} mode. However, in the experiment we find that the unloaded Q factors of both resonances have values of around 3000 – 4000 only. The reason for this discrepancy is currently not fully understood. We speculate that small deviations of the rod positions from their ideal positions in the hexagonal lattice as well as possible rod diameter and dielectric constant variations may have a strong effect on the maximum Q , similar to a distributed Bragg reflector microwave resonator reported in the literature[140]. A second possible explanation is the hybridisation of the defect mode with surface states that have a high magnetic field at the metal walls, and therefore a low quality factor.

It has been shown that EBG line defect waveguides can be matched to external metal waveguides and that defect resonances can be excited in a very well defined manner. These findings represents an important step towards the practical use of EBG structures in microwave circuits. Possible applications are integrated oscillator circuits at millimetre wave frequencies, where transmission line resonators with defined insertion loss represent the frequency and phase noise determining circuit element. In the further frame of this work, similar experiments at millimetre wave frequencies of about 90 GHz will be presented for a TE polarisation of modes.

6.2 - A 3D EBG structure for 20 GHz

In chapter 3, it has been discussed that an ideal case of EBG structure is a three dimensionally periodic structure, that can confine electromagnetic waves for an arbitrary propagation direction and orientation of electric and magnetic field. It has also been pointed out that the fabrication and assembly of these structures can be complicated. A number of 3D EBG structures has been introduced and possible methods of fabrication have been presented. One of the presented structures has the advantage that it is relatively easy to fabricate and assemble, and still can provide a relatively large band gap for all directions of propagation of electromagnetic waves. The structure is made from a layer by layer arrangement of dielectric bars, and is called “woodpile” structure (see schematic of the 3D structure in figure 6.15). It has already been discussed in chapter 3.

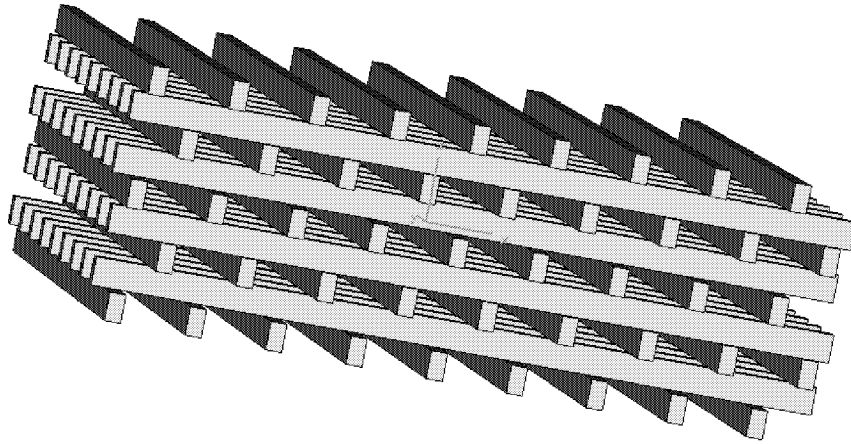


Figure 6.15: Schematic view of the 3D EBG “woodpile” structure. The structure is made from a stack of dielectric bars that are arranged with a lattice constant a and alternating layers that are rotated by 90° relative to each other.

In this chapter of the work we will show investigations of a woodpile structure that has a band gap in the region of 20 GHz. The geometrical and material parameters of the bars were chosen according to band structure calculations already presented in chapter 3 to produce a full 3D band gap.

- anisotropic dielectric constant $\epsilon_x = \epsilon_y = 9.4, \epsilon_z = 11.6$
- bar length $l = 56 \text{ mm}$
- bar width $w = 1.2 \text{ mm}$
- bar height $h = 1.2 \text{ mm}$

With these parameters we can calculate the band gap of the structure to be located at relative frequencies from 0.403 to 0.47. To obtain a band gap in the range of 20 GHz we chose a lattice constant of

- lattice constant $a = 6 \text{ mm}$

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The structure exhibits a complete band gap for frequencies from 20.15 – 23.45 GHz. The midgap frequency is $f_0 = 21.8 \text{ GHz}$ and the gap width is $\Delta f = 3.4 \text{ GHz}$. These values result in a gap-midgap ratio of $\Gamma = \frac{\Delta\omega}{\omega_0} = 0.155$.

It has been pointed out that for a propagation along the stacking direction of the rod layers, the band gap is reasonably larger. In our case the band gap along this direction ranges from relative frequencies of 0.403 up to 0.52, corresponding to absolute frequencies from 20.15 – 26 GHz. The midgap frequency is $f_0 = 23.075 \text{ GHz}$ and the gap width is $\Delta f = 5.85 \text{ GHz}$.

These values result in a gap-midgap ratio of $\Gamma = \frac{\Delta\omega}{\omega_0} = 0.253$.

The structure was made from stacking of dielectric elements, that had the shape of bars with a square profile. The bars were cut from an Al_2O_3 single crystal (Sapphire) that was optically polished. The bars were arranged in a rectangular metal cavity resonator made from OFHC copper. The resonator walls were patterned with slits that acted as a mask for the position of the dielectric bars. With this setup, it was ensured that a flexible redesign of the lattice was possible, so rods could be removed to form various line defects. To increase the mechanical stability of the structure, we have used a special low loss polymer glue (OptiClean) to keep bars in adjacent layers together. A photograph of the cavity is shown in figure 6.16.

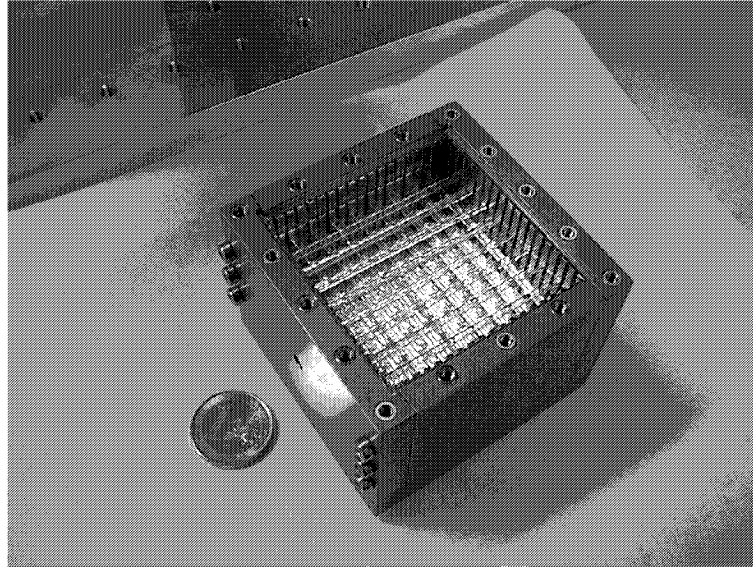


Figure 6.16: Photograph of the experimental setup that was used to investigate the 3D EBG woodpile structure. The sapphire bars are arranged in a rectangular cavity resonator made from OFHC copper.

In the measurement setup the microwave signal was coupled to the cavity by two horn antennas. For a plane wave excitation, the cavity was opened at the top and bottom sides and placed between the antennas. A rotation of the antennas determined the polarisation of the plane waves incident on the EBG structure. See figure 6.17 for a photograph of the experimental setup. The high frequency signal was provided by a HP 83640A synthesizer with a frequency range of 45 MHz - 40 GHz. The S parameters of the resonator structure were measured with an HP 8510C vector network analyser and an S parameter test set. The setup was calibrated before the measurement to remove systematic measurement errors. The number of measurement points was 800 over the chosen frequency range.

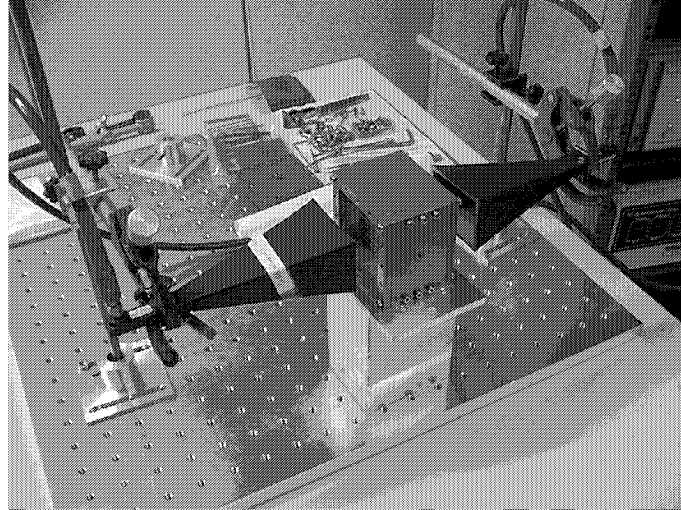


Figure 6.17: Photograph of the two experimental setup The cavity was left open at two sides and the signal was coupled into it by two horn antennas.

Verification of the band gap

As a first step, the existence of the band gap for the desired frequency interval had to be verified. In our experimental setup, we could measure the transmission through the structure, which is supposed to drop in the frequency region of the band gap. To validate our measurement results, we have compared them with an FDTD simulation as described in a previous chapter. The structure was modelled completely, also taking into account the influence of the metal housing, and the transmission and reflection parameters of the 3D structure were calculated over the frequency range of interest. In the measurement, two horn antennas as shown in figure 6.17 were placed at a fixed distance.

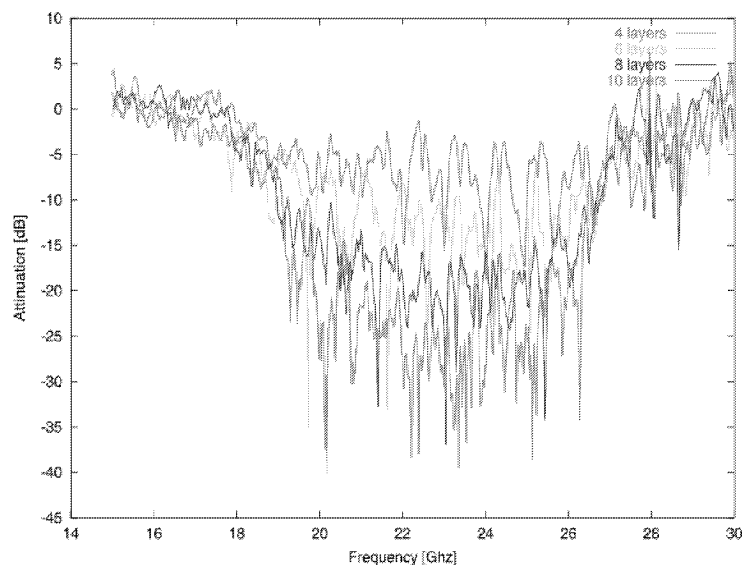


Figure 6.18: Comparison of the measured transmission drop in the band gap for different numbers of rod layers. For every additional layer the transmission in the band gap drops by about 5 dB.

We have first measured a transmission curve of the high frequency signal travelling from one horn antenna to another without the EBG structure in place to measure a reference curve. The

measurement curve with the EBG structure was then divided by the reference curve in order to eliminate any influences of the frequency behavior of the horn antennas. In figure 6.18, a series of measurements is shown to demonstrate the influence of an increasing number of layers (four layers are equal to one lattice period) in the EBG structure on the transmission. For increasing number of layers, the transmission in the band gap drops from -5 dB to about -20 dB, which yields an additional drop by about -5 dB for every layer. We have then measured the transmission behavior of the structure for a height of four layers (according to one complete lattice period) and eight layers (according to two full lattice periods) and compared them with the result from the corresponding simulation. The curves verify the existence of a band gap in the investigated structure and especially, the increasing attenuation for a growing number of layers.

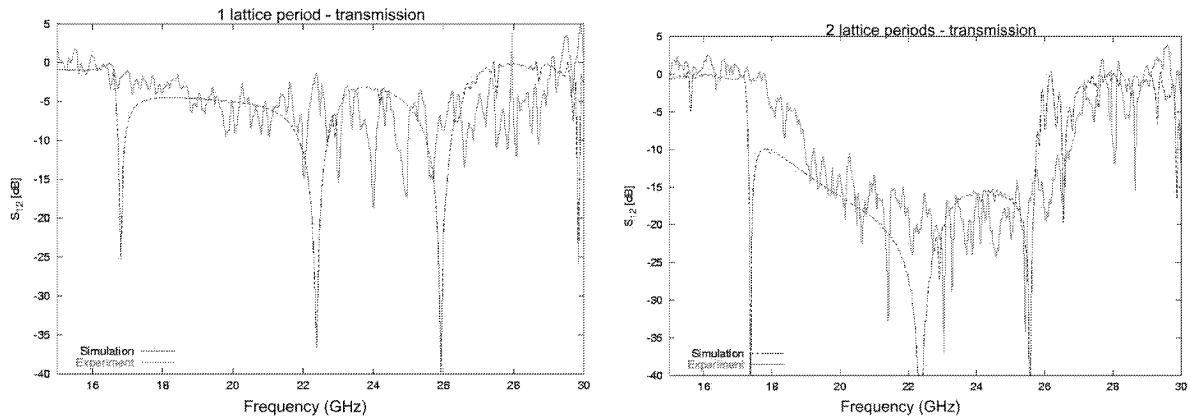


Figure 6.19: Comparison between simulation and experimental curve for the transmission of the signal through one and two periods of the 3D EBG lattice

In both figures, it can be seen that the measured curve and the simulated curve coincide nicely. Both the frequency range and the depth of the band gap found in the simulation can be verified in the experiment. For the case of one lattice period, we observe a frequency drop by about 5 dB, for two lattice periods, the attenuation in the band gap reaches more than 15 dB. The dips in the simulation curve are artifacts from the simulation and have no relation to the experiment. However, the density of spurious modes is extremely large in this case, and even for frequencies inside the band gap, the transmission by these mode is still possible.

Line defects in 3D EBG structures

It has been discussed before that an EBG structure is capable of guiding waves along defects. Nevertheless, only in a 3D periodic EBG material the wave will be confined by Bragg reflection to all sides for an arbitrary direction of propagation. When a 2D EBG lattice is used, the appropriate parameters must be chosen to have a line defect support a guided mode (see also chapter 3) because in 2D EBG structures, 3D guiding always relies on both Bragg reflection and total internal reflection. Therefore, 3D EBG structures have to be investigated regarding a possibly more general suitability as waveguiding elements. After the verification of the existence of a band gap in the 3D woodpile lattice, the behavior of line defect modes was investigated. To create a line defect, one or more dielectric bars have been removed from a layer that is located in the middle of the volume. Again, the transmission curve was measured. Additional to the comparison with the results from simulation, we can compare the transmission curve of the defect structure with the transmission curve for a structure where no defect is present. Figure 6.20 shows the measured transmission curve for the case that one dielectric bar was removed to form a line defect.

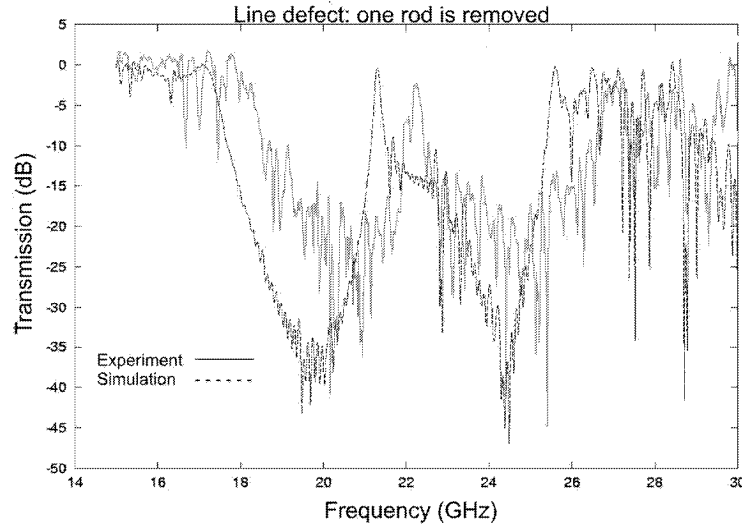


Figure 6.20: Comparison between simulation and experimental transmission curve for a line defect in the 3D EBG structure where one rod has been removed to form a line defect.

From the curve we observe a transmission peak in the band gap region with a frequency of about 22 GHz. This peak is related to a defect mode of the line defect. A simulation of the field distribution of the defect mode can be seen in figure 6.21. From the experimental curve we can observe, that the defect peak is relatively broad, and it is split into a number of smaller peaks. The defect mode exhibits a very low quality factor.

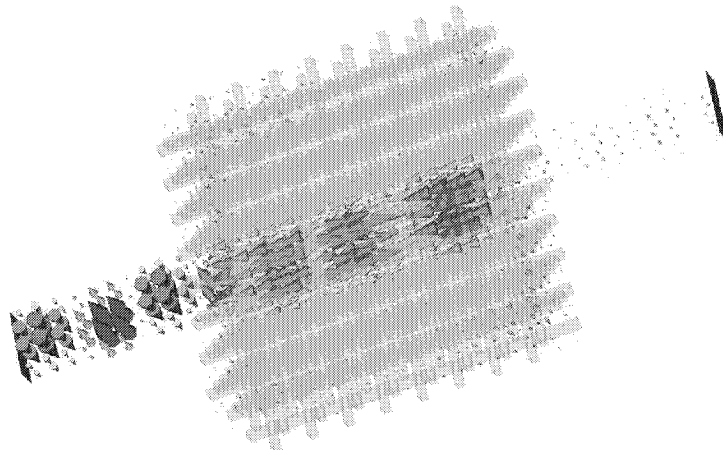


Figure 6.21: Simulated distribution of the electric field related to the defect peak that appears in the transmission curve when one rod is removed (compare figure 6.20)

The low quality factor of the defect mode can be explained from its field distribution: a part of the energy of the mode is not guided by the defect mode, but flows around the EBG lattice as a surface mode between the dielectric lattice and the metal walls of the housing. There is a high magnetic field strength at the metal cavity walls, therefore this mode has a very high geometric factor, resulting in a bad mode Q factor. An interaction of these two modes can lead to a decrease of the line defect mode Q factor. Unfortunately, the frequency behavior of the structure as simulated differs slightly from the experimental values. All features are by

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about 2 GHz shifted to lower frequencies. This behavior has been observed for a number of measurements and was already reported in the first section of this chapter. Nevertheless, all features in the curve are identical, just at a different frequency position.

To further investigate the behavior of line defect modes in the 3D EBG structure, we have removed more than one rod. In this case the measurement was compared with the transmission of the undisturbed lattice, to show more clearly what spectral features are added to the transmission curve when introducing the defect. Figure 6.22 shows the transmission measurement for two and three rods removed.

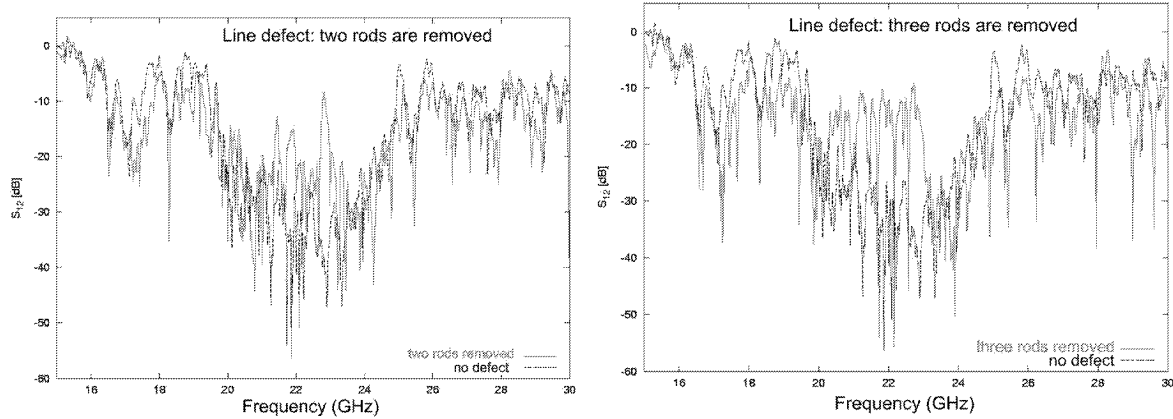


Figure 6.22: comparison of measured transmission curves where two and three rods have been removed, respectively. The curve is compared with the transmission curve measured for a structure without defect.

A comparison of the measured transmission curves shows clearly the effect of the introduction of a line defect in the lattice: A series of defect mode peaks appears, with frequencies in the band gap. The number of transmission peaks strongly increases for the larger defect. This is due to the fact that in this kind of lattice there is a relatively small dielectric volume filling factor. Therefore, the removal of a rod always creates a defect that has a large extension compared with the wavelength. So the possibility of the existence of very high order modes is given. When the different transmission curves are compared, it becomes obvious that the line defect modes in the 3D structure guide for a very small frequency region in the order of a fraction of GHz only, and the matching between an external signal and the defect mode is bad with an insertion loss of about 10 dB.

Overall one can conclude that it is basically possible to utilize 3D EBG structures as waveguiding elements in a micro- or millimetre wave circuit. However, these structures exhibit some drawbacks: The lattice is extremely large compared with the free space wavelength corresponding to its band gap frequencies. This is due to the fact that several lattice periods have to be used to achieve a reasonable band gap depth, as pointed out in the previous part of this chapter. This large size will lead to a large mode density both in the band gap and outside the band gap. Even though these spurious modes in the band gap are damped, they will cause perturbations due to mode coupling and thus decrease the quality factor of defect modes. Additionally, unwanted surface modes are excited which will further decrease the quality of guided defect modes.

6.3 - A 2D TM EBG structure for 30 GHz prepared by moulding

In Chapter 4 we have introduced a moulding technique for the fabrication of EBG structures that was used to create a 2D EBG lattice for the frequency range of about 30 GHz. In this part of the chapter we want to present measurements that were done to characterize the fabricated EBG structures. The measurement was performed in the frequency range from 25 to 40 GHz . Again, we have used an HP 8510 network analyser and a full 2 port S parameter test set.

Structure design

The EBG structure was designed to be a hexagonally arranged lattice of dielectric rods made from polycrystalline aluminium oxide (Al_2O_3). The background material was chosen to be wax, with a dielectric constant of $\epsilon_{wax} = 2.2$ and a dielectric loss tangent of $\tan \delta_{wax} = 0.005$. The rods had a radius of $r = 0.7 \text{ mm}$ and were arranged with a lattice constant of $a = 3 \text{ mm}$. This design leads to a 2D EBG structure with its first band gap for TM modes at relative frequencies of

$$\frac{fa}{c_{start}} = 0.25 \Rightarrow \frac{fa}{c_{stop}} = 0.33$$

The lattice constant was chosen to be $a = 3 \text{ mm}$, this corresponds to a band gap from 25 GHz up to 33 GHz. The gap width is 8 GHz, corresponding to a gap-midgap ratio of $\frac{\Delta\omega}{\omega_0} = 0.275$.

The total size of the EBG structure was $W = 64 \text{ mm}$ and $H = 40 \text{ mm}$ corresponding to 14×14 lattice periods. The structure is shown schematically in figure 6.23.

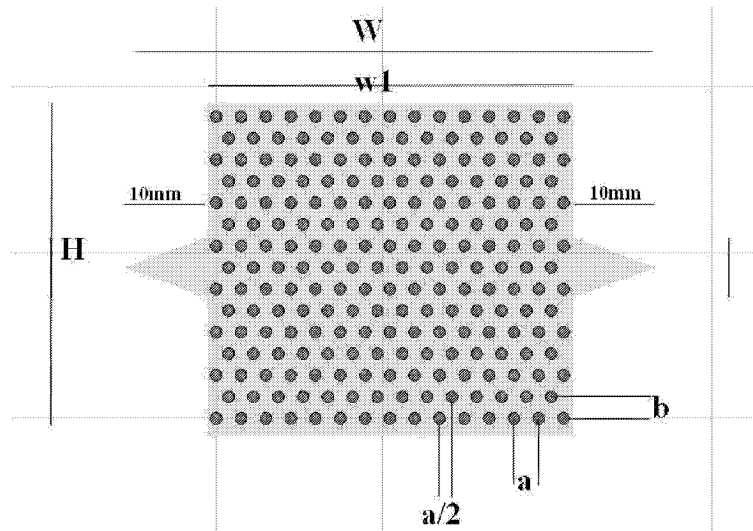


Figure 6.23: Schematic drawing of the total size of the fabricated structure with an extension of 14×14 lattice periods. At the left and right side of the structure tapers were introduced to improve the coupling to the rectangular metal waveguides. The parameter b denotes the distance between rod rows and is given by $b = a/2 \cdot \sin(60^\circ)$.

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The thickness of the structure was chosen to be 3.6 mm, according to the height of a standard metal waveguide for the chosen frequency range. This height is one third of the wavelength at a frequency of 30 GHz, to make sure that only the lowest order TM modes without nodes along the rod axis could propagate. At both sides of the structure, the background material was extended in a triangular shape. The structure was then placed into a rectangular metal cavity resonator in which the measurement was supposed to be done. The structure was placed in the metal housing so, that the triangular shaped noses would fit into the waveguide coupling flanges that were used to couple the high frequency signal into the EBG structure. These noses should act as a taper that shall minimize reflection losses of incoming waves at the boundary of the wax body. A photograph of the experimental setup is shown in figure 6.24.

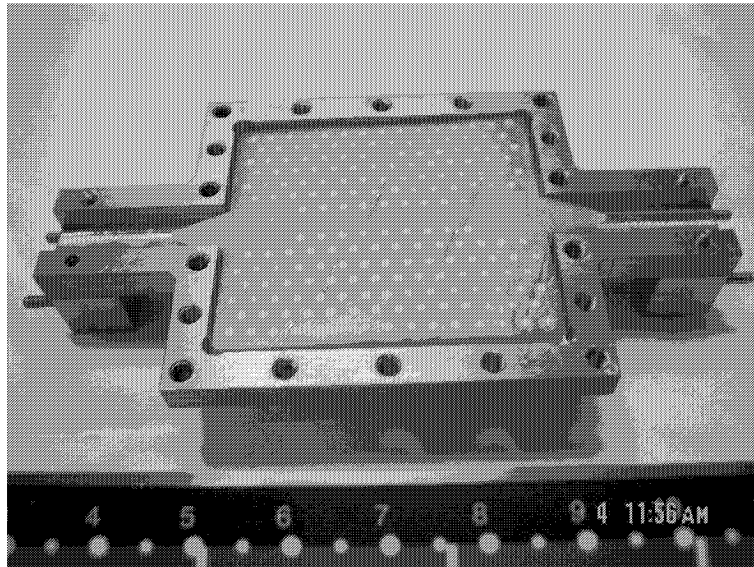


Figure 6.24: Photograph of the experimental setup for the measurement at a frequency of about 30 GHz. The EBG structure is enclosed in a rectangular metal cavity that can be connected to standard rectangular waveguide ports. The cavity is made from OFHC copper and can be closed tightly by several screws to prevent radiation losses and leakage currents.

The cavity resonator was made from oxygen free high conductivity copper. The rectangular waveguides at the side of the cavity were connected on the left and right side of the device to standard waveguide connectors with a width of 7.2 mm and a height of 3.6 mm. The top of the resonator was connected to the bottom part by a number of screws to make sure that the cavity was firmly closed and thus avoid leakage currents.

We have measured an EBG structure without defects to verify the existence of a band gap. A measurement of the transmission parameter S_{12} can be seen in figure 6.25. A drop in transmission by about 30 dB in the frequency range from 30 GHz up to almost 40 GHz can be observed, indicating an electromagnetic band gap. The difference in frequencies from the nominal value can be explained from the fabrication of the structure:

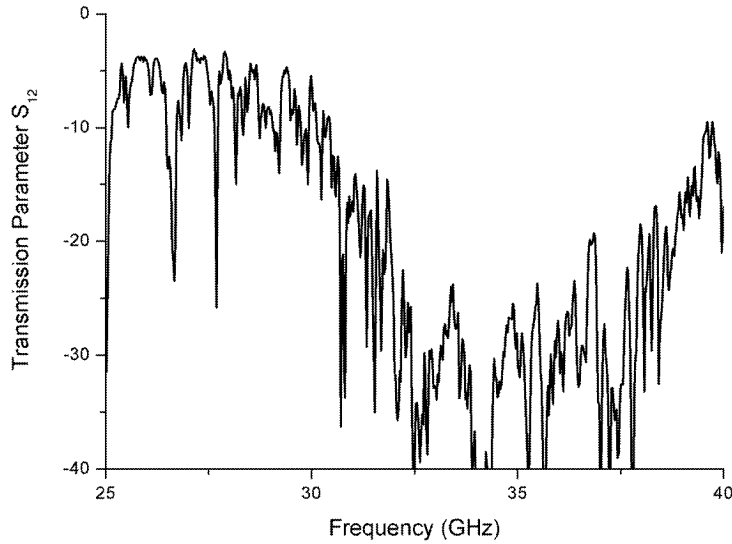


Figure 6.25: Experimental verification of the band gap by measurement of the transmission parameter S_{12} . In the frequency range from about 30 GHz up to 38 GHz the transmission drops by about 20 dB.

During the fabrication process, both the absolute size of the sample and the size of single dielectric parts will shrink, when the binding system is removed during the sintering at high temperatures. The sizes of the measured structure were significantly different from the original values.

- The dielectric rods had radii between 0.58 and 0.63 mm instead of an intended size of 7 mm. This will shift the band gap of the structure in relative frequencies to $\frac{fa}{c_{start}} = 0.27 \Rightarrow \frac{fa}{c_{stop}} = 0.36$
- The distance between the single rods (lattice constant) was measured to be 2.79 mm instead of an intended value of 3 mm. This results in frequencies for the band gap from 29 GHz up to 38.6 GHz.

Taking into account these changes to the lattice structure, the measured frequencies for the band gap are in relatively good agreement with the calculated values. Remaining differences are most likely related to the dielectric constant of the rods, which can differ from its nominal value of 9.6 during the fabrication process, due to incomplete removal of the binding system and creation of porous regions for a non optimised fabrication process.

Below the band gap, the transmission curve exhibits a high density of spectral features that are related to resonances in the metal housing of the resonator, which will have a relatively low ground mode frequency due to its filling with dielectric material. At frequencies of 25 GHz and above, the cavity will already be highly overmoded, and therefore exhibit a dense mode spectrum in the region, where the existence of modes is not prohibited by the band gap. These modes are also present in the band gap region, but here they are strongly suppressed due to the band gap. As the EBG structure has finite size, this suppression is not perfect.

As a next step we have investigated the behavior of a defect mode in the lattice. Therefore, in the middle of the structure, one of the dielectric rods was left out. To provide a suitable

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coupling to the defect mode, a W3 line defect was also introduced at both sides. The defect was surrounded by three lattice periods of the EBG lattice. In figure 6.26, the simulation of the field distribution of the expected defect mode is shown, figure 6.27 shows the transmission behavior of the defect structure with the transmission peak of the defect mode at a frequency of $f_{defect}=30.1\text{ GHz}$.

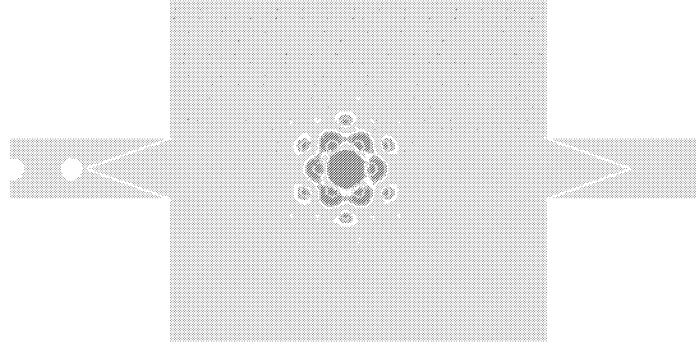


Figure 6.26: Distribution of the electric field amplitude in the 2D EBG defect structure. The electric field of the defect mode is localised at the position of the defect.

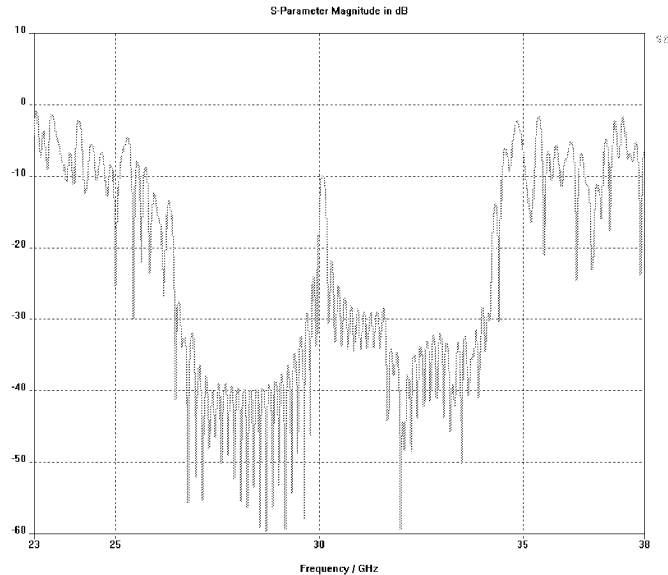


Figure 6.27: Simulated transmission curve of the waveguide-cavity structure as seen in figure 6.26. For the frequency of the defect mode, a resonance peak with a height of 30 dB above the background can be observed.

We have to keep in mind that due to the changes to the lattice that were explained before, also this defect mode frequency can be expected to be shifted to higher frequencies. We expect the defect mode to be at a value of $f_{defect}^*=34.8\text{ GHz}$. The experimental curve is shown in figure 6.28.

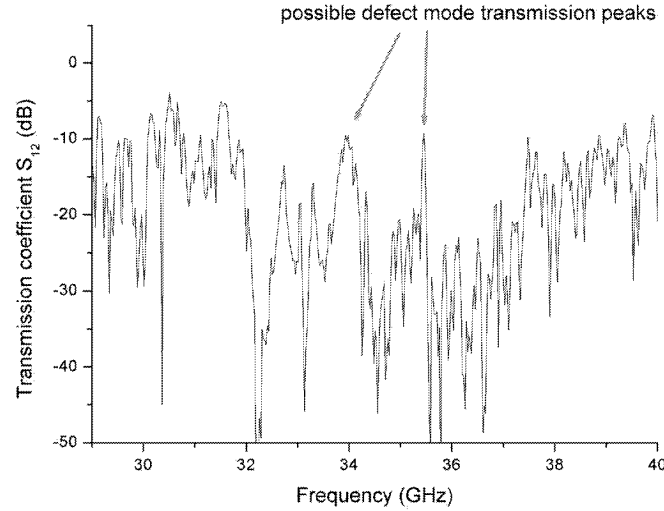


Figure 6.28: Experimental verification of the existence of a defect mode in the fabricated structure. From an analysis of frequency and approximate quality factor the transmission peak at 35.4 GHz (marked with an arrow in figure 6.28) can be identified as related to the point defect.

We can observe that at a frequency of 34 GHz and 35.4 GHz, defect mode peaks in the transmission spectrum can be seen. The peak at 35.4 GHz has a quality factor of about 1700, while the quality factor for the mode at 34 GHz is hard to measure due to the broadness of the peak, but it can be seen from the graph that it is reasonably lower. The wax material has a quality factor of $Q_{wax}=200$, and the quality factor of the dielectric rods is in the order of a few thousand typically. As can be seen in the field distribution of the mode in figure 6.26, the field of the defect mode is located in the area around the defect, and mainly in the first row of dielectric rods surrounding the defect. The defect mode would then exhibit a higher quality factor than another mode that is mainly located in the wax. Therefore we assume that the higher quality factor defect peak is related to the defect mode, and the peak with the very low quality factor is related to another mode that is mainly concentrated in the wax, most likely a standing wave resonance between the edge of the waveguide and the dielectric rods surrounding the defect. The simulation did not yield this second peak, which is an indication for the relation of the second peak to some unwanted defect in the structure, most likely created during the fabrication of the structure.

We have demonstrated that the existence of a band gap and defect modes in the 2D EBG structure made by ceramic moulding can be verified. Nevertheless, the results from the experiment show that some improvements to the structure must be made. Especially, the reflection of energy into the waveguide due to a not optimised coupling between the metal waveguide and the EBG material is problematic. Most reflection is due to the transition from the air filled rectangular waveguide and the EBG structure filled with the wax background material with a dielectric constant of $\epsilon_{wax} = 2.2$. Therefore, tapers at the sides of the structures were introduced. Nevertheless, the shape of the taper has to be made as precisely as possible. In figure 6.29, two tapers can be seen, where one has a nice triangular shape (left side), while the other taper is distorted (right side).

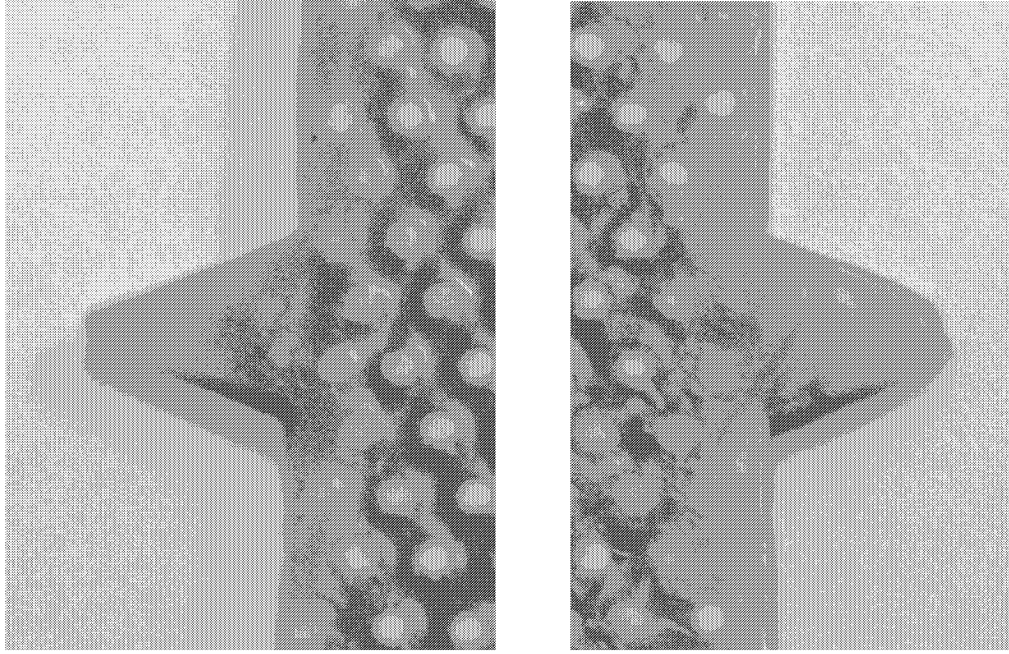


Figure 6.29: Photograph of two triangular taper structures that were used to improve the coupling between waveguide and EBG structure. The deviation from the triangular shape that can happen during the fabrication process can be seen on the right side.

In figure 6.30, the measured reflection parameter for the full EBG lattice structure is shown, for a wave incident on the two tapers displayed above.

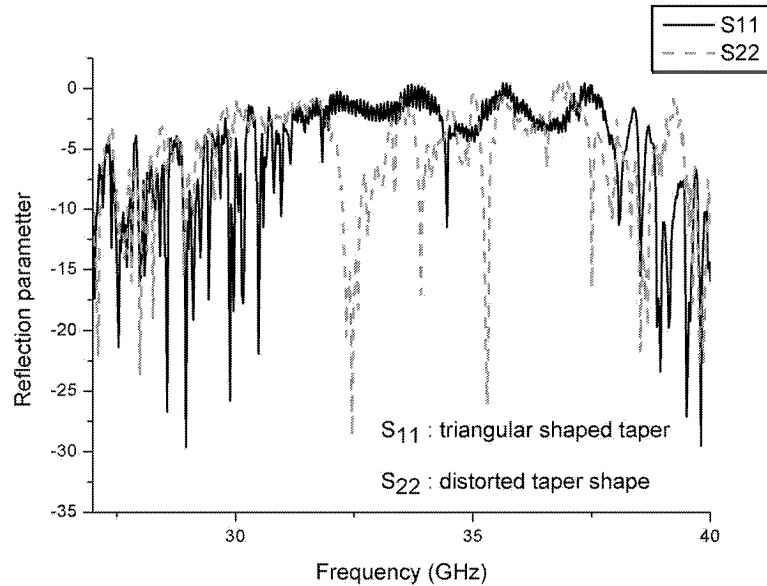


Figure 6.30: Experimental investigation of the influence of the taper shape on the reflection from the EBG structure. In case of the triangular shaped taper that can be seen on the right side of figure 6.29, the reflection is at a relatively high level of -3 dB between 30 and 38 GHz, as expected for frequencies inside the band gap. In case of the distorted taper, the reflection shows a number of dips, indicating that energy can be coupled into the EBG structure without being affected by the bandgap. These dips are related to unwanted mode that can for example exist at the surface of the EBG structure.

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It is obvious from figure 6.30 that the shape of the taper has a high influence on the coupling between the metal waveguide and the EBG lattice, and therefore special emphasis must be laid on the precision of its shape during the fabrication process. For the triangular shaped taper the reflection coefficient has values between -0.5 dB and -3.5 dB throughout the band gap, while for the distorted taper it is in the range of -6 dB with strong reflection dips with a depth of -15 dB and more.

Overall it is demonstrated that a 2D EBG structure made with moulding techniques can exhibit a band gap in the desired frequency range, when the shrinking during the fabrication process is precisely known and taken into account when designing the structure. Defect modes can be found that are related to removed lattice elements and the modes exhibit quality factors that are in the range of the ones expected from the material parameters. With a further improvement of the machining process, the moulding technique can be used to create EBG structures for the range above 20 GHz.

6.4 - A 2D interconnected EBG structure for TM modes at millimetre waves

A strong focus for the development of new EBG structures lies nowadays on the optical communication bands at wavelengths of about 1.5 μm . Nevertheless, the unique properties of EBG structures such as

- the possibility of employment of a purely dielectric structure, that could be made from low loss materials,
- low dispersion of defect modes over a large frequency range,
- the capability to integrate waveguiding and resonant defect structures as it was shown in the previous part of this chapter

make them interesting for applications in many other frequency ranges. For the millimetre wave W band at frequencies above 75 GHz and especially for the adjacent submillimetre wave range, passive elements can be either metallic structures which are relatively lossy due to the frequency dependent increase of metal surface resistance, or quasioptical devices which are extremely bulky. A technology for passive structures based on EBG materials for this frequency range could be a promising alternative to existing technologies, because it can combine integrated structures with feature sizes of the order of a fraction of the wavelength and a choice of materials that can have extremely low dielectric losses, like low doped, high resistive semiconductors. The most common integrated transmission lines in the mentioned frequency range are rectangular metal waveguides and microstrip lines. In both cases the propagating wave has an electric field directed perpendicular to the plane of propagation (TM or quasi-TM waves). To establish a suitable transition between those standard transmission lines and EBG structures there is a need for a two-dimensional (2D) periodic, compact and integrated EBG structure with a large band gap for TM waves.

In chapter 3 we have investigated the existence of band gaps in EBG materials for different types of lattice elements and symmetries. There it was found that a gap for TM waves is normally supported by isolated dielectric structures. Obviously, the EBG structure has no structural stability and the isolated rods will fall apart. There is a number of ways to overcome this problem:

1. The isolated dielectric structures can be clamped between metal endplates. On the one hand, it is possible that the existence of metal plates in the device is not tolerable due to design issues or even fabrication issues. On the other hand, it has been mentioned that with increasing frequency the losses due to the finite conductivity of a metal become problematic. So it would be advantageous if the metal plates could be avoided.
2. Another possibility is the utilisation of a backfilling material, as it has been presented in the frame of this work regarding EBG structures for 30 GHz. Anyhow, the choice of low dielectric, low loss materials that can be filled into a filigrane structure is limited, especially the losses due to the backfilling material may be high.
3. A third option is the fabrication of the dielectric structures on a substrate. Even though this approach might be not very complicated to fabricate, it has other disadvantages: The brittle dielectric structures are freestanding and thus extremely prone to distortion by mechanical forces. As most materials suited for a high frequency operation (semiconductors) are relatively brittle, the EBG structure could be destroyed easily. Additionally, the existence of a substrate can give rise to surface modes, because at this surface there is no EBG lattice present when a substrate is used.

In this part of the chapter we will investigate a 2D periodic EBG structure made from a low loss dielectric material (high resistive Silicon) that consists of a hexagonal array of rods, interconnected with thin dielectric bridges. The rod array is supposed to provide a suitably large band gap for TM waves, while the structure can maintain a very high mechanical stability due to the bridges connecting the otherwise isolated dielectric rods. We will describe the results of numerical simulations as well as time and frequency domain transmission measurements. A 3D schematic view of a section of the investigated EBG structure is shown in Figure 6.31.

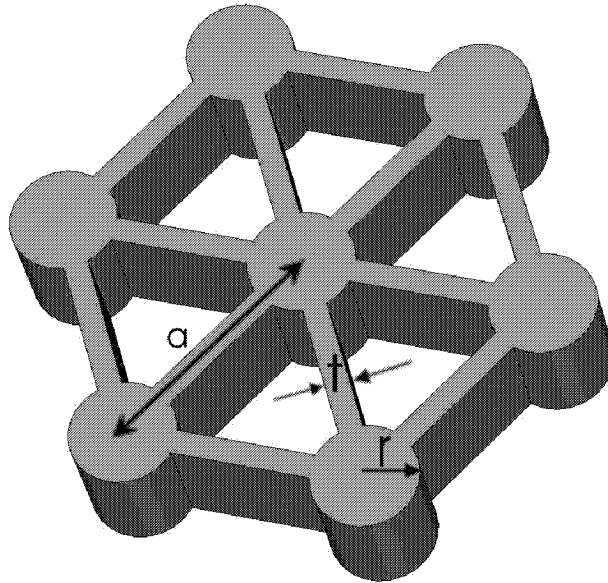


Figure 6.31: Schematic view of the layout of the interconnected hexagonal EBG structure. The structure is made from a hexagonal arrangement of dielectric rods with radius r , separated by a lattice constant a and interconnected by dielectric bridges of thickness t .

The rods are made of dielectric material with a dielectric constant $\varepsilon=11.56$ and have a radius r . They are arranged in a hexagonal lattice structure with a lattice constant a and are interconnected with bridges made from the same dielectric material, with a width t . We have

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chosen a ratio of rod radius and lattice constant of $r/a=0.22$ with a dielectric constant of the material of 11.56 (Silicon). The structure was assumed to have infinite height along the axis of the rods. As expected from literature, a hexagonal structure of unconnected rods supports a large band gap for TM waves in a relative frequency $\omega a/2\pi c$ range from 0.267 to 0.421 (see band structure displayed in Figure 6.32).

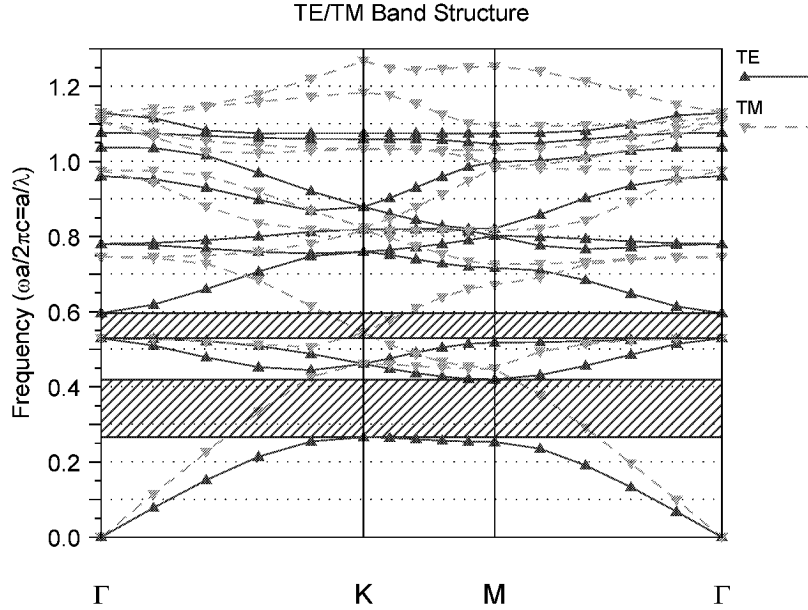


Figure 6.32: Band structure for a hexagonal lattice of dielectric rods in an air background. The ratio of rod radius and lattice constant is $r/a=0.22$, the dielectric constant of the rods is $\epsilon_{rod}=11.56$. Shown are the first ten bands for TM and TE modes. Two band gaps for TM modes can be observed, the lower band gap ranges from relative frequencies of 0.267 to 0.421, the higher one reaches from relative frequencies of 0.531 to 0.598.

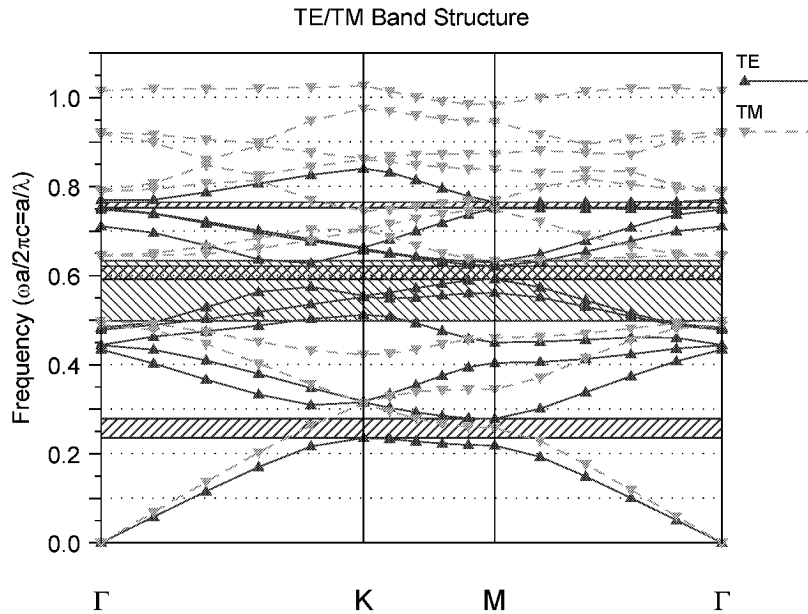


Figure 6.33: Band structure for an interconnected structure of dielectric rods with parameters according to Fig. 6.32, and as seen in Figure 6.31 with a relative bridge width of $t/a=0.1$. The first ten bands for TE and TM modes are shown. The structure exhibits band gaps for both TM and TE modes.

A higher band gap exists for relative frequencies from 0.531 to 0.598. We have then calculated the band structure for the interconnected rod lattice (see figure 6.33) for a relative bridge width $t/a=0.1$. It can be seen that the band gaps for TM modes still exist, even though they are decreased in both relative frequency and size. Also, as it would be expected, the increasing size of interconnected dielectric parts in the lattice will support the existence of a band gap for TE waves. This is true only for certain bridge widths t/a larger than 0.035, as can be seen from figure 6.34, where the widths of the TE and TM bands are plotted for a varying relative bridge width t/a from 0 to 0.2. It can be seen that there is a region of overlapping TE and TM bands, however, there will be a large TM band for small bridge widths while a large TE band is found for large bridge widths. The higher frequency band gaps are still existing, but suffer from a strongly increasing effect of the stabilizing bridges, and are therefore not taken into account in the further considerations.

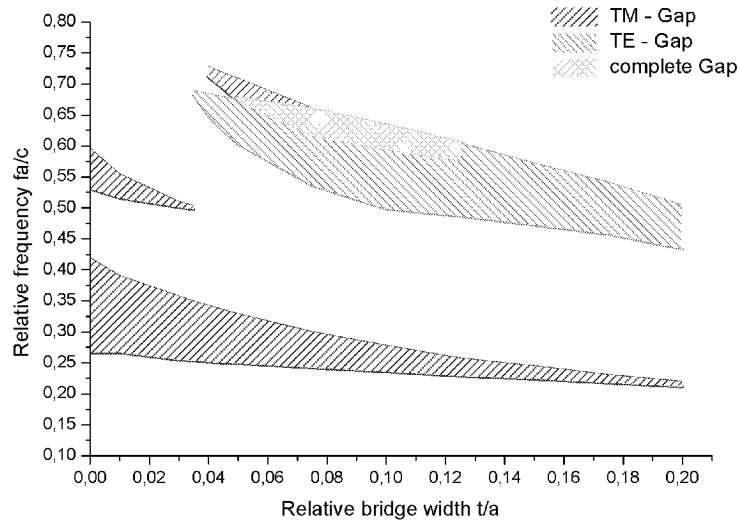


Figure 6.34: Band gap map of the interconnected 2D structure showing the band gaps for TE, TM and for both polarizations as a function of the relative width t/a of the dielectric bridges.

As the target frequency was in the region of 100 GHz, we have chosen a lattice constant a of $1000\mu\text{m}$. To achieve a reasonable trade off between band gap and feasibility of manufacturing, we have chosen a relative bridge width of $t/a=0.1$, which results in a bridge width of $t=100\mu\text{m}$. This will lead to a TM band gap in relative frequencies from $\omega a/2\pi c=0.236$ to $\omega a/2\pi c=0.279$. The gap to midgap ratio for this band gap is $\Delta\omega/\omega_0=0.16$, which is still relatively large. The choice of parameters leads to a band gap for all propagation directions from 70.1 GHz to 83.7 GHz, and for the $\Gamma-K$ propagation direction from 70.1 GHz to 93 GHz.

We have then calculated the transmission properties of the EBG structure using a 3D solver for a propagation of waves excited from a rectangular metal waveguide along the $\Gamma-K$ direction of the lattice and travelling through ten lattice periods of the structure (see figure 6.35 for the calculated transmission curve). It can be seen that the band gap of the structure results in a transmission drop in the corresponding frequency range of about 50 dB.

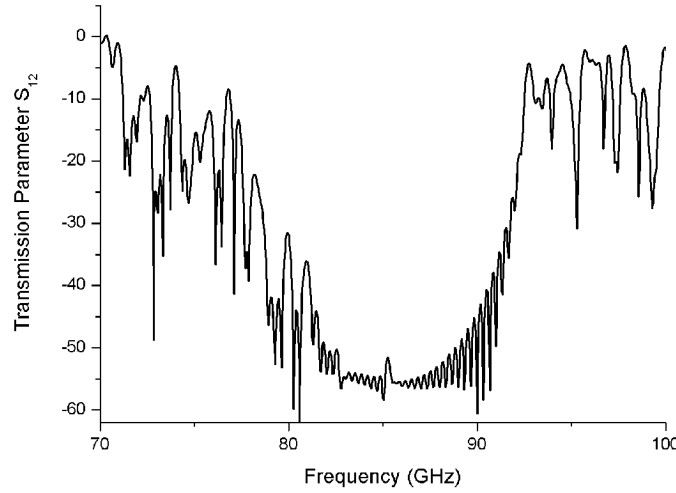


Figure 6.35: FDTD simulation of the transmission along $\Gamma-K$ direction through ten lattice periods of the structure.

For a dielectric structure the non-radiative losses will be determined by the dielectric loss tangent, which is related to the resistivity ρ of a semiconducting material given by its level of doping. It is expressed in the quality factor Q :

$$Q \geq \frac{1}{\tan \delta} = \frac{\epsilon_0 \epsilon \omega}{\sigma} = \epsilon_0 \epsilon \omega \rho \quad (6.4)$$

with the loss tangent $\tan \delta$ given by the fraction of the real and imaginary part of the dielectric constant, angular frequency ω and electrical conductivity $\sigma = 1/\rho$. In case of an $\epsilon_r = 11.56$, $\omega = 2\pi \cdot 100 \text{ GHz}$ and $\sigma = 1/10 \text{ k}\Omega \cdot \text{cm}$, we expect the quality factor to be larger than 6500 at the target frequency. It has to be mentioned that the rigid equality in equation 6.4 is valid only when the electric field energy is confined completely in the dielectric material, which is generally not the case. As seen from equation 6.4, the material parameter σ is crucial for the losses in the EBG structure, but also the existence and the size of the band gap is strongly dependent on its value, since it corresponds to the doping level of the employed Silicon. For a high doping level, Silicon will have a large number of free charge carriers available and lose its dielectric properties to some extent which will decrease the band gap. For low doping levels, corresponding to high resistivity, the Silicon is a very good dielectric, and the EBG structure exhibits a large band gap. A comparison of the EBG behavior for different doping levels is shown in figure 6.36, where the transmission properties of the EBG structure have been calculated for different doping levels of Silicon.

It is obvious from figure 6.36 that for resistivity values of around $200 \Omega \cdot \text{cm}$ the band gap starts to become a pronounced feature. Thus it is necessary to choose low doped material with a value of ρ not lower than $200 \Omega \cdot \text{cm}$ for the fabrication of EBG structures. However, the dielectric losses in this case are still relatively high and thus a resistivity as high as possible is desirable.

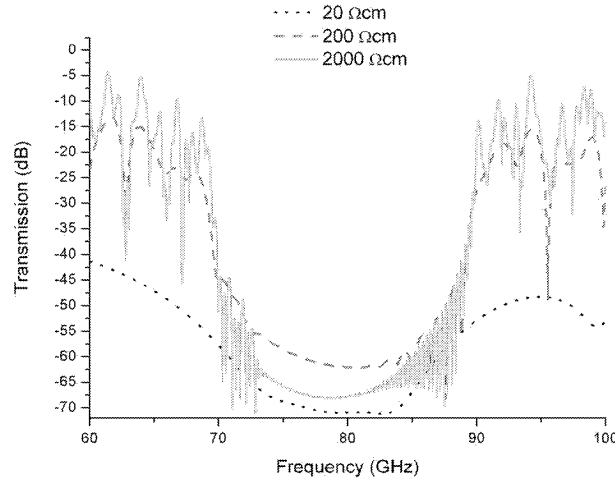


Figure 6.36: Dependence of the transmission through an EBG device on the doping level. Shown is the transmission through an EBG structure with a band gap around 80 GHz for various doping levels of the material (Silicon).

We have conducted experiments to confirm the existence of a bandgap for the structure described above. We have investigated the transmission properties described by the parameters S_{ij} , which will display the transmission and reflection of a wave entering the structure at port i and leaving it at port j . We have done both time domain and frequency domain measurements. The time domain measurements were made with the time domain terahertz spectroscopy (TDTS) setup described in the previous chapter. The frequency domain measurement was performed with a backward wave oscillator (BWO) signal source that was also described before. In both cases, a metallic taper structure has been used to guide the quasioptical wave into the EBG structure (see figure 6.37). By choosing the polarisation of the free propagating wave perpendicular to the EBG wafer plane, it was ensured that the properties of TM bandgaps become measurable.

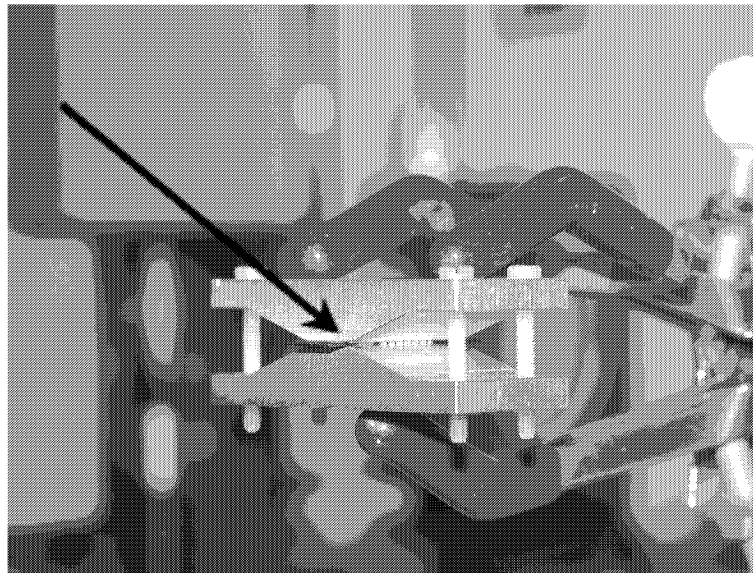


Figure 6.37: Metal taper made from Aluminium that was used to guide the quasioptical wave into the EBG structure. The EBG structure is clamped between the upper and lower half of the taper (marked with an arrow in the figure).

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We have determined the transmission properties of the EBG structure by measuring the transmission curves of the metallic taper with and without the EBG structure inside. The influence of the EBG structure was then determined by a division of the values of those two curves for each frequency point. The frequency domain measurements with a BWO signal source yield a very good frequency resolution of 10 MHz, but a small frequency band (see figure 6.38).

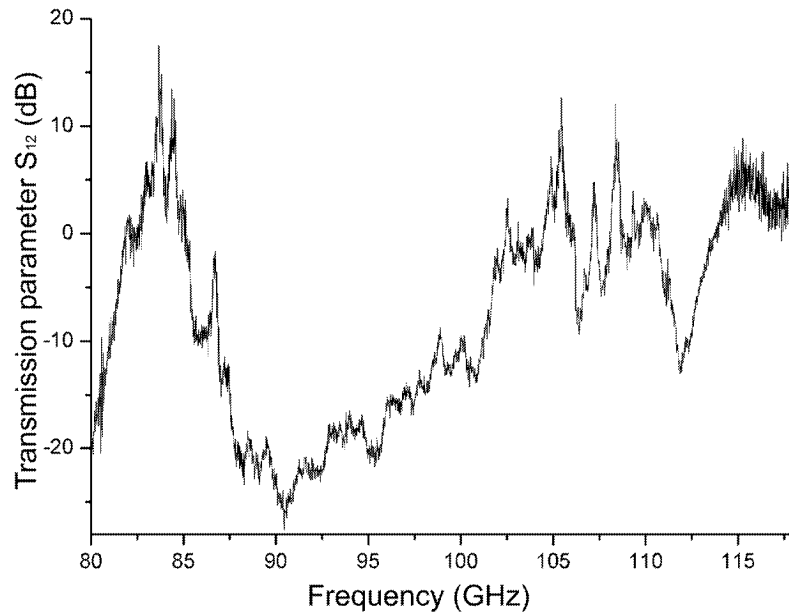


Figure 6.38: Measured frequency dependence of the transmission parameter S_{12} for the EBG structure extending over ten lattice periods in the beam propagation direction. The signal was produced with a BWO source. The unphysical values of S_{12} larger than zero can arise from the frequency response of the taper.

Thus, the measurement was performed for frequencies from 78 GHz up to 118 GHz. In this measurement, the band gap can be clearly seen by a transmission drop of about 20 dB in the range from 85 GHz to 102 GHz. The measured curve shows a number of transmission peaks and dips for frequencies outside the band gap, too. Also, it exhibits a transmission larger than 0 dB. Those features are related to the spectral response of the taper itself, which is different for an empty taper and a taper partially filled with dielectric material. Due to some mismatching at the taper boundaries, e.g. the opening on both sides and the edges of the EBG structure, there is the possibility of the excitation of standing waves in the beam path, which will influence the measured signal. Furthermore, the taper is open at its sides and may therefore radiate. This radiation is dependent on the filling of the taper with dielectric material and therefore the transmitted signal may be higher with a EBG metal inside than for an empty taper, making an S parameter greater than zero possible. Unfortunately, the frequency range of the band gap does not coincide with the range found in the simulation. The experimentally obtained band gap is located at frequencies more that 10 GHz higher. This effect is possibly caused by the nonuniform thickness of the dielectric bridges. This variation of structural geometry is due to changes in etching conditions during the etch process as well as inhomogeneities across the wafer. Therefore, the bridges may be thinner at their base than the nominal value of 100 μm . This variation will happen (i) along the height of the wafer (ii) at different positions on the wafer (iii) depending on the orientation of the bridge. Furthermore, a lower quality of the etching mask can be held responsible for inaccuracies. As is has been seen from the previous calculations, the position and size of the band gap are strongly

dependent on the bridge thickness, so that this fabrication tolerance plays a crucial role in the determination of the band gap position.

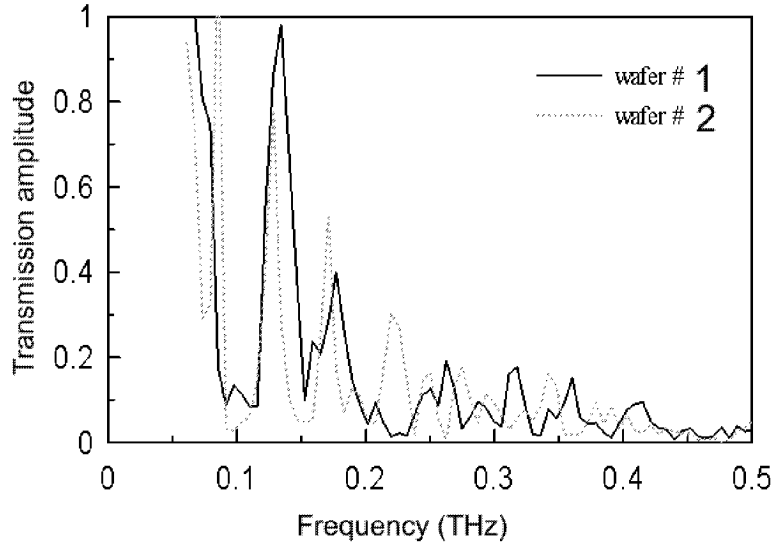


Figure 6.39: Transmission curve measured with a Terahertz time domain spectroscopy setup. The first band gap around 100 GHz can be recognized nicely, and the indication of the second band gap at approximately 200 GHz can be seen as well.

To confirm the existence of the band gap and examine the spectral properties of the EBG material for higher frequencies, we have also performed time domain measurements. In these measurements it can also be seen that there is a transmission drop for the frequencies of the first band gap around 100 GHz (see figure 6.39) which confirms the existence of a band gap. Also, around 220 GHz, a feature reminding the second band gap can be seen. We have measured two different samples that were cut from different parts of the patterned Silicon wafer. The curves that can be seen in figure 6.39 show a slightly different behavior concerning the frequency range of the band gap positions, this again indicates the influence of fabrication tolerances on the position of the band gap. The experimental data below 100 GHz are qualitative only due to diffraction effects in the TDTS setup. The results gained with the TDTS method confirm our previous findings. Transmission results greater than 0 dB are not found here, because in TDTS measurements standing wave effects are less dominant, as they will be separated from the signal pulse by their additional delay. Low transmission of the structure at high frequencies may be caused by residual absorption of the Silicon wafer. Indeed, an absorption coefficient $\tan \delta$ as small as 0.01 – 0.02 is sufficient to induce a decrease of the transmittance similar to that observed experimentally.

The interconnected rods structure that has been designed fabricated and measured in the frame of this work is very promising for the application of EBG structures as integrated technology for passive transmission lines in the millimetre wave range. With the utilisation of this structure, 2D EBG slab structures with three dimensional confinement could be realised. In addition, the structure may be attractive for the possible realization of a 3D structure composed of an alternating sequence hexagonal rod and hole layers as suggested in the literature[81] and shortly described in chapter 3.

6.5 - A 2D EBG slab structure for TE modes at millimetre waves

In Chapter 3 it was discussed that a defect mode in an EBG line defect structure could be guided in all three space dimensions, if the size and the average dielectric constant of the material in the line defect is chosen appropriately. In this case, the wave would be confined inside the plane of periodicity by Bragg reflection, and in the direction perpendicular to it by total internal reflection in the dielectric slab that provides the line defect. These kinds of structures are promising for the development of new integrated circuit devices for the millimetre wave range, because they can comprise low losses (due to their pure dielectric structure) as well as integration capability, broad band application and possibly high quality factors. The demonstration of waveguiding and the existence of high quality factor resonant structures in EBG slab materials for the millimetre wave range is therefore an important step towards the realisation of a novel circuit technology for millimetre and submillimetre waves.

In this part of the chapter we want to investigate a 2D EBG structure made from air holes in a dielectric background material, that possesses a band gap for TE-type even modes (modes with their electric field mainly in the plane of periodicity) at frequencies of around 90 GHz. We have investigated the existence of a band gap for TE modes in the structure, the behavior of line defect modes and the existence of point defect cavity modes that were coupled to the propagating wave of the defect waveguide.

The EBG lattice was made from a high resistive Silicon wafer with a thickness of 525 μ m patterned with a hexagonal arrangement of air holes. The relative height of the slab structure was desired to be between 0.5 and 0.6, but its absolute value was fixed due to the given thickness of the dielectric wafer. Therefore, a lattice constant of 1000 μ m would be a good choice, as in this case the relative height of the structure would be $h\pi=0.525$. For a hexagonal lattice of air holes with a dielectric background material that has a dielectric constant of $\epsilon_{high}=11.56$ and a relative hole radius of $r\pi=0.3$, suspended in air, we expect several band gaps for TE polarised modes with their electric field in the plane of periodicity. The band structure of this system can be seen in figure 6.40. The lowest order band gap for TE modes is located at relative frequencies of

$$\left(\frac{fa}{c}\right)_{start} = 0.273 \quad \rightarrow \quad \left(\frac{fa}{c}\right)_{stop} = 0.352$$

For the desired lattice constant of 1000 μ m, this band gap would be located at frequencies of

$$f_{start} = 81.9 \text{ GHz} \quad \rightarrow \quad f_{stop} = 105.6 \text{ GHz}$$

In this case, the radius of the air holes has to be $r = 300 \mu\text{m}$.

The structure was fabricated by laser machining as described in chapter 5. An analysis of the holes shape and the condition of the surface can be found in chapter 5 as well.

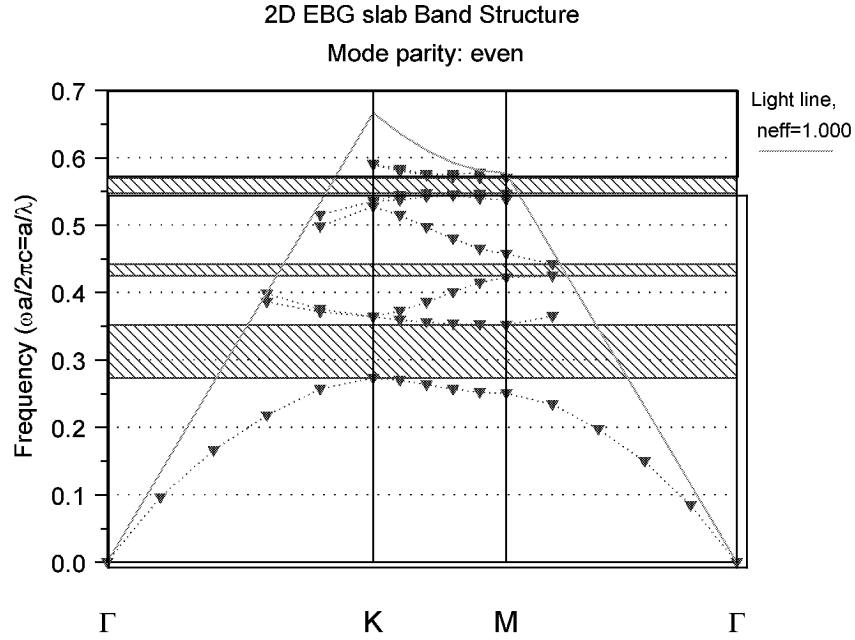


Figure 6.40: Calculated band structure for the 2D EBG lattice of air holes in dielectric background material (Silicon) for a relative hole radius of $r=0.3$ and a relative height of the slab of $h=0.525$. It can be seen that the structure exhibits a number of band gaps for even modes (corresponding to TE polarised waves).

We have measured the transmission of a millimetre wave through the sample with a signal generated by two heterodyne multipliers (Millitech FEX 10-1, FEX 10-6) that had a frequency range from 70-90 GHz and 90-110 GHz, respectively. The multipliers were fed with a microwave signal from a synthesized sweeper (HP 83630-A) that delivers frequencies from 10 MHz up to 26.5 GHz. The millimetre wave signal was guided into the EBG structure by a standard rectangular metal waveguide for this frequency band (WR-10) with edge sizes of 2.5 mm and 1.25 mm, respectively.

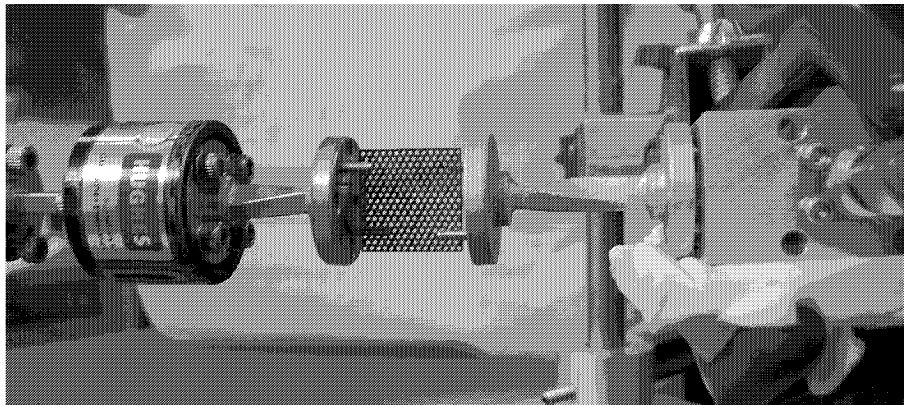


Figure 6.41: Experimental setup: The patterned Silicon structure was clamped between two rectangular waveguide ports, the signal source was connected on the left side and the detector diode was connected on the other side.

The EBG structure under investigation was attached to the waveguide with a triangular shaped taper structure that was designed to provide a smooth transition between the rectangular metal waveguide filled with air and the Silicon slab in which the EBG structure

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was patterned, and to minimize reflection of the wave at the air-dielectric boundary. The outgoing signal was coupled back into the rectangular waveguide with a similar taper and is subsequently fed into a Schottky detector diode (Millitech DXP-10 for frequencies from 75-110 GHz). A photograph of the experimental setup can be seen in figure 6.41. To avoid reflections from the interconnects of the waveguide parts, an isolator was used that prohibited the backward propagation of a reflected signal into the source. We have measured the frequency dependent signal strength from the two multipliers over the frequency range from 70-110 GHz and divided every transmission measurement curve by this reference. To confirm the validity of the measured curve, we have compared the measurement signal with the transmission curve from a 3D field simulation of the experimental setup that was gained with a FIT solver as explained in chapter 2.

Due to the fact that a dielectric taper was used to attach the EBG structure to the rectangular waveguide and provide a suitable coupling from the waveguide to the dielectric material off the EBG slab, we have been able to measure one direction of propagation only: the $\Gamma - K$ symmetry direction. Therefore the measured bandgap will not have the size of the complete band gap of the structure, but the one in $\Gamma - K$ direction which has a slightly higher upper edge frequency of 112.5 GHz, while the lower edge frequency remains constant.

Verification of the band gap

The first measurement was done to confirm the existence of the band gap and investigate the strength of the coupling between the waveguide parts and the EBG structure. Also, the influence of the positioning of the structure inside the waveguide had to be investigated, as it was done manually and therefore no high reproducibility could be expected. This first measurement was performed with an EBG structure that had no defects at all and a transmission drop for frequencies of the band gap is expected.

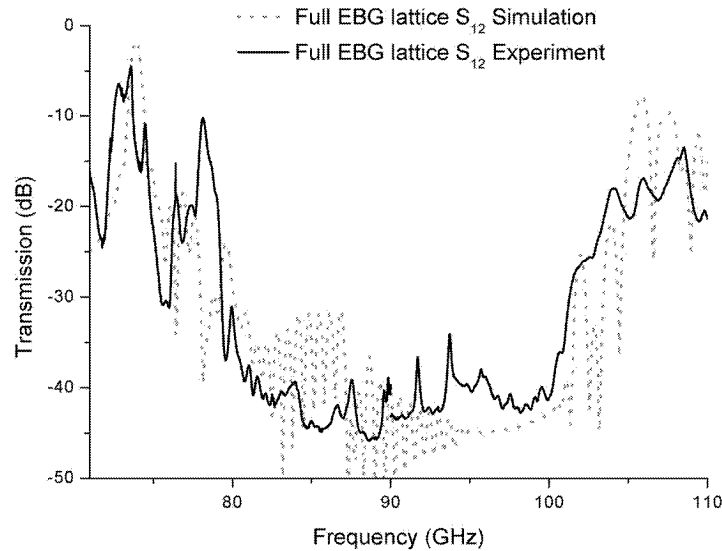


Figure 6.42: Comparison between experimental curve and simulation for the full EBG lattice without defects. The frequency range for which there is a transmission drop due to the band gap of the structure coincides in both curves.

Overall it can be seen from figure 6.42 that the curves of both measurement and experiment are in coincidence. Both the transmission inside and outside the band gap are at similar

values. The insertion loss of about 5-10 dB can be related to the not optimised coupling from the rectangular waveguide to the dielectric structure. A further optimisation of the shape of the taper is necessary. At a frequency of about 80 GHz and 105 GHz, the falling and rising slopes of the band gap can be seen. These frequencies coincide nicely with the expected frequency of the band gap of 81.9 and 112.5 GHz. Inside the band gap the transmission is dampened by about 35 dB relative to frequencies outside the band gap. There is a number of in-gap transmission peaks that are equidistant with a frequency spacing of about 2 GHz. These peaks are related to standing waves in the measurement setup and have no relation to the band gap properties of the structure. To investigate the precision of placement of the structure in the waveguide, we have removed the sample from the setup and put it back again, and measured the same curve a second time. In this case only a very slight change to the transmission curve could be observed. The most prominent difference is the different height of the equidistant peaks that are present in the transmission curve. This is a further indication for the fact that these peaks arise from unwanted standing waves at some point in the setup and are not related to the EBG lattice properties.

Line defect waveguiding

In chapter 3 we have investigated line defects, where one row of dielectric lattice elements was removed to form a so called W1 line defect. In the previous part of this chapter we have presented measurements in the microwave range around 10 GHz that show that this type of line defect has an in-gap cutoff defect frequency $f_{c,d}$ and shows a good transmission behavior for frequencies $f > f_{c,d}$, but no transmission for $f < f_{c,d}$.

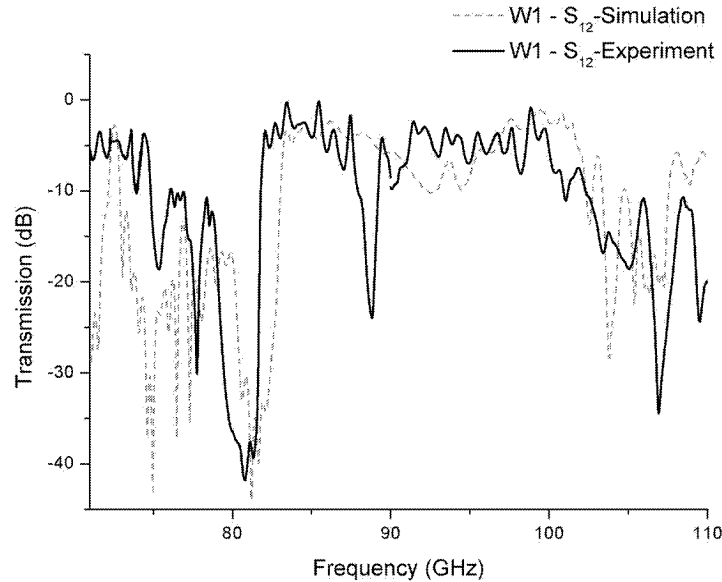


Figure 6.43: Comparison between experimental curve and simulation for the EBG structure with a W1 line defect waveguide. For the frequency range above 82 GHz, the waveguide acts as a waveguide with high transmission between -1 and -6 dB.

We have measured the W1 line defect structure to confirm these findings at millimetre wave frequencies. Figure 6.43 shows the comparison between measurement and simulation for the transmission parameter of the EBG structure with a W1 line defect. Again, the coincidence between the measured and simulated curve can be seen nicely. The start of the band gap at frequencies of 75 GHz can be recognized by a transmission drop of about 30 dB for

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frequencies $f > f_{b1}, f < f_{c,d}$. When the defect waveguide cutoff frequency is reached, the transmission rises to a level of about -3 dB and, apart from a standing wave pattern that arises from uncontrolled reflections in the setup, there is a broadband high transmission with values between -1 and -6 dB by the waveguide from frequencies of 82 GHz up to 99 GHz. The transmission drop by more than 20 dB at a frequency of 88 GHz can currently not be explained. It is not a feature of the band gap structure however, because it exists consistently in all our measurements independent from the kind of structure being measured, but can not be reproduced by simulation. Therefore, we assume an influence of the measurement setup that could so far not be eliminated.

With this measurement it was demonstrated that the W1 waveguide can act as a transmission line for millimetre waves very similar to what was found for the microwave range before. The coupling between the metal waveguide and the defect waveguide exhibits a low transmission loss. In further experiments we will employ the W1 waveguide to guide the signal inside the EBG structure and to provide a coupling of the external signal to localised resonant cavities.

Resonant cavities

As a next step we have investigated the possibility of using a point defect in the EBG lattice as a resonant cavity that can support a localised defect mode with a high quality factor. Therefore we have investigated both a band pass transmission cavity and a band reject notch cavity. In the band pass setup the cavity is arranged in line with the waveguide and in the band reject setup it is placed at the side of the waveguide. Both setups are shown schematically in figure 6.44. In case of a band pass setup we expect an increased transmission at resonance frequencies of the cavity because the signal can propagate from the left side of the waveguide to the right side by coupling to the resonant mode. In the band reject setup the signal is coupled from the waveguide into the cavity, and a transmission is decreased at the resonance frequencies of the cavity. We do therefore expect a dip in the transmission curve.

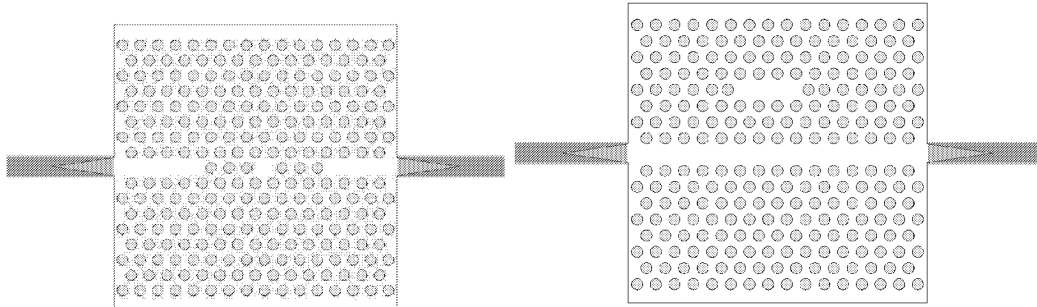


Figure 6.44: Transmission measurement setup for a resonant cavity. Left side: band pass arrangement. Right side: band reject arrangement.

It has been reported in the literature[141][142][143] that a resonant cavity embedded in a 2D EBG slab can exhibit an extremely high quality factor, if a number of the surrounding holes was shifted from their positions by a percentage of the lattice constant (see figure 6.45 for a schematic drawing of the shifting).

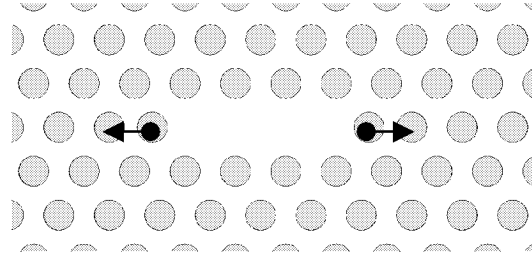


Figure 6.45: Shift of the adjacent lattice holes away from the cavity

These findings were made at optical frequencies, however, we have investigated the similar structure at a frequency of 100 GHz to achieve a high quality factor cavity at millimetre wave frequencies. A transmission spectrum of the band reject cavity is shown in figure 6.46.

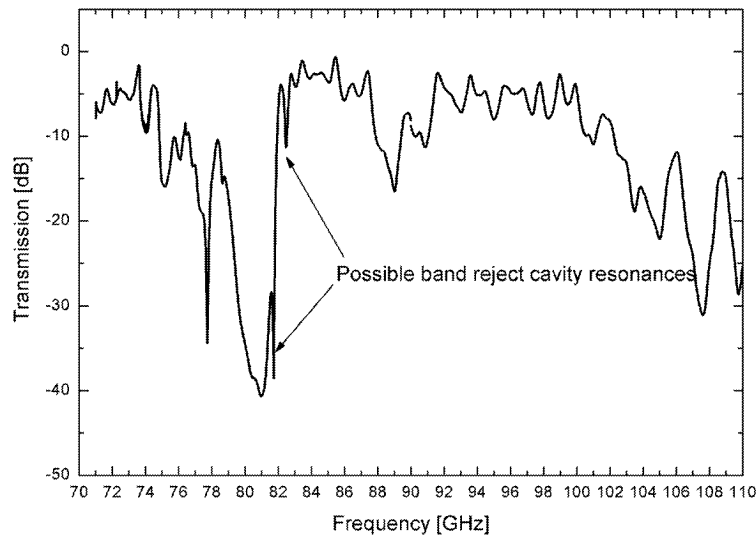


Figure 6.46: Measured transmission curve of the resonant cavity in band reject configuration. The curve is very similar to the transmission curve for the W1 waveguide, however small dips indicate the possible existence of band reject resonances.

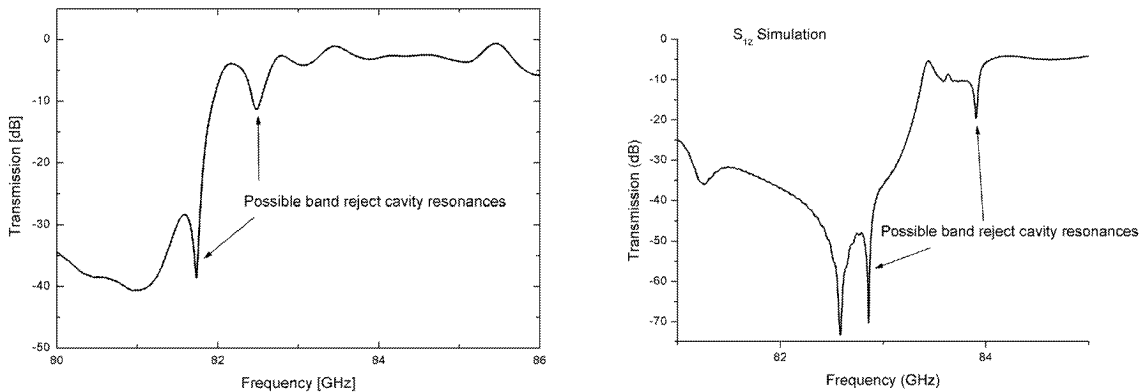


Figure 6.47: Close view of the transmission dips possibly related to band reject cavity defect modes.

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The transmission curve in this configuration is very similar to the one already observed for the W1 waveguide. The influence of the resonant cavity can be seen from small transmission dips at frequencies of $f_1 = 81.74 \text{ GHz}$ and $f_2 = 82.47 \text{ GHz}$ that have been marked with arrows in figure 6.46. For a clarification of the situation, the frequency range of these resonances is plotted in a larger resolution in figure 6.47.

To verify that these dips are actually related to resonant modes we have compared our measured curve with a curve that was calculated from the simulation. It can be seen that even though the frequency range gained in simulation differs from the one found in the experiment, the dips can be found in both curves. However, when the distribution of the electric field at the frequencies of the dips is calculated, it becomes obvious that only one of them is related to a cavity resonant mode. The field distributions for this peak at a frequency of 82.85 GHz are shown in figure 6.48.

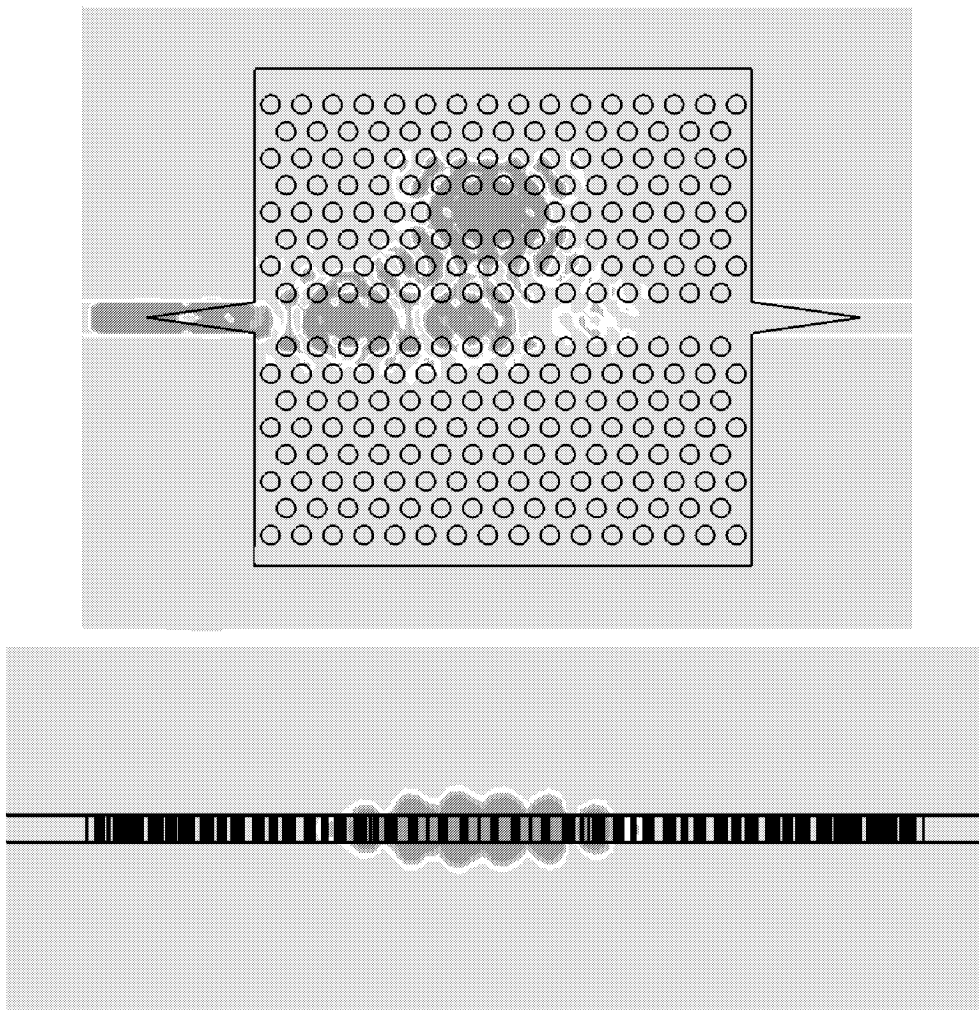


Figure 6.48: Simulated distribution of the electric field amplitude for the resonance frequency at 82.85 GHz. From the upper picture it can be seen that the dip is related to a cavity mode and energy is coupled from the W1 waveguide into the cavity, which causes the dip in transmission. From the lower picture it becomes clear that the mode is nicely confined to the plane of the 2D EBG slab and radiation is not significant.

The lower frequency peak at 82.58 GHz is related to a surface mode that has its field maxima at the side edges of the wafer. It is connected with the cavity because the distance between the

upper edge of the structure and the cavity is relatively small (four lattice periods), but the amount of energy of this mode that is stored in the volume of the cavity is rather small. We can guess that this mode would correspond to a resonant mode of the cavity, but it is not possible to couple to the mode because its frequency is located at the very beginning of the slope related to the cutoff of the defect waveguide. Therefore, energy can not be transferred to the cavity through the waveguide. A second indication that the observed dips are related to the defect cavity modes is gained when the effect of the shifting of the lattice elements on the Q factor and frequency of the resonant mode, given by the width depth and position of the dip, is observed. We have measured a number of structures with different shifting of the holes. The comparison of the experimental curves, for the frequency range of interest (80-86 GHz) is shown in figure 6.48.

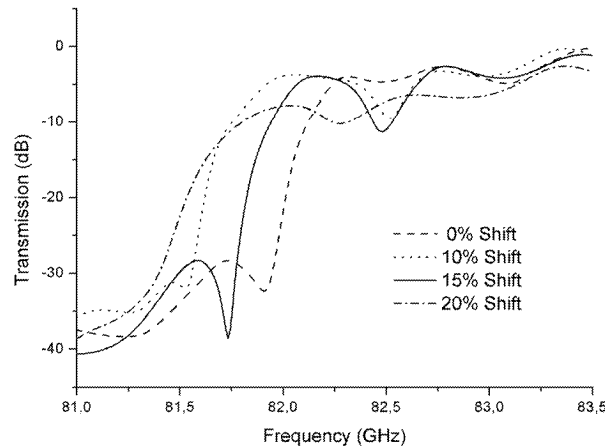


Figure 6.48: Comparison of the transmission curves for band reject cavities, where the first holes of the lattice are shifted by a fraction of the lattice constant. Both the resonant frequency and the depth of the dip are strongly dependent on the shift.

It is observed that for a shift of 10 % and 15 % the transmission dips are clearly pronounced. For both 0 shift and 20 % shift, the dips are broader and less deep. This result is similar to the findings that have been reported in literature[141][142]. From the shape of the dip we can calculate the unloaded quality factor of the resonant mode. In the following table the resonance frequencies and loaded quality factors for the cavity mode for different shifts of the holes are compared.

<i>Shift (% of lattice constant)</i>	<i>Mode frequency (GHz)</i>	<i>Mode quality factor</i>
0	82.478	290
10	82.519	760
15	82.478	700
20	82.273	350

Similar to the findings reported in literature[141][142], the quality factor is relatively high for a shift of 10 % and 15 %, while it is reasonably lower for shifts of 0 % and 20 %. The dependence of the quality factor on the shift of the holes can be explained, when the Fourier transform of the electric field distribution is calculated and compared with the region of radiative modes with small k vectors that are able to couple to the continuum of modes above

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and below the slab. The explanation is given in the literature[141] and will not be further discussed here.

From the material properties of the Silicon we can expect a maximum quality factor of about 6500 (compare the previous section of this chapter), related to the resistivity of the Silicon. We can see that the experimental findings differ quite significantly from this value, by about one order of magnitude. This decreased quality factor can be explained if the bad condition of the sample surface is taken into account, as it was reported in chapter 4. Additionally, it can be assumed that during the treatment with the laser beam, amorphous regions near to the drilled holes are formed, which will exhibit a significantly lower quality factor. To estimate this influence of the surface condition on the quality factors of structures in the 2D EBG slab, we have mechanically polished one of the samples that had a cavity arranged in band pass configuration. A comparison of the transmission spectra for a polished and an unpolished sample is shown in figure 6.49.

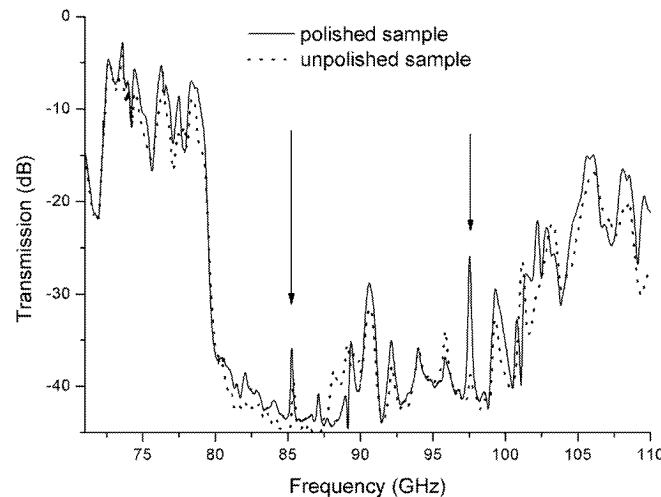


Figure 6.49: Comparison of the measured transmission curve for a polished and an unpolished sample. For the polished sample, small spectral features are more pronounced and possibly have a higher quality factor (peaks marked with the arrows).

From the comparison of the measured curves of the polished and unpolished sample it can already be seen that even a very simple mechanical polishing has an influence on the transmission behavior: Spectral features like the transmission peaks that can be observed in the band gap are more strongly pronounced. Two of these peaks have been marked with arrows in figure 6.49. For a more detailed analysis of the dependence of the achievable quality factors on the surface, more careful investigations of alternative polishing methods, that also involve chemical polishing must be made. Additionally, alternative drilling methods like ultrasonic drilling or water beam drilling should be investigated to avoid a possible degradation of the Silicon during the fabrication process. Alternatively, a different fabrication method could be employed for the creation of the structure, here the method already presented for the fabrication of the interconnected structure, high aspect ratio Silicon etching, could be a suitable alternative.

Overall we have shown that a 2D EBG slab structure that can be made by simple laser drilling can provide a bandgap for frequencies around 90 GHz, and that low loss waveguiding for a broad frequency range of more than 20 GHz is possible. A three dimensional confinement of

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both the travelling line defect mode and a localised point defect mode could be demonstrated. It has also been shown that it is possible to couple the signal that propagates through a line defect into a resonant cavity and to tune the quality factor of the cavity mode by a shift in the position of the adjacent lattice elements. These results show that EBG structures are very well suited for the development of an integrated circuit technology based on 2D EBG slab structures for frequencies in the millimetre wave range.

Chapter 7: Conclusion and Outlook

In the frame of this work, electromagnetic bandgap structures for microwave and millimetre wave frequencies have been investigated with respect to a possible application in future integrated circuit technologies. Different types of one, two and three dimensional EBG structures have been analysed by simulations, several methods of fabrication of EBG structures have been investigated in cooperation with partners, and the fabricated EBG structures have been investigated experimentally in the frequency range from 10 GHz to 100 GHz.

It has been pointed out that there are different ways to achieve a confinement of electromagnetic energy in an EBG structure: A three dimensionally periodic dielectric structure can confine modes at defects for all directions of propagation by Bragg reflection due to the dielectric lattice. This behavior has been demonstrated in both simulation and experiment for a 3D EBG structure with a band gap at 20 GHz. However, it has been found that 3D EBG structures suffer from a number of drawbacks. These drawbacks are either related to difficulties in fabrication, as mentioned in chapter 3, or to their relatively large size compared to the free space wavelength corresponding to the frequency range of their band gaps, as shown in chapter 6. This large spatial extension leads to the existence of a huge density of unwanted modes in the volume of the EBG structure that can not be completely suppressed due to its finite size, additionally the existence of surface modes limits the performance of 3D EBG structures severely in an application in the microwave range.

It has been shown that the utilization of 2D EBG structures is a valuable alternative to the 3D periodic structures. It was confirmed in simulations that in 2D EBG structures a large complete band gap in the plane of periodicity can be created for TM waves, when a lattice of dielectric rods is used, and a large complete band gap for TE waves exists, when a lattice of holes in dielectric background material is used. For TM waves the confinement in the third dimension can be achieved by enclosing the EBG structure between metal endplates, effectively acting as an infinitely extended 2D structure. This configuration has been realised for different frequencies from 10 to 100 GHz. For TE waves, the three dimensional confinement can not be achieved by endplates due to the lack of appropriate boundary conditions for electric and magnetic field. In this case, it has been shown that an arrangement in a slab structure where the 2D EBG structure is suspended in a low dielectric background medium (air) can yield a confinement in the third direction (index guiding). If a line defect is introduced, it is possible to guide a defect mode through the line defect if the right defect parameters are chosen. Such an EBG slab structure has been investigated for frequencies around 90 GHz.

The fabrication of 2D EBG structures for TE waves is relatively easy, because holes can be drilled into a dielectric substrate. This has been demonstrated for a structure that was made from laser machining of a Silicon wafer for a band gap at a frequency of about 100 GHz. However, the fabrication of a dielectric rod structure with a band gap for TM waves is more difficult as the lattice elements will not form a connected structure and might fall apart without stabilization. This problem can be overcome by various approaches that have been realised in the frame of this work: The dielectric rods can be clamped between metal endplates. Another way is to backfill the rod lattice with a stabilizing material with low dielectric constant. This approach has been realised in two different structures for frequencies around 30 GHz that were made with moulding techniques. It has been found that these structures can yield a band gap, however, the backfilling material will give rise to a higher spurious mode density and will also produce additional losses. A careful selection of the material system for both mould and slurry is necessary to produce high aspect ratio freestanding dielectric structures. This problem has been solved by the utilisation of a sodium chloride mould system. A third way has been found where a modified hexagonal lattice has been investigated where the dielectric rods are interconnected with thin dielectric bridges. This approach has been realised in fabrication by etching of a Silicon wafer. To achieve this, a chemically assisted ion etching method for high aspect ratio structures has been successfully applied to the fabrication of an EBG structure that has a band gap at frequencies of around 100 GHz.

Several experiments have been conducted to confirm the results that were gained from the simulation, and to measure the properties of the structures that were fabricated in order to give a judgement about the suitability of the applied fabrication processes. For frequencies of 10 GHz, it has been shown that in a 2D EBG structure for TM waves the strength of the coupling to a defect resonance could be tuned and optimised by size variation of adjacent lattice elements to yield low insertion loss. Furthermore, a broadband high transmission waveguiding by line defects with a width of one and three lattice periods could be shown. For frequencies around 30 GHz, the creation of a band gap in a 2D EBG structure that was prepared by a ceramic moulding technique with a band gap for TM waves has been demonstrated and a resonant cavity mode with moderate quality factor could be observed. Two different structures with band gaps at frequencies around 100 GHz have been fabricated and measured. Here it was shown that a 2D interconnected structure could exhibit a band gap for TM waves and provide a high mechanical stability without the need for a backfilling material. Furthermore, it was shown that a 2D slab structure could provide a three dimensional confinement of defect modes by a combination of both band gap guiding and index guiding. A broadband waveguiding by a line defect mode in this slab structure was shown, and it was demonstrated that a localised mode in a point defect could act as a high quality factor cavity in both band pass and band reject configuration. The scalability of EBG properties has been utilized, and results gained from both simulation and experiment in the microwave range have been transferred to millimetre wave frequencies. It has been shown that electromagnetic bandgap materials can be utilized as passive elements for the millimetre and submillimetre wave range in an application for future integrated structures for this frequency regime.

Future work will be devoted to further investigations of EBG materials at frequencies around 100 GHz or higher with respect to the optimisation of the performance of both waveguiding line defect structures and localised resonant structures. Additionally, coupling schemes based on coplanar and slotline technology for the connection of EBG structures with external high frequency circuitry will be investigated and the integration of active devices such as high electron mobility transistors (HEMT) or Gunn diodes will be researched.

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