High-Q Cryogenic Dielectric Resonator Filters for C-band and Ku-band Frequencies

H. R. Yi and N. Klein
Institut für Schicht- und Ionentechnik (ISI), Forschungszentrum Jülich (FZJ), D-52425 Jülich, Germany

***Abstract*— Dielectric resonator filters for C-band and Ku-band were designed and built. The C-band filter was based on the $HEM_{11\delta}$ dual-mode of hemispherical resonators machined from BaMgTaO ceramics, which has a dielectric constant of around 24. The Ku-band filter was based on the $HEM_{11\delta}$ dual-mode of cylindrical resonators machined from sapphire single crystals. For both filters with cavity made from copper, unloaded quality factors of 30,000 and more than 60,000 were registered at room temperature and 77 K, respectively. For a four-pole quasi-elliptic filter with center frequency of around 3.72 GHz and bandwidth of 36 MHz, the measured insertion loss was 0.17 dB at room temperature and 0.08 dB at 77 K. For a four-pole quasi-elliptic filter with center frequency of 10.76 GHz and bandwidth of 24 MHz, the measured insertion loss was 0.9 dB at room temperature. We also estimated the unloaded quality factor of the C-band filter when the top copper endplate was replaced by a $YBa_2Cu_3O_7$ superconducting film. In this case the unloaded quality factor was 100,000 at 77 K.**

I. Introduction

For the miniaturization of microwave circuits, low-loss temperature-stable dielectric resonator filters are used to replace waveguide filters for those applications where high power transmission and low-loss filtering are essential, such as satellite communications. The dielectric resonator filter can be operated either with single-mode or with dual-mode. For the dual-mode operation, it is possible to build a two-pole bandpass filter with only one resonator [1, 2]. The dual-mode filters can also be designed to exhibit an elliptic behavior [2].

In this paper, we report about our recent investigations on dual-mode dielectric resonator filters. Two filters with quasi-elliptic characteristics are presented. One is a four-pole C-band filter with center frequency of about 3.72 GHZ and the other is a four-pole Ku-band filter with center frequency of about 10.76 GHz. These filters can be operated either at cryogenic temperatures or at room temperature.

II. Resonator Geometry

We used both hemispherical resonators and cylindrical resonators for the realization of the dielectric resonator filters. Figure 1 shows the schematic view of these two resonator structures. In Fig. 1 (a), a hemispherical resonator is separated from the bottom endplate by a small dielectric cylinder (spacer). Usually, the spacer and the hemispherical resonator are machined from the same piece of dielectric material. The spacer is positioned by a cylindrical shaped groove on the bottom endplate. The diameter of the groove is slightly larger than that of the spacer. A thin dielectric holder with low permittivity is used to fix the resonator. The hemispherical resonator structure was first investigated more than two years ago in our group [3]. Recently, we also investigated the cylindrical resonator structure as shown in Fig. 1 (b). Here, two dielectric spacers are separating a cylindrical resonator from the bottom and top endplates. Both spacers are positioned by the grooves on the bottom and top endplates, respectively.

Figure 2 shows the electric filed distributions of the $HEM_{11\delta}$ mode for the hemispherical resonator and the cylindrical resonator. The simulation was performed with MAFIA software [4]. In Fig. 2 (a) the strong electric field (big arrows) at the bottom endplate allows for sufficiently strong coupling by using electric probes, e.g., dielectric tuners and metallic antennae. In Fig. 2 (b), the strong electric field is distributed at both the top and bottom endplates. Therefore, it is possible to introduce electric coupling and tuning both from the top and bottom endplates.

Figure 3 shows the magnetic field distributions of the $HEM_{11\delta}$ mode for both resonators. In both cases, the strong magnetic field is located within the dielectrics, while the magnetic field on the inner cavity surfaces is very small. This field distribution leads to a very low loss contributions from the surfaces of the shielding cavity, which gives a very high quality factor of the resonator housing.

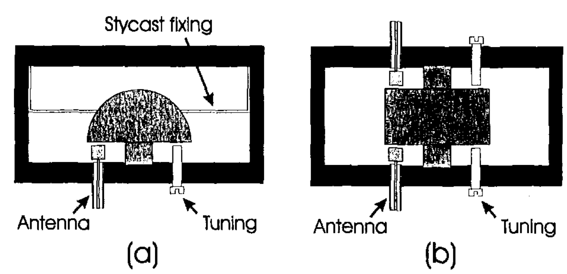

Fig. 1. Side view of the resonator geometry of (a) a hemispherical dielectric resonator separated from the endplate by a small dielectric cylinder (spacer), the resonator is fixed by a stycast holder; (b) cylindrical dielectric resonator separated from the two endplates by two small dielectric cylinders. The spacer(s) and the resonator can be machined from the same piece of dielectric material.

Manuscript received September 17, 2000.

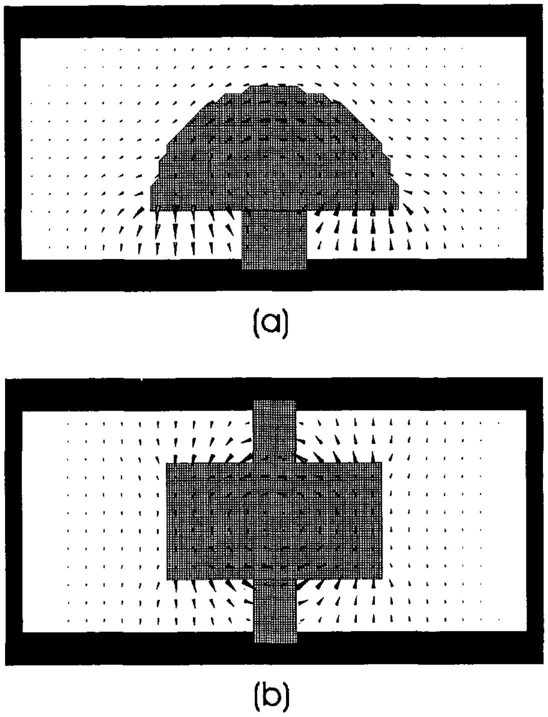

Fig. 2. Simulated electric field distribution for (a) the hemispherical dielectric resonator and (b) the cylindrical dielectric resonator. The strong electric field is distributed between resonator and the endplate(s).

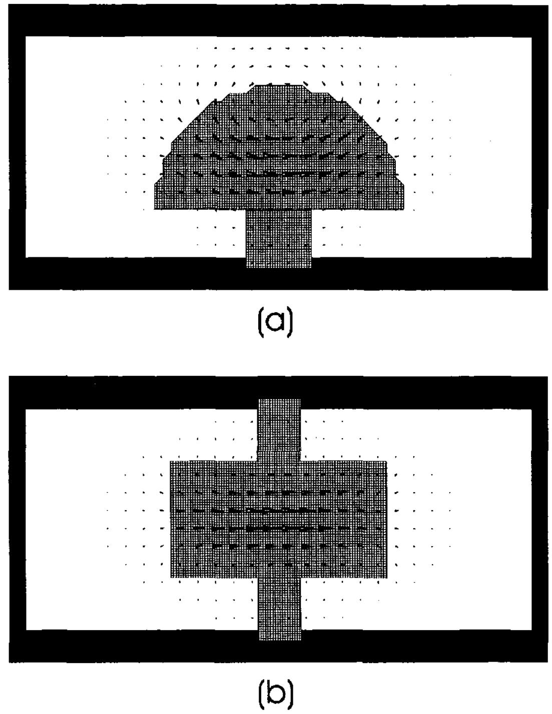

Fig. 3. Simulated magnetic field distribution for (a) the hemispherical dielectric resonator and (b) the cylindrical dielectric resonator. The strong magnetic field is distributed within the dielectric resonator.

A four-pole quasi-elliptic filter can be constructed by arranging two dual-mode resonators in one metallic shielding cavity, one being separated from the other by a metallic aperture [3,5].

III. Unloaded Quality Factor

The unloaded quality factor (Q_0) of a dielectric resonator is given by

$$Q_0 = \left(R_s / G + k \cdot \tan\delta\right)^{-1}, \qquad (1)$$

where G is the geometry factor of the resonator housing, R_s is the surface resistance of the housing material, $\tan\delta$ is the loss tangent of the dielectric material, and k is the electrical filling factor that represents the fraction of the electrical energy stored in the dielectric materials. In order to achieve a high Q_0, one should manage to have high G, low R_s, and low $\tan\delta$. The geometry factor can be calculated from the magnetic field distribution on the surface of the resonator housing. In our design, we have used MAFIA software to optimize the G factor. The G factor is dependent on the resonator geometry and the permittivity of the resonator material.

Experimentally, the unloaded quality factors were measured with the transmission method under weak-coupling conditions. The modes were separated from each other by tuning the appropriate tuning and coupling screws. The quality factor of the mode with highest frequency was determined from $Q_L = f_L / \Delta f$, where f_L was the measured resonant frequency of the mode and Δf was the 3 dB width of the resonant peak from the transmitted signal. The unloaded quality factor was calculated by [6]

$$Q_{0,\mathrm{exp}} = 2Q_L \Big/ \left(1/\sqrt{10^{S_{11}/10}} + 1/\sqrt{10^{S_{22}/10}}\right), \qquad (2)$$

where S_{11} and S_{22} were the amplitude in dB of the reflected signals from port 1 and port 2, respectively.

IV. C-band Filter

Our C-band filter was built using the hemispherical resonator geometry shown in Fig. 1 (a). The filter housing was made of OFHC (oxygen-free high conducting) copper. The hemispherical resonators were machined from sintered BaMgTaO (BMT) ceramics provided by MURATA. BMT has a dielectric constant of around ε_r = 24, and its temperature coefficient is only a few ppm / K at around 300 K and can be optimized to zero [7]. At room temperature, $Q \cdot f$ can be as high as 350,000 GHz for frequencies above

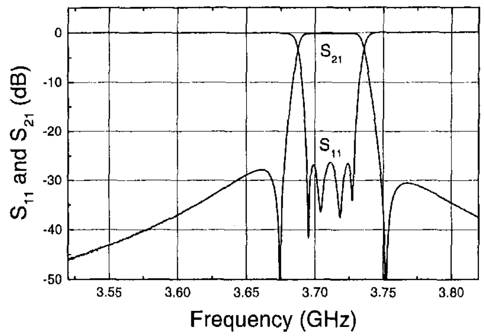

Fig. 4. S_{21} and S_{11} of a quasi-elliptic four-pole filter measured at room temperature. The center frequency is 3.712 GHz, the bandwidth is 36 MHz. The insertion loss in the passband center is 0.17 dB.

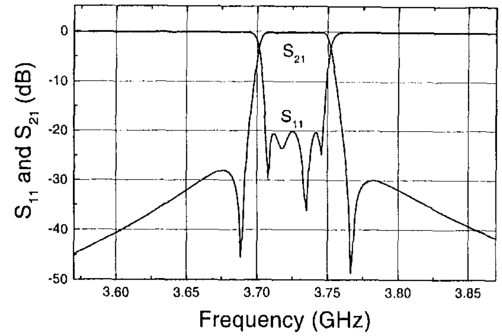

Fig. 5. S_{21} and S_{11} of a quasi-elliptic four-pole filter measured at 77 K. The center frequency is 3.725 GHz, the bandwidth is 36 MHz. The insertion loss in the passband center is 0.08 dB.

10 GHz. At low frequencies, it drops continuously according to our own measurement [8], e.g., at 4 GHz, $Q \cdot f$ is about 200,000 GHz at room temperature and about 600,000 at 77 K.

The measured values of $Q_{0,exp}$ of this filter were 30,000 at T = 300 K and 65,000 at T = 77 K. We also estimated the Q_0 values by Eq. (1). The total geometry factor G = 1339 Ω, where the contribution from the side wall G_1 = 5601 Ω, from the top endplate G_2 = 2194 Ω, and from the bottom endplate G_3 = 8840 Ω. The electrical filing factor k = 0.873. Taking the surface resistance values of copper from [9], i.e., R_s = 18 mΩ at T = 300 K and R_s = 9.5 mΩ at T = 77 K, and the loss tangent values of BMT from [8], i.e., $\tan\delta = 2 \times 10^{-5}$ at T = 300 K and $\tan\delta = 8 \times 10^{-6}$ at T = 77 K, we calculated Q_0 = 32,000 at T = 300 K and Q_0 = 70,000 at T = 77 K. The calculated values were in good agreement with the measured ones.

For this filter, the main loss contribution comes from the top endplate. The loss from the top endplate is two and one half times as higher as from the side wall and four times as high as from the bottom endplate. It is worth replacing the top copper endplate with a $YBa_2Cu_3O_7$ (YBCO) film, while keeping the side wall and the bottom endplate unchanged (OFHC copper). Taking a typical surface resistance value of YBCO, e.g., R_s = 500 μΩ at 10 GHz and 77 K, scaling down to 3.7 GHz using the quadratic frequency dependence, i.e., R_s = 68 μΩ, we estimated Q_0 = 100,000 at 77 K. This value is only slightly lower than the measured Q_0 of 120,000 for $LaAlO_3$ resonators shielded by YBCO film [5].

Figure 4 shows the amplitude of S-parameters of a four-pole filter measured at room temperature. The measurement was performed with an HP 8510C network analyzer. The loss contributions from the microwave cables have been subtracted by performing a two-port full calibration with 3.5 mm calibration kit. This filter showed quasi-elliptic characteristics. Two transmission zeros were seen from the transmitted signals outside the passband (one on each side). The center frequency of this filter was 3.712 GHz and bandwidth was 36 MHz. The return loss in the passband was more than 25 dB and the insertion loss in the passband center was 0.17 dB at room temperature. The lower adjacent mode was 3.31 GHz and the higher adjacent mode was 4.20 GHz.

By cooling down the filter with liquid nitrogen, we also tuned the filter at the liquid nitrogen temperature. Figure 5 shows the amplitude of S parameters of this filter measured at 77 K. The return loss in the passband was more than 20 dB, and the insertion loss in the passband center was 0.08 dB.

V. Ku-band Filter

For dielectric resonator filter in the Ku-band frequencies, their size becomes very small. Therefore, we used the

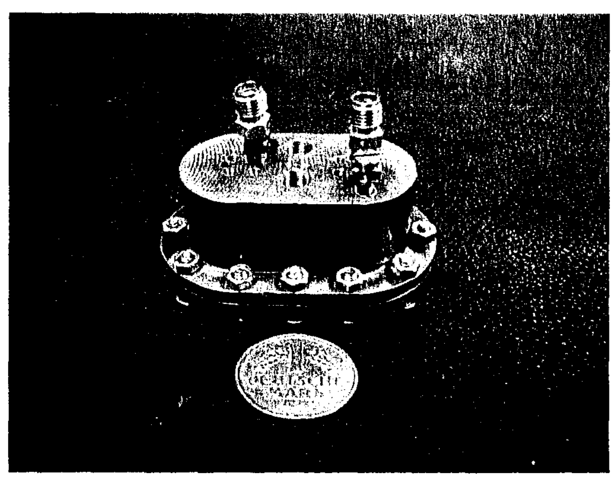

Fig. 6. Photo of the Ku-band filter.

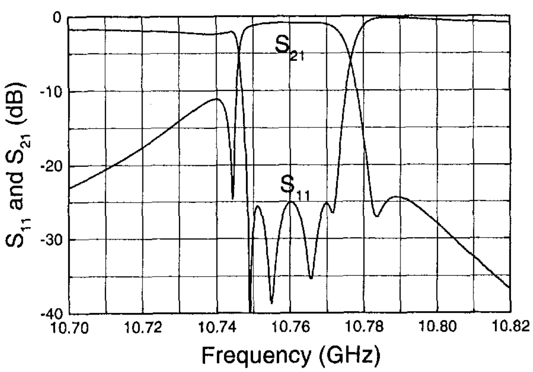

Fig. 7. S_{21} and S_{11} of a quasi-elliptic four-pole filter measured at 300 K. The center frequency is 10.76 GHz, the bandwidth is 24 MHz. The insertion loss in the passband center is 0.9 dB.

cylindrical resonator geometry as shown in Fig. 1 (b) to build the Ku-band filter, where the tuning and coupling can be introduced both from the top and bottom endplates. Since the loss tangent of most dielectrics is proportional to frequency in the GHz range, i.e., $Q \cdot f$ is constant, the dielectric loss also becomes high in the Ku-band frequencies. We have chosen sapphire as the dielectric material to build our Ku-band filter, as sapphire has a very low loss tangent [10] and a relatively low permittivity. At room temperature, the permittivity of sapphire is 11.6 along the c-axis and 9.4 in the a-b plane [10].

Using two sapphire cylindrical resonators, we designed and built a four-pole filter as shown in Fig. 6. The filter housing was made of OFHC copper. The measured values of $Q_{0,exp}$ were 30,000 at T = 300 K and 63,000 at T = 77 K. Figure 7 shows the S parameters of the Ku-band filter measured at room temperature. The center frequency was 10.76 MHz and the bandwidth was about 24 MHz. The return loss in the passband was more than 25 dB and the insertion loss in the passband center was about 0.9 dB. The higher adjacent mode was at 11.51 GHz and the lower adjacent mode was at 10.51 GHz. Note that the lower adjacent mode (10.51 GHz) was too close to the passband. The couplings between the lower adjacent mode and the $HEM_{11\delta}$ dual-mode resulted in asymmetric characteristics of S parameters.

The asymmetric characteristics can be minimized by changing the ratio of the height and diameter of the resonator. For example, by increasing the diameter and reducing the height of the resonator, it is possible to shift the lower adjacent mode to a lower value while keeping the center frequency of the filter unchanged. Certainly, the higher adjacent mode will also be shifted at the same time to a lower value. The optimization of this filter is still our ongoing work.

VI. Summary

We have designed and built two dielectric resonator dual-mode filters. One was a four-pole C-band filter and the other was a four-pole Ku-band filter. Both filters showed quasi-elliptic characteristics, where two transmission zeros were present on the transmitted signals outside the passband.

The C-band filter was based on the $HEM_{11\delta}$ dual-mode of hemispherical resonators machined from BMT ceramics, which has a dielectric constant of around 24. The filter housing was made of OFHC cooper. The values of unloaded quality factor were 30,000 at room temperature and 65,000 at T = 77 K. The center frequency of this filter was around 3.72 GHz and the bandwidth was 36 MHz. The measured insertion loss was 0.17 dB at room temperature and 0.08 dB at 77 K. We also estimated the unloaded quality factor of the C-band filter when the top copper endplates was replaced by YBCO superconducting films. In this case the unloaded quality factor was 100,000 at 77 K.

The Ku-band filter was based on the $HEM_{11\delta}$ dual-mode of cylindrical resonators machined from sapphire single crystals. The filter housing was also made of OFHC copper. The unloaded quality factor was 30,000 at room temperature and 63,000 at T = 77 K. The center frequency of this filter was 10.76 GHz and bandwidth was 24 MHz. The measured insertion loss was 0.9 dB at room temperature.

Acknowledgment

This work has been performed in close collaboration with Bosch Telecom in the framework of a project funded by the German Federal Ministry of Education and Research.

References

[1] P. Guillon and Y. Garaut, "Dielectric resonator dual modes filters," *Electronic Lett.*, vol. 16, p. 646, 1980.

[2] S. J. Fiedziusko, "Dual mode dielectric resonator loaded cavity filters," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-30, no. 9, p. 1311, 1982.

[3] S. Schornstein, I. S. Ghosh, and N. Klein, "High-temperature superconductor-shielded high power dielectric dual-mode filter for applications in satellite communications," *Conference Digest of the 1998 MTT Symposium, Baltimore*, pp. 1913-1916, 1998.

[4] Computer Simulation Technology GmbH, Darmstadt, Germany, 1997.

[5] N. Klein, S. Schornstein, I. Ghosh, D. Schemion, M. Winter, and C. Zuccaro, "High-Q dielectric resonator devices at cryogenic temperatures," *IEEE Trans. Appl. Supercond.*, vol. 9, pp. 3573-3576, 1999.

[6] N. Tellmann, Ph.D. thesis, University of Wuppertal, Wuppertal, 1996.

[7] K. Wakino, "Recent development of dielectric resonator materials and filters in Japan," *Ferroelectrics*, vol. 91, pp. 69-86, 1989.

[8] N. Klein, M. Winter, and H. R. Yi, "Cryogenic dielectric resonators for future microwave communication systems," *Supercon. Sci. Technol.*, vol. 13, pp. 527-531, 2000.

[9] C. Zuccaro, Ph.D. Thesis, University of Aachen, 1999.

[10] V.B. Braginski, V.S. Ilchenko, and Kh. S. Bagdassarov, "Experimental observation of fundamental microwave absorption in high quality dielectric crystals," *Phys. Lett. A*, vol. 120, pp. 300-305, 1987.