Ferroelectric $BaTiO_3$ thin-film optical waveguide modulators

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(Received 4 March 2002; accepted for publication 13 June 2002)

High-quality $BaTiO_3$ epitaxial thin films on MgO substrates have been grown by pulsed-laser deposition. Both, c-axis and a-axis $BaTiO_3$ orientations were studied. Mach–Zehnder optical waveguide modulators with a fork angle of 1.7° have been fabricated by ion-beam etching. The waveguides are of the ridge type, the $BaTiO_3$ thickness is 1 μm, the ridge step 50 nm, and the width 2 μm. Light was coupled into the waveguides from optical fibers. The $BaTiO_3$ waveguide propagation losses are 2–3 dB/cm. Electrodes of 3 mm length were deposited besides the waveguides. Electro-optic modulation has been demonstrated with $V_\pi = 6.3$ V at 632 nm wavelength and $V_\pi = 9.5$ V at 1550 nm wavelength for the a-axis samples, and with $V_\pi = 8$ V at 632 nm wavelength and $V_\pi = 15$ V at 1550 nm for the c-axis samples. Theoretical modelling of the Mach–Zehnder modulators for both crystalline orientations of the $BaTiO_3$ films gave the Pockels coefficients $r_{51} = 80$ pm/V for the c-axis film and an effective Pockels coefficient $r_{\mathrm{eff}} = 734$ pm/V for the a-axis films at 632 nm wavelength. © *2002 American Institute of Physics.*
[DOI: 10.1063/1.1498151]

The realization of thin film electro-optical devices is of strong scientific and technological interest. $BaTiO_3$ (BTO) is an attractive candidate for thin film electro-optic switches due to its large electro-optical coefficients,[1] its high optical transparency, and its favorable growth characteristics. Straight channel waveguide phase modulators made from BTO grown by metalorganic chemical vapor phase deposition (MOCVD) have been reported by Gill *et al.*[2] In contrast, we have used a much more rapid process, the pulsed-laser deposition (PLD). High quality single crystalline films of BTO with the c-axis or the a-axis oriented vertical to the surface have been grown on MgO substrates.[3,4] For c-axis films (a-axis in-plane), we used a laser power of 1100 mJ/pulse and a MgO substrate temperature of 800 °C. a-axis films (c-axis in-plane) were formed using a reduced laser power of 300 mJ/pulse and a substrate temperature of 850 °C. The growth rate was around 4 nm/s. Atomic force microscopy (AFM) showed smooth film surfaces of 1.1 nm rms roughness, which is needed for waveguides of low scattering losses. The propagation losses of the planar waveguides are 2 dB/cm for the c-axis films and 3 dB/cm for the a-axis films at 633 nm. Mach–Zehnder waveguide modulators have been patterned using optical lithography and ion-beam etching. The BTO waveguides for these experiments have been patterned "as grown" without additional poling steps. The waveguides are of the ridge type, 2 μm wide, with a ridge step height of 50 nm on a 1-μm-thick BTO film. They allow propagation of a single optical mode both at wavelengths of 633 nm and 1550 nm. A lithographic lift-off process with subsequent deposition of a metal layer of 10 nm Cr and 90 nm Au was used to prepare the electrodes. The length of the electrodes is 3 mm and the distance between adjacent electrodes is 10 μm. The modulator input and output faces have been cleaved.

According to finite element calculations, a ridge of 2 μm width with a height of less than 50 nm on a 1 μm BTO thin-film is a single mode waveguide at a wavelength of 633 nm. The geometry of the Mach–Zehnder modulator and the profile of the waveguides are presented in Fig. 1.

For a c-axis BTO thin-film, the optical axis is perpendicular to the plane of the film. BTO is an uniaxial dielectric crystal. Taking into account the linear electro-optic effect (Pockels effect) produced by an applied electric field along the x-axis and neglecting the elasto-optic effect, the impermeability tensor of the BTO crystal $\eta = \varepsilon_0 \varepsilon^{-1}$ in contracted notation is

$$\eta_{BTO} = \begin{pmatrix} \eta_o & 0 & r_{51}E_x \\ 0 & \eta_o & 0 \\ r_{51}E_x & 0 & \eta_e \end{pmatrix},$$

with $\eta_o = 1/n_o^2$, $\eta_e = 1/n_e^2$, n_o and n_e being the ordinary and the extraordinary refractive index.

We have used the Jones matrix formalism to evaluate the devices. The impermeability tensor may be diagonalized[5] by a rotation of φ around the y-axis

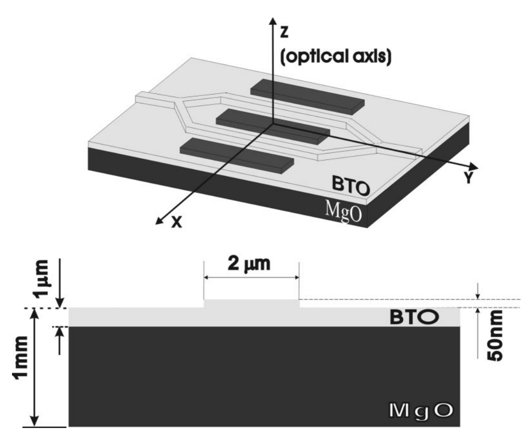

FIG. 1. Geometry of a c-axis type modulator and cross section of a strip waveguide. The spacing between adjacent electrodes is 10 μm, their length is 3 mm. For the a-axis modulators the z-axis (optical axis) is included in the sample plane and the y-axis is perpendicular to the plane.

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$$\varphi=\arctan\left\{\frac{1}{2r_{51}E_x}\left[\frac{1}{n_e^2}-\frac{1}{n_o^2}-\sqrt{\left(\frac{1}{n_o^2}-\frac{1}{n_e^2}\right)+4r_{51}^2E_x^2}\right]\right\}. \tag{1}$$

This leads to

$$\eta'_{\mathrm{BTO}}=\begin{pmatrix}\eta_o+r_{51}E_x\tan\varphi & 0 & 0\\ 0 & \eta_o & 0\\ 0 & 0 & \eta_e-r_{51}E_x\tan\varphi\end{pmatrix}. \tag{2}$$

Using $\Delta n_{ii}\simeq-(n_i^3/2)\,\Delta n_{ii}$ with $i=1,2,3$ we obtain the new refractive indices in the presence of the electric field:

$$n'_x=n_o-\frac{n_o^3}{2}r_{51}E_x\tan\varphi,$$
$$n'_y=n_o,\ n'_z=n_e+\frac{n_e^3}{2}r_{51}E_x\tan\varphi. \tag{3}$$

The phase retardation due to the natural and induced birefringence for the first arm of the Mach–Zehnder modulator (the arm under the influence of the external applied electric field) is given by

$$\Gamma_1=\frac{2\pi l}{\lambda}(n'_x-n'_z)=\frac{2\pi l}{\lambda}\left[n_o-n_e-\frac{1}{4}(n_o^3+n_e^3)\times\left(\frac{1}{n_e^2}-\frac{1}{n_o^2}-\sqrt{\left(\frac{1}{n_o^2}-\frac{1}{n_e^2}\right)+4r_{51}^2E_x^2}\right)\right]. \tag{4}$$

For the second arm, the phase retardation is given the natural birefringence of the film:

$$\Gamma_2=\frac{2\pi l}{\lambda}(n'_x-n'_z)=\frac{2\pi l}{\lambda}(n_o-n_e). \tag{5}$$

The Jones vectors after propagation through the modulator arms are given by

$$J_1=R(-\varphi_1)W_0^1R(\varphi_1)J_0\,\tfrac{1}{2}, \tag{6}$$

$$J_2=R(-\varphi_2)W_0^2R(\varphi_2)J_0\,\tfrac{1}{2}, \tag{7}$$

where

$$R(\varphi)=\begin{pmatrix}\cos\varphi & \sin\varphi\\ -\sin\varphi & \cos\varphi\end{pmatrix}$$

is a matrix operator that performs a coordinate transformation,

$$J_0=\begin{pmatrix}\cos\psi\\ \sin\psi\end{pmatrix}$$

is the Jones vector of the incoming light, ($\psi=0$ for transverse electric (TE) polarization on the input),

$$W_0^{1,2}=\begin{pmatrix}e^{-i\Gamma_{1,2}} & 0\\ 0 & e^{i\Gamma_{1,2}}\end{pmatrix}$$

is the Jones matrix for retardation plate, upper indices denoting the first and the second arm of the Mach–Zehnder device, respectively.

After the interference of the two beams, the output Jones vector is

$$J=J_1+J_2=\begin{pmatrix}A_{\mathrm{TE}}\\ A_{\mathrm{TM}}\end{pmatrix}.$$

The output intensity is $I=|A_{\mathrm{TE}}|^2+|A_{\mathrm{TM}}|^2$.

For the a-axis oriented films Mach–Zehnder modulators the electric field is applied in the direction of the optical axis and the impermeability tensor in the presence of the electric field has a diagonal form

$$\eta_{\mathrm{BTO}}=\begin{pmatrix}\eta_o+r_{13}E_z & 0 & 0\\ 0 & \eta_o+r_{13}E_z & 0\\ 0 & 0 & \eta_e+r_{33}E_z\end{pmatrix},$$

r_{13} and r_{33} being the Pockels coefficients and E_z the applied electrical field ($E_x=E_y=0$).

The phase retardation for the arm under the influence of the external applied electric field of the Mach–Zehnder modulator is given by

$$\Gamma_1=\frac{2\pi l}{\lambda}(n_x-n_z)=\frac{2\pi l}{\lambda}\left[(n_o-n_e)+\frac{1}{2}(n_e^3r_{33}-n_o^3r_{13})E_z\right]. \tag{8}$$

For the second arm the phase retardation is

$$\Gamma_2=\frac{2\pi l}{\lambda}(n_x-n_z)=\frac{2\pi l}{\lambda}(n_o-n_e). \tag{9}$$

Therefore, the Jones matrices for retardation plate are

$$W_0^{1,2}=\begin{pmatrix}e^{-i\Gamma_{1,2}} & 0\\ 0 & e^{i\Gamma_{1,2}}\end{pmatrix},$$

upper indices denoting the first or the second arm of the Mach–Zehnder device. $J_1=W_0^1J_{\mathrm{in}}\frac{1}{2}$, $J_2=W_0^2J_{\mathrm{in}}\frac{1}{2}$ are the Jones vectors after propagation of the polarized light through the first or second arm of the modulator. The output Jones vector is

$$J_{\mathrm{out}}=J_1+J_2=\begin{pmatrix}A_1\\ A_2\end{pmatrix},$$

where A_1 and A_2 are complex numbers.

The intensity of the output light is given by

$$I_{\mathrm{out}}=|A_1|^2+|A_2|^2=\left|\frac{1}{2}e^{i\ \pi\ell/\lambda[(n_e-n_o)-\frac{1}{2}r_{\mathrm{eff}}E_z]}+\frac{1}{2}e^{i\ \pi\ell/\lambda(n_e-n_o)}\right|^2, \tag{10}$$

where we have defined an effective Pockels coefficient as $r_{\mathrm{eff}}=n_e^3r_{33}-n_o^3r_{13}$.

The experimental setup for the electro-optic measurements includes a He-Ne laser (633 nm) or a laser diode at 1550 nm that is coupled into a single mode fiber. A fiber polarizer has been used for defining the polarization state of the input light (TE). The light is end-fire coupled into the waveguide. The output of the waveguide is coupled to another single mode fiber, which leads to a silicon detector.

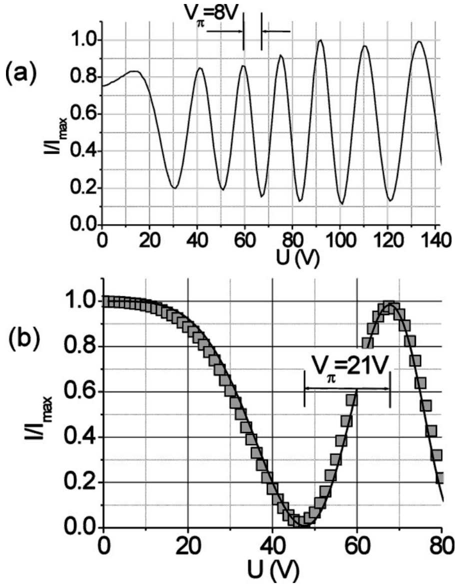

FIG. 2. Intensity modulation of a c-axis film electro-optic thin-film Mach–Zehnder modulator vs applied voltage. (a) At 633 nm. (b) At 1550 nm, the dots are the measured data, the line is given by the theory.

Contact needles, supported by micromanipulators, are used to apply the voltage to the middle and to one outer electrode. The transmitted optical intensity is measured as a function of the applied voltage.

Experimental results for a c-axis modulator at 633 nm wavelength are plotted in Fig. 2(a). A modulation of 90% of the intensity at a half wave voltage of 8 V has been measured.

The r_{51} Pockels coefficient at 633 nm wavelength has been measured to be 86 pm/V. The numerical values $n_o = 2.349$, $n_e = 2.324$ (at 633 nm) of the ordinary and extraordinary refractive indices, respectively, have been determined by a prism coupling setup.

The c-axis Mach–Zehnder modulators have been measured at 1550 nm wavelength as well. The results are shown in Fig. 2(b). The half wave voltage is 21 V if the device operates in the range 46 to 67 V. The half voltage drops to 15 V in the range 67 to 82 V.

We have measured the modulation depth versus frequency at 1550 nm by driving the device with a square wave electrical signal of 21 Vpp (at a bias of 46 V). The result is shown in Fig. 3. The performance is very stable over the entire tested frequency range up to 1 MHz.

Identical experiments have been performed for a-axis BTO modulators (see Fig. 4). The ordinary and the extraordinary refractive indices $n_o = 2.365$, $n_e = 2.353$, respectively, have been measured. A half wave voltage $V_\pi = 6.3$ V has been measured at 633 nm [Fig. 4(a)]. For low modulating fields (up to 1.5×10^6 V/m, U = 15 V) we find $r_{eff} = 536$ pm/V. For electric fields in the range from 2×10^6 to 3×10^6 V/m the value of this coefficient increases to $r_{eff} = 734$ pm/V. For high applied electric fields (3.5×10^6 to 5×10^6 V/m) r_{eff} decreases again. The increase of r_{eff} for medium fields may be explained by some poling of the film due to the applied field. The decrease of r_{eff} for high applied fields is probably due to leakage currents. At 1550 nm a half wave voltage $V_\pi = 9.5$ V has been measured, with 99.1% modulation depth, corresponding to a 20.5 dB extinction ratio [see Fig. 4(b)].

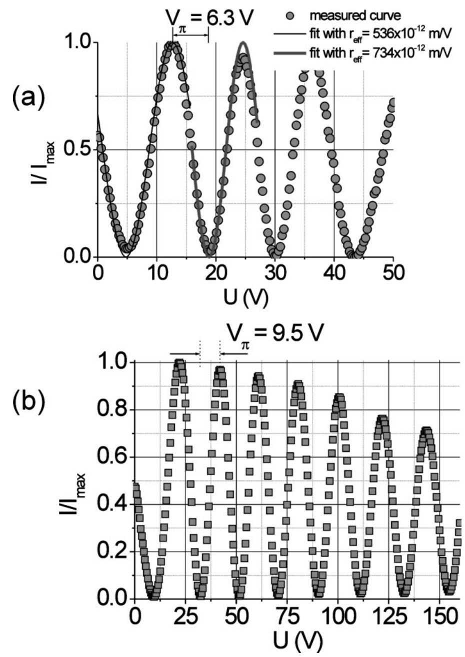

FIG. 4. Performance of Mach–Zehnder modulators made from a-axis films at: (a) 633 nm and (b) 1550 nm.

Both c-axis and a-axis Mach–Zehnder modulators are polarization maintaining devices and operate with TE linear polarized light.

In conclusion, thin-film Mach–Zehnder modulators from ferroelectric $BaTiO_3$ have been demonstrated. The measured electro-optic performance is in good agreement with the theory for both c-axis and a-axis crystals. The low V_π voltage at 1550 nm wavelength and the short electrodes (3 mm) make these $BaTiO_3$ thin-film optical modulators attractive candidates for practical application in optics communications.

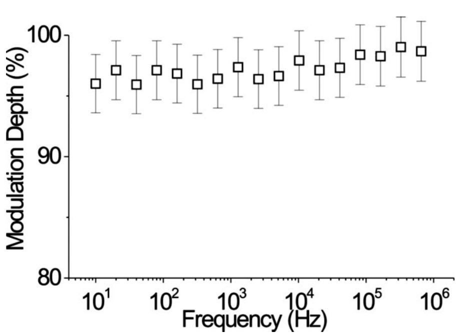

FIG. 3. Modulation vs frequency (21 V_{pp} modulating square signal, 46 V_{dc} bias, 1550 nm light).

This work was supported by the EU (LTR Program No. 31838 ''SCOOP—Silicon Compatible Optoelectronics'') and by the DFG (Deutsche Forschungsgemeinschaft).

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