International Journal of Nanoelectronics and Materials
Volume 14 (Special Issue) December 2021 [349-353]

Analysis of an Electrically Induced Optical Waveguide in a c-axis Barium Titanate Thin Film

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ABSTRACT

In this paper, we report our analysis of an electrically generated optical waveguide in a c-axis barium titanate (BTO) thin film. The waveguide consists of a BTO thin film which is sandwiched between two electrodes. The thin film forms a waveguide when a voltage difference is applied across the electrodes. It is found that the formed waveguide supports both TE and TM modes, with TM modes more tightly confined within the waveguide than TE modes. The possibility to turn the waveguide on and off simply by turning the electric field on and off may prove useful for optical switching.

Keywords: Barium titanate, optical waveguides, electro-optic effect, optical switching

1. INTRODUCTION

Optical waveguides are central to photonic integrated circuits to carry light between components with minimal loss. They can be fabricated into various forms including strip-loaded, ridge, slot, and rib waveguides. Recently, a novel type of optical waveguide which can be turned on on-demand by applying a voltage has been demonstrated [1]. It makes use of the electro-optic effect (EO) of lithium niobate (LN). When a voltage difference is applied across two electrodes sandwiching a LN thin film, a waveguide is formed in the LN film through the EO effect. Such a waveguide may potentially find applications in optical switching.

In this work, we propose and analyze a similar waveguide structure where the LN film is substituted with a barium titanate (BTO) thin film, which is also an EO material. Compared to LN, BTO is more interesting in several ways. Firstly, BTO has larger Pockels coefficients than LN [2]. In fact, it has been reported that even though the Pockels coefficients of a BTO thin film are lower than those of a BTO bulk, but they are five times larger than those of a bulk LN [3]. Secondly, a BTO thin film with high crystal quality can be grown as an epitaxial single crystal on the Si (100) surface [3], [4], something that is not possible with LN.

This paper is organized as follows. In Section 2, a brief theoretical background of BTO is presented to facilitate our subsequent discussions. In Section 3, an analysis of the indicatrix is performed to determine the modes supported by the BTO waveguide. In Section 4, the electric field distributions and the effective refractive indices of the waveguide modes are calculated. This knowledge is important as it provides the basis for potential applications of the proposed waveguide.

2. THEORETICAL BACKGROUND

BTO is a uniaxial crystal with a spontaneous polarization along the crystallographic c-axis. Its ordinary and extraordinary refractive indices are $n_o = 2.444$ and $n_e = 2.383$, respectively [5]. BTO exhibits a linear EO effect, and its electro-optic tensor takes the form:

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$$r_{ij} = \begin{pmatrix} 0 & 0 & r_{13} \\ 0 & 0 & r_{13} \\ 0 & 0 & r_{33} \\ 0 & r_{42} & 0 \\ r_{42} & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}, \tag{1}$$

where $r_{13} = 10.2 \pm 0.6$ pm/V, $r_{33} = 105 \pm 10$ pm/V, and $r_{42} = 1300 \pm 100$ pm/V [6]. In the presence of an external electric field $\vec{E} = E_x\hat{a}_x + E_y\hat{a}_y + E_z\hat{a}_z$, the modifications of the principal refractive indices and crystal axes can be modeled by the following indicatrix:

$$\left(\frac{1}{n_o^2} + r_{13}E_z\right)x^2 + \left(\frac{1}{n_o^2} + r_{13}E_z\right)y^2 + \left(\frac{1}{n_e^2} + r_{33}E_z\right)z^2 + 2r_{51}E_y yz + 2r_{51}E_x zx = 1. \tag{2}$$

A BTO thin film can be grown with either its optical axis being in-plane or out-of-plane with the growth plane [7]. The former is referred to as an a-axis film, while the latter as a c-axis film. In this work, we consider only a waveguide formed in a c-axis BTO film.

3. WAVEGUIDE STRUCTURE

The proposed waveguide structure is shown in Figure 1. It is similar to the structure used in Ref. [1], except that the LN thin film is substituted with a BTO thin film. It consists of a c-axis BTO thin film which is sandwiched between two SiO_2 cladding layers. An electrode of a finite width is placed on top of the upper SiO_2 layer, and another electrode is placed underneath the lower SiO_2 layer. When a voltage difference is applied across the electrodes, an electric field is set up in the BTO film. The resultant electric field is spatially varying, and it is strongest in the region below the top electrode. Through the EO effect, the spatially varying electric field in turn induces a spatially varying change in the refractive index of the BTO film. Resultant refractive index gradient is what provides a spatial confinement for an optical field in the BTO film in the horizontal direction.

At a given potential difference across the electrodes, the electric field distribution in the BTO film produced by the electrodes can be calculated by taking the gradient of the electric potential, which can be calculated by solving Laplace's equation. Figure 2 shows the resultant electric field distribution at a potential difference of 200 V, which is calculated using the finite element method as implemented in the FEMM software. From the figure we can see that the electric field in the BTO thin film is oriented predominantly along the z direction.

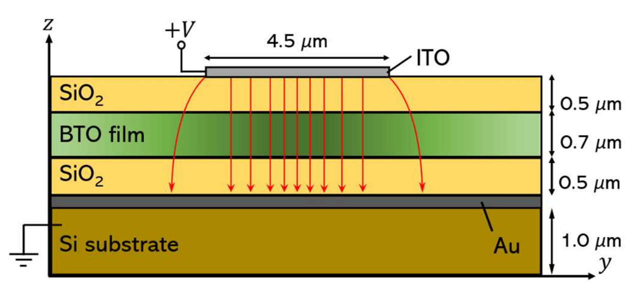

Figure 1. Waveguide structure. The horizontal confinement of an optical field in the BTO film is provided by a gradient in its refractive index which is induced by the applied electric field.

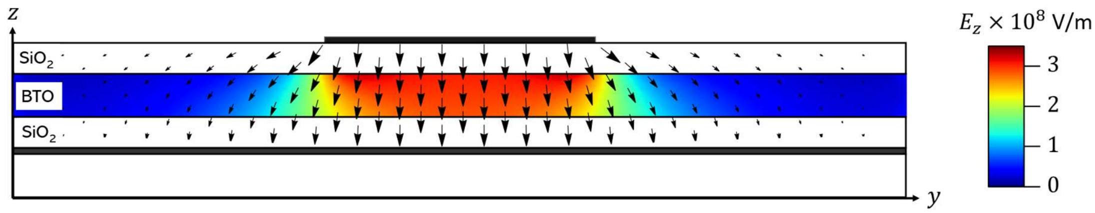

Figure 2. Electric field distribution at a potential difference of 200 V. The density plot represents the spatial distribution of the z-component of the electric field in the BTO film.

Neglecting the y-component of the electric field, the indicatrix reduces from Eq. (2) to

$$\left(\frac{1}{n_o^2}+r_{13}E_z\right)x^2+\left(\frac{1}{n_o^2}+r_{13}E_z\right)y^2+\left(\frac{1}{n_e^2}+r_{33}E_z\right)z^2=1, \tag{3}$$

where the cross terms have now disappeared. Hence, the effect of the electric field is to modify the principal refractive indices without changing the principal axes. Accordingly, the waveguide supports in-plane polarized optical modes (TE modes) and out-of-plane polarized optical modes (TM modes). The modifications of the ordinary and extraordinary refractive indices are given by:

$$\Delta n_o=-\frac{1}{2}n_o^3 r_{13}E_z, \tag{4}$$

and

$$\Delta n_e=-\frac{1}{2}n_e^3 r_{33}E_z, \tag{5}$$

respectively, and they both depend linearly on the z-component of the applied electric field.

4. RESULTS AND DISCUSSION

The spatial distribution of the z-component of the applied electric field, E_z, in the BTO film is shown as a density plot in Figure 2. It is apparent that E_z has a horizontally symmetric gradient profile. It follows from Eq. (3) and Eq. (4) that, under the applied electric field, n_o and n_e should have the same gradient profile as E_z. The former is responsible for guiding TE modes, while the latter is responsible for guiding TM modes.

With the knowledge of the refractive index profile of the whole waveguide structure, the waveguide modes can be calculated by solving Maxwell's equations. Figure 3 shows the electric field distributions of the fundamental TE and TM modes at a wavelength of 532 nm at different applied voltages, which are calculated using the MIT Photonic-Bands (MPB) package [8]. With increasing applied voltage, the fundamental TE and TM modes become more tightly confined in the horizontal direction. At any given applied voltage, the fundamental TM mode has a tighter horizontal confinement than the fundamental TE mode. This observation can be attributed to the larger value of r_{33} (associated with TM modes) compared to that of r_{13} (associated with TE modes). Therefore, TM modes are preferable for the waveguide structure.

Figure 4 shows the calculated effective refractive indices for the fundamental TE and TM modes at different applied voltages. For both modes, the effective refractive index increases linearly with the applied voltage. The TM mode exhibits a stronger dependence of the effective refractive index on the applied voltage. One interesting thing to note here is that, at around

300 V, the effective refractive indices for the two orthogonally polarized modes cross each other. This implies that at that particular voltage, the waveguide becomes nonbirefringent.

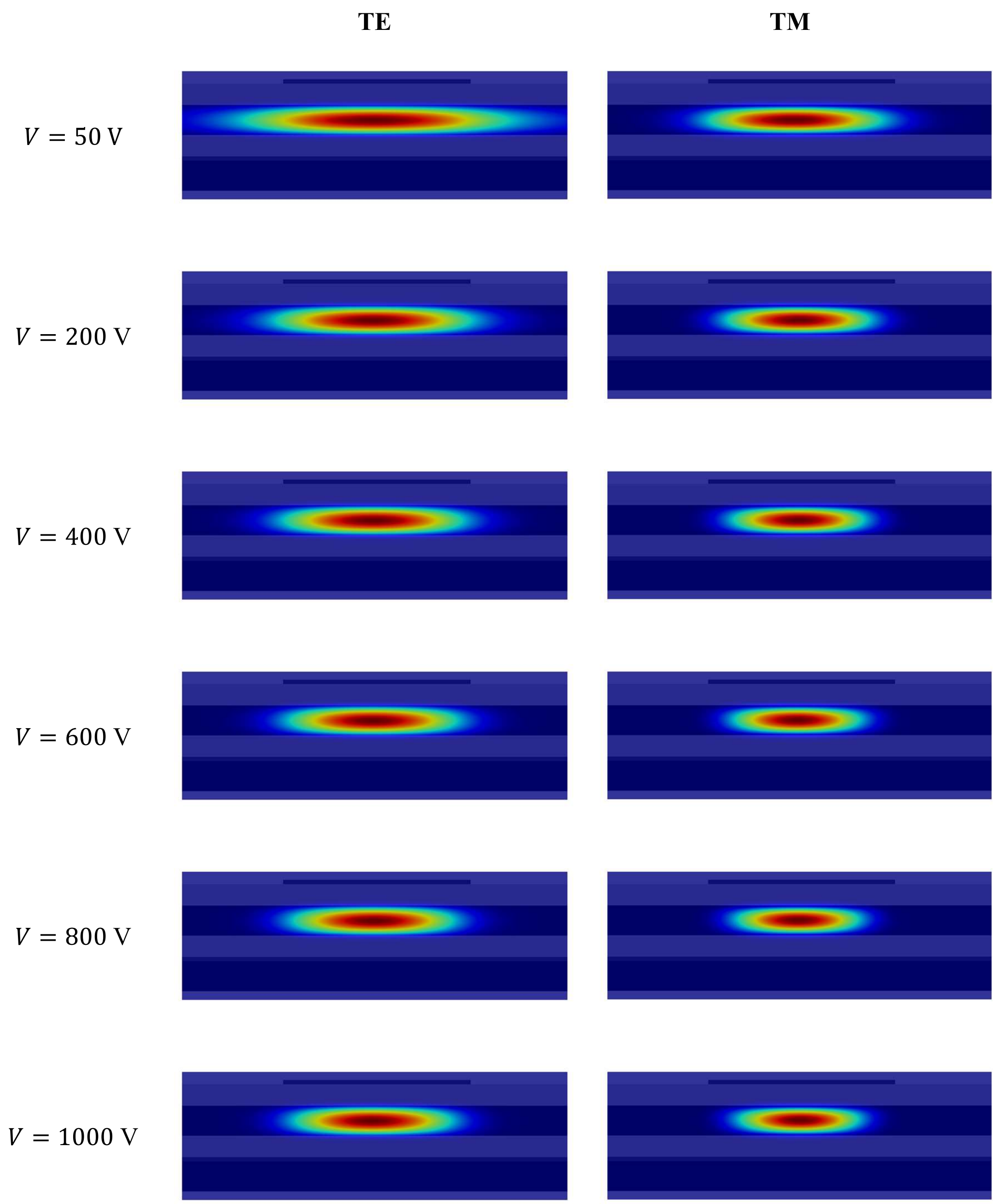

Figure 3. Electric field distributions of the fundamental TE and TM modes at a wavelength of 532 nm at different applied voltages.

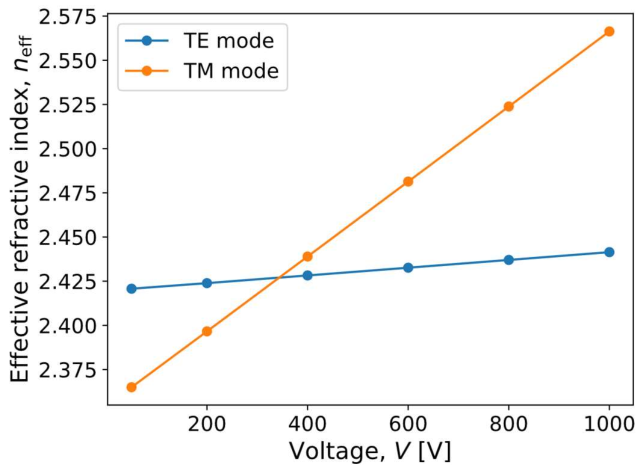

Figure 4. Effective refractive indices for the fundamental TE and TM modes at a wavelength of 532 nm as a function of the applied voltage.

5. CONCLUSION

An analysis of an electrically induced waveguide in a c-axis BTO thin film has been presented. It is revealed that the waveguide supports both TE and TM modes. However, TM modes are more tightly confined within the waveguide than TE modes. This waveguide structure has the advantage that it may be turned on and off simply by turning the voltage across the electrodes on and off, making it potentially useful for optical switching.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the support from the Mentorship Research Grant under a grant number of 9001-00602 from Universiti Malaysia Perlis.

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