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Analysis of Coplanar $LiNbO_3$ Waveguide Structures Applicable to Electrooptic Modulator with FDTD Method

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Abstract

The three-dimensional finite-difference time-domain (FDTD) method and the two-dimensional quasi-static formulation have been used to calculate the characteristic impedance and the microwave effective index of coplanar waveguide structures on Lithium Niobate ($LiNbO_3$) single crystal substrates with a yttria-stabilized zirconia (YSZ) or SiO_2 buffer layer. The results shown can be a good source to predict the modulator characteristics. The effects of the thin buffer layer and anisotropy of the $LiNbO_3$ crystal (x-cut and z-cut) are discussed. The comparison between the FDTD and quasi-static results shows good agreement. In this paper, the efficient modeling technique of the FDTD method for the coplanar waveguide (CPW) structures based on an anisotropic substrate with a thin buffer layer is developed.

Ⅰ. INTRODUCTION

The information revolution has created a huge demand for high-speed communications. Optical communication systems have been studied and developed because of their huge transmission capability. The design of electrooptic (EO) devices as sub-systems is a key process element to optimize the transmission velocity. In particular, the Mach-Zenhder EO modulator has been identified as one of the most interesting devices. The presence of both optical and microwave technologies and a multi-layer, highly anisotropic $LiNbO_3$ substrate creates a complex component. Different numerical analyses involving frequency analyses have been presented to simulate the microwave parameters of the coplanar waveguide (CPW) electrode configuration and to deduce the modulator performances[1],[2]. More recently, FDTD algorithm has been employed for the analysis of CPW on a anisotropic substrate without buffer layer in 2D[3] and 3D[4].

The present paper shows a full-wave FDTD analysis and compares it with the quasi-static Point Matching Method (PMM) analysis. In designing the traveling-wave (TW) electrode, the FDTD algorithm and the PMM were applied to CPW structures. The FDTD method has been successfully used for simulting the performance of a broad class of microwave structures and allows simulation of the dynamics of pulsed spatial solutions[5]. Even though the Method of Moments (MoM) has established itself as a predominant numerical method with its high accuracy, the method has been limited to relatively simple geometries due to the complexity in preprocessing, specifically, deriving geometry specific Green functions. The FDTD, unlike the MoM, has very little preprocessing, and thus, quickly became a very popular numerical tool as computing costs continued to decline. Also, the method has advantages such as simplicity, flexibility, and good accuracy. Since the $LiNbO_3$ substrate has a strong anisotropic nature, FDTD modeling for the anisotropic material

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[6],[7] was taken into consideration. In this paper, the characteristic impedance and the microwave effective index of CPW structures based on an anisotropic substrate with a thin buffer layer are discussed. In particular, as in EO modulator structures, the dielectric buffer employed is usually SiO_2; its effects on the CPW microwave characteristics are clarified.

Ⅱ. FDTD FORMULATION

The FDTD algorithm is formulated by discretizing Maxwell's equations both in time and space[8]. In anisotropic material, the electric flux density is related to the electric field by a permitivity tensor. For this case, due to the strong anisotropy of the $LiNbO_3$ layer, a uniaxial permitivity tensor was employed in the simulation. Maxwell's curl equations in this case are:

$$\nabla \times E = -\mu \frac{\partial H}{\partial t}$$

$$\nabla \times H = \sigma E + \bar{\bar{\varepsilon}} \frac{\partial E}{\partial t} \tag{1}$$

where,

$$\bar{\bar{\varepsilon}} = \begin{bmatrix} \varepsilon_x & 0 & 0 \\ 0 & \varepsilon_y & 0 \\ 0 & 0 & \varepsilon_z \end{bmatrix} \tag{2}$$

The subcell model eliminates the normal restriction that sets the spatial grid increment to be less than or equal to the smallest physical feature in the solution space. Removing this restriction leads to substantial savings in computer storage and execution time. Recently several different methods have been proposed for efficiently modeling electrically thin material sheets in the FDTD method[9],[10]. In this case, the thin material sheets technique is used to model the thin buffer layer. To model the exact location of a thin material sheet within a cell, the thickness of the sheet is weighted by a factor proportional to its distance from the center of the cell.

In the calculation of characteristic impedance Z_0 (ω), geometric averaging can reduce the phase shift error that is caused by the separation between the voltage and current by one-half of a cell and time-step[11]:

$$Z_0(\omega) = \frac{V(\omega)}{\sqrt{I_1(\omega) I_2(\omega)}} \tag{3}$$

The propagation constant β is calculated by finding the ratio of two voltages:

$$\frac{V(\omega, z_2)}{V(\omega, z_1)} \cong \frac{V_0 e^{-(\alpha+j\beta)z_2}}{V_0 e^{-(\alpha+j\beta)z_1}} = e^{-(\alpha+j\beta)(z_2-z_1)} \tag{4}$$

The microwave effective index n_m (ω) can be simply calculated through $\beta(\omega)$.

$$n_m(\omega) = \frac{C_0 \beta(\omega)}{\omega} \tag{5}$$

Ⅲ. PMM FORMULATION

In order to confirm the FDTD code, the PMM code has been developed. The method formulation is presented in [12]. The PMM algorithm allows C, the capacitance per unit length for the structure in Fig. 1,

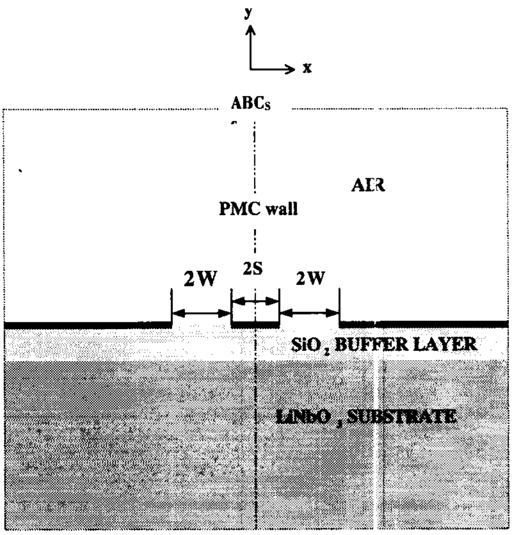


Fig. 1. Geometry of CPW (x-cut : $\varepsilon_y = \varepsilon_z = 43$ and $\varepsilon_x = 28$, y-cut : $\varepsilon_x = \varepsilon_y = 43$ and $\varepsilon_z = 28$, z-cut : $\varepsilon_x = \varepsilon_z = 43$ and $\varepsilon_y = 28$).

and C_0, the capacitance of the same structure embedded in vacuum, to be calculated. The microwave effective index can be expressed as

$$n_m = \sqrt{C/C_0} \tag{6}$$

By the same process, the characteristic impedance Z_o can be defined by the two capacitances:

$$Z_0 = \frac{1}{C_0\sqrt{CC_0}} \tag{7}$$

with c_o the speed of the light in a vacuum. The initial model has been completed by the introduction of a top-plate on the top of the electrodes. Its influence may represent an important parameter during the modulator design process.

Ⅳ. NUMERICAL RESULTS

The cross-sectional view of the analyzed CPW structure is shown in Fig. 1. The characteristic impedance Z_0 and the microwave index nm were calculated by employing the FDTD and PMM. The FDTD results in this paper have been obtained by using the discretization 4 μm in space and 6.67 ns in time. The problem we are considering in this paper has a thin buffer layer at the top portion of the FDTD cell. This buffer layer is immediately under the perfect electric conductor (PEC) which can be modeled only at the cell edge where the electric field components are located. Therefore, the efficient modeling technique is developed by the simple modification with weighting the thickness of the cell by a factor proportional to its distance from the center of the cell. The basic idea of this technique comes from that the closer field gives the stronger contribution. Fig. 2 shows the calculated line microwave parameters of characteristic impedance Z_0 and effective index nm, as a function of the buffer layer thickness. The buffer layer thickness can be one of the parameters for impedance matching with the external 50 Ω circuit. As shown in the Fig. 2, FDTD and PMM agree well. The maximum difference between the two methods is 0.575 Ω on the characteristic impedance and is 0.094 on the microwave effective index in the 0 to 1.5 μm range of buffer thickness. These two graphs are very useful for designing CPW traveling-wave electrodes. Fig. 3 shows the calculated line microwave parameters of the CPW with x-cut, y-cut, and z-cut as a function of frequency. The cut of $LiNbO_3$ has a great influence on modulator performance. The results confirm that for the usual CPW configuration, the line microwave parameters are essentially dispersiveless and in case of the modulator design process can be considered constant. This should be because of the small dimension of the central

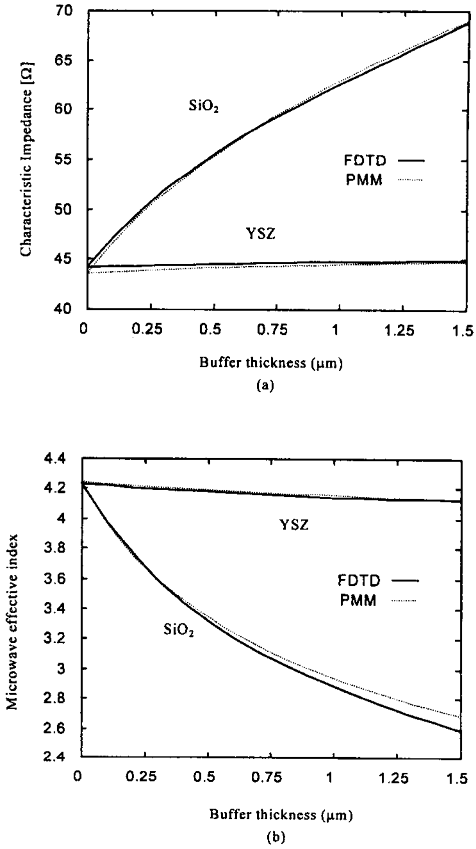
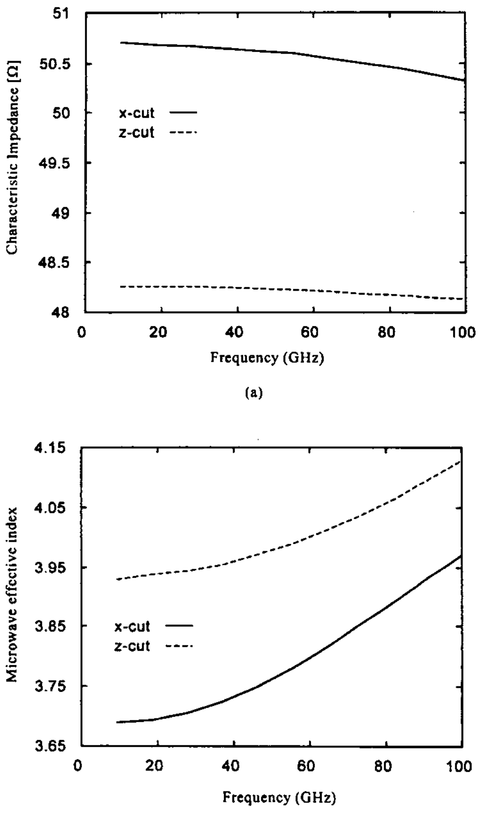


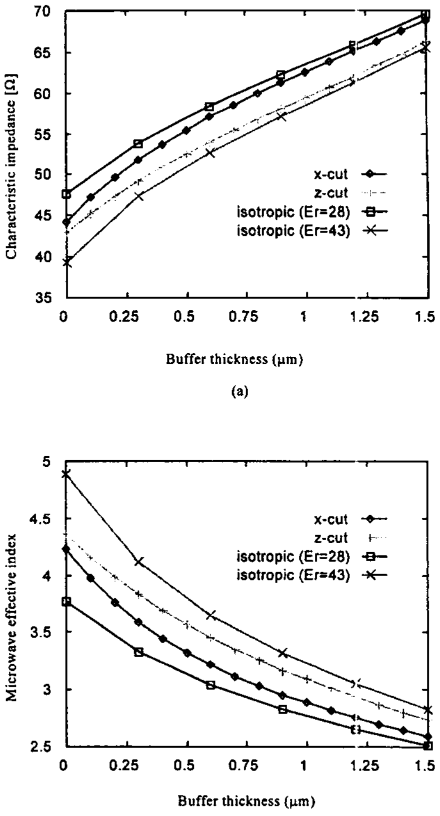
Fig. 2. Dependence of (a) Z_0 and (b) n_m on buffer thickness. Buffer materials are SiO_2 and YSZ on z-cut $LiNbO_3$ (at 17 GHz in FDTD).



(a)

(b)

Fig. 3. (a) Z_0 and (b) n_m of CPW with x-cut, y-cut, and z-cut as a function of frequency. The center conductor and gap widths are 8 μm and 16μm, respectively, with 0.25 μm thick SiO_2 buffer layer (FDTD).



(a)

(b)

Fig. 4. (a) Z_0 and (b) n_m of CPW with x-cut and z-cut $LiNbO_3$ single crystals. The center conductor and gap widths are 8 μm and 16 μm, respectively, with SiO_2 buffer layer (FDTD).

electrode width and separation gap comparing to the operating microwave wavelength. Fig. 4 shows the calculated line microwave parameters of the CPW with x-cut and z-cut $LiNbO_3$ single crystals. As shown in Fig. 3 and Fig. 4, the cut of $LiNbO_3$ and the buffer thickness has a great influence on modular performance. These results may be useful for the impedance matching the CPW electrodes and the external 50Ω circuit. The results show the importance of the anisotropy in modulator design. However, quasi-static analysis seems to be sufficient to compute microwave parameters, it is shown that the cut has also a great influence of these values and is not taking in account in a quasi-static formulation. The EO Mach-Zender modulator performances may be predicted from the evaluation of the microwave parameters from the PMM analysis. In particular, the modulation depth, which characterizes the phase shift obtained as a function of the frequency, *F(f)* is expressed by [1].

$$F(f)=\sqrt{\frac{e^{-2\alpha L}-2e^{-\alpha L}\cos\theta+1}{(\alpha L)^2+\theta^2}} \tag{8}$$

where α is the line attenuation and θ is given as

$$\theta=\frac{2\pi f}{c}(n_m-n_0)L \tag{9}$$

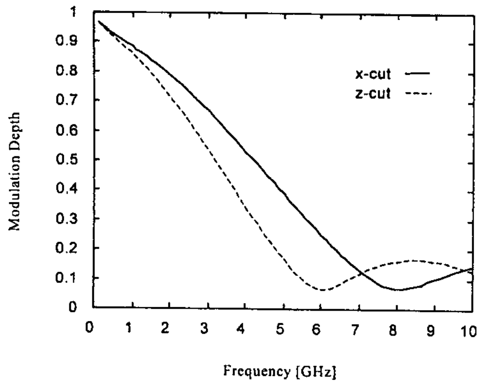


Fig. 5. Modulation depth for different crystal cut (PMM). The center electrode width and the electrode gap separation are 16μm and 22μm, respectively, with electrode thickness $5\ \mu$m and SiO_2 thickness 1μm.

The θ is the walk-off induced by the difference between the optical propagation index (n_o) and the microwave propagation index (n_m). L is the modulator active length. In Fig. 5, the modulator modulation depth is represented for the same electrode structure in the two different cuts. It can be observed for x-cut, the modulation depth obtained is better and the device will be able to operate at a higher frequency.

V. CONCLUSION

In this paper, we have described numerical methods and results for optical modulator from the viewpoint of CPW traveling wave electrode design. The analyses were based on FDTD and PMM with the anisotropic effect in corporate. The characteristic impedance and the microwave effective index are essential in accurately modeling modulator characteristics, such as modulation depth, which was shown.

It has been confirmed that the modulator characteristics can be adjusted to match the external circuit by properly selecting the gap width, line width, the buffer layer thickness, and material. Agreement between FDTD and PMM was quite good. Furthermore, the cut of $LiNbO_3$ has a great influence on modulator performance. It has been observed that for x-cut, the modulation depth obtained is better and the device will be able to operate at a higher frequency.

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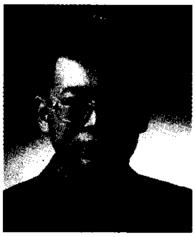

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