THE $LiNbO_3$ ELECTROOPTIC MODULATOR WITH FOUR-PLATE ELECTRODE STRUCTURE

Chetsada Sakhornsaeng Suripon Somkuarnpanit and Suchart Khoonthaweetep

Electronics Department, Faculty of Engineering, King Mongkut's Institute of Technology, Ladkrabang,
Chalong-Krung Rd., Ladkrabang, Bangkok, 10520, Thailand.
Tel. (662) 326 9968 ext. 123,   Fax (662) 739 2398
email: kssuripo@kmitl.ac.th

Abstract

This paper presents the electrooptic modulator with a structure of four-plate-electrode on *z*-cut *y*-propagating $LiNbO_3$ substrate and its transfer characteristics. The device consists of 4 plates of electrodes, which are applied the electric fields in *x* and *z*-axes to form guiding path in the crystal. With the specified dimensions, the electrooptic conversion factors of 49.1deg/V and of 5deg/V are obtained for z-axis and x-axis modulations, respectively. It is obvious that z-axis is chosen to be the preferable direction for the single-signal modulation. Modulation in x-axis seems to raise a problem of crossed modulation from the z-axis. This problem could be solved by signal subtraction arrangement and provide possibility of two-axis electrooptic modulation.

1. Introduction

The demand for wideband optical communication systems has developed in high-speed integrated electrooptic devices in these years. Electro-optic modulators are one of the most important devices used for typical optical communications. There are a number of structures of the high-speed modulators structures have been proposing [1]-[5]. The simplest structure is the one with two-pair electrodes attached to each side of the electrooptic crystal [1]-[2]. However, such modulator found difficulty with its requirement of considerably high voltages applied to vertical electrodes. Another structure in the form of Mach Zehnder interferometers fabricated with titanium in diffused $LiNbO_3$ waveguide are proposed for electrooptic modulators since the advantage of the large electrooptic coefficients of $LiNbO_3$ crystal [3], and simple manufacturing structure. However, there is a possible structure using a coplanar electrode with two or more electrodes on the same face of the $LiNbO_3$ substrate with the waveguide situated in the region between or below the electrodes. The transverse electrooptic modulator is presented in [6]. It is a novel technique in a fabrication of an electrooptic modulator. These techniques can fabrication of electrodes on each face of the $LiNbO_3$ substrate and straddling waveguides. This paper proposes the electrooptic modulator using four electrodes on z-cut y-propagating $LiNbO_3$ substrate. The structure consists of four plates of electrodes, which are applied the electric fields in *x*-axis and *z*-axis in order to change refractive indices in both axes, and to form the guiding medium in the $LiNbO_3$ crystal. Three electrodes are laid parallel on the top of the crystal and left one electrode at the bottom along the crystal to produce the horizontal and vertical electric fields across the crystal. A comprehensive study is presented here in terms of the analysis of the effect of the phase shift and magnitude of optical output against the applied electric fields in *x*-axis and *z*-axis. The numerical computations will be conducted for such effects.

2. Method

In the electromagnetic principles, the wave propagation inside an anisotropic dielectric medium has two distinct properties. Firstly, the phase velocity depends on the polarization of the propagation light relative to the crystal axes. Secondly, the phase velocity direction could be different from the direction of energy flow. The phase velocity can be obtained by constructing an index ellipsoid (or indicatrix) if the crystal does not show optical activity, which can be expressed by [7].

$$\frac{x^2}{n_x^2}+\frac{y^2}{n_y^2}+\frac{z^2}{n_z^2}=1 \tag{1}$$

where n_x, n_y and n_z are the principal refractive indices of coordinate axes of *x*, *y*,and *z* respectively. The changes of the coefficients due to the applied electric field can be expressed by

$$\Delta \left(\frac{1}{n^2}\right)_i = {}_k\, r_{ik} E_i \qquad i = 1, 2,\ldots,6 \text{ and } k = 1, 2, 3 \tag{2}$$

Where E_i is the applied field, and r_{ik} are elements of the linear electrooptic tensor. For the $LiNbO_3$ crystal, its tensor matrix can be written by [8]-[10]

$$[r] = \begin{matrix} 0 & -r_{22} & r_{13} \\ 0 & r_{22} & r_{13} \\ 0 & 0 & r_{33} \\ 0 & r_{51} & 0 \\ r_{51} & 0 & 0 \\ -r_{22} & 0 & 0 \end{matrix} \qquad (3)$$

Then index ellipsoid for $LiNbO_3$ due to the applied Electric field E_x E_y and E_z to the device may be written

$$x^2 \ \frac{1}{n_o^2} - r_{22}E_y + r_{13}E_z \ + y^2 \ \frac{1}{n_o^2} - r_{22}E_y + r_{13}E_z \ + z^2 \ \frac{1}{n_e^2} + r_{13}E_z \ + 2yzr_{51}E_y + 2zxr_{51}E_x - 2xyr_{22}E_x = 1 \qquad (4)$$

where n_o and n_e are the ordinary and extraordinary indices of refraction, respectively. When electric fields in *x*-*z* axes are applied, the directions and magnitudes of the principal axes of the index ellipsoid are determined by its eigenvalues. The principal axes are normal to the surface, the points of intersection (*x, y, z*) with the ellipsoid can be determined by that at such points the radius vector be parallel to the normal, that is,

$$S_{ij}\, x_j = \lambda\, x_i \qquad (5)$$

where λ is a constant independent of *i*. Three homogeneous linear equations in the variables x_i can be extracted from (5) by

$$\begin{aligned} (S_{11} - \lambda)x_1 + S_{12}\,x_2 + S_{13}\,x_3 &= 0 \\ S_{21}x_1 + (S_{22} - \lambda)\,x_2 + S_{23}\,x_3 &= 0 \\ S_{31}x_1 + S_{32}\,x_2 + (S_{33} - \lambda)x_3 &= 0 \end{aligned} \qquad (6)$$

The condition for a nontrivial solution is that determinant of the coefficients vanished by [11]

$$|\, S_{ij} - \lambda\, \delta_{ij} \,| = 0 \qquad (7)$$

This is a cubic equation with λ. For lossless crystals, S_{ij} are real. The three roots, λ', λ'' and λ''', are real numbers. Each of the roots defines a direction in which the radius vector of the quadric is parallel to the normal i.e. the direction of one of the principal axes. The magnitudes of the principal axes of index ellipsoid are

$$|\mathbf{X}| = \frac{1}{\sqrt{\lambda}}, \quad |\mathbf{X}| = \frac{1}{\sqrt{\lambda}}, \quad |\mathbf{X}| = \frac{1}{\sqrt{\lambda}}. \qquad (8)$$

The principal-axis vectors: **X'**, **X"** and **X"'**, are mutually orthogonal. In the Cartesian coordinate system these vectors are parallel to *x'*, *y'*, *z'*, respectively. When electric fields in *x*-*z* axes are applied to the crystal, the equations of index ellipsoid can be written by

$$x^2 \ \frac{1}{n_o^2} + r_{13}E_z \ + y^2 \ \frac{1}{n_o^2} + r_{13}E_z \ + z^2 \ \frac{1}{n_e^2} + r_{33}E_z \ + 2zxr_{51}E_x - 2xyr_{22}E_x = 1 \qquad (9)$$

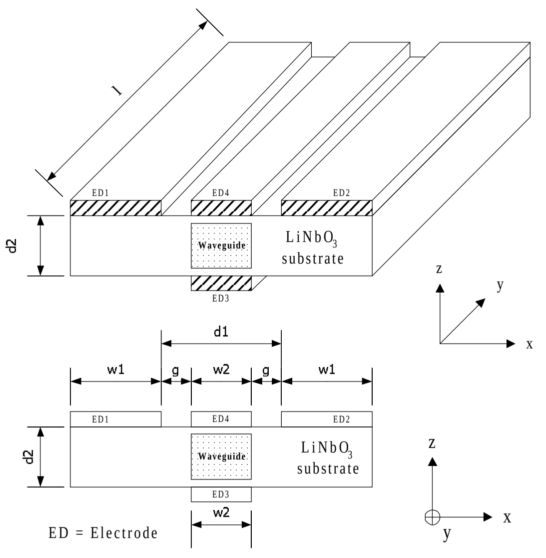


Fig.1. Configuration of the electrooptic modulator using 4-plate electrode structure on *z*-cut $LiNbO_3$

We can determine the index ellipsoid by this method for the numerical computations. The index ellipsoid to get in form of *n'*, *n"* and *n"'*, which cause the shift phase of the optical signals along principal axes.

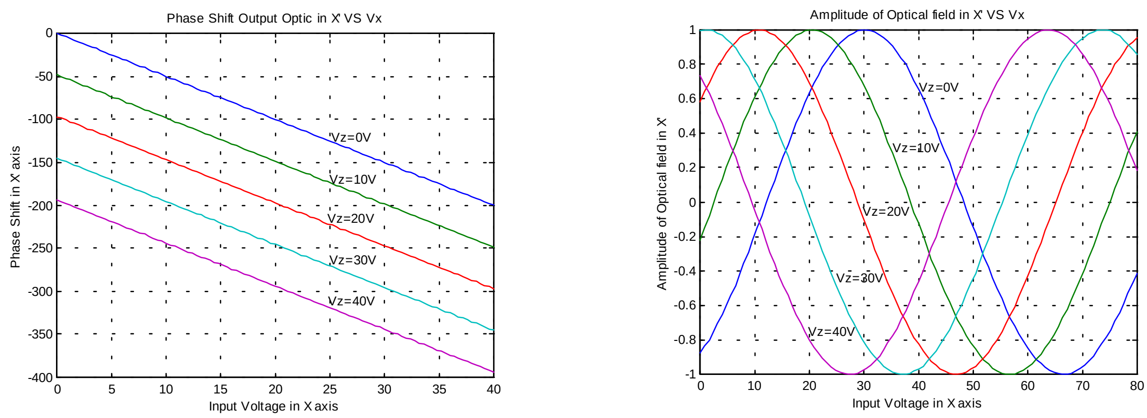
3. Results

The simulation results are based on the structure shown in Fig. 1. The electrooptic modulator consists of 4-plate electrodes structure on z-cut y-propagating $LiNbO_3$ substrate. The parameters: d1, d2 and w1, w2 are the space and thickness between electrodes ED1-ED2, and between electrodes ED3-ED4, respectively. The g is the gap between ED1 and ED4, and between ED2 and ED4. The parameters used in the simulation are concluded in Table 1. The electric field E_x and E_z are defined by the applied signal in *x* and *z* direction and the space d1 and d2, respectively. Fig.2 shows the phase shift and normalized optical intensity developed by the applied voltage in *x*-axis at arbitrary voltages applied in *z*-axis. Fig.3 shows the phase shift and normalized

Table 1 Parameters used in simulations

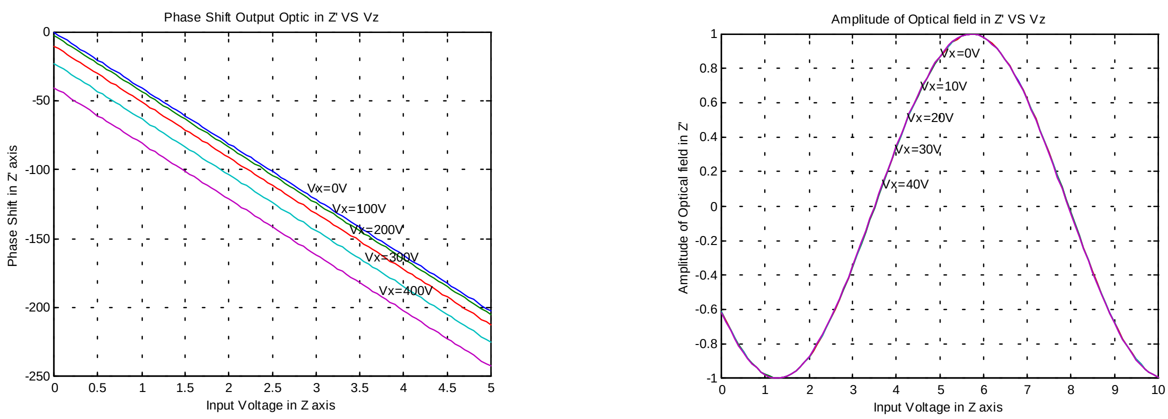
Optical wavelength	1550 nm
Waveguide length	40 mm
W1	23 μm
W2	8 μm
Gap	15 μm
D1	38 μm
D2	0.1 mm

optical intensity induced by the applied voltage in *z*-axis at arbitrary voltages applied in *x*-axis. In Fig.2 the voltage-induced phase shift in *x* direction has the electrooptic conversion factor of 5.0 deg/V, namely *V*π approximately of 36V, with the comparable conversion of 5.0.deg/V interfered from *z*-axis. In Fig.3 the voltage-induced phase shift in *z* direction has the electrooptic conversion factor of 49.1deg/V, namely *V*π approximately of 4.6V, with the comparable conversion of 0.1.deg/V interfered from *x*-axis.



(a) (b)

Fig. 2. The phase shift (a) and normalized optical intensity (b) of output against the voltage in *x* axis with arbitrary voltages in *z*-axis.



(a) (b)

Fig. 3. The phase shift (a) and normalized optical intensity (b) of output against the voltage in *z* axis with arbitrary voltages in *x*-axis.

4. Discussion

The simulation results show that the phase change of the $LiNbO_3$ in *z* direction is relatively sensitive to the electric field than that on the other direction. This indicates *z*-axis has the most strong modulation effect. Therefore, it should be selected for one axis electrooptic modulation. Two-axis modulation is also feasible for the structure by assistance with the process as in Fig.4. The information signal in z direction is easily demodulated from the signal obtained from the modulator. However, in x direction, the demodulated signal contains the information signals of both x and z directions with the approximately same conversion factors. By subtracting the modulated signal in *x* direction with the signal in *z* direction, the information in *x* direction is possible retrieved. So, the structure would be impractical for the QPSK system However, if the offset voltages are provided to both axis, the device could be for digital PSK modulation since it does not require the balance of the modulated signals. This structure is just guidance for the development of device in integrated optics in terms of the signal mixing such as signal modulation, optical sensors, optical switches etc.

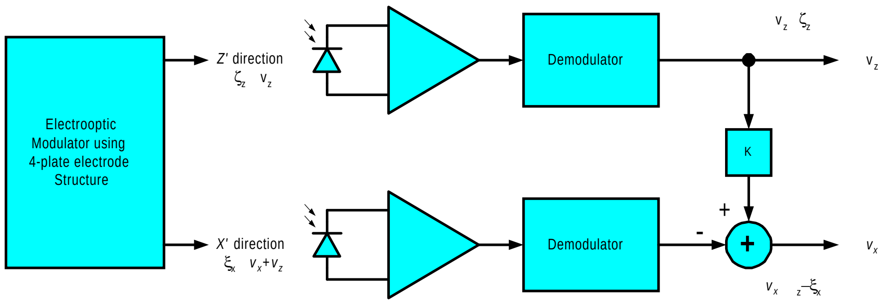


Fig. 4. Two axis signal demodulation by the arrangement of signal subtraction to retrieve the information signal applied in x direction.

5. Conclusions

The electrooptic modulator with four electrodes has been analyzed in terms of the modulation phase change due to the transverse applied voltages. For the *z* cut $LiNbO_3$ substrate modulator, *z*-axis is the appropriate direction for the single signal modulation because of its high electrical to optical conversion – nearly ten times for the quoted dimension. For the two-axis modulation, crossed interfering could be taken place. However, this problem could be overcome by signal subtraction arrangement. So the z-cut $LiNbO_3$ electrooptic modulator with four electrodes could therefore operate either single- or two-axis modulation.

References

[1] James P. Campbell and William H. Steier, *Rotating-Waveplate Optical Frequency Shifting in Lithium Niobate*, IEEE J. Quantum Electronics, vol. QE-7, No.9, pp.450-457, Sep. 1971.

[2] Yoshikazu Ishii, Katsutoshi Tsukamoto, Shozo Komaki, and Norihiko Morinaga, *Coherent Fiber-Optic Microcellular Radio Communication system Using a Novel RF-to-Optic Conversion Scheme*, IEEE Trans. Microwave Theory Tech., vol. 43, No. 9, pp. 2241-2248, Sep. 1995.

[3] Kwok Wah Hui, Kin Seng Chiang, Boyu Wu, and Z. H. Zhang, *Electrode Optimization for High-Speed Traveling-Wave Integrated Optic Modulators*, IEEE J. Lightwave Tech. Vol. 16, No. 2, pp. 232-238, Feb. 1998.

[4] Kazuto Noguchi, Osamu Mitomi, and Hiroshi Miyazawa, *Millimeter-Wave Ti:$LiNbO_3$ Optical Modulators*, IEEE J. Lightwave Tech., vol. 16, No. 4, pp. 615-619, Apr. 1998.

[5] Kazuto Noguchi, Hiroshi Miyazawa, and Osamu Mitomi, *LiNbO3 high-speed modulator*, CLEO Pacific Rim'99, pp. 1267-1268, 1999.

[6] Scott McMeekin, Richard M. De La Rue, and W. Johnstone, *The Transverse Electrooptic Modulator (TEOM): Fabrication, Properties, and Applications in the Assessment of Waveguide Electrooptic Characteristics*, IEEE J. Lightwave Tech., vol. 10, No. 2, pp. 163-168, Feb 1992.

[7] Fahg-Shang Chen, *Modulators for Optical Communications*, Proceeding of the IEEE. Vol. 58, No. 10, pp. 1440-1457, Oct. 1970.

[8] Amnon Yariv, *Optical Electronics in Modern Communications*, New York: Oxford University Press, Inc., 1997.

[9] Ajoy Ghatak and K. Thyagarajan, *Optical Electronics*, Great Britain: University of Cambridge, 1989.

[10] Shun Lien Chuang, *Physics of Optoelectronic Devices*, John Wiley & Sons. Inc., 1995.

[11] J. F. Nye, *Physical Properties of Crystals*, Great Britain: Oxford University Press, 1979.