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Enhancement the Performance of 2×2 MZI Electro Optical Switch based on Lithium Tantalate $LiTaO_3$

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Abstract: This research presents a technique of an electro optic effect and electro-refractive which considered as one of the important techniques in the optical communication systems. In this study, a method is introduced to solve the problem of large length of 2×2 MZI electro-optical switch forlithium tantalate $LiTaO_3$. By using mathematical model for designing MZI electro-optical switch by analyzing the effect of external electrical field on the refractive index with better electro-optical coefficient and refractive index. Finally, in this research, the researchers achieved better performance with low driving electrical field, small size of switch and wide band using near infrared wavelength.

Key words: Lasersource, 2×2 Mach-Zehnder interferomet erelectro-optical switch, electro-optic effect (pockels effect), electro-refractive technique, electro-optic material, analyzing

INTRODUCTION

A simple definition of an electro-optic impact would be the alteration in the material's optical properties as a result of applying an electric field which differs gradually with the frequency of light. The optical properties of the materials are varied when exposed to an electric field. This change happens as a result of the forces that distort the location, predilection or the style of the molecules forming the materials. Subsequently, the electro-optic impact takes place based on the change in the refractive index after applying a dc or low-frequency electric field (Saleh and Teich, 1991) (Fig. 1).

In solid-state and soft strong material physics, there are some materials with good electro-optic effects (Miroshnichenko *et al*., 2017; Liu, 2009; Pozhidaev *et al*., 2013) that motivate the mode of the process of some of the optical devices such as tunable spectral filters, optical switches, polarizing converters and modulators. These materials analyzed physically the pockels effect which happened in nonlinear crystals such as Lithium Niobate ($LiNbO_3$) and applied externally microwave field on the modulator. It has been proven that the electro-optic effect is one of the mainly suitable properties that could be used to achieve fast Q switching.Though, $LiNbO_3$ (LN), $LiTaO_3$ (LT), $KTiOPO_4$ (KTP) and BaB_2O_4 (BBO) are widely used as Pockels cells for laser Q-switching (Abarkan *et al*., 2017; Salvestrini, *et al*., 2003; Volk and Wohlecke, 2008). For fast Q-switching, a driving voltage of 700 V and switching voltage V of 220 with high and low-frequency electro-optic coefficient was used for a comparison between a doping concentration in LN: in crystal materials. Another technique is done by using semiconductor materials for optical switching which relies on the fact that the interplay between photons could be recognized effectively based on nonlinear optical media. As one of the most important properties of the optical materials, the non-linear optical response has evaluated the possible interpretation factors of all-optical switching to an enormous level. According to this approach, electro-optic effect is employed as nonlinear Kerr effect, i.e. (electro-optical and thermo-optical switching) which realizes excitation under external voltage (temperature variation) (Chai *et al*., 2017). Also, a high power electro-optic switch based on interferometer and transparent electro-optic ceramics i.e., lead magnesium niobate-lead titanite PMNT lanthanum modified lead zirconate titanate PLZT and characterize a class of materials have relaxor properties which can easily create polarization and exhibit high-quality electro-optic effects. In addition, a nonlinear electro-optic effect was achieved when applying an electric field to induced changing of

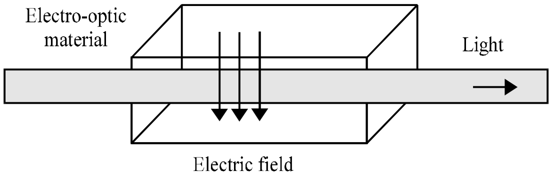

Fig. 1: The refractive index of the material is altered when the material is exposed to an electric field

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Corresponding Author: Haidar N. Al-Anbagi, Department of Communications, College of Engineering, University of Diyala, Baqubah, Iraq, Haider_alanbaky2000@yahoo.com efractive index with a high driving voltage at reach 1200 V (Zhang *et al*., 2016). Another methodology uses current driven phase change optical switch gate whose length of several micrometers with large refractive index. This switch manipulates the phase of the material.While an optical switch based on the effects of thermo-optic or electro-optic could have a length larger than 100 μm (Kato *et al*., 2017). Where current driven phase change optical gate switch employing Indium-Tin-Oxide (ITO) heater and a silicon wave guide and injected 100 nsec current pulse of 20 mA into ITO heater (Stanley *et al*., 2016).

By comparing that with the technique of current driven phase change optical gate switch, the researchers proposed a model to handle the problem of large length of an optical switch based on an electro-optic effect by the applied electrical field on the electrodes of optical-switch based on Lithium Tantalate ($LiTaO_3$). The proposed technique has reflected high performance of electro-optical switch with low driving electric field, small size and wideband.

MATERIALS AND METHODS

The symmetric Mach-Zehnder Interferometer (MZI) switch structure has been chosen to design supple and high-speed switches with low driving voltage requirements for smaller bandwidth operation (Stanley *et al*., 2016; Singh *et al*., 2008, 2012; Maat, 2001; Zheng *et al*., 2011). Because of large electro-optic coefficients, Lithium Tantalate ($LiTaO_3$) is an appropriate selection for MZI structure-based switches. These switches have steady performance factors, yet for inputs having a broad range of optical power levels. Also, optical switches employ metal electrodes above the interferometric arms that produce an index of refraction slope of an optical medium due to the effect of the electrical field. This results into a bending impact on light transmitted during the medium (Stanley *et al*., 2016) that named phase modulation. Therefore, the mach-zehnder interferometer as shown in Fig. 2, modulates wave amplitude, Eq. 1 which is an incident electric wave. The intensity Io is separated into two arms of the interferometer, that is fixed in an electro-optic medium with the lengths of the arm and refractive indices are equal:

$$E = E_0 e^{i(Kx-wt)} \tag{1}$$

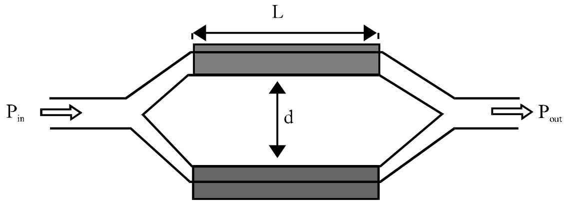

Fig. 2: Mach-Zehnder Interferometer (MZI) based optical switch

Thus, the optical path length down each arm is the same and constructive interference is obtained on the end of arms with recombined of waves, therefore, if electrical field E is applied in the direction of the extraordinary axis of the medium the ordinary refractive index no will change as:

$$n_0(E) \approx n_0 - \frac{1}{2} r_{33} n_0^3 E \tag{2}$$

where, r_{33} is electro optic coefficient of the medium. the phase difference $\Delta\phi$ will result because of effect external voltage on the electrodes of the arms L as:

$$\Delta\varnothing = \frac{\pi L r_{33} n_0^3 E}{\lambda} \tag{3}$$

and intensity is:

$$I = I_0 \cos^2\left(\frac{\Delta\phi}{2}\right) \tag{4}$$

While, the recombined waves are:

$$E = E_0 \cos^2\left(\frac{\Delta\phi}{2}\right) e^{i(Kx-wt)} \tag{5}$$

Also, the switching voltage is:

$$V\pi = \frac{d\lambda}{L r_{33} n_0^3} \tag{6}$$

where, d is distance separation between waveguide arm. Therefore, the MZI optical switch operates as an ON/OFF switch when intensity is maximum and zero intensity for $V = 0$ and $V = V\pi$, respectively.

Electro-optic MZI switch: The electro-optic MZI switch can act as bar state where the light which moves between the input and the output waveguide and back again to the same side of the input. While in cross-state, the light transfers from input to the other side of the output waveguide. An electro-optic 2×2 MZI switch based on the electro-optic effect as shown in Fig. 3 is divided into two interferometric arms with equal length coupled between two 3 dB couplers. The gap between arms is wide enough, so as to avoid evanescent coupling between them. The first coupler is separating the light equally into two branches which pass through the arms to achieve phase change equal to $2\Delta\phi$. The second coupler is used to recombine the two beams on the end of the switch.

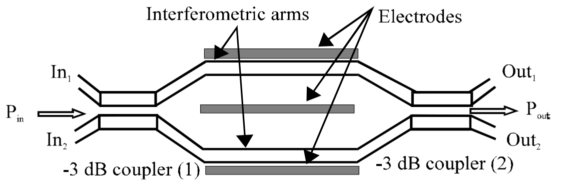

Fig. 3: The 2×2 MZI electro-optical switch based on electro-optic effect (Stanley *et al*., 2016; Papadimitriou *et al*., 2003)

Because of the phase difference, the constructive or destructive interference is induced at the output and that depends on the applied electrical field. Therefore, the following equation explains the interference phenomena as:

$$\frac{P_0}{P_{in}} = \frac{\left[1+\cos(\Delta\varnothing)\right]}{2} \tag{7}$$

This interference due to the output light has a periodic intensity with maxima and minima value appearing at even and odd integer multiples of applied voltage (Stanley *et al*., 2016). By using this technique, a mathematical model was proposed and switching operation demonstrated theoretically. In this study, we proposed Mach-Zehnder electro-optical switch for $LiTaO_3$ based on the electro-optic effect (pockels effect). The distance of separation between waveguide is 0.001 μm and various lengths of electrode reach into 15 μm. The Lithium Tantalate ($LiTaO_3$) was used which recognized with large electro-optic coefficients and large refractive index change for phase change material as shown in Table 1.

Table 1: Wavelengths (λ), electro-optic coefficients (r_{33}) and refractive index (n_o) for $LiTaO_3$

Wavelength (nm)	r_{33} (pm/V)	n_o	References
632.8	30.5±0.3	2.1763	Casson *et al.* (2004)
1558	27.4±0.3	2.1186	Casson *et al.* (2004)

Mathmatical model: Equation 8 illustrates the general equation of an optical switch where the incident light is divided into two parts (I_1 and I_2). Where each one of them has an independent optical path and then added up together in a combiner wherever they interfere with each other. Therefore, the laser diode is used. Thus:

$$\frac{2I_1\text{-}I_2}{I_2} = 2E_1\left[(E_1\text{-}1)+(1\text{-}E_1)\cos\Delta\varnothing\right] \tag{8}$$

Where:

I_1 and I_2 = Intensity of light for the arm one and two, respectively
E_1 = The Electric field of the waveguide

Therefore, if an electric field is applied to the electrodes, an electro-optic switch will be achieved as given in Eq. 9 by Yariv and Pochi (2007) that case:

$$E = \frac{2\Delta_n V_{(\pi)} L}{\lambda d} \tag{9}$$

Where:

Δ_n = Relative refractive index difference (unit less)
V_π = Switching Voltage (V)
L = A Length of the electrodes (μm)
λ = An optical wavelength (nm)
d = A distance of the division between the electrodes (μm)

Hence, substituting Eq. 9, into Eq. 8 will give:

$$\begin{aligned}
\frac{2I_1\text{-}I_2}{I_2} &= 2\left(\frac{2\Delta_n V_\pi L}{\lambda d}\right)\left[\left(\frac{2\Delta_n V_\pi L}{\lambda d}\text{-}1\right)+\left(1\text{-}\frac{2\Delta_n V_\pi L}{\lambda d}\right)\cos\Delta\varnothing\right] \\
\frac{2I_1\text{-}I_2}{I_2} &= \left(\frac{4\Delta_n V_\pi L}{\lambda d}\right)\left[\frac{2\Delta_n V_\pi L\text{-}\lambda d+(\lambda d\text{-}2\Delta_n V_\pi L)\cos\Delta\varnothing}{\lambda d}\right] \\
\frac{2I_1\text{-}I_2}{I_2} &= \left[\frac{8\Delta_n^2 V_\pi^2 L^2\text{-}4\Delta_n V_\pi L\lambda d+(4\Delta_n V_\pi L\lambda d\text{-}8\Delta_n^2 V_\pi^2 L^2)\cos\Delta\varnothing}{\lambda^2 d^2}\right] \\
2I_1\text{-}I_2 &= \frac{I_2\left(8\Delta_n^2 V_\pi^2 L^2\text{-}4\Delta_n V_\pi L\lambda d+(4\Delta_n V_\pi L\lambda d\text{-}8\Delta_n^2 V_\pi^2 L^2)\cos\Delta\varnothing\right)}{\lambda^2 d^2} \\
2I_1 &= \frac{I_2\left(8\Delta_n^2 V_\pi^2 L^2\text{-}4\Delta_n V_\pi L\lambda d+(4\Delta_n V_\pi L\lambda d\text{-}8\Delta_n^2 V_\pi^2 L^2)\cos\Delta\varnothing\right)}{\lambda^2 d^2}+I_2 \\
I_1 &= \frac{I_2\left[\lambda^2 d^2+8\Delta_n^2 V_\pi^2 L^2\text{-}4\Delta_n V_\pi L\lambda d+(4\Delta_n V_\pi L\lambda d\text{-}8\Delta_n^2 V_\pi^2 L^2)\cos\Delta\varnothing\right]}{2\lambda^2 d^2}
\end{aligned} \tag{10}$$

$$\because \Delta\varnothing = \frac{\pi L}{\lambda} n_o^3 r_{33} \frac{V}{d} \tag{11}$$

Adding Eq. 11 into Eq. 10, it becomes:

$$I_1 = \frac{I_2\left[\lambda^2 d^2 + 8\Delta_n^2 V_\pi^2 L^2 - 4\Delta_n V_\pi L\lambda d + \left(4\Delta_n V_\pi L\lambda d - 8\Delta_n^2 V_\pi^2 L^2\right)\cos\left(\frac{\pi L}{\lambda} n_o^3 r_{33} \frac{V}{d}\right)\right]}{2\lambda^2 d^2} \tag{12}$$

From Eq. 12-14:

$$n_0 = \sqrt[3]{\frac{\lambda d \cos^{-1}\left(\frac{2I_1\lambda^2 d^2}{I_2\left[\lambda^2 d^2 + 8\Delta_n^2 V_\pi^2 L^2 - 4\Delta_n V_\pi L\lambda d + 4\Delta_n V_\pi L\lambda d - 8\Delta_n^2 V_\pi^2 L^2\right]}\right)}{\pi L r_{33} V}} \tag{13}$$

$$r_{33} = \frac{\lambda d \cos^{-1}\left(\frac{2I_1\lambda^2 d^2}{I_2\left[\lambda^2 d^2 + 8\Delta_n^2 V_\pi^2 L^2 - 4\Delta_n V_\pi L\lambda d + 4\Delta_n V_\pi L\lambda d - 8\Delta_n^2 V_\pi^2 L^2\right]}\right)}{\pi L n_0^3 V} \tag{14}$$

where, V, n_o and r are DC bias voltage, refractive indexand electro-optic coefficient, respectively.

RESULTS AND DISCUSSION

According to the proposed technique, the system utilizes a scientific model by Eq. 13 and 14 based on the fact that the refractive index is changing with respect to the applied electrical field. In this model, we used applying a voltage of 30 V/μm. This applied voltage results in lower driving electrical field for this system with a small length of electrodes which is less than or equal to 15 μm. This is considered a good performance especially for 3 μm as shown in Fig. 4 and 5. When using a different electrical field as E = 60 V/μm with a length of the electrode is 3 μm, it can achieve a better refractive index as shown in Fig. 5. Therefore, we have come up with small size of MZI electro-optical switch. As shown in Fig. 6 and 7, the proposed methodology accomplishes better

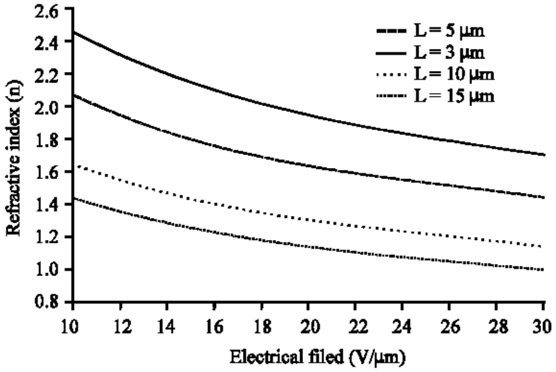

Fig. 4: Applying electrical field with different lengths of electrode

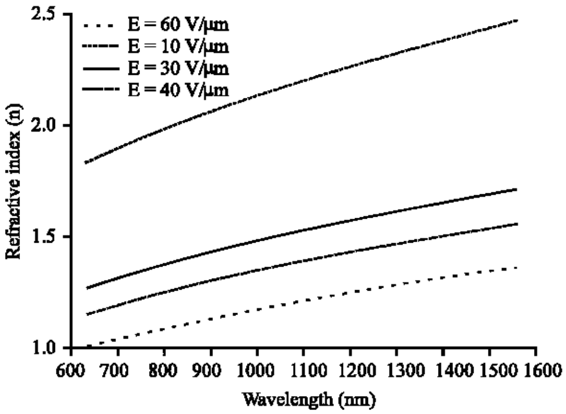

Fig. 5: Various electrical field with changing refractive indices

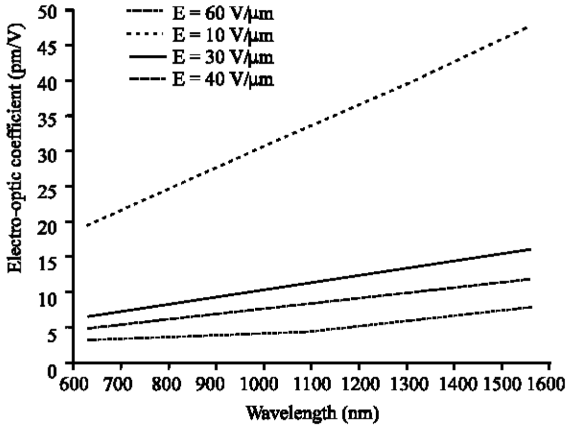

Fig. 6: Electro-optical coefficient as a function of wavelength with variou selectrical field

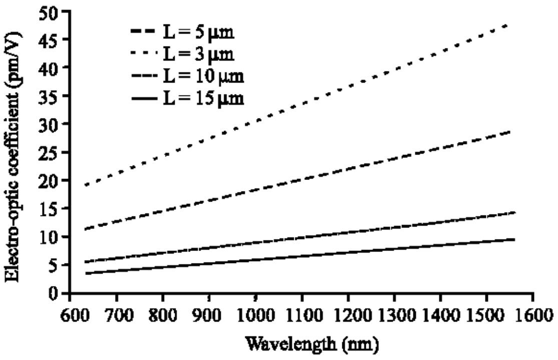

Fig. 7: Electro-optical coefficient as a function of wavelength with various lengths

electro-optic coefficient when the length of the electrode is 3 μm with the applied electric field of 10 V/μm. Finally, in this system, high performance with wideband is achieved by using near-infrared wavelengths.

CONCLUSION

In this study, an electro-optic switch for $LiTaO_3$ based on the electro-optic effect, i.e. (pockels effect) and electro-refractive technique (Eq. 13 and 14) is proposed by using a mathematical model with better performance, low power consumption, small size and wideband. According to this proposed method, a small length of switch electrodes (about 3 μm) is used with low power (between 10 and 30 V/μm) where the driving voltage is very low. Based on the simulation results, good electro-optic coefficient up to 50 pm/V is achieved in addition to a refractive index of 2.5 using a wide band of near-infrared wavelengths (632.8-1558 nm).

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