2×2 electro-optic switch based on MZI at 1.55 μm: design and performance evaluation

HUDA S. ABO ELNASR, MOUSTAFA H. ALY[#,*]
Electronics and Communication Engineering Department, Faculty of Engineering, Pharos University, Alexandria, Egypt
[#] *Member of OSA*

This paper introduces a 2×2 opto-electronic switch based on Mach-Zehnder interferometer (MZI) with a channel profile of Titanium (Ti) diffused in potassium niobate ($KNbO_3$) at a wavelength of 1.55 µm. The insertion loss and the extinction ratio are the evaluation parameters. The $KNbO_3$ crystal as a host while optimizing the Ti strip thickness to provide a remarkable switching performance. The designed switch has a high switching capability. Optimization leads to a lower switching voltage of 4 V, an insertion loss of 0.044 dB and an extinction ratio of 20.9 dB.

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1. Introduction

One of the key elements which have many applications in optical network domain such as wavelength division multiplexing (WDM) are all optical switches. They play a major role to enable routing of optical data signals without even the need to convert them to electrical signals, this mechanism is necessary for fast networks to make use of WDM technology [1]. This results in a reduction in the network equipment with a major decrease in the overall system cost and improves the network speed. In addition, they manage workable layout of optical network by increasing its accuracy, flexibility and scalability efficiently to fit new generation of photonic networks such as optical cross connect (OXC) switching network. OXC is a smart switching network which carries, control and switch light to its target destination throughout integrated switching node [1, 2].

In the effort to extend optics from transmission to switching, all-optical switching fabrics play a central role. Most solutions for all-optical switching are still under study. In recent years, various materials and configurations have been employed for the development of MZI optical switches [3]. In [4], an optimize 2×2 electro-optic switch based on MZI with tapered s-bend interferometric arms at 1.3 μm and 1.55 μm with insertion loss ((≤ 0.5dB) and extinction ratio (≥ 20dB). While in [5], a 2×2 Si waveguide with a ferro-electric liquid crystal cladding based on MZI switch is designed with a 15 dB extinction ratio at 1.55 μm biased at ±30 V. In [6] a 2×2 MZI photonic switch using lead zirconate titanate (PLZT) films which exhibits a low half-wave voltage of 4.8 V with an extinction ratio of 28 dB and insertion loss measured as 2–3 dB at a wavelength of 1.55 µm is investigated. Shaochun Cao et al. [7] an examined a 2×2 optical MZI switch fabricated by GaAs- GaAlAs with a 2 dB insertion loss and 20 dB extinction ratio at 1.55 μm. G. Singh [8] investigated a 2×2 optoelectronic switch based on MZI with a 27 dB crosstalk and switching voltage of 6.75 V for 1.3 μm operation.

In [9], a 4×4 Banyan optical switch using optoelectronic MZI switches with a 22.7dB crosstalk with switching voltage of 6.75 V, at 1.3 μm operation. Ghanshyam Singh [10] introduced a 2×2 MZI switch using Ti: $LiNbO_3$ at 1.55 μm operateing with 8.25 V and crosstalk (≤ 41.73 dB). Finally, in [11], an electro-optic 2×2 switching device using Ti: $LiNbO_3$ at 1.55 μm is designed and optimized to achieve switching voltage of 8 V, insertion loss ≤ 0.0138 dB and extinction ratio of 30 dB.

Lately, the majority of researches and designs have been directed towards materials suitable for integrated electro-optic applications [3, 4, 6, 8-12]. These materials belong to the ferroelectrics class, this class includes the well known Barium Titanate ($BaTiO_3$), Lead Lanthanum Zirconate Titanate (PLZT), Lithium Niobate ($LiNbO_3$), Lithium Tantalate ($LiTaO_3$) as well as Potassium Niobate ($KNbO_3$) [13, 14].

$KNbO_3$ attracted much attention because of its larger electro-optical coefficients and more effective nonlinear-optical characteristics compared to the materials which are used in potential electrical, optical and acoustic applications [14, 15]. This leads to a recent study of designing 2×2 switch, Titanium diffused in this electro-optic material $KNbO_3$ based on an MZI technology which operates at 1.3 µm, low insertion loss of 0.026dB and high extinction ratio of 30 dB had been calculated to validate those claims [16]. It was confirmed that $KNbO_3$ is indeed a promising alternative since it can provide a better switching performance with lower losses for high speed application.

The present work will verify the validity of the aforementioned claim by designing and optimizing a basic, 2×2 Titanium diffused in Potassium Niobate switch which is based on an MZI operating at 1.55 μm is to achieve a remarkable switching performance. In order to evaluate the switching performance at 1.55 μm the following parameters are used: electric field distribution, power in output waveguide, insertion loss and extinction ratio. The optimization process takes place by choosing the optimum thickness, of the titanium strip, required to achieve compactness of design, the lowest insertion loss, lowest switching voltage and highest extinction ratio.

The remainder of the paper is organized as follows: in Sec.2, the model device is presented. The designed switch, along with its parameters and specifications, are presented in Sec.3. Section 4 covers performance evaluation and optimization for the designed 2×2 Ti:$KNbO_3$ switch operating at 1.55 μm. Finally, Sec.5 summarizes and concludes the obtained results.

2. Device model

2.1 Introduction

An optical switch controls and routes an optical signal from N inputs to N outputs of switch in optical domain. Network flexibility is maintained by unlimited flexibility of optical switches, as they are theoretically independent of bit rate and protocols. In addition, size and architectures are most important parameters in enhancing performance of all optical switches [3, 17].

Electro optic coefficient variation of material used in MZI leads light to be switched to target output destination. This terminology is known as converting phase modulation into an intensity modulation, which is commonly used in optical applications [17]. Fig. 1 shows the 2×2 MZI switch with basic structure operating in the two well known switching states; cross & bar. Two inputs and two outputs (In 1, In 2, Out 1, and Out 2) are switched in optical domain within the device. This switch in Fig. 1 consists of two interferometric arms, both are equal in length and they are connected between two 3dB-couplers. These arms are placed far enough from each other to avoid evanescent coupling between them [3, 8, 16].

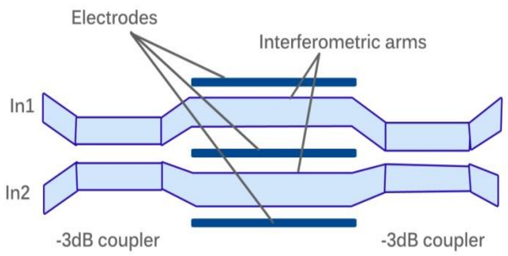

Fig. 1. Conventional MZI switch

The first coupler is used to divide light evenly into two signals. Both experience a net phase change after passing through interferometric arms [2, 3]. This change occurs when voltage applied to the electrodes deposited on the integrated MAI and creates an electric field distribution within the substrate, which consequently changes its refractive index. This causes the light to constructively or destructively interfere at the output depending on the voltage applied [2, 17].

Although there are great numbers of numerical methods can simulate a propagating optical field within a waveguide, beam propagation method (BPM) is chosen due to its increased speed, comparable accuracy and suitability for optimization of devices [17].

The influence of electro-optic refers to changes in the refractive index of material induced by the application of an external electric field, which therefore modulates the optical properties. To evaluate switching performance and investigate the effect of this approach, it is required to define both insertion loss and extinction ratio. The insertion loss (IL) is a part of power that is lost and has to be low for good performance. But, for extinction ratio (ER), it is the ratio of output power in ON state to output power in OFF state which ideally must be very high [8, 12].

$$IL(dB) = 10\log_{10}\left(\frac{P_{out}}{P_{in}}\right) \tag{1}$$

$$ER(dB) = 10\log_{10}\left(\frac{P_{on}}{P_{off}}\right) \tag{2}$$

2.2 Diffusion process

To form a waveguide, a strip of titanium is deposited on the $KNbO_3$ substrate. This process causes existence of extraordinary and ordinary refractive index regions in the crystal substrate. The amount of titanium is characterized by the strip thickness before diffusion. The titanium potassium niobate sample is heated for a few hours at temperatures that range from hundreds to a thousand degrees Celsius [3]. The titanium ions penetrate the host substrate and form a graded index waveguide. The index distribution can be characterized phenomenological by diffusion lengths or, as an alternative, by diffusion constants, diffusion temperature and a diffusion temperature coefficient. This graded refractive index profile can be characterized by [10]

$$n_i(\lambda, x, y) = n_i^{(0)}(\lambda) + \nabla n_i(\lambda, x, y)\; i = o, e \tag{3}$$

where $n_i^{(0)}$ is the bulk crystal index, ∇n_i is the diffusion induced index change, and the subscripts (o) and (e) are ordinary and extraordinary index distributions. In turn, the diffusion induced distribution function is a function of the distribution constant, the dopant concentration profile and the distribution power factor [10, 18].

$$\nabla n_i(\lambda,x,y)=d_i(\lambda)\left[F_i c_o\left\{\begin{matrix} erf\left[\frac{w}{2D_H}\left(1+\frac{2x}{w}\right)\right]+ \\ erf\left[\frac{w}{2D_H}\left(1-\frac{2x}{w}\right)\right]\end{matrix}\right\}\right]^{\gamma_i}.\exp\left(\frac{y^2}{D_v^2(z)}\right). \quad (4)$$

All the definitions of this function can be found in Table 1.

Table 1. Parameters definition

Variable	Meaning	Variable	Meaning
λ	Wavelength 1.55(μm)	D_{OH}	Horizontal diffusion length constant
$D_i(\lambda)$	Dispersion factor	D_{OV}	Vertical diffusion length constant
F_i	Distribution constant	$D_H(z)$	Horizontal diffusion length function
C_o	Concentration profile constant	$D_V(z)$	Vertical diffusion length function
γ_i	Distribution power factor	x	Horizontal distance from the waveguide centre
W	Width of the stripe before diffusion	y	Vertical distance from the top of substrate top
τ	Thickness of the stripe before diffusion	z	Propagation distance

The dopant strip width before diffusion is identified with the waveguide width provided by the layout. The horizontal and vertical diffusion lengths are given by [10]

$$D_H = 2\sqrt{t\,D_{OH}\exp(-T_o/T)} \quad (5)$$

$$D_V = 2\sqrt{t\,D_{OV}\exp(-T_o/T)} \quad (6)$$

Both are functions of the diffusion time t and the diffusion temperature T. The temperature coefficient T_o and the diffusion constants D_{OH} and D_{OV} are specific for Ti: $KNbO_3$ in the following section.

The concentration profile constant C_o is a function of parameters (identified in Table 1) represented by

$$C_o = \tau C_m / \sqrt{\pi_v} D_V \quad (7)$$

The dopant constant

$$C_m = (\rho / M_{at}) N_A \quad (8)$$

is a material parameter determined by the dopant density ρ, atomic weight M_{at} and the Avogadro's number N_A. In the case of titanium dopant, nominal values are ρ= 4.51g.cm^{-3}, M_{at}= 47.9 g.mol^{-1} which gives C_m= 5.67×10^{22} cm^{-3} [10].

The previous equations describe the titanium during the diffusion process which is required to establish a waveguide structure (Ti: $KNbO_3$) required to build the designed basic 2× 2 switch based on MZ.

3. Switch design and parameters

Fig. 2 shows the MZI switch layout, which has been designed with the OptiBPM 9.0 layout designer.

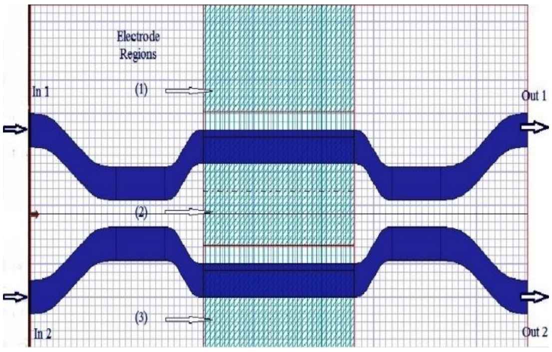

Fig. 2. Design of 2×2 MZI switch.

A z-cut wafer of potassium niobate is created and surrounded by air cladding for designing this switch. Y– optical axis of the potassium niobate is for device orientation. Along z-axis is the crystal cut and y-axis is for propagation for this material. This crystal attracts much attention because of its large electro-optic coefficient, nonlinear optical specification and excellent photorefractive properties [13-15]. Table 2 introduces those coefficients [18].

Table 2. Substrate KNOB3 specifications.

Crystal name	Potassium niobate (KNbO3)		
Electro-optic coefficients 10^{-12} (m/V)			
r33	64	r13	28
r51	270	r12	1.3
Refractive index			
Ordinary no	2.25	Extraordinary ne	2.169

The waveguides of MZI are created by titanium diffusion in potassium niobate substrate. Ti:$KNbO_3$ is the only needed profile for fabrication. Table 3 represents the specifications of Ti strip which are extracted from [3, 10, 11] and are used in the switch design of Fig. 2.

Table 3. Titanium strip secifications.

Strip thickness before diffusion = 0.0725-0.09 μm			
Dopant constant = 5.67e+022 per cm³			
D_V	4 μm	D_H	3.5 μm

Moreover, Table IV introduces the whole dimensions and the design specification for the proposed switch which is to be comparable with other switch designs as in [3, 8-11].

Table 4. Design specifications for proposed MZI switch

Wafer	Width(µm)	Wafer Dimensions(µm)	
Ti: $KNbO_3$	8	Length 33000	Breadth 100
3D wafer properties			
Cladding		Substrate	
Material	Thickness (µm)	Material	Thickness (µm)
Air	2	$KNbO_3$	10

The switch was created using the layout designer provided in the OptiBPM 9.0 which based on the proposed mathematical model with previously mentioned design parameters. The switch's RI profile of the XY slice was checked. The substrate has defined electrode region as shown in Fig. 2. It was defined as follows. On the top of a buffer layer electrodes with thickness 0.3 µm and refractive index of 1.47 are built (electrodes 1 & 3, Fig. 2).

Both horizontal and vertical permittivities are set to 4 and the last electrode is built with a thickness of 4.0 µm. The three electrode regions defined have separate design parameters. The first region has a width of 50 µm and voltage of 0.0 V. The second electrode region has a width of 26 µm and a variable voltage V2. The third electrode region has a width of 50 µm and a voltage of 0.0V.

There is a direct relation between the number of iterations and the switching behavior. This behavior is analyzed initially during both the first (at 0 V) and final iterations until the switch provides the best observable switching operation. After numerous trials, it was determined that the most efficient switching operation takes place at the aforementioned voltage of 4 V. This operation depends on the operating wavelength, material and dimensions (size) of the switch [8, 11].

The input plane parameters have been chose with MODE as the starting field and 0.0 as Z–offset. MODAL refractive index is set for the global data and wavelength is set to be 1.55 µm, after the input plane has been defined.

4. Performance evaluation

The device performance is checked by performing

2D isotropic simulation using the paraxial beam propagation method with a finite difference engine scheme parameter of 0.5, propagation step of 1.55 and transparent boundary conditions [10, 11]. MODAL refractive index is set for global data and TM polarized test signals at wavelengths of 1.55 µm is considered.

The titanium strip thickness has been varied according to the range showed in Table 3 [4]. This is used to determine the amount of titanium diffused in the host and to select the best value in order to achieve the best device switching performance according to both insertion loss and extinction ratio.

After a huge number of trials, remarkable performance (minimum insertion loss and maximum extinction ratio) is observed for the designed switch at 0.0825 µm. The result (switching voltage, In/Out port's power, insertion loss and extinction ratio) will be discussed in details in Figs. 3-7.

Figs. 3 and 4 represent a 2D isotropic optical field distribution for XZ cut of the designed switch at the optimized Ti strip thickness (0.0825µm). In Fig. 3, the MZI switch is represented in its cross state at 0 V which means at first iteration (0 V) the input light at (In1) will be switched totally at (Out 2). While in the last iteration, the switch is forced to go into bar state (light will be observed and cycled totally at Out1) due to an electro-optic effect by applying voltage across the electrodes. For only 4 V, the best observed switching operation is shown in Fig. 4.

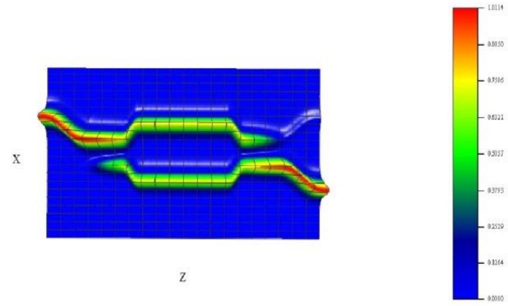

Fig. 3. Optical field propagation in XZ slice for 0 V

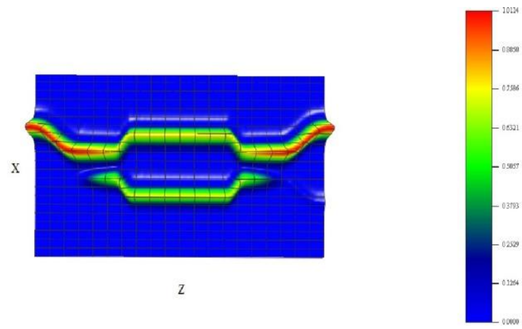

Fig. 4. Optical field propagation in XZ slice for 4 V

Introducing $KNbO_3$ in this design matches expectations stating that $KNbO_3$ with its high electro-optic coefficient and effective nonlinear optical properties [13-15] can enhance the switching performance (by reducing the required switching voltage greatly) with added benefit of reducing switching losses (will be proved through Fig. 7). Fig. 4 shows clearly that the voltage required for a perfect switching behavior is reduced greatly compared to other switches utilizing host materials other than $KNbO_3$ based on same the structure and diffusion process [3, 8, 10, 11].

Figs. 5 and 6 display the electric field for both Out 1 and Out 2 during the first and final iterations, respectively. The ideal switching operation is represented by the red graph, while the blue one represents the operation of the proposed switch. Compared with [3, 8-11] that use $LiNbO_3$ as a host, level of matching between the ideal switching behavior and the actual one is enhanced in our work using $KNbO_3$.

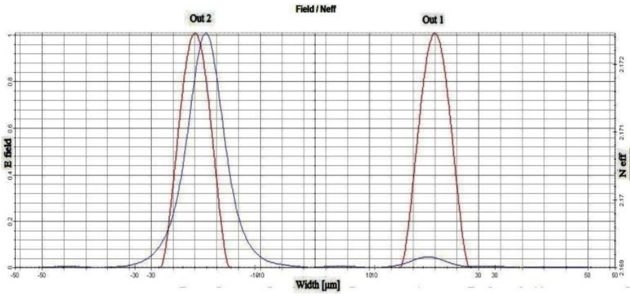

Fig. 5. Electric field at 0 V

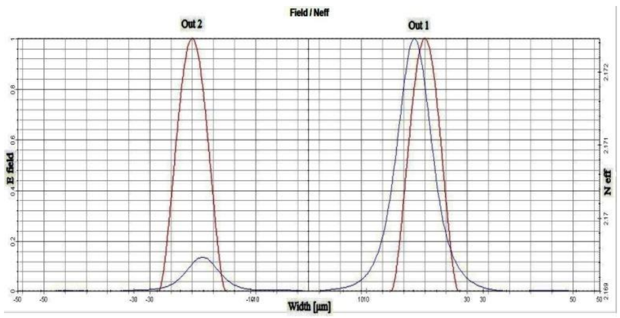

Fig. 6. Electric field at 4 V

An ideal representation for this figure, Fig. 7, should be a unity value for power at Out 2 and a value of 0 at Out1 during the first iteration (when no voltage is applied). While in the final iteration, the whole input light must be fully switched to Out 1 to get a unity power at this port and no power at Out 2 [3,8, 9].

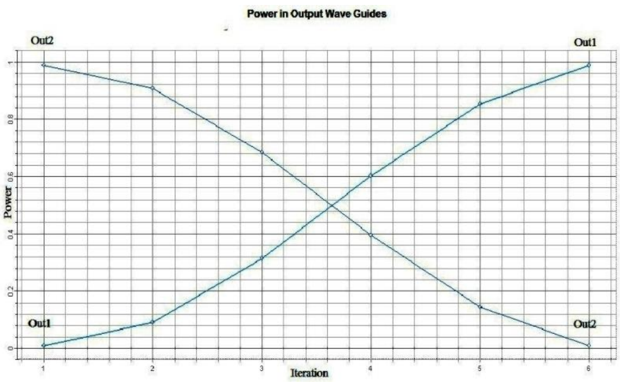

Fig. 7. Power in output waveguide

Fig. 7 shows that the switch provides the best practical switching operation after 6 iterations (4V).

For iteration 1 (0 V), Out 2 provides only a power of 0.990033 mW and a power of 0.00813298 mW is provided by Out1. When light is switched after 6 iterations, the output power at Out1 is 0.990001 mW and 0.00846298 mW at Out2.The previous values can be evaluated using insertion loss and extinction ratio. Eq. 1 results an insertion loss of 0.044 dB for Out 2 and Out 1. Incrementing the titanium strip thickness little by little enhances the concentrated optical power through the channel waveguides, which results in the reduction of insertion losses of the switch. Eventually an optimum thickness is achieved which if exceeded causes the losses to start increasing instead. We think after exceeding the optimum thickness some power radiates resulting on small increase in the insertion losses.

The high extinction ratio of 20.7 dB for Out2 and 20.9 dB for Out1a re-obtained and calculated using Eq. 2. At higher values of Ti strip thickness, extinction ratio can be maintained at comparatively higher levels. We think this is because increasing the thickness of the strip results in more power confinement in the switch waveguide, which results in low coupling losses, thereby reducing the possibility of power leakage to the undesired path and higher extinction values until the optimum strip thickness is reached.

Additional merits for exploring the usage of $KNbO_3$ as a host in the proposed switch can be added now. Previous literatures [3, 10, 11] that share the same structure and diffusion process while utilizing other materials, rather than $KNbO_3$, as a host achieved the best switching voltage of 8 V. Noting that, this work has the best switching performance at 4 V (lower power consumption) for same wavelength of 1.55 µm. In addition, over all previous works, this work adds extra information about performance evaluation (insertion loss of 0.044 dB and extinction ratio of 20.9 dB) for switch operation. These values are considerate promising for the future of optical switch network.

5. Conclusion

This work presents a 2×2 Ti diffused in $KNbO_3$ based on MZI optical switch with a low insertion loss of 0.044 dB for Out2 and Out 1. High on-off extinction ratio beyond 20.9 dB for Out2 and 20.7 dB for Out1 with a low switching voltage of 4 V are achieved. The proposed switch can be used as a building block to form more complex and reliable all optical switches suitable for WDM networks.

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*Corresponding author: drmosaly@gmail.com