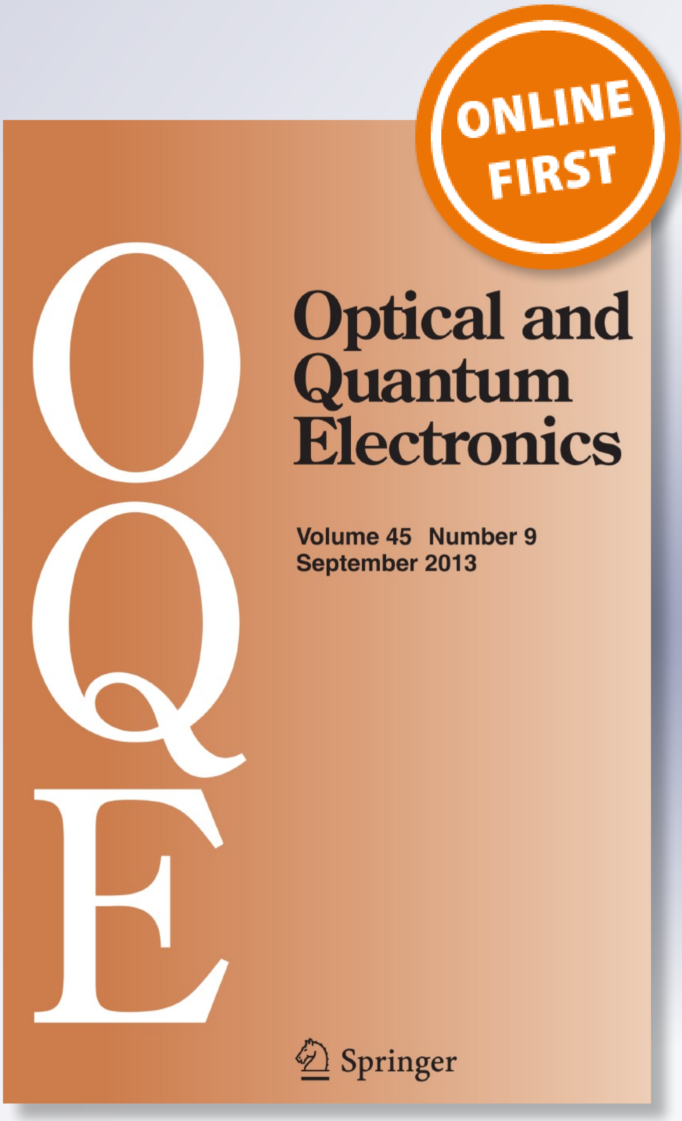
Analysis and design of an electro-optic $ $2\times 2$$ 2×2 switch using Ti: $$\hbox {KNbO}_3$$ KNbO3 as a waveguide based on MZI at $$1.3\,\upmu \hbox {m}$$ 1.3μm

Nazmi A. Mohammed, Huda S. Abo Elnasr & Moustafa H. Aly

Optical and Quantum Electronics

ISSN 0306-8919

Opt Quant Electron
DOI 10.1007/s11082-013-9760-7



Opt Quant Electron
DOI 10.1007/s11082-013-9760-7

Analysis and design of an electro-optic 2 × 2 switch using Ti: $KNbO_3$ as a waveguide based on MZI at 1.3 μm

Nazmi A. Mohammed · Huda S. Abo Elnasr · Moustafa H. Aly

Received: 25 July 2013 / Accepted: 22 August 2013

Abstract This work describes an approach to design a 2 × 2 optoelectronic switch based on the Mach–Zehnder interferometer with a channel profile of Titanium (Ti) diffused in Potassium niobate ($KNbO_3$) at a wavelength of 1.3 μm. The evaluation parameters used are the insertion loss and the extinction ratio. The originality of this work is introducing the $KNbO_3$ crystal as a host while optimizing the Ti strip thickness to provide a remarkable switching performance. Optimization leads to a lower switching voltage of 4 V, an insertion loss of 0.0261 dB and extinction ratio of 29.4 dB. The designed switch has a high switching capability and degree of reliability.

Keywords Mach–Zehnder interferometer · Electro-optics · Potassium niobate · Titanium · Insertion loss · Extinction ratio

1 Introduction

Recently, wavelength division multiplexing (WDM) systems have been widely used. Optical functional devices, such as optical switches and tunable filters, are needed for flexible transmission in WDM systems (O'Mahony 2006). Different electro-optical materials have been studied for use in optical devices suitable for WDM systems. For all optical processing purposes, materials with high nonlinear characteristics suitable for rapid response times of

Moustafa H. Aly is a OSA Member.

N. A. Mohammed · H. S. Abo Elnasr (✉)
Department of Electronics and Communication, Faculty of Engineering,
Arab Academy for Science, Technology and Maritime Transport, Cairo, Egypt
e-mail: eng_huda_samir@yahoo.com

M. H. Aly
Department of Electronics and Communication, Faculty of Engineering,
Arab Academy for Science, Technology and Maritime Transport, Alexandria, Egypt

Published online: 03 September 2013

sub-microseconds and bi-stable characteristics that eliminate a state-sustaining voltage are required for device design (Papadimitriou 2003).

In recent years, various materials and configurations have been employed for the development of MZI optical switches. An optimized 2×2 electro-optic switch based on MZI with tapered s-bend interferometric arms at wavelengths of 1.3 and 1.55 μm with insertion loss (≤ 0.5 dB) and extinction ratio (≥ 20 dB) is achieved (Singh et al. 2011). An extinction ratio of 15 dB at 1.55 μm and ±30 V bias is accomplished in a 2×2 Si waveguide with a ferro-electric liquid crystal cladding (Sasaki 2007). Shaochun Cao et al. 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 (Cao 2010). 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 is investigated (Singh et al. 2008). Beside that a 4×4 Banyan optical switch using optoelectronic MZI switches with a 22.7 dB crosstalk and switching voltage of 6.75 V at 1.3 μm operation (The insertion loss and extinction ratio are not mentioned) is examined (Sachdeva1 2009).

Finally, an electro-optic 2×2 switching device using Ti: $LiNbO_3$ at 1.3 μm is designed and optimized to achieve a switching voltage of 7.2 V, insertion loss (≤ 0.048 dB) and extinction ratio (=30 dB) (Nazmi et al. 2012).

Lately, the majority of researches and designs have been directed towards materials suitable for integrated electro-optic applications (Singh et al. 2008, 2010, 2011; Nazmi et al. 2012; Syuhaimi Ab 2010). Those 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 ($KNbO_3$) which is mentioned in the present study (Sastry 2002; Simoes 2004). $KNbO_3$ 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 (Simoes 2004; Nakamura and Ito 2004).

After undergoing several experiments using different optical materials ($LiNbO_3$, $BaTiO_3$, $LiTaO_3$ and $KNbO_3$, 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. This 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 1.3 μm is to achieve a remarkable switching performance. In order to evaluate the switching performance at 1.3 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 Sect. 2, the model device is presented. The designed switch, along with its parameters and specifications, are presented in Sect. 3. Section 4 covers performance evaluation and optimization for the designed 2×2 Ti: $KNbO_3$ switch operating at 1.3 μm. Finally, Sect. 5 summarizes and concludes this paper.

2 Model device

The diffusion of Ti in $KNbO_3$ creates an increase in extraordinary and ordinary refractive index regions through the crystal substrate. In this process either Ti atoms disperse interstitially in the crystal lattice or Potassium atoms are replaced with dopant atoms. The titanium strip of determined thickness for a given waveguide of specific width is heated for a few hours at a temperature ranging from a few hundreds to a few thousands of Celsius Singh et al. (2010). The Titanium ions penetrate the host substrate and form a graded index waveguide. This graded refractive index profile can be characterized by the following equation (Ghanshyam 2012; Tehranchi 2002)

$$n_i(\lambda, x, y) = n_i^{(0)}(\lambda) + \Delta n_i(\lambda, x, y) \qquad i = o, e \tag{1}$$

where $n_i^{(0)}$ is the bulk crystal index, Δn_i is the diffusion induced index change, and the subscripts o and e are ordinary and extraordinary index distributions. The concentration profile can be derived following the classical diffusion theory expressed in the following equation (Ghanshyam 2012; Tehranchi 2002).

$$c(x, y) = c_o \left\{ erf\left[\frac{w}{2D_H}\left(1 + \frac{2x}{w}\right)\right] + erf\left[\frac{w}{2D_H}\left(1 - \frac{2x}{w}\right)\right]\right\} \exp\left(-\frac{y^2}{D_V^2}\right) \tag{2}$$

The profile's parameters include the profile constant c_o, the dopant strip width before diffusion w, the horizontal (lateral) diffusion length D_H, and the vertical (in depth) diffusion length D_V .

The dopant strip width before diffusion is identified by the waveguide width provided by the layout. The horizontal and vertical diffusion lengths (Ghanshyam 2012; Tehranchi 2002)

$$D_H = 2\sqrt{t D_{OH} \exp(-T_o/T)} \tag{3}$$

$$D_V = 2\sqrt{t D_{OV} \exp(-T_o/T)} \tag{4}$$

are functions of the diffusion time t and the diffusion temperature T. The temperature coefficient T_0 and the diffusion constants D_{OH} and D_{OV} are specified for the Ti:$KNbO_3$ in the following section.

The concentration profile constant is a function of the strip thickness before diffusion τ, the dopant constant C_m, and the vertical diffusion length D_V

$$C_o = \tau C_m / \sqrt{\pi D_v} \tag{5}$$

The dopant constant,

$$C_m = (\rho / M_{at}) N_A \tag{6}$$

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 the Titanium dopant, nominal values are $\rho = 4.51\,\text{g}\,\text{cm}^{-3}$, $M_{at} = 47.9\,\text{g}\,\text{mol}^{-1}$ which gives $C_m = 5.67 \times 10^{22}\text{cm}^{-3}$.

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 MZI.

To evaluate switching performance and investigate the effect of optimizing the titanium strip thickness, it's required to define the insertion loss and extinction ratio. The insertion loss is a part of power that is lost and has to be low for good performance while the extinction ratio is a ratio of output power in the ON state to output power in the OFF state which ideally must be very high (Nazmi et al. 2012; Syuhaimi Ab 2010).

$$I.L\,(dB) = 10 \log_{10}\left(\frac{P_{out}}{P_{in}}\right) \tag{7}$$

$$Ex.R.\,(dB) = 10 \log_{10}\left(\frac{P_{on}}{P_{off}}\right) \tag{8}$$

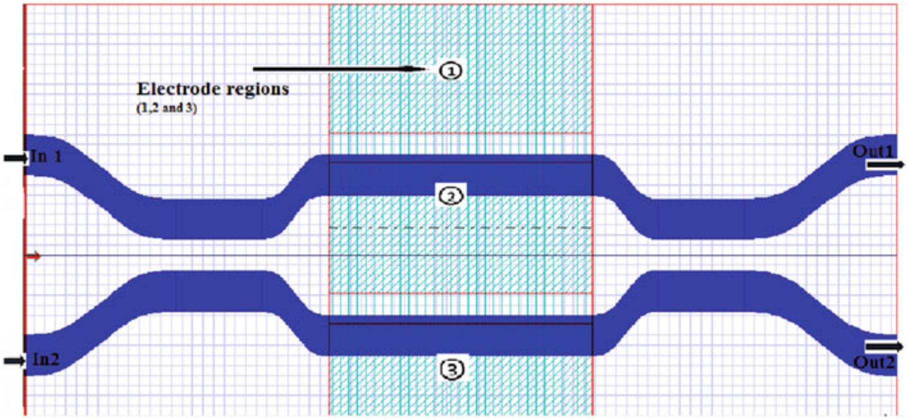


Fig. 1 Design of 2 × 2 MZI switch

Table 1 Substrate ($KNbO_3$) specification

Crystal name		Potassium niobate ($KNbO_3$)	
Electro-optic coefficients 10^{-12}(m/V)			
r_{33}	64	r_{13}	28
r_{51}	270	r_{12}	1.3
Refractive index			
Ordinary n_o	2.25	Extraordinary n_e	2.169

3 Switch design and parameters

Figure 1 shows a schematic diagram of the designed MZI optical switching device having Titanium diffused in Potassium niobate. The device has two input and two output ports (In 1, In 2, Out 1, and Out 2). This conventional electro-optic 2 × 2 MZI-based switch consists of two interferometric arms of equal length which are connected between two 3 dB-couplers. These arms are placed far enough from each other to avoid evanescent coupling between them (Singh et al. 2008, 2010; Nazmi et al. 2012).

The first coupler is used to split light evenly into two beams, which when passed through the interferometric arms experiences a net phase change. This change occurs when voltage applied to the electrodes deposited on the integrated Mach–Zehnder interferometer 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 field (phase) applied (Singh et al. 2008; Katsunari 2006).

In this design, an MZI switch structure (Fig. 1) is created on a z-cut wafer of Potassium niobate and is surrounded by air cladding. The device is oriented along the Y-optical axis of the Potassium niobate. This material has a crystal cut along the z-axis and propagation direction along the y-axis. This crystal attracts much attention nowadays because of its large electro-optic coefficient, nonlinear optical specification and excellent photorefractive properties (Sastry 2002; Simoes 2004; Nakamura and Ito 2004). Table 1 introduces those coefficients (National Physical Laboratory 2008; Cox and Turner 2003).

The waveguides of Mach–Zehnder interferometer are created by diffusion of Titanium in Potassium niobate substrate. Only one diffused profile is needed (Ti:$KNbO_3$). Table 2

Table 2 Titanium strip specifications

Strip thickness before diffusion	0.048 − 0.055 µm
Dopant constant	5.67e + 022 per cm^3
D_V 4 µm	D_H 3.5 µm

Table 3 Design specifications for proposed MZI Switch

Wafer profile	Width(µm)	Wafer dimensions(µm)			
Ti: $KNbO_3$	8	Length	33000	breadth	100
2D wafer properties:					
Wafer refractive index		Potassium niobate ($KNbO_3$)			
3D wafer properties:					
Cladding		*Substrate*			
Material	Thickness (µm)	Material		Thickness (µm)	
Air	2	$KNbO_3$		10	

represents the specifications of Ti strip which are used in the switch design of Fig. 1 (Singh et al. 2011, 2008, 2010). Moreover, Table 3 introduces the whole dimensions and the design specifications for the proposed switch which is to be comparable with other switch designs in previous literature (Singh et al. 2008; Sachdeva1 2009; Nazmi et al. 2012; Ghanshyam 2012).

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 air cladding of 2 µm thickness has been used for the computation purposes and represents an infinite air half-space. The RI profile of the XY slice was checked. An electrode region on the substrate as shown in Fig. 1 was defined as follows. Electrodes on the top of a buffer layer with thickness 0.3 µm and refractive index of 1.47 are built (electrodes 1 and 3 Fig. 1). 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 0.0 V.

There is a direct relation between the number of iterations (as will be seen later in Fig. 6) 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 (Singh et al. 2008, 2010).

The input plane has been selected with MODE as the starting field and 0.0 as the Z-offset. After the input plane has been defined, the global data is set with refractive index MODAL and the wavelength is set to be 1.3 µm.

4 Performance evaluation and optimization of 2 × 2 $KNbO_3$ switch operating at 1.3 µm

The device performance is checked by performing 2D isotropic simulations using the paraxial beam propagation method with a finite difference engine scheme parameter of 0.5, propagation step of 1.3 and transparent boundary conditions (Singh et al. 2008, 2010). The global

Table 4 Switching performance for Ti: $KNbO_3$ switch with different Ti strip thickness

Thickness width (µm)	Switching voltage (V)	In/out (mW)		Insertion loss (dB)	Extinction ratio (dB)
0.048	0	In 1	1	1.24	19.7
		Out 1	0.24163		
		Out 2	0.751635		
	4	In 1	1	0.062	6.1
		Out 1	0.985768		
		Out 2	0.00803756		
0.05	0	In 1	1	0.41	28.9
		Out 1	0.0852814		
		Out 2	0.910178		
	4	In 1	1	0.0261	10.7
		Out 1	0.99400		
		Out 2	0.0011603		
0.0525	0	In 1	1	0.032	29.4
		Out 1	0.0021594		
		Out 2	0.992563		
	4	In 1	1	0.0261	26.6
		Out 1	0.994001		
		Out 2	0.0011301		
0.055	0	In 1	1	0.116	19.3
		Out 1	0.0211115		
		Out 2	0.973539		
	4	In 1	1	0.074	16.7
		Out 1	0.98321		
		Out 2	0.0113679		

data is set with refractive index MODAL, and TM polarized test signals at wavelengths of 1.3 µm is considered.

The titanium strip thickness has been varied to determine the amount of titanium diffused in the host and to select the best value in order to optimize the device switching performance in Table 4.

A remarkable performance (insertion loss and extinction ratio) is observed for the designed switch at 0.0525 µm. This is discussed in details in the following Figs. (2, 3, 4, 5 and 6).

Figures 2 and 3 represent a 2D isotropic optical field distribution for an XZ cut of the designed switch at the optimized Ti strip thickness (0.0525 µm). In Fig. 2, the MZI switch is represented in its cross state at 0 V which means during the first iteration (0 V) the input light at (In1) is switched totally to (Out 2). While in the last iteration, the switch is forced to go into a bar state (light will be observed and cycled totally at Out 1) due to an electro-optic effect caused by applying voltage across the electrodes. For only 4 V, the best observed switching operation is shown in Fig. 3.

Introducing $KNbO_3$in this design matches expectations stating that $KNbO_3$ with its high electro-optic coefficient and effective nonlinear optical properties (Sastry 2002; Simoes 2004; Nakamura and Ito 2004). This can enhance switching performance (by reducing the required switching voltage greatly) with added benefit of reducing switching losses (will be proven

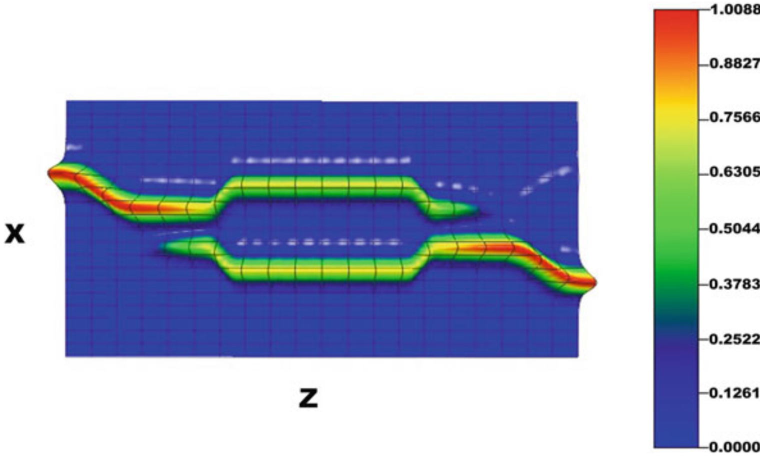


Fig. 2 Optical field propagation in XZ slice for 0 V

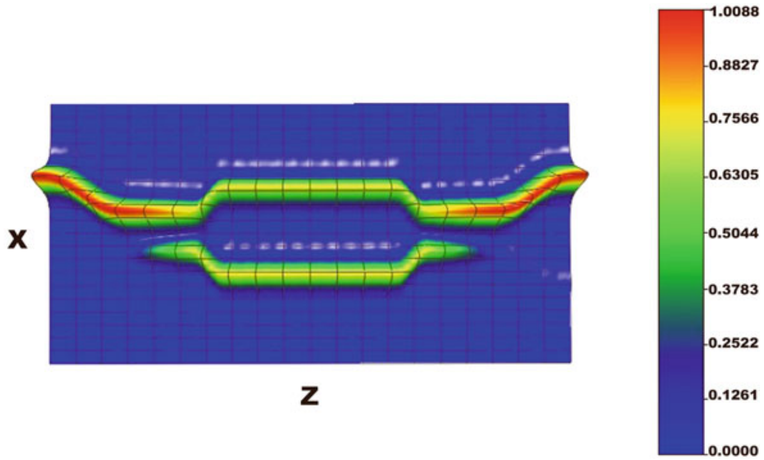


Fig. 3 Optical field propagation in XZ slice for 4 V

through Fig. 6). Figure 3, shows clearly that the voltage required for 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 (Singh et al. 2008, 2010; Sachdeva1 2009; Nazmi et al. 2012).

Figures 4 and 5 represent 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 switches' performance in previous literature that use $LiNbO_3$ as a host, the level of matching between the ideal switching behavior and the actual one is enhanced in this work using $KNbO_3$ (Singh et al. 2008; Sachdeva1 2009).

An ideal representation for this figure (Fig. 6) should be a unity value for power at Out 2 and a value of 0 at Out 1 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 (Singh et al. 2008, 2010; Sachdeva1 2009).

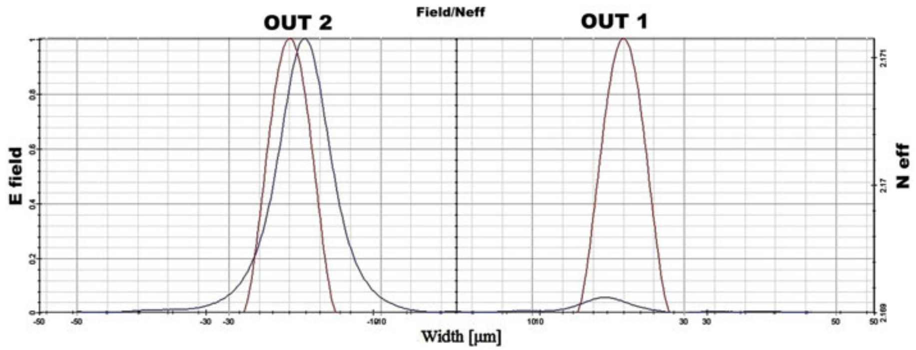


Fig. 4 Electric field at 0 V

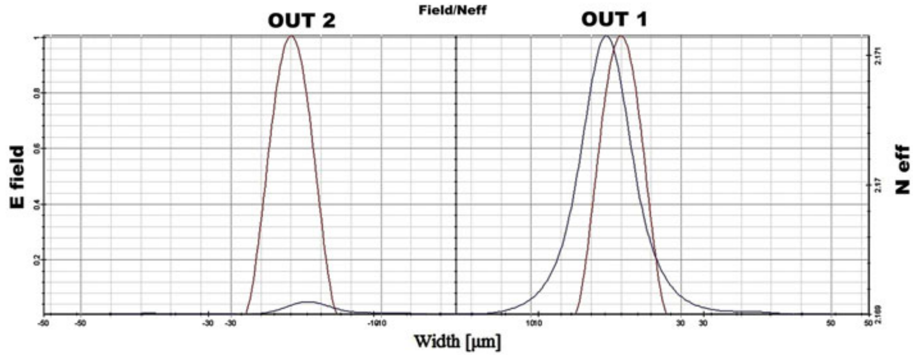


Fig. 5 Electric field at 4 V

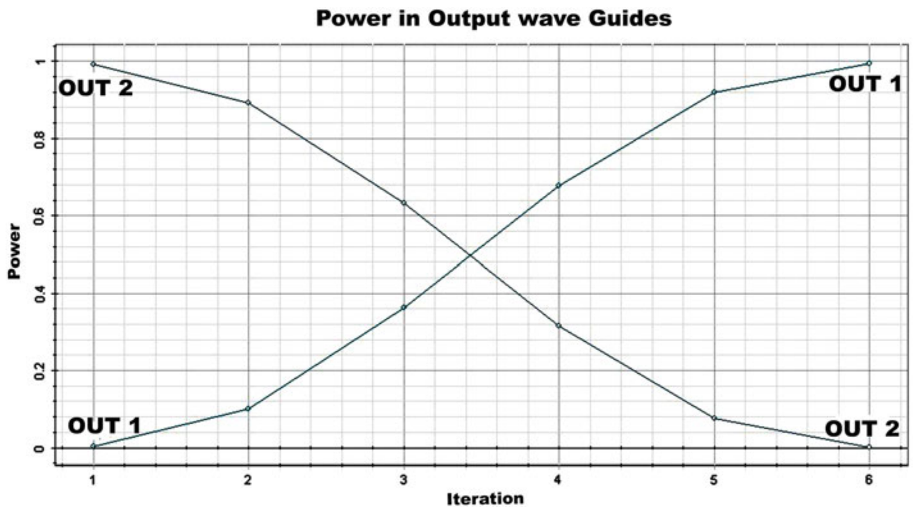


Fig. 6 Power in output Waveguide

Figure 6 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 0.992563 mW and a power of 0.0021594 mW is provided by Out 1. When light is switched after 6 iterations, the output power at Out 1 is 0.994001 mW and 0.0011301 mW at Out 2.

Previous values can be evaluated using the insertion loss and extinction ratio. Equation 7 results an insertion losses of 0.032 dB for Out 2 and 0.0261 dB for 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 as indicated clearly in Table 4. 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 in a small increase in the insertion losses.

The high extinction ratio of 29.4 dB for Out 2 and 26.6 dB for Out 1 are obtained and calculated using Eq. 8. At higher values of Ti strip thickness, the 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 that share the same structure and diffusion process while utilizing other materials, rather than $KNbO_3$, as a host achieved the best insertion losses of 0.048 dB for Out 2 and 0.022 dB for Out 1 for a Ti optimum strip thickness of 0.055 µm (Singh et al. 2008; Sachdeva1 2009; Nazmi et al. 2012). Also in those references, extinction ratios of 30 dB for Out 2 and 22.3 dB for Out 1 are achieved at 1.3 µm.

5 Conclusion

This work presented a 2 × 2 Ti diffused in $KNbO_3$ based on the MZI optical switch with a low insertion loss of 0.032 dB for Out 2 and 0.0261 dB for Out 1. A high on-off extinction ratio beyond 29.4 dB for Out 2 and 26.6 dB for Out 1 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 optical switches suitable for WDM networks.

References

Cao, Shaochun: 2 × 2 MMI–MZI GaAs-GaAlAs carrier-injection optical switch, Proceedings of IEEE Conference on Society Summer Topical Meeting Series, Playa del Carmen, Mexico. pp. 207–208 (2010)

Cox, Charles, Turner, J.S.: Design of a broadband electro-optic modulator with very low V_π. Technical Paper, Photonic Systems, United States (2003)

Ghanshyam, Singh: Modeling of a high performance Mach–Zehnder interferometer all optical switch. J. Opt. Appl. **XLII**, 614–625 (2012)

Katsunari, Okamoto: Fundamentals of Optical Waveguides, 2nd edn. Laboratory ltd ibaraki, Japan (2006)

Nakamura, Kiyoshi., Ito, Shigeo.: KNbO3 Single Crystals and Thin Films for SAW and BAW Devices. Research Paper, University of Tohoku, Japan (2004)

National Physical Laboratory : Electro-optic material. http://www.kayelaby.npl.co.uk/general_physics/2_5/2_5_11.html. Accessed 1 April 2013) (2008)

Nazmi, A., Huda, S., Moustafa, H.: Performance evaluation and enhancement of 2 × 2 Ti:$LiNbO_3$ Mach–Zehnder interferometer switch at 1.3 μm and 1.55 μm. J. Open Electr. Electron. Eng. **6**, 36–49 (2012)

O'Mahony, Michael J.: Future optical networks. IEEE J. Light. Tech. **24**, 4684–4696 (2006)

Papadimitriou, Georgios I.: Optical switching: switch fabrics, techniques, and architectures. IEEE J. Light. Tech. **21**, 384–405 (2003)

Sachdeval, Vandana: Design of 4 × 4 banyan optical switch using optoelectronic MZI switches with low crosstalk. Ind. J. Sci. Tech. **2**, 48–51 (2009)

Sasaki, T.: Demonstration of switching operation in a symmetric Mach–Zehnder interferometer switch using Si waveguide with a ferro-electric liquid crystal cladding. Proceedings of IEEE Conference on Lasers and Electro-Optics, Seoul, pp. 1–2 (2007)

Sastry, P.U.: Linear electro-optical properties of orthorhombic $KNbO_3$. J. Solid State com. **122**, 41–44 (2002)

Simoes, A.Z.: Potassium niobate films prepared through polymeric precursor method. J. Mat. Lett. **58**, 2537–2540 (2004)

Singh, G., Yadav, R.P., Janyani, V.: Ti indiffused lithium niobate (Ti: $LiNbO_3$) Mach-Zehnder interferometer all optical switches: a review. In: Lazinica, A. (eds.) New Advanced Technologies, Jaipur, pp. 312–322 (2010)

Singh, G., Yadav, R.P., Janyani, V.: Design of 2 × 2 optoelectronic switch based on MZI and study the effect of electrode switching voltages. J. World Acad. Sci. Eng. Tech. **39**, 401–407 (2008)

Singh, G., Yadav, R.P., Janyani, V.: Modeling of a 2 × 2 electro-optic Mach–Zehnder interferometer optical switch with s-bend arms. J. Photonic Lett. Pol. **3**, 119–121 (2011)

Syuhaimi Ab, M.: Analytical and Simulation of New Electro-Optic 3 × 3 Switch Using Ti: $LiNbO_3$ As a Wave Guide Medium. Proceedings of IEEE Conference on Photonics, Langkawi, pp. 1–5 (2010)

Tehranchi, A.H.: Optical beam propagation in Ti: $LiNbO_3$ Mach-Zehnder modulator. Proceeding of Laser and Fiber Optical Networks Modeling, Kharkiv, pp. 613–625 (2002)