Modeling of a 2×2 electro-optic Mach–Zehnder Interferometer optical switch with s–bend arms

G. Singh, V. Janyani, R.P. Yadav

Department of Electronics and Communication Engineering
Malaviya National Institute of Technology Jaipur-India

Received July 22, 2011; accepted August 25, 2011; published September 30, 2011

Abstract—In this paper, we present a 2×2 electro-optic switch based on a Mach-Zehnder interferometer (MZI) with tapered (s-bend) interferometric arms. All structures have been designed with a channel profile of titanium indiffused lithium niobate waveguides. The crosstalk analysis of the switch suggests that the crosstalk levels become worse (-12dB) when both interferometric arms of the structure are tapered. We have optimized the structure in order to reduce the overall switch losses (≤ 0.5dB) and to achieve the best possible extinction ratio (≥ 20dB).

Mach-Zehnder structures have been used to design all optical switches in order to use them for high speed optical computers and communication networks [1–4]. All optical switches do not require electrical-optical inter conversion. Lithium niobate (LN) is a uniaxial crystal with two types of crystal orientation widely termed as z-cut and x-cut. Lithium niobate based switches and modulators are compatible with large capacity and long-haul optical transmission systems operating above 40 Gbit/s [5]. Ti indiffused LN waveguides are suitable for switching applications because of their large electro-optic coefficient [6] that results in small transition time. In MZI structures, tapered interferometric arms have been used to compensate the phase error, generated by mismatching of the 3dB-couplers of the structure. Such structures, when connected to each other as interleavers can separate the odd and even wavelengths from a WDM signal consisting of a number of wavelengths and are suitable for designing wavelength selective modulators/switches. In these structures, the periodic response varies with respect to optical path length difference between the interferometric arms. The longer the length differences, the shorter the wavelength response oscillations [7].

This paper elaborates the design and analysis of MZI switches with tapered (s-bend shape) interferometric arms. The s-bends waveguide sections are designed using the adiabatic criterion [8] in order to suppress optical losses due to tapering arms. The performance of the switch is checked for low attenuation optical windows i.e. test wavelengths of 1.3μm and 1.55μm. In electro-optic switches [9], switching is achieved by changes in physical properties of materials due to modulating voltage. The observed phenomenon typically include changes in the index of refraction of materials, which are collectively referred as electro-optic effects. An electrical voltage changes the refractive index of the substrate which in turn manipulates the light through the appropriate waveguide path to the desired port [10]. A conventional 2×2 MZI switch shown in Fig. 1, consists of two interferometric arms of equal length connecting two -3dB couplers. The first coupler splits the input signal in two beams which, when passed through the interferometric arms, experience phase difference caused by voltage variations across electrodes. Finally, both beams with different phases are put together again into a single signal by the second -3dB coupler at the output ports in accordance with constructive or destructive interference [10].

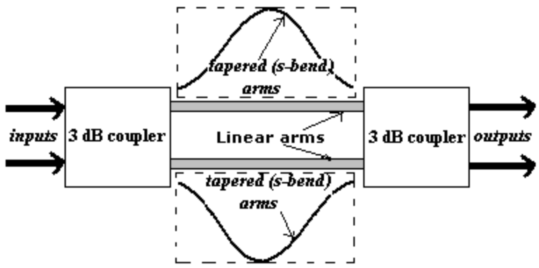


Fig.1. MZI structure with straight and tapered interferometric arms.

In our proposed MZI–switch designs, LN with z-cut orientation is chosen as substrate and y is set as a direction for optical power propagation. To create channel waveguides of Ti–indiffused LN, a titanium (Ti) strip of definite thickness is placed on the substrate and heated for few hours at a temperature ranging from hundreds to few thousand degrees Celsius so that the Titanium diffuses into the host lithium niobate [11]. The resultant change in the refractive index is a function of parameters like Ti-strip thickness, lateral diffusion length (D_H), vertical diffusion length (D_V), and other process parameters. For our designs, the Ti-strip thickness is varied for a definite range, i.e. from 0.048μm–0.062μm for 1.3μm of wavelength and from 0.0725μm–0.09μm for 1.55μm of wavelength and the corresponding insertion loss and extinction ratio are calculated and plotted. The cross-sectional view of the switch is shown in Fig. 2 and important design parameters are summarized in Table 1. Figures 3 and 4 depict the BPM layout of the switch with tapered interferometric arms and their respective optical

 © 2011 Photonics Society of Poland

field propagation under the influence of modulating voltage across the linear electrodes.

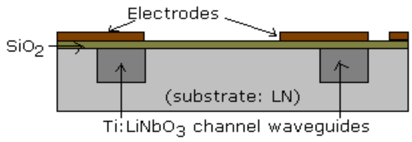
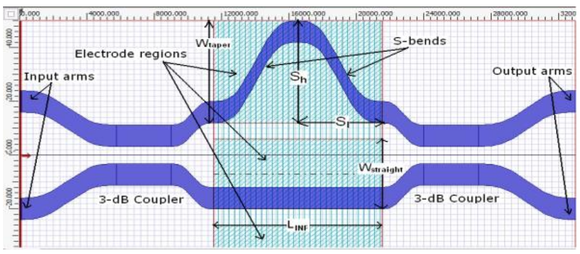


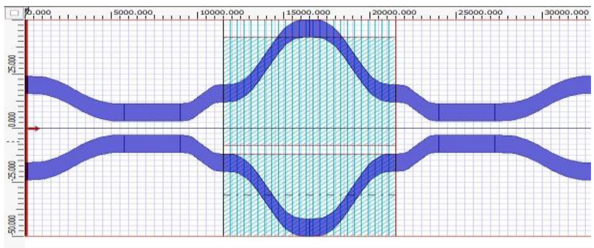
Fig.2. Cross-sectional view (front side) of the proposed switch.

Table 1: Design spec.

Wafer profile	Channel width	Wafer dimensions	
		breadth	length
$LiNbO_3$	8 µm	100 µm	33000 µm
EO–coefficients (10^{-12}m/V): r_{33}= 30.8, r_{13} = 8.6, r_{51} = 28, r_{22} = 3.5			
Path length of the interferometric arms (L_{INF}) = 10 mm			
Diffused profile: z-cut Ti:$LiNbO_3$			
S-bend dimension	S_l = 5 mm, S_h = 38 µm		
Dimension of electrode regions	L_{INF} = 10 mm, W_{taper} = 38 µm, $W_{straight}$ = 26 µm		

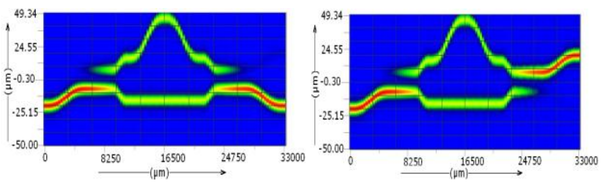


(a)

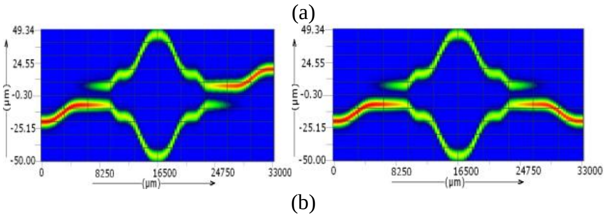


(b)

Fig.3. Switch layouts while tapering (a) one arm (b) both arms of the interferometric section.



(a)

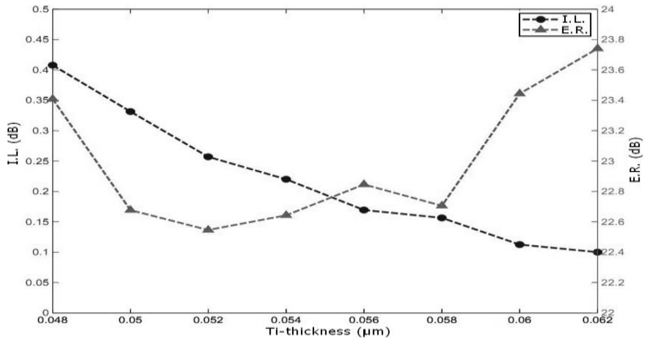


(b)

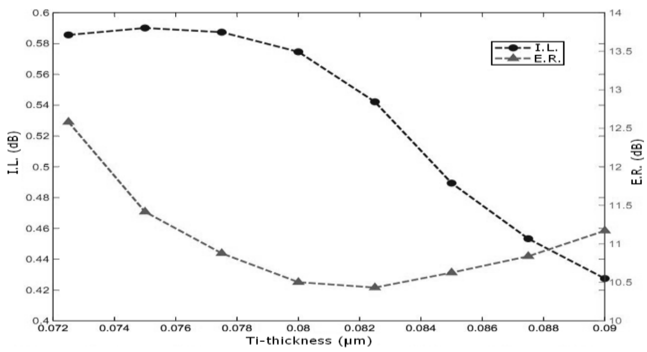
Fig.4. Optical field propagation across the bar and cross states of the switch with (a) one interferometric tapered arm (b) both interferometric arms are tapered.

We have designed the switches using the OptiBPM layout designer and simulation has been done using a beam propagation method [11]. We have simulated our design for low attenuation optical windows, most suitable for optical communication systems, i.e. with test wavelengths of 1.3µm and 1.55µm. We have also focused on the optimization of driving voltage required to operate the switch and their corresponding switching behavior.

When a single interferometric arm is tapered, the ranges of Ti-strip thickness (as indicated above) have been selected because in these ranges the Ti atoms cause sufficient changes in the refractive index of lithium niobate substrate, needed for the switch to remain in the bar state for zero voltage. When the structure is having one tapered interferometric arm, the structure becomes asymmetric at the interferometric arm section. As shown in Figs. 5(a-b), with little increment in Ti-strip thickness (t_s), provisioning of concentrated optical power through the channel waveguides enhances, which results in reduction of insertion losses of the switch. However, at less valued Ti-strip thickness, E.R. can be maintained comparatively at higher levels due to unequal interferometric path length, which results in low coupling losses, thereby reducing the possibility of power leakage to undesired path. This inequality in the path length does not influence the E.R. at higher values of t_s as on that stage, the concentrated power capability of channel waveguides increases sufficiently to put a shadow on these issues.



(a)



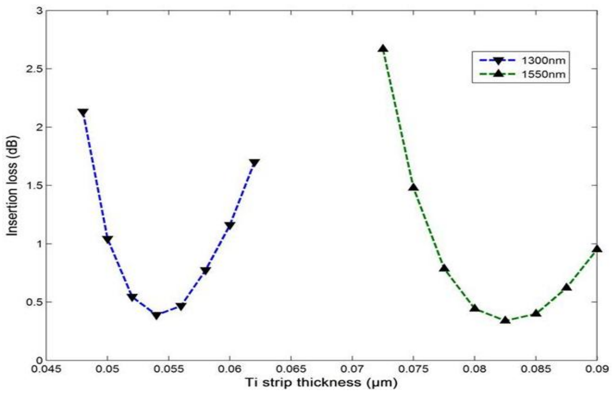
 © 2011 Photonics Society of Poland

(b)

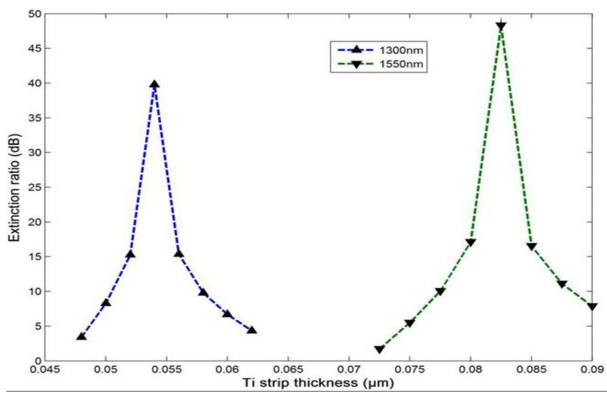
Fig.5. Calculated I.L. and E.R. (in dB) with variation in Ti-strip thickness, while the test wavelength is (a) 1.3µm and (b) 1.55µm.

The structure found to operate best as a switch with a driving voltage of 14.5V. However, as compared to the conventional MZI-switching structure (when interferometric arms are straight waveguides), overall losses within this switch increases due to the increase in the path to be traversed by the optical signal and the bending losses introduced by the curvature of the additional s-bends. Also, due to an increase in the asymmetry and path difference the crosstalk (CT) level of the switch is reduced and the CT equaling -19dB can be achieved for the present structure.

When both interferometric arms are tapered, see Fig. 3(b), they become symmetric and possess equal path length for optical field propagation. The overall losses in the switch increase due to additional path length as compared to the previous case and also I.L. and E.R. become more sensitive to variation in the t_s. For constant process time and temperature, different but fixed values for t_s for either input wavelengths are required to produce sufficient diffusion-induced index change for the Ti–indiffused LN channel waveguides [11]. Therefore the constructive and destructive interference of the MZI structure requires appropriate t_s to optimize I.L. and E.R. of the switch. Figures 6(a) and 6(b) depicts the calculated I.L. and E.R. with respect to Ti–strip thickness variations.



(a)



(b)

Fig.6. Variation in (a) Insertion Loss (b) Extinction ratio with respect to Ti strip thickness.

However, a higher driving voltage (16.5V) in this case is required as compared to the previous model (Fig. 2(a)), due to a decrease in the phase difference caused by symmetry of the interferometric arms. The overall losses of the switch increase, to a large extent, the effective path length for the transversal of the optical signal increases. The total transition losses can be reduced to a minimum of 8–9% by varying various indiffusion parameters. The CT level is reduced to a large extent and the best CT achieved is nearly –12dB. It has been observed that the device can operate for both test wavelengths; however the equivalent results can be obtained by selecting different ranges of Ti-strip thickness. Also with an increase in the symmetry of the structure (if both interferometric arms are tapered, i.e. path lengths become equal), variation in the insertion losses reduces and there is a significant improvement in the E.R. for both test wavelength cases. However, the switch shows better performance with 1.55µm operation in this case, while it shows satisfactory performance with an asymmetric case if the test wavelength is reduced to 1.3µm. In addition to this, the switch needs different ranges of Ti-strip thickness to define, in accordance with the applied input wavelength. Therefore introducing slight asymmetry in the interferometer arms for the switch compaction in length does not lead to major alterations in optical field propagation through the waveguide and the concurrent losses are also bearable up to some extent. The scope of further work lies in the flexibility enhancement of the structure and loss minimisation with proper channelling of the signals.

The work is dedicated to the Institutional excellence in optics research under the grants available from project TEQIP, Ministry of HRD, Government of India, for procurement of Optiwave Design and simulation tool.

References

[1] N. Agrawal *et al.*, IEEE Phot. Techn. Lett. **7**, 644 (1995).
[2] H.Y. Wong *et al.*, IEEE Phot. Techn. Lett. **17**, 783 (2005).
[3] K. Suzuki, *et al*., IEEE Phot. Techn. Lett. 19, 674 (2007).
[4] G.Singh, R.P. Yadav, V. Janyani, Int. J. Comp. Appl. **33**, 36 (2011).
[5] K. Noguchi, J. Opt. Fiber Commun. Rep. **4**, 1 (2007).
[6] A.M. Prokhorov, S. Yu, *Physics and Chemistry of Crystalline Lithium Niobate* (Hilger, New York 1990).
[7] W.-Y. Hwang *et al.*, IEEE Phot. Techn. Lett. **9**, 6 (1997).
[8] G. Ducournau, O. Latry, M. Kétata, Proc. of SPIE **6019**, 60190A, (2005).
[9] P.J. Dong *et al.*, Peleton Photonic Systems Inc., US Patent 6763155 B2, July 13th, 2004.
[10] G.I. Papadimitriou *et al*., J. Lightw. Techn. **21**, 384 (2003).
[11] OptiBPM, Waveguide optics modeling software system, version 8.0, second edition, Optiwave Inc. 2006.

 © 2011 Photonics Society of Poland