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2×2 Ti:LiNbO$_3$ Waveguide Digital Optical Switches

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We propose and demonstrate a novel polarization- and wavelength-independent digital electro-optic switch in Ti:LiNbO$_3$ with switching voltage of ±32V at 1.55μm wavelength. This 2×2 integrated optic switch is characterized by a step-like response to the applied voltage. Switching is achieved through adiabatic mode evolution in an asymmetric waveguide junction. An average insertion loss of ~4.5dB and polarization independent switching with average crosstalk of -12dB are achieved.

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I. INTRODUCTION

The optical switch is one of the key components to be used in optical communication systems such as large capacity optical cross-connector(OXC) network systems or local area networks. Optical components should be polarization independent in order to accommodate systems using single mode fibers that do not maintain polarization.

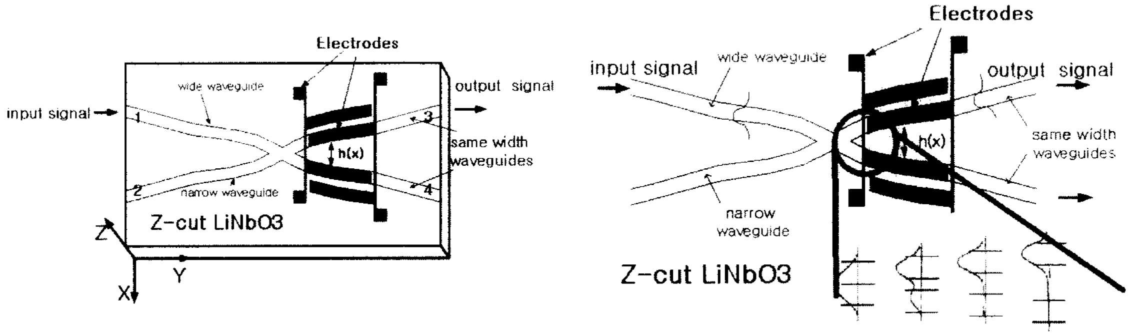
Most electro-optic switches are interferometric in nature, i.e. they require a precise phase shifter to achieve a switched state with low cross-talk. The directional coupler switch, for example, requires a phase shift of $\sqrt{3}\pi$ between its two waveguides to switch [1]. Because of small fabrication variations, this phase shift requires slightly different voltages for each switching element in a switch array. It is also very difficult to switch the two orthogonal polarization components simultaneously. Another class of 2×2 switches is based on modal interference. This class includes the bifurcation optique active (BOA) switch, the X switch, and the symmetric directional coupler switch. All exhibit a sinusoidal response to the applied voltage and therefore require precise voltage control as well [2,3].

On the other hand, the digital optical switch(DOS), exhibiting step-like response, has shown many advantages, such as tolerance to fabrication condition deviations, insensitivity to polarization, the wide operating wavelength range and the immunity to the DC drift. This response characteristic eliminates the need for precise voltage control for switching and it therefore enables the operation of many such elements by a single voltage source, (as required for a switching array). Moreover, the devices can switch both polarization components simultaneously and are insensitive to the precise wavelength of light. The performance of this switch does not depend critically on any of the design parameters, and therefore it is quite tolerant to variation in the fabrication process. However, the exceptionally high drive voltage of the digital drive optical switches has limited the number of input and output ports of the switch matrix [4,5].

In this paper, we report a Ti:LiNbO$_3$ waveguide-type 2×2 digital optical switch. In section II the operational principles and properties of DOS are discussed. Section III describes the design and fabrication. The device performance is presented and discussed in section IV.

II. DEVICE DESIGN AND PRINCIPLE OF OPERATION

The 2×2 digital optical switch as shown in Fig. 1(a) operates ideally as an adiabatic device (no mode



(a) (b)

FIG. 1. (a) Schematic diagram of the digital switch with electrode pattern suitable for z-cut LiNbO$_3$, (b) principle of operation and mode evolution of a 2×2 DOS.

coupling between local normal modes). The structure is based on an asymmetric waveguide junction, composed of two unequal input waveguides, a double-mode central region, and a symmetric output branching. In Fig. 1(b) the principle of operation of the Y-branch optical switch is shown schematically. The left-hand input waveguides are made geometrical asymmetric with different arm widths to act as a mode splitter (mode sorting) [6]. The fundamental or first-order mode of the central region can be excited by launching light through the wider or the narrower input guides, respectively. Mode sorting is obtained if the angle θ satisfies

$$\theta \ll (\delta\beta)/\gamma \tag{1}$$

where $\delta\beta$ is the average difference between the propagation constants of the two normal modes and γ is their transverse propagation constant in the cladding region [7,8]. The particular feature of the asymmetric Y junction is the fact that mode sorting is obtained not at a particular point of operation, but for a range of parameters satisfying eq. (1). By making the angle small enough one can assure mode sorting. The two normal modes in the junction area can similarly be routed to the required output guide by properly biasing the output branching. The fundamental mode will be directed always to the arm with higher index of refraction if the bias is high enough.

The devices switches by symmetry breaking: switching is not periodic or quasi-periodic, but depends only on the direction of the bias. Each input arm excites an orthogonal normal modes at the input plane. This mode evolves adiabatically so that it remains a local normal modes at each location along the structure. Switching is the therefore achieved without resorting to modal interference. Care must be taken to ensure that the applied field does not disrupt the adiabatic propagation. For this purpose the electrodes in Fig. 1(a) are shaped so that the electric field increases gradually towards the junction area [9,10].

There are two effects that give rise to cross-talk in this device. One effect is the mode coupling and the other is due to the field distribution of the first-order local normal mode at the end of the branch. Where the waveguide gap is large, in contrast to the first order mode, the most power of the second order local normal mode is in the waveguide in which the refractive index is lowest. Thus, if the mode coupling effect transfers the power of the first order mode to the second-order mode, the unwanted output power emerges as cross-talk. The mode coupling effect takes place at two locations: at the edge of the electrode near the branching point, where the refractive index asymmetry is introduced abruptly, and at a specific region in the branch due to the change in the geometry of the structure along the direction of propagation.

Fig. 2 shows a simulation of light propagation in such a DOS. The simulation assumes a Ti diffused channel waveguide configuration, and it uses the beam propagation method. Light is assumed to be coupled to the input port 1 of the structure. As can be expected, the optical power is then routed to the output ports alternatively depending on the bias polarity. The output is evenly split between the output guides without any bias. As the bias is increased, light is coupled preferentially to the output waveguide with higher index of refraction. Switching is obtained when an index imbalance of 0.0002 is induced between the output guides. Note that the required index imbalance, and hence the switching voltage, depends on the design parameters. Unlike most electro-optic switches, there is no precise voltage-length product which is required for switching [11].

III. DESIGN AND FABRICATION

To fabricate optical waveguides, 1000Å thick and ~ 8μm wide Ti film was diffused into a z-cut LiNbO$_3$

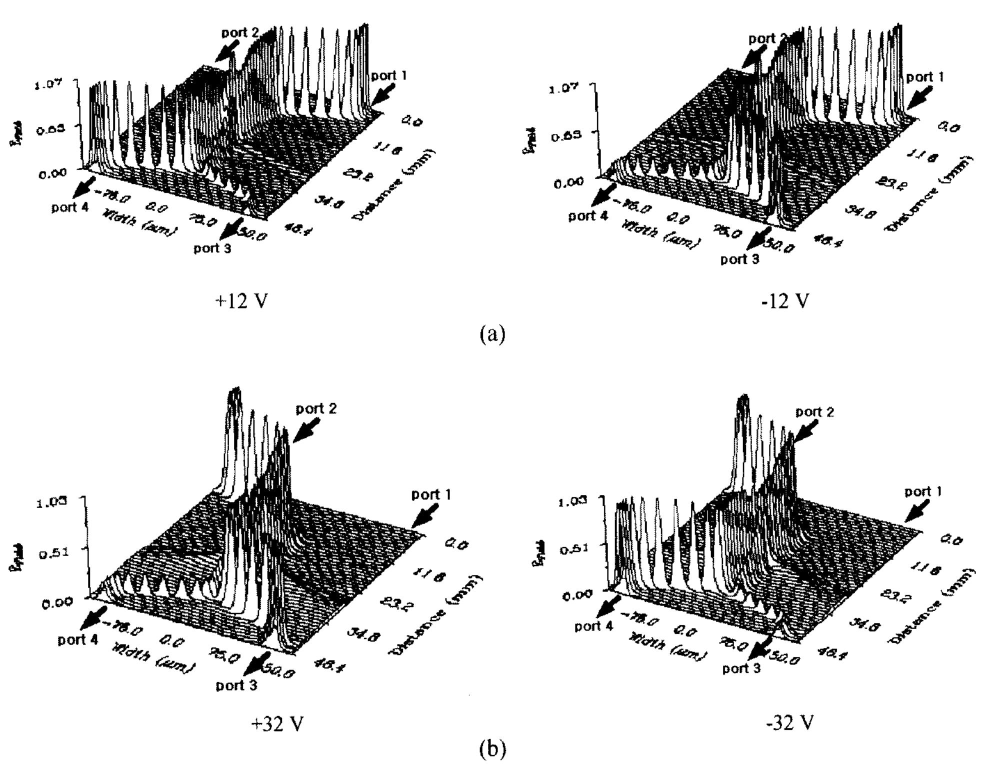


FIG. 2. Simulations of (a) TM light propagation under ±12V and (b) TE light propagation under ±32V. The input waveguides are 8 and 8.5μm wide, the output guides are 8μm wide each. The angle between the guides is 0.5°.

substrate at 1050°C for 8 hours in a wet O_2 atmosphere. The input waveguides were 8.5 and 7.5μm wide, the output waveguides were 8μm wide, and the junction angle was 0.5°. The waveguide gap at the end of the interaction region was 2μm. The waveguide gap at the edge of the electrode near the branching point was 11μm.

The substrate end-faces were polished for optical coupling. The thickness of the SiO_2 buffer layer was ~3000Å. ~3000Å aluminium push-pull electrodes with 10μm width were defined. The gap of the electrode was 5μm. Electrode length was 10mm long. Measurements on the 35mm long sample showed total insertion losses of 4.49 and 4.51dB for the extraordinary (TM) and ordinary (TE) polarizations, respectively, including spatial mode mismatch and Fresnel reflection losses. Fig. 3 is the microscope surface photograph of fabricated DOS.

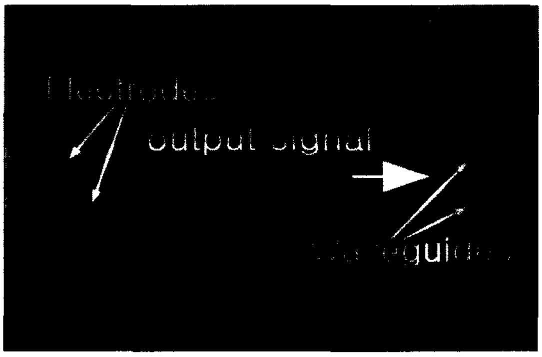


FIG. 3. The microscope surface photograph of a fabricated 2×2 digital optical switch.

IV. DEVICE PERFORMANCE

Fig. 4 shows the measured superimposed responses of TE and TM polarizations at 1.55μm as a function of voltage from both output ports. The steplike response is clearly demonstrated. It is obvious that by applying a strong enough field both polarizations can be switched simultaneously. The measured cross-talk was lower than -12dB for the TE polarization and was slightly worse for TM because of out-diffused surface guiding. The switching voltages to obtain at least -12dB crosstalk were ±12V and ±26V for TM and TE polarization, respectively. This switch can therefore switch simultaneously randomly polarized light.

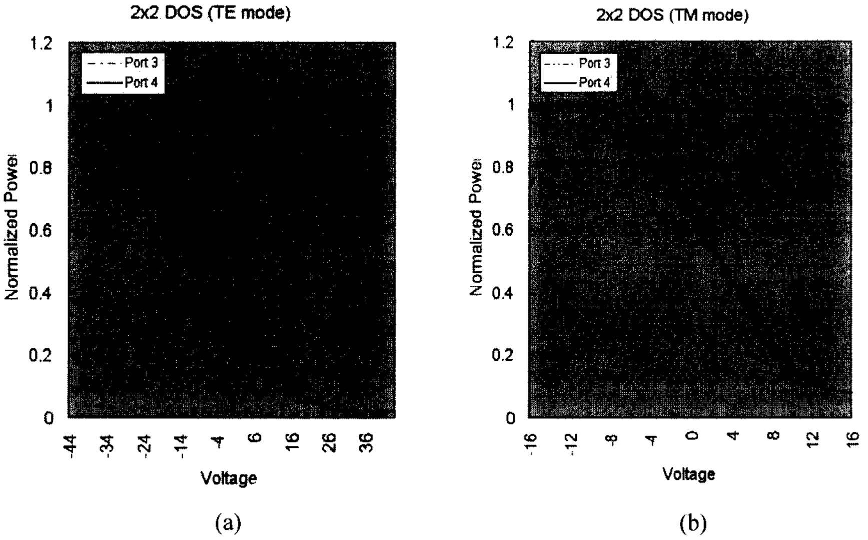


FIG. 4. Experimental results. Superimposed light outputs from the two output waveguides vs bias voltage for (a) TE, (b) TM polarized light at 1.55μm input mode.

For TE and TM input polarization fig. 5 shows the output near field mode patterns of 2×2 DOS without applying switching voltage. It reveals clearly two well-confined spots with almost equal intensity. Near field mode patterns from each output port, depending on the polarity of applied switching voltage, ±26V and ±12V are shown in Figs. 5(a) and (b), respectively.

The steplike response eliminates the need for precise voltage control. Moreover, this response can be used to generate polarization-independent switching in lithium niobate devices. In common z-cut $LiNbO_3$ TE polarization is affected by an electro-optic interaction which is three times weaker than the other component. It is obvious that in a switch with the above response both polarizations can be switched by a strong enough bias. Another advantage of this switch is its insensitivity to the precise wavelength. Indeed, the switching voltage may change with wavelength due to changes in optical mode size. However, switching with a good cross-talk figure should still be obtained, provided that the waveguides involved are still single mode. It is conceivable then that a single element will switch a broad wavelength range, for example, 1.3~1.55μm, simultaneously.

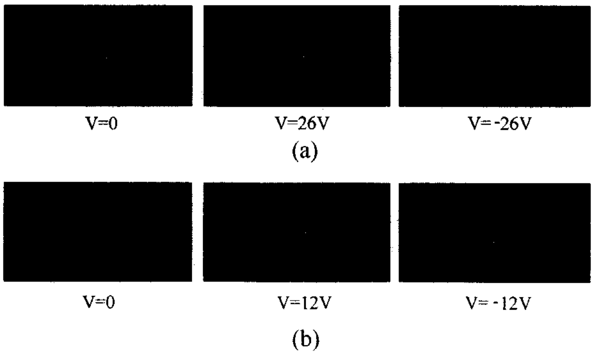


FIG. 5. Near field output mode patterns with bias voltages for (a) TE mode (b) TM mode.

Although the switching voltages obtained were relatively high, we believe that they can be lowered considerably by improving the beginning part of output branch junction to decrease coupling. A simple and straightforward modification would be to fabricate the DOS on X-cut $LiNbO_3$. This would enable bigger and more uniform refractive index changes along the output guides for the same applied voltage. Unlike electro-optic switches that are operated by interference, the digital switch can not be characterized by a single phase shift required for switching. The amount of phase change required for switching can probably be lower by optimization of the design parameters. Note for example that as the voltage is increased the output branch waveguides are decoupled closer to the Y junction part. It may be advantageous, then, to shorten the electrodes and decouple the waveguide externally by changing their width. In addition, one may optimize the switch parameters by using curved waveguide junctions.

V. CONCLUSION

We propose and demonstrate a novel polarization- and wavelength-independent digital electro-optic switch in $Ti:LiNbO_3$ with maximum switching voltage of ±26V at 1.55μm wavelength. The theoretical

TABLE 1. Comparison of the theoretical and measured switching voltage

input port	mode	output port			
		port 3		port 4	
		theory	measured	theory	measured
port 1	TM	12V	12V	-12V	-12V
	TE	32V	26V	-32V	-26V
port 2	TM	12V	12V	-12V	-12V
	TE	32V	26V	-32V	-26V

and measured switching voltages are compared in Table 1 depending on port and polarization mode. This 2×2 integrated optic switch is characterized by a step-like response to the applied voltage. Switching is achieved through adiabatic eigenmode transformation in an asymmetric waveguide junction. The average insertion loss of ~4.5dB and polarization independent switching with average crosstalk of -12dB are achieved. It should be useful in switching arrays and as a polarization- and wavelength-independent switch.

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