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Fabrication of Optical Modulator Based on Proton Exchange

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Abstract

For the investigation of optical modulator, the optical wave-guide was fabricated on x-cut $LiNbO_3$ substrate using proton exchange method with self-aligned electrode. The electrode pattern was designed using a self-aligned thin film electrode method. After proton exchange process, the wave-guide could be prepared by annealing process to control the width and depth of the optical wave-guide.

The initial crossover state of the fabricated 1×2 optical switch was observed with controlling the annealing process variables and the structure of self-aligned thin film electrodes.

As the results in the present work, the measured cross talk and minimum detectable switching voltage were obtained at the values of -29.5dB and 8.0V, respectively, with good merits.

Introduction

Signal processing, optical communication and computer technologies require broadband optical modulators operating with low power consumption and fast speed or high frequency range. Optical wave-guides, due to the confinement of the optical beams over long distances, could make modulation with long interaction length possible.

As a result, the power required to drive a modulator can be significantly reduced. The bandwidth of traveling wave modulators is determined, on one hand, by the velocity difference between the optical and electrical waves and, on the other hand, by the dispersive properties of the transmission line resulting from electrical dispersion, and skin effect losses. The invention of semiconductor laser and development of optical electron technology leads to taking advantage of laser light source instead of electricity. In order to transfer optical signal in conversion of electrical signal using photodiode and the method of going steps of optical signal utilized laser diode and switching, the profits of optical switch could be employed. $LiNbO_3$ uni-axial, ferroelectric crystal satisfies this requirement and can be fitted to make clause optical wave in low guided loss and to obtain single mode optical wave-guide on $LiNbO_3$ substrate. Electrical field through electrode to electrode on $LiNbO_3$ substrate can change refractive index of wave-guide channel by electro-optic effect. Optical switch can make good use of this refractive index alteration, and hence optical beam can be easily modulated or switched by electric field applied to electrodes on $LiNbO_3$ substrate.

It is also proceeding actively to study integrated optics utilized concept of guided wave for supplying the light signal source [1]. Research and development of coherent optical fiber communication systems have been accelerated because of the possibility of sensitive receiver improvement reaching 25dB and the possibility of frequency division multiplex (FDM). However, the practical application of the systems has not been developed, mainly because of the poor spectral purity and frequency stability of semiconductor lasers and the system complexity.

In this research, optical switch having several input and output ports for light beam signal transport into wave-guide was investigated and fabricated to overcome the limiting factors for coherent optical communications. It was fabricated using new method of self-aligned thin film electrode method. The optical switch operated based on the switching phenomenon of optical beam power by electro-optic effect between two close channels of optical wave-guide [2]. It was using forward giving and taking optical beam power between two channels of optical wave-guide. Applying input power into input port of optical switch, the measurements of switching voltage, cross-talk, and switching rate were analyzed for investigation of optical switch characteristics.

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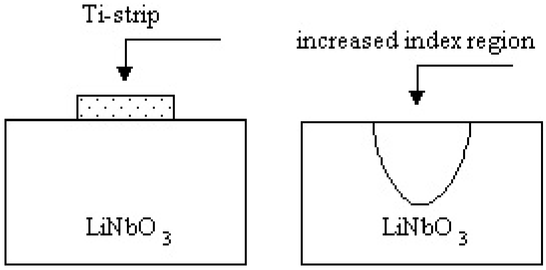
Experimental Procedure

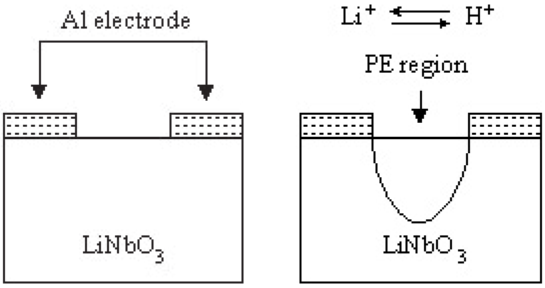
Patterning of wave-guide

The fabrication of optical switch is the method for making a small, low loss optical wave-guide for control the refractive index, which is the most important problem in the fabricating conditions of optical modulator [3].

The refractive index could be changed and decided under the annealing process of the substrate with enough quantity of oxygen flow into furnace (400°C) during 10 to 15 minutes for deep diffusion of proton (H^+) exchange at surface. The typical fabricating methods of wave-guide are illustrated at Fig.1, where Ti-in-diffusion and proton exchange methods were used [4]. As the method of making optical wave-guide with low loss by changing or increasing refractive index on substrate, $LiNbO_3$ is to be a useful substrate material for use of proton exchange and titanium in-diffusion processing.



(a) Ti-in-diffusion



(b) Proton exchange

Fig. 1. Method of Ti-in-diffusion and Proton exchange.

The process of titanium in-diffusion was carried out by diffusion of Ti atoms penetrating into $LiNbO_3$ forming a channel depth for several hours in high temperature and then, by annealing process after lifting up with Ti strip to be formed optical wave-guide. After the Ti-in-diffusion processing, the refractive index of $LiNbO_3$ under the Ti strip increased and the channel of the optical wave-guide was formed with proper thickness and width by the processing conditions.

The proton exchange process is one of ways to make optical wave-guide on the $LiNbO_3$ with use of open-window on metal mask intending only to make channel portion on x-cut $LiNbO_3$ substrate. The Li^+ ion of x-cut $LiNbO_3$ can move away in melted acid or hydrate solution and ion exchange can occur with H^+ ion supplied from acid or hydrate melt under the proper temperature condition. Therefore, the chemical reaction of proton exchange goes like as following equation:

$$LiNbO_3 + xH^+ \rightarrow Li_{1-X}H_XNbO_3 + xLi^+$$

Patterning of electrode

The mask of proton exchange for patterning optical wave-guide was shown in the Fig. 2 [5]. The self-aligned thin film electrode structure was fabricated on 1×2 optical switch without using mask aligner [6,7]. In order to use only the necessary parts of electrodes, the four extra gaps between electrodes should be designed. Since the extra gaps for separation are connected to the end of channels and so can operate as a wave-guide, the propagation loss of optical power could occur in these regions. Therefore, in order to minimize the propagation loss as it can be ignored, the extra gaps were to be positioned vertical to the channels and to be narrower than 4μm [8,9].

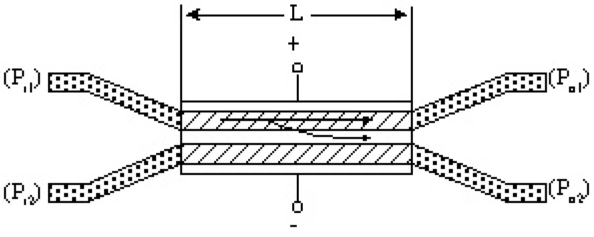
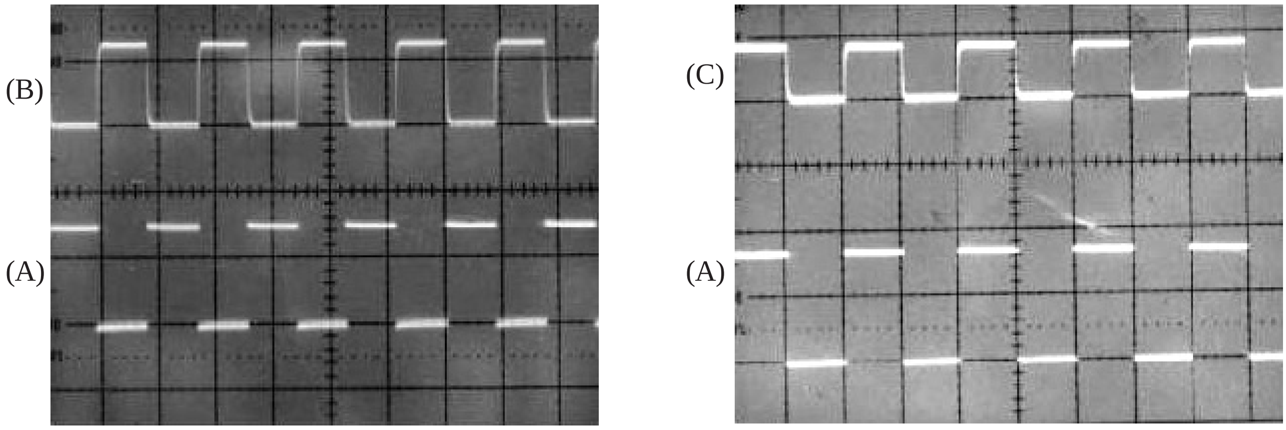


Fig. 2. Structure of optical switch using self-aligned thin film electrode method.

Results and Discussion

Output characteristics

To obtain the characteristics of the optical modulation phenomenon from the fabricated optical device, the modulated output power was measured from the output ports of channels W_1 and W_2 by applying 8.0V of square wave to the electrodes, after irradiating the incident light from light source (He-Ne Laser, λ=0.6328 μm) into the input ports of channels (Fig.3(a) and (b)). The frequency range of driving voltage was from 100kHz to 400MHz in the measuring system.



(a) input wave-guide (W_1) (b) switching wave-guide (W_2)

(A) Input(W_1), (B) Output(W_2), (C) Output(W_1)
* time/div : 500μs * input : 8V

Fig. 3. Output characteristics of optical wave-guide with applied square wave.

The length of switching area in the wave-guide is called *transfer-like length*. The maximum input power transferred to neighbor channel is *cross-over state*. However, a certain degree of input voltage under the maximum optical power transferred is *in cross-over state*, or because of the phase mismatch between channels of optical wave-guide under the zero input voltage. The existing of optical phase mismatch between the channels can occur at the beginning point of wave-guide by the technical error in fabrication. In the case of the switching length is equal to *transfer-like length* without phase mismatch between two optical wave-guides (1×2) at the beginning of switching area, the *transfer length* could have been used instead of *transfer-like length* by using the heat treatment of annealing process. However, although the limitation of outside conditions reduced the optical phase mismatch in the experiment, the remained optical power could exist at the output port of input wave-guide canceling the optical power in the wave-guide *in cross-over state*. This way also left the optical power acting up to *cross-talk*.

Fig. 4 shows the magnification of Fig. 3(a) from 2 V/div to 100 μs/div for measuring the cross-talk -29.5dB of remain output power of W_1 at crossover state, when the input light was irradiated to W_1. Fig.5 shows the modulation characteristics. It appeared that optical power from 1×2 wave-guide driving with 8.0V square wave input voltage of frequency. It can appear with variation of optical power of 1×2 output counted with theory controlled from 100kHz to 400MHz, former of phase mismatched 1×2 output accompanying input voltage. The measurement system is shown

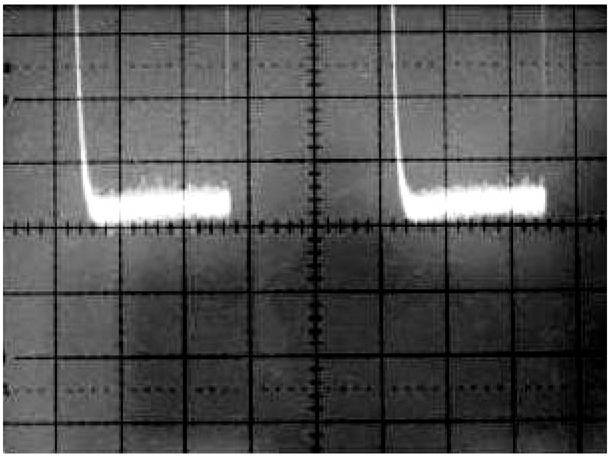
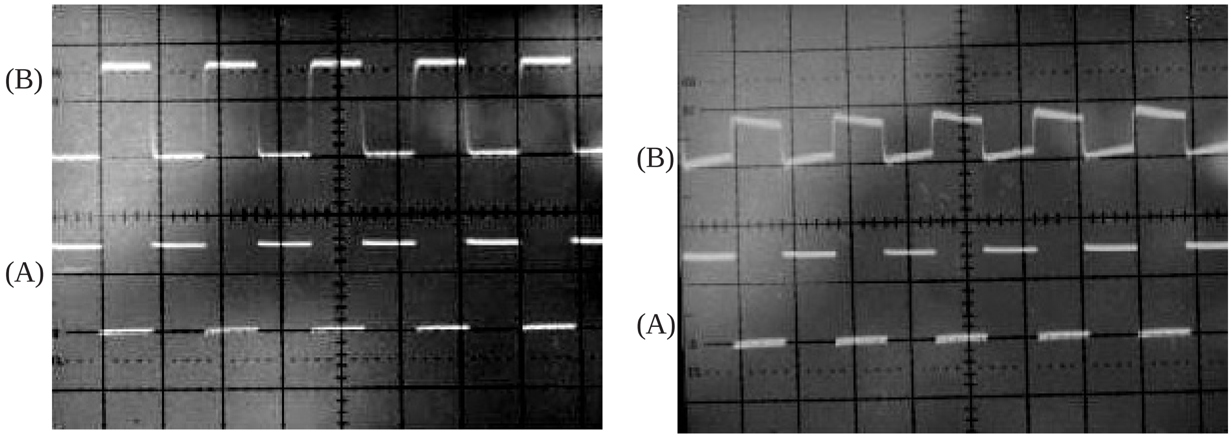
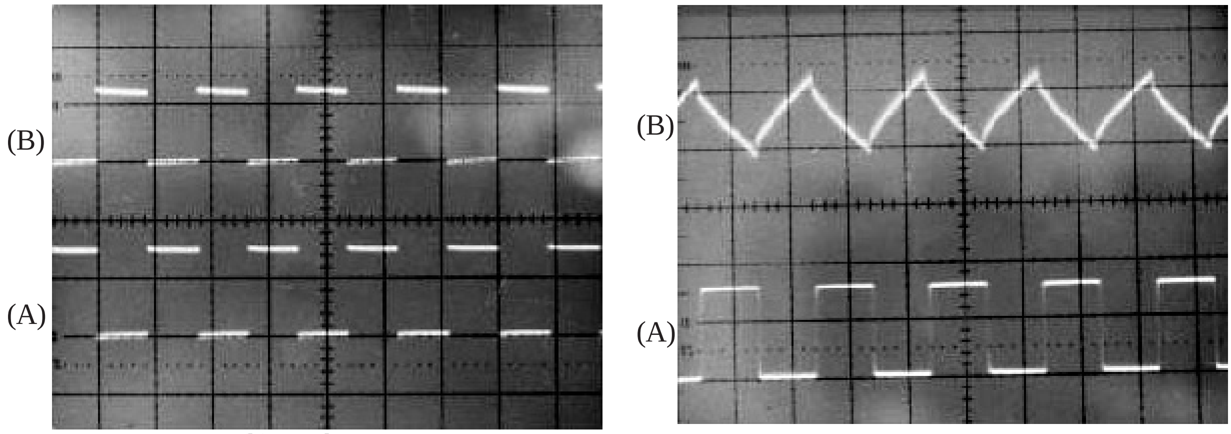


Fig. 4. Enlarged photographs of cross-talk of input wave-guide (W_1)



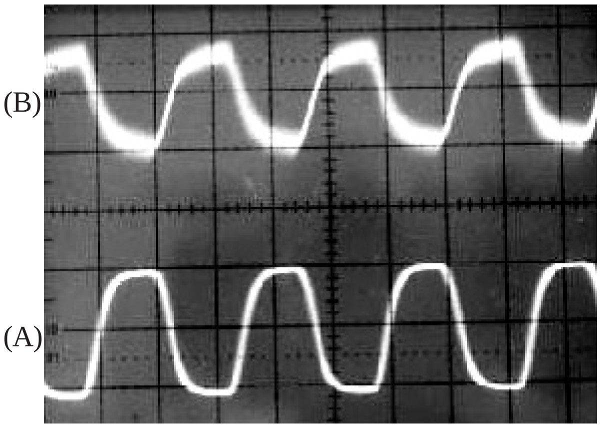
(a) 100 kHz

(c) 1 MHz



(b) 500 kHz

(d) 100 MHz



(e) 400 MHz

Fig. 5. Output characteristics of input wave-guide (W_1) to the applied frequency (from 100 kHz to 400 MHz).(A) Input (W_1), (B) Output(W_2)
* time/div : 500μs
* input : 8V

in Fig.6. In general, the electrodes of optical transfer switch become to align in suitable position by perfect fabricating optical wave-guide. In this case, it is difficult to make in correct points of the width of μm and the length of mm by this simulation. To apply Mach-Zehnder interferometric modulator to x-switch type

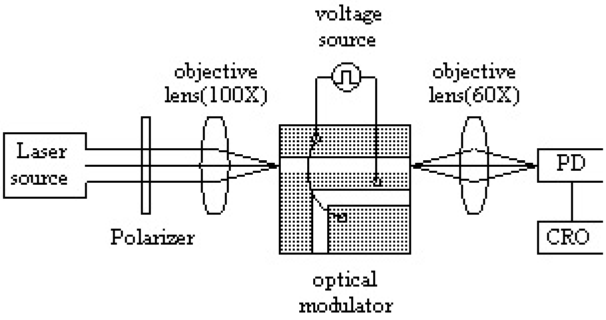


Fig. 6. Measurement system.

modulator or directional couplers with forming electrode by self aligned thin film method will obtain very high effect with the method of going down cross-talk. Also to confirm the process of forming optical wave-guide by proton exchange is sure getting surface single optical wave-guide.

Table shows the results of measuring the characteristics of the 1×2 optical switch light switching on the conditions of Fig. 3. It gives the relationship among the optical output power (by photo detector), the cross-talk at the cross-over state and the bar-state of each channel (W_1 and W_2).

Table 1

Cross-talk and output voltage of electrode-optical switch applied incident input light source at guided wave W_1

(a) oscilloscope scale

State	Volt/div	time base
A (W_1)	5.0 V	500 μs
B (W_2)	2.0 V	500 μs
C	5.0 mV	500 μs

(b) input and output

	V_{p-p} (input)	8 V
A (W_1)	V_{p-p} (W_1)	3.5 V
B (W_2)	V_{p-p} (W_2)	3.9 mV
C	cross-talk	-29.5 dB

Conclusion

The 1×2 electro-optical switch fabricated on x-cut $LiNbO_3$ optimized the efficiency of electrodes and electric field. For using by electrode only necessary part of pattern-mask was used for proton exchange and self-aligned thin film electrodes method.

The following results were obtained from the analysis of characteristics by measuring optical outputs of transferred and remained power with cross-talk in wave-guides after applying the input light to the wave-guide of the 1×2 optical switch.

1) With the input light applied to W_1 of the wave-guide and the drive voltage to the electrodes, it was obtained that transferred power, remained power and cross-talk value were 3.5 V of W_1, 3.9 mV of W_2, and -29.5 dB of cross talk.
2) The switching phenomenon was obtained by proton exchange method to form wave-guide channel on $LiNbO_3$ substrate. The conditions of proton exchange were 200°C, 60min for reaction temp. and time, and 400°C, 10min for annealing temp. and time, respectively.
3) The best switching phenomenon, $V_S = 8.0$ V was obtained with 4 mm of switching length.

The performance of the proposed coupled optical modulator was very superior to that of reported. It was concluded that a stable condition and accurate annealing time of process of the wave-guide were necessary for making a device with less cross-talk and better switching voltage.

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