1 × 2 precise electro-optic switch in periodically poled lithium niobate

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Abstract: A 1 × 2 precise electro-optic switch was demonstrated in a periodically poled lithium niobate crystal. In the experiment, the optical signal was shifted to different channels by adjusting external applied electric fields. The bandwidth of the working wavelength for the switch is nearly 2nm, which makes this device has large tolerance to the drift of the working wavelength in the practical applications. Theoretical discussion about 1 × 2 precise electro-optic switch based on this structure is also presented.

OCIS codes: 230.2090 (electro-optical devices); 130.4815(optical switching devices); 160.3730 (lithium niobate)

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#127272 - $15.00 USD Received 20 Apr 2010; revised 12 Jun 2010; accepted 14 Jun 2010; published 8 Jul 2010

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1. Introduction

Optical switches play a significant role in optical communication and optical information applications, including optical add-drop multiplexing, time division multiplexing and wavelength demultiplexing. Different technologies have been proposed and demonstrated to realize optical switches [1–4]. However, thermal optical switches and the acousto-optic switches usually have a switching time which is longer than a few micro-seconds [1, 2]; all-optical switches are usually complicated and costly at the current stage of development [3]. Comparing to the above switches, electro-optical switches with high speed and related technology have been widely used in optical communication [4]. In order to obtain high speed and stability of the switch for next generation optical network, researchers have made great effort to realize all kinds of optical switches, for instance, integrated electro-optic switch in liquid crystals [4] and high speed electro-optical switch realized in III-V semiconductor materials [5, 6].

In the past two decades, an important artificial nonlinear material called periodically poled $LiNbO_3$ (PPLN) has opened a new window for optical communication [7–9]. In PPLN, the nonlinear optical coefficient, the electro-optic (EO) coefficient, and the piezoelectric coefficient are modulated periodically due to the periodic domain inversion. Based on this structure, essential applications such as wavelength conversion [10], narrow band solc-type filters [11, 12], polarization controllers [13, 14], and laser Q-switch [15] have been successfully demonstrated.

In this paper, we present the principle, theoretical analysis, and experiment design of a new and simple high speed 1 × 2 electro-optic switch in periodically poled $LiNbO_3$ (PPLN). Based on the proposed switch, the optical signal could be shifted to different channels by adjusting driving electric fields. Thanks to the short electro-optical response time, the proposed switch would have a much higher switching speed (~ns) [15, 16].

2. Principle and theoretical analysis

The PPLN we discussed is Z-cut, when a transverse external electric field is applied along the PPLN, based on the electric-optical effect, the optical axis of each domain is alternately aligned at the angles of + θ and –θ, with respect to the plane of polarization of the input light [16]. In this case, the coupled-wave equations of the ordinary and extraordinary waves are:

$$\begin{cases} dA_1 / dx = -i\kappa A_2 e^{i\Delta\beta_z} \\ dA_2 / dx = -i\kappa A_1 e^{-i\Delta\beta_z} \end{cases} \quad (1)$$

with $\Delta\beta = k_1 - k_2 - m\left(\frac{2\pi}{\Lambda}\right)$, and $\kappa = -\frac{\omega}{2c}\frac{n_o^2 n_e^2 \gamma_{51} E_y}{\sqrt{n_o n_e}}\frac{i(1-\cos m\pi)}{m\pi}$ (m = 1, 3, 5 …), where A_1 is the normalized complex amplitude of ordinary wave, and A_2 is the normalized complex amplitude of extraordinary wave. Λ is the period of the PPLN, γ_{51} [16] is the electro-optical coefficient, E_y is the electric field intensity, n_o and n_e are the refractive indexes of the ordinary and extraordinary waves, and with the initial condition:

$$\begin{cases} A_1(0) = 1 \\ A_2(0) = 0 \end{cases} \tag{2}$$

the solution of the coupled-mode Eq. (1) is given as

$$\begin{cases} A_1(z) = e^{i(\Delta\beta/2)z}[\cos sz - i\dfrac{\Delta\beta}{2s}\sin sz] \\ A_2(z) = e^{-i(\Delta\beta/2)z}(-i\kappa^*)\dfrac{\sin sz}{s} \end{cases} . \tag{3}$$

with $s^2 = \kappa\kappa^* + (\Delta\beta/2)^2$. From the solution, the normalized complex amplitudes of the ordinary and extraordinary waves are totally determined by E_y , the transverse external electric field.

Figure 1 presents the theoretical simulating graph of ordinary and extraordinary waves at certain electric fields based on the temperature-dependent Sellmeier equations for the refractive indexes of the ordinary and extraordinary waves [18]. It is clearly shown that the energy of the light exchanges between the coupled TE and TM modes. We assumed the PPLN consists of 2857 domains and the working wavelength is 1541.17nm. After passing this PPLN, the ordinary wave of the 1541.17 nm wavelength almost has no energy loss, while the extraordinary wave is forbidden at the electric fields of 0.03 kV/cm [Fig. 1(a), 1(b)]; In contrary, with the electric fields of 1.26 kV/cm, most of the extraordinary wave of the 1541.17 nm wavelength could pass the PPLN, while the ordinary wave is forbidden [Fig. 1(c), 1(d)]. Crosstalk levels lower than −50dB are obtained at the working wavelength, 1541.17nm [Fig. 1(g)]. Here, the crosstalk level is defined as the difference between the transmitted power level (dB) of the ordinary and extraordinary waves at the output. Thus, we can choose the polarization of the emergent light by switching the external electric field between 0.03 and 1.26 kV/cm.

Furthermore, by increasing the electric field to 3.45 kV/cm, the spectra evolve into broadband with flat-top [Fig. 1(e), 1(f)]. That means the drift of the working wavelength in certain extent could be tolerated, with crosstalk level lower than −25dB at this electric field. Based on above analysis, a 1 × 2 precise electro-optic switch could be realized by tuning external applied electric field.

Considering the practical fabrication errors, the number of the PPLN may not be 2857 precisely. In order to investigate the tolerance of the PPLN domains number, we use p as one of the most important parameters which indicates the percent of deviation of the number. The transmission spectra (extraordinary waves) with different p are shown in Fig. 2. From the figure we can see that when p is within the span (−1%, 1%), the flat-top remains smooth. Else if p is beyond this span, the quality of the flat-top is reduced, that would be solved by changing the applied electric field E_y . By theoretical calculation, if the number of the domains is decreased by 1%, 3%, 5% and 7%, enhancing the electric field can make the flat-top remains smooth, and the corresponding increments of the electric field are 1.21%, 3.19%, 5.10% and 7.19%. Similarly, if the number of the domains is increased by 1%, 3%, 5% and 7%, in order to maintain the flat-top, the corresponding decrements of the electric field should be 1.19%, 2.87%, 4.49%, 6.37%. Hence, the flat-top condition can be achieved by controlling the applied electric field in practice.

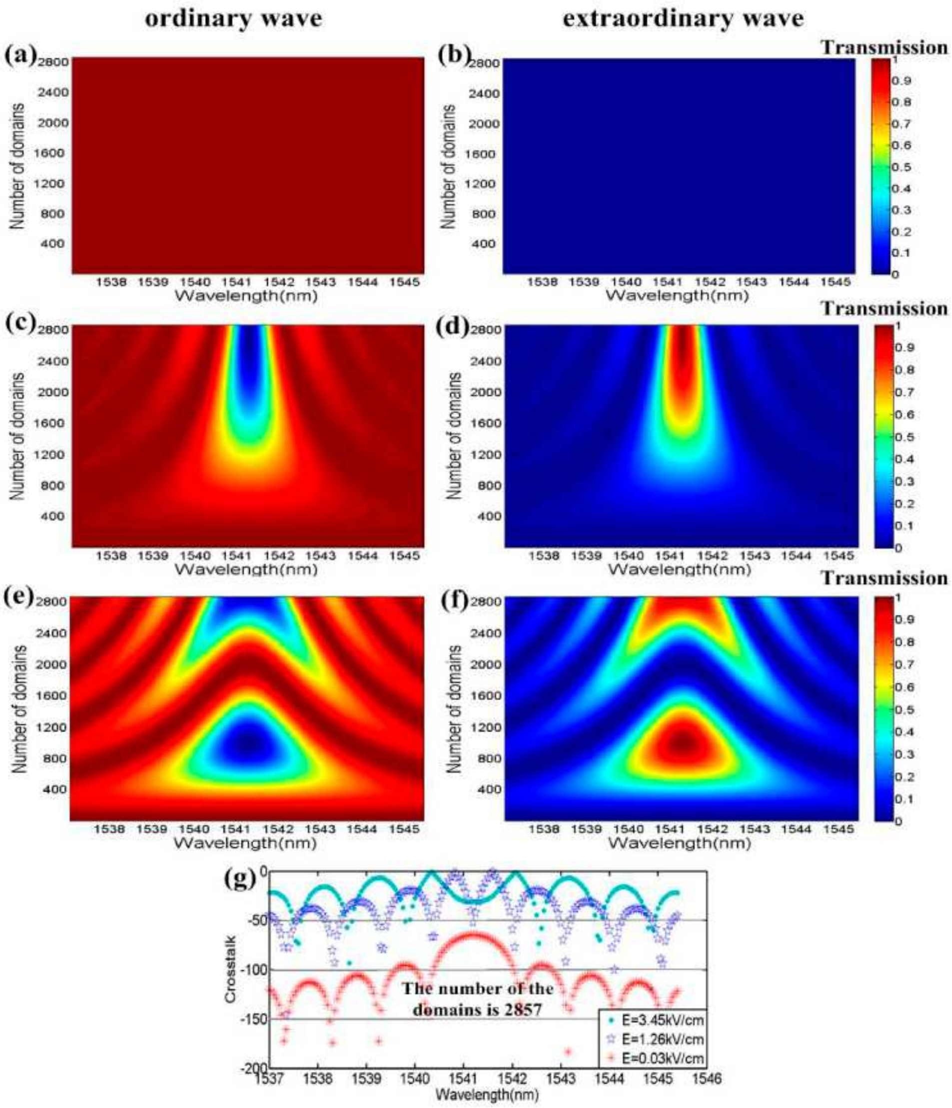

Fig. 1. The theoretical results of the transmission spectra of ordinary and extraordinary waves at certain electric fields. (a), (b) show the transmission spectra at the electric fields of 0.03 kV/cm; (c), (d) show the transmission spectra at the electric fields of 1.26 kV/cm; (e), (f) show the transmission spectra at the electric fields of 3.45kV/cm; (g) presents the crosstalk between ordinary and extraordinary waves at these electric fields when the light has passed the PPLN.

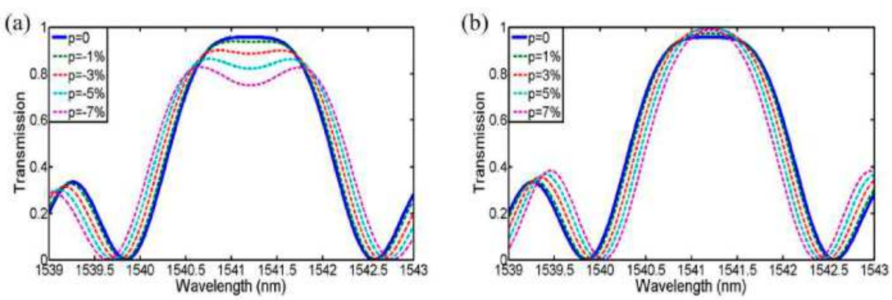

Fig. 2. The transmission spectra when $p = 0\%, \pm 1\%, \pm 3\%, \pm 5\%, \pm 7\%$.

#127272 - $15.00 USD Received 20 Apr 2010; revised 12 Jun 2010; accepted 14 Jun 2010; published 8 Jul 2010

3. Experiment and results

The schematic of the experimental setup is shown in Fig. 3. The arrows inside the PPLN indicate spontaneous polarization directions. The PBS is employed to separate the output light into two channels. In channel A, the polarization direction of the light wave at the output of the PBS is along Z axis of the PPLN sample, and in the channel B, the polarization direction is along Y axis. An electric field is applied along the Y axis. If each domain serves as a half-wave plate, after passing through the stack of half-wave plates, the optical plane of polarization of the input light rotates continually and emerges finally at an angle of 2Nθ, where N is the number of plates. Therefore, when $2N\theta = 0$ at the output, for channel A, the light does not experience loss and the switch is "ON"; for channel B, the light is forbidden and the switch is "OFF". When $2N\theta = \pi/2$ at the output, for channel A, the switch is "OFF" and for channel B, the switch is "ON". As θ can be extremely small (10^{-6} - 10^{-5} radians), precise control of the final rotation angle at the output is accessible [16]. Thereby, the switching state of "ON" and "OFF" can be very precise which enables it to achieve high extinction ratio.

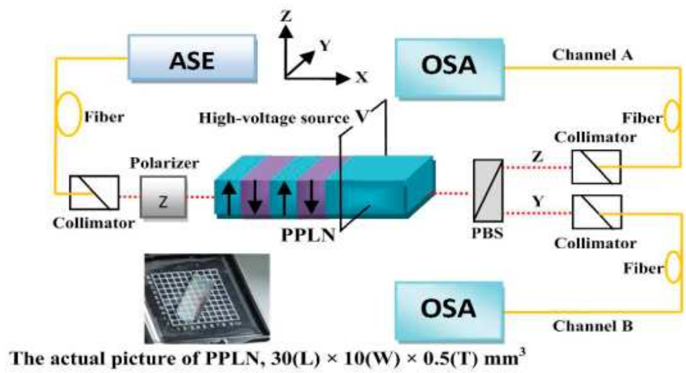

Fig. 3. Experimental setup for a PPLN electro-optic switch; A PPLN crystal, which is Z cut. The sample consists of 2857 domains with the period of 21 μm. The light propagates along the X direction and a uniform electric field is applied along the Y axis of the PPLN sample. ASE, amplified spontaneous emission; OSA, optical spectrum analyzer; PBS, polarization beam splitter; the room temperature is 18.5°C.

Figure 4(a), 4(b) are the experimental observation of the transmission spectra for A and B channels at electric fields of 2.1 kV/cm and 0.5 kV/cm. For A channel, with electric field of 0.5 kV/cm, the light intensity of the 1541.17 nm wavelength attends a maximum value of 2.716 μW and the switch is "ON". When the electric field is shifted to 2.1 kV/cm, the light intensity falls sharply down to nearly zero (15.25 nW) which means "OFF"; For B channel with electric field of 2.1 kV/cm, the light intensity of the 1541.17 nm wavelength attends a maximum value of 2.489 μW and the switch is "ON". When it shifts to 0.5 kV/cm, the light intensity falls sharply down to nearly zero (3 nW) which means "OFF".

Thus, we can control this switch by shifting the electric field between 2.1 kV/cm and 0.5 kV/cm. When the electric field is 0.5kV/cm, only the OSA from A channel can receive the light with the polarization direction which is parallel to the polarizer, which means the switch is "ON" for A channel, and "OFF" for B channel. The same as above, the switch is "ON" for B channel, and "OFF" for A channel, when the electric field is shifted to 2.1 kV/cm, and the polarization direction of the emergent light is perpendicular to the polarizer.

It could not be ignored that the drift of the central wavelength would reduce the precision of such narrowband switch. When we increase the voltage of the electric field to 4.3kV/cm, the spectra evolve into broadband with flat-top and the width is nearly 2nm. Figure 4(c), 4(d) are the experimental observation of the transmission spectra for A and B channels at electric fields of 4.3kV/cm and 0.5 kV/cm. That means the drift of the working wavelength in certain extent has almost no effect on the precision of this 1 × 2 flat-top electro-optic switch.

#127272 - $15.00 USD Received 20 Apr 2010; revised 12 Jun 2010; accepted 14 Jun 2010; published 8 Jul 2010

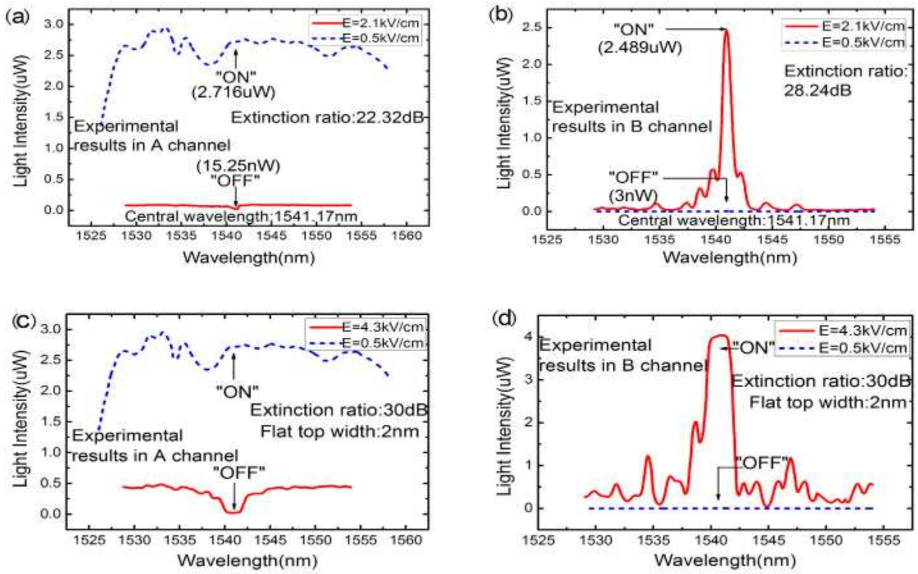

Fig. 4. The experimental transmission spectrums at electric fields of 0.5 kV/cm, 2.1 kV/cm and 4.3 kV/cm for A and B channels.

As we know, precise electro-optic switch desires a low crosstalk. In our experiment the crosstalk level is lower than −20.98dB between A and B channels at the three critical electric fields, which is similar to the theoretical results. Compared with other kind of electro-optic switch [17], the crosstalk of this switch is at the same level. Another important performance of precise electro-optic switch is extinction ratio. In our experiment the extinction ratio (on/off) is more than 22.32 dB, which is a little higher than the switch realized in other material [19]. Although the critical electric fields are little higher than theoretical ones because of the voltage loss in our setup, the proposed 1×2 precise electro-optic switch is still very attractive. It should be noted that the PPLN waveguide has been successfully proposed recently [21], where the gap between the electrodes can be as short as 10 μm, so that only several Volts is enough to switch the light for this kind electro-optic switch.

The key component of this proposed switch is the PPLN, and the key step of designing this electro-optic switch is fabricating the PPLN by aids of electrical poling precisely. In recent years, the technique of electrical poling has processed a lot and become mature [20], making such switch available.

4. Conclusion

A precise 1×2 electro-optic switch is experimentally and theoretically demonstrated in periodically poled lithium niobate (PPLN), in which the output channel can be chosen by external applied voltage. A bandwidth as large as 2 nm for working wavelength is also demonstrated. The kind of 1×2 precise electro-optic switch may find its applications in optical communication and optical information.

Acknowledgements

This research was supported by the National Natural Science Foundation of China (No. 60508015 and No.10574092), the National Basic Research Program “973” of China (2006CB806000), and the Shanghai Leading Academic Discipline Project (B201).