Acousto-optic tunable optical diode based on periodically poled LiNbO3

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***Abstract*—**we propose a bidirectional acousto-optic tunable optical diode based on a periodically poled lithium niobate (PPLN) waveguide with defect. An acoustic wave propagates together with the light beam so that a collinear photon-phonon interaction happens, which affects the nonlinear optical processes in PPLN.

Keywords-QPM;optical diode;acousto-optic

I. INTRODUCTION

Recently, the nonreciprocal structures become hot topics. Periodically poled lithium niobate (PPLN) waveguides with geometrical asymmetries are promising nonreciprocal materials[1], which have been designed as optical diodes alternative to standard magneto-optic Faraday rotators. When the fundamental wave (FW) propagates in a PPLN waveguide with a defect, the second-harmonic wave (SH) and FW would go through different degrees of disturbance owing to the introduced phase discontinuity ($\delta\varphi$) at the defect area. Both the FW and SH thus are sensitive to the defect's parameters like its position and thickness. As long as the defect is not just at the middle of the PPLN waveguide, lights to opposite directions would see different structures then different FW and SH are obtained at the output ports. An extreme case is that one wave, e.g., the FW only may be detected at a single direction. The opposite FW is totally converted to SH. A unitary contrast $C = (T_\lambda^+ - T_\lambda^-)/(T_\lambda^+ + T_\lambda^-)$ was defined the degree of optical isolation, where T_λ^+ and T_λ^- are the FW transmission on forward and backward direction respectively. The contrast is greatly affected by phase discontinuity $\delta\varphi$, the position of $\delta\varphi$, and the fundamental input power. For a given PPLN diode, the $\delta\varphi$ and its location has been fixed. The contrast only can be tuned by the intensity of input power, which is not very convenient.

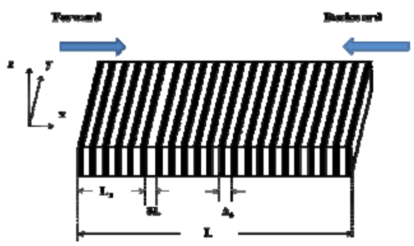

Fig. 1. Schematic diagram of a nonreciprocal PPLN waveguide (Dark and bright sections indicate positive and negative domains respectively). Λ_0 is the period of grating. A defect of length δL is introduced at x=L_1.

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In this letter, the acoustic wave is introduced in asymmetric PPLN waveguides. The isolation of contrast could be tuned more flexible from -1 to 1, by just adjusting the intensity of acoustic wave. This makes the manufacturing and operation of the diode to be more convenient.

The nonreciprocal PPLN waveguide is sketched in Fig. 1. A defect is introduced in a PPLN of length L and period Λ_0. When an acoustic wave travels in it, a periodic index modulation is built up due to the elasto-optic effect, which could induce the acousto-optic (AO) polarization. The polarization rotation effect may be existed for either FWs or SHs depending on the phonon's frequency. Let's assume the FW's polarization is rotated, thus the original FW, the polarized FW and the SH are coupled together. To make use of the largest nonlinear coefficient d_{33}, the input FW is chosen to be Z-polarized. For simplicity, the propagation loss is ignored, and the wave vector mismatching for SHG and polarization rotation are compensated by the reciprocal vector (G1) of PPLN and the acoustic wave vector (H) respectively. The coupling equations could be deduced as follows with consideration of both nonlinear optic and AO interactions.

$$\begin{aligned} dA_{1z}/dx &= -iK_1A_{1z}^*A_{2z} - iK_2A_{1y} \\ dA_{2z}/dx &= -\tfrac{i}{2}K_1A_{1z}^2 \\ dA_{1y}/dx &= -iK_2^*A_{1z} \end{aligned} \tag{1}$$

Where $A_{j\xi} = \sqrt{n_{j\xi}/\omega_j}E_{j\xi}, K_1 = d_{33}g_1/c\sqrt{\omega_1^2\omega_2/n_{1z}^2n_{2z}}, K_2 = \omega_1(n_{1y}n_{1z})^{1.5}p_{41}S/4c$

$E_{j\xi}$, ω_j, $n_{j\xi}$, (the subscripts j = 1, 2 refer to the FW and SH, respectively, and ξ = y, z represent the polarization) are the electric fields, the angular frequencies and the refractive indices, respectively. c is the velocity of light in vacuum. g_1 is the amplitude of the reciprocal vector G_1 whom is adopted to compensate the nonlinear phase match. p_{41} is the corresponding elasto-optic coefficient. S = HD is the amplitude of acoustic wave induced strain. H is the vector of acoustic wave to compensate the polarization rotation phase-matching and D is the amplitude of acoustic wave. A longitudinal acoustic wave along X-axis is considered.

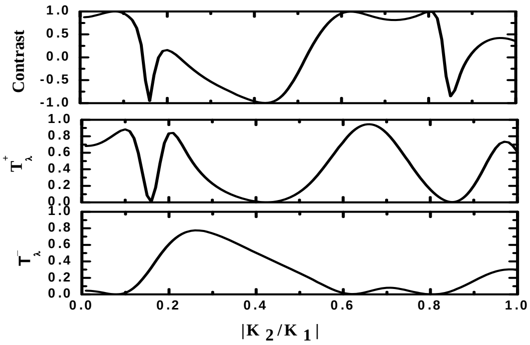

Fig. 2. The contrast is tuned by the intensity of acoustic wave. Here L_1 =4/10 L. The dephasing is 0.3 π. The red solid and green dashes represent the optical isolation with contrast C = 1 and -1 respectively.

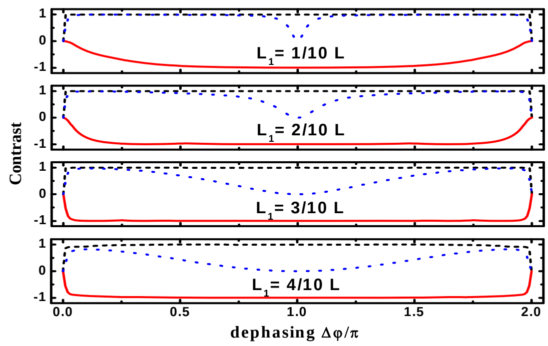

Fig.3. The tunable range of contrast C versus different dephasing $\delta\varphi$ with different lengths of L_1. Black dashes and red solids represent the maximum and minimum contrast by tuning the intensity of acoustic wave, respectively. The blue dots show the contrast without acoustic wave.

Equations (1) are satisfied in the both uniform segments of PPLN waveguide in Fig. 1. In the domain of δL, a phase jump $\delta\varphi$ between FWs and SH is brought in. We suppose δL is short enough to ignore any influences on amplitude changes or phase-matching for both SHG and polarization rotation. While the waves travel forward, the z-polarized FW, y-polarized FW and z-polarized SH are coupled together along the PPLN in the segment L_1 (< 1/2 L). There are two competition processes: SHG and polarization rotation, which are governed by the coupling coefficients K_1 and K_2 and their ratio. When the light waves pass through the defect, their relative phase is changed and the SHG process is not standard any more. Then the seeded SHG and polarization rotation is engaged in the second segment L-L_1-δL. In the backward case, the same approach is adopted, except that the waves travel along the second segment L-L_1-δL firstly and thus the affection induced by dephasing $\delta\varphi$ is different. In both situations, K_2 could be easily controlled by tuning the intensity of acoustic wave (S) that makes the orientation of PPLN diode's unidirection optional.

At the room temperature, we set the pumping FW intensity 10 MW/cm^2 at 1550 nm, L = 1 cm, d_{33} = 25.2 pm/V, p_{41} = -0.05, Λ_0 =18.98 μm to satisfy the QPM condition. On the case of L_1 =4/10 L, $\delta\varphi$ = 0.3 π and π, the contrast and transmission in both directions for z-polarized FW is plotted in Fig. 2. It's obvious that the optical isolation with contrast (C) could be tuned nearly from -1 to 1 by adjusting the ratio of $|K_2/K_1|$, *i.e.*, the intensity of acoustic wave. When $\delta\varphi = 0.3\pi$, $C \approx 1$ (red solid, the forward transmission T_λ^+ = 83.73% and the backward transmission $T_\lambda^- \approx 0$) represents an optical diode which only allows the forward transmission. While $C \approx -1$ (green dash, the forward transmission $T_\lambda^+ \approx 0$ and the backward transmission T_λ^- = 45.38%) represents the same diode but only allows the backward transmission. Thus, the bidirectional optical diode is achieved by tuning acoustic wave.

Simulations have also been done for unequal lengths of L_1, various dephasing $\delta\varphi$, and different input power. Figure 3 shows the tunable range of contrast versus dephasing $\delta\varphi$ with different lengths of L_1 at a lower input power than Fig. 2. Black dashes and red solids represent the achieved maximum and minimum values of the isolation contrast by tuning the intensity of acoustic wave, respectively. The blue dots show the contrast without any acoustic. From Fig. 3:

(I) The contrast is symmetric with regard to π, because the influence induced by positive and negative phase jumps between FWs and SH is equal, i.e., $C(\delta\varphi) = C(-\delta\varphi)$. And the tuning range reaches the largest at $\delta\varphi = \pi$;(II) Although the isolation would be affected by varying $\delta\varphi$, the range of contrast still can be tuned from -1 to 1 at a very large domain of dephasing by tuning the intensity of acoustic wave;(III) Different lengths of L_1 also influence the value of contrast. While the length of L_1 becomes shorter enough, the tuning range shrink on the both sides of dephasing axis. And it makes sense that the shrinkage only exists in the backward isolation. In the backward case, the impact of defect couldn't restore the original FW power efficiently with short L_1. Anyway, the tuning range is from -1 to 1 at the vast majority of $\delta\varphi$s. While the length of L_1 becomes longer (always < 1/2 L), the tuning effect appears better. However, when L_1 is very close to the value of 1/2 L, the tuning range also shrinks, because the spatial nonreciprocity is not obvious any longer;(IV) In Fig. 3, we turn down the input power to one quarter of that in Fig. 2, and the tuning range of isolation contrast is still nearly from -1 to 1. A word, the influences brought by the value and location of $\delta\varphi$, power of incident FW and the intensity of acoustic wave were studied. We found that the affection induced by the first two could be completely covered by the last, which makes our device more tolerant and easy to implement. Moreover, by tuning the intensity of acoustic wave, even the orientation of the optical diode's unidirection could be changed. Finally, another PPLN can be integrated into the device to generate the acoustic wave; it is very compact and has great potential in photonic integrated circuits (PIC)

In summary, we proposed a bidirectional tunable optical diode in an asymmetric PPLN waveguide through cascading SHG and AO interaction. The optical isolation contrast could be tuned from -1 to 1 by adjusting the intensity of an induced acoustic wave. The influence of dephasing, location of defect, input power and the intensity of acoustic wave were discussed.

[1] K. Gallo, and G. Assanto, "Analysis of lithium niobate all-optical wavelength shifters for the third spectral window," J. Opt. Soc. Am. B **16**, 741-753, 1999.