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Electro-optic chirality control in MgO:PPLN

Lei Shi, Linghao Tian, and Xianfeng Chen[a)]
Department of Physics, The State Key Laboratory on Fiber Optic Local Area Communication Networks and Advanced Optical Communication Systems, Shanghai Jiao Tong University, 800 Dongchuan Rd., Shanghai 200240, People's Republic of China

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The chirality of MgO-doped periodically poled lithium niobate (MgO:PPLN) by electro-optic effect was studied. It shows that optical propagation is reciprocal in MgO:PPLN under a transverse electric field and quasi-phase-matching condition, which bears similarity to natural optically active material like quartz. The specific rotation is shown to be proportional to the transverse electric field, making large polarization rotation in optically active material with small size possible. We also demonstrate that the chirality of MgO:PPLN can be controlled by the external electric field. © *2012 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4754861]

I. INTRODUCTION

Optical activity is the turning of the polarization plane of linearly polarized light about the direction of motion as light travels through certain materials. It occurs in solutions of chiral molecules such as sucrose, spin-polarized gases of atoms or molecules, and solids with rotated crystal planes such as quartz. It is widely used in the sugar industry to measure syrup concentration,[1] in optics to manipulate polarization,[2,3] in chemistry to characterize substances in solution,[4] and in optical mineralogy to help identify certain minerals in thin sections.[5] In an optically active material, optical propagation is reciprocal, and the polarization plane rotates in the same sense (e.g., like a right-hand screw) during the forward and backward pass. The rotation angle of the polarization plane in an optically active material such as quartz is $\beta = \alpha L$, where α is the specific rotation, and L is the path length of light in the material. The specific rotation of a pure material is an intrinsic property of that material at a given wavelength and temperature. A positive value corresponds to dextrorotatory rotation while a negative value is related to levorotatory rotation.

The periodically poled lithium niobate (PPLN), an artificial nonlinear material, has received more and more attention owing to its outstanding nonlinear optical properties.[6,7] The even order nonlinear coefficients, such as electro-optic coefficient and photovoltaic coefficient, are periodically modulated due to the ferroelectric domain inversion. It has been widely used in frequency conversion, pulse shaping, optical switching, and other nonlinear optical processes by quasi-phase-matching (QPM) technique.[8–13] Recent research has shown that for a linearly polarized light that satisfies the QPM condition, the polarization plane rotates with the increment of the applied transverse electric field, which is called electro-optic (EO) effect. EO effect of PPLN has been applied to various fields like EO Solc-type wavelength filters,[14,15] logic gate,[16] optical isolator,[17] high frequency modulator,[18] scanner,[19] lens,[20] and polarization state generator.[21] However, the chirality of this kind of optical rotation is still unclear and worth studying for its splendid further applications in optical signal control.

In this paper, we give a deep insight into the chirality of the MgO:PPLN by EO effect. It shows that the polarization plane twists in the same sense during the forward and backward pass, that optical propagation is reciprocal in MgO:PPLN, which is similar to the general optically active medium such as quartz. The specific rotation of MgO:PPLN by EO effect is shown to be proportional to the transverse electric field, making it more convenient to be flexibly adjusted according to practical demand. We also demonstrate that the chirality of MgO:PPLN can be controlled by the external electrical field: the chirality alters when changing the direction of the electric field.

II. THEORETICAL ANALYSIS

EO effect of PPLN has its origin in the work by Lu *et al.*[22] Their study shows that when a transverse electric field is applied along the Y axis of PPLN, the refractive-index ellipsoid deforms, as shown in Fig. 1. Consequently, the Y and Z axis of the refractive-index ellipsoid rotate an angle of θ around X axis. The rocking angle θ is proportional to the external electric field and is given by $\theta \approx \gamma_{51} E_y / [(1/n_e)^2 - (1/n_o)^2]$, where n_o and n_e are refractive indices of the ordinary and the extraordinary wave, respectively; E_y is the external electric field, and γ_{51} is the EO coefficient. Since all elements of the EO tensor have different signs in different domains, the azimuth angle of the new optical axes rock $+\theta$ or $-\theta$ successively when an external electric field is applied. When the QPM condition is satisfied, each domain serves as a half-wave plate with respect to the input light. After passing through a stack of rotated half-wave plates, the optical polarization plane of the input light will rotate continually. Finally, light emerges at an angle of $2N\theta$ relative to the incident azimuth angle, where N is the number of domains. Furthermore, with the increment of the electric field, the rotation angle of the input light will rotate correspondingly, which is similar to a birefringence half-wave plate rotated manually.

When an external voltage V is applied along +Y axis of the PPLN, as presented in Fig. 1, looking along +X axis, the

[a)]Electronic mail: xfchen@sjtu.edu.cn.

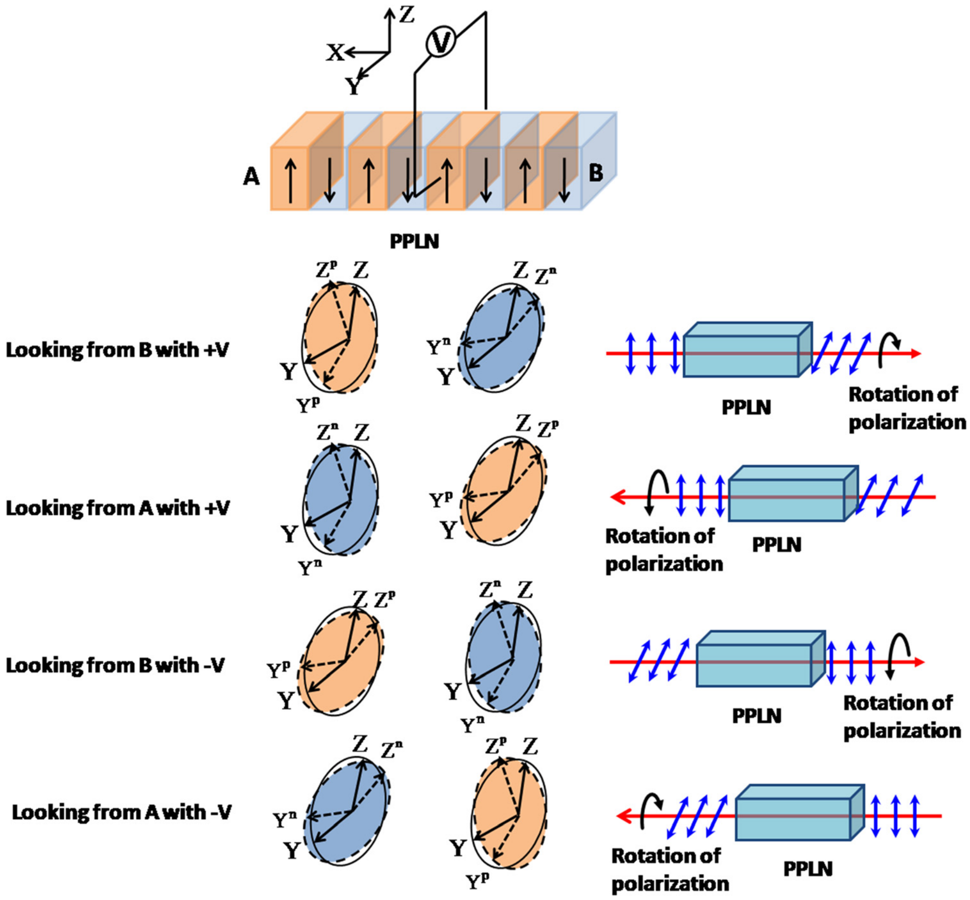

FIG. 1. Schematic diagram of the PPLN crystal, the rotation of principal axes and final rotation direction of the polarization plane when a transverse electric field is applied. The arrows inside the PPLN indicate the spontaneous polarization directions. Deformation of the index ellipsoid is observed from port A and B (representing light travelling along +X and −X axis) under a ±V voltage (±represent transverse electric field along ±Y axis). X, Y, and Z represent the principal axes of the original index ellipsoid, and $Y^{p,n}$, $Z^{p,n}$ are the perturbed principal axes of the positive and negative domain, respectively.

Y and Z axis of the index ellipsoid rotate an angle of θ left-handedly and right-handedly in the positive and negative domains, respectively. When QPM condition is satisfied, the polarization plane of an incident linearly polarized light travelling along −X axis will rotate an angle of $2N\theta$ right-handedly at the output side. However, looking along the −X axis, we see that the Y and Z axis of the index ellipsoid rotate an angle of θ right-handedly and left-handedly in the positive and negative domains, respectively. The overall effect is that a linearly polarized light travelling along +X axis also rotates an angle of $2N\theta$ right-handedly at the output side. Thus, the polarization plane twists in the same sense during the forward and backward pass. Optical propagation is therefore reciprocal in PPLN, which is similar to optically active material such as quartz. When the external voltage V is applied along −Y axis, the rotation directions of the Y and Z axis of the index ellipsoid also reverse, the polarization plane then rotate left-handedly during the forward and backward pass. The chirality of PPLN is thus controlled by the external electrical field.

III. EXPERIMENT RESULTS AND DISCUSSIONS

The rotation angle of the polarized light after passing through the PPLN is $\beta = 2\frac{L}{\Lambda}\frac{\gamma_{51}E}{(1/n_e)^2-(1/n_o)^2} = \alpha L$, where Λ and L are, respectively, domain thickness and length of the PPLN. The specific rotation, defined as $\alpha = \frac{2}{\Lambda}\frac{\gamma_{51}E}{(1/n_e)^2-(1/n_o)^2}$, is relevant to the wavelength, temperature and material. In addition, it is also electric field adjustable, which shows great advantage over optically active material in that the specific rotation can be adjusted according to practical demand. Large optical rotation in materials with small size is then at hand. The PPLN sample used in our experiment is MgO-doped with 3582 domains. The domain period is 20.1 μm with the duty cycle of 1. We measured the specific rotation under different electric field with the working wavelength of 1568.5 nm at 22 °C, as depicted in Fig. 2. The specific rotation increases linearly with the electric field, and reaches

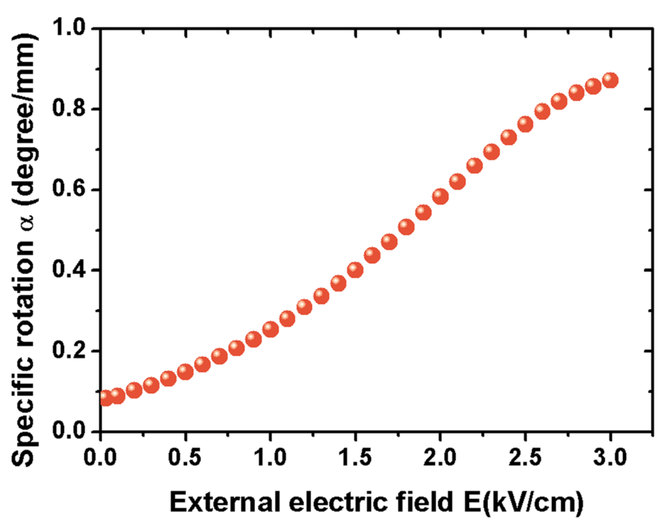

FIG. 2. Experimental measurement of the specific rotation versus external electric field.

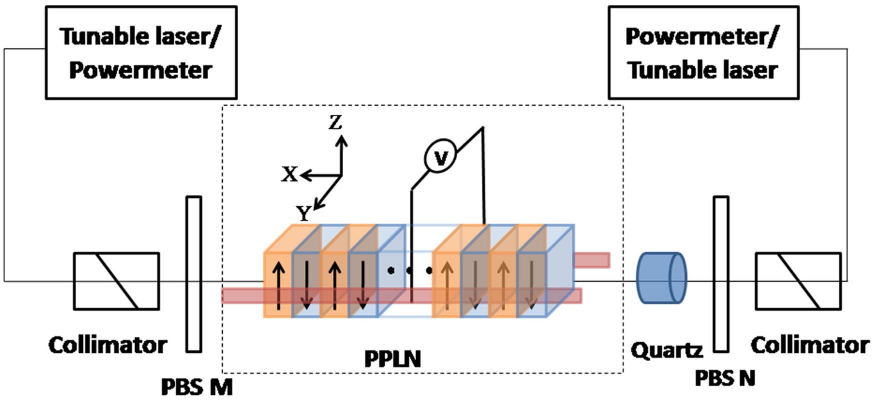

FIG. 3. Experimental setup for studying the optical activity of MgO:PPLN. The MgO:PPLN crystal is Z cut. Two PBSs are perpendicularly placed: M Z-oriented, and N Y-oriented. A uniform electric field is applied along the Y axis.

0.87°/mm under an external electric field of 3 kV/cm. In the waveguide configuration, the width of the MgO:PPLN can be as small as 10 μm. The specific rotation can be as large as 2.43°/mm under an electric voltage of 1 V, which is very attractive.

We designed an experiment to demonstrate the chirality of MgO:PPLN, as shown in Fig. 3. A tunable laser worked as the light source. Two polarization-beam-splitters (PBSs) were set perpendicularly to work as polarizer and analyzer. A MgO:PPLN crystal and a 45° dextrorotatory quartz were placed between the two PBSs. The MgO:PPLN and working environment were the same as that in the specific rotation measurement. We measured the output power of light travelling along X axis with an external electric field applied along Y axis, which is expressed as $T = \sin^2(\pi/4 \pm 2N\theta)$.[7] The results are presented in Fig. 4. The pink and blue curves represent transmissions of light travelling along +X (forward wave) and −X direction (backward wave), respectively. Apply the electric field along +Y axis, we get the transmissions as shown in Fig. 3(a). With the help of the dextrorotatory quartz, transmission curves of light present a form of sinusoidal function. It gets the maxima first with the increment of the electric field, which means a 45° right-hand rotation of the polarization plane from the MgO:PPLN. While when an electric field along −Y axis is employed, the transmission curves appear a cosine-function shape. They reach the minima first when the electric field increases from 0, which indicates that light undergoes a left-hand rotation from the MgO:PPLN, as shown in Fig. 4(b). From Figs. 4(a) and 4(b), we get the conclusion that the change of chirality of MgO:PPLN can be achieved by altering the direction of the applied electric field.

Comparing the pink and blue curve in Fig. 4(a) or 4(b), we find that they are almost of the same shape, which reveals that light experience the same rotation process, verifying that optical propagation is reciprocal in MgO:PPLN. The small shift between these two curves is probably caused by the temperature fluctuation during the experiment, which induces the variation of the QPM wavelength. The electric field where the maximum and minimum transmissions occur is actually larger than the theoretical expectation due to several reasons. The overriding reason is that the external electric field is generated by use of a pair of parallel copperplates, which requires extreme closeness to the MgO:PPLN crystal. During the experiment we found that by slightly pressing the copperplates toward the MgO:PPLN crystal, less external electric field was required to obtain the same rotation angle. However, we did not perform strong pressure on them and

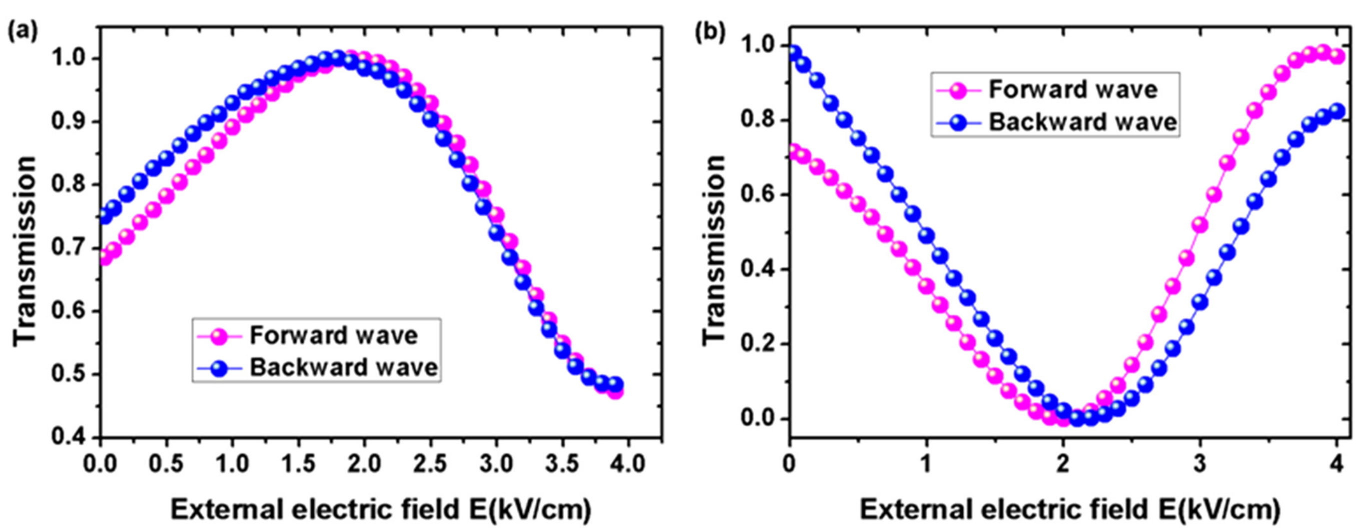

FIG. 4. Normalized transmissions of light traveling along +X (forward wave) and −X axis (backward wave) in MgO:PPLN. (a) The transverse electric field is applied along +Y axis. (b) The transverse electric field is applied along −Y axis.

the pressure was different for each time, which resulted in incomplete closeness between the PPLN sample and the copperplates and consequently led to the discrepancy. Second, the 45^0 dextrorotatory quartz we used is fabricated at the wavelength of 1550 nm. When the wavelength is 1568.5 nm, the rotation angle is 43.88°, which can be obtained from the formula $\phi = \alpha * d$, where ϕ is the rotation angle, α represents the specific rotation, and d stands for the thickness of quartz. Thereupon, the shift of rotation angle from the quartz gives rise to a shift in the applied electric field from the theoretical anticipations. The temperature fluctuation mentioned above is also responsible for the shift.

IV. CONCLUSIONS

In summary, we analyzed the chirality of MgO:PPLN by EO effect. With a transverse electric field applied on the MgO:PPLN, light rotates in the same sense during the forward and backward pass. Optical propagation in MgO:PPLN is shown to be reciprocal, which is similar to natural optical activity. The specific rotation of MgO:PPLN by EO effect is shown to be proportional to the transverse electric field, which makes the rotation angle easily adjusted as request. For a MgO:PPLN of 1 cm long and 10 μm wide, several volts are enough to make the polarization plane rotate 90 degrees. The large specific rotation makes large polarization rotation in optically active materials with small sizes possible. Besides, we also demonstrate the chirality control of MgO:PPLN by the external electrical field. The MgO:PPLN can be dextrorotatory or levorotatory under transverse electric field applied along different directions, which makes it an optically active material with multipurpose.

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