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Linear polarization-state generator with high precision in periodically poled lithium niobate

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In this letter, we propose a simple configuration capable of rotating a linear polarization state of light by a certain angle with high precision for a series of wavelengths. This is achieved in a compact one-chip integration of periodically poled lithium niobate (PPLN) by modulating the external electric field. During the experiment, the rotation angle varies between 0° and 100° with high precision of 0.04° and by changing the temperature of the PPLN the operating wavelength shifts with −0.51 nm/°C. The new device may find many applications where high precision control of linear polarization-state light is requested. © *2009 American Institute of Physics*.
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In the past decades, periodically poled LiNbO3 (PPLN), an artificial nonlinear material, received much attention owing to its outstanding nonlinear optical properties.[1–3] In PPLN, the nonlinear optical coefficient, the electro-optic (EO) coefficient, and the piezoelectric coefficient are modulated periodically due to the periodic domain inversion. Essential applications such as wavelength conversion,[4] narrow band solc-type filter,[5] and laser Q-switch[6] have been successfully proposed based on this structure. However, significantly less research focused on the potential of such structure for rotating a linear polarization state of light. In this paper, based on a theoretical analysis, experimental study of a new and simple device operating as a linear polarization-state generator with high precision is demonstrated in PPLN. In contrast with previous approaches for linear polarization-state generators by use of birefringence plates, liquid-crystal material,[7] and magneto-optic crystals,[8] the present scheme takes advantage of high precision with 0.04° and a compact one-chip integration in lithium niobate. Besides, the rotation angle is controlled by the external electric field, which is faster and more convenient. Furthermore, by changing the temperature of the PPLN within 40 °C, the operating wavelengths shift from 1546.02 to 1525.62 nm in the experiment, limited by the output range of the tunable laser.

EO effect of periodically poled LiNbO3 was first theoretically proposed by Lu *et al.*[9] Their study shows that with transverse electric field along PPLN, the optical axis of each domain is alternately aligned at the angles of $+\theta$ and $-\theta$ with respect to the plane of polarization of the input light and the optical axis of each domain will rotate continually with the increment in the electric field. Their study inspires a new thought to us by using this structure for rotating a linear polarization state of light. That is if each domain serves as a half-wave plate with respect to the input light. After passing through the stack of half-wave plates, the optical plane of polarization of the input light will rotate continually and emerge finally at an angle of $2N\theta$, where N is the number of domains. Besides, with the increment in the electric field, the final rotation angle of the input light will rotate correspondingly because the optical axis of the half-wave plates rotates continually with the electric field, which is similar to a birefringence half-wave plate rotated manually. The rocking angle θ here is proportional with the electric field and given by $\theta \approx \gamma_{51}E/[(1/n_e)^2-(1/n_o)^2]$, where n_o and n_e are refractive indices of the ordinary wave and the extraordinary wave, respectively, E is the electric field intensity, and γ_{51} is the EO coefficient.

For a given operating wavelength, $\gamma_{51}/[(1/n_e)^2-(1/n_o)^2]$ part is a very tiny constant value, which means the rocking angle of the optical axis of each domain can be extremely small, which enables the device an advantage of high precision over the birefringence plate with mechanical control. Meanwhile, because the operating wavelength, which satisfies the condition that each domain serves as a half-wave plate, is given by $\lambda_0=\Lambda(n_o-n_e)$ and is consequently temperature dependent,[10] where Λ is the period of PPLN. The operating wavelength can be extended to a series of different wavelengths by changing the temperature of PPLN.

The schematic of the experiment setup is shown in Fig. 1. During the experiment we first attempted to find out the input lights that satisfy the condition that each domain

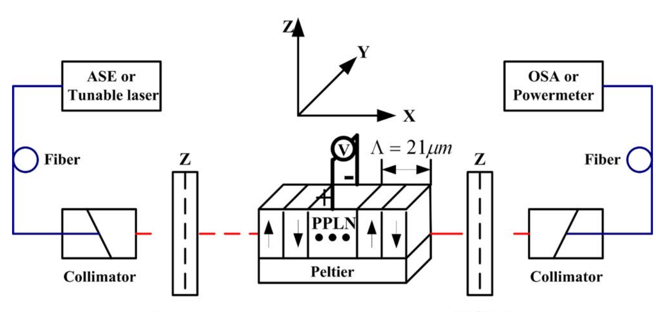

FIG. 1. (Color online) Experimental setup for linear polarization-state generator. The PPLN crystal, used for rotating the polarization angle is Z cut and consists of 2857 domains with the period of 21 (μm). The input light with a fixed polarization along the Z axis, propagates along the X axis. A uniform electric field is applied along the Y axis of PPLN. To change the temperature of PPLN, a peltier is placed under the PPLN sample.

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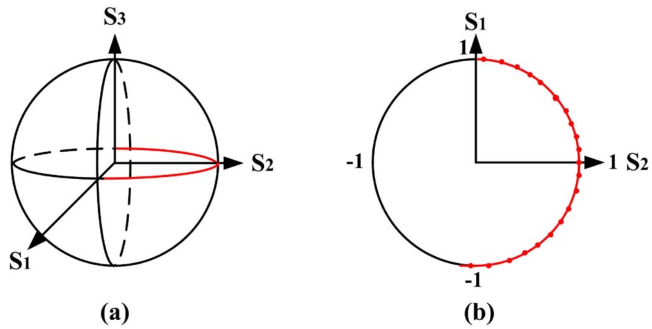

FIG. 2. (Color online) Experimental measurement of the state of polarization of the output light ($\lambda = 1543.47$ nm) on a Poincare sphere when varying the applied electric field from 0 to 3 kV/cm.

serves as a half-wave plate. After that, we observed the rotation angle of the input light at different electric fields. In the above discussion, we knew that the operating wavelengths will remain in the linear state of polarization after passing through the PPLN crystal, because each domain serves as a half-wave plate with respect to them. Therefore, the operating wavelengths can be determined by checking whether the state of polarization of the output light is linear by rotating the analyzer. With this method, the operating wavelength at the temperature of 15 °C is found out to be 1543.47 nm.

Experimental measurement of the state of polarization of the output light ($\lambda = 1543.47$ nm) is shown on a Poincare sphere when varying the applied electric field. The experiment shows that the state of polarization remains on the equatorial plane when changing the electric field as shown in Fig. 2, which indicates that the output light remains in the linear state of polarization. The corresponding rotation angle at each electric field is shown in Fig. 3, where the electric field intensity is tuned from 0 to 3 kV/cm, with the step of 0.1 kV/cm each time and the rotation angle varies between 0° and 100°. From the figure we can see that the rotation angle has a linear relation with the external electric field, which shows agreement with the theory. The experimental result also indicates that there is already a rocking angle between the optical axes of the positive and negative domains when not applying electric field, which may be caused by the photovoltaic effect[11] or strain-optic effect.[12] From the figure, we can also learn that for obtaining a given rotation angle, the theoretical results need less electric field than the experimental results, which is due to several reasons. First, the real refractive indices of this PPLN sample employed in the experiment inevitably have a deviation with the theoretical values calculated by the Sellmeier equation[10] and the real EO coefficient also varies with different PPLN crystals in practice, which consequently contribute to the discrepancy. Second, the external electric field is generated by use of a pair of parallel copperplates, which requires extreme closeness to the PPLN crystal. During the experiment we found that by slightly pressing the copperplates toward the PPLN crystal, less external electric field was required to obtain the same rotation angle. However, for consideration of possible damage to the PPLN, we did not perform strong pressure on them, which resulted in incomplete closeness and consequently led to the discrepancy. Actually, by using more accurate EO coefficient and indices in the theoretical calculation and achieving complete closeness between the copperplates and the PPLN in the experiment, the discrepancy will vanish.

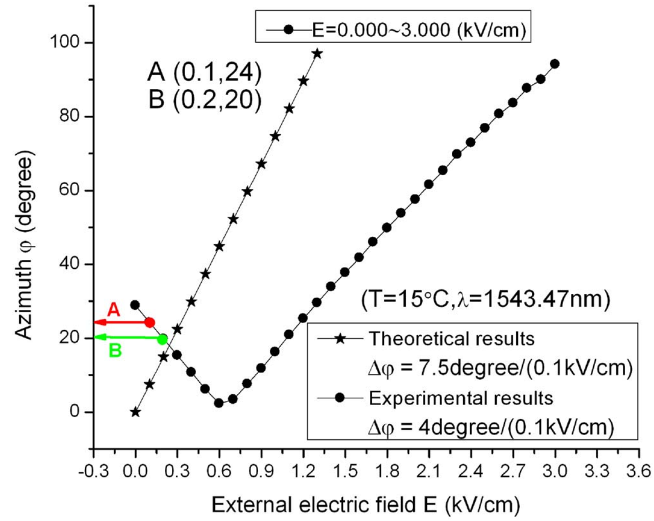

FIG. 3. (Color online) Experimental measurement of the rotation angle of the output light ($\lambda = 1543.47$ nm) when varying the applied electric field from 0 to 3 kV/cm.

The greatest advantage of such linear polarization-state generator is capable of rotating a linear polarization state of light by a certain angle with high precision, which is shown in Fig. 4. In the experiment, different precision has been achieved by reducing the electric field. In Fig. 3, the electric field is tuned with the step of 0.100 kV/cm each time and the rotation angle varies with the step of 4° each time. In order to obtain higher precision, between (A) 0.100 and (B) 0.200 kV/cm, we reduce the electric field step to 0.010 kV/cm each time and the precision is improved to 0.4°, which is shown in Fig. 4(a). Similarly, by further reducing the electric field step

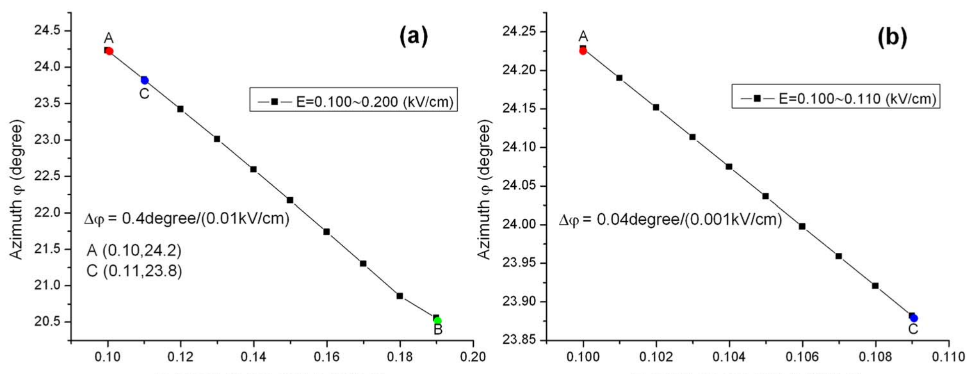

FIG. 4. (Color online) Experimental measurement of the rotation angle of the output light ($\lambda = 1543.47$ nm) when varying the applied electric field with smaller step. (a) The external electric field varies from 0.100 to 0.200 kV/cm. (b) The external electric field varies from 0.100 to 0.110 kV/cm.

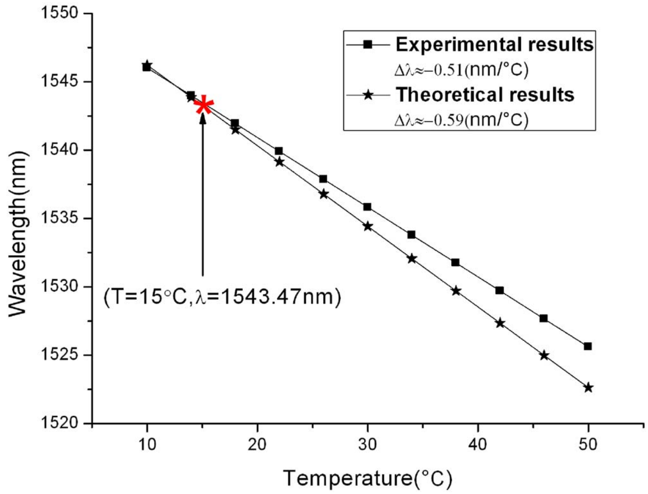

FIG. 5. (Color online) Experimental measurement of the operating wavelengths at different temperatures

to 0.001 kV/cm between (A) and (C), a higher precision with 0.04° is achieved in Fig. 4(b), limited by the accuracy of the measurement system. Actually, higher precision is still possible if we continue to reduce the electric field step.

During the experiment, we also found the operating wavelengths at different temperatures by using a tunable laser (Fig. 5). The experimental temperature dependence shows $d\lambda/dT \approx -0.51$ nm/°C, which shows agreement with the theoretical results $d\lambda/dT \approx -0.59$ nm/°C. By tuning the temperature from 10 to 50 °C, the operating wavelength varies from 1546.02 to 1525.62 nm, with a band of 20 nm, limited by the output range of the tunable laser. If we change the temperature to a wider range of 300 °C, a broader band of 150 nm is still available.

It should be noted that the Ti-indiffusion PPLN waveguide has been successfully proposed recently.[13] In the waveguide configuration, the gap between the electrodes can be as short as 10 (μm), so that only several voltages are enough for such linear polarization-state generator.

In conclusion, we proposed a new method of rotating a linear polarization state of light by a certain angle with high precision for a series of wavelengths. Both the theory and experiment show that the rotation angle has a linear relation with the external electric field. By managing the electric field, a high precision with 0.04° is achieved in the experiment. Besides, by changing the temperature of PPLN the operating wavelengths can be extended to a wider range. The device may find many applications ranging from polarization analysis to monitoring of network performance, material birefringence, and measurement of polarization mode dispersion, swept-wavelength measurement, medical imaging, and fiber sensor systems.

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[1] S. Bains, Laser Focus World **34**, 16 (1998).
[2] G. A. Magel, M. M. Fejer, and R. L. Byer, Appl. Phys. Lett. **56**, 108 (1990).
[3] J. J. Zheng, Y. Q. Lu, G. P. Luo, J. Ma, Y. L. Lu, N. B. Ming, J. L. He, and Z. Y. Xu, Appl. Phys. Lett. **72**, 1808 (1998).
[4] C. Q. Xu, H. Okayama, and M. Kawahara, Appl. Phys. Lett. **63**, 3559 (1993).
[5] X. F. Chen, J. H. Shi, Y. P. Chen, Y. M. Zhu, Y. X. Xia, and Y. L. Chen, Opt. Lett. **28**, 2115 (2003).
[6] Y. H. Chen and Y. C. Huang, Opt. Lett. **28**, 1460 (2003).
[7] Z. Z. Zhuang, Y. J. Kim, and J. S. Patel, Appl. Phys. Lett. **76**, 3995 (2000).
[8] X. S. Yao, Opt. Lett. **30**, 1324 (2005).
[9] Y. Q. Lu, Z. L. Wan, Q. Wang, Y. X. Xi, and N. B. Ming, Appl. Phys. Lett. **77**, 3719 (2000).
[10] D. H. Jundt, Opt. Lett. **22**, 1553 (1997).
[11] L. J. Chen, J. H. Shi, X. F. Chen, and Y. X. Xia, Appl. Phys. Lett. **88**, 121118 (2006).
[12] T. J. Wang and J. S. Chung, Appl. Phys. B: Lasers Opt. **80**, 193 (2005).
[13] Y. L. Lee, Y. Noh, C. Kee, N. E. Yu, W. Shin, C. Jung, D. Ko, and J. Lee, Opt. Express **16**, 13699 (2008).