Optical isolation based on Faraday-like effect in periodically poled lithium niobate with odd number of domains tailed with a semi-domain

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We observe the phenomenon of the Faraday-like effect, which occurs in periodically poled lithium niobate with odd number of domains (OPPLN) by the transverse electro-optic (EO) effect under the quasi-phase-matching condition. In this case, light rotates in the reverse sense during the forward and the backward path, and OPPLN shows a nonreciprocal process that is similar to the magneto-optical Faraday effect, which has served as a routine method for achieving optical isolation. Therefore, a feasible scheme for an EO optical isolator based on the Faraday-like effect by adding an additional semi-domain to OPPLN is also proposed in this article.

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1. INTRODUCTION

The Faraday effect, a magneto-optical phenomenon, causes a rotation of the plane of polarization that is linearly proportional to the component of the magnetic field in the direction of propagation and is identified as a powerful tool in measuring instruments for remote sensing of magnetic fields [1,2], spintronics research to study the polarization of electron spins in semiconductors [3,4] and modulation field to modulate amplitude of light [5]. It originates from the relative phase shift between the left and right circularly polarized light induced by the magnetic field, a property known as circular birefringence. Unlike what happens in an optically active medium such as quartz, light rotates in the reverse sense during the forward and backward pass. Reflecting a polarized light back through the same Faraday medium does not undo the same polarization change in its forward path. In other words, the magneto-optical Faraday effect is a nonreciprocal process. The nonreciprocal property in the magneto-optical Faraday effect has been fully made use of and is still considered one of the basic principles in optical isolation [6–10].

We have previously proved that the periodically poled lithium niobate (PPLN) with an even number of domains (EPPLN) shows optical activity similar to an optically active medium such as quartz [11] by the transverse electro-optic (EO) effect under the quasi-phase-matching (QPM) condition. However, it will be a different case in PPLN with an odd number of domains (OPPLN). The optical activity similar to the magneto-optical Faraday effect, which we call the "Faraday-like effect," occurs in OPPLN. The existence of the Faraday-like effect is confirmed experimentally by observing separately the reverse optical rotation in the forward and backward path through the OPPLN in the presence of a transverse electric field under the QPM condition. This phenomenon is the EO analogue of the magneto-optical Faraday effect whereby the polarization plane of an electromagnetic wave is rotated by a magnetic field applied along the direction of propagation. Besides, with the assistance of the Faraday-like effect, we take a further step to propose a feasible scheme for realizing optical isolation in an OPPLN tailed with an additional semi-domain, which takes the advantage of being used in a weak-light system with low driving voltage.

2. THEORETICAL ANALYSIS

PPLN is a typical QPM material and plays an essential role in compensating the phase mismatching in frequency conversion, optical switching, pulse shaping, and other nonlinear optical processes [12–14]. Lu *et al.* [15] in 2000 proposed that the polarization plane of linearly polarized light propagating in PPLN can rotate linearly by a transverse electric field when QPM condition is satisfied. For a linearly polarized light traveling along PPLN, a transverse electric field brings about a deformation of the refractive-index ellipsoid in PPLN. Consequently, y and z axes of the refractive-index ellipsoid rotate an angle of θ around the x axis. The rocking angle θ here is proportional to the transverse electric field and is given by $\theta = \gamma_{51} E_y / [(1/n_e)^2 - (1/n_o)^2]$, where E_y is the transverse electric field, γ_{51} is the EO coefficient, and n_o and n_e are refractive indices of the ordinary and extraordinary wave, respectively. Optical axes of each domain are alternately aligned at an angle of $+\theta$ or $-\theta$ with respect to the original ones, due to the periodic modulation of the EO coefficient. Under the QPM condition, each domain serves as a half-wave plate with respect to the input light. After passing through a pile of rotated half-wave plates, the input light emerges with the polarization plane at an azimuth angle of $2N\theta$ relative to the original plane, where N is the number of domains. By increasing the electric field, the rotation angle of the input light will increase correspondingly since the optical axes of the half-wave plates rotate continually with the electric field, which bear similarity to a birefringence half-wave plate rotated manually. In our previous work, under the condition of unchangeableness of the direction of transverse electric field, the reciprocal process in an EPPLN based on the transverse EO effect has been confirmed experimentally, which resembles natural optical activity. The direction of the plane of polarization of emergent light in the backward pass restores to the original direction of polarization in its forward pass; in other words, the light rotates in the identical sense during the forward and the backward path. However, as well as the condition of direction of transverse electric field being unchanged, it will be a completely opposite occurrence from the linearly polarized light passing through a PPLN with an odd number of domains in a round trip. The light rotates in the reverse sense during the forward and the backward path. Such a kind of accumulated process of rotation of polarization, which is a nonreciprocal process, is similar to the magneto-optical Faraday effect, so we call it the "Faraday-like effect." The nonreciprocity is thus controlled by the oddness of domains in PPLN.

3. EXPERIMENTAL RESULTS

Figure 1 demonstrates the essential principle of the Faraday-like effect. A transverse electric field (E) is applied on the OPPLN [Fig. 1(a)] along the $+y$ axis. Looking along the $-x$ axis, the y and z principal axes experience R-rotation in positive domains and L-rotation in negative domains. For a z-polarized forward light that satisfies the QPM condition, the plane of polarization rotates an angle of $2N$ right-handedly after passing through N domains [Fig. 1(b)]. On the contrary, looking along the $+x$ axis, one observes that the y and the z axes undergo an L-rotation in positive domains and R-rotation in negative domains. Ultimately, a z-polarized backward light would have an L-rotation by $2N\theta$ at the output side. The plane of polarization thus rotates in the reverse sense during the forward and backward pass. Changing the direction of the electric field, the y and z axes and the plane of polarization of light will rotate reversely compared to that with the $+E$ applied electric field. The chirality of OPPLN is therefore controlled by the direction of the electric field. In the magneto-optical Faraday effect, the plane of polarization of light reverses after changing the direction of the magnetic field. The linearly polarized light thus goes through a polarization rotation similar to the Faraday rotation by EO effect in OPPLN.

The rotation angle of the *polarized* light after passing through the OPPLN is $\beta = 2L\gamma_{51}E/[\Lambda((1/n_e)^2 - (1/n_o)^2)] = V_e EL$, where Λ is the thickness of the domain and L is the length of the OPPLN. In contrast to magneto-optical the Faraday effect, whose rotation angle is proportional to the magnetic field with a proportionality constant V_e, the rotation angle in the Faraday-like effect is proportional to the electric field. The proportionality constant here, which we call the electric Verdet constant, in analogy with the Verdet constant in magneto-optical Faraday effect, is defined as $V_e = 2\gamma_{51}/[\Lambda((1/n_e)^2 - (1/n_o)^2)]$ and is relevant to the wavelength, temperature, and material. Compared with the magneto-optical Faraday effect that produces a linear modulation of the rotation angle as a function of magnetic field, the Faraday-like effect produces one as a function of electric field. For a MgO:OPPLN with 3655 domains, whose thickness is 9.85 μm and duty cycle is 1, our experimental measurement, as presented in Fig. 2, shows that the electric Verdet constant is about 2.1×10^2degree $(\mathrm{cm})^{-1}$ $(\mathrm{V}/\mu\mathrm{m})^{-1}$ for wavelength of 1542 nm at a temperature of 20°C. Under the same working conditions, the electric Verdet constant can in theory be as large as 2.5×10^2degree $(\mathrm{cm})^{-1}$ $(\mathrm{V}/\mu\mathrm{m})^{-1}$, far easier to achieve than the normal magneto-optical Faraday effect [16]. We also observe an instinctive nonzero rotation of the plane of polarization even without the electric field. This is probably caused by the incomplete antiparallel between the optical axes of

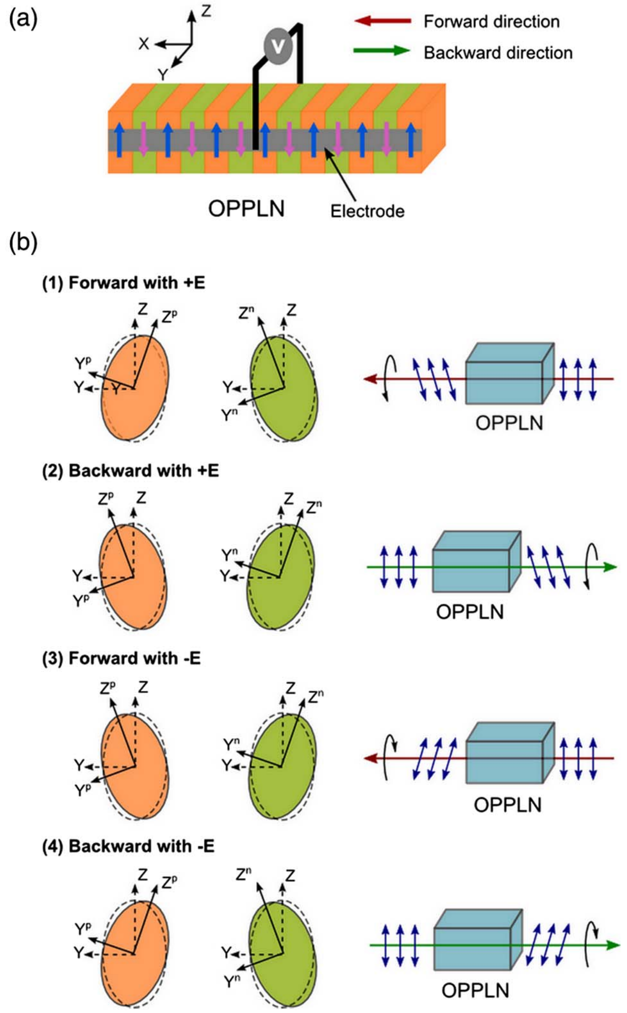

Fig. 1. Schematic diagram of Faraday-like effect. (a) Structure of OPPLN. The OPPLN is z-cut. The arrows inside the OPPLN indicate the spontaneous polarization directions. (b) Observed rotation of the principal axes and final rotation direction of the polarization direction when a transverse electric field is applied. Deformation of the index ellipsoid is observed for a forward (light traveling along the $+x$ axis) and backward (light traveling along the $-x$ axis) light under an $+E$ electric field (+ and − represent transverse electric field along $+y$ and $-y$ axis). x, y, and z represent the principal axes of the original index ellipsoid. $y^{p,n}$ and $z^{p,n}$ are the perturbed principal axes of positive and negative domains, respectively. The incident light is z-polarized.

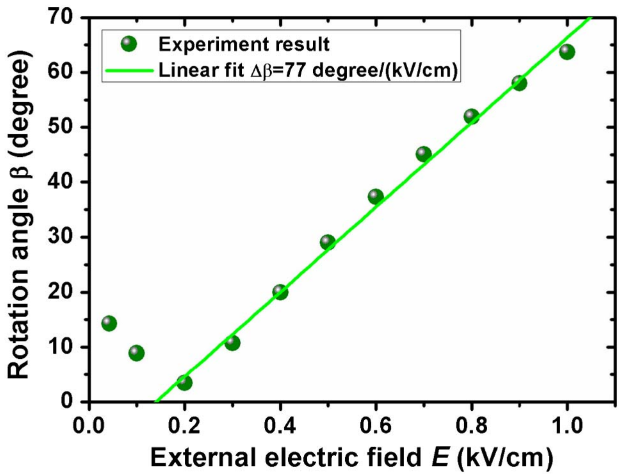

Fig. 2. Experimental measurement of the electric Verdet constant. The electric Verdet constant is given as the quotient of the slope of the rotation angle versus electric field curve divided by the interacting length of light in OPPLN.

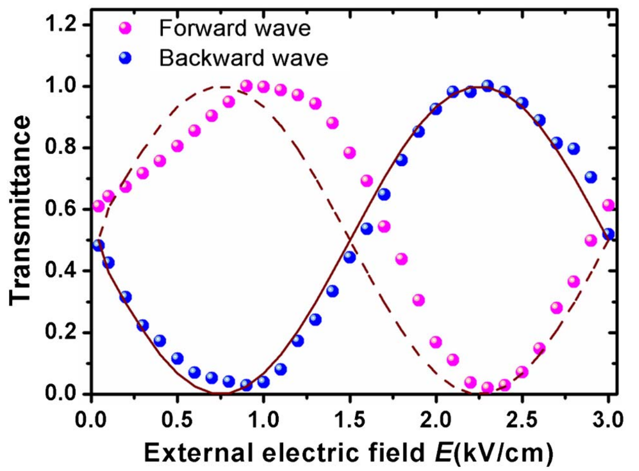

Fig. 4. Normalized transmittance of forward and backward light in MgO:PPLN. The MgO:OPPLN sample and working environment are the same as those in the electric Verdet constant measurement. Pink and blue bubbles represent experiment results, and the dash and solid line represent standard sinusoid and cosinusoid.

positive and negative domains of the PPLN. The imprecise fabrication of PPLN may introduce a small angle between the optical axes of positive and negative domains, which brings about the rotation of the polarization plane of light. A positive electric Verdet constant corresponds to L-rotation in the presence of $+E$ and to R-rotation with $-E$.

The experiment to demonstrate the Faraday-like effect was carried out as depicted in Fig. 3. A tunable laser worked as the light source. Two PBSs were set perpendicularly to work as a polarizer and an analyzer, respectively. A MgO:OPPLN crystal was placed between the two PBSs. The incident light was z-polarized in the forward [Fig. 3(a)] or backward pass [Fig. 3(b)]. In order to observe the reverse optical rotation, an optically active material should be utilized. A 45° dextrorotatory quartz plate was employed in this experiment. We measured the transmittance of the forward and backward light with $+E$, which were expressed as $T_{\lambda}^{\pm} = \sin 2(\pi/4 \pm 2N\theta)$, where + and − represent the forward and the backward light, respectively. The experimental result is shown in Fig. 4. The pink and the blue curves represent the transmittance of the forward and the backward light, respectively. Owing to the dextrorotatory quartz, the transmittance of light in the forward and backward path roughly

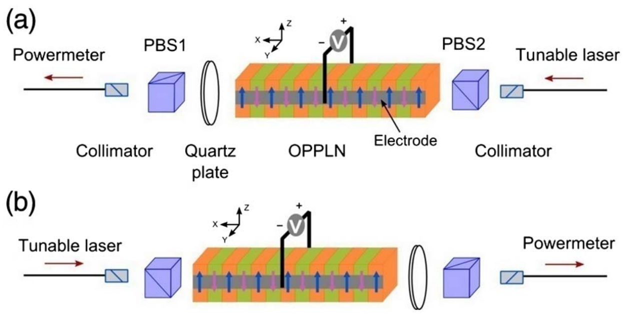

Fig. 3. Experimental setup for demonstrating the Faraday-like effect in MgO:OPPLN. The MgO:OPPLN crystal is z cut. A uniform electric field is applied on MgO:OPPLN along the $+y$ axis. Two polarization-beam-splitters (PBSs) are placed perpendicularly to each other. (a) Forward path: PBS1 y-oriented, PBS2 z-oriented. (b) Backward path: PBS1 z-oriented, PBS2 y-oriented.

satisfies the Pythagorean identity: the former in a shape of sinusoidal function, the latter cosine function. Transmittance of the forward light gets its maxima when the backward light is in its minima and vice versa. With the external electric field being increased from 0, transmittance of the forward light reaches its maxima first, indicating a rotation of the polarization plane of about 45° right-handedly from the MgO:OPPLN, while the backward light gets its minimum transmittance first, implying that light undergoes an L-rotation from the MgO:OPPLN. We thereupon conclude that light rotates in the reverse sense in the Faraday-like effect. Changing the direction of the electric field, transmittance curves of the forward and the backward light exchange their shape but still satisfy the Pythagorean identity. The exchange indicates the change of chirality, which is similar to the magneto-optical Faraday effect. Increasing the electric field restores the transmittance form periodically.

The small shift in the applied electric field where the maximum and the minimum transmittance occur can be attributed to two possible reasons. The first and foremost reason is that the temperature fluctuates during the experiment, yielding a variation of the QPM wavelength. Besides, the 45° dextrorotatory quartz we used is fabricated at the wavelength of 1550 nm. For the wavelength 1542 nm, however, its rotation angle is 45.5°, which can be obtained from the formula $\varphi = \alpha * d$, where φ is the rotation angle, α is the specific rotation that varies with wavelength, and d is the thickness of quartz. As a result, lower electric field is required to obtain maximum transmittance for the forward light and higher electric field for the backward light to obtain its minima. The result is consistent with the anticipated theory, indicating that our idea is convincing and reliable.

Generally, when the electric field is applied along the $+y$ axis, for a forward and a backward light incident with the azimuth angle of $x_f\theta$ and $x_b\theta$, respectively, the rotation angles of light after passing through N domains are $y_f = 2(N - x_f)\theta$ and $y_b = -2(N + x_b)\theta$. Thereupon, light transmits out of the OPPLN with the azimuth angle of $\varphi_f = (2N - x_f)\theta$ and $\varphi_b = -(2N + x_b)\theta$. The value for $x_f\theta$ and $x_b\theta$ ranges from $-\pi$ to π. For $x_{f,b}$ and $\varphi_{f,b}$, a positive value corresponds to

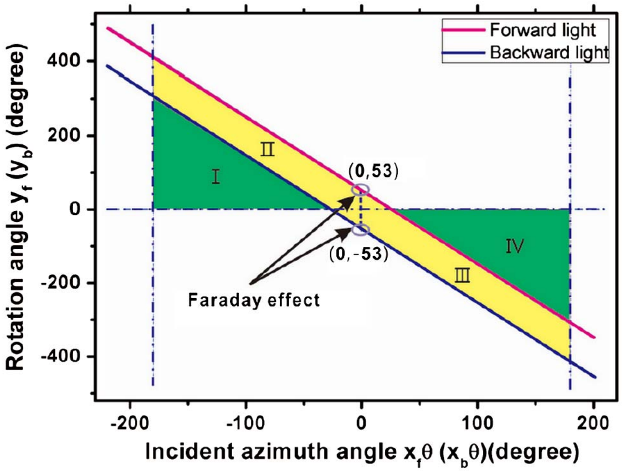

Fig. 5. Variations of the rotation angle with the incident azimuth angles the forward and the backward light. The MgO:OPPLN sample and working environment are the same as the previous description. Green and yellow regions represent the range of the incident azimuth angle of the forward or backward light that satisfies the Faraday-like effect condition.

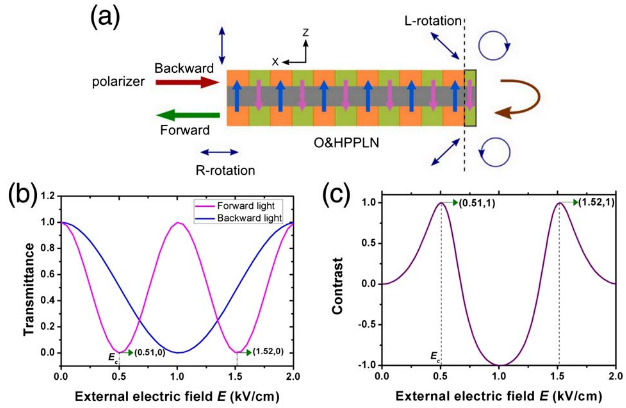

Fig. 6. Schematic diagram of an EO optical isolator based on Faraday-like effect. (a) Evolution process of the polarization state of light in the EO isolator. The arrows in blue indicate the polarization plane of the linearly polarized light, and the circles with an arrow represent circularly polarized light. (b) Normalized transmittance of the forward and backward light T_f and T_b as a function of the electric field. (c) Contrast ratio as a function of the electric field.

the plane of polarization on the right side of $+z$ axis and a negative value corresponds to that on the left side. For $y_{f,b}$, a positive rotation angle means R-rotation and a negative one means L-rotation. For an OPPLN with 3655 domains, the changes of the rotation angle with the incident azimuth angle for the forward and backward light are shown in Fig. 5. It is easily understood that the sign of y_f and y_b should be kept opposite when the Faraday-like effect occurs, which we call the Faraday-like effect condition. As can be seen from the figure, there are two possible regions that satisfy the Faraday-like effect condition: region I & II and III & IV; region I and IV. When x_f and x_b locate in region I & II and III & IV, respectively, $y_f > 0$ and $y_b < 0$, which obviously meets the Faraday-like effect condition, while in region I and IV, the incident azimuth angles make y_f and y_b different by $y_b > 0$ and $y_f < 0$. We also note that when x_f and x_b are zero, y_f is exactly the opposite number of y_b. In the magneto-optical Faraday effect, $y_f = -y_b$ and $\varphi_f = -2\varphi_b$ for all x_f and x_b. So this is a special case in the Faraday-like effect that most resembles the magneto-optical Faraday effect as the principle shown in Fig. 1. The opposite sign of φ_f and φ_b is caused by the different observation points in the forward and the backward path; the planes of polarization are actually in the same side of the z axis in space. We see that these two equations are not exactly satisfied in the Faraday-like effect, whereas a similar isolation effect is still observed.

The Faraday-like effect can also be applicable to the optical isolation by upgrading the composing of domains in OPPLN as depicted in Fig. 1(a). The new type is shown in Fig. 6(a). An additional semi-domain, whose thickness is half of a single domain and acts as a quarter-wave plate is added to the OPPLN to make an OPPLN with a semi-domain (O&HPPLN). Light passing through a quarter-wave plate twice has the same effect as that passing through a half-wave plate. For a z-polarized incident light traveling along the $-x$ axis, $x_b\theta$ is equivalent to zero. When the electric field is applied along the $+y$ axis, light experiences a rotation of $y_b = -2N\theta$ after passing through N domains and emerges at an azimuth angle of $\varphi_b = -2N\theta$; moreover, the linearly polarized light then becomes R-rotation circularly polarized after passing through the semi-domain. However, when it returns and passes through the semi-domain acting as a quarter-wave plate again, the polarization plane of light is adjusted from the left side of $+z$ axis to the right side, due to the different observation points in the forward and the backward path. The azimuth angle of the incident linearly polarized light in the reflected pass is then $x_f = -2N\theta - 2\theta$. Light afterward undergoes a rotation of $y_f = 2(3N+2)\theta$ and transmits out with the azimuth angle of $\varphi_f = (4N+2)\theta$, where 2θ is usually so small that it can be omitted. It is obvious that $\varphi_f = -2\varphi_b$. Thus, the overall effect is that light rotates in the reverse sense during the forward and the backward path and the rotation doubles after a round trip, which is just what happens in optical isolation based on Faraday effect.

For a z-polarized light, transmittance of the backward and forward light along the $+z$ axis can be measured by using the same schematic in Fig. 3. They are $T_b = \cos^2(2N\theta)$ and $T_f = \cos^2(4N\theta + 2\theta)$, as simulated in Fig. 6(b). When the electric field approaches the critical point of $E_c = 0.51$ kV/cm, transmittance of the forward light is zero, implying a total block of the forward reflected light, which is exactly where perfect isolation occurs. According to the definition $C = (T_b - T_f)/(T_b + T_f)$, we obtain the contrast ratio versus external electric field as shown in Fig. 6(c), which gives a straightforward view of the isolation effect. The contrast ratio is smoothly tuned from −1 to 1 with the increase of the electric field. When the electric field is modulated to the critical point of E_c, the contrast ratio can reach 1, indicating a complete isolation. Optical isolation is also available under other electric field like $E_c = 1.52$ kV/cm. By continuing to raise the electric field, we can obtain a similar tunable characteristic. That is, we should now be in a position to realize optical isolation from an EO perspective.

Early attempts to realize nonmagnetic isolators by the use of photonic crystals [17–21] have a limitation in that the required optical intensity is usually strong due to the relatively small nonlinear optical coefficients of unconventional materials. In our proposal, the isolator is controlled by external electric field, taking the advantage of being used in a weak-light system. In the waveguide configuration, the width of the O&HPPLN can be as small as 10 μm, that several volts are enough to make the polarization rotate by 45°, which is very attractive for practical applications. The working wavelength of the EO optical isolator is available by designing the thickness of the domain in PPLN. Besides, the wavelength is temperature-dependent, making it more flexible to be adjusted.

4. CONCLUSIONS

In conclusion, we proposed optical activity in OPPLN called the Faraday-like effect, which is analogous to the magneto-optical Faraday effect by EO effect. The existence of the Faraday-like effect is experimentally verified by observing the reverse optical rotation induced by a electric field under QPM condition. We therefore anticipate that the Faraday-like effect will bring a new vision to people in optical isolation and other optical applications.

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