Optical vortex converter with helical-periodically poled ferroelectric crystal

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Abstract: A kind of optical vortex converter is proposed in helical-periodically poled ferroelectric crystal based on transverse electro-optics effect. It can be used to generate optical vortex from non-vortex beam and transform the topological charge of optical vortex. An optical vortex adder or substrator is proposed under the control of electric filed. This device will find its applications in high dimensional communication system for signal processing and optical manipulation in micro and mesoscopic scale.

OCIS codes: (190.0190) Nonlinear optics; (080.4865) Optical vortices; (160.2100) Electro-optical materials.

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1. Introduction

Light beam may carry both spin angular momentum (SAM) and orbital angular momentum (OAM) [1]. The SAM is associated with circular polarization and arises from the spin of individual photon with a value of $\hbar$ or $-\hbar$, for the left- or right-handed circular polarized light, respectively [2]. In contrast, OAM arises from the spiral phase distribution at the wavefront of a beam [3]. The helical phase structure of light, commonly called as an optical vortex, is described by a phase cross section of $\exp(il\theta)$, where l can take any integer value, referred to as the topological charge(TC). Every photon in such a beam carries OAM of $l\hbar$. The optical vortices have drawn great interest because they are of importance for understanding fundamental physics and of a number of promising scientific applications ranging from optical manipulation [4] to single-cell nanosurgery [5], superhigh-density optical data storage [6], quantum information processing [7,8], cryptography [9]. The control of optical vortex is of great significance for such applications, especially for the management of transfer between optical vortices with different TC. Although vortex beams occur naturally as higher order modes of laser cavities and optical fibers with beam shaping techniques to control their properties, they are mostly generated by some linear optical methods, i.e., mode converters [10], spiral Fresnel zone plates [11], spiral phase plate [12], fork hologram [13], q-plate [14], as well as some nonlinear optical process, specifically in second harmonic generation [15,16], parametric down-conversion [17,18], where a vortex beam is generated by another (already-present) vortex beam. Recently, *Bahabad et al* propose an idea that a vortex beam can be generated from a fundamental beam that contains no singularity with a helical-periodically poled ferroelectric crystal [19]. However, the forementioned methods for the transformation of TC are limited, and thus a more tunable method is desired.

In this paper, a kind of voltage-controlled optical vortex converter is proposed in a helical-periodically poled ferroelectric crystal, for example helical-periodically poled $LiNbO_3$(HPPLN), marked with a TC *l’*. When the incident optical vortex with TC *l* is ordinary light, thanks to the transverse electro-optics effect, the external electric field can add the TC of crystal to extraordinary light, identified by $l+l'$, hence the HPPLN works as an optical vortex adder. On the other hand, the HPPLN can also work as an optical vortex substractor for the extraordinary incidence, and the TC of output ordinary light is identified by $l-l'$. If there is no external electric field, the TC of output optical vortex remains *l*. Meanwhile, the optical vortex come from HPPLN can be served as a voltage-controlled optical spanner.

2. Theory

The transverse electro-optic effect is a nonlinear interaction between a light field and an external electric field. We assume that a monochromatic light with frequency ω is incident along the x-axis of the crystal and the external electric field is applied along the y-axis (Fig. 1), and thus the total electric field can be written as

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$$\mathrm{E}(x,t)=\mathrm{E}(x,\omega=0)+[\mathrm{E}^{\omega}(x)\exp(-i\omega t)+\mathrm{E}^{\omega}(x)\exp(i\omega t)]/2, \qquad (1)$$

where $E(x,\omega=0)$ stands for the dc electric field. The second term of r.h.s of Eq. (1) represents for the light field, which, in our case, has an ordinary component and an extraordinary one, i.e., $\mathrm{E}^{\omega}(x)=\sum_{i=1}^{2}\sqrt{\omega/n_i}A_i(x)\exp(ik_i x)$,where (A_1,A_2) are the normalized amplitudes of ordinary and extraordinary light respectively, while (n_1,n_2) and (k_1,k_2) are their refractive index and wave-vector respectively. By substituting the Eq. (1) into the Maxwell equations, one arrives at the following coupled wave equations for the two components [20],

$$\begin{cases} dA_1(x)/dx=-i\kappa\cdot g(r)A_2(x)\exp(i\Delta k' x)-i\nu_1\cdot g(r)A_1(x) \\ dA_2(x)/dx=-i\kappa\cdot g(r)A_1(x)\exp(-i\Delta k' x)-i\nu_2\cdot g(r)A_2(x) \end{cases}. \qquad (2)$$

Here, $\Delta k'=k_2-k_1$, $\kappa=k_0 r_{51}E_y/2\sqrt{n_1 n_2}$, is polarization coupling coefficient, where r_{51} is the electro-optic coefficient, E_y is the external electric field, $\nu_1=k_0 r_{eff1}E_y/2n_1$, $\nu_2=k_0 r_{eff2}E_y/2n_2$, r_{eff1} and r_{eff2} are the effective electro-optic coefficients, $g(x)$ is the structure function of the material. Usually in the one dimensional quasi-matched-phase (QPM) material [21], $g(x)$ is a periodic function, whose value is $+1$ when x falls in the positive domains of the crystal while -1 when x falls in the negative domain(Fig. 1(a)). By performing a Fourier transformation of $g(x)$, one finds its Fourier coefficients,

$$G_m=\begin{cases} \dfrac{1}{i\pi m}[1-\cos(2\pi mD)+i\sin(2\pi mD)] & (m\neq 0) \\ 2D-1 & (m=0) \end{cases}, \qquad (3)$$

where $D=a/\Lambda$ is the duty cycle, and a is the thickness of positive domain [20].

Here, different from the previous work, we introduce a transverse modulation of function into $g(x)$, thus, instead of $g(x)$, we have $g(r)=g(x+f(y,z))$, in which the transverse function $f(y,z)$ acts as a phase translation factor under the one-dimensional Fourier transform in Eq. (3), and thus $g(r)$ can be written as a Fourier series $g(r)=\sum_{m=-\infty}^{+\infty}G_m\exp(if(y,z)\alpha_m)\exp(i\alpha_m x)$, where $\alpha_m=2\pi m/\Lambda$. Substitution of our g(r) into Eq. (2) leads to the following equations

$$\begin{cases} dA_1(x)/dx=-i\kappa_q A_2(x)\exp(i\Delta kx)-i\nu_{1q}A_1(x) \\ dA_2(x)/dx=-i\kappa_q^{*}A_1(x)\exp(-i\Delta kx)-i\nu_{2q}A_2(x) \end{cases}, \qquad (4)$$

where $\Delta k=\Delta k'+\alpha_m$, $\kappa_q=\kappa G_m\exp(if(y,z)\alpha_m)$, $\kappa_q^{*}=\kappa G_{-m}\exp(if(y,z)\alpha_{-m})$, $\nu_{1q}=\nu_1 G_0$. To get maximal G_m, $D=50\%$ is used following, which means that $G_0=0$ and thus $\nu_{1q}=\nu_{2q}=0$. Therefore, the second terms of r.h.s of Eq. (4) vanish and the corresponding solution is then given by,

$$\begin{cases} A_1(L)=\exp[i(\Delta k/2)L]\{[\cos(sL)-i\Delta k/(2s)\sin(sL)]A_1(0) \\ \qquad -i(\kappa_q/s)\sin(sL)A_2(0)\}, \\ A_2(L)=\exp[-i(\Delta k/2)L]\{-i(\kappa_q{}^*/s)\sin(sL)A_1(0) \\ \qquad +[\cos(sL)+i\Delta k/(2s)\sin(sL)]A_2(0)\}, \end{cases} \tag{5}$$

where $s^2=\kappa_q\kappa_q^*+(\Delta k/2)^2$.

If we take $g(r)=sign\{\cos[\Delta k'/m(x+l'\theta/\Delta k)]\}$ (see Ref [19]. for possible experimental realizations for such a phase-twisted modulation) where $sign(x)=x/|x|$ for nonzero x, then $f(y,z)=l'\theta/\Delta k'$ and a kind of HPPLN is formed, as shown in Fig. 1 (b). Intuitively, the effects of these two coupling progresses in Fig. 1(c) and (d) are different, as the coupling directions are opposite with fixed chirality of HPPLN.

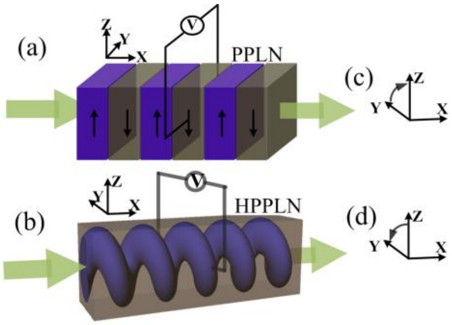

Fig. 1. Schematic diagram of transverse electro-optic effect in (a) periodically poled ferroelectric crystal and (b) helical-periodically poled ferroelectric crystal. (c) The coupling direction from ordinary light to extraordinary light in HPPLN. (d) The coupling direction from extraordinary light to ordinary light in HPPLN.

3. Optical vortex adder and substractor

Assuming that the input light is an ordinary light (this could be achieved by putting a horizontal polarizer in front of the HPPLN), the initial condition at x=0 is given by $A_1=\exp(il\theta)$, $A_2=0$.When the QPM condition is satisfied ($\Delta k=0$), the solution can thus be simplified into:

$$\begin{cases} A_1(L)=\cos(|\kappa_q|L)\exp(il\theta) \\ A_2(L)=-i\exp(i(l'+l)\theta)\sin(|\kappa_q|L) \end{cases}. \tag{6}$$

From Eq. (6), we can see that the output extraordinary light (A_2) possesses both the information of ordinary light and structure of material. The condition that $l'=l=0$, where the incident light is plane wave, and the nonlinear material is normal PPLN, has extensively investigated; in this case, Eq. (6) is reduced to that in PPLN [20,22,23].

In the following, without the loss of generality, the length of HPPLN is fixed as 2.1cm and the period is fixed as 21μm. We also set m =1, corresponding to a QPM wavelength 1.540μm, and γ_{51} =32.6 pm/V for LiNbO$_3$ crystal. Without the external electric field, there is no coupling between ordinary light and extraordinary light, and the output light is still the ordinary one with its original TC. However, when the external electric field is applied on HPPLN whose TC is l', the situation changes. Figure 2 (a) shows the phase distributions of incident ordinary light and the output extraordinary light. The first row shows the phase distributions of incident ordinary lights with different TC identified by l. The second, third and fourth row show the phase distribution of output extraordinary light from HPPLN with $l' = 1, 2, 3$, respectively. We can see that the TC of output extraordinary light is given by $l + l'$. Hence we achieve a kind of optical vortex adder controlled by external electric field, through which the helical poled property of material could be added to the light. We note that this method can be used to generate optical vortex from non-vortex beam and change the TC of already-present optical vortex.

If the input light is an extraordinary light which can be realized, for example, by putting a vertical polarizer in front of the HPPLN, the initial condition at x = 0 is given by $A_1 = 0$, $A_2 = \exp(il\theta)$. When the QPM condition is satisfied, the solution is be simplified to:

$$\begin{cases} A_1(L) = -i\exp(i(l-l')\theta)\sin(|\kappa_q|L) \\ A_2(L) = \cos(|\kappa_q|L)\exp(il\theta) \end{cases}. \tag{7}$$

From Eq. (7), one finds that the output ordinary light possesses the information of incident extraordinary light and structure of material. Figure 2(b) plots the phase distributions of incident extraordinary light and output ordinary light. The first row shows the phase distributions of incident extraordinary lights with different TC identified by l. The second, third and fourth row show the phase distribution of output ordinary light from HPPLN with $l' = 1, 2, 3$, respectively. One finds that the TC of output ordinary light is determined by $l - l'$. Hence we achieve a kind of optical vortex substractor controlled by external electric field, through which the helical poled property of material could be used to substract the TC of the incoming light.

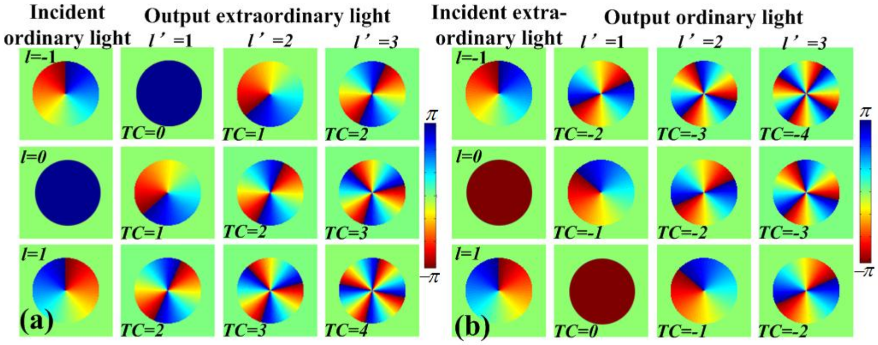

Fig. 2. (a) Phase distributions of incident ordinary light(first column) and output extraordinary light(column 2-4) with external electric field applied. The HPPLN works as an optical vortex adder. (b) Phase distributions of incident extraordinary light (first column) and the output ordinary light with external electric field applied (columns 2-4). The HPPLN works as an optical vortex substractor. l is the TC of incident light, and l' the TC of HPPLN.

4. Discussion

The coupling between ordinary and extraordinary light is controlled by external electric field. When the ordinary light is launched into the HPPLN, the amplitude of extraordinary light coupled from ordinary light is controlled by external electric field, as shown in Fig. 3(a). We can see that, when the external electric field rises to 0.831kV/cm, the ordinary vortex light with TC l can be fully transferred to extraordinary vortex light with TC $l + l'$. Although the OAM of each photon in extraordinary light is given by $(l + l')\hbar$, for the total light beam, the averaged OAM is given by $(N_0 l_o \hbar + N_e l_e \hbar)/(N_0 + N_e)$, where N_0 and N_e are numbers of

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extraordinary photons and ordinary photons, respectively. Note that the averaged OAM can be controlled by the external voltage, as shown in Fig. 3(b), where the dependence of the averaged OAM on the external electric field is plotted for the incoming vortex-less beam. One observes that the averaged OAM of the resulting light continuously increases with the increase of external electric field, and a maximum value of averaged OAM (i.e., $(l+l')\hbar$) is achieved under a suitable electric field when the whole incoming beam is fully transferred into extraordinary beam. Thus, our system can be used in a highly tunable optical spanners [24] where the torques due to the transfer of OAM of photons into particles can be controlled by the external field.

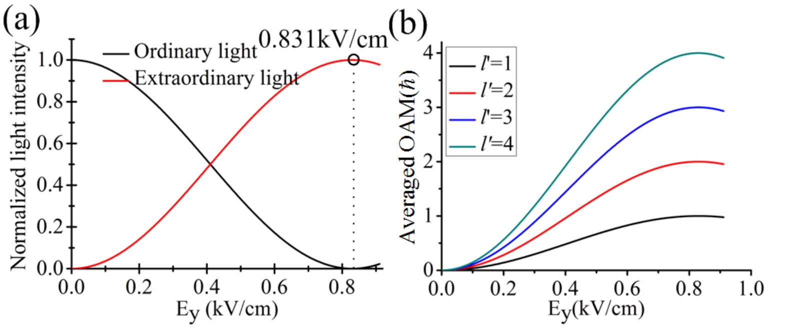

Fig. 3. (a) The normalized light intensity of output ordinary and extraordinary lights controlled by external electric field. (b)The averaged OAM of output light beam passing through the HPPLN with different TC controlled by external electric field.

Experimentally, a possible solution for constructing such HPPLN is by lapping and polishing electric-field poled ferroelectric materials into thin $\chi^{(2)}$-modulated planar plates, which has been reduced to the thickness as thin as 6.2 μm [25], and stacking them together [19]. Compared to other means of nonlinear modulation to optical vortex [15,19], the intensity of optical vortex in our scheme could be much lower because the coupling between ordinary light and extraordinary light is just determined by external electric field. Hence this method can be used to modulate low intensity light or single photon in high dimensional quantum communication system [26] as an optical vortex modulator. Since our method is based on electro-optics effect, it can operate accurately and stably at a high speed up to a multi-gigahertz region [27]. In addition, due to their different polarized directions, the output optical vortices with different TC are readily to be separated with the help of polarizing beam splitter or analyzer, which seems more convenient than the method using complex spatial modulation technique [28]. Meanwhile, in our scheme, the total OAM of light beam is controlled by the external voltage, which implies that the torque acted on particle is highly tunable, thus this method takes some advantages over traditional optical tweezers [4,5].

5. Conclusion

In summary, we have proposed a kind of external voltage-controlled optical vortex converter in HPPLN based on electro-optic effect. According to different incident condition, the HPPLN can be used as a topological charge adder or a substractor. The converter features highly voltage-afforded tunability and thus may serve as a promising candidate for the vortex generation and transformations in diverse applications.

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