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Ultrafast switching of optical singularity eigenstates with compact integrable liquid crystal structures

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Abstract: By using the strong nonlinear effect and ultrafast electronic response of cholesteric liquid crystals (CLC), ultrafast all optical switching between polarization vortex and phase vortex is realized in a system combining CLC and *q*-plate. The experimental result shows that switching with high modulation depth can be accomplished in less than 1 picosecond. Furthermore, CLC and *q*-plates will enable compact integrated devices with sub-mm thicknesses.

1. Introduction

Optical vortices that carry orbital angular momentum (OAM) of photon and techniques for modulating these optical vortices have attracted growing attentions in many fields such as high-speed optical communication [1–4], quantum information [5], optical process [6], high resolution imagine [7–9], and optical tweezers [10,11]. Although many methods had been tried to switch or reconfigure these optical vortices, the most direct method is by spatial light modulator [12], which typically operates with milliseconds response time. Active metasurfaces with photosensitive *trans–cis* dopants can shorten the polarization switching time to microsecond [13]; similar microsecond response can also be achieved with blue phase liquid crystals for switching between different optical vortices [14]. While it is possible to further shorten the response time to the nanosecond time scale by electro-optic or acoustic devices, complications and other limitations begin to set in due to the required electronic circuitry.

For ultrafast operations in sub-picosecond scale, all optical modulation of light field is required. All-optical modulation can be realized by using nonlinear optical effects such as sum and difference frequency generations, self-focusing and -defocusing, and self- or cross-phase modulation in crystals or optical fibers [15,16]. However, due to the relatively small nonlinear index, the propagation length in such devices are at least a few millimeters but often the interaction length can be as long as hundreds of meters. Recently, metamaterials and metasurfaces of subwavelength thickness have been developed to act as active polarization components [17,18]. However, due to the use of resonance-based nonlinear effects and short propagation length in metasurface devices, in both [17] and [18], the response time is limited to picoseconds, and the phase-modulation depth is not enough to achieve complete conversion between two orthogonal polarization states. To date, it is still challenging to

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realize a compact (sub-millimeter) all-optical light field modulation device that possesses simultaneous properties of sub-picosecond response and high modulation depth.

In this work, an all optical modulation device that combines CLC and *q*-plate [19] is introduced to achieve ultrafast switching between polarization singularity and phase singularities. Our experimental results show that switching between polarization and phase vortices can be achieved in the sub-picosecond time scale, by employing the ultrafast electronic optical nonlinearity of CLC used in our previous studies of all-optical self-action femtosecond pulse modulation [20–23].

2. Principle

Q-plate essentially works as a birefringent waveplate with an inhomogeneous distribution pattern of the local optical axis in the transverse plane. The optic axis orientation in the *xy* plane, as specified by the angle α formed with the *x*-axis, is described by [19]:

$$\alpha(r,\varphi) = q\varphi + \alpha_0 \tag{1}$$

Here q is the topological charge of the *q*-plate, r is the polar radius, φ is the azimuthal angle, and α_0 is the initial angle at $\varphi = 0$. When a left-handed circularly polarized plane wave, described by Jones electric field vector $E_{\text{in(C)}} = E_0[1\ i]^{\text{T}}$, passes through a *q*-plate, it will be transformed into a phase vortex described by:

$$E_{\text{out(C)}} = ME_{\text{in(C)}} = E_0 \begin{bmatrix} \cos(2\alpha) & \sin(2\alpha) \\ \sin(2\alpha) & -\cos(2\alpha) \end{bmatrix} \begin{bmatrix} 1 \\ i \end{bmatrix} = E_0 e^{j2\alpha} \begin{bmatrix} 1 \\ -i \end{bmatrix} = E_0 e^{j2q\phi} e^{j2\alpha_0} \begin{bmatrix} 1 \\ -i \end{bmatrix} \tag{2}$$

Similarly, after passing through the *q*-plate, a linearly polarized plane wave input described by the Jones electric field vector $E_{\text{in(L)}} = E_0[1\ 0]^{\text{T}}$ will be transformed into the following vector beam with a φ-dependent polarization:

$$E_{\text{out(L)}} = ME_{\text{in(L)}} = E_0 \begin{bmatrix} \cos(2\alpha) & \sin(2\alpha) \\ \sin(2\alpha) & -\cos(2\alpha) \end{bmatrix} \begin{bmatrix} 1 \\ 0 \end{bmatrix} = E_0 \begin{bmatrix} \cos(2\alpha) \\ \sin(2\alpha) \end{bmatrix} = E_0 \begin{bmatrix} \cos(2q\phi + 2\alpha_0) \\ \sin(2q\phi + 2\alpha_0) \end{bmatrix} \tag{3}$$

Thus, after traversing the *q*-plate, the output beam is converted into a phase (or polarization) vortex beam, corresponding to the input circular (or linear) polarization [19], *i.e.*, depending on the input polarization state, the output is in the form of phase vortex or polarization vortex. With a waveplate of $q = 0.5$, the generated phase vortex carries an OAM of quantum number $l = 1$, while the polarization vortex does not carry OAM (*i.e.*, $l = 0$). The two optical vortices are eigenstates and orthogonal to each other. Hence, for the purpose of realizing ultrafast switching between phase vortex and polarization vortex, it is necessary to switch the input polarization state from linear to circular with ultrafast response time. Here the 1D photonic crystal property in combination with the band-edge enhanced optical nonlinearity of CLC are used to achieve such ultrafast polarization switching.

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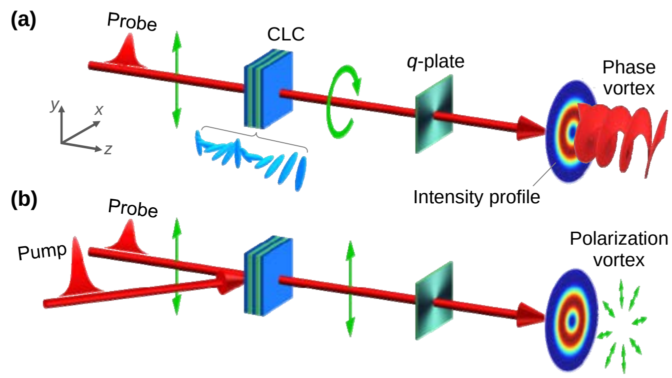

Fig. 1. Schematic of ultrafast switching between (a) phase vortex and (b) polarization vortex.

A photonic band gap for right- or left-handed circularly polarized light arises in cholesteric liquid crystals due to the helical orientation of molecules [20,21,24]. A linearly polarized light can be regarded as a superposition of left- and right-handed circularly polarized light. When the wavelength of the input linearly polarized beam is located inside the photonic band gap, only one of its two circularly polarized components can be transmitted, and the other one will be totally reflected; outside the bandgap, the linearly polarized beam will be totally transmitted. The photonic bandgap of CLC can be blue- or red-shifted [20,21] by high power femtosecond laser due to the induced index change arising from the ultrafast (femtoseconds) electronic optical nonlinearity of the CLC constituent molecules. As a result of such ultrafast band gap shifting, switching between phase vortex and polarization vortex can be achieved in femtosecond scale, as schematically depicted in Fig. 1.

3. Experiment

In our study, CLC with right-handed helical structure in planar texture was fabricated from a mixture of a nematic liquid crystal E7 (King Optronics) with a chiral agent R1011 (Slichem). With an R1011 concentration of ~7.4 wt%, a 9 μm-thick CLC sample with a pitch of ~496 nm is fabricated. With the average refractive index n_{av} = 1.629 and modulation depth Δn = 0.224, the transmission spectrum [Fig. 2] of the CLC cell exhibits a stop band for right-handed circularly polarized light centered around about 800 nm and a bandwidth of about 35 nm. A liquid crystal q-plate with q = 0.5 (from King Optronics) is used to convert the output light from CLC to an optical vortex beam.

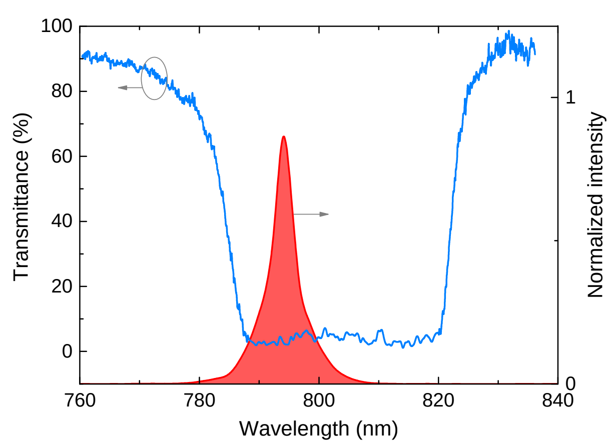

Fig. 2. Transmission spectrum of CLC probed with right-handed circularly polarized light (blue) and laser spectrum of 230 fs input pulses (red).

Figure 3 depicts the complete experimental setup. The Micra-5 Ti:Sapphire mode-locked laser system (Coherent) delivers nearly transform-limited 40 fs laser pulses at a repetition rate of 1 kHz; the wavelength is tunable from 575 to 1300 nm. Since the wavelength dependent *q*-plate cannot provide broad band modulation to a 40 fs pulse whose spectra bandwidth is ~35 nm, the laser pulse duration is lengthened in order to decrease its spectral width. This is accomplished by sending the laser output through a 4*f*-line system as shown in Fig. 3. The home-built system consists of a grating that spatially disperses the laser and a spherical mirror to re-collimate the light; a variable slit is used to narrow the spectrum of the pulse, which is then retro-reflected through the spherical mirror and the grating to generate an output pulse with a lengthened duration. Since all the dispersion is compensated, the output pulse maintains the transform limited nature, with a pulse duration of 230 fs and a corresponding spectral width of 6 nm. The central wavelength of the pulse is 794 nm, cf. Figure 2. In our studies, the probe intensity is ~10 MW/cm^2 and the peak intensity of the pump pulse is ~800 MW/cm^2.

Single-slit diffraction is used to measure the vortex [25]. The diffraction pattern of polarization vortex beam is a series of lines owing to the fact that the phase is a constant in the entire cross-section of the beam. On the other hand, for phase vortex, due to angular dependence of the phase in the cross-section of the beam, the diffraction pattern will be distorted. For further confirming the switching result, the interference between the output beam and a plane linear polarization beam is observed with/without the pump beam on. As the output pulse is a phase vortex, fork-like interference pattern should be observed, due to its helical wavefront; on the other hand, for a polarization vortex beam, the interference fringe should be straight.

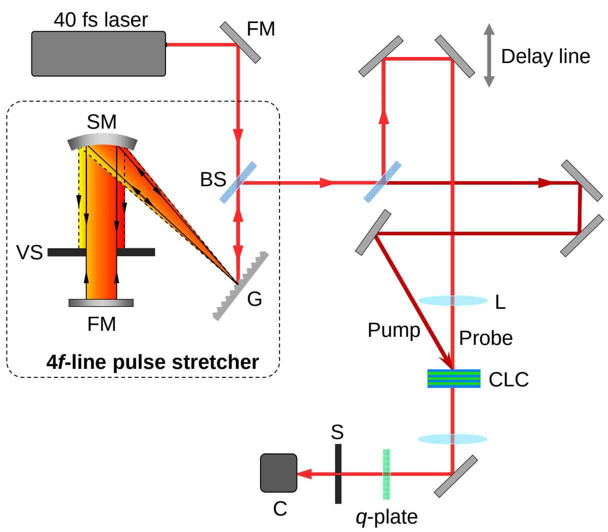

Fig. 3. Experimental setup comprising 40 fs laser, 4f-line pulse stretcher, pump–probe optics surrounding CLC, *q*-plate (*q* = 0.5) for vortex generation, and single-slit diffraction diagnostic instruments. FM: flat mirror, SM: spherical mirror, BS: beam splitter, VS: variable slit, G: grating, L: convex lens, S: slit, C: CCD camera beam profiler.

4. Results and discussion

Due to the steep slopes at the band-edges, the polarization of the transmitted probe beam experiences a pronounced change for any shifting of the bandgap. The wavelength of the probe pulse is 794 nm, and it is initially located inside the bandgap but close to the blue band-edge. With increasing pump power, the bandgap is red-shifted, resulting in an increasing intensity dependence for the probe transmission as shown in Fig. 4; the observed peak transmission of the CLC is ~80%.

Figure 5 shows the ratio between the intensities of the *y*- and *x*-polarized components of the output probe pulses as a function of the pump–probe time delay. The result shows that the output polarization of CLC can be controlled by the nonlinear index change. Absent the pump pulse, the transmitted (output) probe pulse (wavelength of 794 nm is located just inside the photonic band gap) is therefore circularly polarized ($I_y/I_x \approx 1$). When the pump pulse is on, the output polarization is observed to be predominantly linear polarization ($I_y/I_x \approx 9$), due to the nonlinear shifting of the photonic band gap. The total time for such switching process is about 450 fs. Although the underlying mechanism for switching is the so-called 'instantaneous' electronic optical nonlinearity, we have observed a slight lagging in the probe response to the pump pulse; "peak linearly polarized state" occurs with a delay of about 35 fs. Such trailing edge shows that what [electronic excitation] has been assumed to be 'instantaneous' electronic response is not so instantaneous after all; it may be also due to some other undetermined mechanisms following excitation of the electronic clouds that remains to be investigated in a future undertaking.

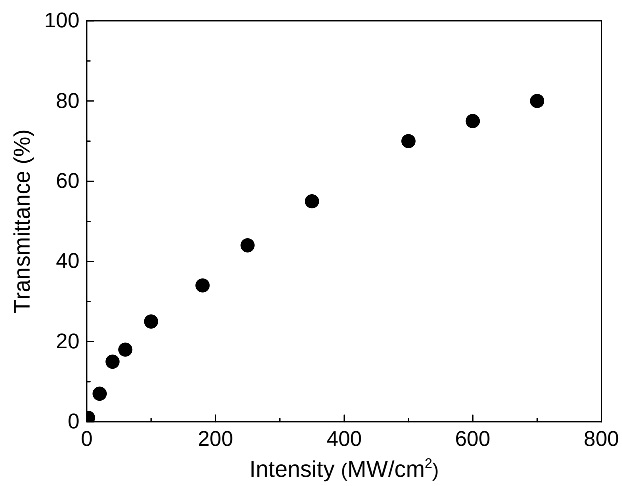

Fig. 4. Probe transmission at 794 nm as a function of pump intensity.

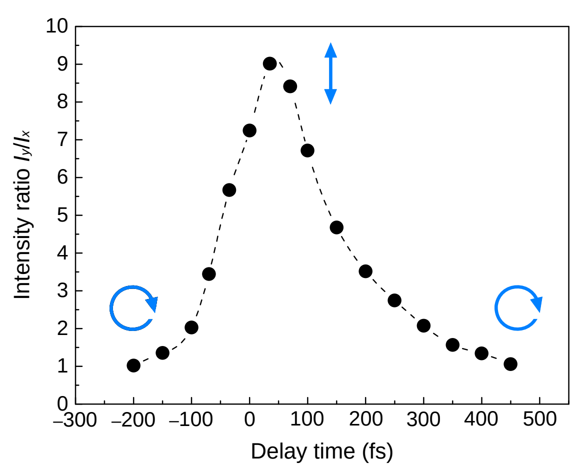

Fig. 5. Intensity ratio between the *y*- and *x*-polarized components of the output probe pulses (I_y/I_x) as a function of pump–probe time delay. The minus sign (–) means that the probe pulse arrives at the CLC earlier than the pump pulse.

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Upon exiting the CLC, the probe pulse propagates through a *q*-plate for generating optical vortex, which is then examined by the single-slit diffraction [25] method. Figure 6 shows the diffraction patterns recorded by SP620U laser beam diagnostics (Ophir Spiricon) for different delay times. The results show that when the delay time between pump pulse and probe pulse is close to zero, the upper part and lower part of zero order diffraction are matched well (in the same line) [see Figs. 6(b)–6(d)]. This means the wave front is a plane without phase differences. Similar to the delayed response shown in Fig. 5, it should be noted that the best matching pattern is observed when the probe pulse is ~35 femtoseconds behind the pump pulse. The radial polarization properties of the beam can be confirmed by a rotating polarizer, that the output of the *q*-plate is indeed a polarization vortex beam. On the other hand, when the pump pulse and the probe beam is well separated in time, a clear mismatching of upper part and lower part is observed [Figs. 6(a) and 6(f)], indicating that the phase difference between the upper and lower parts of the beam is π; hence, the output of the *q*-plate is a phase vortex beam. Comparing Figs. 6(c) and 6(e), these results of the diffraction pattern as a function of delay time shows that phase vortex beam can clearly be switched to polarization vortex beam in ~450 fs.

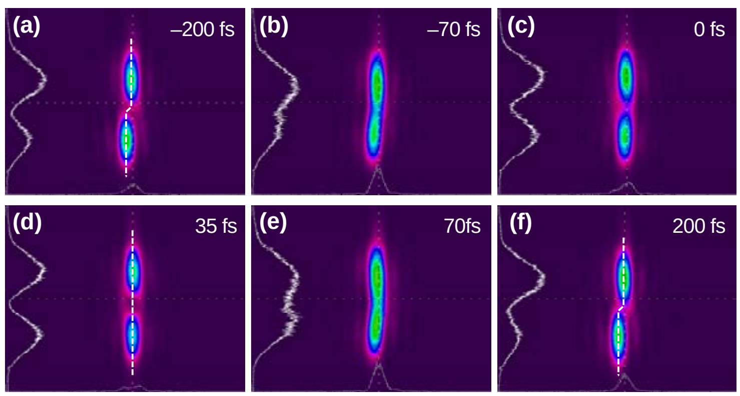

Fig. 6. Single-slit diffraction patterns obtained for different delay times: (a) –200 fs, (b) –70 fs, (c) 0 fs, (d) 35 fs, (e) 70fs, and (f) 200 fs. The minus sign (–) means that the probe pulse arrives at the CLC earlier than the pump pulse.

Further corroboration of such switching process is provided by the interference pattern formed by the output beam from the *q*-plate and a plane wave with linear polarization. When the pump pulse is not on the CLC, a fork-like interference pattern can be observed, meaning that the output pulse from the *q*-plate carries a phase singularity property. When the pump beam is on and produces the switching effect, a non-distorted interference fringe with angular dependent contrast ratio is observed; this means the output pulse carries polarization singularity properties. The interference results are shown in Fig. 7, showing good agreement between experimental observations and theoretical simulations.

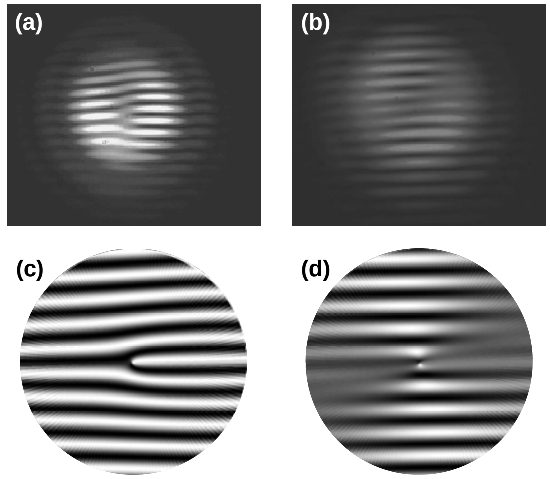

Fig. 7. (a,b) Experimental and (c,d) simulated interferograms of output beams from q-plate with linearly polarized plane-wave reference beam: (a,c) without pumping, (b,d) with pumping.

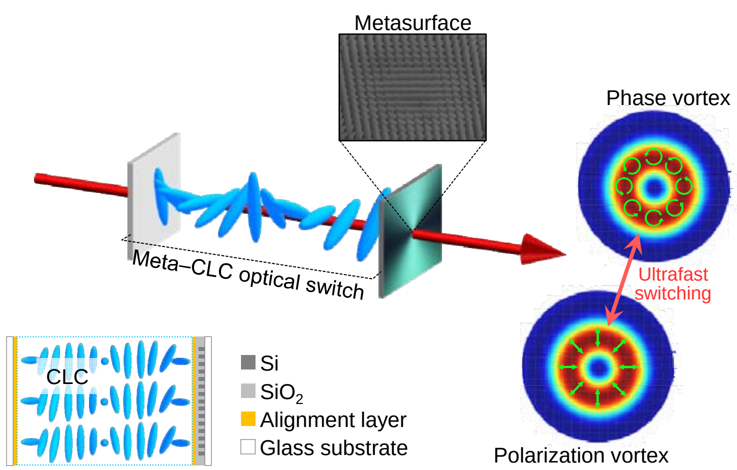

Fig. 8. Schematic proposal for a compact device made by integrating CLC onto metasurface for ultrafast vortex switching.

5. Conclusions

Ultrafast control of beam polarization can be realized by using enhanced electronic optical nonlinearity at band-edges of CLC. Combined with polarization-dependent *q*-plate, we have demonstrated switching between phase vortex beam and polarization vortex beam in femtoseconds time scale. One advantage of such system is the micrometer propagation length in CLC; one can envision therefore, by fabricating solid state vortex generation devices (such as metasurfaces) on the substrate glass of liquid crystal cell, ultrafast vortex switching in single sub-millimeter device can be achieved, cf. Figure 8. We also believe that by suitable combination of the ultrafast nonlinear response of cholesteric liquid crystals with other polarization dependent devices, such as optical polarization grating [26], Pancharatnam–Berry lens [27], metasurfaces [28], and special optical fiber [29], one can devise many more ways of ultrafast manipulating light field.

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References

1. E. J. Galvez, P. R. Crawford, H. I. Sztul, M. J. Pysher, P. J. Haglin, and R. E. Williams, "Geometric Phase Associated with Mode Transformations of Optical Beams Bearing Orbital Angular Momentum," Phys. Rev. Lett. **90**(20), 203901 (2003).
2. X. Cai, J. Wang, M. J. Strain, B. Johnson-Morris, J. Zhu, M. Sorel, J. L. O'Brien, M. G. Thompson, and S. Yu, "Integrated compact Optical Vortex Beam Emitters," Science **338**(6105), 363–366 (2012).
3. J. Wang, J. Y. Yang, I. M. Fazal, N. Ahmed, Y. Yan, H. Huang, Y. Ren, Y. Yue, S. Dolinar, M. Tur, and A. E. Willner, "Terabit free-space data transmission employing orbital angular momentum multiplexing," Nat. Photonics **6**(7), 488–496 (2012).
4. N. Bozinovic, Y. Yue, Y. Ren, M. Tur, P. Kristensen, H. Huang, A. E. Willner, and S. Ramachandran, "Terabit-Scale Orbital Angular Momentum Mode Division Multiplexing in Fibers," Science **340**(6140), 1545–1548 (2013).
5. N. J. Cerf, M. Bourennane, A. Karlsson, and N. Gisin, "Security of Quantum Key Distribution Using d-Level Systems," Phys. Rev. Lett. **88**(12), 127902 (2002).
6. M. Duocastella and C. B. Arnold, "Bessel and annular beams for materials processing," Laser Photonics Rev. **6**(5), 607–621 (2012).
7. S. W. Hell and J. Wichmann, "Breaking the diffraction resolution limit by stimulated emission: stimulated-emission-depletion fluorescence microscopy," Opt. Lett. **19**(11), 780–782 (1994).
8. J. Fölling, M. Bossi, H. Bock, R. Medda, C. A. Wurm, B. Hein, S. Jakobs, C. Eggeling, and S. W. Hell, "Fluorescence nanoscopy by ground-state depletion and single-molecule return," Nat. Methods **5**(11), 943–945 (2008).
9. P. Bianchini, B. Harke, S. Galiani, G. Vicidomini, and A. Diaspro, "Single-wavelength two-photon excitation-stimulated emission depletion (SW2PE-STED) superresolution imaging," Proc. Natl. Acad. Sci. U.S.A. **109**(17), 6390–6393 (2012).
10. M. Woerdemann, C. Alpmann, M. Esseling, and C. Denz, "Advanced optical trapping by complex beam shaping," Laser Photonics Rev. **7**(6), 839–854 (2013).
11. J. Baumgartl, M. Mazilu, and K. Dholakia, "Optically mediated particle clearing using Airy wavepackets," Nat. Photonics **2**(11), 675–678 (2008).
12. C.-H. Yang and A. Y.-G. Fuh, "Generation of optical vortices with controllable topological charges," Proc. SPIE **10125**, 10125P (2017).
13. M. X. Ren, W. Wu, W. Cai, B. Pi, X.-Z. Zhang, and J.-J. Xu, "Reconfigurable metasurfaces that enable light polarization control by light," Light Sci. Appl. **6**(6), e16254 (2017).
14. S. Ge, W. Ji, G. Cui, B. Wei, W. Hu, and Y. Lu, "Fast switchable optical vortex generator based on blue phase liquid crystal fork grating," Opt. Mater. Express **4**(12), 2535–2541 (2014).
15. G. P. Agrawal, *Nonlinear Fiber Optics* (Academic, 2007).
16. Y. R. Shen, *The Principles of Nonlinear Optics* (Wiley-Interscience, 2002)
17. L. H. Nicholls, F. J. Rodríguez-Fortuño, M. E. Nasir, R. M. Córdova-Castro, N. Olivier, G. A. Wurtz, and A. V. Zayats, "Ultrafast synthesis and switching of light polarization in nonlinear anisotropic metamaterials," Nat. Photonics **11**(10), 628–633 (2017).
18. Y. Yang, K. Kelley, E. Sachet, S. Campione, T. S. Luk, J. Maria, M. B. Sinclair, and I. Brener, "M. B. Sinclair1 and I. Brener, "Femtosecond optical polarization switching using a cadmium oxide-based perfect absorber," Nat. Photonics **11**(6), 390–395 (2017).
19. L. Marrucci, "The q-plate and its future," J. Nanophotonics **7**(1), 078598 (2013).
20. L. Song, S. Fu, Y. Liu, J. Zhou, V. G. Chigrinov, and I. C. Khoo, "Direct femtosecond pulse compression with miniature-sized Bragg cholesteric liquid crystal," Opt. Lett. **38**(23), 5040–5042 (2013).
21. Y. Liu, Y. Wu, C.-W. Chen, J. Zhou, T.-H. Lin, and I. C. Khoo, "Ultrafast pulse compression, stretching-and-recompression using cholesteric liquid crystals," Opt. Express **24**(10), 10458–10465 (2016).
22. J. Hwang, N. Y. Ha, H. J. Chang, B. Park, and J. W. Wu, "Enhanced optical nonlinearity near the photonic bandgap edges of a cholesteric liquid crystal," Opt. Lett. **29**(22), 2644–2646 (2004).
23. L. Cattaneo, M. Savoini, I. Muševič, A. Kimel, and T. Rasing, "Ultrafast all-optical response of a nematic liquid crystal," Opt. Express **23**(11), 14010–14017 (2015).
24. Y. Liu, S. Fu, X. Zhu, X. Xie, M. Feng, J. Zhou, Y. Li, Y. Xiang, B. A. Malomed, and G. Kurizki, "Nonlinear light propagation in cholesteric liquid crystals with a helical Bragg microstructure," J. Opt. **17**(6), 065609 (2015).
25. D. P. Ghai, P. Senthikumaran, and R. S. Sirohi, "Single-slit diffraction of an optical beam with phase singularity," Opt. Lasers Eng. **47**(1), 123–126 (2009).

26. M. Sakamoto, Y. Nakamoto, K. Kawai, K. Noda, T. Sasaki, N. Kawatsuki, and H. Ono, "Polarization grating fabricated by recording a vector hologram between two orthogonally polarized vector vortex beams," J. Opt. Soc. Am. B **34**(2), 263–269 (2017).
27. A. M. Tam, F. Fan, H. S. Chen, T. Du, V. G. Chigrinov, Y. H. Lin, and H. S. Kwok, "Nanoscopic patterned photo-alignment for electrically switchable liquid crystal Pancharatnam-Berry phase diffractive lens," J. Soc. Inf. Disp. **47**, 599–601 (2016).
28. F. Yue, D. Wen, J. Xin, B. D. Gerardot, J. Li, and X. Chen, "Vector Vortex Beam Generation with a Single Plasmonic Metasurface," ACS Photonics **3**(9), 1558–1563 (2016).
29. W. Zhang, K. Wei, D. Mao, H. Wang, F. Gao, L. Huang, T. Mei, and J. Zhao, "Generation of femtosecond optical vortex pulse in fiber based on an acoustically induced fiber grating," Opt. Lett. **42**(3), 454–457 (2017).