Pancharatnam-Berry phase optical elements for wave front shaping in the visible domain: Switchable helical mode generation

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We report the realization of a Pancharatnam-Berry phase optical element [Z. Bomzon, G. Biener, V. Kleiner, and E. Hasman, Opt. Lett. **27**, 1141 (2002)], for wave front shaping working in the visible spectral domain, based on patterned liquid crystal technology. This device generates helical modes of visible light with the possibility of electro-optically switching between opposite helicities by controlling the handedness of the input circular polarization. By cascading this approach, fast switching among multiple wave front helicities can be achieved, with potential applications to multistate optical information encoding. The approach demonstrated here can be generalized to other polarization-controlled devices for wave front shaping, such as switchable lenses, beam splitters, and holographic elements. © *2006 American Institute of Physics*.
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When the polarization of an electromagnetic wave undergoes a continuous sequence of transformations following a closed path in the space of polarization states (e.g., the Poincaré sphere), the wave acquires a phase shift, known as Pancharatnam-Berry phase, that is determined only by the geometry of the polarization path.[1,2] By the same principle, if a wave is subjected to transversely inhomogeneous polarization transformations with a homogeneous initial and final polarization state, the associated inhomogeneous geometrical phases will induce an overall wave front reshaping. This approach to wave front shaping is fundamentally different from the usual optical-path-length approaches of standard lenses, curved mirrors, and gradient-index (GRIN) elements. It is also conceptually different from holographic approaches, although the two are related, as we will discuss further below. The realization of so-called Pancharatnam-Berry phase optical elements (PBOEs) for wave front shaping has been proposed only recently,[3,4] and it has been experimentally demonstrated only in the midinfrared domain, using subwavelengths inhomogeneous gratings to manipulate the polarization.[4–7] An additional general feature of PBOEs is that they are *polarization controlled*, i.e., different input polarizations will give rise to different wave front shaping in the same PBOE element. Since the polarization can be electro-optically switched at a high rate, PBOEs allow a very fast control of the generated wave front. This polarization multiplexing is limited to a finite set of predefined wave fronts, so PBOEs cannot compete with spatial light modulators in terms of flexibility, but they will be much faster and cheaper.

To be more specific, let us consider a PBOE made as a single (uniaxial) birefringent plate having a homogeneous phase retardation of π (half-wave PBOE) for light propagation in the longitudinal z direction but a transversely inhomogeneous optical axis $\mathbf{n}(x,y)$, lying in the xy plane. To analyze the effect of this element on the optical field, it is convenient to adopt the Jones formalism. Let $\alpha(x,y)$ be the angle between $\mathbf{n}(x,y)$ and a fixed axis x. The Jones matrix $\mathbf{M}$ to be applied on the field at each transverse position x,y is the following:

$$\mathbf{M}=\mathbf{R}(-\alpha)\begin{pmatrix}1 & 0\\ 0 & -1\end{pmatrix}\mathbf{R}(\alpha)=\begin{pmatrix}\cos 2\alpha & \sin 2\alpha\\ \sin 2\alpha & -\cos 2\alpha\end{pmatrix}, \quad (1)$$

where $\mathbf{R}(\alpha)$ is the two-dimensional rotation matrix by angle α. An input left-circular polarized plane wave, described by the Jones electric-field vector $\mathbf{E}_{\text{in}}=E_0\times[1,i]$, will be transformed by this element into the following field (up to an overall phase):

$$\mathbf{E}_{\text{out}}=\mathbf{M}\cdot\mathbf{E}_{\text{in}}=E_0 e^{i2\alpha(x,y)}\begin{bmatrix}1\\ -i\end{bmatrix}. \quad (2)$$

It is seen that the output wave is uniformly right-circular polarized, but its wave front has acquired a nonuniform phase retardation $\Delta\Phi(x,y)=2\alpha(x,y)$. If the input light is right-circular polarized, it is easy to verify that the output wave front is the conjugate one, i.e., $\Delta\Phi(x,y)=-2\alpha(x,y)$.

To appreciate the possible applications of these devices, consider, for example, a half-wave PBOE having a polarization-grating geometry as that shown in Fig. 1(a). This device will function as a circular-polarizing beam splitter or as polarization-controlled optical switch.[6] A PBOE lens can instead be obtained with an optical axis geometry given by $\alpha\propto r^2$, where r is the radial coordinate in the xy plane, as that shown in Fig. 1(b). This element will be focusing or defocusing, depending on the input circular polarization handedness.[3,7]

Let us consider now a PBOE geometry given by $\alpha=q\varphi+\alpha_0$, where φ is the azimuthal angle in the xy plane, and q and α_0 are two constants. We further assume that q is an integer or a semi-integer, so that the optical axis does not have discontinuity lines in the plate, but only a defect in the center. We will call these devices q plates. Figures 1(c) and 1(d) show examples of these devices for $q=1/2$ and $q=1$, respectively. These q plates give rise to a wave front modulation given by $\Delta\Phi=\pm 2q\varphi$, with a sign depending on the input circular polarization handedness, i.e., they generate helical wave fronts of order $\pm 2q$.[8,9] Thus far, q plates have been

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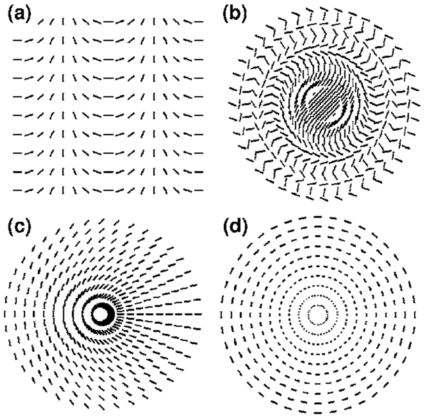

FIG. 1. Examples of half-wave PBOE geometries. Dashes indicate local optical axis direction. (a) PBOE behaving as a circular-polarizing beam splitter or switch; (b) PBOE behaving as a polarization-dependent lens; (c) q-plate PBOE with $q=1/2$ and $\alpha_0=0$, generating helical modes of order ±1; and (d) q-plate PBOE with $q=1$ and $\alpha_0=\pi/2$, generating helical modes of order ±2.

demonstrated only for the midinfrared wavelength of 10.6 μm, based on the subwavelength grating technology.[5,10]

We manufactured $q=1$ plates working at the visible wavelength $\lambda=633$ nm based on the patterned liquid crystal (LC) technology (see, e.g., Refs. 11 and 12 and references therein). Nematic LC planar cells were prepared with a thickness (about 1 μm) and a material (E63 from Merck, Darmstadt, Germany) chosen so as to obtain a birefringence retardation of approximately a half wave. Before cell assembly, one of the inner surfaces of the two containing glasses of the cell was pressed against a piece of fabric kept in continuous rotation. This "circular rubbing" procedure leads to a surface easy axis (i.e., the preferred orientation of LC molecules) having the desired $q=1$ circular-symmetric geometry, as that shown in Fig. 1(d). The other glass was left unrubbed, for degenerate planar alignment. To ensure good LC alignment, the cell was heated above the clearing point and then cooled slowly, keeping the rubbed surface slightly colder than the unrubbed one. In this way, nematic order nucleated on the rubbed surface and then extended to the whole cell. Some cells were prepared with a polyimide coating for planar alignment, others with bare glass, with comparable results (although they required different rubbing pressures and lengths). A photograph of a LC q plate held between crossed polarizers is shown in Fig. 2(a).

To test the optical effect of a q plate, a circularly polarized He–Ne laser beam having a TEM_{00} transverse mode and a beam-waist radius of about 1 mm was sent through it, taking care of aligning the beam axis on the q-plate center. The intensity profile of the output beam, shown in Fig. 2(b), has the "doughnut" shape expected for a helical mode. However, a complete test must be based on measuring the beam wave front shape, rather than its intensity profile. To this purpose, we inserted the q plate in the signal arm of a Mach-Zender interferometer based on the same He–Ne laser source. The input circular-polarization handedness was selected by properly rotating a quarter-wave plate. The beam emerging from the q plate was sent through another quarter-wave plate and a linear polarizer was arranged for transmitting the polarization handedness opposite to the initial one, so as to eliminate any residual unchanged circular polarization (this step would be unnecessary for an exact half-wave retardation of the q plate). The final interference pattern generated after superposition with the reference was formed directly on the sensing area of a charge coupled device (CCD) camera. We used two reference wave front geometries: (i) plane tilted, for which an order of 2 helical wave front will give rise to a double disclination defect in an otherwise regular straightline fringe pattern, and (ii) spherical, for which the helical wave front will give rise to a double spiral fringe pattern. Figures 2(c)–2(f) show the interference patterns we obtained for one of our cells in these two geometries, respectively, for left-circular [panels (c) and (e)] and right-circular [panels (d) and (f)] input polarizations. These results confirm that the wave front of the light emerging from our q plate is indeed helical of order ±2, as expected, with the ± sign determined by the input polarization handedness.

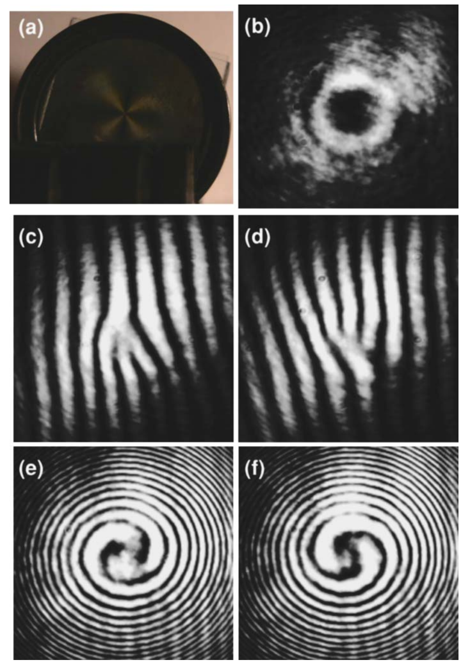

FIG. 2. Experimental images. (a) A LC q plate held between crossed polarizers, showing the expected pattern for $q=1$ geometry. (b) "Doughnut" intensity profile of the beam emerging from the q plate. (c)–(f) Interference patterns of helical modes generated by our q plate. (c) and (d) panels refer to the plane-wave reference geometry, (e)–(f) panels to the spherical-wave reference one. Panels on the left, (c) and (e), are for a left-circular input polarization and those on the right, (d) and (f), for a right-circular one.

This polarization-based control of the generated helical wave front is a good example of the possible advantages of the PBOE approach to wave front shaping. Indeed, all other existing approaches to helical mode generation (i.e., cylindrical lenses, spiral phase plates, and holographic methods) have an essentially fixed output. Of course, by introducing a suitable spatial light modulator, dynamical control becomes possible, but only at relatively low switching rates. In our approach, a simple electro-optical control of the input polarization allows switching of the generated helical mode at very high rate. By cascading several q plates in series with suitable electro-optic devices in between, as shown in Fig. 3, one can obtain fast switching among several different helical orders. This could be very useful if helical modes are to be used in multistate optical information encoding, as recently proposed for classical communication[13] and for quantum communication and computation.[14,15]

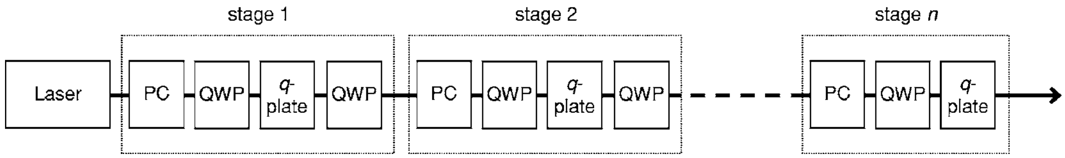

FIG. 3. A n stages PBOE optical system for generating helical modes of light having an order l which can be electro-optically switched in the set $l \in \{-2nq, -2(n-2)q, \ldots, +2(n-2)q, +2nq\}$. Legend: PC–pockel cell, and QWP—quarter-wave plate.

Although in our proof-of-principle demonstration reported here we used a method for patterning our LC cell that works only for circular-symmetric geometries (as in the $q=1$ plate), LC cell patterning has the potential for obtaining any desired PBOE geometry. Different approaches, such as microrubbing,[11] masked or holographic photoalignment,[16,17] and silicon-oxide evaporated coatings,[18] are all suitable.

Finally, we note that the PBOE principle is strictly related to the so-called polarization holography (PH), in which the holographic material records the information contained in the optical polarization.[19] Typically, in PH one needs a light-sensitive polymer that can align its molecular chains parallel or perpendicular to the polarization direction.[20] In order to memorize a given wave front in a PH hologram, one must superimpose the wave carrying that wave front with a plane-wave reference, taking care that both waves are circularly polarized, with opposite handedness. The resulting interference field will have uniform intensity and it will be everywhere linearly polarized, but it will have a nonuniform polarization orientation which will be imprinted in the hologram. When illuminated with a plane wave, this hologram will reconstruct the recorded wave front, or its conjugate, at its ±1 diffraction orders. However, if the hologram is "developed" into an inhomogeneous birefringent plate having half-wave retardation (for example, by using the hologram as a "command" surface of a LC cell, or if the hologram itself has sufficient birefringence), the zero diffraction order will vanish identically and the hologram becomes a PBOE device generating a single optical output with the recorded wave front, or its conjugate, when illuminated with a circularly polarized plane wave.

In conclusion, we have demonstrated a Pancharatnam-Berry optical element working in the visible domain, based on patterned liquid crystal technology. This device can be used for generating fast switchable helical modes, with potential applications to optical information encoding. Some plausible strategies for generalizing our approach have been discussed.

Note added in proof: We have been informed of a recent work demonstrating the PBOE principle in the near infrared domain based on the subwavelength technology.

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