Broadband orbital angular momentum manipulation using liquid crystal thin-films

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ABSTRACT

We introduce two high efficiency thin-film optical elements, operating over a wide spectral range, to generate and control the Orbital Angular Momentum (OAM) of various light sources: a broadband $q$-plate and a broadband Forked Polarization Grating (FPG). The broadband OAM manipulation is achieved by thin liquid crystal polymer layers that are aligned to provide the required spatially varying anisotropy. These elements operate using geometric phase principles to generate raised and lowered OAM modes whose efficiencies are sensitive to the polarization state of the incident light. We discuss the design principles involved and experimentally demonstrate broadband $q$-plates and FPGs that are highly efficient (> 90%) in the visible wavelength range. These thin film elements enable easy integration into various optical systems requiring broadband OAM manipulation such as optical trapping and high capacity information.

Keywords: orbital angular momentum, polarization gratings, liquid crystal, complex beam, broadband

1. INTRODUCTION

The momentum of a propagating light wave has both linear and angular contributions. The linear momentum is associated with the wave vector. The angular momentum can be further broken down into two more parts: Spin Angular Momentum (SAM) that is associated with polarization, and Orbital Angular Momentum (OAM) that is associated with spatial distribution of the phase front. Unlike the first two, current study on OAM of light is fairly recent. Allen et al.\(^1\) identified that lightwaves with azimuthal angle-dependent phase term $\exp(i l \phi)$ carry OAM of $l \hbar$ per photon, where $l$ can take any positive or negative integer. OAM is a new degree of freedom of light that we can utilize. Moreover, comparing to SAM which can only be $\pm \hbar$ per photon, OAM could offer larger momentum to exchange when interact with matter, or wider state set when encode information. An increasingly intense set of work has recently been conducted on the applications of light OAM, including optical trapping\(^2\) and information science and technology.\(^3\),\(^4\) While several OAM manipulation methods (described in more detail below) have been suggested for these applications, none of them has the capability to function over a wide spectral band with good power efficiency and flexibility. Highly efficient broadband OAM will be particularly useful for applications such as OAM-based wavelength-division multiplexing.

Current methods to generate, manipulate, and detect OAM states include the use of spiral phase plate,\(^5\) cylindrical lens pair,\(^1\) computer generated hologram (CGH), and spatial light modulator (SLM).\(^6\),\(^7\) In general, these conventional approaches result in bulky and expensive devices limiting the optical performance. In addition approaches using CGHs usually result in low power efficiency while SLMs suffer from resolution and wavelength limits. Most recently, two novel liquid crystal elements were introduced to manipulate the OAM of light. The first is an axially varying half-wave plate called $q$-plate,\(^8\) where $q$ is the singularity charge. A $q$-plate converts incoming circularly polarized light to OAM $l = \pm 2q$ states, and generally arbitrary polarization to a superposition of these two OAM states. Both static and tunable versions of $q$-plate have been reported.\(^9\)

The second element, introduced by our group,\(^10\),\(^11\), is a Forked Polarization Grating (FPG), which converts incoming light with OAM $l_0$ to one or both of the OAM $l = l_0 \pm l_g$ eigenstates, where $l_g$ is the singularity charge of the FPG. As a diffractive optical element, an FPG also changes the linear momentum. Light that goes through different OAM changes (raising or lowering, depending on input polarization), will be diffracted to different direction as well. We recently introduced this approach with both static and switchable FPG elements.
formed in liquid crystals, where high OAM conversion efficiencies of 96% were demonstrated for UV and visible light sources.

Both q-plates and FPGs can be tailored for nearly any wavelength from ultraviolet to infrared using commercially available nematic LCs. However due to the dispersion in the LC birefringence, the high diffraction efficiency occurs only over a modest bandwidth centered around a single optimized wavelength. Here we report on broadband FPGs and q-plates that accomplish highly efficient (> 97%) OAM manipulation over a much wider spectral range in the visible region (500—700 nm).

2. BACKGROUND

2.1 Polarization Gratings (PG)

PGs are a category of diffraction gratings that are formed in anisotropic materials, and function by affecting the polarization state of the wavefront passing through them via the Pancharatnam-Berry phase effect.12–14 This in-plane wavefront shaping occurs within a thick anisotropic layer and leads to unique behavior: 100% diffraction into a single order for wide angular acceptance and wide range of periods. In one sub-class, researchers suggested to embody the birefringence profile by spatially aligning liquid crystal (LC) materials,15 which was achieved with 100% efficiency by others.16–19 These PGs are thin and lightweight, operate with extremely high efficiency, and can be made either static or switchable, narrowband or broadband.20 These attractive properties of PGs have been used in several applications including laser beam steering,21,22 optical filters,23,24 polarization imaging,25,26 and displays.27,28 Traditional PG has a one-dimensionally spatial varying optical axis that follows \( \Phi(x, y) = \pi x/\Lambda \). FPG and q-plate are two-dimensional variations of PG with \( \Phi(x, y) \), of which the non-zero curl leads to OAM change.

A narrowband PG is tuned for half-wave retardation at a specific wavelength \( \lambda_0 \). The diffraction efficiency is defined as the ratio of the output to input intensity in a particular diffraction order \( (m = 0, \text{ or } \pm 1) \). The zero-order is insensitive to input polarization, while the first-orders are highly polarization sensitive:26

\[
\begin{align*}
\eta_0 &= \cos^2(\zeta) \quad (1a) \\
\eta_{\pm 1} &= \frac{1}{2} (1 \mp S_3') \sin^2(\zeta) \quad (1b)
\end{align*}
\]

where \( \zeta = \pi \Delta nd/\lambda \) is a normalized retardation, \( S_3' = S_3/S_0 \) is the normalized Stokes parameter corresponding to the ellipticity of the incident light. When at a half-wave retardation condition \( (\Delta nd = \lambda_0/2) \), the zero-order diffraction is suppressed, and 100% of the input is diffracted into one or both of the first-orders (depending on polarization).

2.2 Forked Polarization Gratings (FPG)

Unlike conventional one-dimensional PGs, an FPG has a two-dimensional spatially-varying optical axis given by:

\[
\Phi(x, y) = \frac{1}{2} l_g \phi(x, y) + \phi_0 - \pi x/\Lambda
\]

in \( xy \) plane and homogeneous in the third (\( z \)) dimension. In the equation, \( \phi(x, y) \) is the azimuthal angle \( \phi(x, y) = \tan^{-1} \left( \frac{y}{x} \right) \), \( \phi_0 \) is some constant initial angle, \( l_g \) denotes the order of the FPG, which is also called topological charge. \( \Lambda \) is the grating period, which is associated with a grating vector \( \vec{k}_g(\Lambda) \) altering the beam propagation direction. We use a ket notation for a single photon state \( | \vec{k}_g, s, l \rangle \), where \( \vec{k} \) stands for linear momentum, \( s \) and \( l \) are spin and orbital angular momentum in unit of \( \hbar \), respectively. The function of FPG can be summarized as an operator

\[
\begin{align*}
\hat{FPG}_{(\vec{k}_g, l_g)} \ | \vec{k}_g, - \frac{1}{2}, l \rangle &= | \vec{k} + \vec{k}_g(\Lambda), + \frac{1}{2}, l - l_g \rangle \\
\hat{FPG}_{(\vec{k}_g, l_g)} \ | \vec{k}_g, + \frac{1}{2}, l \rangle &= | \vec{k} - \vec{k}_g(\Lambda), - \frac{1}{2}, l + l_g \rangle
\end{align*}
\]

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For coherent light field of arbitrary polarization which is essentially the superposition of $|+\frac{1}{2}\rangle$ and $|-\frac{1}{2}\rangle$, FPG acts as a linear operator and the output is the superposition of the two result states in Eq. 3. In other words, $m = 1 (m = -1)$ diffraction order comes from the left(right) circularly polarized contribution of the incoming lightwave, it is converted to the opposite circular polarization, with OAM charge decreased(increased) by $l_g$.

2.3 $q$-plate

A $q$-plate functions like an FPG, except it does not affect linear momentum. Essentially it is an extreme case of FPG that has an infinite grating period $\Lambda$. Its optical axis follows

$$\Phi(x,y) = q\phi(x,y) + \phi_0$$

where $q$ is the topological charge of a $q$-plate. Its function can be summarized

$$\hat{QP}_l |\frac{1}{2}, l\rangle = |\frac{1}{2}, l - l_g\rangle$$

$$\hat{QP}_l |\frac{1}{2}, l\rangle = |\frac{1}{2}, l + l_g\rangle$$

Thus, $q$-plate and FPG are alike in the sense of OAM control. Eq. 1 applies to both as $\eta_0$ is the efficiency of unchanged field and $\eta_{\pm 1}$ are of the two possible modulated OAM beams, respectively. We notice that $q$-plates work on-axis and FPGs work off-axis. This makes each superior for various applications. A $q$-plate is easy to align optically, however, for arbitrary polarized input its output is not a pure helical mode. On the other hand, an FPG always alter the beam direction by producing the different OAM states as individual diffracted orders, but each of these orders always produce pure helical beams form helical input regardless of the polarization.

2.4 Broadband PG

Introduced by Oh et al., a broadband one-dimensional PG comprises two antisymmetric chiral circular PGs with an opposite twist sense, where the local optical axis follows

$$\Phi(x,z) = \begin{cases} 
\Phi(x,0) + \Phi_0 z/d & \text{if } 0 \leq z \leq d \\
\Phi(x,0) - \Phi_0 z/d + 2\Phi_0 & \text{if } d \leq z \leq 2d 
\end{cases}$$

where $d$ is the thickness, and $\Phi_0$ is the twist angle of each chiral layer. Fig. 1 illustrates this profile. With the two antisymmetric chiral layers counteracting chromatic dispersions in the linear and twist-induced circular birefringences, this double twist structure creates a self-compensation that leads to a half-wave retardation condition over a wide bandwidth. This then leads to new efficiency equations:

$$\eta_0(\lambda) = 1 - K$$

$$\eta_{\pm 1}(\lambda) = \frac{1}{2}(1 \mp S_3')K$$
across a fairly wide bandwidth, where $K$ is a parameter determined by the LC structure and it is approximately 1 within this range. A bandwidth $\Delta \lambda / \lambda_0$ can be defined as the ratio of the spectral range $\Delta \lambda$ (over which high diffraction efficiency $\sum \eta_{\pm 1} \geq 99\%$ occurs) to the center wavelength $\lambda_0$. Through a series of optimizations, this bandwidth is maximum when when $\Phi_0 = 70^\circ$. This represents a fourfold enhancement as compared to a narrowband PG discussed earlier.

3. BROADBAND FPG AND BROADBAND Q-PLATE

We can extend the broadband PG design principles discussed to create broadband FPGs and $q$-plates. Notice that the explicit expression of the surface optical axis pattern $\Phi$ was not part of the derivation and does not appear in the efficiency equations Eq. 7. In other words, although the broadband theory was originally developed for conventional one-dimensional PGs ($\Phi(x)$), we can expand it to two-dimensional PGs ($\Phi(x, y)$) as well. Therefor, we introduce the broadband variation of FPG and $q$-plate that is based on this double twist structure

$$\Phi(x, y, z) = \begin{cases} 
\Phi(x, y, 0) + \Phi_0 z/d & \text{if } 0 \leq z \leq d \\
\Phi(x, y, 0) - \Phi_0 z/d + 2\Phi_0 & \text{if } d \leq z \leq 2d 
\end{cases} \quad (8)$$

where the surface local optical axis $\Phi(x, y)$ follows Eq. 2 and Eq. 4 for FPG and $q$-plate, respectively. These broadband FPGs and broadband $q$-plates should have both the OAM manipulation capabilities and the high diffraction efficiencies over a wide range of wavelength.

4. FABRICATION

We have experimentally realized broadband FPGs and $q$-plates formed as liquid crystal thin films fabricated by polarization holography and photoalignment techniques. We utilized a linear photopolymerizable polymer (LPP) as the photoalignment material (ROP108, Rolic Ltd). The surface alignment pattern was recorded in the LPP layer using an HeCd laser (325 nm). For $q$-plates, this pattern was created by a rotating line beam with appropriately controlled linear polarization.\textsuperscript{10,29} For FPGs, we utilize polarization holography with a $q$-plate as helical beam generator. After UV exposure, liquid crystal polymer (LCP) was spin-coated onto the patterned LPP-coated substrate. We utilized RMS03-001C (EMD Chemicals, $\Delta n 0.16 @ 589$ nm) to create this birefringent LCP film, according to the method previously reported.\textsuperscript{20} A diluted mixture (1:3 of RMS03-001C:PGMEA) layer was first coated to improve later coating quality. The next layer, the first chiral layer, was composed of the LCP doped with a small amount (approximately 0.3%) of the chiral molecule CB15 (EMD Chemicals). The last layer, the second chiral layer, was composed of the LCP doped with a small amount (approximately 0.3%) of the chiral molecule MLC-6742 (EMD Chemicals). The thickness of layers were tuned so that the half-wave retardation $\Delta nd = \lambda_0/2$ (at $\lambda_0 = 550$ nm) and a twist $\Phi = +70^\circ$ occurred simultaneously. Spin-coating speeds were 2000 rpm for the diluted LC layer, 580 rpm and 530 rpm for the first and second chiral layers, respectively.

Polarizing microscope pictures of the samples are shown in Fig. 2 that indicate good LC alignment producing the required spatial pattern in both cases. Both elements are made on one inch square substrates. The FPG has a period of 10 $\mu m$, picture is zoomed in to show the fork-shaped singularity. These results are comparable to prior work on such elements. Next, we attempt to further characterize the optical properties of both the broadband FPG and $q$-plate.

5. EXPERIMENTAL RESULTS

5.1 Polarization-controlled OAM conversion

The characterization of the OAM conversion is conducted with a Mach-Zender interferometer. With Gaussian mode laser beam ($l = l_0$) incident, the output beams are examined by interfering with a tilted plan wave. To demonstrate broadband ability, we repeated this examination using two lasers at 633 nm and 532 nm, respectively. Captured interference patterns are shown in Fig. 3 with optical path illustrations with them.

The result perfectly agrees with the theory. Predicted patterns are observed at both wavelengths. For FPGs, both circularly and linearly polarized input were tested. Circular input will diffract to a single first order and
linear input will diffract to both first orders. At the same time, all polarizations have a very weak zero order leakage. As shown in Fig. 3(a), the zero order diffraction is always unchanged, with \( l = l_0 = 0 \), and the first orders are always modulated: OAM of \( m = -1 \) diffraction is increased by \( l_g = 1 \), which in this case, equals to 1, and for \( m = +1 \) diffraction, OAM is decreased by \( l_g = 1 \), to \( l = -1 \). For \( q \)-plates, circular polarized input is also converted to helical beam (Fig. 3(b)). Opposite polarization handedness result in the same OAM value but opposite helical handedness. Linear polarized input is converted to a superposition of helical modes, which is essentially an “axial polarized beam”. This spatial varying linear polarization can be examined by observing its intensity distribution through an analyzer (Fig. 3(c)).

5.2 Conversion efficiency

To measure the conversion efficiency over the visible range we took the transmission spectra with an unpolarized broadband light source. Due to the diffractive feature of a broadband FPG, its useful output (first orders) can be easily selected by a spatial filter. We measured the zero order transmission by a spectrometer and normalized it by the reference total transmission of a bare glass substrate to get normalized zero order diffraction efficiency \( \eta_0 \). This normalization excludes the effect of substrate reflection and absorption, which could be prominently reduced by proper coating. Then we estimated the normalized total first order diffraction efficiency \( \sum \eta_{\pm} = 100\% - \eta_0 \), shown in Fig. 4. We did this estimation because zero order is non-dispersive thus can be measured most accurately. Clearly, the broadband FPG manifests high diffraction efficiency 97% across almost all visible wavelengths (483—720 nm), which is a substantial improvement over the narrowband FPG (580—675 nm), almost 2.5 times wider. A spectrum of a sample optimized for 633 nm is shown in the figure as reference. Direct first order efficiency measurements using lasers are also shown here as markers. Diffraction efficiency is calculated by single order intensity over total transmitted intensity. A 2% difference from estimated values is due to high order diffraction, scattering, and some material absorption. This should be further optimized by improving fabrication details as we will discuss in a later section. \( q \)-plates fabricated using the same recipe should have the same theoretical efficiency as FPGs. However, because output from \( q \)-plates is not spatially separated, we used a different approach to measure the efficiency by filtering out the useful fraction by polarization. With circularly polarized input, the modulated fraction reverts its handedness, whereas the unmodulated leakage fraction remains the same. Thus, by measuring the transmission through circular polarizer, we verified the \( q \)-plates conversion efficiency of >97.6% at both 532 nm and 633 nm by lasers.

6. DISCUSSION

We fabricated broadband FPGs and broadband \( q \)-plates that extent the working bandwidth significantly comparing to their narrowband versions. These elements have two main advantages over others. First, they can be used to control OAM of a broadband light with high efficiency, which could not be achieved by narrowband elements. For example, a narrowband FPG will have significant higher zero-order leakage at off-center wavelengths, making it low efficient for overall bandwidth. A narrowband \( q \)-plate has even more trouble with broadband light, since the zero-order leakage will superimpose with first-orders and make the output a complex OAM state that varies across the spectral band. The essential that makes our new thin films broadband is the material. Because of

Figure 2. Polarizing microscope pictures of (a) a broadband FPG (zoomed in at singularity) and (b) a broadband \( q \)-plate.
the two opposite chiral doping, there are more parameters we could adjust in the LC coating process in order to adjust both the shape and the position of the spectrum. Although our current recipe is optimized to cover the visible range, these elements are capable of serving other spectral ranges as well. This feature makes the simultaneous OAM controlling of a broadband light field easily achievable and could be particularly useful in wavelength-division multiplexing in OAM-based systems.

Second, these elements are easy to fabricate. Because the broadband versions have the same surface alignment patterns as conventional narrowband versions, they can be easily fabricated by photo-alignment techniques that are currently available. Generally, for most arbitrary two-dimensional LC element, we can keep its surface alignment and introduce this double twist structure to make it broadband. As a result, many nice features of narrowband FPGs and $q$-plates still apply to our broadband elements. For instance, they have good diffraction efficiency, polarization-controlled conversion, they are light weight and flexible. Combining with their wide working wavelength range, this elements are extremely unique and excellent OAM controllers.
Figure 4. Broadband FPG first order efficiency spectrum from spectrometer (curves) and laser (markers) measurements. The spectrum of a narrowband FPG optimized for 633 nm is shown for comparison.

7. CONCLUSION

We introduced two broadband OAM mode generator and transformers using LC thin films. We demonstrated that with our polarization holography and photo-alignment technique we can make high-quality broadband FPGs and broadband q-plates. Their OAM controlling functions are verified with high conversion efficiency (> 97%) in a wide range of visible spectrum (480—720 nm). These elements are thin and light weight, easily processed, and quick responding. They show an efficient mechanical-free method to control OAM of a broadband light source, which will benefit many applications including ultra high capacity information technology.

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