Half-integral spiral phase plates for optical wavelengths

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Abstract
We have fabricated high-quality, half-integral spiral phase plates for generating optical vortices at visible and near-infrared wavelengths. When inserted in the waist of a fundamental Gaussian beam, such a device gives rise to a rich vortex structure in the farfield. The near-perfect cancellation of the effect induced by two nominally identical phase plates shows that we have excellent control of the manufacturing process.

Keywords: optical devices, optical vortex, orbital angular momentum, helical beams

1. Introduction
When the phase distribution of an optical beam is helical, the beam carries orbital angular momentum along its direction of propagation. Such a beam contains a phase singularity, also called an optical vortex; the intensity vanishes at this singularity. In a transverse plane, the field can be written in the polar decomposition,

\[ u(\rho, \theta) = |u(\rho, \theta)| \exp[i\chi(\rho, \theta)]. \]

Following a closed path around the singularity, the topological charge of the vortex is defined as [1]

\[ Q = \frac{1}{2\pi} \oint \text{d}\vec{\ell} \cdot \nabla \chi, \]

where \( \chi \) is the phase of the field. In most studies involving fields with a helical phase distribution, one uses an optical beam in a cylindrically symmetric mode with a vortex at its centre. Photons in such a mode carry orbital angular momentum (OAM) with expectation value \( Q \hbar \), \( Q \) being an integer value [2]. Presently, such photons enjoy great popularity, since a helical photon can be viewed as a high-dimensional quantum system, allowing the construction of high-dimensional alphabets for quantum information [3]. This possibility has been the driving force behind studies of the conservation and entanglement of photonic orbital angular momentum in spontaneous parametric down conversion [3–8].

Optical vortex beams can be generated quite easily by diffracting a non-helical laser beam off a computer-generated hologram that itself carries a helical-phase distribution [9, 10], or off a spiral phase plate (SPP) [2, 11, 12]. We have chosen the latter route.

A SPP is a transparent plate of refractive index \( n \), whose height (thickness) is proportional to the azimuthal angle \( \theta \) (see figure 1),

\[ h = h_s \frac{\theta}{2\pi} + h_0, \]

where \( h_s \) is the step height and \( h_0 \) the base height of the device. When such a plate is inserted in the waist of a Gaussian beam, where the phase distribution is plane, it imprints a vortex charge \( Q = h_s(n - n_0)/\lambda \); the output beam thus carries orbital angular momentum per photon equal to \( Q\hbar \). The vortex charge that such a device imprints on an optical beam can be tuned by modifying either the optical step height \( h_s(n - n_0) \) or the optical wavelength \( \lambda \).
Due to this tunability it is simple to design a SPP so that, at a specific wavelength $\lambda$, the optical step height $h_s(n - n_0)$ is an odd multiple of $\lambda/2$. In the mode that arises when a Gaussian beam is diffracted off such an SPP, the orbital angular momentum per photon has an expectation value that is half-integer. Since this mode can be expanded in Laguerre–Gaussian modes [2], the photon can be viewed as an $N$-dimensional quantum system, i.e. a qubit; this explains our interest in the half-integer OAM case in particular. In the present paper we explore the use of a high-quality SPP for generating such photons.

The manufacturing requirements of a SPP as sketched in figure 1 are quite severe because:

(i) the physical step it carries should be infinitely steep,
(ii) its height in the centre should spiral up in a region of zero diameter, and
(iii) its surface should be completely smooth along the spiral.

In addition, to generate a beam with low vorticity, the optical step height $h_s(n - n_0)$ should be of the order of $\lambda$. The latter condition can be met in two ways: the step height $h_s$ is on the scale of the wavelength, which sets very high requirements on the machining precision when the wavelength is in the visible, or the plate is almost (but not quite) index matched to the surrounding medium ($n - n_0 \approx 0$) [2, 12]. At visible wavelengths the latter approach requires liquid or solid immersion, resulting in an optical step height that is strongly temperature dependent [2].

A technique that meets the manufacturing challenges of a SPP for optical wavelengths is photopolymerization in a mold as used, for example, for CD lenses [13]. A strong point of this approach is that the use of a mold allows for the production of a large set of identical SPPs [14]. In addition, by using different polymers, it allows for the fabrication of SPPs that are geometrically identical but that have variable optical step height. Here we present experimental results for SPPs fabricated with this technique.

2. Polymer SPP

In a replication technology such as photopolymerization the shape accuracy of the final product is determined by the precision of the mold that is used. In our case this mold is machined in a piece of brass in the complementary shape of the SPP, employing a diamond tool on a high-precision computer-driven lathe [15]. Inspection by optical interferometry shows that the mold is very close to ideal in terms of smoothness of the spiral. In the device’s centre, obviously, the mold cannot conform to the ideal because the diamond tool has a finite size. This gives rise to a central ‘anomaly’ with a diameter of $\approx 300 \mu$m, very small compared to the overall diameter of the SPP (8.4 mm). Also the step is not infinitely steep; instead the step has an azimuthal width of $\approx 6^\circ$.

Into the mold a pre-polymer of poly(ethylene glycol) dimethacrylate (PEG-DMA-875) is cast, which is then UV cured. This yields an SPP with a step height of $5.87 \pm 0.07 \mu$m. Using optical interferometry we find that the device has a vorticity at $\lambda = 813$ nm equal to $Q \approx 3.48 \pm 0.02$, very close to the design value $Q = 3.5$.

3. Half-integral spiral phase plate

The far-field diffraction pattern of the SPP inserted in the waist of an almost collimated Gaussian beam at $\lambda = 813$ nm is shown in figure 2. The picture on the left shows a 3D representation of the experimental results while the picture on the right shows the results of a diffraction calculation for a blemish-free spiral phase plate with vorticity $Q = 3.5$. The intensity pattern is ring-like with three slightly separated regions of very low intensity inside. Each of these regions surround a phase vortex. An additional vortex is found outside the high-intensity ring, diagonally across the points of highest intensity. Diffraction calculations show that the far-field position of the latter vortex provides a direct measure of the fractional part of the beam’s vortex charge; in the present case this fractional part equals 0.5. The agreement between the experimental and calculated far-field patterns is excellent, demonstrating that our SPP is eminently suited for generating high-quality vortex beams.

The action of any non-dissipative optical element on a diffracting beam can be undone by inserting a conjugate optical element in the same Fourier plane as the first. Basically, this is a test of unitarity. The conjugate element of a fault-free SPP is another SPP with opposite helicity. This is simply an identical phase plate, oriented in reverse (e.g. the ramps of the two devices face each other). Ideally, the far field of the second SPP is then identical to that of the original beam. Because each
SPP introduces a step in the phase of the transmitted light, it is important that the steps are perfectly aligned. This argument applies for any wavelength, independent of the value of $\lambda$.

To evaluate the unitarity of our non-ideal SPPs we send a Gaussian beam at $\lambda = 632.8$ nm through two oppositely oriented half-integer SPPs replicated in the same mold, positioned in each other’s near field. The far-field of the second SPP is nicely rounded and is very well represented by a Gaussian intensity distribution (see figure 3). This is made quantitative by noting that this output field can be coupled into a single-mode fibre with almost the same efficiency as the original input field (0.98 coupling-efficiency ratio).

These results strongly suggest that our SPPs indeed act as unitary optical elements. This implies that the non-ideal features (the anomaly at the centre, the residual surface roughness) of our SPPs do not play an important role. This experiment also demonstrates that our SPPs are ideally suited to adding and subtracting vorticity from a field, thus providing the possibility of combining devices to generate phase singularities with arbitrary dislocation strength; a combination of two SPPs, for instance produced from the same mold but made of polymers with slightly different refractive indices, can achieve exactly that.

4. Conclusions

We have employed the technique based on photopolymerization in a mould to craft spiral phase plates for visible wavelengths, designed to generate optical beams of low-order vorticity. These plates have, as a distinguishing characteristic, a half-integer vorticity. We have studied the diffraction properties of the resulting phase plates both individually and as a matched pair. All tests indicate that the spiral phase plates produced are of very high quality and replicate very well. We are confident that these plates with half-integer vorticity can be of great use in the study of high-dimensional entanglement [16].

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References