Plasmonic Optical Vortex Analyzer

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Complex light fields, such as speckle patterns, contain many phase vortices. One way of determining a vortex-carrying beam's vortex charge involves interference with another beam. On the other hand, we present a single-beam method for analyzing vortices' wavefronts using surface plasmon polaritons. We use a subwavelength slit in a film to slice up a vortex beam, and measure the diffraction of the generated plasmons by scattering off a second slit. By moving the slits across the beam, we create a tomogram, from which we determine the beam's vortex charge visually. The method can easily be extended to more complex light fields; it is foreseen that it may result in a miniature device.

Introduction

Vortices occur in many branches of physics. A property that all vortices share is that, when traversing a closed path around a vortex, an order parameter of the system changes by $2\pi Q$, with Q the "charge" of the vortex. Here we concern ourselves with phase vortices in the transverse field distribution of an optical beam. For a simple case, the transverse intensity distribution of a vortex beam is doughnut-shaped, the phase increasing azimuthally around the doughnut. At the center the intensity vanishes because the phase is undefined there. The number of cycles with which the phase increases on a closed loop around the doughnut equals the vortex charge Q. There are several ways to measure this charge; most frequently some sort of interferometry is used. We present an alternative approach in the experiment described here, which uses diffracting surface plasmon polaritons (SPPs).

Experiment

Figure 1 shows an artist's impression of our experimental setup. We create a linearly polarized beam of integer vortex charge by diffracting a Gaussian beam ($\lambda = 830$ nm) off of a computer-generated fork hologram [1]. The beams diffracted from this grating carry a vortex charge dependent on the diffraction order and the vortex inscribed in the hologram; we select a diffraction order that carries the desired vortex charge. Once the beam propagates to the far field of the hologram, it has the doughnut-shaped intensity and azimuthal phase as described above. We also create linearly polarized beams of non-integer vortex charge, specifically $Q = +3\frac{1}{2}$, by passing a Gaussian beam through a spiral phase plate [2].

We let such a beam impinge on a 50 µm-long and 100 nm-wide slit that is ion-beam milled in a 200 nm-thick gold film. The latter is attached to a glass substrate by a 10 nm titanium adhesion layer. The slit, henceforth called the emitter slit, converts the incident light into SPPs along the gold-air interface. A second, identical slit, henceforth called the receiver slit, at a distance of tens of micrometers from the emitter slit, converts the incident SPP into light that is imaged and detected on a CCD. In between the slits the SPP wave diffracts freely, the diffracted wave being sampled by the receiver slit. The diffraction

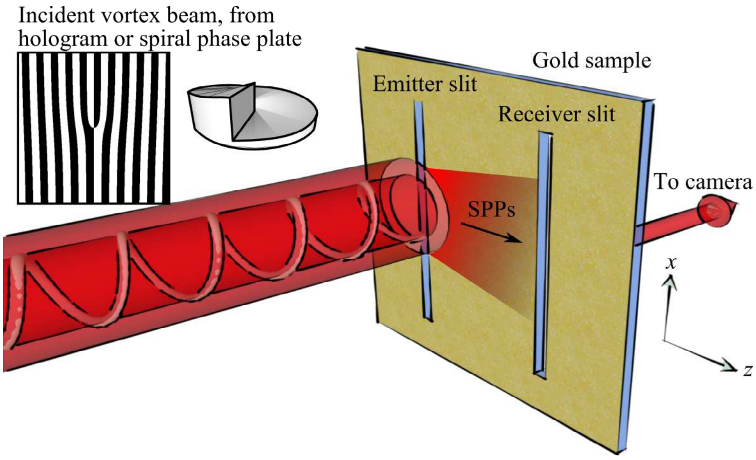

Figure 1: Artist's impression of the experimental setup.

pattern contains information on both the phase and amplitude of the light incident on the emitter slit and thus provides access to the phase distribution of the incident beam. The emitter-receiver distance is comparable to the damping length of SPPs on gold at our operating wavelength. The titanium layer that is used to attach the gold layer to the glass substrate ensures that SPPs cannot propagate on that interface [3].
At the start of a measurement, the beam is incident to one side of the slit pair. We then translate the sample transverse to the incident beam in 100 nm steps so that the emitter slit is scanned through the beam. At each position of the sample, we record the intensity profile of the light scattered from the receiver slit. We then assemble these profiles together in a tomogram, so that each vertical slice of the tomogram corresponds to one slice of the incident vortex beam after propagation and diffraction from emitter to receiver.

Results

Figure 2 shows the calculated and measured tomograms for incident beams of vortex charge $Q = +1$, -1, and -3, respectively, using slits separated by 25 μm. Regions of high intensity are in black, while regions of low intensity are white-colored. The tomographic intensity patterns are seen to be quite different from the intensity patterns of the incident vortex beams, which have circular symmetry. First, the pattern is no longer rotationally symmetric, but has a two-fold symmetric, elongated shape. Second, the patterns for beams with vortex charge $Q = +1$ and $Q = 1$ are each others mirror image. Third, the orientation of the long axis of the pattern carries the sign of the vortex charge. Finally, the magnitude of the vortex charge can be read off directly from the number of spatially separated intensity zeroes in the pattern. Note that the intensity zeroes in the $Q = 3$ tomogram occur nicely along a straight line.
Our calculations, using the Fresnel-Kirchhoff diffraction integral, are in excellent agreement with our experimental results. They allow us to conclude that these intensity zeroes correspond to phase vortices in the tomogram.
There is an intuitive way of explaining why the tomograms look as they do. The field amplitude of the SPPs at the emitter slit undergoes diffraction as the SPPs travel from the emitter to the receiver. We can consider the field's amplitude at the emitter to be

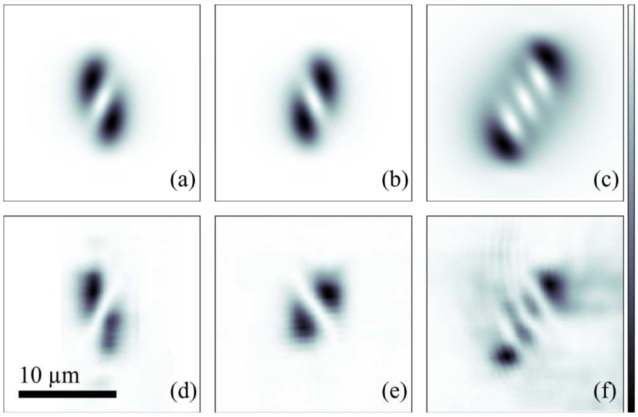

Figure 2: Calculated (a–c) and experimental tomograms (d–f) for beams on slits separated by 25 μm, with vortex charge $Q = +1$ (a and d), $Q = -1$ (b and e), and $Q = -3$ (c and f).

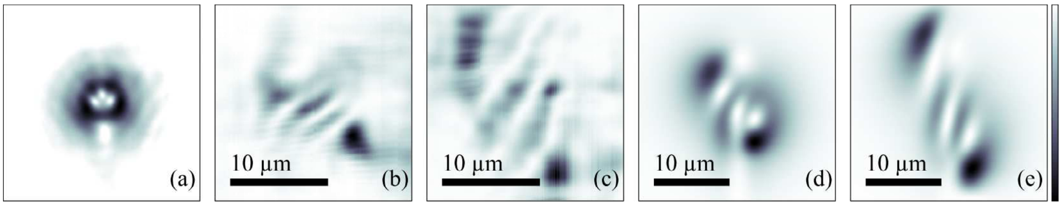

Figure 3: (a) Far-field diffraction pattern of a $Q = +3\frac{1}{2}$ vortex beam; (b) experimental tomogram of this beam on slits separated by 25 μm; (c) 75 μm; (d) calculated tomogram of a $Q = +3\frac{1}{2}$ vortex beam on slits separated by 25 μm; (e) 75 μm.

equivalent to an amplitude mask in a screen, with bright areas corresponding to slits. The screen is illuminated from behind by a plane wave at an angle determined by the fields phase at the emitter. If we place a second screen, corresponding to the receiver, at some distance from the first, then the positions of the bright and dark spots in the tomogram follow directly by considering where constructive and destructive interference occurs on the second screen [4].

We also examined a beam with a non-integer vortex charge ($+3\frac{1}{2}$) in order to consider the application of this method to more complex vortex-carrying fields. The far-field diffraction pattern of such a beam is not rotationally symmetric, so we oriented the phase plate to produce an incident intensity pattern as shown in Fig. 3a, with the emitter-receiver slits oriented vertically. The incident pattern shows three close-lying, separated $Q = +1$ vortices in the center, with an additional one intruding from the bottom. Figures 3b and 3c show two measured tomograms at different slit separations. Figures 3d and 3e show the corresponding calculations. They also show a fourth vortex intruding from the side, although the visibility of this fourth vortex in the measurements is somewhat marginal. Currently we do not account for any inhomogeneity in the slit width; this problem might be solved by using a ptychographical algorithm, which iteratively reconstructs the complex amplitude of a field, and the transfer function of the object used to probe it.

For a better understanding of the relation between the fractional part of the vortex charge and the presence and position of the fourth vortex in the tomogram, we calculated the tomograms of beams with various vortex charges between $+3$ and $+4$, shown in Fig. 4.

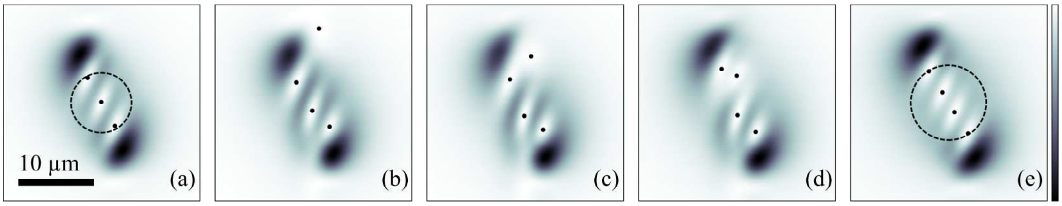

Figure 4: Calculated tomograms of vortex beams with Q ranging from $+3$ to $+4$ on slits separated by 50 μm. (a) $Q = +3$; (b) $Q = +3\frac{1}{4}$; (c) $Q = +3\frac{1}{2}$; (d) $Q = +3\frac{3}{4}$; (e) $Q = +4$. The locations of the intensity zeroes are indicated with dots. In (a) and (e), the size of the original vortex ring is superimposed on the tomogram.

We see that as Q increases, the fourth vortex, as seen in Fig. 3, approaches the three existing vortices, and eventually joins them in a straight line at $Q = +4$. The vortices are arranged in a straight line only when Q is an integer. This suggests that a non-integer vortex charge can be determined from the deviation of the vortices' arrangement from a straight line, the angle of which is determined mainly by the ratio of the distance between the slits to the spot size of the beam. Our calculations indicate that any dependence on Q is less than 1° and may even be a numerical artifact.

Conclusion and acknowledgements

We have used the diffraction of surface plasmon polaritons to analyze a vortex-carrying light beam slice by slice, in order to recover information about the beam's phase: specifically, its integer vortex charge. Although the determination of non-integer vortex charges is not possible at a glance, we have shown through calculations that the magnitude of a non-integer vortex charge may be determined by measuring how much the arrangement of the vortices deviates from a straight line.

Phase retrieval normally requires some technique such as interferometry or a combination of near-field and far-field measurements. The current experiment's two slits can be considered to measure the SPPs' near field and far field. Therefore, the technique might be generalized to phase retrieval of arbitrary fields. Also, the sample's small size and the small distances between the optics involved suggest that the experiment can be easily miniaturized. Therefore, it has a potential application as a wavefront sensor.

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References

[1] V. Yu. Bazhenov, M. V. Vasnetsov, and M. S. Soskin, "Laser beams with screw dislocations in their wavefronts," *JETP Letters,* vol. 52, pp. 429–31, 1990.

[2] S. S. R. Oemrawsingh, E. R. Eliel, J. P. Woerdman, E. J. K. Verstegen, J. G. Kloosterboer, and G. W. 't Hooft, "Half-integral spiral phase plates for optical wavelengths," *Journal of Optics A: Pure and Applied Optics,* vol. 6, pp. S288–S290, 2004.

[3] H. F. Schouten et al., "Plasmon-assisted two-slit transmission: Young's experiment revisited," *Physical Review Letters,* vol. 94, p. 053901, 2005.

[4] P. F. Chimento, G. W. 't Hooft, and E. R. Eliel, "Plasmonic tomography of optical vortices," *Optics Letters,* accepted for publication.