Nanophotonic devices for polarization control

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Experimental characterization of unique nanophotonic devices shows that their polarization can be converted for potential application to the generation of vortex solutions, optical guiding of cold atoms, and high-efficiency laser trapping.

In recent years we have witnessed a growing effort to investigate the properties of optical beams with space-variant states of polarization. For example, it has been shown that radially polarized optical fields can be used to focus light to a spot smaller than the diffraction limit. Unfortunately, the construction of such optical fields is either complicated, or it requires an expensive spatial light modulator. We have developed a unique and simple approach to generating radially and azimuthally polarized light. Our subwavelength structures are realized using space-variant inhomogeneous media (SVIM). In order to locally transform the polarization state, the design uses form birefringence that can be varied across the wavefront, offering high conversion efficiency.

It is well known that sub-wavelength periodic structures can be used to engineer the polarization dispersion relation for propagating transverse electric (TE) and transverse magnetic (TM) polarized optical fields. If the depth of the periodic structure is designed to introduce a \( \pi \) phase shift between the TE and the TM components, it acts as a half-wave retardation plate, rotating the polarization of the incident linearly-polarized field. The rotation angle will be twice that between the polarization vector of the incident field and the optic axis of the form birefringent element. By controlling the orientation of the form birefringent structure, we can engineer the amount of rotation in a space-variant manner and create any desired polarization distribution within the aperture of the incident field.

Our design considers an incident field propagating in the \( z \)-direction, linearly polarized along the \( x \)-axis as shown in Figure 1(a). For our application, we wish to construct a beam with a space-variant polarization state that is linearly polarized in the radial direction along the \( r \)-axis in the polar coordinate system \((r, \theta)\): see Figure 1(b). Thus, we will need to create a half-wave retardation plate with principal axis oriented at an angle \( \theta / 2 \) with respect to the \( x \)-polarized input field. The grating vector \( \mathbf{K}_g \) for achieving such a device can be shown to take the following form:

\[
\mathbf{K}_g = \frac{2\pi}{a_0\sqrt{r}} \left[ \cos \frac{\theta}{2} \mathbf{e}_r - \sin \frac{\theta}{2} \mathbf{e}_\theta \right]
\]

where \( a_0 \) is a constant chosen to meet fabrication constraints and aperture dimension requirements. For the orthogonally polarized incident field—the field that is linearly polarized along the \( y \)-axis—the same element will produce an azimuthal output polarization state, shown schematically in Figure 1(c). From the relation \( \left| K_y \right| = \frac{2\pi}{\lambda} \), it is evident that \( \Lambda \) (the grating period of the SVIM) is proportional to \( \sqrt{r} \), therefore resulting in a hole in its center: see Figure 2(a).

We fabricated SVIM elements using photolithography followed by chemical assisted ion beam etching (CAIBE) to transfer the pattern into the GaAs substrate. The device was designed to operate at a wavelength (\( \lambda \)) of 10.6\( \mu \)m, to support CO\(_2\) laser applications. To obtain \( \pi \) phase retardation, the etching depth was 5.5\( \mu \)m. The minimal and maximal periods were \( \Lambda_{\text{min}} = 2\mu \text{m} \) and \( \Lambda_{\text{max}} = 3.05\mu \text{m} \) respectively (the maximal period needs to be smaller than \( \lambda/n \) where \( n \) is the refractive index of the substrate). We chose the outer radius to be 7mm, resulting in \( a_0 = \frac{10.6}{2\sqrt{7}} \left( \frac{\mu \text{m}}{\sqrt{\text{mm}}} \right) \) with the corresponding inner radius.

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Figure 2. (a) Our initial design yielded a central hole of approximately 18%. (b) It is possible to eliminate the central hole with a modified design constructed by combining a symmetric version of the tangential design and an element introducing a relative $\pi$-phase shift to half of the element plane.

Figure 3. (a) An image of the polarization transformer SVIM element was obtained when it was illuminated by a linearly polarized beam. (b) A comparison of the light intensity data in 3(a) with the theoretical curve shows good agreement between the measured and calculated curves.

The measured light intensity is the projection of the radially polarized light on the analyzer. The image we obtained is shown in Figure 3(a). As expected, the light intensity increases along the azimuthal coordinate $\theta$, up to $\theta = 90^\circ$ where the direction of the polarization coincides with that of the analyzer, followed by a drop in intensity towards $\theta = 180^\circ$ where the polarization and analyzer are orthogonal to each other. This result is depicted in Figure 3(b), where a cross section of this image along the azimuthal coordinate $\theta$ is shown. The normalized intensity is compared with the theoretical curve ($\sin^2 \theta$), showing good agreement between the measured and the calculated curves. (Azimuthally polarized light was also generated by rotating the SVIM element by 90°.)

Next we explored the far-field properties of the beam that emerges from our SVIM element. From theoretical calculations, we predicted the formation of a 'donut-like' intensity distribution in the far field. To observe this, we removed the analyzer and used a converging illumination beam that produces the far-field distribution in the focal plane of the lens. Horizontal cross sections of the calculated and the measured optical field distributions are given in Figure 4, while the inset corresponds to the entire far-field distribution as captured by the charge-coupled device (CCD). The obtained donut-shaped beam clearly shows that the experimental results are in good agreement with the theoretical prediction. These beams can be used for applications such as the generation of vortex solutions, the optical guidance of cold atoms, and high-efficiency laser trapping.

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References