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# Cyclic group symmetric metasurface for optical spin-dependent beam separation

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## Abstract

Geometric phase is introduced when a cross-polarization scattering from nano-rod takes place. Here we introduce a cyclic group symmetric metasurface composed of tapered arc nano-rods and explore how azimuthal angular dependence of geometric phase determines the feature of spin-dependent beam separation.

## 1. Introduction

Vortex beam carries orbital angular momentum associated with topological charge. There are several means to generate vortex beam. Differently from refractive optics employing a set of cylindrical lens or spiral phase plate, spin-to-orbital momentum conversion (SOC) can utilize a geometric phase or Pancharatnam-Berry (PB) phase introduced in a cross-polarization scattering from nano-rod. In Poincaré sphere the solid angle subtended by polarization states of input beam and cross-polarized output beam corresponds to the geometric phase introduced. Instead of a uniform thickness nano-rod, a tapered arc nano-rod provides a non-constant azimuthal gradient of geometric phase  $\nabla_\phi \Phi_{PB}$ . Here we investigate how the feature of spin-dependent beam separation in vortex beam generation is related to the symmetry properties of cyclic group symmetric metasurface. Different sizes of TA are arrayed in a circle to obtain metasurface possessing a point group symmetry of cyclic symmetry of  $C_{nh}$ , and experimental measurement of vortex beam profiles from cross-polarization scattering of circular-polarized beam from  $C_{nh}$  TA-CGSM is performed and a detailed theoretical analysis is carried out.

## 2. PB phase from circular arrays of nano-rods

Linear array and circular array of nano-rods are displaced in Fig. 2 (a) and (b). Beam deflection from a linear array and vortex beam generation from a circular array via SOC are shown in Fig. 2 (d) & (e) and (f) & (g), respectively. Polarization states of cross-polarization scattering are plotted on Poincaré sphere in Fig. 2 (c). Solid angle subtended by two meridians of cross-polarization scatterings from two neighboring nano-rods is a constant, resulting in a circular trajectory of polarization states from near the north-pole

down to near the equator. This leads to  $\Phi_{PB}$  having a constant azimuthal gradient of  $\pm 2$ .

On the other hand, when scattered from a tapered arc nano-rod,  $\Phi_{PB}$  having a non-constant azimuthal gradient. That is,  $\nabla_\phi \Phi_{PB}(\phi)$  depends on the azimuthal angle  $\phi$ , and we can decompose the geometric phase  $\Phi_{PB}(\phi)$  as a sum of constant and non-constant azimuthal gradient terms,

$$\Phi_{PB}(\phi) = \Phi_{PB}^{(0)}(\phi) + \Phi_{PB}^{(1)}(\phi). \quad (1)$$

with  $\Phi_{PB}^{(0)}(\phi)$  having constant azimuthal gradient  $\nabla_\phi \Phi_{PB}^{(0)}(\phi) = \pm 2$ .

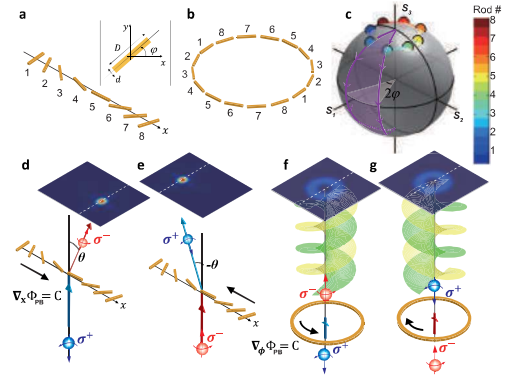


Figure 1: Array of nano-rods with a constant gradient PB phase and Poincaré sphere plot of Stokes parameters. (a) Linear array of rotating nano-rods. (b) Circular array of nano-rods. (c) Poincaré sphere plot of Stokes parameters of optical beams scattered from nano-rods of (a) and (b) for LCP incident beam. Color code corresponds to the nano-rod number. (d,e) Spin-dependent beam deflection of cross-polarization scattered optical beam. (f, g) Generation of vortex beam of topological charge  $l = \pm 2$ .

## 3. Fabrication of cyclic group symmetric metasurface

In Fig. 2 is displayed scanning electron microscope (SEM) image of metasurface composed of a tapered arc nano-rod belong to  $C_{h1}$  cyclic group. Metasurfaces were fabricated on 1mm thick round borosilicate glass substrates with a diameter of 25mm (WBO-215 from UQG Optics).

First, after cleaning substrates 60-70  $nm$  thick layer of e-beam resist (PMMA diluted in ethyl-lactate, AR-P 679 from All-Resist, Germany) was spin-coated onto the clean substrate surfaces at a rotation speed of 6000 rpm. Then, the e-beam resist underwent a soft baking process, and the second, conductive resist was spin-coated on the e-beam resist (SX AR-PC 5000/90.1 from All-Resist) and baked for 2 min at 85°C. Pioneer system (from Raith, Germany) equipped with a field emission electron gun was used for EBL patterning. We used the e-beam acceleration voltage of 20  $kV$ , beam current of 0.016  $nA$ , and aperture of 7.5  $m$ . The working distance was about 5  $mm$ .

Each sample contained a design of multiple metasurfaces organized in a matrix with a pitch of 2  $mm$  in order to prevent eventual interactions during optical measurements. We slightly varied the EBL exposure dose in order to finely tune the width of individual features constituting the CGSMs. In the matrix rows, the nominal exposure dose was increased from 130 to 180  $\mu C/cm^2$ , and the order of different metasurfaces increased from  $C_{1h}$  to  $C_{6h}$  in the matrix columns. PMMA is a positive resist, and the exposed resist areas are then easily dissolved in a corresponding solvent during the development step. After exposure, the conductive resist layer was removed with deionized water. The samples were then developed for 60 s in a commercial solution (AR 600-55 from All-Resist) containing a mixture of methyl isobutyl ketone (MIBK) and IPA. The development was stopped in pure IPA bath and the samples were dried under nitrogen flow. Third, a 2-3  $nm$  thick chromium seed layer and 27  $nm$  thick optically active gold layer were successively evaporated under vacuum (Auto 306 tool from Edwards). The thickness of deposited metal was monitored in situ using a quartz crystal microbalance. A lift-off process in ethyl-lactate in an ultrasonic bath was used to remove the e-beam resist as well as the excess of gold and chromium in the sample areas which were not exposed to the electron beam during EBL. Finally, the samples were rinsed in deionized water and dried under nitrogen flow.

After fabrication of the samples, the total thickness of deposited metal layer (30  $nm$ ) was confirmed by contact mechanical profilometer measurements (Dektak XT, Bruker, Germany). Then, the samples were characterized by optical microscopy as well as by SEM using the same Pioneer system as for EBL. All the metasurfaces were verified one by one by SEM observation in order to check for eventual (very rare) defects appeared during the lithography or lift-off steps. The sizes of individual nanofeatures were measured from SEM images taken at a low acceleration voltage (3  $kV$ ) in order to decrease sample charging. Quick optical microscope observations were performed using Nikon optical microscope at Planete.

#### 4. Results and Discussion

Experimental measurement of spin-dependent beam separation is performed at a propagating distance of  $D = 50mm$ , which gives the transverse shift of  $\Delta = 2 \times$

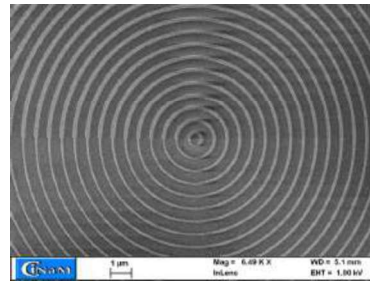


Figure 2: Scanning electron microscope image of metasurface composed of a tapered arc nano-rod belong to  $C_{h1}$  cyclic group.

$0.02 \times \sigma \times D = 2mm$  for 1310 $nm$  incidence beam wavelength. The vortex charge of cross-polarization scattering beam from  $C_{\infty h}$  metasurface is identified by an interference pattern between scattering vortex and incidence Gaussian beams. Counter-clockwise and clockwise twisted fringes confirmed topological charges of  $l = 2$  and  $l = -2$  of  $I_{-+}$  and  $I_{+-}$ , respectively.

Spin-dependent beam separation was analyzed in terms of partial-wave expansion, azimuthal interference, and a non-constant azimuthal gradient of geometric phase  $\nabla_{\phi} \Phi_{PB}$ . It is found that odd- and even-number group orders  $n$  of cyclic group  $C_{nh}$  plays an important role in giving rise to the beam separation profile, and a wavelength dispersion of spin-dependent beam separation of vortex beam indicated that there is a photonic spin Hall effect.

#### 5. Conclusions

By introducing a tapered arc cyclic group symmetric metasurface, the details of optical spin-dependent beam separation in spin-to-orbital angular momentum conversion are investigated. Presence of non-constant azimuthal gradient of PB phase is found to be responsible for azimuthal interference pattern in vortex beams with asymmetric helical wavefront. By identifying the role of non-constant azimuthal gradient of PB phase in giving rise to spin-dependent beam separation, spatial separation and vortex beam profiling are achieved in a controllable manner.

Azimuthal interference pattern in vortex beams with asymmetric helical wavefront found to be related to symmetry property of cyclic group  $C_{nh}$ , and group order  $n$  determines topological charge  $l \neq \pm 2$  of additional vortex beams.

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