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Measuring Phase and Polarization Singularities of Light Using Spin-Multiplexing Metasurfaces

Yanan Fu,[a, ‡] Changjun Min,[a, ‡] Jiahao Yu,[a] Zhenwei Xie,[a] Guangyuan Si,[b] Xianyou Wang,[a] Yuquan Zhang,[a,*] Ting Lei,[a] Jiao Lin,[a,b,c] Dapeng Wang,[a] H. P. Urbach,[d] and Xiaocong Yuan[a,*]

[a.] *Nanophotonics Research Center, Shenzhen Key Laboratory of Micro-Scale Optical Information Technology, Shenzhen University, Shenzhen 518060, China.*

[b.] *Melbourne Centre for Nanofabrication, Australian National Fabrication Facility, Clayton, VIC 3168, Australia.*

[c.] *School of Engineering, RMIT University, Melbourne, Victoria 3001, Australia.*

[d.] *Optics Research Group, Delft University of Technology, Lorentzweg 1, 2628CJ Delft, The Netherlands*

‡ *These authors contributed equally to the work.*

* *Corresponding authors. E-mail addresses: xcyuan@szu.edu.cn. yqzhang@szu.edu.cn.*

Simulation method

All the numerical simulations were carried out using the finite difference time domain method (FDTD, commercial code). The three-dimensional (3D) FDTD model used for the calculation of the detection of singularities of singularity beams consists of a volume that spans 120 μm along both the x and y direction, and spans 5μm along z direction. All six boundaries for the computation volume are terminated with perfectly matched layers(PML) to avoid parasitic unphysical reflections around the structure. A special grid is set up for the metal film, the grid resolution is 20nm along both x and y direction, and 5nm along z direction. the grid resolution in other region is according with the FDTD region which is set as auto-non-uniform, and the mesh accuracy is set as 2. The three-dimensional (3D) FDTD model used for the calculation of the parameter sweep of the semi-ring unit cell consists of a volume that spans 0.896 μm along the x and 0.45 μm along the y direction, and spans 5μm along z direction. the boundaries for computation volume in x and y direction is periodic, and perfectly matched layers(PML) is used for z direction to avoid parasitic unphysical reflections around the structure the grid resolution for metal film is 4nm along both x and y direction and 1nm along z direction. the grid resolution of FDTD region is the same as the former one.

Generations of light source

According to Ref. 1, a common phase singularity beam containing vortex phase is a Laguerre-Gaussian beam, which can be describes as

$$u_l(r,\varphi,z=0)=(\frac{\sqrt{2}r}{w_0})^{|l|}L_p^{|l|}(\frac{2r^2}{w_0^{\ 2}})\exp(il\varphi)\exp(\frac{-r^2}{w_0^{\ 2}}) \tag{1}$$

where *r*, φ , and *z* are cylindrical coordinates, w_0 is the beam waist, $L_p^{|l|}$ is the Laguerre polynomial, *l* is the OAM quantum number (i.e. TC), and *p* is the radial node index which is set to zero in this paper.

First the function above is written in MATLAB, and the complex amplitude of a Laguerre-Gaussian beam with TC=*l* is obtained.

Then a CVB can be described as

$$E_m=u_m\left|R\right\rangle+u_{-m}\left|L\right\rangle \tag{2}$$

That is $Ex_m = u_m + u_{-m}$, $Ey_m = iu_m - iu_{-m}$, and Ez is set to be zero. Then the Ex, Ey and Ez component of a m-order CVB can be obtained.

A CVVB can be obtained by set $Ex_{l,m} = u_{l+m} + u_{l-m}$, $Ey_{l,m} = iu_{l+m} - iu_{l-m}$,and $Ez_{l,m} = 0$

Spin response of structural unit

The semi-ring aperture can be regarded as a series of continuous rectangular aperture with inclination angle $\theta(x,y) = \tan^{-1}(dy/dx)$,the left side endpoint and right side endpoint of the semi-ring generated $-\pi$ and π PB phase, respectively. And the PB phase in other position is defined as $\Phi = 2\sigma\theta(x,y)$,where $\sigma = \pm 1$ represent RCP and LCP, respectively. The spin dependent PB phase of the unit cell finally lead to the different propagating path between RCP and LCP. The detailed information can be found in Ref. 2.

Take a periodic semi-ring aperture array with the parameters of the unit cell defined as Px=0.896 µm, Py=0.45 µm, d=0.08 µm, r=0.37 µm, w=0.1 µm as an example, figure S1a shows the far field pattern of the structure, the incident light is RCP at the wavelength of 633nm.figure S1(b) shows case with LCP incident, figure S1(c) shows the result along the line in figure S1(a) and S1(b), it intuitionally shows that the unit cell has a high efficiency and extinguish ratio.

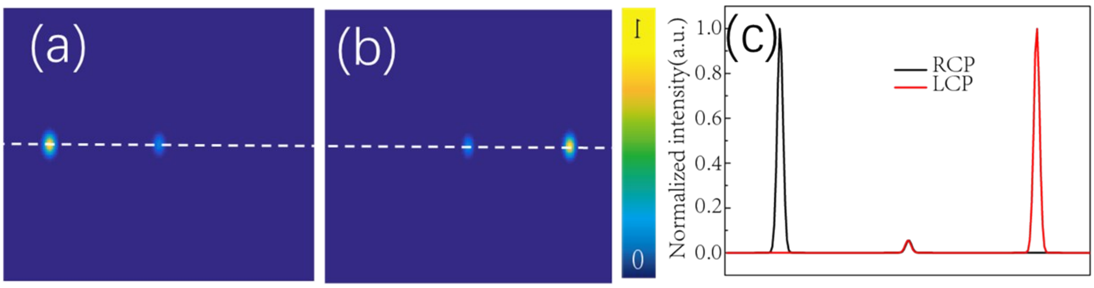

Figure S1 (a) Far field distribution of the periodic semi-ring aperture with the parameters of the unit cell defined as Px=0.896µm, Py=0.45µm, d=0.08µm, r=0.37µm, w=0.1µm when the incident light is RCP, (b) the case of LCP, (c) the intensity distribution along the white line in figure S2(a) and (b).

Principle of detour phase

Here, the meta-hologram is designed with a gold film etched with semi-ring-shaped nano-aperture. the scattered light beams from the two adjacent unit cells in the metal film act as two parallel line sources with equal phase and the optical path difference at the output angle θ is $\Delta L = D\sin\theta$, The corresponding phase difference is $\Delta\varphi = 2\pi\Delta L/\lambda = 2\pi D\sin\theta/\lambda$, if the value of D properly selected , the phase difference $\Delta\varphi$ can be modulated from 0 to 2π . Furthermore, we extend the two apertures to a two-dimensional aperture array with a period length $Px = D = \lambda/\sin\theta$. then we can determine the phase difference of each aperture from 0 to 2π through adjusting the aperture position in each period. Then a hologram with two-dimensional phase distribution φ(i,j) can be formed through the aperture array by selecting all of the aperture positions in each unit cell. In our design, we define the central position of the unit cell as $\varphi(i,j) = 0$, and then we could get $\varphi(i,j)$ changing from $-\pi$ to π when the slit location changes from the left to the right border of cell.

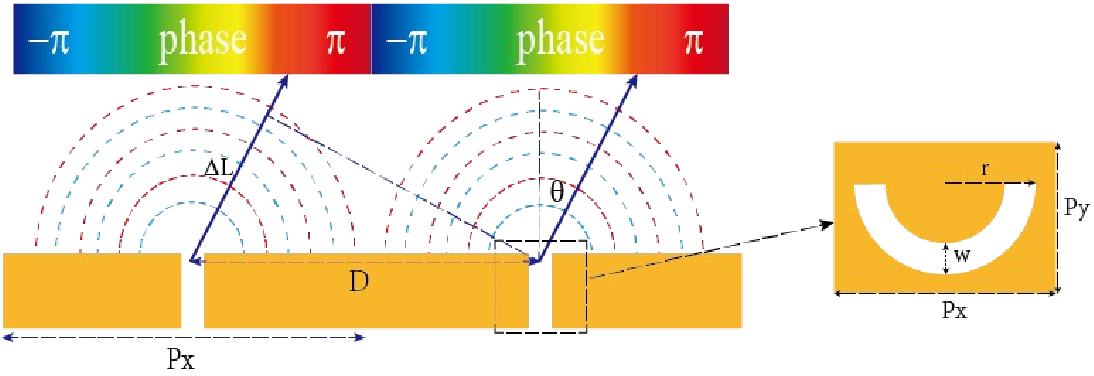

Figure S2. Schematic of detour phase principle, Px denotes the period length along x axis of a single cell. D denotes the distance between two adjacent unit cells , ΔL is the optical path difference induces by the two cells at $\theta = ar\sin(\lambda / P)$,W is the width of the semi-ring aperture, r is the radius and Py is the period length along y axis.

Detection of OVs with fractional OAM

The FDTD simulation results of a LCP incident light with fractional OAM (topological charge l=2.5and l=1.5) are shown in Fig. S3. When the incident beam is a left circular polarized OV with l=2.5, we can get two quasi-gaussian points in the position of l_0=−3 and l_0=−2. Consequently, the fractional OAM (l=2.5) can be detected as a combination of l=3 and l=2. When the incident beam is a left circular polarized OV with l=1.5, we can observe that quasi-gaussian points appears in the position of l_0=−1 and l_0=−2, hence the fractional OAM (l=1.5) can be detected as a combination of l=1 and l=2. Here we found that the fractional OAM could also be detected by extracting the intensity value of the two quasi-gaussian points, demonstrating that our metasurface has potential application in detecting fractional OAM.

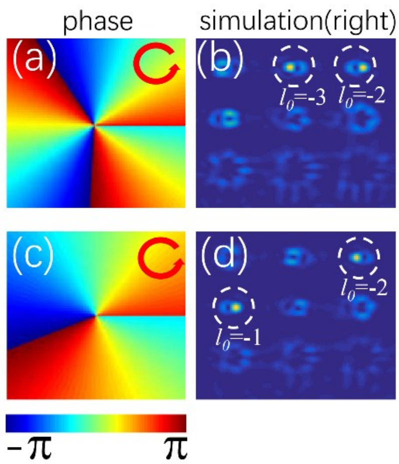

Fig. S3. (a)The phase distribution of fractional OAM beam with topological charge l=2.5, (b) the FDTD simulation result of the generated pattern through metasurface in the right side of the far field.(c) and(d) the corresponding result of a left circular polarized OV beam with l=1.5.

References

1. Y. Zhang, P. Li, J. Zhong, S. Qi, X. Guo, D. Wu, S. Liu, and J. Zhao. Applied Physics Letters, 2018, **113**, 221108.
2. G. Zheng, H. Mühlenbernd, M. Kenney, G. Li, T. Zentgraf, S. Zhang. Nature Nanotechnology, 2015, **10**, 308-312.