Hypergrating for Focusing Vortex Beam Below Diffraction Limit

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Abstract: Light with an orbital angular momentum can strongly modify optical transition selection rules when beam size is reduced to subwavelength scale. We demonstrated a method for focusing orbital angular momentum beams below the diffraction limit.

Vortex beam carries orbital angular momentum (OAM) due to the rotational energy flow around its phase singularity. It has been shown that such angular momentum can be transferred to bounded electrons and thus modifies the optical transition selection rules [1]. The light matter interaction strength depends on the relative scale of the vortex beam and electron wave functions in the matter [2, 3]. In order to enhance the interaction the size of the vortex beam size needs to be reduced to subwavelength dimensions. However the spatial extent of vortex beams is governed by diffraction with conventional focusing method.

Here we demonstrate a new method for focusing vortex beam using a hypergrating system, which allows focusing vortex beam below diffraction limit, and enables spin angular momentum (SAM) to OAM conversion. The hypergrating consists of a hyperbolic metamaterial stab (HMMS) on top of a diffraction grating. The HMMS is made of stacked alternating layers of dielectric material Ti_3O_5 and metal Ag, whose permittivities are $\varepsilon_D = 5.1$ and $\varepsilon_M = -11.8+0.4i$, respectively, at the wavelength of 532 nm.

Note that the HMM layers in our design are too thick to apply the effective medium theory [4, 5]. We therefore describe modes supported by these structures using analytical expression developed for periodically stratified media [6, 7]

$$\cos\left(k_r(a_D+a_M)\right) = \cos\left(k_D a_D\right)\cos\left(k_M a_M\right) - \gamma \sin\left(k_D a_D\right)\sin\left(k_M a_M\right), \tag{1}$$

where $k_{D,M}^2 = \varepsilon_{D,M}\omega^2/c^2 - k_z^2$ and γ is given by $\frac{1}{2}\left(\frac{\varepsilon_M k_D}{\varepsilon_D k_M} + \frac{\varepsilon_D k_M}{\varepsilon_M k_D}\right)$ and $\frac{1}{2}\left(\frac{\varepsilon_D}{\varepsilon_M} + \frac{\varepsilon_M}{\varepsilon_D}\right)$ for the TM and TE polarization, respectively. The former modes are responsible for sub-wavelength light focusing.

Focusing of modes requires constructive interference of the signals generated by multiple openings of the Fresnel gratings. The design of the grating employs the analytical relationship between the directions of the phase and group velocities of the beam, combined with numerical solutions of the relationship between the position of the opening and phase delay between the opening and the focal point. The results of such calculations are adopted in the design shown in Fig. 1. (a) where slits generate constructively interfering beams. Note that in type-II hyperbolic composites the openings are limited to relatively large radii.

The Fresnel gratings are fabricated by curving the designed concentric rings on a 50 nm thick Cr layer with focused ion beam. The rings are filled with PMMA for planarization as is shown in Fig. 1. (b, c). The designed and fabricated Fresnel zones boundaries are shown in Table. 1 and in Fig. 1. (d).

Designed $x_m(\mu m)$	1.250	1.312	1.376	1.440	1.506	1.570	1.637	1.701	1.768	1.834
Measured $x_m(\mu m)$	1.250	1.305	1.360	1.425	1.490	1.560	1.625	1.690	1.765	1.830

Table 1. Designed and fabricated boundary positions of the Fresnel zones

The Fresnel gratings also serve as an SAM to OAM converter when incident beams are circularly polarized. The period of the gratings is much smaller than the incident wavelength and only light with polarization perpendicular to the gratings are transmitted [8]. Circularly polarized beam can be decomposed into the combination of radial polarization and azimuthal polarization components with a spiral phase wavefront.

$$\vec{E_{in}} = \vec{e}_x + i\vec{e}_y = e^{i\phi}\left(\vec{e}_r + i\vec{e}_\phi\right), \tag{2}$$

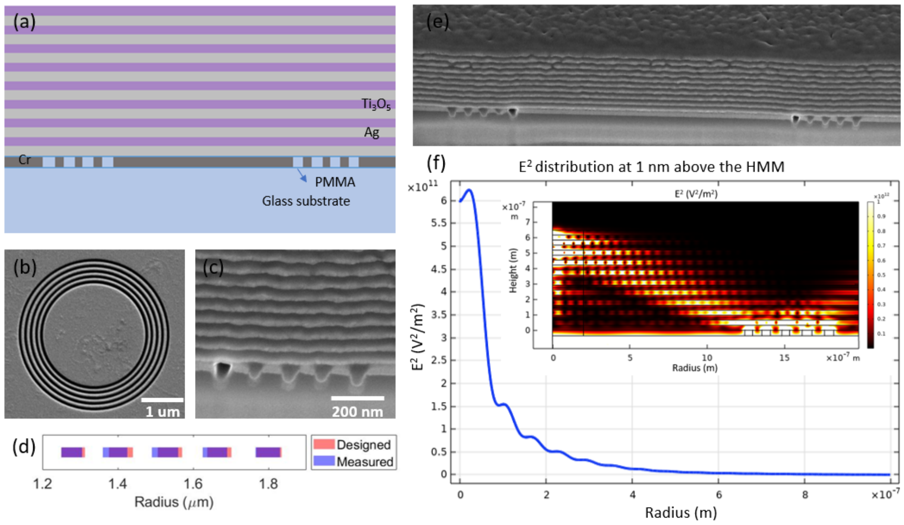

Fig. 1. **(a)** Schematic diagram of the hypergrating system. **(b)** Scanning electron microscope(SEM) image of the Fresnel gratings made with focused ion beam. **(c)** SEM iamge of the cross section of the Fresnel gratings and the HMMS. **(d)** Designed and measured positions of the Fresnel grating rings. **(c)** SEM iamge of the cross section of the hypergrating. **(f)** Intensity distribution of the focused beam at 1 nm above the surface of hypergraing. Inset shows the 2D simulation of the light propagation inside the hypergrating

$\vec{E_{out}} = e^{i\phi}\vec{e}_r$. By blocking the azimuthal polarization component $\vec{e}_\phi$, the transmitted beam becomes a radially polarized vortex beam $e^{i\phi}\vec{e}_r$.

On top of the Fresnel grating, 20 alternating layers of Ti_3O_5 and Ag were deposited using E-beam evaporation. To study the light propagation in the hypergrating, numerical simulation is performed with COMSOL. A circularly polarized plane wave was incident from the substrate and converted to a radially polarized vortex beam after passing through the Fresnel gratings. The vortex beam is then focused by the HMMS and forms a subwavelength focal spot at the surface of the hypergraing. The full width at half maximum of the light intensity distribution peak is about 100 nm which is around $\frac{\lambda}{5}$ as is shown in Fig. 1 (f). The light intensity quickly drops above the surface due to total internal reflection on the HMMS surface. A near field experimental method will be used to confirm the focusing effect of the hypergrating in the following work.

To conclude, we demonstrate a hypergrating system for focusing vortex beam below diffraction limit. Numerical simulation is employed to study the light propagation in the hypergrating. The vortex beam can be focused down to $\frac{\lambda}{5}$ with owning to the high in-plane wave number modes in the hypergrating, which could enhance the vortex beam to matter interaction strength.

This research has been partially supported by the NSF (grant #2004298 and grant #3332481)

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