Investigation of a vectorial Gaussian beam with higher-order cylindrical polarization near the tight focus: spin Hall effect

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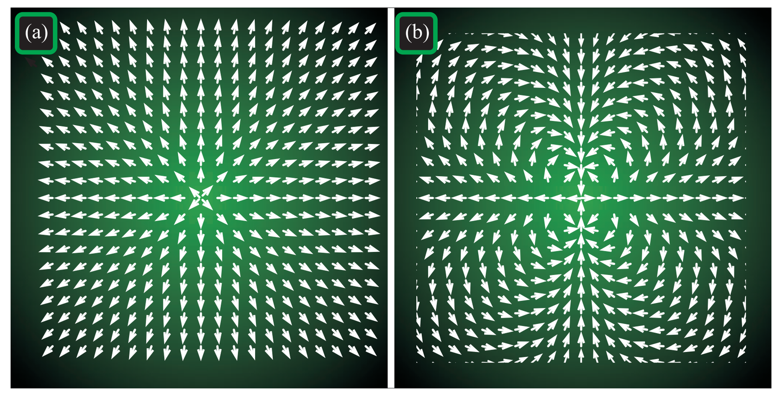
Theory

Jones vectors:

$$E_n(\varphi)=\begin{pmatrix}\cos n\varphi\\ \sin n\varphi\end{pmatrix},\quad H_n(\varphi)=\begin{pmatrix}-\sin n\varphi\\ \cos n\varphi\end{pmatrix},$$



Examples

Field in the focus:

$$\begin{aligned}
E_x(r,\varphi)&=i^{n-1}\left[\cos(n\varphi)I_{0,n}+\cos((n-2)\varphi)I_{2,n-2}\right],\\
E_y(r,\varphi)&=i^{n-1}\left[\sin(n\varphi)I_{0,n}-\sin((n-2)\varphi)I_{2,n-2}\right],\\
E_z(r,\varphi)&=2i^{n}\cos((n-1)\varphi)I_{1,n-1},\\
H_x(r,\varphi)&=-i^{n-1}\left[\sin(n\varphi)I_{0,n}+\sin((n-2)\varphi)I_{2,n-2}\right],\\
H_y(r,\varphi)&=-i^{n-1}\left[-\cos(n\varphi)I_{0,n}+\cos((n-2)\varphi)I_{2,n-2}\right],\\
H_z(r,\varphi)&=-2i^{n}\sin((n-1)\varphi)I_{1,n-1}.
\end{aligned}$$

where

$$I_{\nu,\mu}=2kf\int_0^{\theta_0}\sin^{\nu+1}\left(\frac{\theta}{2}\right)\cos^{3-\nu}\left(\frac{\theta}{2}\right)\times\cos^{1/2}(\theta)A(\theta)e^{ikz\cos\theta}J_\mu(kr\sin\theta)d\theta$$

Spin angular momentum:

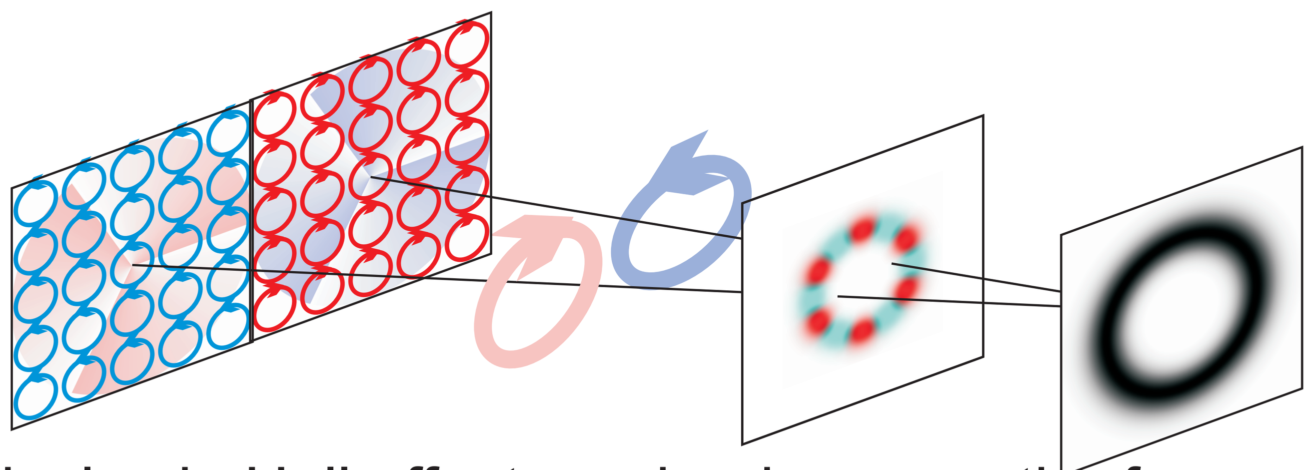
$$\mathbf{S}=\frac{1}{16\pi\omega}\mathrm{Im}\left(\mathbf{E}^{*}\times\mathbf{E}\right)$$

$$S_z\simeq 2kz\sin(2(n-1)\varphi)\left(I_0R_2-I_2R_0\right),$$

where

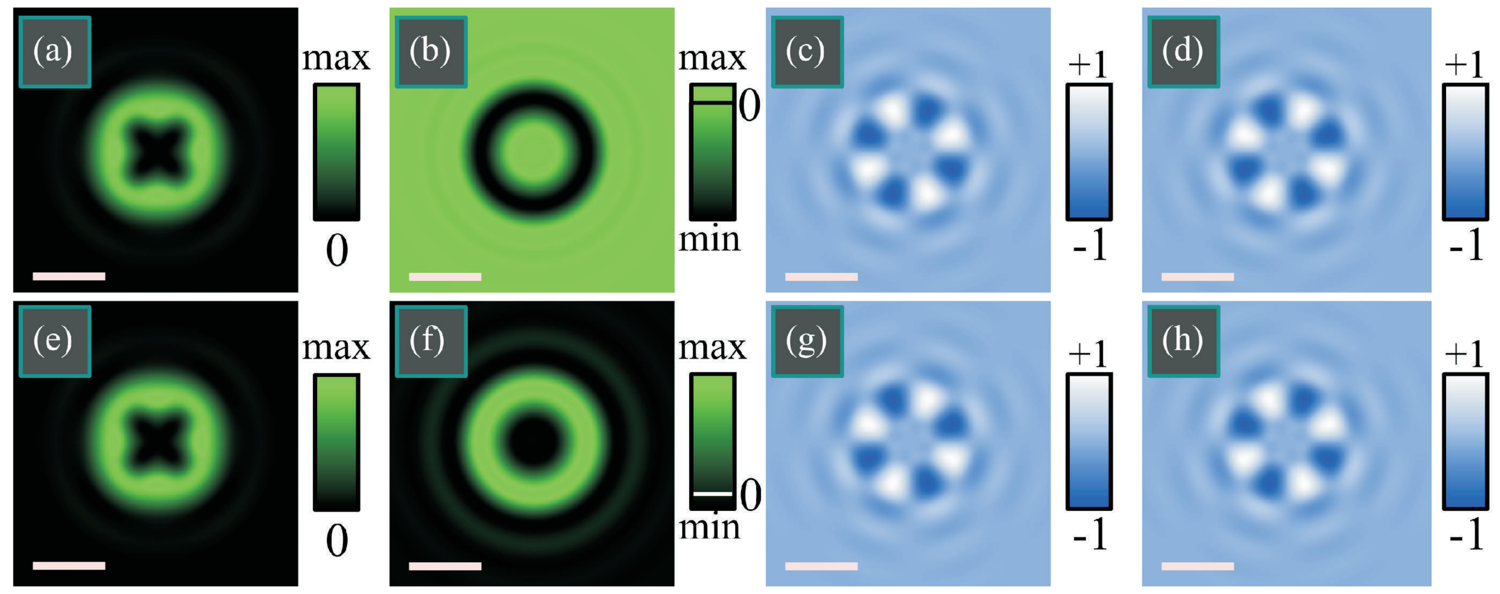
$$R_0=I_{0,n}(z=0),\ I_0=\bar{I}_{0,n},\ \ R_2=I_{2,n-2}(z=0),\ I_2=\bar{I}_{2,n-2},$$

$$\bar{I}_{\nu,\mu}=\left(\frac{4\pi f}{\lambda}\right)\int_0^{\theta_0}\sin^{\nu+1}\left(\frac{\theta}{2}\right)\cos^{3-\nu}\left(\frac{\theta}{2}\right)\cos^{3/2}(\theta)A(\theta)J_\mu(\xi)d\theta.$$

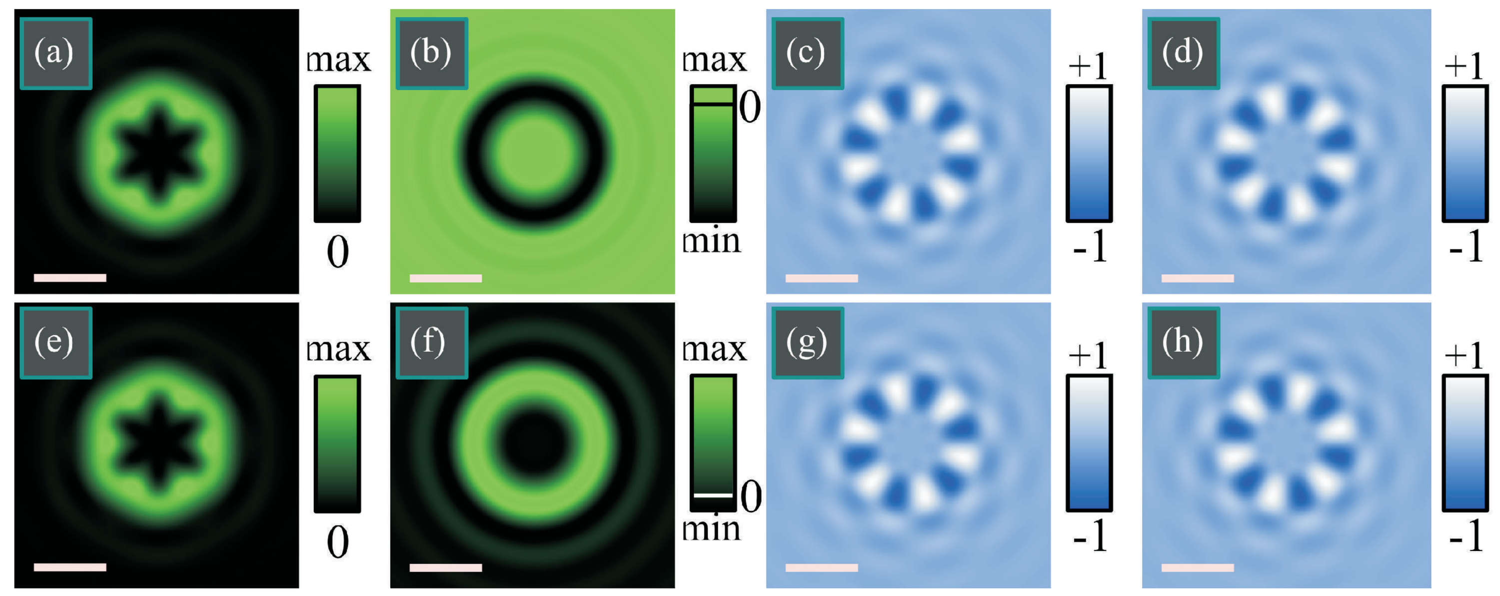


Optical spin Hall effect mechanism near the focus of two vortices with opposite topological charges and with opposite circular polarizations. Due to the opposite angular momenta, the vortices rotate in opposite directions and their interference generates a light field with alternating areas of positive and negative SAM.

Simulation



Distributions of intensity (column 1), radial component of the Poynting vector (column 2), normalized-to-maximum longitudinal component of the SAM vector (column 3), and normalized-to-maximum longitudinal component of the OAM vector (column 4) of a sharply focused Gaussian beam with 3rd-order cylindrical polarization before the focus (row 1) and beyond the focus (row 2). In all the figures light and black colors mean respectively maximum and minimum. Scale marks (in the left bottom corner) denote 1 μm.



Distributions of intensity (column 1), radial component of the Poynting vector (column 2), normalized-to-maximum longitudinal component of the SAM vector (column 3), and normalized-to-maximum longitudinal component of the OAM vector (column 4) of a sharply focused Gaussian beam with 4th-order cylindrical polarization before the focus (row 1) and beyond the focus (row 2). In all the figures light and black colors mean respectively maximum and minimum. Scale marks (in the left bottom corner) denote 1 μm.

Conclusion

It is also known that both in the initial plane and in the focus, a cylindrical vector beam (CVB) has neither the spin angular momentum (SAM) nor the orbital angular momentum (OAM). Here we demonstrated that near the focal plane, $4(n-1)$ local subwavelength areas are generated (n is the polarization order), where the polarization vector is rotating in each point. The rotation direction is opposite in the neighboring areas so that the longitudinal component of the SAM vector has opposite sign. Such separation of left and right rotation of the polarization vectors manifests that the optical spin Hall effect arises. Such a phenomenon can be used in optical sensorics for determining the CVB order, as well as for spin-dependent beam splitting, surface sensing, determining a biomolecules concentration.

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