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Plasmonic resonance scattering from a silver nanowire illuminated by a tightly focused singular beam

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Scattering features of tightly focused singular beams are investigated by placing a cylindrical nanowire in the vicinity of a line phase singularity. Applying illumination wavelength corresponding to silver cylinder plasmonic resonance, we compare the scattering response with that of a perfect conductor. The rigorous modeling employs a 2D versions of the Richards-Wolf focusing method and the source model technique. It is found that a cylinder with a plasmonic resonance produces a strong scattering response by deflecting the power flow towards the optical singularity region, where otherwise the power approaches zero.

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Objects that are significantly smaller than the wavelength are known to produce a strong scattering response when illuminated at wavelengths corresponding to their plasmonic resonance [1, 2]. The scattering properties of silver nanowires, which are considered in this work, have been thoroughly investigated as a function of their cross-sectional shape under plane wave illumination (see, for example, [3] and references therein). In this Letter, we are concerned with scattering of tightly focused beams containing wavefront dislocations [4], referred to here as singular beams. Scattering of focused beams by cylinders can be analyzed with the help of the generalized Lorentz-Mie theory, as in [5, 6], where the focused beam is represented using basis functions that lend themselves to analytical scattering solution. Alternately, one may evaluate first the tightly focused incident field distribution and then employ a numerical method such as in [7] where the optical force on elliptic nanowires is investigated in a tightly focused Gaussian beam, to derive the scattered field. A common feature of the indicated approach and many other investigations is that the scattering object is exposed to a significant incident power density. In contrast, our investigation deals with a situation where a nanowire is placed in a region where the density of the incident power flow, the Poynting vector, approaches zero. This region corresponds to the location of an optical singularity. Our results suggest that for the case of plasmonic resonance, the power flow is significantly altered, thus producing a strong impact on the scattered far-field.

The optical system is schematically illustrated in Fig. 1. A line phase singularity is formed in an incident plane wave, propagating along the z axis, by means of a π phase step. The phase step is located at the entrance pupil of a focusing optical system with $NA = 0.87$. The tightly focused beam is scattered by a nanowire placed along the geometrical focal line O, parallel to the y axis. The scattering angle ϕ is measured in the x-z plane, relative to the positive direction of the z axis. The illumination wavelength of $\lambda = 338nm$ is chosen for silver cylinder resonance with corresponding $\varepsilon_{Ag} = -1.07 + 0.29i$ and diameter $30nm$. This diameter is adequately small as compared to the focused field distribution, but large enough to allow us to neglect the dependence of the imaginary part of ε_{Ag} on the cylinder size [8].

We evaluate the tightly focused field impinging on the cylinder employing a modification of the rigorous Richards-Wolf focusing method [9]. The scattered field is calculated using the source model technique [10]. It must be noted that the incident illumination should be *x* polarized to excite plasmonic resonance in an infinitely long cylinder whose axis is parallel to the *y* axis. The real part of the Poynting vector of the incident, tightly focused field looks similar to Fig. 2. Actually, Fig. 2 shows the real part of the Poynting vector for the case of scattering by a perfectly conducting nanowire, placed in the waist region of the tightly focused singular beam. The perfect conductor is modeled by a dielectric constant with a large imaginary part, $\mathrm{Im}\left(\varepsilon_{PC}\right) >> 1$. Fig. 3 shows the same situation as Fig. 2, with a silver nanowire of the same size. Fig. 4 presents a zoom-in at the vicinity of the silver nanowire of Fig. 3. It is apparent from Fig. 4 that the resonant silver nanowire deflects the power flow, which is in turn, either dissipated or re-radiated. It must be noted that our evaluation did not take into account non-linear effects. We tried to compare our results with the Poynting vector field structure, investigated under plane wave illumination in [11], but unfortunately, the nature of the incident field was too different to yield a basis for comparison. Yet, some general conclusions in [11], for example the strong influence of the cylinder radius on the Poynting vector field distribution, were valid in our case as well.

The interesting effect of the power flow deflection can be attributed to the presence of the strong electric axial field component, E_z, which is shown in Fig. 5. This field can be intuitively connected to the generation of dipole polarization along the propagation direction – z, in contrast to a classical Rayleigh approximation, where, for an incident plane wave, the dipole axis coincides with the incident field polarization. The scattered far-field angular distribution, shown in Fig. 6, supports this by featuring distinct peaks at about $\phi = \pi/2$, which indeed corresponds to a z directed dipole. To check the above hypothesis, we also investigated the case of $NA = 0.2$. For commensurable comparison with the previous case, the overall incident wave power was kept constant. In this, essentially paraxial case, the axial component of the electric field is weak and the field patterns indicate a significantly smaller difference between the scattered field of the perfect conductor and silver. For comparison, the corresponding far-field angular distributions are shown dotted in Fig. 6. In addition to the difference in field amplitude, the shape of the distribution is different for the lower NA, suggesting that the scattering pattern is also different. It must be noted that in order to compensate for the increased focused field spot size, which is, approximately, inversely related to the *NA*, the cylinder was proportionally scaled. Consequently, the weakening effect is partly due to increasing cylinder size which is known to red-shift plasmonic resonance and make it broader and lower.

We have numerically shown that a combination of an axial field, obtained under tight focusing conditions, with plasmonic resonance produces significant scattering response in the vicinity of an optical singularity, where the transversal field and the power flow density approach zero. This interesting phenomenon can be helpful in optical trapping applications or metrological applications, like singular beam microscopy. It can also be useful in investigation of the axial field structure of tightly focused fields.

Acknowledgements

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Figures

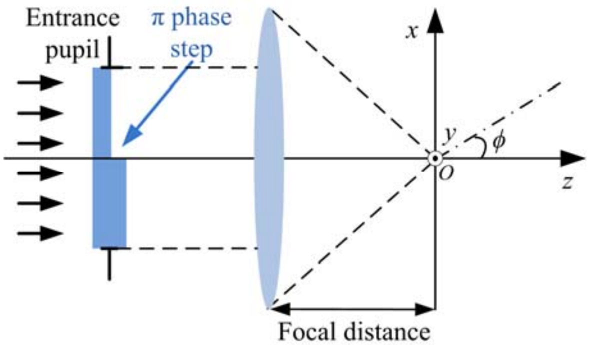

Fig. 1. (Color online) Optical system schematics.

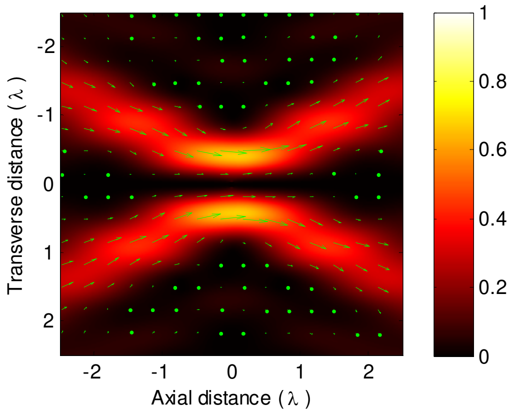

Fig. 2. (Color online) Tightly focused singular beam power flow density in case of scattering by a perfectly conducting nanowire 30 nm in diameter, normalized by the maximum value of Fig. 3. The spots indicate nearly zero density. Arrow size is proportional to power flow density and arrow direction corresponds to power flow direction at the arrow origin.

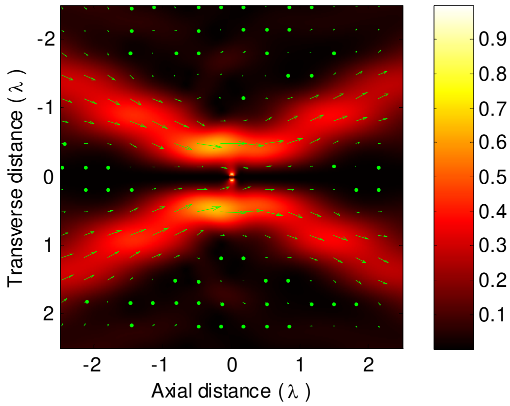

Fig. 3. (Color online) The same as Fig. 2 for the case of scattering by a silver nanowire 30 nm in diameter. The result is normalized by the maximum power flow density .

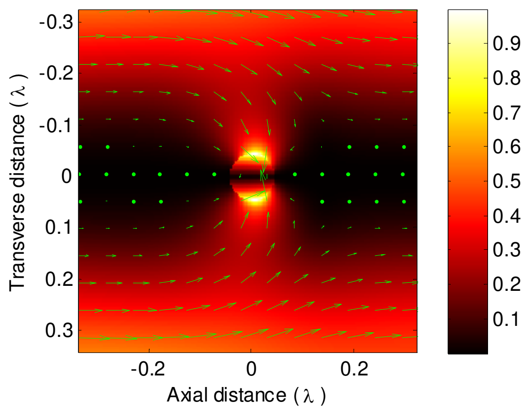

Fig. 4. (Color online) Zoom in on the silver nanowire of Fig. 3.

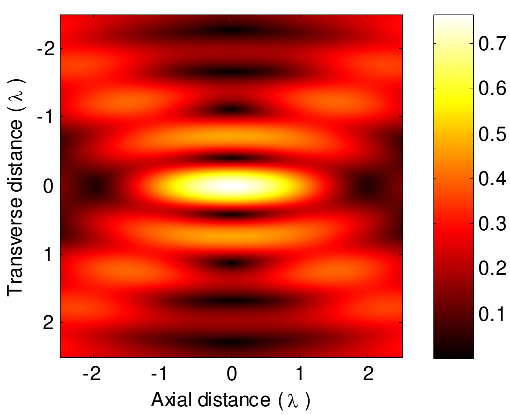

Fig. 5. (Color online) Tightly focused singular beam – E_z field component amplitude. The values are normalized by the maximum of the E_x amplitude.

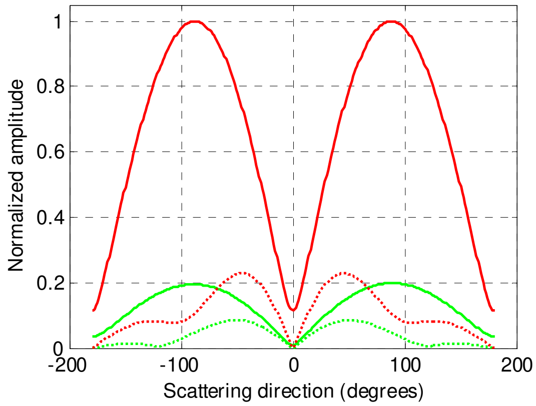

Fig. 6. (Color online) The scattered far-field amplitude for the silver nanowire - black (red) line, and perfect conductor nanowire - grey (green) line. The solid lines correspond to *NA* = 0.87 and the dotted lines correspond to *NA* = 0.2.