NANO LETTERS

Letter

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Spin-Dependent Plasmonics Based on Interfering Topological Defects

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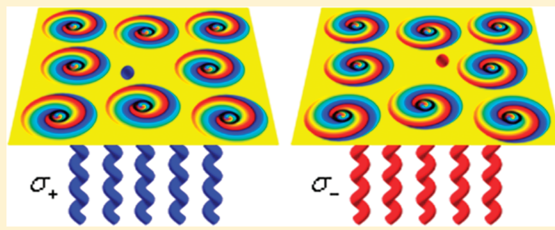
ABSTRACT: Observation of spin-dependent plasmonics based on the interference of topological defects in the near-field is presented. We utilize the surface plasmons' scattering dynamics from localized vortex sources to create spinoptical devices as an ensemble of isolated nanoantennas to observe a "giant" spin-dependent plasmonic vortex and a spin-dependent plasmonic focusing lens. The spin−orbit point spread function, a spiral wavefront, is introduced, where the optical spin is a degree of freedom.



KEYWORDS: *Plasmonics, topological defects, nanoantennas, angular momentum, polarization*

Topological defects (TDs) are among the most intriguing signatures of symmetry breaking in the laws of physics.[1] A TD is a singular spatial configuration of a vector field that cannot unwind under continuous deformations.[2] Knowledge of TDs has great importance for many areas in physics since they are ubiquitous; TDs have attracted extensive attention in various realms such as condensed matter physics,[3,4] superfluidics,[5] hydrodynamics,[6] cosmology,[7] liquid crystals,[8] and optics.[9] A light field can carry spin and orbital angular momenta;[10] the intrinsic spin angular momentum of $\sigma_\pm\hbar$ per photon is associated with the polarization helicity, where $\sigma_\pm = \pm 1$ correspond to right- and left-circularly polarized light, respectively, while the orbital angular momentum (OAM) is associated with the spatial structure of the field. The optical TDs are termed vortices and they carry an OAM of $l\hbar$ per photon manifested by the spiral phase $l\varphi$ of the beam, where the integer number l is the topological charge and φ is the azimuthal angle. Observation of TDs in plasmonic systems is possible via the spin−orbit interaction (SOI), which provides a suitable mechanism to couple the optical spin to an OAM carried by the surface plasmons (SPs). Moreover, a measurement of a wavefront phase dislocation due to the scattering of SPs from a macro-wavelength TD was recently presented.[11]

Plasmonics takes advantage of the properties of SPs, which are localized plasmons or propagating SP polaritons in which an electromagnetic field is coupled to the quasi-free electrons in metals. Scattering from a subwavelength protrusion or a hole on the surface is a convenient way to locally generate SPs. When a linearly polarized light illuminates a local scatterer, a typical dipolar SP polariton emission pattern is observed, aligned with the incident polarization direction,[12,13] and comprises a perpendicular dislocation line. The scattering dynamics of SP waves propagating away from the point scatterer is described as a spherical (Huygens) wave,[14] with π-phase retardation between the two sections intersected by the dislocation line (Figure 2c). In order to realize plasmonic devices, an ensemble of subwavelength scattering sources is required, and the global SP field is created from the coherent summation of all the elemental fields.[12,15]

In this Letter, we theoretically and experimentally investigate spin-dependent plasmonics based on the interference of TDs in the near-field. An annular subwavelength nanoantenna was chosen as a source to launch a spiral wavefront with an OAM equal to the incident optical spin. We utilize the scattering dynamics of the SPs from localized vortex sources to create spin-dependent plasmonics based on the interference of multiple sources (Figure 1). The spin−orbit point spread

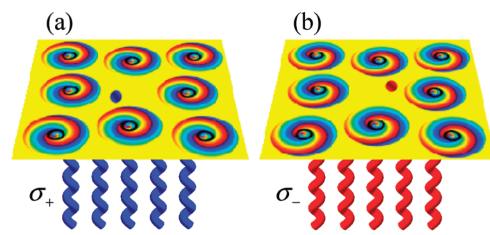


Figure 1. Spin-dependent plasmonics based on the interference of TDs. (a,b) Conceptual scheme of interfering plasmonic vortex sources for $\sigma_\pm$, respectively; due to the spin-dependent spiral phases, the resulting field distributions for $\sigma_\pm$ are inherently different, as manifested by the blue and red spots, respectively, which represent the constructive interference locations.

function (PSF), a spiral wavefront, is introduced, where the optical spin is a degree of freedom, and when it is convolved with the system input, spin-based plasmonics is obtained. A circular plasmonic chain and a plasmonic lens were realized as an ensemble of nanoantennas to observe an intensity-enhanced spin-dependent plasmonic vortex, and a spin-dependent shift of

Received: December 27, 2011
Revised: February 17, 2012
Published: February 17, 2012

the focal spot, respectively. The proposed spinoptical devices are the milestones for a new study of TDs in nanoscience and will pave the way for spin-dependent plasmonic manipulation on the nanoscale.

We consider a circular nanoslit as a source for a propagating plasmonic wavefront. A finite difference time domain (FDTD) algorithm was used to calculate the near-field electromagnetic fields of an annular nanoantenna (Figure 2a, inset), illuminated

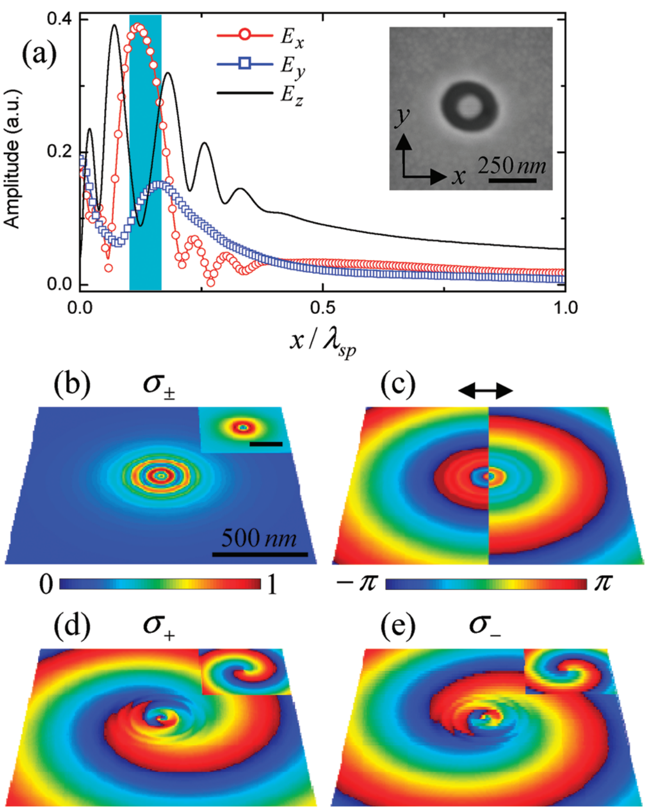


Figure 2. Plasmonic vortex source. (a) Horizontal cross sections of the near-field electromagnetic fields of the nanoantenna, normally illuminated with circularly polarized light, at a wavelength of 780 nm; the blue area corresponds to the width of the etched circular nanoslit. The inset shows a scanning electron microscopy (SEM) image of an annular nanoantenna with inner and outer radii of 75 and 125 nm, respectively, upon a 200 nm thick Au film. (b) FDTD simulation of the E_z magnitude for $\sigma_{\pm}$. (c) FDTD simulation of the E_z phase for horizontally linear polarization. (d,e) FDTD simulations of the E_z phases for $\sigma_{\pm}$, respectively. The insets in panels b, d and e show the corresponding analytical calculation.

with a circular polarization. Figure 2a shows the horizontal cross sections of the electric field components. In the vicinity of the slit, all the fields have comparable amplitudes, while those components in the out-launching plasmonic wave decay in a different manner. After propagation to a distance of half a plasmonic wavelength λ_{sp}, the contribution of the normal E_z component to the intensity distribution is an order of magnitude larger than those of the E_x and E_y components. Hence, for multiple-wavelength propagation distances, the complex plasmonic wavefront launched from the nanoantenna mainly contains the E_z signature. Figure 2b shows the spin-degenerated magnitude of the electric field component E_z with zero-field amplitude in the origin. Moreover, the phase of the E_z field is spiral and its helicity is spin-dependent (Figures 2d,e), resulting from the optical SOI. Because of the SOI, the excited SPs acquire an OAM that is equal to the incident spin, resulting in a nanoscale TD: a plasmonic vortex source.

We derived an analytical model to calculate the E_z field launched from an annular nanoantenna. An infinitely narrow circular slit with a radius r_0 in a medium supporting SPs was chosen to be the scattering source. The selected shape of the nanoantenna as a circular nanoslit originates from the simple boundary conditions formulation. A one-dimensional nanoslit provides a momentum modification in the perpendicular direction, which is essential for the coupling of light to nonradiative surface modes, thereby exciting a surface wave with a phase front parallel to the slit. Moreover, only transverse magnetic polarized incident waves with an electric field perpendicular to the slit are efficiently coupled by the slit to SPs. If we consider a circularly polarized light as a rotating in time linear polarization, the maximal coupling efficiency along a circular nanoslit follows the local polarization selectivity of the one-dimensional slit.[11] The phase delay due to the varying polarization state results in a geometric phase, leading to a plasmonic field $E_z(r_0,\varphi) = e^{-i\sigma\varphi}$, where σ is the incident spin. Two additional boundary conditions are required: zero-field amplitude at the origin and at infinity, arising from the spiral phase and a single point source, respectively.

The two-dimensional (2D) Helmholtz equation with the SP wave vector k_{sp}, is separable in polar coordinates (r,φ), where r is the radius and φ is the azimuthal angle. The different boundary conditions for the internal and external regions dictate different solutions for the in- and out-propagating plasmonic fields. The resulting solution of the in- and out-propagating plasmonic fields are $E_z(r,\varphi) = \{[J_{-\sigma}(k_{sp}r)]/[J_{-\sigma}(k_{sp}r_0)]\}e^{-i\sigma\varphi}$ and $\{[H_{-\sigma}(k_{sp}r)]/[H_{-\sigma}(k_{sp}r_0)]\}e^{-i\sigma\varphi}$, respectively. Here, J_m and H_m are the mth-order of the Bessel and Hankel functions of the first kind, respectively. The analytical results, presented in the insets of Figure 2b,d,e, confirm the scattering dynamics of the SPs from the localized vortex source obtained by the FDTD simulations.

The described mechanism of spin degeneracy removal in a single nanoantenna paves the way for consideration of spin-dependent plasmonic devices based on multiple plasmonic vortex sources. In conventional optics, the 2D PSF in free space is given by the spherical wave $h \propto e^{ikr}/\sqrt{r}$, and it links between the input and output of a space-invariant system via the superposition (convolution) integral. We herein propose the spin–orbit PSF, a spiral wavefront $h_\sigma \propto H_{-\sigma}(kr)e^{-i\sigma\varphi}$, where the incident spin is a degree of freedom. Hence, for a system consisting of multiple TD sources with an input g_1, the system output g_2 is spin-dependent and is described by the convolution relation $g_{2,\sigma} = g_1 \otimes h_\sigma$. This concept encourages one to demonstrate different configurations of sources arrangements to experimentally observe spinoptical effects.

A circular plasmonic chain of nanoscale annular apertures was fabricated using a focused ion beam (FIB; FEI Strata 400s dual beam system, Ga^+, 30 keV, 48 pA), to etch a thin Au film deposited on a glass substrate (Figure 3a). The element was illuminated by a continuous wave Ti:sapphire tunable laser (Spectra-Physics 3900S) via a circular polarizer, and the excited SP wave was directly probed by the 150 nm aperture near-field scanning optical microscopy (NSOM) tip (Nanonics Imaging, MultiView 2000). The measured spin-degenerated intensity distribution is presented in Figure 3b; the inset of Figure 3a shows a horizontal cross section of the measured intensity and analytically calculated interference pattern of isolated TDs at the center of the chain. A plasmonic interference pattern with a

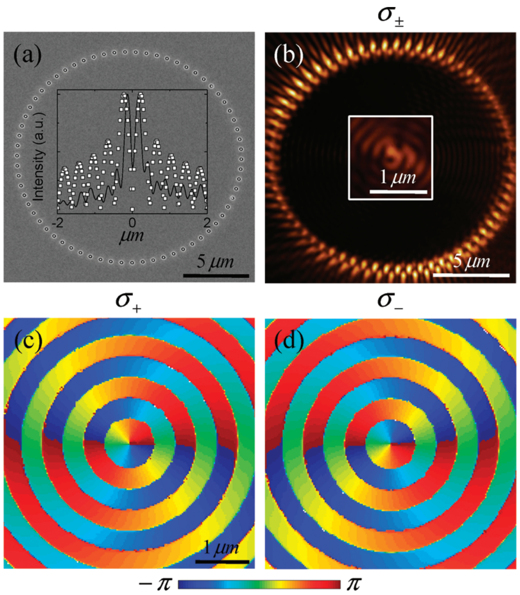


Figure 3. Circular plasmonic chain of TDs. (a) SEM image of the chain consisting of annular nanoapertures arranged in a circular path with a radius of 8 μm and with a period of 760 nm. Note that for a wavelength of 780 nm the SP polariton propagation length and wavelength are 40 μm and 760 nm, respectively. The inset shows a horizontal cross section of the intensity at the center of the chain; the curve and the squares represent the measured and analytically calculated intensities, respectively. (b) Measured near-field intensity distribution for normally incident $\sigma_\pm$ at a wavelength of 780 nm; the inset represents a magnification of the dark spot. (c,d) Analytical calculations of the phase distributions of the plasmonic fields for $\sigma_\pm$, respectively.

dark spot in the center (Figure 3b, inset) is observed for the distinct spin states; such a singularity indicates a nonzero OAM, corresponding to a spiral phase. We also calculated the phase distribution by FDTD simulations (not shown) and by the model for multiple plasmonic vortex sources (Figure 3c,d), and verified its spin-dependent helicity. Moreover, this calculation provided the quantitative value of the OAM per photon, shown to be equal to the incident optical spin; therefore, the superposition of vortex sources in a circular symmetry results in an intensity-enhanced plasmonic vortex with a higher total OAM. Note that if spherical waves from point sources are considered, a bright spot at the center would be expected.

The global field of uncoupled plasmonic nanoantennas, separated by a distance of the SP wavelength, is the coherent summation of all the elemental fields. The absence of a collective coupling between TDs in the proposed plasmonic device was verified by FDTD simulations of the same geometry with a random distribution of nanoantennas; the similar spin-based effect observed in ordered and disordered chains (not shown) is a signature for the noncollective behavior of the localized modes in the near-field. In contrast, the collective interaction within periodic plasmonic chains, manifested by a nonzero OAM in the far-field, plays a crucial role in the recoupling of SPs to a propagating mode via the momentum-matching condition, as was recently presented.[16] Moreover, the transition from isolated to collective modes in a plasmonic system consisting of nanoantennas was investigated,[17] and a collective mode was observed for internanoparticle separations smaller than 60 nm. The isolated nature of TDs in the near-field is the basis for our multisource calculation as the interference of vortex sources, and shows a good agreement with the spin-dependent experimental results.

Another interesting spin-dependent plasmonic device based on the interference of TDs is a plasmonic focusing lens. We fabricated a semicircular plasmonic chain consisted of annular nanoapertures with the previous parameters (Figure 4a). Figure 4c,d presents the measured intensities of the focusing plasmonic waves for $\sigma_\pm$, respectively. A spin-dependent transverse shift of the focal spot is easily observed from the compared cross sections (Figure 4b). The obtained focal shift is a manifestation of the optical spin Hall effect,[16,18−20] associated with the SOI, inducing the plasmonic vortex sources. The relocation of the spot can be calculated using the optical path condition with a spiral wavefront $k_{sp}r_i - \sigma\varphi_i = 2\pi m$, where r_i is the distance between the ith source and the shifted spot, φ_i is the corresponding azimuthal angle, and m is an integer. Using this formalism, we estimate the spin-dependent deflection by σ/k_{sp} ($\sim$120 nm), and it evidently supports the experimental results as well as the analytical calculations (Figure 4b). Moreover, the calculation of the plasmonic fields reveals π-phase retardation between the spin-dependent focusing waves. Hence, when the superposition of the spin states $|\sigma_+\rangle + |\sigma_-\rangle$, a horizontal linear polarization, is illuminated, the focal spot splits in the lateral direction;[12,19] however, for the superposed excitation $|\sigma_+\rangle - |\sigma_-\rangle$, a vertical linear polarization, the retardation is compensated, and as a result the plasmonic wave homogeneously converges without a focal spot splitting.[12]

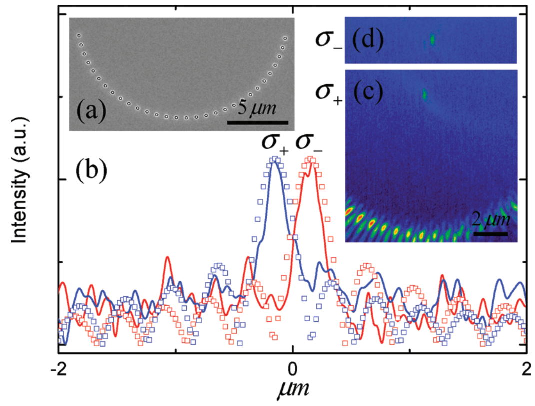


Figure 4. Spin-dependent plasmonic focusing lens. (a) SEM image of the plasmonic lens consisting of annular nanoapertures arranged in a semicircular path. (b) Transverse cross sections of the intensity distributions in the focal plane; the blue and red curves (squares) represent the measured (analytically calculated) intensities for $\sigma_\pm$, respectively. (c,d) Measured near-field intensity distributions of the plasmonic lens at a wavelength of 780 nm for normally incident $\sigma_\pm$, respectively.

In summary, we introduced spin-dependent plasmonics based on the interference of TDs. Because of the SOI, an annular nanoantenna launches a spiral wavefront with an OAM equal to the incident optical spin. This nanoscale TD, a plasmonic vortex source, was utilized to form spin-dependent plasmonics from an ensemble of isolated interfering sources. Our experiments emphasize one of the optical SOI manifestations: subtle deviations from the laws of geometrical optics, deriving from the presented spin−orbit PSF, a spiral wavefront, where the spin is a degree of freedom. The spin-dependent plasmonics can be utilized for spin-controlled nanoparticle rotation, trapping and tweezing by a surface mode,[21,22] for the study of nanoparticle dynamics in a vortex field, for spin-dependent plasmonic vortex-driven nanomotors, and for interconnects and polarimetry in subwavelength scale. The presented concepts may lead to novel nanoscale photonic devices in the emergent field of spinoptics.

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Notes

The authors declare no competing financial interest.

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