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Obtaining Circularly Polarized Optical Spots beyond the Diffraction Limit Using Plasmonic Nano-Antennas

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ABSTRACT

With advances in nanotechnology, emerging plasmonic nano-optical applications, such as all-optical magnetic recording, require circularly-polarized electromagnetic radiation beyond the diffraction limit. In this study, a plasmonic cross-dipole nano-antenna is investigated to obtain a circularly polarized near-field optical spot with a size smaller than the diffraction limit of light. The performance of the nano-antenna is investigated through numerical simulations. In the first part of this study, the nano-antenna is illuminated with a diffraction-limited circularly-polarized radiation to obtain circularly polarized optical spots at nanoscale. In the second part, diffraction limited linearly polarized radiation is used. An optimal configuration for the nano-antenna and the polarization angle of the incident light is identified to obtain a circularly polarized optical spot beyond the diffraction limit from a linearly polarized diffraction limited radiation.

INTRODUCTION

Circular polarization is utilized in various applications at radio frequency and microwave regimes due to its advantages, such as increased efficiency in power transmission [1]. At optical frequencies, circular polarization promises to be a rotary power source for various applications [2-6]. With advances in nanotechnology, circularly-polarized electromagnetic radiation beyond the diffraction limit is desired in emerging plasmonic nano-applications. One of these applications is all-optical magnetic recording [7-8]. Stanciu et al. [7-8] demonstrated that magnetization can be reversed in a reproducible manner by using a circularly polarized optical beam without any externally applied magnetic field. The size of the magnetization reversal in that study was on the order of 20 microns due to the large optical spots that were utilized. To advance the areal density of hard disk drives beyond 1 Tbit/in.^{2}, magnetization reversal areas much smaller than 100 nm are required. To achieve sub-100 nm bits in an all-optical magnetic recording system, a circularly polarized optical spot beyond the diffraction limit is necessary.

In this study, two different schemes are investigated to obtain a circularly polarized optical spot with dimensions smaller than the diffraction-limit. In the first part of this study, a cross-dipole nano-antenna is investigated to obtain a circularly-polarized optical spot with a size beyond the diffraction limit when the antenna is illuminated with diffraction-limited circularly-polarized radiation. An optimal antenna geometry is specified to obtain an intense optical spot that satisfies two necessary conditions for circular polarization: a phase difference of 90° and a unit amplitude ratio between the electric field components in the vicinity of the antenna gap. In the second part of this study, we demonstrate that the phase difference between the electric field components can be adjusted by selecting either different antenna lengths or gap distances in the vertical and horizontal directions. Since the plasma wavelengths on the antenna are much shorter than the wavelength of incident radiation, a circularly polarized optical spot beyond the diffraction limit is obtained from diffraction limited linearly polarized incident radiation.

CIRCULARLY POLARIZED OPTICAL SPOTS BEYOND DIFFRACTION LIMIT

Three main features of the antennas have been attractive for existing and emerging applications: their ability to obtain optical spots beyond the diffraction limit, their potential to achieve higher power transmittance to the sample, and a narrow and adjustable spectral response. Although their ability to achieve these three goals has attracted a significant amount of interest, their ability to obtain light with various polarizations has attracted little attention. Ohdaira et al. [9] obtained local circular polarization by superposing two cross propagating evanescent waves. In this study, we suggest an alternative technique to obtain intense localized circular polarization with a plasmonic nano-antenna. The nano-antennas in the literature [10-18] obtained optical spots beyond the diffraction limit with linear polarization. However, there are emerging nanotechnology applications, such as all-optical magnetic recording [7-8], that require circularly polarized light beyond the diffraction limit. To address this emerging need, it is desirable to obtain optical spots with circular polarization.

A metallic cross-dipole antenna is investigated to obtain a circularly polarized optical spot with a size beyond the diffraction limit. A cross-dipole antenna, which is shown in Fig. 1, is composed of four metallic nano-rods placed at a perpendicular orientation with respect to each other. The geometric parameters are identified in Fig. 1. The antenna particles have equal horizontal and vertical lengths $L_h = L_v$ and are separated from each other by a distance $G_h = G_v$ in both vertical and horizontal directions. To obtain circular polarization from linearly polarized incident light, these conditions will be relaxed in the next section and antennas with different lengths and gap distances will also be used. The length of each antenna particle is $L_h = L_v = 130$ nm, the width is $W = 10$ nm, and the particle thickness is $T = 20$ nm. The center of the antenna is located at the origin, therefore, it lies between $z = -10$ nm and $z = 10$ nm. The antenna is surrounded by vacuum. Based on a previous study [18] on nano-antennas, the operating wavelength is selected as $\lambda = 1100$ nm. The dielectric constant of gold at $\lambda = 1100$ nm is selected as $\varepsilon_{gold} = -58.8971\text{-}j4.61164$ [19]. The amplitude of the incident radiation is selected as 1 V/m, therefore, the electric field values reported in this study correspond to the field enhancement of the antenna. Incident circularly polarized radiation propagates in the negative z-direction.

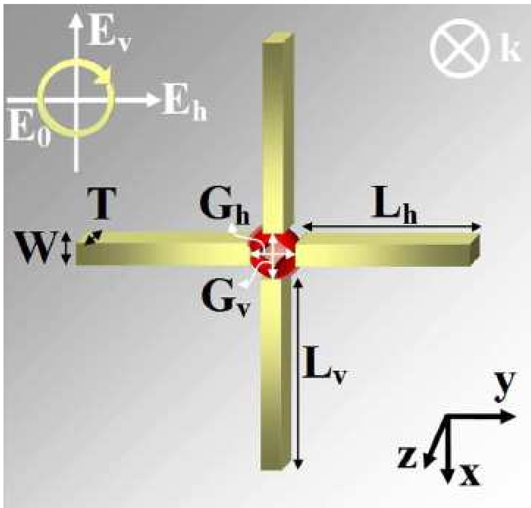

Figure 1. Schematic illustration of the cross-dipole antenna. The incident electric field has a clockwise orientation, which propagates along the **k-**vector. L_h and L_v are the lengths of the horizontal and vertical antenna particles, and G_h and G_v are the gap distances of the horizontal and vertical antenna particles. T is the thickness and W is the width of the antenna particles.

Figure 2 illustrates the intensity distributions for a cross-dipole antenna when it is illuminated with a diffraction limited circularly polarized light at λ = 1100 nm. Projection of the cross dipole antenna boundaries (thin white contour) is added to the figure to illustrate the relative position of the optical spot with respect to the antenna. In Fig. 2 (a) the intensity distribution is presented at the z = 0 nm, which passes through the center of the antenna. The results in Fig. 2 (a) suggest that the cross-dipole antenna achieve a localized intense spot in the gap region of the antenna. In Fig. 2 (b), intensity distribution on the z = 20 nm is illustrated. This plane is located at a distance of 10 nm below the bottom surface of the antenna; therefore, it represents a typical intensity distribution at the sample plane. Since a tightly confined optical spot diverges quickly in relatively short distances [20], a broader optical spot is observed in Fig. 2 (b) as compared to Fig. 2 (a). As the observation plane is placed further away from the antenna, the intensity obtained by the antenna gets smaller and the spot size increases. The reduction of the field intensity is due to the sharp decay of evanescent fields away from the nano-antenna.

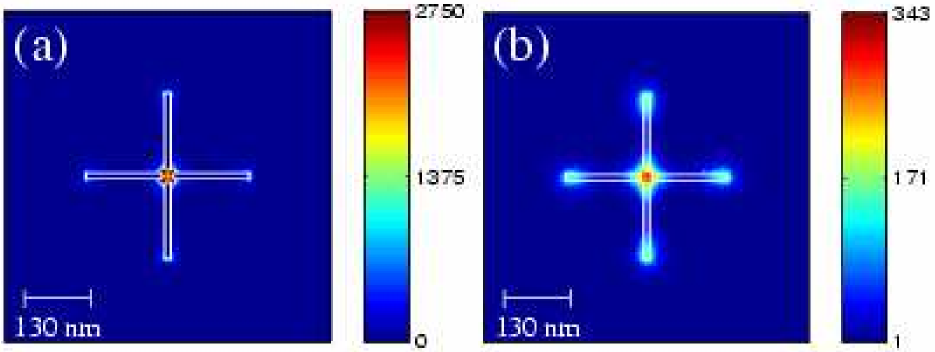

Figure 2. Intensity distributions for a cross-dipole antenna on z = 0 and z = 20 nm when the antenna is illuminated with a diffraction limited circularly polarized light: **(a)** $|E(x, y, z = 0)|^2$ and **(b)** $|E(x, y, z = 20)|^2$. Projection of the cross dipole antenna boundaries (thin white contour) is added to the figure to illustrate the position of the optical spot with respect to the antenna.

The incident circularly polarized diffraction limited radiation can be decomposed into two components: a horizontal and a vertical component of equal amplitude with a 90° phase difference between them. Each of these components creates an induced current along their respective axes on the antenna. These induced currents are the source of charge accumulation at the ends of the antenna. The charges created across the gap separating the metallic parts of the antenna have opposite polarity. The oscillation of the charges in the horizontal and vertical directions is the source of the localized near-field electromagnetic radiation.

To obtain circular polarization within the localized optical spot, two additional requirements need to be met: a phase difference of 90° and a unit amplitude ratio between the **x** and **y** oriented electric field components in the vicinity of the antenna gap. Due to the symmetry of the geometry in perpendicular directions, a 90° phase difference is obtained in the gap region of the antenna as shown in Fig. 3 (a). Since our aim is to obtain a circularly polarized optical spot, the 90° phase difference requirement needs to be satisfied only within the optical spot in the gap region. As shown in Fig. 3 (b), the relative amplitude of the horizontal and vertical field is the same within the optical spot due to the symmetry of the geometry. Therefore, the unit amplitude ratio requirement between the horizontal and vertical components is satisfied within the optical spot. The results in Fig. 3 suggest that all three conditions, i.e. localized radiation with intense amplitude, phase difference, and relative amplitude between components, are only satisfied in the optical spot defined by the gap region of the cross-dipole nano-antenna. As illustrated in Figs. 2 and 3, all three conditions are met within the optical spot; therefore, a circularly polarized localized optical spot is obtained. The sense of circular polarization is right-handed, since the electric field k-vector is directed along the negative z-direction and the circularly polarized light is clockwise oriented.

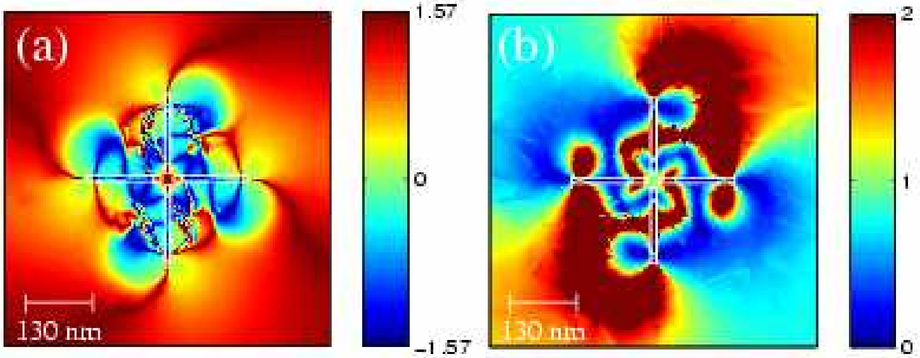

Figure 3. (a) Phase difference $\Delta\phi(x, y, z = 20)$ and **(b)** Electric field intensity ratio $|E_y(x, y, z = 20)| / |E_x(x, y, z = 20)|$ for circularly polarized incident light. Dimensions are selected as $L_h = L_v = 130$ nm, $G_h = G_v = 20$ nm, W = 10 nm, T = 20 nm and $\lambda = 1100$ nm. Projection of the cross dipole antenna boundaries (thin white contour) is added to the figure to illustrate the relative position of the optical spot with respect to the antenna.

OBTAINING CIRCULARLY POLARIZED OPTICAL SPOTS FROM A LINEARLY POLARIZED DIFFRACTION LIMITED ILLUMINATION

Circularly polarization can be decomposed into a horizontal and a vertical component. Similarly, any linear polarization can also be decomposed into a horizontal and a vertical component. One of the main differences between linear and circular polarization is the phase difference between the perpendicular components. The phase difference between the perpendicular components for linear polarization is 0°, whereas the difference is 90° for circular polarization. The phase difference is not the only difference in between linear and circular polarization. The amplitude ratio for the horizontal and vertical components is unity in circular polarization, whereas, there is no such requirement for linear polarization.

Based on the aforementioned differences, there are three challenges for producing a circularly polarized optical spot beyond the diffraction limit from a linearly polarized diffraction-limited incident radiation: (1) focusing the incident light into an optical spot beyond the diffraction limit, (2) producing a 90° phase difference at the output radiation from an incident radiation that has a 0° phase difference, and (3) obtaining horizontal and vertical components with equal amplitude. Focusing the incident light into a small optical spot will be achieved by the cross-dipole nano-antenna. To obtain a nonzero phase difference and a unit perpendicular amplitude ratio, the cross-dipole nano-antenna will be modified.

An additional phase term is necessary to convert a linearly polarized incident beam to a circularly polarized output. Producing the desired phase difference can be accomplished by creating an asymmetry in the antenna geometry. In this study, an additional phase term is introduced by using a slightly different antenna length for the horizontal oriented antenna L_h and vertical-oriented antenna L_v. A similar result can also be achieved using a different horizontal gap distance G_h and a vertical gap distance G_v for the cross-dipole antenna.

The amplitude of the near-field radiation depends on the antenna length and the gap distance. Changing the symmetry of the antenna by using either different (L_h, L_v) or (G_h, G_v) values will impact the amplitude of the horizontal and vertical components. The decay of the amplitude of the vertical (or horizontal) field component needs to be compensated to achieve a circular polarization, which requires these components to be equal. Any decay of the output field amplitudes can be compensated by adjusting the polarization angle of the incident linearly polarized wave, as shown in Fig. 4. If the amplitude of the vertical field component is small due to the created asymmetry, the polarization angle α_{pol} needs to be increased to achieve circular polarization.

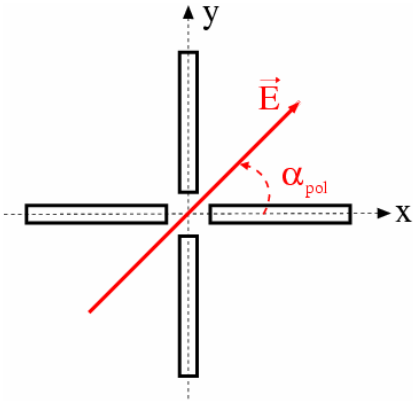

Figure 4. Illustration of the top view of the cross-dipole antenna. The polarization angle of the linearly polarized incident field is shown with respect to the antenna orientation.

In Fig. 5, electric field intensity $|E|^2$, phase difference $\Delta\phi$, and intensity ratio $|E_y| / |E_x|$ are plotted on the z = 20 nm for L_v = 160 nm and L_h = 130 nm. The polarization angle α_{pol} is selected as 72°. Fig. 5 (a) shows the localized region of intense electric field distribution. Figs. 5 (b) and (c) represent the localization of phase difference and amplitude ratio between the field components. The phase difference is confined in a small space with dimensions beyond the diffraction limit and with a value around -1.57 rad. The amplitude ratio is also confined in a small space with a value around 1. Therefore, the result in Figs. 5 (b) and (c) indicate that a circularly polarized region of space is obtained at z = 20 nm. The sense of circular polarization is left-handed, since the electric field k-vector is directed along the negative z-direction, the circularly polarized light is counter clockwise oriented.

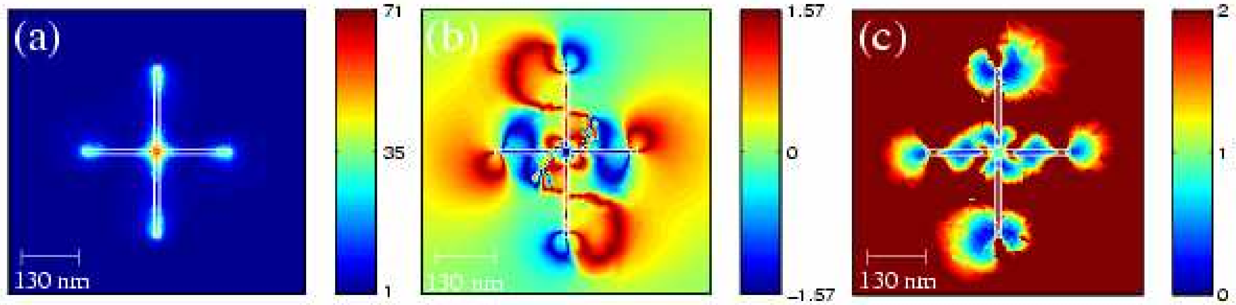

Figure 5. **(a)** $|E (x, y, z = 20)|^2$, **(b)** $\Delta\phi(x, y, z = 20)$, and **(c)** $|E_y (x, y, z = 20)| / |E_x (x, y, z = 20)|$ for α_{pol} = 72°. Dimensions are selected as L_v = 160 nm and L_h = 130 nm.

CONCLUSIONS

In this study, a near-field localized region of circularly polarized light beyond the diffraction limit was achieved using a cross-dipole optical antenna. It was demonstrated that a cross dipole nano-antenna with a symmetric structure can convert diffraction limited circularly polarized radiation into a circularly polarized optical spot well-beyond the diffraction limit. It was also shown that a phase difference can be obtained between field components by utilizing an asymmetric cross-dipole nano-antenna. It was shown that a phase difference between the electric field components can be adjusted by selecting either different antenna lengths or different gap distances in the vertical and horizontal directions. Our results indicate that it is feasible to convert linearly polarized diffraction limited radiation into a circularly polarized optical spot well-beyond the diffraction limit due to the short wavelength of surface plasma waves.

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