Tuning the Polarization States of Optical Spots at the Nanoscale on the Poincaré Sphere using a Plasmonic Nanoantenna

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Abstract— It is shown that the polarization states of optical spots at the nanoscale can be manipulated to various points on the Poincaré sphere using a plasmonic nanoantenna. Linearly, circularly, and elliptically polarized near-field optical spots at the nanoscale are achieved with various polarization states on the Poincaré sphere using a plasmonic nanoantenna. A novel plasmonic nanoantenna is illuminated with diffraction-limited linearly polarized light. It is demonstrated that the plasmonic resonances of perpendicular and longitudinal components of the nanoantenna and the angle of incident polarization can be tuned to obtain optical spots beyond the diffraction limit with a desired polarization and handedness.

1. INTRODUCTION

Polarized electromagnetic radiation has led to interesting technical applications and significant advancements at both optical [1, 2, 3, 4] and microwave frequencies [5]. With advances in nanotechnology, electromagnetic radiation beyond the diffraction limit with a particular polarization is an emerging need for plasmonic nano-applications. Among these applications, all-optical magnetic recording [6, 7] is a novel application which requires circular polarization. In the literature, it has been demonstrated that the magnetization can be reversed in a reproducible manner using a circularly polarized optical beam without an externally applied magnetic field [6, 7]. To advance the areal density of hard disk drives beyond 1 Tbit/in.^{2} using such a scheme, a sub-100 nm circularly polarized optical spot beyond the diffraction limit is required.

Recently, there has been growing interest in obtaining optical spots with various polarizations beyond the diffraction limit. Ohdaira et al. [8] obtained local circular polarization by superposing two cross propagating evanescent waves. Lindfors et al. [9] illuminated an optical lens with unpolarized light, and obtained fully polarized light in rings on the focal planes. It has been recently demonstrated that the polarization of diffraction limited incident beams can be manipulated using nanoparticle based antenna geometries [10, 11, 12, 13] and nanorod arrays [14]. Elliptically and circularly polarized near-field radiation can also be achieved through subwavelength apertures by utilizing a circular hole surrounded by elliptical gratings [15] and L-shaped hole arrays [16].

It is well known that the polarization of an optical beam can be represented by the phase difference and amplitude ratio of the electric field components. Any polarization state on the Poincaré sphere can therefore be achieved by properly tuning the amplitude ratio and phase difference of the beam. In this study, we have achieved this tuning process at the nanoscale by using a plasmonic nanoantenna. A plasmonic nanoantenna is illuminated with diffraction-limited linearly polarized radiation. Plasmonic resonances of perpendicular and longitudital components of the nanoantenna are adjusted to obtain optical spots at the nanoscale with linear, circular, and elliptical polarizations. We have shown that the nanoscale optical spots with different polarizations can be achieved on the Poincaré sphere by tuning two parameters: (a) the horizontal or vertical antenna length and (b) the polarization angle of the incident linearly polarized beam.

2. OPTICAL SPOTS AT THE NANOSCALE WITH LINEAR POLARIZATION STATES

Polarization state of an optical beam can be represented by the amplitude-ratio and phase-difference between field components of the beam. The Stokes parameters and the Poincaré sphere representation [17] are alternative, yet more rigorous ways to characterize the polarization states. These representations are widely used in the literature to describe the polarization state of diffraction-limited electromagnetic radiation. In this study, these representations are utilized to characterize polarization state of optical spots beyond the diffraction limit obtained from a plasmonic nanoantenna. The Stokes parameters that correspond to a specific polarization state are then utilized
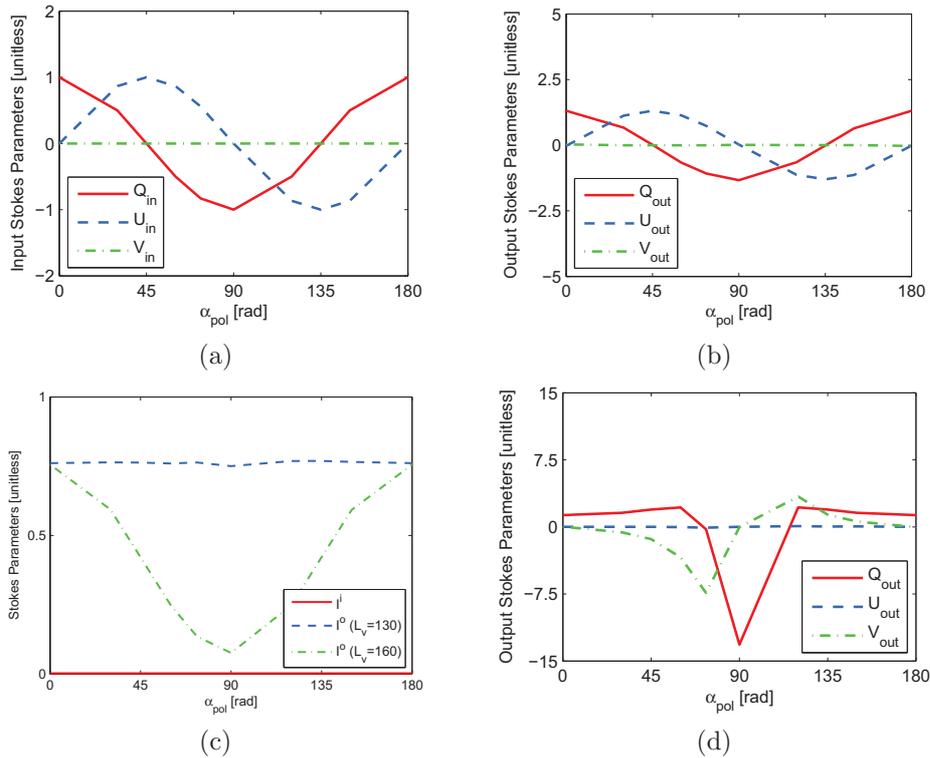
Figure 1: Effect of α_{pol} on (a) the Stokes parameters of the incident linearly polarized radiation (Q^{inc}, U^{inc}, V^{inc}), (b) the Stokes parameters of the output radiation from the nanoantenna for $L_v = 130$ nm, (c) I^{inc}, I^{out} for $L_v = 130$ nm , and I^{out} for $L_v = 160$ nm, and (d) the Stokes parameters of the output radiation from the nanoantenna for $L_v = 160$ nm.

to construct a Poincaré sphere that visually describes the polarization state and intensity of the optical spot. The handedness of the optical spot is determined by its location on the upper or lower half of the Poincaré sphere.

A cross-dipole plasmonic nanoantenna [11, 12, 13] is investigated to convert diffraction limited linearly polarized light into an optical spot with linear, circular or elliptical polarization beyond the diffraction limit. In this study, the thickness of each antenna particle is $T = 20$ nm and the width is $W = 10$ nm. Antennas with various horizontal and vertical lengths are investigated. The operating wavelength is selected as $\lambda = 1100$ nm, which corresponds to the resonance wavelength of the cross-dipole geometry. The dielectric constants of gold at $\lambda = 1100$ nm is chosen as $\epsilon_{gold} = $ -58.8971+i4.61164 [18].

To characterize the polarization states of near-field radiation from the nanoantenna, the Stokes parameters 20 nm below the gap center of the antenna are used. The Stokes parameters are given as [17]

$$I^{out} = (1/\eta)[(e_h^{out})^2 + (e_v^{out})^2] \tag{1}$$

$$Q_N^{out} = (1/\eta)[(e_h^{out})^2 - (e_v^{out})^2]/I^{out} \tag{2}$$

$$U_N^{out} = (2/\eta)e_h^{out}e_v^{out}cos\psi^{out}/I^{out} \tag{3}$$

$$V_N^{out} = (2/\eta)e_h^{out}e_v^{out}sin\psi^{out}/I^{out} \tag{4}$$

where the subscript $_N$ represents the normalized Stokes parameters projected onto a Poincaré sphere with unit intensity. The superscript $_{out}$ represents the Stokes parameters of the near-field radiation from the nanoantenna, whereas, superscript $_{in}$ represents the Stokes parameters of the input diffraction limited optical beam. e_h^{out} and e_v^{out} are the field amplitudes within the optical spot and ψ^{out} is the phase difference between field components.

First, we obtain optical spots at the nanoscale with linear polarizations at various points on the equator of a Poincaré sphere. For this purpose, we utilized a symmetric cross-dipole nanoantenna with $L_h = L_v = 130$ nm, where L_h and L_v represent the length of horizontal and vertical particles [12]. The nanoantenna is illuminated with a diffraction limited linearly polarized radiation
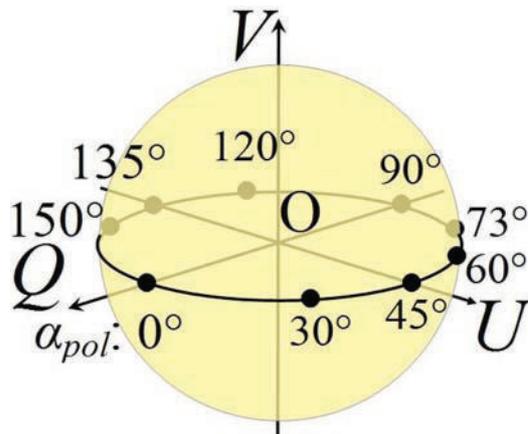
Figure 2: A unit Poincaré sphere with certain polarization states illustrated as points on its surface. Q, U, and V are the Stokes parameters, and α_{pol} is the angle of incident linear polarization.

with a polarization angle α_{pol} varying between $0°$ and $180°$. Fig. 1(a) shows the Stokes parameters of the diffraction-limited incident beam as a function of incident polarization angle α_{pol}. The location of the polarization states of the incident beam on the Poincaré sphere are depicted in Fig. 2. Fig. 1(b) illustrates Stokes parameters of the near-field radiation as a function of α_{pol} for a symmetric nanoantenna with $L_h = L_v = 130$ nm. The result suggests that optical spots with linear polarization are obtained at the output via the nanoantenna.

In Fig. 1(c), I^{inc} is 0.002 for α_{pol} between $0°$ and $180°$. In Fig. 1(c) $I^{out}(L_h = 130)$ shows an increased value of around 0.76, which highlights the enhanced output radiation due to plasmonic resonance of the nanoantenna. The remaining three Stokes parameters of the incident and output radiations, Q^{inc} and Q_N^{out}, U^{inc} and U_N^{out}, and V^{inc} and V_N^{out} behave similarly, as seen in Fig. 1(a) and 1(b). The reason for the similar behavior is due to two reasons:

(i) Since the antenna components have equal lengths, the phase difference between the field components is kept the same without a change at the opposite space of the antenna. We observed that the $\psi^{out} = \psi^{inc}$ at all angles $\alpha_{pol} = 0° - 180°$. This means that $V^{out} = 0$ at all the incident linear polarizations for a symmetric cross-dipole. $V^{out} = 0$ ensures that the polarization states that are obtained from the antenna are located on the same coordinate of the Poincaré sphere for a linearly polarized diffraction-limited illumination. In other words, the output polarization state lies on the equator of the Poincaré sphere, as shown in Figure 2, depending on the angle of incident linear polarization α_{pol}.

(ii) Cross-dipole antenna produces both field components, e_h^{out} and e_v^{out}, within the optical spot. Both e_h^{out} and e_v^{out} are enhanced with the same amount by the horizontal and vertical antenna components, since the antenna is symmetric. For this reason, the polarization angle of the diffraction-limited incident linear polarization is equal to the polarization angle of the linearly polarized optical spot produced by the antenna.

3. OPTICAL SPOTS AT THE NANOSCALE WITH CIRCULAR AND ELLIPTICAL POLARIZATION STATES

A cross-dipole plasmonic nanoantenna is investigated to convert diffraction-limited linearly polarized radiation into circularly and elliptically polarized near-field localized radiation beyond the diffraction limit. The plasmonic resonances of the perpendicular and longitudinal components of the nanoantenna and the angle of incident polarization are tuned to obtain circular and elliptical polarization states from a linearly polarized illumination.

An asymmetric antenna with $L_h = 130$ nm and $L_v = 160$ nm is investigated. In Fig. 1(c), as α_{pol} varies between $0° - 180°$, I^{out} varies between 0.08 and 0.76, since e_h^{inc} and e_v^{inc} result in different enhancements for various angles on the horizontal and vertical components of the antenna. For instance, at $\alpha_{pol} = 0°$, e_h^{inc} is supported merely by the horizontal component, and at $90°$, e_v^{inc} is supported merely by the vertical component. At $\alpha_{pol} = 0°$ the horizontal antenna particle is in resonant with e_h^{inc}. At $90°$, however, the vertical particle is slightly out of resonant with e_v^{inc} because L_v is greater than L_h. Therefore, the plasmonic enhancement at $\alpha_{pol} = 0°$ is larger than the plasmonic enhancement at $\alpha_{pol} = 90°$. As a result, $I^{out} = 0.08$ at $\alpha_{pol} = 90°$, and $I^{out} = 0.76$
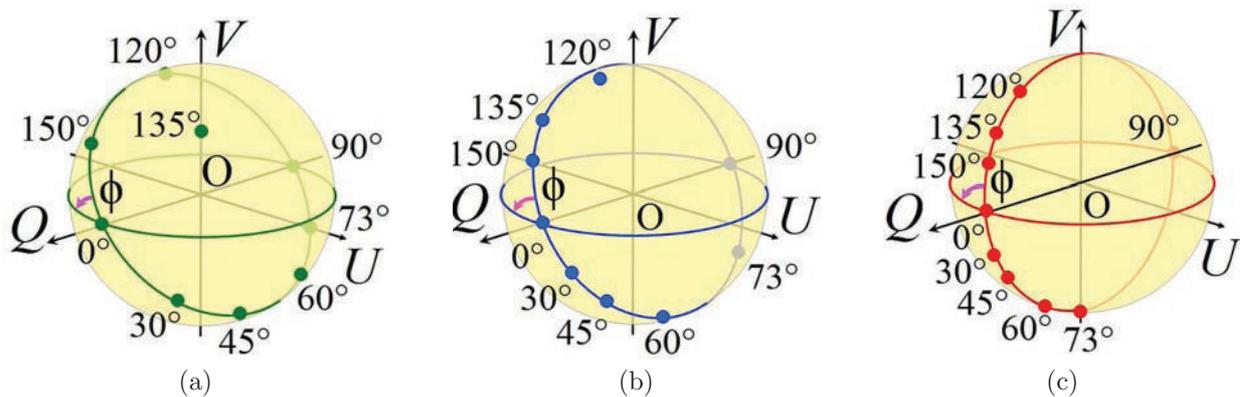
Figure 3: Unit Poincaré spheres with certain polarization states illustrated as points on their surfaces. ϕ illustrates the angular distance from different cut-planes passing through spheres onto the equator of the spheres.

at $\alpha_{pol} = 0°$.

In Fig. 3(a), (b), and (c) various polarization states from an asymmetric antenna geometry are presented for $L_v = 140$ nm, 150 nm, and 160 nm, respectively. A linearly polarized diffraction-limited radiation is incident upon the antenna at $\alpha_{pol} = 0°$, 30°, 45°, 60°, 73°, 90°, 120°, 135°, and 150°. At $L_v = 140$ nm and $L_v = 150$ nm, linear, right-hand, and left-hand elliptical polarization states are obtained on the surface of the Poincaré spheres, as depicted with solid points in Fig. 3(a) and (b). These states exist on the intersection curve between a Poincaré sphere and a cut-plane that passes through the sphere, and which makes an angle ϕ with the equator of the sphere, as illustrated in Fig. 3. If a linear polarization is incident on the antenna with $L_v = 130$ nm, then $\phi = 0°$ as shown in Fig. 2. When $L_v = 160$ nm this cut-plane is perpendicular to the equator, as demonstrated in Fig. 3(c). As a result, there exist both linear and elliptical polarization states, as well as at $\alpha_{pol} = 73°$, a left-hand circular polarization state on the surface of the Poincaré sphere. An important consequence of the result in Fig 3 is the following. If L_v is increased from 130 nm to 160 nm when the nanoantenna is illuminated with a linearly polarized diffraction-limited radiation with α_{pol} from 0° to 180°, then the whole surface of the Poincaré sphere can in principle be obtained at the output optical spot at the nanoscale.

4. CONCLUSION

In summary, optical spots with linear, circular, and elliptic polarizations were achieved via symmetric and asymmetric cross-dipole nanoantennas. It was demonstrated that a cross-dipole nanoantenna can convert diffraction-limited linearly polarized light into linearly, circularly, or elliptically polarized optical spots beyond the diffraction limit. It was shown that the nanoscale optical spots with different polarizations can be achieved on the Poincaré sphere by tuning two parameters: (a) the horizontal or vertical antenna length and(b) the polarization angle of the incident linearly polarized beam.

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