Birefringent and Dichroic Behaviour of Plasmonic Nano-Antennas

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Abstract: Birefringence and dichroism of plasmonic nano-antennas are investigated. We demonstrate that birefringent and dichroic behaviour of a cross-dipole nanoantenna is due to a length difference, and a relative plasmonic enhancement of the antenna particles, respectively.

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1. Introduction

Polarized electromagnetic radiation has led to interesting technical applications and significant advancements at both optical and microwave frequencies. With advances in nanotechnology, electromagnetic radiation beyond the diffraction limit with a particular polarization is an emerging need for plasmonic nano-applications. Among these, all-optical magnetic recording [1] requires circularly polarized optical spots. 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 [1]. To advance the areal density of hard disk drives beyond 1 Tbit/in.^{2}, 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 using plasmonic nano-antennas [2]. Although, plasmonic nano-antennas have been investigated to be utilized as potential nano-optical polarization elements, two crucial polarization related properties, birefringence and dichroism, of optical antennas have not been investigated. In this study, we examine the birefringence and dichroism of cross-dipole plasmonic nano-antennas. The underlying reasons of birefringent and dichroic behaviour in nano-antennas are provided.

2. Birefringence and dichroism of plasmonic nano-antennas

Birefringence and dichroism characteristics of nanoantennas are obtained from Jones matrix representations of the nanoantennas, which are formed using finite element method (FEM) based solution of Maxwell's equations. A Jones matrix of cross-dipole nanoantenna can be given as

$$J = \begin{bmatrix} 1 & 0.00 \\ 0.00 & \rho e^{j\phi} \end{bmatrix} \tag{1}$$

where the matrix elements are normalized with the first matrix element. The parameters ϕ and ρ in Eq. (1) characterize the birefringence and dichroism of a nanoantenna, respectively. To calculate the Jones matrices these parameters are calculated at the point 20 nm below the gap center of various cross-dipole nanoantennas for a diffraction-limited incident radiation with a linear polarization angle α_{pol} = 45°.

In this study, the thickness of each antenna particle is T = 20 nm, the width is W = 10 nm, and gap is G = 20 nm. The operating wavelength is selected as $\lambda = 1100$ nm based on a previous study [2]. Equations (2)-(5) represent the Jones matrices for nanoantennas with horizontal and vertical rod lengths of L_h = 130 nm and L_v = 130 nm, 140 nm, 150 nm, and 160 nm.

$$J^{130nm} = \begin{bmatrix} 1 & 0.00 \\ 0.00 & 0.99e^{j0} \end{bmatrix} \tag{2}$$

$$J^{140nm} = \begin{bmatrix} 1 & 0.00 \\ 0.00 & 0.77e^{-j1.04} \end{bmatrix} \tag{3}$$

$$J^{150nm} = \begin{bmatrix} 1 & 0.00 \\ 0.00 & 0.46e^{-j1.41} \end{bmatrix} \tag{4}$$

$$J^{160nm} = \begin{bmatrix} 1 & 0.00 \\ 0.00 & 0.32e^{-j1.57} \end{bmatrix} \tag{5}$$

Birefringence is observed in an optical medium when the field components experience a different refractive index in parallel and perpendicular directions to the optical axis of the medium. Since a refractive index difference is typically small, a retardation between the field components requires relatively long distances. For example, to create a $\pi/2$ retardation for a refractive index difference of $\Delta n = 0.005$, an optical wave needs to propagate about $5.5\mu m$. On the other hand, a length difference of 30 nm is sufficient to create a $\pi/2$ retardation using a resonant optical antenna, as calculated from Eqs. (2)-(5). Therefore, birefringence of a resonant cross-dipole nano-antenna is much more sensitive to small changes in the geometry compared to birefringence observed in other optical media that does not support plasmon resonances. As represented in Fig. 1 a very small increase in the vertical rod length L_v of the nano-antenna causes a strong increase in negative birefringence ϕ of the nano-antenna.

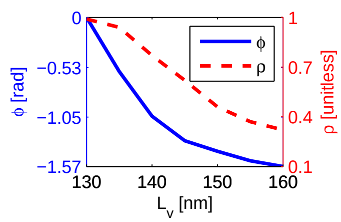

Fig. 1. Effect of various L_v values on ϕ and ρ for L_h = 130 nm.

The main cause of the birefringent behaviour is the length difference between the antenna components, which creates a retardation of the plasma wave due to an optical path difference. The short wavelength of plasma waves over gold antenna particles create large retardation over a very short distance. For very thin antennas, the plasmon wavelength is on the order of $\lambda_{spp} = 50$-200 nm in the near-infrared [2]. Thus, to create a $\pi/2$ retardation, $\lambda_{spp}/4$ difference which is on the order of 15-50 nm is sufficient.

Dichroism is observed in an optical medium when the field components parallel and perpendicular to the optical axis are attenuated by a different amount. Relative attenuation of the field components are relatively small for a typical dichroic medium. For a resonant optical antenna, however, the relative attenuation is significant as shown in Eqs. (2)-(5) for very short length scales. Fig. 1 suggests that a very small increase in antenna asymmetry causes strong increase in dichroism ρ.

The main cause of a strong dichroism in a nanoantenna is the change in the resonant behaviour of the antenna components. First, consider a resonant symmetric antenna. Due to symmetry, an incident field is enhanced with the same amount by the antenna particles. If an asymmetry is created one of the antenna component becomes slightly out of resonance, which result in a significant drop in the field enhancement for the antenna component. Due to a difference in plasmonic enhancements an asymmetric cross-dipole antenna shows a strong dichroic behaviour. Dichroism of an asymmetric nano-antenna is not due to the difference in relative attenuation of the field components, but rather due to the difference in relative plasmonic enhancement between the antenna components.

In summary, birefringence and dichroism of cross-dipole plasmonic nanoantennas are quantified using Jones matrix representation, which show an increase as the antenna asymmetry increases. Birefringence was explained with the retardation of the field components due to an optical path difference, which results from an asymmetry. Dichroic behaviour was explained with the relative plasmonic enhancement between asymmetric antenna components.

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