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Plasmon resonance enhanced optical transmission and magneto-optical Faraday effects in nanohole arrays blocked by metal antenna

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ABSTRACT

The properties of the optical and magneto-optical effects of an improved plasmonic nanohole arrays blocked by gold mushroom caps are investigated by using the finite difference time domain (FDTD) method. It is most noteworthy that the strongly enhanced Faraday rotation along with high transmittance has been achieved simultaneously by optimizing the parameters of nanostructure in a broad spectrum spanning visible to near-infrared frequencies, which is very important in practical application for designing novel optical and magneto-optical devices. In our designed structure, we obtained two extraordinary optical transmission (EOT) resonant peaks along with enhanced Faraday rotation and two peaks of the figure of merit (FOM). By optimizing the geometrical parameters of the structure, we can obtain an almost 10-fold enhancement of Faraday rotation with a corresponding transmittance 50%, and the FOM of 0.752 at the same wavelength. As expected, the optical and magneto-optical effects sensitively depends on the geometrical parameters of our structure, which can be simply tailored by the height of pillar, the diameter of mushroom cap, and the period of the structure, and so on. The physical mechanism of these physical phenomena in the paper has been explained in detail. These research findings are of great theoretical significance in developing the novel magneto-optical devices in the future.

1. Introduction

Surface plasmons (SPs) are a collective oscillation of electrons at the boundaries between materials and are often categorized into two classes: propagating surface plasmons (PSPs) and localized surface plasmons (LSPs) [1]. PSPs are propagating electromagnetic waves bound to the interfaces between two media with permittivity of opposite sign, typically such as a dielectric and a metal. While LSPs are non-propagating excitations of the electrons in metal nanoparticles that are much smaller than the incident wavelength. The resonance wavelength of LSP modes are dependent on the size, shape, and dielectric function of the nanoparticle as well as the dielectric environment [2,3]. For some particular geometries, photons can couple to such surface plasmon modes, modifying the optical response of the system. For example, LSP modes are responsible for the peaks observed in the extinction spectra of metallic nanoparticles, and the perforated metallic films show an EOT due to the excitation of surface plasmon polariton (SPP) modes [4]. Upon the right excitation conditions these two surface plasmon modes may interact, modifying the dispersion curves and leading to hybrid LSP/SPP modes due to the strong coupling between them [5–7]. Moreover, excitation of the surface plasmon resonance was shown to influence not only on the optical but also on the magneto optical (MO) properties of the metal-dielectric systems [8–12].

Magneto-plasmonic nanostructures have so far drawn great attention due to their multi-functionality that allows active control of SPs and significant enhancement of MO effects [13–20]. One of the efficient structures for plasmon-induced control of the MO effects is a magnetoplasmonic crystal, which is composed of the noble metals and magnetic dielectrics. In this structure, the noble metals support propagating or localized plasmon modes with the lowest possible absorption losses, and the ferromagnetic dielectrics possess a large MO activity, which should demonstrate the effect of EOT due to the SPPs and acquire MO effects due to the presence of the ferromagnetic layer. Therefore, appropriately structured magneto-plasmonic crystal systems can provide impressive opportunities for tailoring the EOT and the magneto-optical Faraday effects. However, the conditions of high transmittance along with large Faraday are still not easy to meet. It is well known that the enhancement of MO effect is usually accompanied

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by the decrease in the detected signal [10,11], which was insufficient for practical applications. Therefore, the enhanced MO effects along with low light loss, which is of prime importance optical devices, is a quite urgent task. So far, the EOT phenomenon with a giant MO effects in both 1D and 2D subwavelength structure has been investigated in just a few works [21–26]. For example, Belotelov and colleagues obtained the enhanced Faraday rotation angle of 0.78° and high transmittance of about 35%, and with a FOM of 0.46 at λ=963 nm by optimizing the thickness of the magnetic layer in the bilayer systems [24]. Chin and co-workers investigated a periodic arrangement of Au annogratings on top of a Bi:YIG film and obtained a maximum Faraday rotation of 0.8° at 963 nm, which is an 8.9-fold enhancement as compared with the Faraday rotation in the BIG film without gold wires. However, the same sample shows a just 36% transmittance and a FOM of 0.48 at the 963 nm [26]. Although, Belotelov and colleagues achieved a nearly 10-fold enhancement of Faraday rotation with a corresponding transmittance 35% at 883 nm in one-dimensional metallic-magnetic slit arrays [21]. Nevertheless, the thickness of Bi:YIG film is much higher than that of Ref. [22–24], which is the main reason of the higher Faraday rotation. In a word, despite the considerable enhancement of the Faraday rotation, these values of transmittance and the FOM are still small, and the resonant wavelengths of the Faraday rotation and transmittance are focus on the near-infrared range, which is not useful for the magneto-optical devices whose work frequency is in the visible range. Consequently, we are necessary to try our best to build a magneto-plasmonic crystal system, which can demonstrate the high transmittance accompanied by the enhanced Faraday rotation. In addition, in these aforementioned works, qualitative explanations for the discovered phenomena were presented, suggesting that its origin was attributed to the SPPs coupled with quasi-guided waves in the thin dielectric slab. Nevertheless, the search for new mechanisms of the MO activity enhancement and superior optical performance is still an urgent work, especially for the complicated nanostructures. Therefore, the present paper needs to be further studied to obtain the high transmittance as possible accompanied by enhanced Faraday rotation for practical applications, especially in the visible spectral range and it is necessary that the physical mechanism of the EOT and enhanced Faraday rotation is deeply discussed.

In this paper we propose a mushroom cap model instead of the simplified nanodisc model, because the former has obviously more advantages than that of the nanodiscs in the optical and magneto-optical performance (Supplementary Fig. S1). We investigate the optical and magneto-optical characteristics of the mushroom cap model using the FDTD method. By optimizing the parameters of the nanostructure, the enhanced Faraday rotation (by a factor of 10) along with high optical transmission (50%) and large FOM of 0.752 in the visible and near-infrared spectral range can be obtained. The intensity and positions of the transmittance and the Faraday rotation can be efficiently tailored by changing the height of pillar, the diameter of the mushroom cap, and the period of the structure.

2. Structure model and simulation method

Fig. 1 schematically shows the tri-layer structure deposited on a glass substrate. The perforated Au film is covered on the SiO_2 media layer with a thickness of H_2, and the SiO_2 pillar arrays get through the holes. The gold mushroom cap lies on the top of the SiO_2 pillar whose height is H. The bottom is a continuous Bi-substituted yttrium iron garnet (Bi:YIG) film with a thickness of H_3. The gold mushroom cap can be characterized as a half-ellipsoid with a thickness of H_1 and diameter of D. The thickness of gold film is H_1. We note that the gold mushroom caps that we consider here are symmetric under rotation in the x-y plane, while the lattice is identical in the x and y directions, i.e., P_x=P_y=P. This configuration is chosen because, for normally incident light, the polarization modes are degenerate and thus we expect more

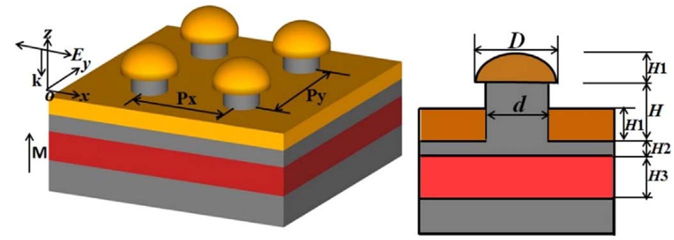

Fig. 1. A schematic of the tri-layer structure under consideration on a glass substrate: the right subplot is the cross-section in the x-z plane. The structure is illuminated by normally TM-polarized light that has the electric field parallel to x axis.

efficient polarization conversion rates. In order to achieve the enhanced Faraday rotation and high optical transmission simultaneously, we systematically optimize the parameters of this structure, which are as follows: H_1=40 nm, H_2=20 nm, H_3=150 nm, P=200 nm and d=80 nm. The D and H are varied to study the change of transmittance and Faraday rotation with their variation in our simulation.

In this structure, the magnetic Bi:YIG film is uniformly magnetized perpendicularly to its x-y plane (i.e., $\mathbf{M}||\mathbf{z}$), its dielectric tensor is described as follows:

$$[\varepsilon] = \begin{bmatrix} \varepsilon & -ig & 0 \\ ig & \varepsilon & 0 \\ 0 & 0 & \varepsilon \end{bmatrix}. \tag{1}$$

The dielectric tensor of Bi:YIG film is slightly dispersive in the wavelength range of our simulation, and the average value of the tensor with $\varepsilon = 5.5 + i0.0025$, $g = (1 - i0.15) \times 10^{-2}$ is adopted [21,24]. Here we assume the case that the magnetic medium is optically isotropic and second order MO effects are negligible. The dielectric function of glass is provided by Palik [27]. The frequency-dependent permittivity of gold is characterized by the well-known Drude model, given by [27].

$$\varepsilon_1 = \varepsilon_\infty - \frac{\omega_p^2}{(\omega^2 + i\gamma\omega)} \tag{2}$$

where we set $\varepsilon_\infty = 7.9$, $\omega_p = 8.77eV$, $\gamma = 1.13 \times 10^{14}s^{-1}$ to fit the empirical data [27] for the gold film over the wavelength range of interest.

In our structure, the main effect of the nonmagnetic dielectric layer is a strong redistribution of the EM field inside the structure upon plasmon resonance excitation, increasing the EM field in the MO active layer (Bi:YIG) with its simultaneous reduction in the other absorbing but non-MO-active components of the system, and the magnetic dielectric layer plays a twofold role. On the one hand the magnetic layer engenders the MO effects because of its magnetization; i.e., it produces TM-TE mode conversion, and, on the other hand, it makes the TE-mode localized [24]. The structure is illuminated normally by a linearly polarized plane wave with the electric field vector parallel to the x direction (p-polarized light, i.e., TM-polarized light). When the extraordinary transmission light tunneling through the holes travels through the Bi:YIG film, because of the coupling with the magnetization $\mathbf{M}$ in the MO dielectric layer, another component of electric field $\mathbf{E_y}$ (i.e., TE-polarized light) will produce, which can be attributed to the change of the polarization orientation, and the Faraday rotation produces. As a result, large enhancement of Faraday rotation along with high optical transmittance requires strong coupling between the TM and TE modes, and the value of the Faraday rotation strongly depends on the TM-to-TE conversion efficiency [21,26].

By understanding the underlying physical mechanism which involves the coupling between LSPR and SPP modes of the structure, we will be able to design structures with the desirable figure of merit, which expresses the trade-off between transmittance and Faraday rotation angles. These structures are fully tunable with the geometry and the materials, large Faraday rotation angles accompanied by high transmittance can be achieved. Of course, such an optimization process requires large-scale systematic and rigorous calculations which, in the