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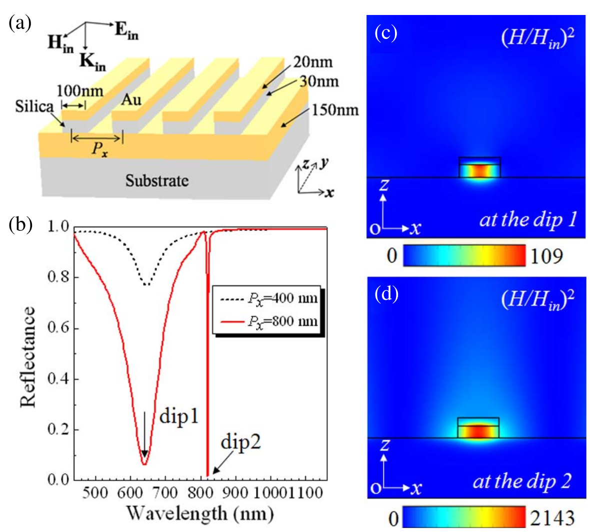

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Surface-Plasmon-Polaritons-Assisted Enhanced Magnetic Response at Optical Frequencies in Metamaterials

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Abstract: We theoretically study the coupling of magnetic plasmon polaritons (MPPs) with propagating surface plasmon polaritons (SPPs) in a system composed of an array of metal nanowires close to a metal film with a dielectric spacer. Strong coupling between MPPs and SPPs is observed, manifested by the anticrossing behavior of the resonant positions in the reflection spectra. It creates narrow-band hybridized MPPs with Rabi-type splitting as large as 250 meV. Moreover, we also found that the coupling between the MPPs and the SPPs can be tailored by the period of the metal nanowire array to affect the magnetic response of the plasmonic structure. Above the resonant wavelength of the MPPs, coupling between two kinds of resonance modes can lead to a 20-fold enhancement of the magnetic fields in the dielectric spacer, as compared with the pure magnetic resonance upon the excitation of the hybridized MPPs, whereas below it, coupling cannot lead to a magnetic field enhancement. We suggest that this feature could offer a feasible way to achieve huge magnetic field enhancement at optical frequencies and hold promising potential applications in magnetic nonlinearity and sensors.

Index Terms: Metamaterials, magnetic field enhancement, magnetic plasmon polaritons, surface plasmon polaritons.

1. Introduction

Metal nanoparticles are the object of renewed scientific interest because of their remarkable optical properties [1], related to the excitation of localized surface plasmons (LSPs) [2], [3]. The LSPs can induce strongly enhanced electric fields around the metal nanoparticles, which have found interesting applications in surface enhanced Raman spectroscopy [4], [5], biosensing [6]–[9], solar cells [10], and so on. Due to radiative damping, however, the particle LSPs

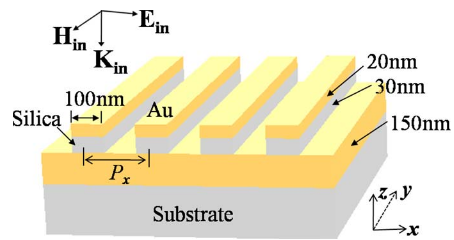

Fig. 1. Geometry of the system investigated. A 1-D gold nanowire array is stacked above a gold film, and the two layers are separated by a SiO_2 film. The incident light is normally incident on the array with its electric field perpendicular to the nanowires.

have a large spectral bandwidth or short lifetime [11], which significantly limit the intensity of localized electric fields that can be achieved in isolated nanoparticles. An effective way to reduce the radiative damping lies in coupling the LSPs to a narrow-band resonance mode. For example, through coupling broad particle LSPs to narrow-band waveguide modes, almost complete suppression of light extinction within narrow spectral bands can be realized due to destructive interference [12]. In a similar way, Brunazzo *et al.* couple the broadband LSPs to narrow-band propagating SPPs modes to obtain an enhancement of electromagnetic fields with narrow resonances [13]. Furthermore, enhanced and direct fluorescent emission is achieved based on the combination of LSPs and narrow lattice surface modes in periodic plasmonic nanoantenna arrays [14].

On the other hand, the realization of a large amplification of magnetic fields at optical frequencies is now as important an issue in nanophotonics as achieving electric field enhancement, due to its potential applications such as magnetic nonlinearity and magnetic sensors [15]–[18]. However, in the interactions of light with matter at optical frequencies, magnetic contribution is generally neglected since the effect of light on the magnetic permeability is a factor 10^{-4} weaker than on the electric permittivity [19]. Therefore, seeking new mechanisms to enhance the magnetic fields becomes quite important. Being similar to electric plasmon resonances, the interactions of the MPPs with other resonances in metamaterials are also used to realize the magnetic field enhancement, but are still rarely investigated. For example, through coupling to resonance modes with narrow bandwidth such as the waveguide modes [20] and Bloch surface waves [21], enhanced magnetic resonances can be achieved with a huge magnetic field enhancement. More recently, we also theoretically show that when the coupling took place between the MPPs and lattice surface modes arising from light diffraction in periodic arrays of metallic split-ring resonators, an enhancement factor as high as 1753 could be achieved for magnetic field intensity at a near-infrared wavelength of 1864 nm [22].

In this letter, we investigate the coupling between MPPs and SPPs in metamaterials consisting of a 1-D metal nanowire array stacked above a metal film with a dielectric spacer. Narrow-band hybridized MPPs were observed due to the strong interaction between MPPs and SPPs. More interestingly, we found that the coupling between the MPPs and the SPPs can be tailored by the period of the metal nanowire array to affect the magnetic response of the metamaterials, and above the resonant wavelength of the MPPs, coupling between two kinds of resonance modes leads to a 20 times enhancement of the magnetic fields in the dielectric spacer as compared with the pure magnetic resonance at the optical excitation of this hybridized MPPs, whereas below it, the coupling does not lead to a magnetic field enhancement.

2. Modeling Structures

The system under study is schematically depicted in Fig. 1. It consists of a 1-D gold nanowire array stacked above a 150 nm thick gold film, and the two layers are separated by a 30 nm dielectric SiO_2 spacer layer. In our analysis, all gold nanowires have a cross section of 100 nm $\times$ 20 nm. The nanowires are assumed to be infinite along the *y* direction and periodic along

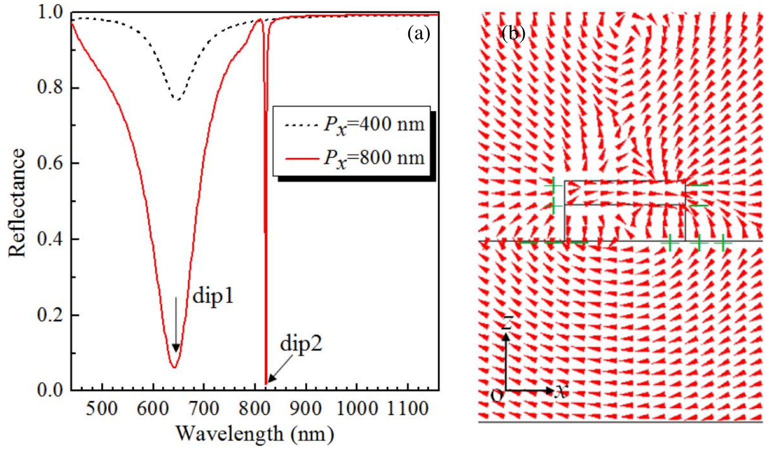

Fig. 2. (a) Normal-incidence reflection spectra of the two typical 1-D gold nanowire arrays lying on a gold film with a dielectric spacer for different periods along the x direction, $p_x = 400$ nm (black dotted line), and 800 nm (red solid line). (b) Electric field vectors mapped on the xoz plane for dip 1 in (a). Arrows represent field direction, black solid lines outline the boundaries between different material regions, and green signs "+" and "–" stand for positive and negative charges, respectively.

x direction with a period of p_x. The real fabrication process for the proposed plasmonic structure could be easily completed via using the standard electron beam lithography (EBL) for the patterning of the 1-D nanowire array [23], [24] and using the standard deposition method for the metal and dielectric film fabrication [6].

The reflectance spectra and the electromagnetic field distributions of the plasmonic structure are numerically calculated. The numerical simulations are performed using the commercial finite-element software package (Comsol Multiphysics). In the simulations, the perfectly matched layer (PML) absorbing boundary conditions are applied at either end of the computing space whereas periodic boundary conditions are used at other boundaries. The simulated structure is normally illuminated by a plane wave with its electric field perpendicular to the nanowires [see Fig. 1]. The refractive index of the SiO_2 spacer layer is taken as 1.45 and the relative permittivity of gold is described by a Drude model $\varepsilon_{\text{gold}} = 1 - \omega_p^2/[\omega(\omega + i\omega_c)]$ with plasma frequency $\omega_p = 1.367 \times 10^{16}$ rad/s and collision frequency $\omega_c = 4.084 \times 10^{13}$ rad/s [25].

3. Results and Discussion

Fig. 2(a) presents the normal-incidence reflectance spectra of two typical 1-D gold nanowire arrays stacked above a thick gold film with a dielectric spacer. The two arrays are infinite along the y direction and periodic along x direction with $p_x = 400$ nm and 800 nm, respectively. A broad reflection dip (labeled as dip 1) centered at $\lambda_1 = 640$ nm is observed for both arrays. However, for the array with $p_x = 800$ nm, as shown by the red solid line in Fig. 2(a), a relatively narrow reflection dip (labeled as dip 2) appears at $\lambda_2 = 820$ nm.

The position of the broad dip is almost independent of the period p_x, indicating that this reflection dip results from the resonance excitation of individual Au nanowires stacked above the thick gold film with a dielectric spacer. In fact, such a resonance state is a MPPs mode. To show this, Fig. 2(b) maps the electric field vectors on the xoz plane for dip 1. It is evident that at this resonance, the electric fields in the upper metal nanowires and lower metal film oscillate out of phase and produce antiparallel currents, accompanied by an antisymmetric charge distribution on the edge of Au nanowire and on the surface of Au film. The antiparallel ohmic currents, together with the displacement currents in the dielectric layer, form a current loop that induces a magnetic dipolar moment [26]. The formation of such a magnetic resonance can be well understood through plasmon hybridization between the Au nanowire and the Au film, similar to the case of metal nanosandwiches [27].

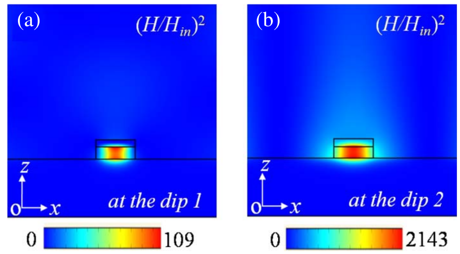

Fig. 3. (a) and (b) Normalized magnetic field intensity distributions $(H/H_{\rm in})^2$ on the *xoz* plane for the dip 1 and dip 2 marked in Fig. 2(a). Black solid lines outline the boundaries between different material regions.

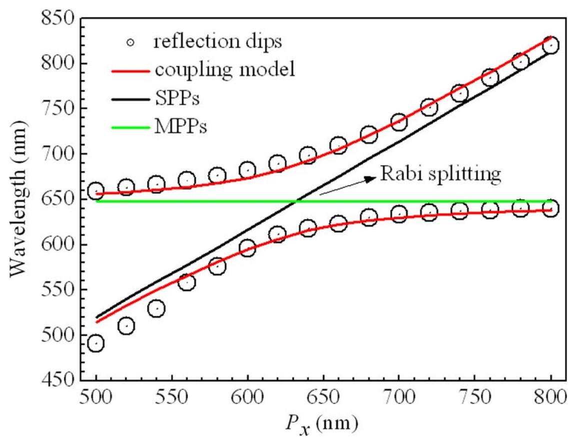

Fig. 4. p_x dependences of the positions of reflection dips (open black circles) and the predicted positions (two red curved lines) using a coupling model of the MPPs and the SPPs. The position (black diagonal line) of the SPPs and the position (horizontal green line) of the MPPs are also shown.

Fig. 3(a) shows the magnetic field intensity distributions on the *xoz* plane for the dip 1 resonance located at $\lambda_1 = 640$ nm. It is clear that the magnetic fields are highly confined within the SiO_2 spacer layer, which is typical characteristics of MPPs [27], [28]. In Fig. 3(b), we plot the corresponding magnetic field intensity distributions on the *xoz* plane for the resonance λ_2. Although the field pattern is almost the same as the case shown in Fig. 3(a), the magnetic fields in the SiO_2 spacer layer become much stronger, with a nearly 20 times enhancement. In particular, the maximum magnetic fields are enhanced to be about 2143 times of the incident field [please see Fig. 3(b)].

Next, we will show that such a huge enhancement of magnetic fields at optical frequency results from the strong coupling of the MPPs and propagating SPPs on the metal-film interface induced by the grating structure. This strong coupling leads to the formation of two hybridized modes, i.e., the high- and low-energy states, whose energies can be calculated with a coupled oscillator model [29]: $E_{+,-} = (E_{\rm MPPs} + E_{\rm SPPs})/2 \pm \sqrt{\Delta/2 + (E_{\rm MPPs} - E_{\rm SPPs})^2/4}$. Here, $E_{\rm MPPs}$ and $E_{\rm SPPs}$ are the energies of the MPPs and SPPs, respectively; and Δ stands for the coupling strength. For a 1-D grating array structure, the wavelengths of the SPPs at normal incidence can be calculated as: $\lambda^n_{\rm SPPs} = p_x/n\sqrt{\varepsilon_m/(\varepsilon_m + 1)}$, where n is integer, and ε_m is the dielectric permittivity of the gold. $E_{\rm MPPs}$ is determined by both the geometrical and material parameters of the nanowires and the distance between the Au nanowires and Au film but independent of the array periods. Through numerical simulations, we found that $E_{\rm MPPs}$ is about 1.914 eV, corresponding to a wavelength of 648 nm. The open black circles in Fig. 4 summarize the p_x

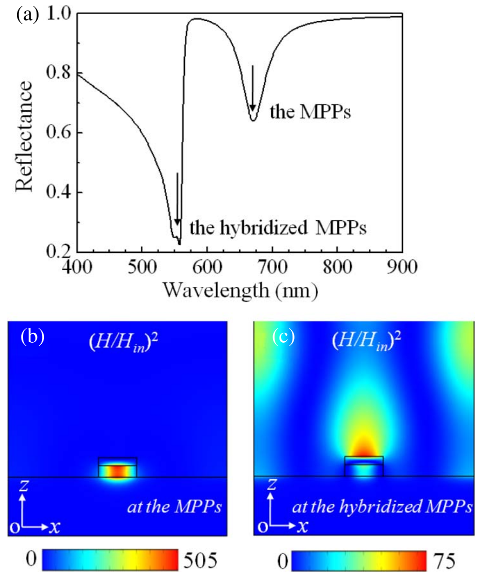

Fig. 5. (a) Normal-incidence reflectance spectrum of similar plasmonic structure but with the period $p_x = 560$ nm. (b) and (c) Normalized magnetic field intensity distributions $(H/H_{\text{in}})^2$ on the *xoz* plane for the MPPs and the hybridized MPPs. Black solid lines plotted in (b) and (c) outline the boundaries between different material regions.

dependences of the calculated positions of reflection dips with p_x being varied from 500 nm to 800 nm in steps of 20 nm. By taking the coupling strength to be $\Delta = 250$ meV in the above coupled oscillator model, we can predict the positions of reflection dips for different period p_x. The two branches of red lines in Fig. 4 give the predicted results. Obviously, they are in a good agreement with the locations dictated from the reflection spectra. The black line and the horizontal green line in Fig. 4 show the positions of the SPPs and MPPs, respectively. At the crossing of these two lines, the positions of reflection dips present an obvious anticrossing, which is a characteristic of the strong coupling between the SPPs and MPPs. Away from this strong coupling regime, the reflection dip positions follow approximately one of these two lines. Furthermore, because the SPPs propagating in the *x* direction has a magnetic field of the same direction as the induced magnetic moment (along the *y* direction) in the metamaterials, it can strongly interact with the MPPs when grazing the metamaterial surface [22]. Such a strong interaction can suppress radiative damping since the electromagnetic fields of the SPPs are trapped on the metal-film surface, thus resulting in the much narrower line shape and stronger magnetic field enhancement at the dip 2 resonance.

Here, it should be pointed out that for the proposed plasmonic structure, the magnetic response is actually determined by the coupling between the MPPs and the SPPs, and above the resonant wavelength of the MPPs, coupling between two kinds of resonance modes can lead to a huge magnetic field enhancement at the excitation of this hybridized MPPs, whereas below it, the coupling cannot lead to a magnetic field enhancement. To show this, Fig. 5(a) presents the normal-incidence reflectance spectrum of similar plasmonic structure but with the period $p_x = 560$ nm, in which the resonant position of the hybridized MPPs is tuned below resonant wavelength of the MPPs. As clearly seen in Fig. 5(a), a narrow-band hybridized MPPs mode is also observed when the period p_x approaches the resonant wavelength of the MPPs. Nevertheless, unlike the former situations, at the narrow-band mode resonance the magnetic fields in SiO_2 spacer layer become weaker, rather than get enhanced, as compared at the pure MPPs. This is due to the fact that in this case, the hybridized MPPs will approximately exhibit the characteristics of the SPPs, and consequently, the enhanced magnetic field is no longer tightly confined within the SiO_2 spacer layer but instead extends into the surrounding medium [see Fig. 5(c)] [30].

4. Conclusion

In conclusion, we have shown that in metamaterials consisting of a 1-D metal nanowire array stacked above a metal film with a dielectric spacer, the interaction between the MPPs originating from the plasmon hybridization of metal nanowires with metal film and the grating-induced SPPs on the metal-film interface can form a narrow-band hybridized MPPs. It was also found that the coupling between the MPPs and the SPPs can be tuned by the nanowire array period to determine the magnetic response of the metamaterials, and above the resonant wavelength of the MPPs, coupling between two kinds of resonance modes can lead to a strongly enhanced magnetic fields at optical frequencies at the hybridized mode resonance, whereas below it, the coupling cannot lead to a magnetic field enhancement. These findings have potential applications in fields employing enhanced magnetic fields, such as magnetic nonlinearity and magnetic sensors.

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