The Coupling Effects of Surface Plasmon Polaritons and Magnetic Dipole Resonances in Metamaterials

Bo Liu†, Chaojun Tang‡, Jing Chen§, Zhendong Yan, Mingwei Zhu, Yongxing Sui and Huang Tang

Abstract

We numerically investigate the coupling effects of surface plasmon polaritons (SPPs) and magnetic dipole (MD) resonances in metamaterials, which are composed of an Ag nanodisk array and a SiO₂ spacer on an Ag substrate. The periodicity of the Ag nanodisk array leads to the excitation of SPPs at the surface of the Ag substrate. The near-field plasmon interactions between individual Ag nanodisks and the Ag substrate form MD resonances. When the excitation wavelengths of SPPs are tuned to approach the position of MD resonances by changing the array period of Ag nanodisks, SPPs and MD resonances are coupled together into two hybridized modes, whose positions can be well predicted by a coupling model of two oscillators. In the strong coupling regime of SPPs and MD resonances, the hybridized modes exhibit an obvious anti-crossing, resulting into an interesting phenomenon of Rabi splitting. Moreover, the magnetic fields under the Ag nanodisks are greatly enhanced, which may find some potential applications, such as magnetic nonlinearity.

Keywords: Metamaterials, Plasmonics, Surface plasmon polaritons, Magnetic dipole resonances, Magnetic field enhancement

Background

It is well known that naturally occurring materials exhibit the saturation of the magnetic response beyond the THz regime. In light-matter interactions at optical frequencies, the magnetic component of light generally plays a negligible role, because the force exerted by the electric field on a charge is much larger than the force applied by the magnetic field, when light interacts with matter [1]. In the past few years, developing various metallic or dielectric nanostructures with appreciable magnetic response at optical frequencies has been a matter of intense study in the field of metamaterials. Recently, there is increasing interest in optical magnetic field characterization in nano-scale, although it remains a challenge because of the weak matter-optical magnetic field interactions [2]. At the same time, there have also been many efforts to obtain strong magnetic response with magnetic field enhancement in a wide spectrum range from visible [3–22] to infrared [23–44] regime. The physical mechanism underlining strong magnetic response is mainly the excitation of MD resonance in a variety of nanostructures including metal-insulator-metal (MIM) sandwich structures [3, 12, 16, 31, 32, 40], metallic split-ring resonators [29, 30, 36, 41, 42], high-refractive-index dielectric nanoparticles [14, 15, 17, 18, 20, 21], plasmonic nanoantennas [6, 8, 24–26, 28, 34, 37, 43], metamolecules [7, 9, 11, 13, 19, 33, 35, 38], and so on. To obtain strong magnetic response with magnetic field enhancement, MD resonance is also coupled to different narrow-band resonance modes with a high-quality factor, e.g., surface lattice resonances [4, 22, 39, 44], Fabry-Pérot cavity resonances [10, 23], Bloch surface waves [5], and Tamm plasmons [27]. A strong magnetic response with a great enhancement of magnetic fields at optical frequencies will have many potential applications, such as MD spontaneous emission [45–52], magnetic nonlinearity [53–56], optically controlled magnetic-field etching [57], magnetic optical Kerr effect [58], optical tweezers based on magnetic-field gradient [59, 60], circular dichroism (CD) measurement...
etc. It is well known that plasmonic electric dipole resonance can hugely enhance electric fields in the vicinity of metal nanoparticles, and its coupling to SPPs can further enhance electric fields and generate other interesting physical phenomena. However, there are only a few researches on the coupling effects of SPPs and MD resonances.

In this work, we will numerically demonstrate the huge enhancement of magnetic fields at optical frequencies and the interesting phenomenon of Rabi splitting, due to the coupling effects of SPPs and MD resonances in metamaterials composed of an Ag nanodisk array and a SiO$_2$ spacer on an Ag substrate. The near-field plasmon interactions between individual Ag nanodisks and the Ag substrate form MD resonances. The periodicity of the Ag nanodisk array leads to the excitation of SPPs at the surface of the Ag substrate. When the excitation wavelengths of SPPs are tuned to approach the position of MD resonances by changing the array period of Ag nanodisks, SPPs and MD resonances are coupled together into two hybridized modes, whose positions can be well predicted by a coupling model of two oscillators. In the strong coupling regime of SPPs and MD resonances, the hybridized modes exhibit an obvious anticrossing, resulting into an interesting phenomenon of Rabi splitting. Moreover, the magnetic fields under the Ag nanodisks are greatly enhanced, which may find some potential applications, such as magnetic nonlinearity.

The unit cell of the designed metamaterials for the coupling effects of SPPs and MD resonances is schematically shown in Fig. 1. The Ag nanodisks lie on the $xy$ plane, and the coordinate origin is supposed to be located at the center of the SiO$_2$ spacer. The incident light propagates in the negative $z$-axis direction, with its electric and magnetic fields along the $x$-axis and the $y$-axis directions, respectively. The reflection and absorption spectra and the electromagnetic field distributions are calculated by using the commercial software package “EastFDTD,” which is based on finite difference time domain (FDTD) method [62]. In our numerical calculations, the refractive index of SiO$_2$ is 1.45, and the frequency-dependent relative permittivity of Ag is taken from experimental data [63]. This work mainly focuses on numerical investigation, but the designed metamaterials should be realized experimentally by the following procedures: the SiO$_2$ spacer is first coated on the Ag substrate through thermal evaporation, and then the Ag nanodisk array is fabricated on the SiO$_2$ spacer by some advanced nanofabrication technologies, such as electron beam lithography (EBL).

**Methods**

Figure 2 shows the calculated absorption and reflection spectra of a series of metamaterials under normal incidence of light, with the array period $p_x$ along the $x$-axis direction.
increased from 550 to 900 nm in steps of 50 nm. For each \( p_x \), two resonance modes are found in the spectra, which result into the appearance of two absorption peaks and two reflection dips in Fig. 2a and b, respectively. The positions and bandwidths of two resonance modes are strongly dependent on the array period \( p_x \). For \( p_x = 900 \) nm, the right sharp peak of absorption nearly reaches to 1. Such a strong light absorption in MIM structures is usually called as perfect absorption [64–66]. In addition, we have also investigated the effect of the array period \( p_x \) along the \( y \)-axis direction on the optical properties of metamaterials (not shown here). It is found that simultaneously changing \( p_y \) has no significant effect on the optical properties, except for the appearance of a high-order SPP mode when both \( p_x \) and \( p_y \) are increased to 700 nm. The high-order SPP mode will have an obvious red shift for the array period to be further increased. In Fig. 2, by keeping \( p_y = 500 \) nm unchanged, only the lowest order SPP mode propagating in the \( x \)-axis direction is excited in the spectral range of interest. In the following, we will demonstrate that these two resonance modes originate from the strong coupling between SPPs and MD resonances in the designed metamaterials.

In order to reveal the physical mechanism of two resonance modes in Fig. 2, we have proposed a coupling model of two oscillators to accurately predict the positions of two resonance modes for different array period \( p_x \). In the coupling model, one of the oscillators is SPPs, and the other is MD. The strong coupling between SPPs and MD leads to the formation of two hybridized modes, i.e., the high- and low-energy states, whose energies can be calculated by the equation [67]:

\[
E_{+,−} = (E_{MD} + E_{SPP})/2 ± \sqrt{Δ/2 + (E_{MD}−E_{SPP})^2}/4.
\]

Here, \( E_{MD} \) and \( E_{SPP} \) are the excitation energies of MD and SPPs, respectively; and \( Δ \) stands for the coupling strength. In Fig. 3, the open black circles show the positions of two resonance modes for different array period \( p_x \) and the two branches of red lines give the corresponding results calculated by the coupled oscillator model with the coupling strength \( Δ = 100 \) meV. Obviously, the above model predicted well the positions of two resonance modes. This suggests that the appearance of two resonance modes in Fig. 2 is the result of the interaction of SPPs and MD in metamaterials.

The black diagonal line in Fig. 3 gives the excitation wavelengths of SPPs for different array period \( p_x \), which is calculated by matching the reciprocal vector of the Ag nanodisk lattice with the momentum of SPPs under normal incidence [68]. The horizontal green line in Fig. 3 shows the position of MD mode, whose resonance wavelength is mainly determined by the size of Ag nanodisks and the thickness of the SiO\(_2\) spacer, but is independent of the array periods. At the crossing of the two lines for \( p_x = 750 \) nm, SPPs and MD are overlapped in positions, which are strongly coupled together. Therefore, the positions of two resonance modes in Fig. 2 exhibit an obvious anti-crossing, thus forming an interesting phenomenon of Rabi splitting [67]. Far away from the strong coupling regime, the positions of two resonance modes follow approximately one of the two lines.

Beside Rabi splitting, another effect of the strong coupling between SPPs and MD is the enhancement of magnetic fields. To exhibit this effect, in Fig. 4, we first plot the distributions of electromagnetic fields at the resonance wavelengths of \( λ_1 \) and \( λ_2 \) labeled in Fig. 3 for \( p_x = 550 \) nm. In this case, the positions of SPPs and MD are far, and their coupling is weak, as exhibited in Fig. 3. At the resonance wavelength of \( λ_1 \), the electric fields are highly confined near the edge of the Ag nanodisks and have two field “hotspots” on the left and right sides extending into the SiO\(_2\) spacer (see Fig. 4a). The magnetic fields are concentrated within the SiO\(_2\) spacer and have a maximum under the Ag nanodisks (see Fig. 4b). Such distribution properties of electromagnetic fields are mainly the typical characteristics of a MD resonance [69–71]. At the resonance wavelength of \( λ_2 \), parallel electromagnetic field bands stretching along the \( y \)-axis direction are formed, although they are disturbed near the Ag nanodisks (see Fig. 4c and d). In fact, such electromagnetic field distributions mainly correspond to the excitation of SPPs [68].

In Fig. 5, we plot the distributions of electromagnetic fields at the resonance wavelengths of \( λ_3 \) and \( λ_4 \) labeled in Fig. 3 for \( p_x = 700 \) nm. In this case, the positions of SPPs and MD are close, and their coupling becomes relatively stronger, as exhibited in Fig. 3. A result, the
positions of two resonance modes are red-shifted from $\lambda_1$ and $\lambda_2$ to $\lambda_3$ and $\lambda_4$, respectively, and the electromagnetic fields near the Ag nanodisks are further enhanced. As clearly seen in Fig. 5a and b, at the resonance wavelength of $\lambda_3$, the maximum electric and magnetic fields are enhanced to be about 3500 and 2560 times of the incident field, which are 1.80 and 1.82 times stronger than the corresponding values at the resonance wavelengths of $\lambda_1$, respectively. In Fig. 5c and d, the maximum electric and magnetic fields at the resonance wavelength of $\lambda_4$ are enhanced to be about 1650 and 870 times of the incident field, which are 6.98 and 3.53 times stronger than the corresponding values at the resonance wavelengths of $\lambda_2$, respectively.

Figure 6 shows the electromagnetic field distributions at the resonance wavelengths of $\lambda_5$ and $\lambda_6$ labeled in Fig. 3 for $p_x = 900$ nm. The mixed mode at $\lambda_5$ has a very narrow bandwidth, as clearly seen in Fig. 2. As a result, its electromagnetic fields are hugely enhanced, with the maximum electric and magnetic fields exceeding 6500
and 6100 times of the incident fields, respectively. The huge enhancement of electromagnetic fields may find potential applications in nonlinear optics and sensing [72, 73]. In Fig. 6b, there exist three relatively weak field enhancement bands parallel in the y-axis direction and a pronounced field hotspot at the center. Such a field distribution directly indicates the hybridization feature of SPPs and MD. The mixed mode at $\lambda_6$ has a broad bandwidth, which has more component of MD than SPP, as indicated in Fig. 6c and d.

Conclusions

In this work, we have numerically investigated the coupling effects of SPPs and MD resonances in metamaterials, which are composed of an Ag nanodisk array and a SiO$_2$ spacer on an Ag substrate. The near-field plasmon interactions between individual Ag nanodisks and the Ag substrate form MD resonances. The periodicity of the Ag nanodisk array leads to the excitation of SPPs at the surface of the Ag substrate. When the excitation wavelengths of SPPs are tuned to be close to the position of MD resonances by varying the array period of Ag nanodisks, SPPs and MD resonances are coupled together into two hybridized modes, whose positions can be accurately predicted by a coupling model of two oscillators. In the strong coupling regime of SPPs and MD resonances, the hybridized modes exhibit an obvious anti-crossing and, thus, result into an interesting phenomenon of Rabi splitting. At the same time, the magnetic fields under the Ag nanodisks are enhanced greatly, which may find some potential applications, such as magnetic nonlinearity.

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Authors’ Contributions

BL, CT, and JC contributed equally to this work. BL, CT, and JC did the calculations. CT and JC wrote the manuscript. All authors read and approved the final manuscript.

Competing Interests

The authors declare that they have no competing interests.

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