Robust switch effect based on surface plasmon resonance in magnetic metamaterials

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The optical characteristics of the magnetic metamaterial (MM) composed of the ferrite rods are theoretically investigated. Firstly, a photonic band-gap (PBG) resulting from the magnetic surface plasmon (MSP) resonance is recognized by observing the photonic band structure. Moreover, the PBG can be manipulated flexibly by using an external magnetic field (EMF). In particular, the effect is very roust against structural perturbations, which can be corroborated by examining the transmittances for a MM slab with different position disorders and size fluctuations. Based on this peculiar property, we design an electromagnetic switch with fast response, which is demonstrated by calculating the electric field patterns of a Gaussian beam incident on a MM slab.

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During recent decades, metamaterials, made up of diverse sub-wavelength building blocks, have attracted increasing interest due to the exotic properties such as negative refraction[1−5], subwavelength imaging[6,7], invisibility cloaking[8−10], and subwavelength propagation[11,12]. Particularly, for the metamaterials consisting of metals, the surface plasmon can be excited, which originates from the interaction between the surface free electrons oscillation and the light wave. Its magnetic counterpart, the magnetic surface plasmon (MSP)[13,14], arising from the coupling of an electromagnetic wave and the collective resonance of spin wave in magnetic metamaterial (MM), have been investigated recently for its potential applications in designing electromagnetic waveguide, integrated optical circuit, beam splitter and so on. More importantly, the MSP resonance can be modulated by adjusting an external magnetic field (EMF), which makes the designed devices more feasible in practical applications. Nevertheless, some underlying characteristics of the MSP are not revealed.

In this letter, by calculating the photonic band structures (PBSs) we have examined the electromagnetic properties of the MSP resonance induced photonic bandgap (PBG). Furthermore, by calculating the transmittances of a Gaussian beam incident on a MM slab with different disorders, it is shown that the tunability of this PBG is immune to both the position disorder and the size fluctuation of ferrite rods, which is illustrated from the simulations of electric field patterns as well. The results show that the incident Gaussian beam can be manipulated flexibly by a MM slab through tuning the EMF, suggesting that the MM slab can be used as an electromagnetic switch with fast response.

For definiteness, we consider a MM slab consisting of ferrite rods arranged periodically in air with all the axes of the rods along the z direction. The magnetic permeability of the fully magnetized ferrite rods is given by[15]

$$\widehat{\mu} = \mu_s \begin{pmatrix} \mu_r & -\mathrm{i}\mu_k & 0 \\ \mathrm{i}\mu_k & \mu_r & 0 \\ 0 & 0 & 1 \end{pmatrix}, \tag{1}$$

with

$$\mu_\kappa = \frac{\omega_m \omega}{(\omega_0 + \mathrm{i}\alpha\omega)^2 - \omega^2},$$

$$\mu_r = 1 + \frac{\omega_m(\omega_0 + \mathrm{i}\alpha\omega)}{(\omega_0 + \mathrm{i}\alpha\omega)^2 - \omega^2},$$

where $\omega_m = 2\pi f_m = 2\pi\gamma M_0$ is the characteristic frequency with the gyromagnetic ratio $\gamma = 2.8$ MHz/Oe, $M_0 = 1\,700$ Oe is the saturation magnetization along the z direction, $\omega_0 = 2\pi f_0 = 2\pi\gamma H_0$ is the spin wave resonance frequency with H_0 the sum of the EMF applied in the z direction and the shape anisotropy field. For the ferrite rods, the permittivity is $\varepsilon_s = 12.3 + \mathrm{i}6 \times 10^{-3}$ and the damping coefficient is $\alpha = 7 \times 10^{-3}$. In this letter, we only concentrate on the transverse magnetic (TM) Gaussian beam with its electric field polarized along the z direction while the ferrite materials do not take effect for the transverse electric beam.

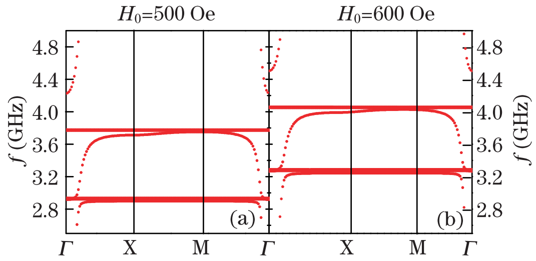

Fig. 1. PBSs for a periodic MM under the EMF (a) $H_0 = 500$ Oe and (b) $H_0 = 600$ Oe, respectively. The lattice constant of the MM is $a = 4$ mm and the radius of the ferrite rod is $r = 1$ mm.

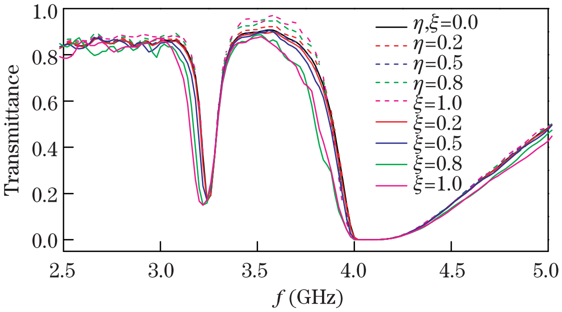

Fig. 2. Transmittances of a 5-layer MM slab under the EMF $H_0 = 600$ Oe and with the position disorder and size fluctuation characterized by η and ζ, respectively. The other parameters are the same as those in Fig. 1.

By employing the multiple scattering method[16], we first calculated the PBSs of a two-dimensional (2D) square lattice composed of ferrite rods under the EMF $H_0 = 500$ Oe and $H_0 = 600$ Oe as presented in Fig. 1(a) and (b), respectively, where $\varepsilon_s = 12.3$ and $\alpha = 0$, namely, the loss is neglected in order to find the eigenmodes of the periodic MM. In Fig. 1(a), it can be obviously observed that two groups of flat bands appear in the PBSs, indicating that two resonances are excited. Concretely, the one located at the higher frequency corresponds to the MSP resonance and the lower frequency one corresponds to the spin wave resonance, and the detailed explanation was mentioned in Ref. [14]. With the increase of the EMF from 500 to 600 Oe, the frequency of the MSP resonance shifts from 3.78 to 4.06 GHz, as illustrated in panel (b). Accordingly, the PBGs around the flat bands move upwards as well, which implies that the MSP resonance is very sensitive to the EMF. Therefore, we can manipulate the electromagnetic properties by tuning the MSP resonance with an EMF. In fact, at the higher frequency around 20 GHz there exists another PBG originating from the Bragg scattering, which is not presented in the PBSs because this PBG is very inert to the EMF and hardly tuned.

Next, we calculated the transmittances of a Gaussian beam incident normal to a MM slab for the cases when different degrees of position disorder and size fluctuation are considered. In Fig. 2, for different randomness η and ζ ranging from 0 to 1.0, we calculated the transmittances as the functions of frequency for a 5-layer MM slab under the EMF $H_0 = 600$ Oe. The MM slab without disorder corresponds to the case of $\eta, \zeta = 0$. Notably, it can be seen that the transmittances for different degrees of disorder bear resemblance to that without disorder. Compared with the results shown in Fig. 1(b), it can be found that the transmittances are consistent with the PBSs. Namely, the photonic bands correspond to the transmittances while the flat bands and PBGs correspond to the transmission gaps. Moreover, it can also be found that the lower frequency PBG arising from the spin wave resonance is much narrower than that induced from the MSP resonance. The persistence of the transmission gaps under different position disorders and size fluctuations suggests that the two types of PBGs originating from resonances are quite robust against the position disorders and the size fluctuations.

To examine the tunability of the MSP induced PBG, we have also simulated the electric field patterns when a TM Gaussian beam is incident normal to a 5-layer MM slab arranged periodically as a square lattice. The results are displayed in Figs. 3(a) and (b) for the MM slab under the EMF $H_0 = 500$ Oe and $H_0 = 600$ Oe, respectively, where the working frequency is $f = 3.8$ GHz, locating in the MSP resonance induced PBG under $H_0 = 500$ Oe as shown in Fig. 1(a). It can be observed that the incident Gaussian beam is forbidden to pass through the MM slab as presented in Fig. 3(a). However, by tuning the EMF to $H_0 = 600$ Oe, the working frequency lies in the photonic band as shown in Fig. 1(b). Hence, the Gaussian beam can propagate through the MM slab as illustrated in Fig. 3(b) with nearly no reflection. In addition, although there is a phase delay occurring in the MM slab, the field pattern is nearly not affected. As a consequence, the MM slab can be operated as a good

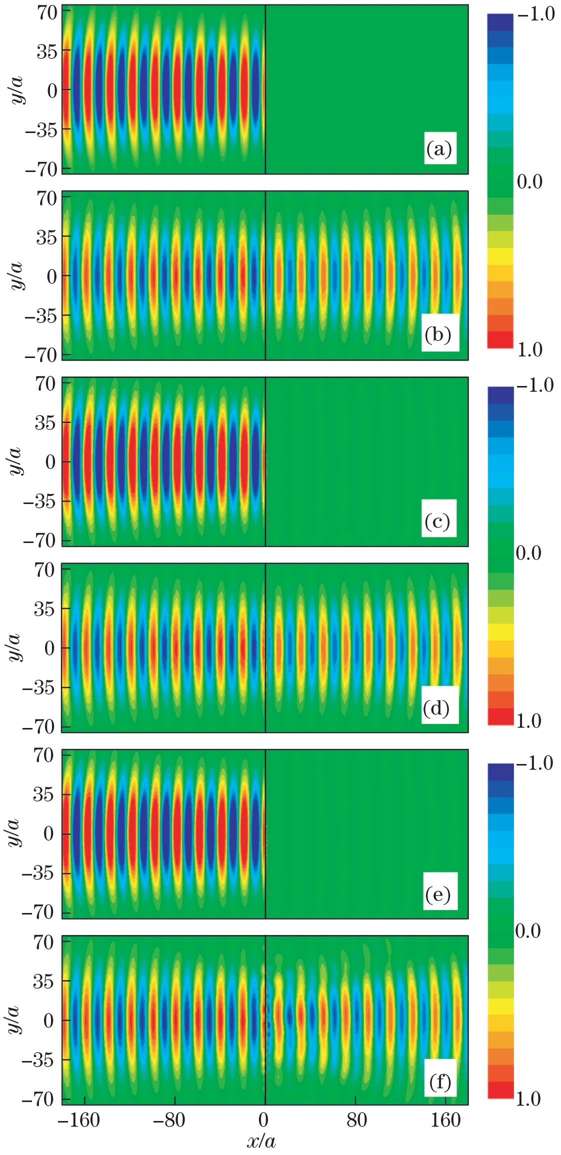

Fig. 3. Electric field patterns of a TM Gaussian beam incident on a periodic MM slab (a), (b); a MM slab with the position disorder $\eta = 0.5$ (c), (d); a MM slab with the size fluctuation $\zeta = 0.5$ (e), (f). The working frequency is $f = 3.8$ GHz, the EMF $H_0 = 500$ Oe for panels (a), (c), (e) and $H_0 = 600$ Oe for panels (b), (d), (f). All the other parameters are the same as those in Fig. 2.

electromagnetic switch. Besides, this switch possesses a fast response, which has already been corroborated by a previous experiment in Ref. [17].

In realistic situation, we expect that the switch effect is still workable when an external perturbation is involved. Therefore, we further examined the workability of the switch effect as the position disorder and size fluctuation of the ferrite rods are introduced in the MM slab. In the simulations, the position disorder and the size fluctuation are defined in Ref. [18]. Firstly, for a MM slab with the position disorder $\eta = 0.5$ operating at the working frequency $f = 3.8$ GHz and under the EMF $H_0 = 500$ Oe is simulated, the electric field pattern is displayed in Fig. 3(c) where no transmittance can be observed, suggesting the robustness of the switch effect against position disorder. With the increase of the EMF to $H_0 = 600$ Oe, the photonic gap is switched off so that the Gaussian beam can transport through the MM slab as presented in panel (d), where only a slight distortion of the field pattern can be found and most of the EM energy can pass through the MM slab. Besides, we also simulated the field pattern when the size fluctuation $\zeta = 0.5$ is introduced in the MM slab. In panel (e), a similar phenomenon with panel (c) is demonstrated. The PBG manifests its immunity against the size fluctuation by the persistence of PBG. By tuning the EMF to $H_0 = 600$ Oe, the MSP resonance induced PBG is switched off so that the Gaussian beam can propagate through the MM slab as illustrated in panel (f), where most of the EM energy can pass through the MM slab and the deformation of the Gaussian beam is also weak. Compared with Fig. 3(d), the size fluctuation is able to generate much stronger influence on the propagation of the EM wave. The above results imply that the MM slab can present a robust switch effect, which is a desirable aspect for the practical applications.

In conclusion, we calculate the PBSs of a MM under different EMFs, which indicate the MSP resonance induced PBG can be controlled by tuning an EMF. To examine the robustness, the transmittances for an MM slab with various disorders is also calculated, which is not only very robust against the structural perturbations but also in agreement with the PBSs. We simulate the electric field patterns of a TM Gaussian beam incident normal to a MM slab with different disorders, which clearly exhibit that the Gaussian beam can be manipulated by controlling the EMF. The results confirm the robustness of the tunability once again. Therefore, the MM slab can be used as an electromagnetic switch.

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