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Effects of magnetic anisotropy on the stop band of ferromagnetic electromagnetic band gap materials

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Abstract
We have studied the transmission properties of two-dimensional (2D) ferrite electromagnetic band gap (EBG) materials under a static applied magnetic field by the multiple-scattering method and experiments. We find remarkable changes in the stop-band of the ferrite EBG due to magnetic anisotropy, which can be correctly predicted by the multiple-scattering method. Both the calculated and the experimental results confirm that the stop-band of magnetized 2D ferrite EBG structures can be tuned by the applied static magnetic field for radiations in the transverse magnetic mode.

1. Introduction

Electromagnetic band gap materials (EBGs) or photonic band gap materials (PBGs) are periodic structures which possess a stop-band in their electromagnetic transmission spectra [1, 2]. The increasing interest in EBGs arises from their extraordinary properties such as suppression of spontaneous emission [1], a complete stop-band [3], negative refraction [4] and also their possible applications, e.g. in optical switches, filters, resonators and substrates for microwave devices [3]. Up to now, most research has concentrated on PBGs consisting of dielectrics or metals [1–4]. PBGs made of magnetic materials have not attracted much attention since the relative permeability of most magnetic materials is equal to unity in the optical frequency range. However, at microwave or radio frequencies many ferromagnetic materials, like ferrites, have permeabilities that are quite different from unity and they can be exploited in magnetic EBGs. Some work has been done on magnetic EBGs [5–7]. Sigalas *et al* have investigated the effects of isotropic magnetic permeability on the band structure of EBGs [6]. To lower the magnetic loss, magnetic materials are usually operated in a magnetized state. Under this condition, the magnetic permeability is anisotropic and depends on the saturation magnetization of the material, the working frequency and the applied static magnetic field. Therefore, the band gap of magnetic EBGs could be tuned by the applied

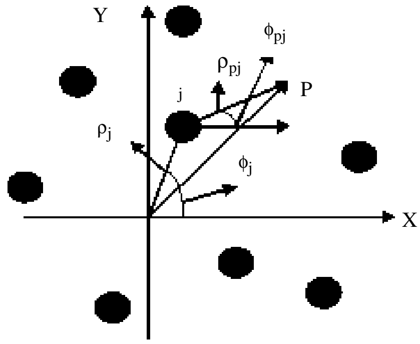

Figure 1. General calculation model of a 2D cylinder EBG structure.

field. Kee *et al* theoretically studied the effect of magnetization on the band structure of two-dimensional (2D) ferrite EBGs using the plane wave expansion method, where the magnetized ferrite is modelled by an equivalent isotropic magnetic medium [7]. For bulk ferrites, equivalent isotropic magnetic models are widely used when the ferrites are magnetized. However, for EBG structures, in order to satisfy the electromagnetic boundary condition at the interface of the ferrite and the dielectric matrix, the equivalent isotropic magnetic model should be modified. Therefore, for magnetized magnetic EBGs it may be difficult to obtain the band structure using the general plane wave expansion method. In order to study the band gap of magnetized ferrite EBGs, other methods such as the multiple-scattering method (MSM) [8–10] or the finite-difference time-domain (FDTD) method [11] could be used. A previous study has shown that for 2D EBG structures the MSM is more efficient than the FDTD method, for example the computation time of MSM for the field distribution is much shorter than that of FDTD [12].

In this paper, using the multiple-scattering method, we have investigated the effects of magnetic anisotropy of 2D ferrite EBGs on their transmission properties. We find that the magnetic anisotropy can greatly change the stop-band of the ferrite EBG. To verify the calculation results, an EBG sample made of ferrite rods has been fabricated and its transmission spectra have been measured. The results of the experiments and the MSM calculations are in good agreement.

2. Theory

The multiple-scattering method has already been described in detail elsewhere [8, 9], and here we will briefly review the MSM for a set of parallel cylinders illuminated by a plane wave. Figure 1 shows the general calculation model of a 2D EBG structure, where N parallel cylinders are embedded in a homogeneous dielectric matrix and the cylinders are assumed infinite long along the z direction. The total field at the point p outside the cylinder j can be written as the sum of the incident and the scattered fields with a Fourier–Bessel expansion:

$$E^{\mathrm{Total}} = \sum_m [\alpha_m(j) J_m(k_0\rho_{pj}) + B_m(j) H_m^{(2)}(k_0\rho_{pj})] \mathrm{e}^{\mathrm{i}m\phi_{pj}}$$

$$= \sum_m \alpha_m^0(j) J_m(k_0\rho_{pj}) \exp[\mathrm{i}m\phi_{pj}] + \sum_{j=1}^{N}\sum_m B_m(j) H_m^{(2)}(k_0\rho_{pj}) \exp[\mathrm{i}m\phi_{pj}] \quad (1)$$

where $\vec{\rho}_{pj} = \vec{\rho}_p - \vec{\rho}_j = (\rho_{pj}, \phi_{pj})$, k_0 is the wavenumber in the background material, and $J_m(x)$ and $H_m^{(2)}(x)$ are respectively the Bessel function of the first kind and the Hankel function of the second kind. The $\alpha_m(j)$ and $B_m(j)$ are, respectively, the coefficients of the local incident field and the scattering field, which are linked by

$$B_m(j) = D_m(j)\alpha_m(j) \tag{2}$$

where $D_m(j)$ is the scattering coefficient of each cylinder. According to equation (1), the coefficient $\alpha_m(j)$ can be written as the sum of the external incident field coefficient $\alpha_m^0(j)$ and the coefficients of the scattered field from other cylinders that depend linearly on $B_q(l)$. Then from equation (2) we can obtain a self-consistent equation for $B_m(j)$ [8]. From the solution of this linear equation, we can calculate the total field at the point p. And then the power transmission spectrum of the EBGs can be obtained from the Poynting vector [13].

The scattering coefficient $D_m(j)$ of each ferrite cylinder is determined by its scattering properties, and has been studied in previous works [14, 15]. For fully magnetized ferrite rods, if the static magnetic field is applied along its axis, the relative magnetic permeability, according to the Landau–Lifshitz model [16], is a tensor

$$\overleftrightarrow{\mu_r} = \begin{bmatrix} \mu & \mathrm{j}k & 0 \\ -\mathrm{j}k & \mu & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{3}$$

where

$$\mu = 1 + \frac{\omega_m(\omega_0 + \mathrm{j}\alpha\omega)}{(\omega_0 + \mathrm{j}\alpha\omega)^2 - \omega^2} \tag{4a}$$

$$k = \frac{\omega_m \omega}{(\omega_0 + \mathrm{j}\alpha\omega)^2 - \omega^2} \tag{4b}$$

where $\omega_0 = \gamma H_0$ is the ferromagnetic resonance frequency, γ is the gyromagnetic ratio, H_0 is the static applied magnetic field, $\omega_m = 4\pi\gamma M_{\mathrm{s}}$ is the characteristic frequency of the ferrites, M_{s} is the saturation magnetization and α is the damping coefficient. Supposing the propagation direction of the radiation is perpendicular to the applied magnetic field, there are two independent eigen-modes for the incident radiation. The first case is the TE_z mode, in which the magnetic field of the radiation is parallel to the applied magnetic field. In this case, the alternating magnetic field does not interact with the aligned magnetic dipole moments and the tensor permeability degenerates to the scalar unity. Therefore, 2D ferrite EBGs are the same as 2D dielectric EBGs. The second is the TM_z mode, in which the magnetic field of the incident wave is perpendicular to the applied field. For this mode, the magnetic field will interact with the precessing magnetic dipoles of the ferrite so that the ferrite EBGs are quite different from the dielectric EBGs. Using the continuity of the tangential electric E_z and magnetic field H_ϕ at the interface of the ferrite rods and the dielectric matrix

$$E_z^{\mathrm{inc}}\Big|_{\rho=r_j} + E_z^{\mathrm{scat}}\Big|_{\rho=r_j} = E_z^{\mathrm{ferr}}\Big|_{\rho=r_j} \tag{5a}$$

$$H_\phi^{\mathrm{inc}}\Big|_{\rho=r_j} + H_\phi^{\mathrm{scat}}\Big|_{\rho=r_j} = H_\phi^{\mathrm{ferr}}\Big|_{\rho=r_j} \tag{5b}$$

we have scattering coefficient

$$D_m(j) = \frac{C_m(k_2r_j)J_m(k_0r_j) - J_m'(k_0r_j)J_m(k_2r_j)}{H_m^{(2)\prime}(k_0r_j)J_m(k_2r_j) - C_m(k_2r_j)H_m^{(2)}(k_0r_j)} \tag{6}$$

where

$$C_m(k_2r_j) = \frac{\mu_0}{\mu_{\mathrm{eff}}}\frac{k_2}{k_0}\left[J_m'(k_2r_j) - \frac{k}{\mu}\frac{n}{k_2r_j}J_m(k_2r_j)\right] \tag{7a}$$

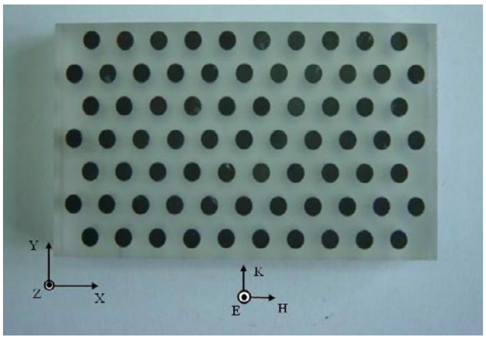

Figure 2. 2D hexagonal lattice magnetic EBG sample made of Mg–Mn ferrite cylinders and a Plexiglas substrate.

(This figure is in colour only in the electronic version)

$$\mu_{\mathrm{eff}} = \frac{\mu^2 - k^2}{\mu}. \tag{7b}$$

$$k_2^2 = \omega^2 \mu_{\mathrm{eff}} \varepsilon_2 \tag{7c}$$

where ε_2 is the permittivity of the ferrite.

3. Experiments

In order to validate the numerical results of the MSM, we designed and fabricated the 2D EBG sample with Mg–Mn ferrite rods. The ferrite has a complex relative permittivity of about $\varepsilon_2 = 12.3$–j0.006, a saturation magnetization $4\pi M_s = 2200$ G and a damping coefficient of about $\alpha = 0.007$. The sample has a hexagonal lattice with the lattice constant $a = 8$ mm as shown in figure 2. The ferrite rods with radius $r = 2$ mm are inserted into a Plexiglas substrate with a relative permittivity of about $\varepsilon_1 = 2.6$–j0.005.

Measurement of the transmission coefficient of the sample is carried out in a parallel plate waveguide. The sample is placed in the middle of the waveguide, and the transmission spectrum is automatically measured by the Agilent vector network analyser E8363A. Figure 2 shows the wave polarization direction of the incident plane wave in Cartesian coordinates. In order to investigate the effects of magnetic anisotropy on the stop-band, a uniform static magnetic field is applied on the EBG sample, which is provided by a Helmholtz coil. The field direction is parallel to the z-axis that is along the direction of the cylinder axis, and perpendicular to the direction of the magnetic field and wavevector $\vec{k}$ of the incident radiation. The experimental set-up supports the TM_z propagation mode in the EBG sample.

4. Results and discussion

With the multiple-scattering method, we first calculated the transmission coefficients of the sample under an applied magnetic field H_0 and compared them with the experimental results. Figure 3 shows the calculated and the measured results under an applied field $H_0 = 800$ Oe. Comparing the results, we can see that the numerical results using tensor permeability are in good agreement with the experimental results. This demonstrates that MSM can be used to correctly predict the band gap of anisotropic magnetic EBGs.

To simplify the analysis, some work has used an equivalent isotropic magnetic permeability μ_{eff} to model the magnetic anisotropy of ferrite EBGs [7]. The magnetized ferrite

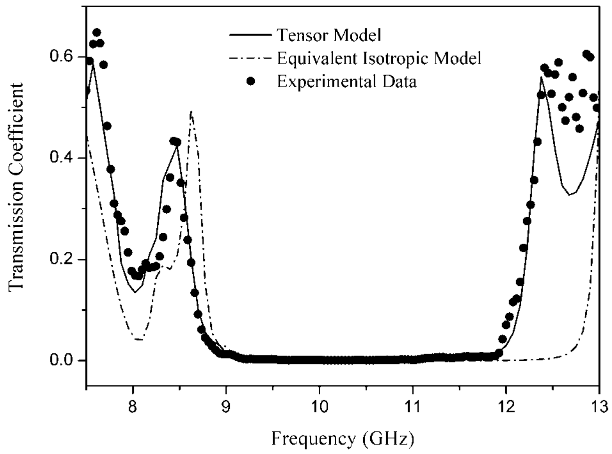

Figure 3. The measured and calculated transmission spectrum of a 2D hexagonal EBG sample at $H_0 = 800$ Oe.

is considered as an isotropic medium with the equivalent permeability which is related to the working modes. For the TM_z mode, the equivalent permeability is the same as equation (7*b*). Following this model, we also calculated the transmission spectrum of the sample. The results are shown in figure 3 by a dot–dashed lines. Though the lower frequency of the stop-band is about the same as in the experiments, the upper frequency deviates greatly from the measured results. The great differences in the stop-band width between the experimental results and the calculated results indicate that the magnetic anisotropy of the ferrite EBG structures cannot be simply modelled by an equivalent isotopic magnetic medium.

As shown in equation (4), the degree of magnetic anisotropy of the ferrite changes with intensity of the applied magnetic field. This in turn will be reflected in the stop-band of the sample. The measured and calculated transmission spectra under applied fields $H_0 = 200$, 400 and 800 Oe are plotted in figure 4. Comparing the figures, we find that the stop-bands shift to higher frequencies when the applied magnetic field increases. Good agreement between the experimental and numerical results with the MSM can also be found. Since the magnetic fields provided by the Helmholtz coils in our experiment are less than 1000 Oe, the frequency shift of the stop-band is about 300 MHz and the relative frequency shift is only about 3%. If we can increase the applied magnetic field further, we can find that not only does the stop-band shift to higher frequencies but also the stop-band width decreases. Figure 5 plots the top and bottom frequencies of the sample with applied magnetic field H_0 from 200 to 1600 Oe, which are determined from the calculated transmission curves with magnitude −20 dB. We can find that the rate of frequency shift with applied magnetic field is different for the top and the bottom frequencies. For the lower applied fields, the shift rate for the top and bottom frequencies is almost the same, as verified by our experiment results shown in figure 4. However, for the higher fields, the shift rate for the bottom frequency is higher than that of the top frequency, consequently the magnetic EBGs shows a stop-band shift to a higher frequency together with a decrease of bandwidth. This phenomenon is quite different from the result of [7] and is caused by the magnetic anisotropy. Nevertheless, our experimental and numerical results confirm the previous theoretical prediction of [7] that the stop-band of ferrite EBGs can be tuned by the applied magnetic field.

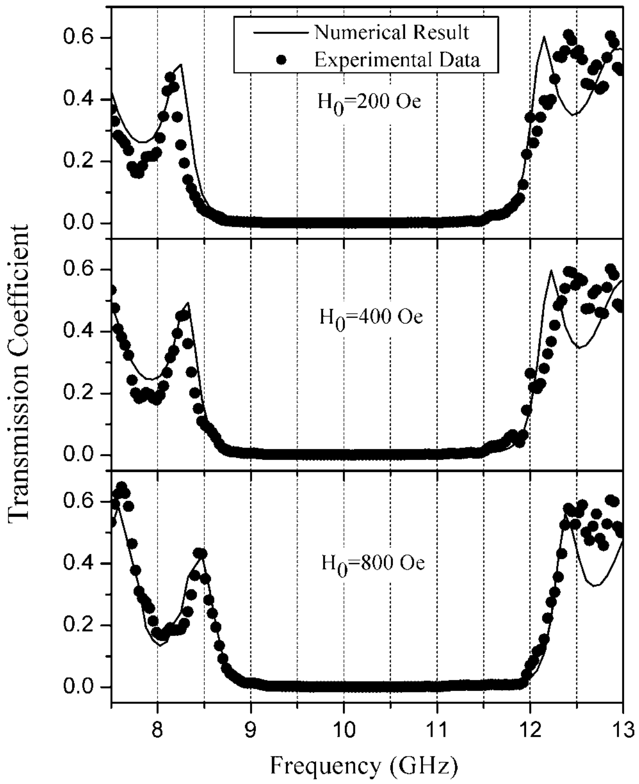

Figure 4. Measured and calculated (using tensor permeability) transmission spectra of the ferrite EBG sample under applied magnetic fields of $H_0 = 200$, 400 and 800 Oe, respectively.

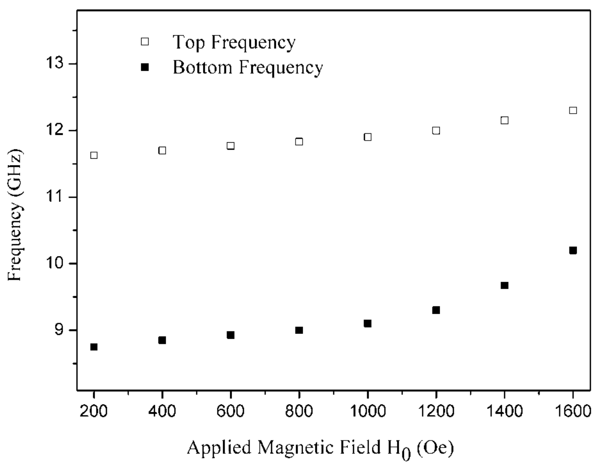

Figure 5. The numerical results for the top and bottom frequencies of EBGs with applied magnetic field H_0 from 200 to 1600 Oe.

5. Conclusion

In conclusion, we have studied the transmission spectrums of 2D ferrite EBGs by means of the multiple-scattering method and experiments. The results demonstrate that the stop-band and its frequency shift of magnetized EBGs can be correctly predicted by the multiple-scattering method. Both the experiments and calculations confirm that the stop-band in the TM_z mode can be tuned by the applied magnetic field, due to the dependence of the elements of tensor permeability of the ferrite on the applied field. We have pointed out that the magnetic anisotropy of magnetized ferrites in EBGs cannot be simply modelled by an effective isotropic permeability as is commonly done for bulk materials in a magnetized state

Acknowledgments

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