Enhanced transmission and giant Faraday effect in magnetic metal–dielectric photonic structures

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Abstract

Due to their large electrical conductivity, stand-alone metallic films are highly reflective at microwave (MW) frequencies. For this reason, it is nearly impossible to observe Faraday rotation in ferromagnetic metal layers, even in films just tens of nanometres thick. Here, we show using numerical simulations that a stack of cobalt nano-layers interlaced between dielectric layers can become highly transmissive and display a large Faraday rotation in a finite frequency band. A 45° Faraday rotation commonly used in MW isolators can be achieved with ferromagnetic metallic layers as thin as tens of nanometres.

(Some figures may appear in colour only in the online journal)

1. Introduction

Magnetic materials are of great importance to microwave (MW) engineering and optics due to their nonreciprocal properties, such as the Faraday and Kerr effects (see, e.g. [1, 2] and references therein). These are utilized in various nonreciprocal devices including isolators, circulators, phase shifters, etc. The functionalities of these devices stem from the intrinsic gyrotropy of their magnetic components, such as ferrites and other magnetically polarized materials, in which left and right circularly polarized waves experience nonreciprocal differential attenuation and/or phase shifts. When the magnetic component is introduced in a photonic crystal, the nonreciprocal response can be significantly enhanced at a resonance with the periodic or nearly periodic photonic structure [3, 4]. A noticeable enhancement of the magneto-optical Faraday effect was observed in magnetic thin-film layers sandwiched between Bragg reflectors [5–7], periodic magnetophotonic (MP) layer stacks [8, 9] and other MP structures supporting slow and localized modes [10]. The enhancement of the Faraday rotation, however, was accompanied by a significant decrease in the optical transmittance [5–10]. Although it has been shown that transmittance can be improved by minimizing reflectance in MP structures incorporating multiple defects [4, 11, 12], the output can still be severely affected by absorption losses [13, 14]. This limitation stems from the fact that at optical frequencies, both the nonreciprocal response and photon absorption are governed by the permittivity tensor of the magneto-optical material [2]. Thus, any significant enhancement of the Faraday effect is accompanied by the same enhancement of absorption losses.

At MW frequencies, on the other hand, the nonreciprocal response is usually associated with the magnetic permeability tensor, whereas absorption is often caused by electric conductivity of the magnetic material. This implies that the magnetic component of the electromagnetic wave is responsible for the nonreciprocal effects while the electric component for the losses. In this case, the magnetic Faraday effect might be significantly enhanced while drastically reducing the absorption losses [16]. In fact, at the transmission resonance, the nodes of the electric field component coincide with the antinodes of the magnetic field component and vice versa, as shown in figure 1. When conducting magnetic
layers are positioned at the nodes (antinodes) of the electric (magnetic) field, the MP response is enhanced and absorption is suppressed simultaneously.

We remark that the nodes and antinodes of the electric and magnetic components of the electromagnetic wave are only well-defined at high-$Q$ transmission resonances. In addition, the magnetic layer should be thin enough to fit in the electric field node. Otherwise, the absorption suppression will not be significant and the Faraday rotation enhancement will be compromised. To meet the above conditions, one has to utilize magnetic materials with exceptionally strong circular birefringence, such as ferromagnetic metals (e.g. iron and cobalt). However, stand-alone metallic layers are highly reflective at MW frequencies due to their large electric conductivity. For this reason, it is nearly impossible to observe Faraday rotation in ferromagnetic metal layers, even in films just tens of nanometres thick. In this work, we use numerical simulations to demonstrate that a stack of cobalt nano-layers interlaced between dielectric layers can become highly transmissive and display a large Faraday rotation, simultaneously. The Faraday rotation can be controlled with the cobalt thickness and bias magnetic field. The optimized structures produce a 45° Faraday rotation commonly used in MW isolators. We also consider coupled-resonance MP structures in which high transmission and large Faraday rotation can be achieved over a finite frequency band.

2. Magnetic metal–dielectric photonic structures

MP structures that are studied here are constructed as the following. We consider 1D MW photonic crystals consisting of layers of alumina ($H$) and air ($L$) of dielectric constants $\epsilon_H = 10$ and $\epsilon_L = 1$, respectively, and magnetic permeability $\mu = 1$. Since alumina and air have negligible absorbing at MW frequencies, we take them to be lossless in our numerical simulations. The dielectric layers have quarter-wave thicknesses $d_j = n_0/4\sqrt{\epsilon_j}$, for $j = H, L$, at the wavelength $\lambda_0 = 4\text{ cm}$ corresponding to the midgap frequency $f_0 = 7.5\text{ GHz}$ of the quarter-wave layer stack. Starting with a periodic stack $H L H \ldots L$ of $M = 2N + 1$ unit cells ($N$ is a positive integer), we add layer $H$ at the end of the stack and remove the middle layer $L$, to construct a symmetric layer stack with a central half-wave defect. The resulting structure is designated $N : N$ (figure 1 depicts 3 : 3 structure). The half-wave defect introduces a pair of polarization-degenerate localized states at the midgap frequency $f_0$. The spatial profiles of the electric and magnetic field amplitudes of the localized mode of the 3 : 3 structure are shown in figure 1. Whereas the electric field is seen to have a node at the middle of the defect, the magnetic field is sharply peaked at the same position. The MP structure $NCN$ is then constructed by inserting a cobalt (C) layer in the node of the electric field at the middle of the defect. We also consider periodic arrangements with multiple defects ($N : M : N$, $N : M : M : N$, etc) and multiple cobalt layers ($NMCN$, $NCMCN$, etc).

The MW permittivity of cobalt is large and almost purely imaginary, $\epsilon_C \approx 14\pi\sigma_C/\omega$, where $\omega$ is the angular frequency, and the electric conductivity of cobalt is $\sigma_C = 1.44 \times 10^{17} \text{ s}^{-1}$ [17]. Stand-alone metallic layers are highly reflective to MW radiation even at thicknesses far less than the skin depth, due to multiple reflections in the metallic layer [18]. The MW transmittance of a cobalt layer of thickness $d_C$ at frequencies not too close to the ferromagnetic resonance can be approximated by $T \approx (1 + 2\pi d_C\sigma_C/\omega)^{-2}$, where $\sigma_C$ is the speed of light. For example, for $d_C = 33\text{ nm}$, $T \approx 10^{-4}$.

The MW permeability of cobalt is described by the Polder permeability tensor [19]. We assume that a static uniform magnetic field is applied perpendicular to the cobalt layer along the $z$-axis, $\mathbf{b} = \hat{z}b_0$.

\begin{align}
\hat{\mu} &= \begin{pmatrix}
\mu & i\kappa & 0 \\
-i\kappa & \mu & 0 \\
0 & 0 & 1
\end{pmatrix},
\end{align}

with the elements [15]

\begin{align}
\mu &= 1 + \frac{\omega_M(\omega_H + i\omega)}{(\omega_H + i\omega)^2 - \omega_C^2}, \\
\kappa &= \frac{\omega_M^2\omega}{(\omega_H + i\omega)^2 - \omega_C^2},
\end{align}

where $\omega_H = \gamma H$, $\omega_M = \gamma 4\pi M$, $\gamma/2\pi = 2.8\text{ GHz/kOe}$ is the gyromagnetic ratio, and $\alpha$ is the dissipation parameter. Here we use the parameters of bulk cobalt [20], $4\pi M = 17900\text{ G}$ and $\alpha = 0.027$. The actual conductivity and saturation magnetization of ferromagnetic cobalt nano-layers may be
considerably lower than the above values, depending on their fabrication conditions.

The nonreciprocity of cobalt is determined via the off-diagonal elements of the permeability tensor. One can show that for circularly polarized waves the permeability tensor becomes diagonal with the effective permeabilities

\[ \mu_\pm = \mu \pm \kappa = 1 + \frac{\omega_M}{\omega_H + i \alpha \omega - \omega}, \]

where the resonant behaviour occurs only for the right (+) circularly polarized wave. For \( \alpha \ll 1 \), the imaginary part of \( \mu_+ \), which is responsible for magnetic losses, is important only in the vicinity near the ferromagnetic resonance, \( \omega^2_H = (1 + \alpha^2)\omega^2 \), where it develops a steep maximum [21]. On the other hand, the real part of \( \kappa \) is responsible for magnetic circular birefringence, remains considerable even far from resonance where it can be approximated as \( \kappa' \approx \omega_M \omega/(\omega_H - \omega^2) \).

We consider a linearly polarized MW field normally incident on MP structures. Designating the incident, reflected and transmitted electric field components by \( E_i, E_r \) and \( E_t \), respectively, we define the complex reflection and transmission coefficients of the MP structure, \( \rho = |\rho| \exp(i\phi) \) and \( \tau = |\tau| \exp(i\phi) \), by \( E_r = \rho E_i \) and \( E_t = \tau E_i \). The reflectance \( R \) and transmittance \( T \) are given by \( R = |\rho|^2 \) and \( T = |\tau|^2 \), and the absorbance \( A \) is \( A = 1 - R - T \). Since the linearly polarized incident wave can be considered as composed of two circularly polarized components of equal amplitude, the reflected and transmitted waves are in general elliptically polarized due to the difference in the permeabilities \( \mu_+ \) and \( \mu_- \) of equation (3). For the transmitted wave, the Faraday rotation of the plane of polarization of the wave relative to the incident polarization is \( \theta_{FR} = (\phi_+ - \phi_-)/2 \), and the Faraday ellipticity is \( \epsilon_F = (|\tau_+|^2 - |\tau_-|^2)/(|\tau_+|^2 + |\tau_-|^2) \) [22]. The transfer-matrix method is used to calculate the variation of \( \rho \) and \( \tau \) with wave frequency \( f \), cobalt thickness \( d_C \) and magnetic field \( H_i \).

3. Results and discussion

The frequency response of the 3C3 structure in the vicinity of the transmission resonance as a function of detuning \( \delta f = f - f_0 \) is presented in figure 2. The transmission of linearly polarized incident wave (solid blue line) can be decomposed into the sum of two components, \( |\tau_+|^2 \) and \( |\tau_-|^2 \), shown in figure 2(a) by dash-dotted and broken lines, respectively. The splitting of the transmission resonance into two peaks is caused by the difference in the magnetic permeability for the left and right circularly polarized waves propagating in the direction of \( M \). The amount of the splitting depends on the cobalt thickness \( d_C \) and the magnetic field \( H_i \). It increases with increasing \( d_C \) and as \( H_i \) approaches the resonance field, \( 2\pi f_0/\gamma \). In the vicinity of the resonance peak, the transmission phase \( \phi_+ \) and \( \phi_- \), shown in figure 2(b) by the dash-dotted and broken lines, respectively) increases by \( \pi \), so that the Faraday rotation \( \theta_{FR} \) (shown by solid black line) has a maximum at \( \delta f = 0 \). Note that the pure Faraday rotation of linearly polarized wave, i.e. with no wave ellipticity, occurs when \( |\tau_+| = |\tau_-| \), and thus falls between the resonance peaks.

![Figure 2](image-url)

**Figure 2.** Frequency response of 3C3 structure (3 : 3 structure with a cobalt layer added into the defect) to a linearly polarized, normally incident MW field. Upper panel: transmittance, \( T \), (blue), reflectance, \( R \), (black) and absorbance, \( A \), (red) are plotted versus the detuning \( \delta f \) from the midgap frequency \( f_0 = 7.5 \) GHz, left and right circularly polarized transmission contributions, \( |\tau_+|^2 \) (dash-dotted line) and \( |\tau_-|^2 \) (broken line). Lower panel: phase spectra of the circularly polarized components, \( \phi_+ \) (dash-dotted) and \( \phi_- \) (broken), and Faraday rotation, \( \theta_{FR} = (\phi_+ - \phi_-)/2 \). The 3C3 structure was optimized for a pure 45° Faraday rotation with \( d_C = 180 \) nm and \( H_i = 0.1 \) kOe.

The 3C3 structure can be optimized for the pure 45° Faraday rotation by adjusting the separation of the resonance peaks with a proper combination of \( d_C \) and \( H_i \). A \( \pi/2 \)-phase difference occurs at the midpoint between the two resonances at which \( |\tau_+| = |\tau_-| \) when the resonance separation is equal to the FWHM of the resonance. In figure 2, the 3C3 structure is optimized for a pure 45° Faraday rotation with \( d_C = 180 \) nm and \( H_i = 0.1 \) kOe. The corresponding transmittance \( T_{45°} \) is 0.46, which is only slightly below \( T_{45°} = 0.5 \) for the case of no absorption. The absorbance and reflectance are shown in figure 2(a).

For NCN structures, there is a range of combinations of \( d_C \) and \( H_i \) for the pure 45° Faraday rotation. A few such combinations with corresponding values of \( T_{45°} \) are shown in figure 3 for \( N = 2 \) (circles), \( N = 3 \) (squares) and \( N = 4 \) (triangles). Except for \( N = 2 \), high values of \( T_{45°} \) occur both above and below the resonant field, \( 2\pi f_0/\gamma = 2.68 \) kOe, at which \( T_{45°} \) vanishes due to magnetic circular dichroism. Note that in figure 3 suitable values of the cobalt thickness \( d_C \)
differ by orders of magnitude for different \( N \), falling to tens of nanometres for \( N = 4 \).

The periodic arrangements with multiple defects, \( N : M : N, \ N : M : M : N, \) etc., can be considered as a superlattice of \( N : N \) structures coupled via phase-matching air layers, or coupled-resonance structures (CRSs) (see \[23\]). As a result of the coupling, the eigenmodes of individual \( N : N \) structures split into a miniband of polarization-degenerate localized states centred at the midgap frequency \( f_0 \) of the \( N : N \) structure. The miniband width depends on the coupling strength, and thus on \( N \). One of the most important properties of CRS is that the dispersion relation and transmission spectrum for a moderate number of unit cells of the superlattice can be optimized to closely approximate that of the infinite CRS \[24, 25\]. As a result, the transmission phase via a finite-size CRS exhibits a smooth increase through a finite and high transmission miniband summing up to a total phase shift equal to the number of half-wave defects in the structure multiplied by \( \pi \) \[25\]. When magnetic layers are introduced into the finite-size CRS, it is possible to achieve a uniform Faraday rotation in a finite and high transmission miniband.

The frequency response of the 3C7C3 structure (2-unit cell CRS) is presented in figure 4. As in the 3C3 structure, the cobalt layers lift the polarization degeneracy of localized modes, resulting in splitting of transmission resonances for \( |\tau_+|^2 \) and \( |\tau_-|^2 \) (figure 4(a)). In contrast to the 3C3 structure, however, each of the two resonances represents a band of two overlapping localized modes. The transmission phases \( \phi_+ \) and \( \phi_- \) increase by \( 2\pi \) through the resonances (figure 4(b)), and the pure 45° Faraday rotation can be achieved with a smaller resonance separation (note the different scales on the frequency axes in figures 2 and 4). This, in turn, leads to a significantly higher transmittance, \( T_{45^\circ} = 0.82 \), as compared to the 3C3 structure. The results of figure 4 are obtained with \( d_C = 70 \) nm and \( H_I = 0.1 \) kOe. We note that a wider and higher transmission miniband of the pure 45° Faraday rotation can be obtained with a larger number of unit cells of the CRS.

We have so far considered the case of normal incidence of a plane electromagnetic wave on layered structures with mirror plane symmetry. In the case of oblique incidence, while the results for TE and TM polarized waves are quantitatively different, they remain qualitatively similar to that of the case of normal incidence. The only difference is a blue shift of the transmission resonance, which increases with the angle of incidence. If the incident wave frequency is fixed and equal to that of the transmission resonance at normal incidence, the entire layered structure of figure 1 acts as a collimator reflecting obliquely incident waves and transmitting normally incident wave, while rotating its polarization. If the layered structure does not possess the mirror plane symmetry, the results can be quite different. The latter problem, as well as the entire case of oblique incidence, will be the subject of a separate study.

4. Conclusion

In this paper we have demonstrated that a properly designed magnetic metal–dielectric photonic structure can not only become highly transmissive at microwave frequencies, but it can also produce a large Faraday rotation. Remarkably, the same metallic ferromagnetic layer taken out of the layered structure is neither transmissive, nor does it produce any measurable Faraday rotation. Strong Faraday rotation in combination with a high transmission is achieved by placing ferromagnetic metallic nano-layer in a node of the electric field component of the quasi-localized electromagnetic mode of
the layered structure, which results in simultaneous reduction of the Ohmic losses (by up to 6 orders of magnitude) and enhancement of the magnetic Faraday rotation (by up to 2 orders of magnitude). This approach can be utilized for any lossy magnetic material of considerable magnetic gyrotropy, provided that the gyrotropy is predominantly associated with the permeability tensor, while the losses are caused by the electric conductivity. Such magnetic materials are readily available at MW frequencies. Some examples can also be found at higher frequencies, including far infrared [26]. At optical frequencies, however, most of the known magneto-optical materials have the magnetic permeability close to unity. Using the example of ferromagnetic cobalt, we demonstrated that a 45° Faraday rotation and high transmission in a finite frequency band can be obtained with metallic layers as thin as tens of nanometres. These results suggest that photonic structures involving conducting ferro- or ferrimagnetic components can be used in various nonreciprocal photonic devices from MWs to far infrared.

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