Enhanced electromagnetic wave transmission and Faraday rotation of a ferromagnetic metal layer embedded in dielectric slab

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Abstract

We report microwave measurements and numerical calculations of the electrodynamic properties of a cobalt layer embedded in dielectric slabs. We observe enhanced (up to 3 orders of magnitude) transmission and Faraday rotation as compared to that of the cobalt layer, suggesting its important applications in photonics.

Magnetic materials are of great importance in optics and microwave technology due to their nonreciprocal properties, such as magnetic Faraday rotation, linear magnetoelectric response, etc. They are employed in various microwave and optical devices, including isolators, circulators, phase shifters, etc. They can also provide tunability, miniaturization, better impedance matching and other important features. A major obstacle for their broader applications, however, is their significant electromagnetic losses. Many magnetic materials with otherwise excellent physical characteristics are completely ignored because of their strong absorption.

Recently, magnetic photonic crystals, that are periodic assemblies with a component being a ferrite or a ferromagnet, have been shown to allow for a significant reduction of electromagnetic losses as compared to homogeneous samples of the same lossy magnetic materials [1]. The loss suppression mechanism is due to a specific electromagnetic field distribution inside the magnetic photonic crystal, suppressing the energy dissipation by the lossy magnetic component, while preserving or even enhancing its useful properties.

In this work, we employ essentially similar approach to achieve strong microwave transmission and enhanced Faraday rotation in a ferromagnetic metal layer embedded in dielectric slabs. We utilize a thin cobalt layer and investigate the two structures: the cobalt layer sandwiched between two identical dielectric layers, and the cobalt layer embedded at the middle of a binary periodic dielectric structure. In the former, we utilize the electromagnetic field distribution of Fabry-Perot resonance of the dielectric slab; in the latter, the electromagnetic field distribution of a “defect state” at the middle of the photonic crystal. The parameters of the structures studied are the following. A 276-nm cobalt film was RF-sputtered on a 0.510 mm glass wafer; an identical glass layer was added to provide symmetry of the structure, i.e., glass-cobalt-glass (G-Co-G). Cobalt film conductivity of 4.245×10^{15} Hz was measured. Dielectric layers were of 99.6% alumina with a permittivity of 9.8 and were approximately 4.19 mm thick. For the periodic structure, air layers were included by the use of 4.15 mm spacers. All samples were 15 cm in diameter.

1. Setup

The structures were positioned in the bore of a DC magnet, and microwave transmission measurements of the structures were made with and without magnetic field. The bore was furnished with microwave absorbent and capped with two identical microwave antennae. The field measurements were carried out in the frequency range of 4.5-8.5 GHz with the use of a network analyzer. The microwave transmission was measured first through the G-Co-G structure, and then though G-Co-G structure

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sandwiched between two alumina layers and embedded in the periodic structure. Then, transmission measurements were taken for each structure, when an external magnetic field was applied.

2. Results

Figure 1 shows microwave transmission in a zero magnetic field. The cobalt film (top panel, blue curve) is seen to provide -30dB transmission due to its reflection and absorption. The "sandwich" structure (middle panel, blue curve) exhibits significantly enhanced transition (up to 20 dB, as compared to the cobalt folm) at about 5 GHz which corresponds to a Fabry-Perot resonance of an 8-mm thick alumina slab. Then, the periodic structure shows up to 30 dB transmission enhancement at about 7 GHz which corresponds a defect mode in the band gab of the periodic structure. A good agreement was found between the measured data (Fig.1, blue curve) and numerical calculations (Fig. 1, red curve). The numeric calculations were carried out by using the transfer matrix method.

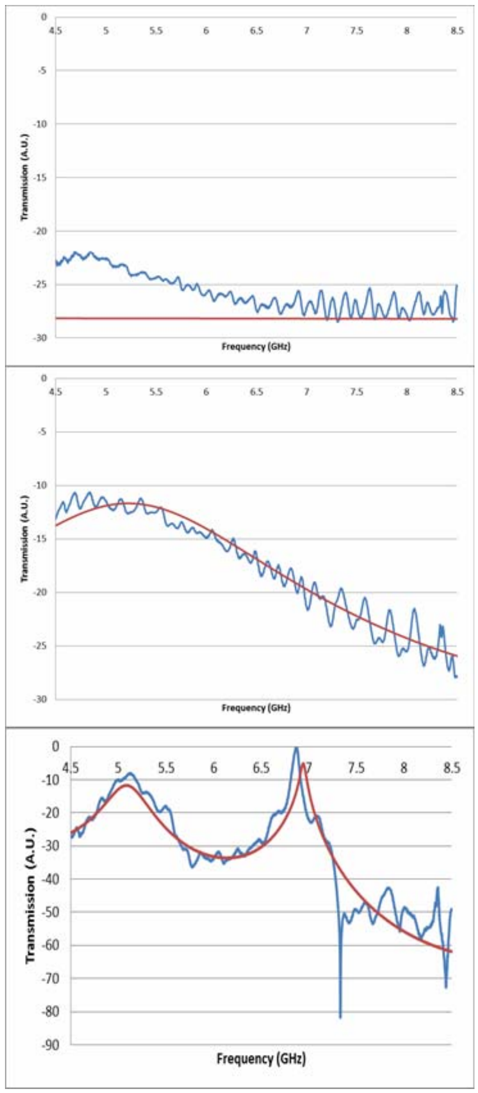

Fig. 1: Microwave transmission through a 275-nm thick cobalt layer (no external magnetic field). Cobalt layer is embedded between (a) two identical 0.5-mm thick glass layers, (b) two 4-mm thick alumina layers, and (c) at the middle of periodic binary dielectric structure.

When an external magnetic field was applied, the transmission did not change, except that we were able to observe a tiny dip (about 1 dB) in the transmission spectra, corresponding to the ferromagnetic resonance of the cobalt film. The resonance frequency was found to vary linearly with the external magnetic field (Fig. 2). The linear fit of the data in Fig. 2 yielded an increase rate of 24.4 ± 1.0 GHz/Tesla. This matches closely with Kittel's equation for the frequency of the ferromagnetic resonance in magnetic field. The presence of the ferromagnetic resonance is closely related to existence of nonreciprocal phenomena in the cobalt film. Though we could not reliably detect Faraday rotation in the present work due to relatively weak isolation between the linearly cross polarised microwave signals, more precise microwave measurements in thick (up to 2 micron) cobalt films are underway.

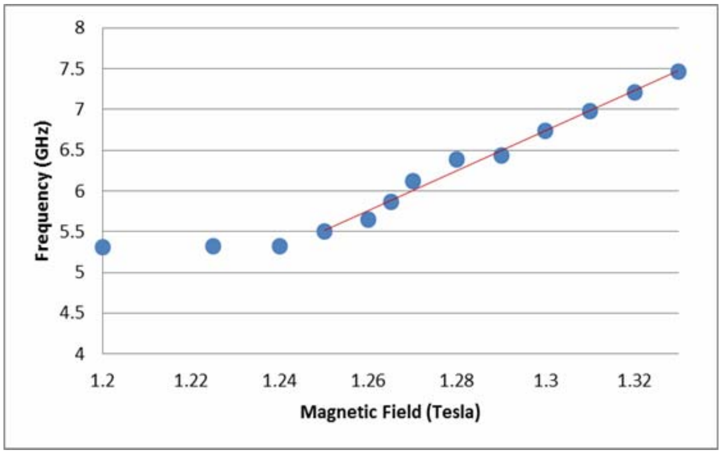

Figure 2. The field dependence of the ferromabnetic resonance of the cobalt film. The red line is a linear fit of the data.

4. Conclusion

It is clear from the results presented that transmission through a ferromagnetic metal layer can be significantly enhanced by embedding the metal layer in a dielectric slab or periodic dielectric layered structure. Under resonance conditions of dielectric structures, the electric field in lossy ferromagnetic layer is greatly diminished and therefore its reflection and absorption are reduced. At the same time, the ac magnetic field is increased at the ferromagnetic layer, leading to enhanced nonreciprocal effects in the presence of magnetic field. A successful match to theory and measure of the trend between the ferromagnetic resonance of the structure and the applied external magnetic field proves given the right conditions, a tuneable shift of the ferromagnetic resonance can be done. This suggests that ferromagnetic metal films may have important applications in photonics.

References

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