

Bias Field Effects on Microwave Frequency Behavior of PZT/YIG Magnetolectric Bilayer

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Magnetolectric behavior of a yttrium iron garnet (YIG)/zirconate titanate (PZT) magnetolectric bilayer composite was studied over 1–7 GHz under different bias magnetic fields and electric fields by using a broadband air-gap microstrip with the PZT/YIG loaded in the air gap. Electrostatically induced ferrimagnetic resonance (FMR) frequency shifts of the YIG/PZT bilayer composite were studied. The FMR frequency shift was negligible at bias fields when the YIG was not saturated. After saturation, the FMR frequency increased nearly linearly from 15 MHz at a bias field of 100 Oe to 30 MHz at 1200 Oe and dropped suddenly at a field of 1300 Oe to about 20 MHz. This nonlinear bias magnetic field dependence was due to magnetic domain activities when the YIG was not saturated and due to the interference between the uniform mode and other magnetostatic spin waves after saturation. An electrostatically tunable band-reject filter device was demonstrated which has a peak attenuation of greater than 50 dB, 40 dB rejection band of 10 MHz, and pass band insertion loss of <5 dB at ~4.6 GHz.

Index Terms—Ferrimagnetic resonance (FMR), magnetolectric (ME) composites, microwave ME devices.

I. INTRODUCTION

LAYERED magnetolectric (ME) composites have drawn a lot of attention recently due to the strong achievable ME coupling, which can be used in different devices [1]–[4]. These layered ME composites typically contain at least one magnetic layer (or phase) and one piezoelectric layer (or phase). The elastic coupling between these two phases leads to the tuning of dielectric polarization under an applied magnetic field or the control of an induced magnetization under an external electric field, thus enabling an effective energy conversion between electric and magnetic fields.

There are two ways to excite the ME composites, either by a magnetic field or by an electric field. The first way to excite an ME composite is by an ac magnetic field at low frequencies (typically <5–10 MHz). This can be done either by a sinusoidal magnetic field [5]–[9] or by an impulse magnetic field [10]–[12]. The second way to excite an ME composite is by an electric voltage, which is essentially an inverse magnetoelastic effect typically at microwave frequencies. An applied electric field-induced deformation in the piezoelectric phase leads to deformation of the magnetic phase and therefore a change of the effective magnetic field which is reflected in a shift of the ferromagnetic resonance frequencies.

There has been an extensive amount of work on the low frequency ME response when the ME composites were excited by either a sinusoidal or impulse magnetic field [5]–[12]. In contrast, there has been a limited amount of work on ME coupling driven by an electric field at microwave frequencies, particularly across a broadband frequency range. Srinivasan and Bichurin *et al.* [13], [14] established the phenomenological

theory predicting electrostatic stress-induced FMR shift and demonstrated the electrostatically induced FMR frequency shift at a fixed frequency of 9.3 GHz with a narrowband microwave cavity exciting the ME bilayers [14].

In this paper, we used a broadband excitation for a YIG/PZT ME composite, and studied the bias magnetic field effects on FMR frequency shifts over 1–7 GHz. An electrostatically tunable magnetic microwave band-reject filter was also demonstrated.

II. EXPERIMENT

We used 100- μm yttrium iron garnet (111) film (YIG) on a 200- μm -thick substrate of gadolinium gallium garnet (GGG) that was epoxy bonded to a silver-coated 500- μm -thick lead zirconate titanate (PZT) layer to form the YIG/PZT bilayer ME composite. The YIG layer has a dimension of $6 \times 7 \text{ mm} \times 100 \mu\text{m}$. The magnetic hysteresis of the YIG/PZT bilayer was measured on a vibrating sampling magnetometer. Low-frequency ME coupling of the YIG/PZT bilayer composite was measured under a sinusoidal magnetic field excitation at 85 kHz under different bias fields.

The ME coupling at microwave frequencies was investigated over a broad frequency range of 1–7 GHz under different magnetic bias fields and different electric fields. The YIG/PZT bilayer was loaded into the air gap of a microstrip, which generates a broadband excitation, as shown in Fig. 1. Compared to the microwave narrowband cavity excitation for the ME materials [14], this broadband air-gap microstrip excitation for ME materials allows for a broadband frequency sweep and a strong magnetic material microwave coupling due to the strong microwave drive magnetic field. The two ports of the microstrip were connected to an HP8510 vector network analyzer, which generates the microwave excitation at one port and measures the transmission (S_{21}) at the other port. The ferromagnetic resonance of the YIG leads to a narrowband absorption in the transmission at the FMR frequency. A pair of electromagnets was

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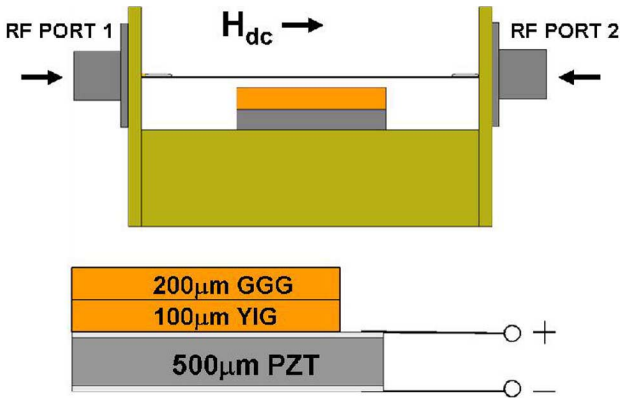


Fig. 1. Depiction of electrostatically tuned microwave band-reject filter with embedded GGG/YIG layer facing signal line.

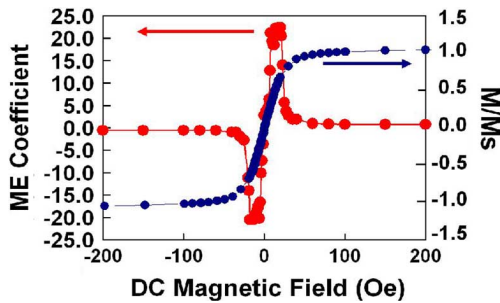


Fig. 2. Continuous wave response of ME voltage coefficient (in kilovolts per centimeter per oersted) versus dc magnetic field (in oersted). Axis 2: In-plane hysteresis of M/M_s .

used to generate the bias field along the wave propagation direction in the microstrip for sweeping the bias magnetic field. A high-voltage amplifier for sweeping the bias magnetic field. A high-voltage amplifier was connected to the two electrodes of the PZT layer for providing the electric field to mechanically deform the YIG/PZT bilayer, leading to the FMR frequency shift of the YIG layer. The FMR response was measured as a function of both an applied dc magnetic field and an applied dc voltage. The dc magnetic field was swept from +1600 to -1600 Oe. At each magnetic field bias, the FMR response was measured in between ± 7.2 kV/cm. An electrostatically tunable band-reject filter device was made with the PZT/YIG/GGG trilayer composite loaded in a microstrip fixture with a 1-mm air gap.

III. RESULTS AND DISCUSSION

The ME voltage coefficients were measured by exciting the YIG/PZT bilayer under different dc bias fields with an ac magnetic field at 85 kHz, shown in Fig. 2 together with the hysteresis loop as a function of the dc bias field. Clearly, the ME voltage coefficients peak at 10 and -10 Oe and disappear beyond 50 Oe, which correlates well with the hysteresis loop of the YIG material, which shows saturation at fields above 50 Oe. This correlation indicates that the low-frequency ME response from magnetic field excitation originates from the magnetization process, mainly due to domain activities such as wall motion and domain rotation of the YIG layer, consistent with what was reported [5]–[7].

The FMR frequency of the YIG/PZT bilayer was measured at different bias magnetic fields and with zero

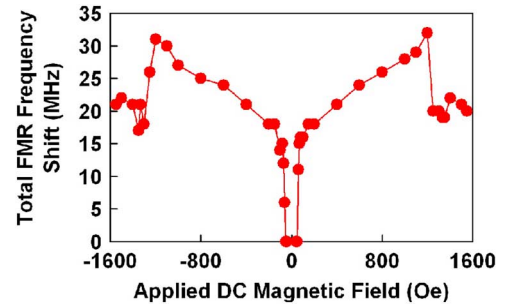


Fig. 3. Total electrostatically induced FMR frequency shift (in megahertz) versus applied dc magnetic field (in oersted).

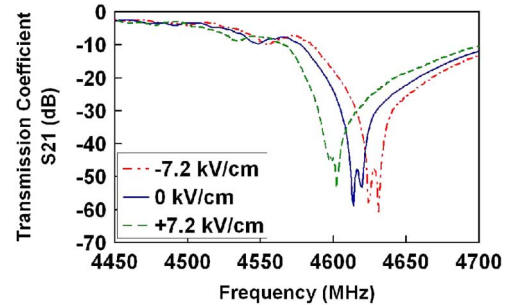


Fig. 4. Transmission S_{21} of electrostatically tuned microwave band-reject filter.

applied electric field, which can be well fitted with the Kittel equation with $H_k = 42$ Oe, and $4\pi M_s$ of 1950 G for magnetic thin film with in-plane magnetization $f_{\text{FMR}} = \gamma \sqrt{(H_k + H_{\text{dc}}) \cdot (4\pi M_s + H_k + H_{\text{dc}})}$, where γ is about 2.8 MHz/Oe.

The total FMR frequency shift at ± 7.2 kV/cm was measured and plotted in Fig. 3 as a function of the magnetic bias field. The FMR frequency shift of the YIG/PZT bilayer shows nonlinear bias magnetic field dependence, which is nearly zero when the bias field is between ± 50 Oe, indicating that there is no electrostatically induced FMR shift occurring. This observation is consistent with the low frequency ME voltage coefficients and the hysteresis loop, in which the inverse magnetoelastic effect causes domain activities in the YIG layer. The FMR frequency shifts rise nearly exponentially to ~ 15 MHz when the YIG material is saturated. After the saturation, the tunable bandwidth exhibits nearly a linearly increase from 15 MHz at a bias field of 100 Oe to 30 MHz at 1200 Oe and dropped suddenly at a field of ~ 1300 Oe to about 20 MHz. This nonlinear bias field dependence is a direct consequence of the interference between the uniform mode ferromagnetic resonance and the other magnetostatic spin waves. This is clearly shown in Fig. 4, in which double absorption peaks are observed in the S_{21} , indicating the close overlapping of the uniform mode and the other magnetic spin wave mode. The position of the spin wave modes may push the FMR frequency higher or lower, leading to the nonlinear bias field dependence of the FMR frequency shift.

In this experiment, the YIG layer has a plane normal of [111]. Assuming both the stress and the magnetization of the YIG layer is in-plane along the $[1\bar{1}0]$ direction, the magnetoelastic energy will be $E_{\text{ME}} = -(3/4)\sigma(\lambda_{100} + \lambda_{111})$,

leading to a stress-induced effective magnetic field strength $\delta H_E = (-3(\lambda_{100} + \lambda_{111})\sigma/2M_s) \equiv A \cdot E$ (cgs unit), where A is defined as the ME constant and E the electric field applied on the ME bilayer. Depending on the tensile or compressive stress, the stress-induced effective magnetic field δH_E will change sign, leading to a shift of the FMR frequency of $\delta f_{\text{FMR}} = \gamma^2[4\pi M_s + 2(H_k + H_{\text{DC}} + \delta H_E)] \cdot \delta H_E / f_{\text{FMR}}$. The YIG/PZT device showed 20–30 MHz FMR frequency shift at a bias magnetic field of 1000–1500 Oe with electric field of ± 7.2 kV/cm. Plugging in the electric field of 7.2 kV/cm, $\lambda_{100} = -1.4$ ppm, and $\lambda_{111} = -2.85$ ppm [15], we get δH_E in the range of 7–10 Oe, A in the range of 0.5–1 Oe · cm/kV, and a stress exerted on the YIG of 200–300 Mdyne/cm² (or 20–30 MPa). The magnetoelectric constant of 0.5–1 Oe · cm/kV observed in this paper is comparable to what was predicted [13]. According to the above equation, the FMR frequency shift will have a strong dependence on the applied field, particularly at small bias fields when the FMR frequency is low. Interestingly, this field dependence is not observed in our experiments, which may be due to the complication of the magnetostatic spin waves.

It is notable that the broadband testing technique for magnetoelectric materials in our experiments, i.e., an air-gap microstrip loaded with the YIG/PZT device, constitutes a magnetostatically tunable band reject filter. The transmission coefficients (S_{21}) versus frequency (at $H_{\text{dc}} = 880$ Oe) is shown in Fig. 4, with the electrostatic field at +7.2 kV/cm, 0 kV/cm, and -7.2 kV/cm. The device has a peak attenuation of ~60 dB and a 40-dB rejection band of ~13 MHz. The maximum insertion loss is ~5 dB, and the electrostatically tunable range (total FMR frequency shift) is ~30 MHz, which can be further enhanced by optimizing the properties of the composite, such as the volume ratio of the magnetic phase and the piezoelectric phase [13].

IV. CONCLUSION

By using a broadband excitation technique, we observed a nonlinear bias magnetic field dependence of the FMR shift in the YIG/PZT magnetoelectric bilayer. The negligibly small FMR frequency shift at low frequencies was due to the magnetic domain activities; meanwhile, the magnetostatic spin waves were responsible for the nonlinear bias field dependence of the FMR frequencies at high magnetic bias fields. The same technique for the broadband testing of the ME device is also an excellent magnetostatically tunable band-reject filter with very high attenuation (40 dB nominal) and reasonable insertion loss (<5 dB).

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REFERENCES

- [1] S. Dong, J.-F. Li, and D. Viehland, "Vortex magnetic field sensor based on ring-type magnetoelectric laminate," *Appl. Phys. Lett.*, vol. 85, no. 12, pp. 2307–2309, Sep. 2004.
- [2] J. Zhai, Z. Xing, S. Dong, J. Li, and D. Viehland, "Detection of pico-Tesla magnetic fields using magneto-electric sensors at room temperature," *Appl. Phys. Lett.*, vol. 88, pp. 062510-1–062510-3, Feb. 2006.
- [3] A. S. Tatarenko, V. Gheevarghese, and G. Srinivasan, "Magneto-electric microwave bandpass filter," *Electron. Lett.*, vol. 42, no. 9, Apr. 2006.
- [4] Y. K. Fetisov and G. Srinivasan, "Electric field tuning characteristics of a ferrite-piezoelectric microwave resonator," *Appl. Phys. Lett.*, vol. 88, pp. 143503-1–143503-3, Feb. 2006.
- [5] C. Nan, "Magneto-electric effect in composites of piezoelectric and piezomagnetic phases," *Phys. Rev. B*, vol. 50, no. 9, pp. 6082–6088, Sep. 1994.
- [6] J. Ryu, S. Pyla, A. V. Carazo, and K. Uchino, "Effect of the magnetostrictive layer on magneto-electric properties in lead zirconate titanate-Terfenol-D laminate composites," *J. Amer. Ceram. Soc.*, vol. 84, pp. 2905–2908, Jul. 2001.
- [7] G. Srinivasan, E. T. Rasmussen, J. Gallegos, R. Srinivasan, Yu. I. Bokhan, and V. M. Laletin, "Magneto-electric bilayer and multilayer structures of magnetostrictive and piezoelectric oxides," *Phys. Rev. B*, vol. 64, pp. 214408-1–214408-6, Nov. 2001.
- [8] U. Laletsin, N. Padubnaya, G. Srinivasan, and C. P. Devreugd, "Frequency dependence of magneto-electric interactions in layered structures of ferromagnetic alloys and piezoelectric oxides," *Appl. Phys. A*, vol. 78, pp. 33–36, Jan. 2004.
- [9] J. G. Wan, Z. Y. Li, Y. Wang, M. Zeng, G. H. Wang, and J.-M. Liu, "Strong flexural resonant magneto-electric effect in terfenol-D/epoxy-Pb(Zr,Ti)O₃ bilayer," *Appl. Phys. Lett.*, vol. 86, pp. 202504-1–202504-3, May 2005.
- [10] M. I. Bichurin, D. A. Filippov, V. M. Petrov, V. M. Laletsin, N. Padubnaya, and G. Srinivasan, "Resonance magneto-electric effects in layered magnetostrictive-piezoelectric composites," *Phys. Rev. B*, vol. 68, pp. 132408-1–132408-4, Oct. 2003.
- [11] S. X. Dong, J. R. Cheng, J. F. Li, and D. Viehland, "Enhanced magneto-electric effects in laminate composites of Terfenol-D/Pb(Zr,Ti)O₃ under resonant drive," *Appl. Phys. Lett.*, vol. 83, no. 23, pp. 4812–4814, Dec. 2003.
- [12] Y. K. Fetisova, K. E. Kamentseva, A. Y. Ostashchenko, and G. Srinivasan, "Wide-band magneto-electric characterization of a ferrite-piezoelectric multilayer using a pulsed magnetic field," *Solid State Commun.*, vol. 132, pp. 13–17, Jul. 2004.
- [13] M. I. Bichurin, I. A. Kornev, V. M. Petrov, A. S. Tatarenko, Y. V. Kiliba, and G. Srinivasan, "Theory of magneto-electric effects at microwave frequencies in a piezoelectric-magnetostrictive multilayer composite," *Phys. Rev. B*, vol. 64, pp. 094409-1–094409-6, Aug. 2001.
- [14] S. Shastry, G. Srinivasan, M. I. Bichurin, V. M. Petrov, and A. S. Tatarenko, "Microwave magneto-electric effects in single crystal bilayers of yttrium iron garnet and lead magnesium niobate-lead titanate," *Phys. Rev. B*, vol. 70, pp. 064416-1–064416-6, Aug. 2004.
- [15] A. R. Callen, A. E. Clark, B. De Savage, W. Coleman, and H. B. Callen, "Magnetostriction in cubic neel ferrimagnets, with application to YIG," *Phys. Rev.*, vol. 130, pp. 1735–1740, Jun. 1963.

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