Strong Converse Magnetoelectric Effect in a Composite of Weakly Ferromagnetic Iron Borate and Ferroelectric Lead Zirconate Titanate

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(Received 13 April 2020; revised 29 June 2020; accepted 14 August 2020; published 15 September 2020)

This report is on a model and experiment on the nature of mechanical-strain-mediated converse magnetoelectric (CME) effect in a composite of single-crystal iron borate, a canted antiferromagnet with a weak ferromagnetic moment, and ferroelectric lead zirconate titanate (PZT). The piezoelectric strain generated in PZT by an electric field E manifested as a shift in the quasiferromagnetic resonance (FMR) field in iron borate due to strong magnetoelastic interactions. The CME interaction strength determined from data on field shift in FMR versus E is 46–54 MHz cm/kV at 5.5–6.5 GHz. The strength of the CME is comparable to values reported for composites of ferrimagnetic oxides and PZT. A model that considers the effect of piezoelectric deformation on magnetic order parameters and magnetic resonance in iron borate is proposed for the CMEs in the composite and estimated ME coupling coefficients are in good agreement with data. The E tunability of the high-frequency AFMR mode at about 300 GHz is estimated to be on the order of 1.7 MHz kV/cm and is very small relative to the quasi-FMR mode. Composites of iron borate and ferroelectrics are very attractive for use in dual electric field and magnetic field tunable signal processing devices due to strong CME interactions and the need for a rather small bias magnetic field compared with traditional ferrimagnetic oxide based devices.

DOI: 10.1103/PhysRevApplied.14.034039

I. INTRODUCTION

Converse magnetoelectric effects (CMEs) in ferromagnetic-ferroelectric composite systems are of significant interest for the development of dual electric and magnetic field tunable microwave devices. An electric field E applied to the ferroelectric phase gives rise to a piezoelectric deformation, which, when transferred to the ferromagnetic phase, produces a change in the magnetic order parameter. Such a magnetic response to E can be studied by ferromagnetic resonance (FMR) under an E field. The shift in the resonance frequency $\omega_F/2\pi$ (which is equivalent to the shift δH_{0r} in the resonance field H_{0r}) as a function of E is measured to determine the CME coefficient $A_f = \delta(\omega_F/2\pi)/E$. The effect is reported in a variety of ferromagnetic (or ferrimagnetic)-ferroelectric composites, including yttrium iron garnet (YIG), nickel ferrite (NFO), M-type strontium (SrM), barium (BaM) hexagonal ferrites, or Fe-Ga-B alloys for the magnetic phase and lead zirconate titanate (PZT) or lead magnesium niobite-lead titanate (PMN-PT) for the ferroelectric phase [1–7]. Since the strength of the CME is directly proportional to magnetostriction for the magnetic phase, the A_f values are rather low and in the range of 1–3 MHz cm/kV for composites with YIG and M-type hexaferrites, which are known to have a weak magnetostriction [2]. Much stronger CMEs are reported for composites with NFO or Fe-Ga-B alloys [2,7].

Here, we report the results of studies on CMEs in a composite of iron borate, a canted antiferromagnetic system [8], and ferroelectric PZT. Iron borate, $FeBO_3$, is often referred to as a green weak ferromagnet, in which

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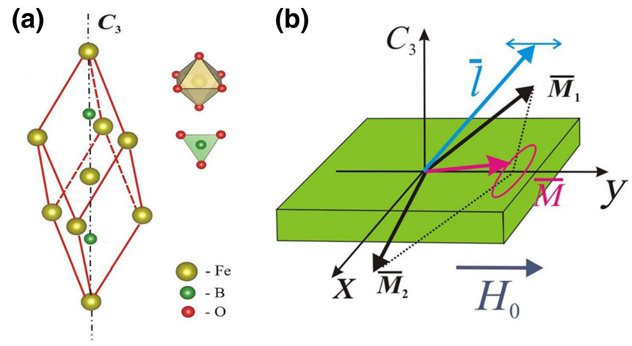

FIG. 1. (a) Rhombohedral unit cell of $FeBO_3$ containing two formula units. Each Fe atom is surrounded by six oxygen, forming an octahedron, and B atoms are situated in the center of flat oxygen equilateral triangle. (b) Sketch showing directions of sublattice magnetizations $\bar{M}_1$ and $\bar{M}_2$, weak ferromagnetic moment $\bar{M}$, and antiferromagnetic vector $\bar{l}$. Also, the behavior of $\bar{M}$ and $\bar{l}$ during quasi-FMR oscillations is schematically shown.

the antiferromagnetic ordering is slightly canted by the Dzyaloshinskii-Moriya interaction [9–13] with a Neel temperature of 348 K [14,15]. It has a rhombohedral crystal structure [see Fig. 1(a)] with its magnetic moments aligned in the (111) plane. The net ferromagnetic moment is small, on the order of $4\pi M \sim 115$ G at 300 K, and magnetic anisotropy fields are less than 1 Oe in the easy (111) plane and 62.5 kOe along the hard [111] axis [16,17].

Studies of $FeBO_3$ report a low-frequency quasi-FMR mode at frequencies from 5 to 30 GHz for applied fields of a few Oe to a few hundred Oe, and the high-frequency quasi-antiferromagnetic resonance (AFMR) occurs at several hundred GHz [10,11,18,19]. Iron borate is also reported to show very high Faraday rotation at 525 nm [20]. $FeBO_3$ is of interest for studies on parametric excitation of spin waves and magnetoelastic waves [21,22] and for a variety of applications, including magnetic sensors, microwave devices, and optical filters and modulators [14,15,20].

This study is on (i) the theory for the effects of an in-plane strain on the quasi-FMR mode in a single-crystal platelet of (111) $FeBO_3$ and the CMEs in a composite with PZT and (ii) experiments on the nature of CMEs in the composite. In the model, we estimate the variation in the magnetoelastic anisotropy field of iron borate due to the in-plane component of the piezoelectric deformation in PZT and the resulting variation in the FMR field or frequency. Expressions for the CME coefficient A are obtained in terms of both field and frequency shift in FMR. This is followed by details of studies on FMR in the composite with a c-plane iron borate and PZT. Measurements in the frequency range 5 to 7 GHz are carried out and data on the shift in the resonance field as a function of the dc voltage applied to PZT are utilized to estimate the CME coefficient A. Estimated CME coefficients are found to be in good agreement with data. Details on the model and experiments on the CMEs are provided next.

II. THEORETICAL BACKGROUND

First, we develop a model for the CMEs in a composite of platelets of iron borate and PZT. It is assumed that PZT is poled perpendicular to its plane and subjected to an electric field along the poling direction and resulting in an in-plane uniaxial piezoelectric deformation that is transmitted to iron borate. In this section, we estimate the shift in the resonance field or frequency due to the mechanical deformation and the CME coefficient. There are two uniform magnetic oscillations in $FeBO_3$; quasi-FMR and quasi-AFMR modes [8,23–25]. The quasi-FMR mode frequency can be written as

$$\omega_F/(2\pi) = \gamma\{[H_0 + 4\pi M(N_x - N_z)] \times [H_0 + 4\pi M(N_y - N_z) + H_{\mathrm{DM}}] + 2H_{\Delta 1}{}^2 + 2H_{A1}(V)H_E\}^{1/2}, \tag{1a}$$

and an approximate expression for the quasi-AFMR mode frequency is

$$\omega_{\mathrm{AF}}/(2\pi) = \gamma\{2H_AH_E + H_{\mathrm{DM}}(H_0 + H_{\mathrm{DM}}) + H_{\Delta 1}{}^2 + H_{\Delta 2}{}^2 + [H_{A1}(V) + H_{A2}(V)]H_E\}^{1/2}, \tag{1b}$$

where $\gamma = 2.8$ GHz/kOe is the gyromagnetic ratio, H_0 is the external magnetic field, $4\pi M$ is the net ferromagnetic moment, N_i are the demagnetizing factors, H_{DM} is the Dzyaloshinskii-Moriya field, and H_A is an easy-plane anisotropy field. The last terms in Eq. (1) represent the energy gap that is a function of the exchange field and the magnetoelastic anisotropy field. Specifically, $H_{\Delta 1}{}^2$ and $H_{\Delta 2}{}^2$ are the magnetoelastic energy gaps determined by the spontaneous striction (see Ref. [23] for exact expressions) and other types of static mechanical deformation, for example, due to defects generated during crystal growth or hydrostatic pressure [23,26]; $H_{A1}(V)$ and $H_{A2}(V)$ are parts of anisotropy field induced by mechanical stress caused by external forces; and H_E is the exchange field. Due to the large value of H_E, any small change in the anisotropy field H_{A1} will have a very significant influence on the resonance frequency. In a composite with PZT one expects a variation in $H_{A1}(V)$ for $FeBO_3$ due to the piezoelectric deformation of the PZT under a dc voltage V and, therefore, electric field control of the quasi-FMR frequency, according to Eq. (1a).

The expression for H_{A1} in the case of uniaxial deformation in the crystal basal plane is given by [23,25]

$$H_{A1} = -K\sigma\cos(2\Psi), \tag{2}$$

where σ is the internal uniaxial stress and Ψ is the angle between the deformation direction and the antiferromagnetic vector $\bar{l}$ ($\bar{l}$ is orthogonal to the direction of applied magnetic field $\bar{H}_0$) in the basal plane [see Fig. 1(b)]. The coefficient K is given by

$$K = \frac{1}{4M_0}\frac{(4B_3c_{44} - B_4c_{14})}{2(c_{11} - c_{12})c_{44} - c_{14}^2}, \tag{3}$$

where M_0 is the sublattice magnetization, B_i are the magnetoelastic constants, and c_{ij} are the elastic constants. From Eq. (1b), neglecting H_0 and $4\pi M$ in comparison with H_{DM}, and for a fixed resonance frequency, one obtains the following expression for the deformation-induced shift of resonance field

$$\delta H_{0r}(V) = (2H_E/H_{\mathrm{DM}})K\sigma\cos(2\Psi). \tag{4}$$

To compare experimental results with theoretical estimation, one needs to determine the uniaxial stress acting on the magnetic material. Expressions for this internal stress for the given in-plane strain (assuming that the planar deformations of PZT and ferrite material are identical) are presented, for example, in Refs. [27,28]:

$$\sigma_{xx} = \frac{Y}{1-\nu^2}(\varepsilon_{xx} + \nu\varepsilon_{yy}),\ \sigma_{yy} = \frac{Y}{1-\nu^2}(\varepsilon_{yy} + \nu\varepsilon_{xx}), \tag{5}$$

where Y is the magnetic material's Young's modulus, ν is the Poisson ratio, and ε_{ij} is the in-plane strain. Hence, the net uniaxial stress is given by

$$\sigma = \sigma_{xx} - \sigma_{yy} = \frac{Y}{1+\nu}(\varepsilon_{xx} - \varepsilon_{yy}). \tag{6}$$

In general, both ε_{xx} and ε_{yy} are functions of transversal coordinates (x,y) and the sample aspect ratio. These functions can be found by solving the full electromechanical problem with the proper boundary conditions, which is a separate cumbersome task [29]. For the rectangular sample considered in this study, in the general case, $\varepsilon_{xx} \neq \varepsilon_{yy}$ and some net uniaxial stress along the larger side is always present [29]. We may estimate the maximum stress in the center of the PZT (where the $FeBO_3$ sample is situated) by assuming a fundamental transverse deformation mode [30], for which in the center $\varepsilon_{xx} \gg \varepsilon_{yy}$. Then, neglecting ε_{yy}, we obtain

$$\sigma = \frac{Y}{1+\nu}\varepsilon_{xx} = \frac{Y}{1+\nu}d_{31}E, \tag{7}$$

where d_{31} is the piezoelectric coefficient and E is the electric field strength inside the piezoelectric. In summary, the deformation-induced shift of the resonance field is

$$\delta H_{0r} = AE, \tag{8}$$

where the CME coefficient A is given by

$$A = \frac{2H_E}{H_{\mathrm{DM}}}K\frac{Y}{1+\nu}d_{31}\cos(2\Psi) \tag{9}$$

Notably, the field dependence of the frequency in Eq. (1a) differs from a typical FMR frequency and, therefore, the shift $\delta(\omega_F/2\pi)$ in this frequency is no longer equivalent to the shift δH_{0r} in the resonance field as it takes place in ferromagnets. The CME coefficient in terms of frequency, A_f, for iron borate and PZT composite can be calculated using the resonance condition in Eq. (1a) from

$$\delta(\omega_F/2\pi) = \left.\frac{\partial(\omega_F/2\pi)}{\partial H_0}\right|_{\substack{H_0=H_{0r}\\ H_A=0}}\delta H_{0r}, \tag{10}$$

where $[\partial(\omega_F/2\pi)]/\partial H_0|_{\substack{H_0=H_{0r}\\ H_A=0}} = (\gamma^2 H_{\mathrm{DM}})/[2(\omega_F/2\pi)]$. Taking into account Eqs. (8) and (9), one obtains

$$\delta(w_F/2\pi) = -A_f E, \tag{11}$$

where

$$A_f = \frac{\gamma^2 H_E}{(\omega_F/2\pi)}K\frac{Y}{1+\nu}d_{31}\cos(2\Psi). \tag{12}$$

The field and frequency CME coefficients are related by

$$A_f = \frac{\gamma^2 H_{\mathrm{DM}}}{2(\omega_F/2\pi)}A. \tag{13}$$

The expressions for the CME coefficients are used in Sec. III to estimate the ME coefficients for comparison with results from experiments.

In addition to the magnetoelastic effect considered here, the mechanical deformation is also known to result in deformation of the M-O-M bond angles and lengths, which, in turn, affects the magnitudes of exchange coupling constants and Dzyaloshinskii–Moriya (DM) interactions [31,32]. However, it follows from the theory discussed in Refs. [31] and [32], a significant change in exchange coupling strengths and DM interactions are expected only for in-plane tensile or compressive strains on the order of 3%–4%. In this study (as discussed in Sec. III), the strain $\varepsilon \approx d_{31}E$ does not exceed 0.02% and is expected to lead to very small variations in H_E and H_{DM} and, therefore, will lead to negligible changes in the resonance magnetic field. Therefore, we must conclude that, although the deformation of the M-O-M bond angles and lengths may be present in $FeBO_3$, their influence on FMR resonance field and frequency, is too weak, and a major contribution arises from the magnetoelastic spin-orbital term in Eq. (1).

III. EXPERIMENTAL RESULTS AND DISCUSSION

Flux-grown $FeBO_3$ single crystals used in this study are provided by the group at the Taurida National University, Simferopol, Crimea [18]. The *solution in the melt* technique is utilized for growth to obtain (111) single-crystal platelets 0.05–0.1 mm thick. The bilayer of $FeBO_3$ and PZT, shown in Fig. 2(a), is made by bonding a $2 \times 2 \times 0.2\,\text{mm}^3$ (111) platelet of iron borate to $10 \times 5 \times 0.3\ \text{mm}^3$ polycrystalline PZT (No. 850, American Piezo Ceramics [33]). A quick-dry epoxy, cyanoacrylate, of 2 μm thick is used for bonding.

Studies on the CME in the iron borate-PZT composite are carried out in two steps. First, profiles of FMR absorption versus magnetic bias field, H_0, are obtained for a series of frequencies and data on the resonance magnetic field, H_{0r}, versus $\omega_F/(2\pi)$ are used to estimate the magnetic parameters of $FeBO_3$. Second, the resonance profiles are acquired at a constant frequency as a function of dc voltage, V, applied across the thickness of PZT and data on H_{0r} versus V are then used to estimate the strength of the CME.

The broadband FMR measurement setup is shown in Fig. 2(b). The sample is placed in a coplanar waveguide excitation structure. A static magnetic field is applied parallel to the sample plane perpendicularly to the larger side of PZT and perpendicular to the rf magnetic field. A modulating field of amplitude 1 Oe at 1 kHz is applied, so that the derivative of the power absorbed, P, by the sample, dP/dH_0, can be recorded as H_0 is scanned.

Figure 3(a) shows profiles of dP/dH_0 versus H_0 at 5.5–7 GHz. The profiles indicate that H_{0r} increases from 31 Oe at 5.5 GHz to 75 Oe at 7 GHz. We do not observe any variation in H_{0r} with the in-plane orientation of the magnetic field and any variation would be too small to measure, since the in-plane anisotropy field is quite small. The peak-to-peak line width, ΔH, is found to increase with frequency, from about 20 Oe at 5.5 GHz to about 30 Oe at 7 GHz.

Data in Fig. 3(b) are used to estimate the magnetic parameters of $FeBO_3$. From the resonance condition in Eq. (1a), neglecting the contribution from the demagnetizing field and assuming that a voltage-induced magnetoelastic field is absent, we get

$$\omega_F/(2\pi) = \gamma[H_{0r}(H_{0r} + H_{\text{DM}}) + 2H_{\Delta 1}{}^2]^{1/2}. \quad (14)$$

The resonance frequencies $\omega_F/(2\pi)$ versus H_{0r} are fitted to Eq. (14). The parameters obtained for the FMR data are $H_{\text{DM}} = 58.8\,\text{kOe}$ and $H_{\Delta 1} = 0.99\,\text{kOe}$. These parameters agree with values of $H_{\text{DM}} = 62 - 64\,\text{kOe}$ and $H_{\Delta 1} = 1.07\,\text{kOe}$ reported in Ref. [11].

Next, we focus on the magnetoelectric effect. The CME in the composite is investigated by FMR at a constant frequency under a static electric field, E, applied across the PZT layer. Results of measurements at 5.5 GHz are shown in Fig. 4. A dc voltage of positive polarity up to a maximum of 350 V is applied. Positive voltage corresponds to the same polarity as that for the voltage applied for poling the PZT. Representative resonance profiles in Fig. 4(a) show a decrease in H_{0r} with the magnitude of voltage. Figure 4(b) shows measured H_{0r} as a function of V. A sharp decrease in H_{0r} from 31 to 18 Oe is measured as V is increased from 0 to +350 V. The overall V-induced change in H_{0r} is on the order of 13 Oe and, from data in Fig. 3(b),

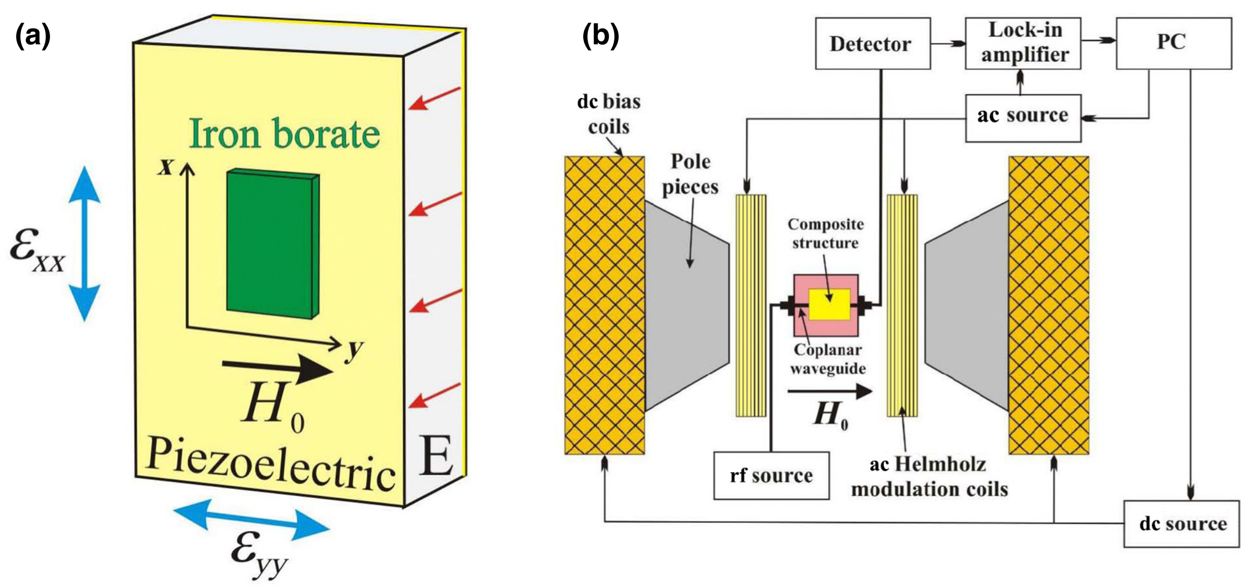

FIG. 2. (a) $FeBO_3$-PZT bilayer composite structure. (b) Block diagram showing the field sweep wideband ferromagnetic resonance measurement system.

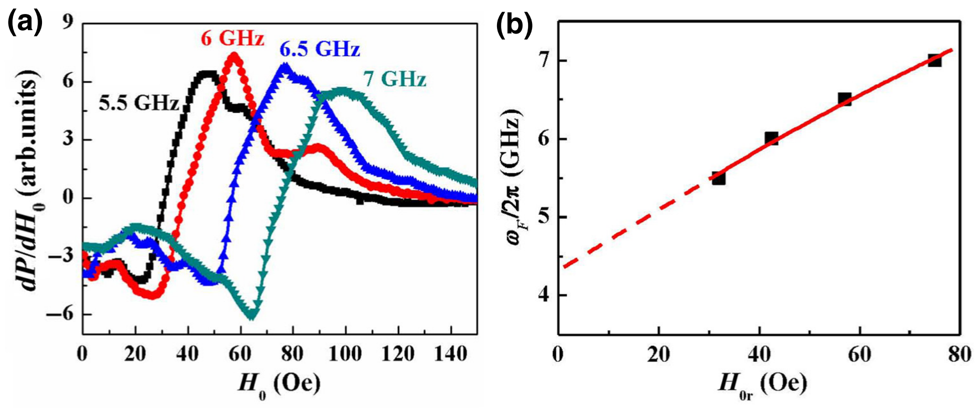

FIG. 3. (a) Profiles showing low-frequency quasi-FMR for $FeBO_3$ in a composite with PZT. Inset shows the bilayer composite. (b) Frequency versus resonance field H_{0r} for FMR in the composite. Solid and dashed lines are theoretical fits to the data.

is equivalent to tuning the quasi-FMR frequency by about 500 MHz or 10% tuning of the resonance frequency.

We consider the cause of CMEs in the composite. First, there is a finite deformation in the equilibrium state of the weak ferromagnet, which manifests as a change in the term $H_{\Delta 1}^2$ in Eq. (1a). The E-induced FMR frequency and field shift in the $FeBO_3$-PZT system is due to strain-mediated ME coupling in the composite. Under an applied V, the in-plane component of piezoelectric strain in the PZT layer used in this study is in the order of −175 pm/V. This strain, when transferred to iron borate, will give rise to an additional deformation. It will result in an increase in the anisotropy field, which will be a function of the elastic and magnetoelastic constants and applied strain, as discussed in Sec. II.

Next, we estimate the expected variation in the resonance field with V using our model. Upon substituting the magnetic, elastic, and magnetoelastic parameters of $FeBO_3$ [25,34] ($c_{11} = 44.5 \times 10^{11}$ erg/cm^3, $c_{12} = 14.5 \times 10^{11}$ erg/cm^3, $c_{14} = 2.0 \times 10^{11}$ erg/cm^3, $c_{44} = 9.5 \times 10^{11}$ erg/cm^3, $B_3 = 2.5 \times 10^6$ erg/cm^3, $B_4 = 3.7 \times 10^6$ erg/cm^3, $H_E = 2.6 \times 10^6$ Oe, $M_0 = 1056$ G) and $d_{31} = -1.75 \times 10^{-10}$ m/V for PZT [33] into Eqs. (3) and (9), and calculating the Young's modulus and Poisson ratio using the expressions $Y = (c_{11} - c_{12})(c_{11} + 2c_{12})/(c_{11} + c_{12})$ and $\nu = c_{12}/(c_{11} + c_{12})$, respectively, we obtain a CME coefficient of $A = \delta H_{0r}/E = 1.5$ Oe cm/kV. Thus, $V = 300$ V applied to 0.3-mm-thick PZT and for the case of $\cos(2\Psi) = 1$, the H_{0r} variation should be −15 Oe. Consequently, the frequency of the CME coefficient is $A_f = 65$ MHz cm/kV for $\omega_F/2\pi = 5.5$ GHz.

Data in Fig. 4(b) show that the experimental resonance field variation is smaller than that of the theoretical estimation, amounting to −13 Oe for $V = +350$ V, with the average CME coefficient being $A = 1.14$ Oe cm/kV. The frequency CME coefficient is then $A_f = 54$ MHz cm/kV. The direction of uniaxial stress during experiments is perpendicular to the bias field (i.e.,$\Psi = 0$), and thus, provides the most favorable geometry. Therefore, agreement between data and the model is very good and the minor discrepancy can be attributed to the finite aspect ratio of the piezoelectric platelet.

We carry out similar measurements on the CME for several FMR frequencies. Figure 5 shows the results for the dependence of V on H_{0r} and the estimated variation of δH_{0r} versus electric field for resonances at 6 and 6.5 GHz, and the features are identical to the results in Fig. 3 for 5.5 GHz. One obtains $A = 1.09$ Oe cm/kV, $A_f = 47$ MHz cm/kV at 6.0 GHz, and $A = 1.15$ Oe cm/kV, $A_f = 46$ MHz cm/kV at 6.5 GHz. These results agree with

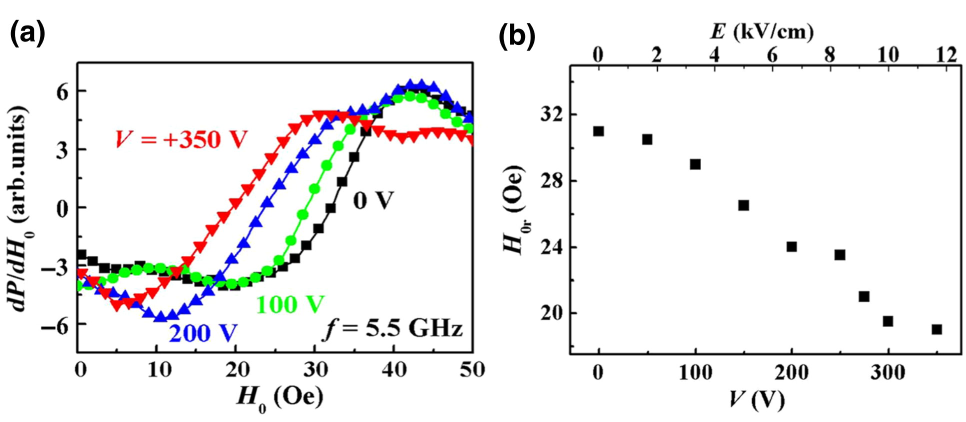

FIG. 4. (a) Low-frequency quasi-FMR profiles for $FeBO_3$-PZT composite at 5.5 GHz for dc voltages applied to PZT. (b) Variation of the resonance field H_{0r} as a function of V obtained from profiles shown in (a).

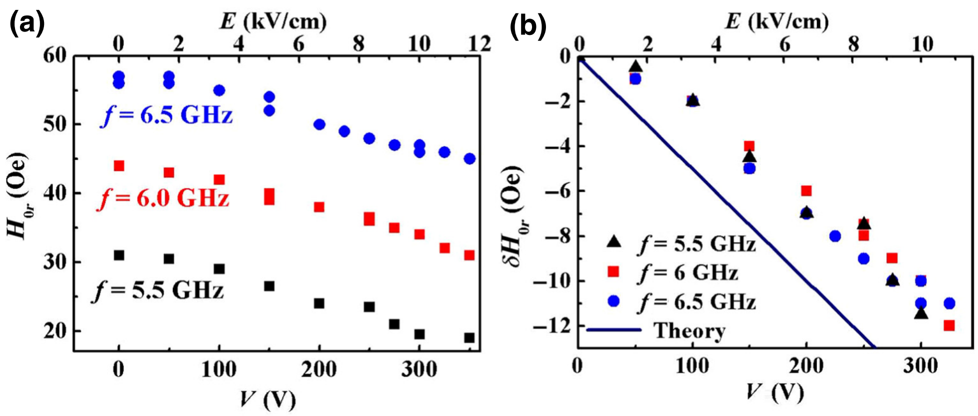

FIG. 5. Data on variation in the quasi-FMR resonance field H_{0r} and its experimental and theoretical variations with V for frequencies of 5.5, 6, and 6.5 GHz.

theoretical predictions, according to which δH_{0r} is independent of FMR frequency. The theoretical dependence is obtained using the expression $\delta H_{0r} = -AE$, with the CME coefficient A that is calculated in Sec. II. One can see a reasonable agreement with theory, which predicts a larger change in δH_{0r} with the slope of E that could be due to the assumption of uniaxial strain $\varepsilon_{xx} \gg \varepsilon_{yy}$ assumed in deriving Eq. (7). Data in Fig. 5 are approximated by a linear dependence of δH_{0r} on V. Nonlinear behavior becomes evident for a voltage of $V > 300$ V due to a switch in the polarization direction in PZT that occurs for E higher than a critical field of $E_c \sim 11.7$ kV/cm in PZT [35].

The frequency CME coefficient A_f obtained in this work is compared with reported results for ferrite-ferroelectric composites published elsewhere and results are presented in Table I. The coefficient A_f for $FeBO_3$-PZT is about an order of magnitude higher than those for YIG and M-type hexaferrites [3,5,6] and is comparable to that of $A_f = 8$–50 MHz cm/kV [4,36,37] reported for nickel ferrite films prepared by a variety of techniques, such as liquid-phase epitaxy, pulsed laser deposition, and chemical vapor deposition techniques, which are used in composites with PMN-PT or PZT. The much higher CME coefficient for iron borate is determined by the specific form of dispersion, Eq. (1a), for the quasi-FMR mode, which contains the

TABLE I. Comparison of magnetoelectric coefficients for some ferrite-ferroelectric composites.

CME coefficient A_f (MHz cm/kV)	Composite structure	Operating frequency f (GHz)	Ref.
1.6–2.5	YIG-PZT	5	[5]
2.8–15	YIG-PMN-PT	9.3	[3]
0.8	barium ferrite-PZT	50	[6]
50	NFO-PMN-PT	6–11	[4]
Up to 31	Nickel zinc ferrite-PZT	7–15	[37]
8.7–25.1	NFO-PZT	8–24	[36]
46–54	Iron borate-PZT	5.5–6.5	This work

$2H_EH_A$ term. Due to the presence of a very large H_E prefactor, even a small change in the anisotropy field H_A will result in significant changes in the resonance frequency or resonance field. The CME for the iron borate and ferroelectric composite can be further strengthened with the use of PMN-PT with d values an order of magnitude higher than those for PZT.

Finally, similar CME studies can be carried out for the high-frequency quasi-AFMR mode in iron borate-ferroelectric composites. We make a theoretical estimation using Eq. (1b) and magnetic and elastic parameters of iron borate from Ref. [23]. Also, it is assumed that coefficient K is the same as that measured experimentally for the low-frequency mode. Thus, we calculate a maximum frequency shift of 20 MHz for $E = 11.2$ kV/cm for the unperturbed AFMR mode frequency of $\omega_{AF}/(2\pi) \approx 300$ GHz, which corresponds to $A_f = 1.7$ MHz cm/kV.

The results of this study on the CME in a canted antiferromagnet and a ferroelectric composite are very attractive for dual magnetic field and electric field devices for the following reasons. (i) The quasi-FMR mode in iron borate occurs at a much lower dc bias magnetic field, which can be produced with a permanent magnet or a solenoid, compared with the H_0 values for traditional ferrimagnetic materials, such as YIG. For example, at 5.5 GHz, the FMR occurs for $H_0 = 32$ Oe in $FeBO_3$, whereas a bias field of 1275 Oe is required for YIG. (ii) The FMR line width for $FeBO_3$ is small, 25 Oe at 5.5 GHz, and is comparable to values reported for nickel ferrite or lithium ferrite single crystals or epitaxial films. (iii) The E tuning is rather high for $FeBO_3$ compared with that for YIG. The frequency tuning at 5.5 GHz for $E = 11.2$ kV/cm for iron borate is 500 MHz, compared with 22 MHz for YIG. Thus, the iron borate-PZT composite has the potential for use in miniature microwave devices, in which broadband tuning can be achieved with a magnetic field and narrow-band tuning with an electric field.

The quasi-AFMR mode in $FeBO_3$ has a frequency of hundreds of GHz under the same ultralow H_0 values (≈300 GHz for iron borate) and magnetoelectric tuning of such modes proposed in this work can lead to device applications in the sub-THz range.

IV. CONCLUSIONS

Studies on the nature of strain-mediated converse ME effects are carried out on a composite of single-crystal iron borate and polycrystalline PZT. An electric field applied across the thickness of PZT results in an in-plane piezoelectric deformation, leading to a change in the magnetoelastic anisotropy field in iron borate that is observed as a shift in the quasi-FMR frequency. Data on the E-field shift in FMR is utilized to determine the CME coupling coefficient, A_f, in the composite. Measurements in the frequency range of 5.5–7 GHz yield values of $A_f = 46$–54 MHz cm/kV; the maximum value is attained at 5.5 GHz. A model for CME coupling in the composite is discussed and the estimated value of $A_f = 65$ MHz cm/kV is in good agreement with the measured value. Since the proposed ME tuning mechanism affects both quasi-FMR and quasi-AFMR modes, it is suggested that it can be used for higher-frequency-mode electrical tuning. A theoretical evaluation of the quasi-AFMR mode frequency shift yields a value of 20 MHz for $E = 12$ kV/cm at 300 GHz, with effective $A_f = 1.7$ MHz cm/kV. Iron borate-PZT composites, due to the low FMR line width, relatively small bias magnetic field, and large A values, are very attractive for dual H- and E-tunable microwave devices, such as resonators and filters, capable of operating in both microwave and sub-THz frequency bands.

ACKNOWLEDGMENTS

The research at Oakland University is supported by grants from the National Science Foundation (Grants No. ECCS-1307714 and No. DMR-1808892) and by the Air Force Office of Scientific Research (AFOSR), Award No. FA9550-20-1-0114. Y.L. is supported by the Chinese Scholarship Council. The efforts at Hubei University are supported by the National Science Foundation of China (Grants No. 51372074 and No. 51472078). J.Z. is supported by a grant from the Natural Science Foundation of China (NSFC), Grant No. 61979287. The research at AFRL is supported by the Air Force Office of Scientific Research under Grant No. FA955020RXCOR074 and a Summer Faculty Fellowship for G.S. V.L.S. is grateful to the NRC for a fellowship.

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