Electric-field-induced magnetization in Pb(Zr,Ti)O_3/Terfenol-D composite structures

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We report the electric-field-induced magnetization (EIM) in the composite structures made by combining $Pb(Zr_{0.52}Ti_{0.48})O_3$ (PZT) and $Tb_{0.30}Dy_{0.7}Fe_2$ (Terfenol-D). The results showed that the EIM could be generated in the composite structures due to the efficient stress-mediated electromagnetic coupling interaction between the piezoelectric PZT and magnetostrictive Terfenol-D. This EIM effect depended significantly on the driving electric field frequency and was highly sensitive to the dc magnetic bias, which exhibited a promising potential in the low-level dc magnetic field detecting application. © *2006 American Institute of Physics*.
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Multiferroic materials, such as magnetoelectric materials, have been receiving continuous attention due to their multifunctionality.[1–3] Magnetoelectric materials are a type of multiferroic materials in which ferroelectric and ferromagnetic orders coexist and interact. In such materials, an electric polarization induces in an applied magnetic field, or a magnetization generates in an external electric field.[4] In the past decades, a great deal of studies of magnetoelectric effect in single phase materials and composites has been reported, most of which focused on the magnetic-field-induced electric polarization (MIEP) response to an applied magnetic field.[5–16] This MIEP effect is generally weak in the single phase materials,[5–7] but much stronger in the piezoelectric/magnetostrictive composites due to the product property and effective stress-mediated magnetoelectric coupling.[8–13] The present work has shown the possibility for the MIEP effect in the applications of magnetic field detection and magnetoelectric energy conversion.[14–17] However, to date, the investigations on the induced magnetization by an applied electric filed in the magnetoelectric materials were seriously absent.

In this letter, we report the electric-field-induced magnetization (EIM) in a longitudinal-coupling composite structure made by combining $Pb(Zr_{0.52}Ti_{0.48})O_3$ (PZT) and $Tb_{0.30}Dy_{0.7}Fe_2$ (Terfenol-D). The composite structure exhibits an apparent ac magnetization under an ac driving electric field. Moreover, this EIM effect is highly sensitive to the dc magnetic bias, which is suitable for the magnetic field detecting application.

Figure 1 is a schematic illustration of our composite structure with the EIM effect. The Terfenol-D component was magnetized in its length (or longitudinal) direction, and the PZT component was poled along its thickness direction. Both components were bonded together at one end by epoxy binder. This configuration could make the magnetoelectric coupling of the composite structure strong when it operates on the longitudinal vibrational mode. Upon applying an ac electric field to the PZT, the induced mechanical deformation in the PZT is acoustically transferred to the Terfenol-D, thereby resulting in an induced magnetization in the Terfenol-D due to the magnetoelastic coupling.

In order to obtain the effective EIM coupling, we designed the composite structure operating at the fundamental longitudinal half-wavelength resonance mode. Both PZT and Terfenol-D components were set to the same thickness of $h=1$ mm and the same width of $w=6$ mm. The lengths of the PZT and Terfenol-D were set to $l_p=16.0$ mm and $l_t=11.7$ mm, respectively. Accordingly, the relationship between the length and acoustic velocity can be written as $l_p/l_t=V_p/V_t$, where $V_p=2350$ m/s is the acoustic velocity of PZT and $V_t=1720$ m/s is the acoustic velocity of Terfenol-D. This design permits both PZT and Terfenol-D components to operate at the quarter-wavelength resonance mode. Therefore, the composite structure operates as a half-wavelength resonator whose fundamental longitudinal resonance frequency is given by $f_r=V_p/4l_p$ or $f_r=V_t/4l_t$. And the nodal face of the composite structure is located at the interface between the PZT and Terfenol-D, where the vibration velocity is zero.

We firstly analyzed the EIM coupling of the composite structure when it operated at f_r. Assuming that the driving electric field for the PZT is $E=E_0\cos(2\pi f_r t)$, the induced deformation in the PZT is acoustically transferred to the Terfenol-D and the longitudinal stress in the Terfenol-D can be derived from

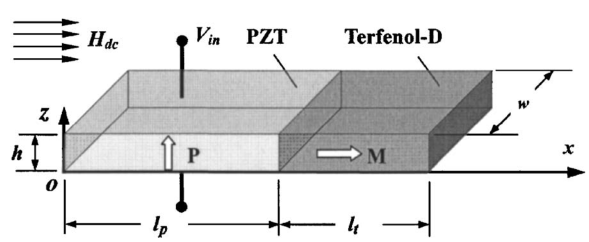

FIG. 1. Schematic illustration of the composite structure made by PZT and Terfenol-D. V_{in} represents the driving electric voltage applied to the PZT.

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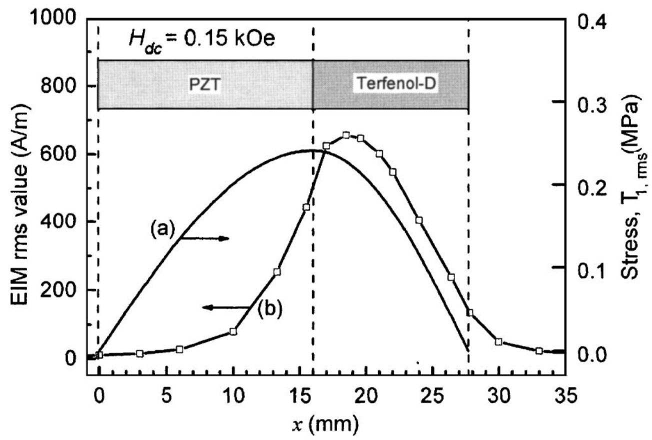

FIG. 2. EIM distribution in composite structure along the longitudinal direction. The driving electric field amplitude is $E_0 = 3 \times 10^4$ V/m and the external dc magnetic bias is $H_{dc} = 0.15$ kOe. The composite structure operates at the fundamental longitudinal resonance frequency of $f_r = 37.6$ kHz.

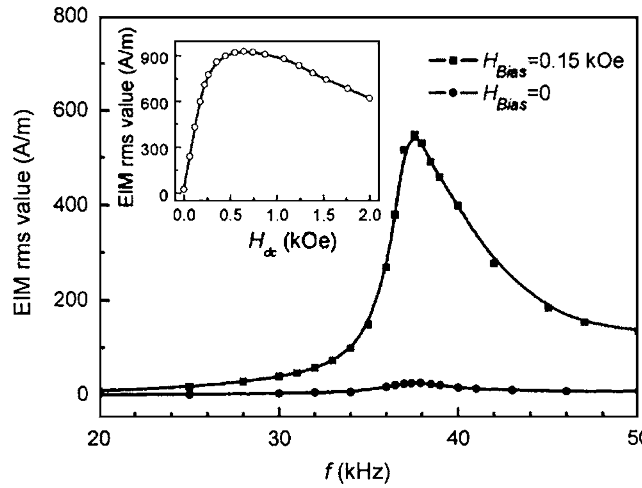

FIG. 3. EIM in the middle of the Terfenol-D component as function of the driving electric field frequency f under different H_{dc} at $E_0 = 3 \times 10^4$ V/m. Inset is the H_{dc} dependence of the maximum EIM value at EMR frequency.

$$T_1(t) = \frac{\beta d_{31} E_0}{s_{11}^E} \sin\left[\frac{\pi}{2l_t}(x + l_t - l_p)\right]\cos(2\pi f_r t), \qquad (1)$$

where d_{31} is the piezoelectric strain coefficient and s_{11}^E is the elastic compliance for PZT. $\beta \leq 1$ is a factor related to the coupling efficiency. Under the transferred stress $T_1(t)$ and external magnetic field H along the longitudinal direction, the induced magnetization in the Terfenol-D is given by

$$M = \mu_0^{-1} d(H) T_1(t), \qquad (2)$$

where μ_0 is the permeability of free space, and $d(H)$ is the piezomagnetic coefficients of Terfenol-D which is evaluated by $d(H) = 3\lambda_s H / H_a^2$, where λ_s is the saturation magnetostriction and H_a is the anisotropy field.[18] Using the material parameters for PZT of $d_{31} = 175$ pC/N and $s_{11}^E = 15.4 \times 10^{-12}$ m^2/N, and assuming $E_0 = 3 \times 10^4$ V/m and $\beta = 1$, the stress distribution in the composite structure was calculated, as shown in Fig. 2(a). The maximum stress (rms value) in the Terfenol-D was predicted to be 0.24 MPa at the interface where the maximum EIM value should be induced. Taking the material parameters for Terfenol-D of $\lambda_s = 1600 \times 10^{-6}$, $H_a = 1.4$ kOe, we predicted the maximum EIM rms value at $H = 0.15$ kOe to be $\sim$790 A/m at the interface.

The EIM in the Terfenol-D was subsequently measured by using a search coil connected to a fluxmeter. Given $E_0 = 3 \times 10^4$ V/m and the dc magnetic bias $H_{dc} = 0.15$ kOe, the fundamental longitudinal resonance of the composite structure appeared at $f_r = 37.6$ kHz. Figure 2(b) presents the EIM distribution in the composite structure along the longitudinal direction. The EIM value was found to be maximum at $x = 18.5$ mm, reaching $\sim$650 A/m. Compared to Figs. 2(a) and 2(b), the practical location of the maximum EIM is approximately in agreement with the predicted location of the maximum stress in the Terfenol-D (at $x = 16.0$ mm), only being a small right shift of 2.5 mm, which may be caused by the measurement error due to the magnetic flux leakage at the edge of the Terfenol-D. Additionally, the EIM value decreased rapidly when the location moved towards the right end of the Terfenol-D, simultaneously accompanying with a sharp drop of the stress in the Terfenol-D. According to these results, we were convinced that the stress in the Terfenol-D dominated the EIM when the composite structure operated at a given driving electric field and magnetic bias.

We then investigated the EIM dependence on the driving electric field frequency f and external dc magnetic bias H_{dc}. Figure 3 shows the EIM value in the middle of the Terfenol-D component as function of f with different H_{dc} at given $E_0 = 3 \times 10^4$ V/m. One observed in Fig. 3 two facts: (i) When the driving electric field was tuned to the electromechanical resonance (EMR) frequency, the EIM value enhanced largely, e.g., reaching 25 A/m at $H_{dc} = 0$, a factor of $\sim$100 higher than the nonresonant values. (ii) In addition, at the EMR state, the maximum EIM value further increased significantly with increasing H_{dc}, e.g., from 25 A/m at $H_{dc} = 0$ to 548 A/m at $H_{dc} = 0.15$ kOe, increasing by $\sim$20 times in magnitude. The two facts indicated that the EIM effect depended significantly on the driving electric field frequency and was highly sensitive to the external dc magnetic bias. Further investigations on the H_{dc} dependence of the maximum EIM value at EMR frequency were subsequently carried out, as shown in inset of Fig. 3. We found that the EIM response to H_{dc} was almost linear in the low-level magnetic bias range of $0 < H_{dc} < 250$ Oe. In the meantime, We also noted that there existed a so-called optimized $H_{dc} = \sim 0.6$ kOe at which the EIM reached the maximum value of 930 A/m. This H_{dc} dependence should be attributed to the negative ΔE effect of Terfenol-D.[19]

Since the EIM in the composite structure is highly sensitive and has a good linear response to the low-level dc magnetic bias at the EMR state, it is possible to use the EIM effect for the low-level dc magnetic field detection. To illustrate it, we would a pickup coil around the left end of the Terfenol-D component. When the PZT is driven by an electric field E at the EMR frequency, an electromotive force (EMF) will be induced in the pickup coil due to the EIM effect in the Terfenol-D. The induced EMF ε is proportional to the external magnetic bias H_{dc}, which could be described by

$$\varepsilon = \frac{6\pi\beta N w h \lambda_s f_r d_{31} E_0 H_{dc}}{H_a^2 s_{11}^E} \sin(2\pi f_r t), \qquad (3)$$

where $N = 100$ is the number of turns of the pickup coil. The magnetic field detection could thus be achieved by detecting the EMF generated in the pickup coil.

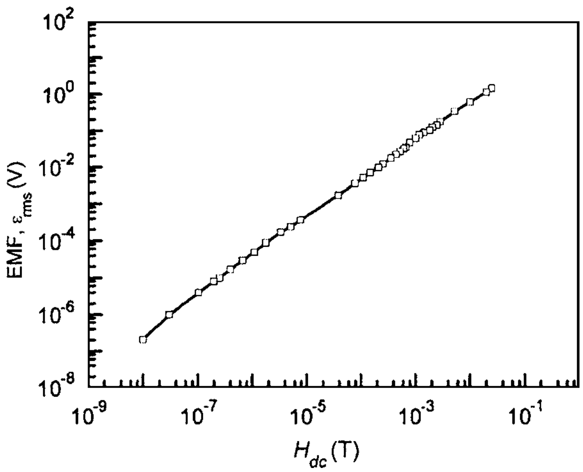

FIG. 4. Induced EMF as function of the dc magnetic field from $10^{-8} < H_{dc} < 2.5\times 10^{-2}$ T. The measurement conditions were $E_0 = 3\times 10^4$ V/m and $f_r = 37.6$ kHz.

The EMF was then detected over a broad dc magnetic field range of $10^{-8} < H_{dc} < 2.5\times 10^{-2}$ T, using a lock-in amplifier (SR830). The driving electric field was set to $E_0 = 3\times 10^4$ V/m and $f_r = 37.6$ kHz. As shown in Fig. 4, the EMF (rms value) has a good linear response to H_{dc} in the range of $10^{-8} < H_{dc} < 2.5\times 10^{-2}$ T, and a detection sensitivity of $\sim$20 nT/μV was obtained. Further investigations showed that the detection sensitivity increased proportionally with increasing the driving electric field strength. These results demonstrate that the composite structure with EIM effect is highly sensitive to the low-level dc magnetic field and is an idea candidate for the dc magnetic field detection. Recently, Dong *et al.* also reported the similar low-level dc magnetic field detection based on alternate MIEP effect in the Terfenol-D/PMN-PT laminates.[20] They detected dc magnetic field by measuring the induced voltage in piezoelectric layer by an applied magnetic field, and their detection sensitivity could also be very high due to the enhanced MIEP gain if the laminates operate at resonance. Additionally, we noted that, for our EIM composite structures, as the system noise was well controlled and the driving electric field strength was enough, the EMF output could still be detected even if H_{dc} was below 10^{-10} T. Further work will be done to extend the detection limits and increase the detection sensitivity.

In summary, the EIM effect has been found in the longitudinal-coupling composite structure made by combining PZT and Terfenol-D. The acoustics-transferred stress in the Terfenol-D induced by the piezoelectric effect of the PZT is responsible for this EIM effect. The results showed that this EIM effect depended significantly on the driving electric field frequency and was highly sensitive to the external dc magnetic bias. The results also demonstrated the potential for the EIM effect in the application of low-level dc magnetic field detection.

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