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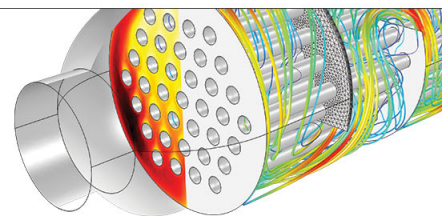
Resonant bending mode of Terfenol-D/steel/Pb(Zr,Ti)O$_3$ magnetoelectric laminate composites

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Resonant bending-mode Tb$_{1-x}$Dy$_x$Fe$_{2-y}$/elastic-steel/Pb(Zr,Ti)O$_3$ magnetoelectric (ME) laminate composites have been investigated. An elastic-steel layer with a relatively high Q_m significantly increases the resonant enhancement of the ME coefficient due to an increased effective Q_m of the laminate. The three-phase ME laminates have a low first-order bending frequency of ~5 kHz, with a resonance-enhanced ME coefficient of ~40 V/cm Oe. © *2006 American Institute of Physics*.
[DOI: 10.1063/1.2353819]

The magnetoelectric (ME) effect is characterized by an induced electric polarization in response to an applied magnetic field (H), or by an induced magnetization in response to an applied electric field (E).[1] Materials with a ME effect have been reported in single phase materials, composites, and thin films.[2–7] ME effects in two-phase magnetostrictive/piezoelectric composites are known to be much higher than those in single phases, offering promise for magnetic moment sensing and other applications.[8–10] Due to a strong elastic coupling between magnetostrictive and piezoelectric layers, laminated composites (constructed by epoxing the two layers together) have recently been the focus of investigations.[5,6,8–17] In this case, when an ac magnetic field is applied to the laminated composite, the magnetostrictive layer(s) will elastically force the piezoelectric layer(s) to strain, generating a piezoelectric charge.

To date, investigations have focused on two phase laminates: consisting of piezoelectric Pb(Zr,Ti)O$_3$ (PZT) or PbMg$_{1/3}$Nb$_{2/3}$O$_3$−PbTiO$_3$ layer(s) epoxied to magnetostrictive Tb$_{0.3}$Dy$_{0.7}$Fe$_2$ (Terfenol-D), Fe–Ga, or Co/Zn-ferrite ones.[5,6,8,18] Various laminate configurations have been studied including longitudinal-longitudinal (LL), transverse-longitudinal (TL), LT, TT, push-pull, bimorph, and multilayer.[11–17,19,20] A resonance enhancement (~100 times) of the ME voltage coefficient (V_{ME}) has been reported at the first longitudinal mode (f_0).[21–23] Such enhancement is potentially very important; however, it is limited to a relatively high frequency: for example, consider a 15 mm long Terfenol-D/PZT LT mode laminate, $V_{ME} \approx 18.5$ V/cm Oe at $f_0 \approx 80$ kHz.[11] For ME laminates having a Terfenol-D layer(s), a high resonant frequency of ≥ 10 kHz will result in significant eddy current losses due to the conductive nature of the Terfenol-D layer, which in turn will dramatically lower the efficiency of energy conversion. The longitudinal resonance frequency could be lowered by increasing the length of the Terfenol-D/PZT laminate; however, this goes against the need for miniaturization of devices. Another alternative method to overcome eddy current losses might be to cut Terfenol-D into thin pieces, and then bond these pieces into stacked layers with high resistant epoxy. Unfortunately, Terfenol-D is very brittle,[24] making it very difficult to cut into thin layer of <0.5 mm. A unimorph type of ME

Terfenol-D particulate-epoxy composite/piezoelectric laminate operating in bending mode[19] also has relative lower resonance frequency. However, compared with longitudinal (LL or LT) modes, the ME coupling in a unimorph bending mode is relative lower: ~15 V/cm Oe in the first bending resonance mode.[19] We believe that this low efficiency is due to the low effective mechanical quality factor $Q_{m,eff}$ in bending resonance modes.[25–28]

In this letter, we will show by incorporating a relatively high-Q_m elastic steel (third phase) layer in magnetostrictive/piezoelectric laminates that (i) the resonance frequency can be notably decreased without increasing the size of Terfenol-D, while (ii) the resonance enhancement of the ME effect is significantly increased. Our concept for a Terfenol-D/elastic-steel/PZT ME laminate is illustrated in Fig. 1(a). For comparisons, part (b) of this figure illustrates a Terfenol-D/PZT unimorph-type construction. The sizes of the Terfenol-D, PZT (APC-850), and steel layers in Fig. 1(a) are $14 \times 6 \times 1.1$, $15 \times 6 \times 0.5$, and $32 \times 6 \times 0.09$ mm^3, respectively. These layers were bonded together using an epoxy. The magnetization (**M**) of the magnetostrictive Terfenol-D layer was oriented along the longitudinal (or X axis) direction and that of the polarization (**P**) of the piezoelectric PZT ones were along the thickness (or Z axis) direction. Because the Terfenol-D layer was asymmetrically bonded to one side of the elastic-steel layer [see Fig. 1(a)], a low-frequency bending moment was produced in response to an applied magnetic field **H** that was ∥X.

We suppose that the ME laminate is a free bar. Its first bending-mode resonance frequency is much lower than that
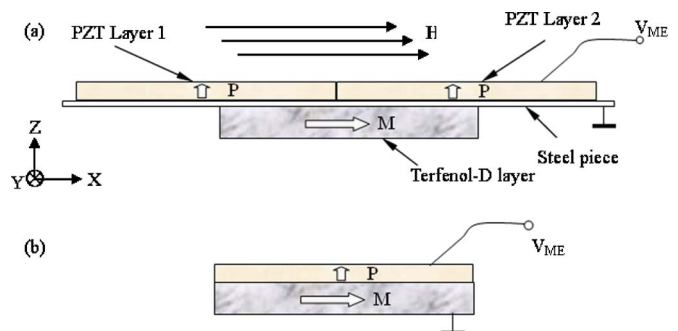

FIG. 1. (Color online) Illustration of ME laminate configurations (a) Terfenol-D/steel/PZT three-phase bending-mode unimorph and (b) Terfenol-D/PZT unimorph.

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TABLE I. Typical material parameters for the laminate layers.

	Q_m	Density (g/cm)	Elastic compliance (m²/N)	Volume fraction	Area fraction
Terfenol-D	<10	9.2	1.67×10^{-11}	0.463	0.651
Steel	~200	7.7	5.12×10^{-12}	0.0865	0.053
PZT-850	~80	7.7	1.59×10^{-11}	0.225	0.296

of the fundamental longitudinal mode. Precise solutions to first bending-mode resonance frequency of this ME laminate are quite complicated, because of its irregular shape. However, we noted that the first bending-mode of ME laminate is mainly determined by high-stiffness elastic steel layer's length l and the laminate's thickness d. By introducing a mean mass density $\bar{\rho}$ and the equivalent elastic compliance $\bar{s}_{11}$ of the laminate, we suppose that the first bending-mode resonant frequency of the laminate is[19,29]

$$f_l = \frac{\pi d}{4\sqrt{3}l^2}\sqrt{\frac{1}{\bar{\rho}\bar{s}_{11}}}\beta_1^2, \qquad (1)$$

where $\beta_1 \approx 3/2$ is the first mode order, and the average density $\bar{\rho}$ and equivalent elastic compliance $\bar{s}_{11}$ of our three-phase bending-mode laminate are then

$$\bar{\rho} = \gamma_m \rho_m + \gamma_s \rho_s + \gamma_p \rho_p, \qquad (2a)$$

$$\overline{S_{11}} = \frac{S_{11}^m S_{11}^P S_{11}^S}{\chi_m S_{11}^P S_{11}^S + \chi_m S_{11}^m S_{11}^S + \chi_S S_{11}^m S_{11}^P}, \qquad (2b)$$

where γ_m, γ_s, and γ_p are the volume fractions of Terfenol-D, elastic-steel, and PZT-850 layers, respectively, ρ_m, ρ_s, and ρ_p the respective densities of the layers, S_{11}^m, S_{11}^S, and S_{11}^P the respective elastic compliances of the layers, and χ_m, χ_S, and χ_P the respective cross-sectional area fractions. Using typical material parameters for the respective layers of the laminate given in Table I, Eqs. (1) and (2), and the laminate geometries given above, we can predict the resonance frequency of the first bending mode ($n=1$) of the three-phase laminates to be ~5.1 kHz. This predicted value is very close to the measured one (as will be shown below in Fig. 3).

We next calculated the vibrations of the first bending mode of our three-phase ME laminate using finite element analysis (FEA), assuming free-free boundary conditions, as shown in Fig. 2. Both nodes were located near the two ends of the Terfenol-D layers. Since the middle part of the laminate has higher effective stiffness and mass than those at the two ends, the vibration amplitudes at the ends are much larger than that at the center. Furthermore, the elastic-steel (high Q_m) layer will increase the effective mechanical factor $Q_{m,\text{eff}}$ of the laminate, which will in turn increase the reso-
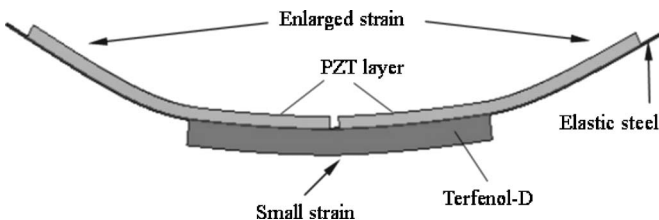

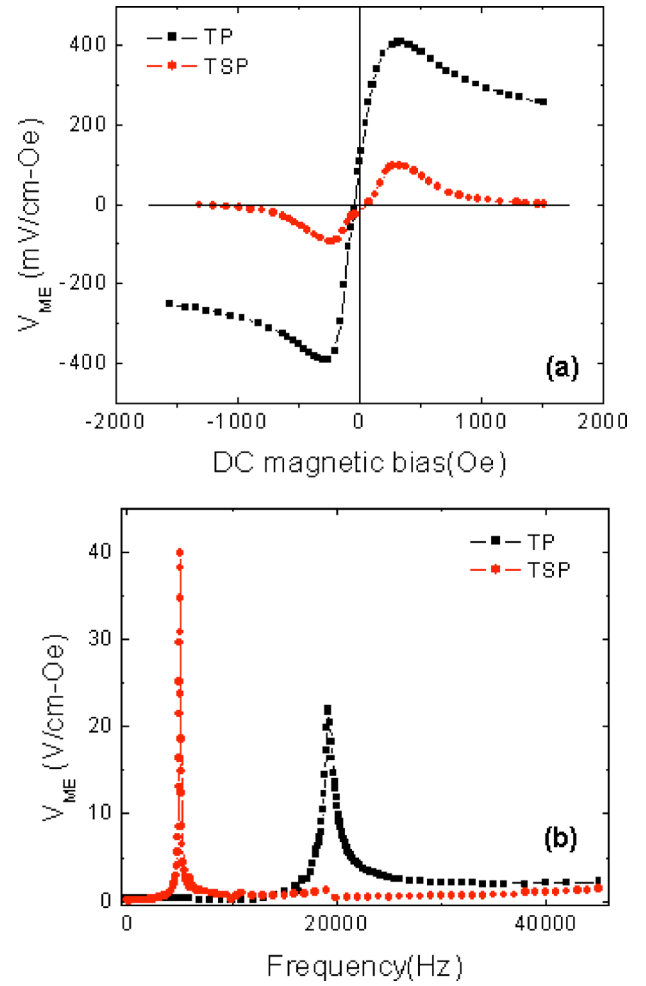FIG. 2. Illustration of the first bending-mode vibrations, calculated using FEA method.

FIG. 3. (Color online) Magnetoelectric voltage coefficient (V_{ME}) for both our Terfenol-D/steel/PZT and Terfenol-D/PZT laminates: (a) as a function of dc magnetic bias taken at a measurement frequency of $f=100$ Hz and (b) as a function of frequency taken under a dc magnetic bias of $H_{dc}=300$ Oe.

nance enhancement of V_{ME}, in a manner that is directly proportional to the $Q_{m,\text{eff}}$ of the laminate,[30] given as

$$dV_{ME}/dH \propto \frac{Q_{m,\text{eff}}\varphi_m\varphi_p}{Z_0}, \qquad (3)$$

where φ_m and φ_p are magnetoelastic and elastoelectric coupling factors in the bending mode and Z_0 the characteristic mechanical impedance of the laminate.

Experimental investigations of the ME properties were then carried out by placing the laminates in a Helmholtz coil (holding the sample at the two nodes) and applying a small ac magnetic field (H_{ac}) along the longitudinal direction of the laminate. A dc magnetic bias (H_{dc}) was superimposed to H_{ac} along that same direction. The voltages induced across the PZT layer(s) were then measured for various H_{dc} and H_{ac} over a wide frequency range of 10–50 kHz using a lock-in amplifier method.

Figure 3(a) shows V_{ME} (in V/cm Oe) for both our three-phase bending-mode laminate [Fig. 1(a)] and for comparisons a corresponding unimorph [Fig. 1(b)]. Data are shown as a function of H_{dc} at a measurement frequency of $f=100$ Hz. A maximum value of V_{ME} can be seen for both laminates at $H_{dc} \approx 300$ Oe: this maximum occurs when the magnetic layer has a maximum effective piezomagnetic coefficient. At low frequencies (subresonant), the unimorph

ME laminate has a notably higher value of V_{ME} than our three-phase one. From these data, it can be concluded that a colaminated elastic-steel layer in ME laminates does not facilitate ME coupling at low frequencies.

However, under resonance drive, we will next show that colamination with an elastic-steel layer increases the resonance enhancement of V_{ME}. Figure 3(b) shows V_{ME} of both the bending-mode and unimorph laminates as a function of the drive frequency. In this figure, our three-phase bending-mode laminate can be seen to have a sharp resonance frequency at ~5 kHz, in agreement with that predicted by Eq. (3), with a resonance-enhanced ME coefficient of V_{ME} =40 V/cm Oe, whereas, the unimorph of similar Terfenol-D and PZT layer geometries had a first bending-mode resonance frequency of 19.2 kHz and a resonance-enhanced V_{ME} of 22 V/cm Oe.

The effective mechanical quality factor can be determined from the resonance peak as $Q_{m,\text{eff}} = f_r / \Delta f$, where Δf is the 3 dB bandwidth. For our three-phase laminate $Q_{m,\text{eff}} \approx 78$, whereas that of the unimorph was ≈ 30: a ratio of $\approx 2:1$, similar to that experimentally observed in V_{ME} [see Fig. 3(b)], and consistent with predictions of Eq. (3). These data demonstrate that a relatively high Q_m elastic phase will increase the value of laminate's $Q_{m,\text{eff}}$, which result in increased resonance enhancement in V_{ME}. The results provide insights into how enhanced ME interactions over desired frequency ranges can be developed by designing laminate configurations: such flexibility could be important to electromagnetic energy conversion, sensors, filters, and resonators based on ME laminates.

In summary, a resonant bending-mode has been investigated in Terfenol-D/elastic-steel/PZT ME laminates. We have found that said three-phase laminates have larger resonance enhancements in the ME voltage coefficient (i.e., high $Q_{m,\text{eff}}$ due to a high Q_m colaminate elastic-steel layer), while operated at significantly lower resonance frequencies (i.e., length extensional bending-mode vibration). Our three-phase bending-mode laminates had ME voltage coefficients of ~40 V/cm Oe at resonance frequencies of ~5 kHz.

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