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Enhanced magnetoelectric effect in Terfenol-D and flextensional cymbal laminates

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A magnetoelectric (ME) laminate configuration was fabricated using a flextensional cymbal located between two magnetostrictive Terfenol-D ($Tb_{1-x}Dy_xFe_2$) plates. The laminate, operating in transverse magnetized/transverse polarized mode, has a ME voltage coefficient of 56.8 mV/Oe under a magnetic bias field of 1 kOe, which is larger than that of conventional Terfenol-D/PZT/Terfenol-D configuration. It is believed that the enhancement of ME effect is due to the coupling between the magnetostriction of Terfenol-D and the high piezoelectric response of cymbal. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2200389]

Recently the magnetoelectric (ME) effect has been intensively studied in single-phase materials that simultaneously reveal ferromagnetic and ferroelectric properties and in multiphase materials that are composed of ferromagnetic and ferroelectric phases in laminate and composite configurations, due to their potential applications as current and magnetic sensors and magnetic-electric transformers.[1–3] A three-layer laminate of Terfenol-D ($Tb_{1-x}Dy_xFe_2$)/piezoelectrics (e.g., PZT, PMN-PT, or PZN-PT)/Terfenol-D exhibits giant ME voltage coefficient and ultrahigh sensitivity in detection of electric current and magnetic field.[4,5] To date, it is known that magnetostrictive/piezoelectric laminates have become more promising magnetoelectric devices than single-phase material derived ME devices. For conventional transverse magnetized/transverse polarized (T-T) mode, the magnetostrictive layer and piezoelectric layer in ME laminate were magnetized and polarized along their thickness directions, respectively.[2] This kind of laminates may be in the type of disk or rectangular ones. However, it is found the laminate in T-T mode has a smaller ME voltage coefficient compared to other longitudinal magnetized/longitudinal polarized (L-L) mode and transversed magnetized/logitudinal polarized (T-L) mode,[1] which limit its application as high sensitivity current detectors. It is still a challenge to improve the ME coupling coefficient for laminates operated in T-T mode. A simple way is to find out a piezoelectric material or its alternative with a higher piezoelectric constant. Of all the alternatives, cymbal is one of the best promising candidates. The cymbal transducer is a class V flextensional transducer capable of tailoring ultrasound applications with near 40 times higher displacement and 40 times higher effective piezoelectric charge coefficient.[6–8] In this letter we report a novel ME laminate by using a flextensional cymbal as the piezoelectric layer placed between two magnetostrictive Terfenol-D plates. Their ME properties were measured and compared with the conventional T-T mode using PZT ceramic as the piezoelectric layer.

The configuration of our laminate is shown in Fig. 1. Details regarding the design and construction of the cymbal transducer can be found elsewhere.[7] In this work, the cymbal layer was prepared using the piezoelectric ceramic disk (PZT, Piezo Kinetics Inc.) and titanium end caps. The ceramic disk is 12.7 mm in diameter and 1.0 mm in thickness, poled in the thickness direction. The end caps are made of 0.3 mm thick titanium. The Terfenol-D ($Tb_{1-x}Dy_xFe_2$) plates with 4 mm in diameter and 2 mm in thickness were magnetized in the thickness direction under a static direct current (dc) magnetic field of 1.5 kOe for about 30 min. The cymbal was bonded between two Terfenol-D disks, using Eccobond epoxy (Emerson & Cuming, Billerica, MA). As shown in Fig. 1(b), the laminate was fixed in a jig in order to obtain optimum output signal.

An electromagnet was used to apply a dc magnetic bias H_{bias} of 0–3 kOe, equipped with water-cooled solenoids. A pair of Helmholtz coils were applied to excite an alternating current (ac) magnetic field H_{ac} of 0–310 Oe at $f=1$ kHz, which was superimposed on H_{bias}. The laminate was placed in the center of small Helmholtz coils. The Helmholtz coils and the ac electromagnetic field were driven by a signal generator (HP 33120A) via a power amplifier (Sorensen DHP Series), monitored by an oscilloscope (HP 54522A). Both the magnetic drive and bias fields were parallel to the transverse (thickness) direction of the laminate. The magnetic field was measured using a Hall-effect probe situated adjacent to the laminate and connected to a gaussmeter (model 7030, Gausee/Teslameter, SYPRIS). The ME voltage was determined by the electric voltage, induced on the end caps of cymbal under an open-circuit condition, and recorded by a network analyzer [a multipurpose fast Fourier transform (FFT) analyzer (ONOSOKKI CF-5220].

Figure 2 shows the impedance spectra of the ME laminate in a broad frequency range. For the cymbal that we used, the first resonance peak of frequency corresponds to

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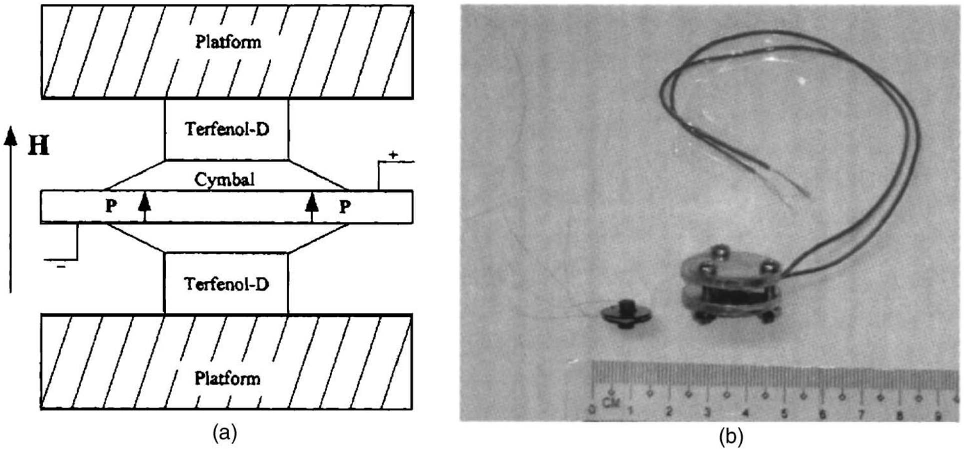

FIG. 1. (a) Schematic configuration of ME laminate; (b) photo of the ME laminate.

the flextensional mode and can be expressed as[9]

$$f_{\mathrm{ft}} \propto \sqrt{\frac{E}{\rho}\left[\frac{1}{\phi_c^2(1-\sigma^2)}+\frac{1}{R^2}\right]}, \quad (1)$$

where ρ is the density of end cap material, ϕ_c is the diameter of the end cap cavity, R is the end cap radius, E is Young's modulus of the end cap, and σ is Poisson's ratio. For the ME laminate based on the cymbal, the effective radius R and ϕ_c increased due to the bonding of Terfenol-D plates, which causes the f_{ft} to dramatically shift towards low frequency and even disappear from the impedance-frequency spectra. As shown in Fig. 2, the first resonance peak (~20 kHz for the cymbal) indeed disappears. The resonance peak at 203 kHz comes from the coupling between the radial mode of PZT and higher order flextensional modes. It is slightly larger than that of the cymbal without bonding to the Terfenol-D (197 kHz).[8] The impedance spectrum shown in Fig. 2 is an indication of a well-bonded and symmetric ME laminate in the design. It is deduced that the second large peak makes great contribution to the resonance of the ME device in a magnetic field. Since the frequency (~200 kHz) is beyond the measuring frequency of our setup, the dV/dH as a function of frequency did not show any significant resonance peak in the frequency range of 0–100 kHz.

The d_{33} value measured was 12 009 and 7308 pC/N for cymbal and ME laminate, respectively. It significantly decreased after bonding the cymbal with Terfenol-D but was still considerably larger than that of PZT ceramics (550 pC/N).

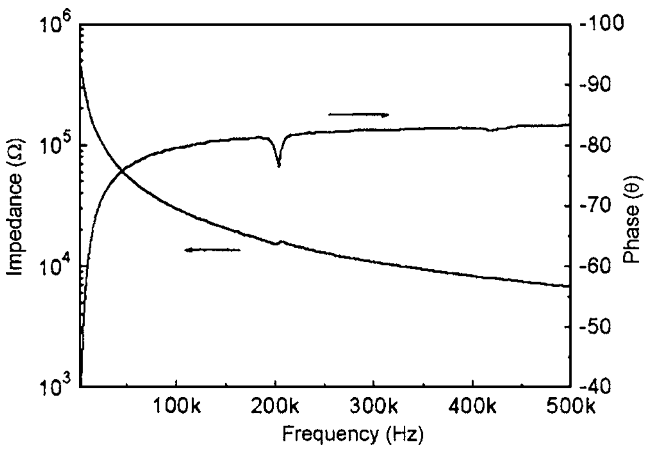

FIG. 2. Impedance spectra of ME laminate.

Figure 3 shows the induced ME voltage V_{rms} (root mean square value of voltage) as a function of H_{ac} ($f=1$ kHz). The magnetic bias field H_{bias} was increased from 0, 500, 1000, to 1500 Oe. In a magnetic bias field of 500 Oe and at 1 kHz of ac magnetic field, the induced ME voltage coefficient is 41.0 mV/Oe. While the ME voltage coefficient of the counterpart laminate using PZT ceramic as piezoelectric material is 10 mV/Oe under the same measuring conditions,[10] the ME voltage coefficient of the new laminate is four times that of previous counterpart laminate.

Assuming that there are no dielectric loss and no magnetic loss in the bonding layer and the laminate is similar to a sandwiched Terfenol-D/PZT/Terfenol-D configuration, the ME voltage coefficient can be in principle adopted from the formula that was deduced by Dong *et al.*[1] for a L-L mode. However, the difference is that the z direction is in the thickness direction in our laminate and the interaction between the magnetostrictive material and the metallic end cap is different from that between the Terfenol-D and the PZT ceramic. Here we use a magnetoelastic coupling factor φ_m to illustrate the interaction between the Terfenol-D and the cymbal. In addition, the interaction between the metallic end cap and the PZT ceramic is in terms of the effective piezoelectric coefficient d_{33}^{eff} of the cymbal. The effective piezoelectric charge coefficient d_{33} for a "cymbal" transducer can be expressed as $d_{33}^{\mathrm{eff}}=d_{33}-d_{31}\tan\theta$, where θ is the angle between the slope of metal end cap and the normal of the cavity in the cymbal

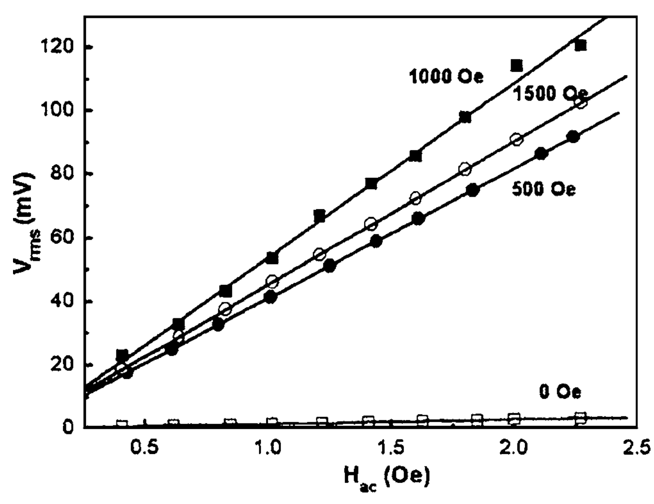

FIG. 3. The ME voltage as a function of H_{ac}. $H_{\mathrm{bias}}=0$, 500, 1000, and 1500 Oe.

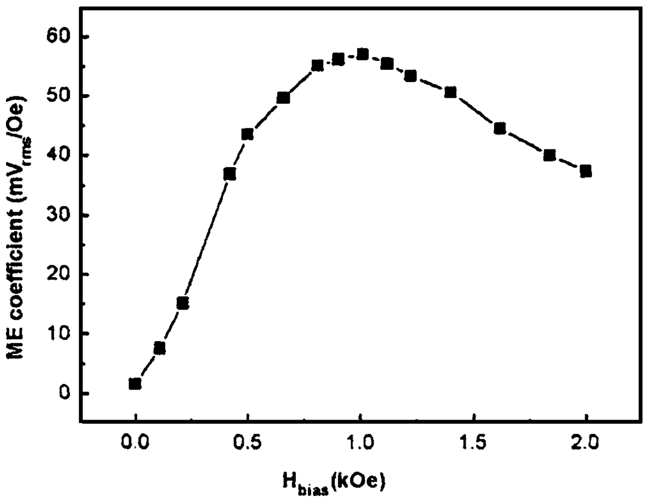

FIG. 4. The ME voltage coefficients as a function of H_{bias} at $H_{ac}=2$ Oe and $f=1$ kHz.

layer. Note that the negative value of d_{31} acts positively to the d_{33}^{eff}.[11] Therefore, the ME voltage coefficient can be roughly expressed as[1,12,13]

$$\left|\frac{dV}{dH}\right|_{\text{T-T}} = \left|\frac{dV_{out}}{dH}\right| \propto \varphi_m d_{33}^{eff}. \quad (2)$$

It can be seen that the increase of effective piezoelectric coefficient will result in the enhancement of the ME voltage coefficient of the laminate.

Figure 4 shows the ME voltage coefficient as a function of H_{bias} with an ac driving field of 2 Oe ($f=1$ kHz). The ME voltage coefficient of the Terfenol-D/cymbal laminate is strongly dependent on the dc magnetic bias and there is an optimum H_{bias} at which the ME effect reaches a maximum. $|dV/dH|_{\text{T-T}}$ has a maximum value of 56.8 mV/Oe at $H_{bias}=1$ kOe. However, with further increasing the dc magnetic bias, the ME voltage coefficient decreases. The reason may mainly be that the effective magnetostrictive coefficient (or $d\lambda/dH$) decreases with the magnetic bias field,[14] then $d_{33,m}$ also decreases with H_{bias}.

In conclusion, magnetoelectric laminate composite using Terfenol-D and flextensional cymbal has been fabricated and characterized in transverse-transverse (T-T) operation mode. The maximum value of $|dV/dH|_{\text{T-T}}$ was 56.8 mV/Oe under a dc magnetic bias field of 1 kOe. The ME voltage coefficient is four times that of the conventional Terfenol-D/PZT/Terfenol-D laminate in T-T mode under the same measuring conditions.

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