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Giant magnetoelectric effect in $Pb(Zr,Ti)O_3$-bimorph/NdFeB laminate device

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A $Pb(Zr,Ti)O_3$-bimorph/NdFeB laminate device has a giant magnetoelectric (ME) effect. Our results reveal a giant ME coefficient of 16 V/cm Oe or 62 nC/cm Oe at a low (subresonant) frequency of 10 Hz, and one of 250 V/cm Oe or 960 nC/cm Oe at a first order resonant bending mode frequency of ~60 Hz. The findings show a simple means by which to achieve magnetoelectric effects, without the use of magnetostrictive material. © *2008 American Institute of Physics*.
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Giant magnetoelectric (ME) effects are well known in laminated composites consisting of piezoelectric and magnetostrictive layers, such as Terfenol-D/$Pb(Zr_{1-x}Ti_x)O_3$ (PZT) and Metglas/PZT.[1,2] To obtain the highest ME coefficients (α_{ME}), laminates must be dc biased to the point of maximum slope in the ε-H (strain-magnetic field) curve. Because the demagnetization factor of the magnetostrictive layer depends on laminate geometry, the magnetic dc bias (H_{dc}) required to achieve the maximum value of α_{ME} depends strongly on laminate construction and geometry.[3–7] Also, it is not easy to make H_{dc} uniform within a modest-sized laminate: this is because the field distribution within a permanent magnet is not perfectly uniform, nor is the permeability of the magnetostrictive layer perfectly uniform.

Under electromechanical resonance (EMR) drive, the ME effect is known to be dramatically enhanced.[8,9] The largest ME voltage coefficients (α_{ME}) to date have been reported for the Metglas/$Pb(Zn_{1/3},Nb_{2/3})O_3-7\%\ PbTiO_3$ (PZNPT) fibers laminate, where $\alpha_{ME}\approx 10.5$ V/cm Oe at low (subresonant) frequencies, and $\alpha_{ME}\approx 400$ V/cm Oe at EMR frequencies of about $\geqslant 20$ kHz.[10] Recently, a low resonant bending mode in three phase Terfenol-D/Steel/PZT ME laminates was reported. A steel phase with a high mechanical Q increased the ME coefficient, while lowering the resonant frequency without increasing the size of the magnetostrictive phase.[11] In this case, lower resonance frequencies offer the potential to enhance the ME coefficient for applications such as small magnetic field sensors.

The giant ME effect in current ME laminates has a very simple magnetoelastoelectric origin: application of magnetic field (H) results in a shape change in the magnetostrictive layer, which due to elastic bonding transmits the induced shape change to the piezoelectric one that subsequently induces a voltage across the dielectric layer via piezoelectricity.

Giant ME effect is not limited to piezoelectric layers laminated together with magnetostrictive ones, but will rather be apparent for the general case when a magnetic force can mechanically act upon a piezoelectric layer. Here, we show that an apparent ME effect can be simply realized by attaching permanent magnets to a piezoelectric cantilever. In this case, magnetostrictive layers are not required to achieve giant ME coefficients. When we applied an external ac magnetic field to this device, the applied ac magnetic field will then interact with the static magnetic field provided by the magnets; this interaction will induce a magnetic force which will pass through the magnets to the piezoelectric cantilever; and the electromechanical coupling in piezoelectric cantilever will then induce a charge output. This ME effect is a complex coupling resulted from the magnetomagnetic coupling, magnetomechanical coupling, and electromechanical coupling. Further, the attached magnets will also serve as a tip mass loading which will further reduce the resonant frequency,[12,13] offering the potential of resonance-enhanced ME coefficients at extremely low frequencies.

In Fig. 1, we show (a) the structure of our PZT bimorph with attached NdFeB magnets, and (b) a photograph of a prototype bimorph which when clamped at one end acts like a cantilever if acted upon by an external magnetic field. The PZT bimorph was constructed using two pieces of PZT-850 (each $28\times 6\times 0.3$ mm^3 in size), whose layers were poled in opposite thickness directions. The size of the NdFeB magnets was $\Phi 6.35\times 9.5$ mm^2, which were attached to the PZT bimorph by use of a high strength epoxy. For a clamped-free mode bar (i.e., a vibrating cantilever), the bending resonance frequency (f_n) is given as[14]

$$f_n = \frac{\pi d}{4\sqrt{3}l^2}\sqrt{\frac{1}{\bar{\rho}\bar{s}_{22}}}\beta_n^2, \qquad (1)$$

where d is the thickness of the laminate, l is its length, $\bar{\rho}$ its average density, and $\overline{S_{22}}$ its equivalent elastic compliance; and where $\beta_1=0.597$, $\beta_2=1.494$, and $\beta_n\approx(n-0.5)$ for $n>2$, where n is the order of the bending mode. The first order bending mode resonance frequency can be estimated by Eq. (1) to be about 180 Hz for the PZT-bimorph cantilever, where $\rho=7.7$ g/cm^3 and $s=1.6\times 10^{-11}$ m^2/N for PZT-850. The attached NdFeB magnets will then act as a tip mass loading, further lowering its resonance frequency.

An external magnetic field applied along the length of the bimorph will interact with the permanent magnets attached on the free end. This interaction will then induce a bending moment on the PZT bimorph, as illustrated in Fig. 1(c). Please note that there is a neutral surface between the PZT layers of the bimorph, where the stress statuses are opposite to each other: in this case, the induced charges across the PZT layers will also be opposite. In our experiments, the magnets attached to the bimorph cantilever were excited using a Helmholtz coil, and α_{ME} was measured using a lock-in amplifier (SR850).

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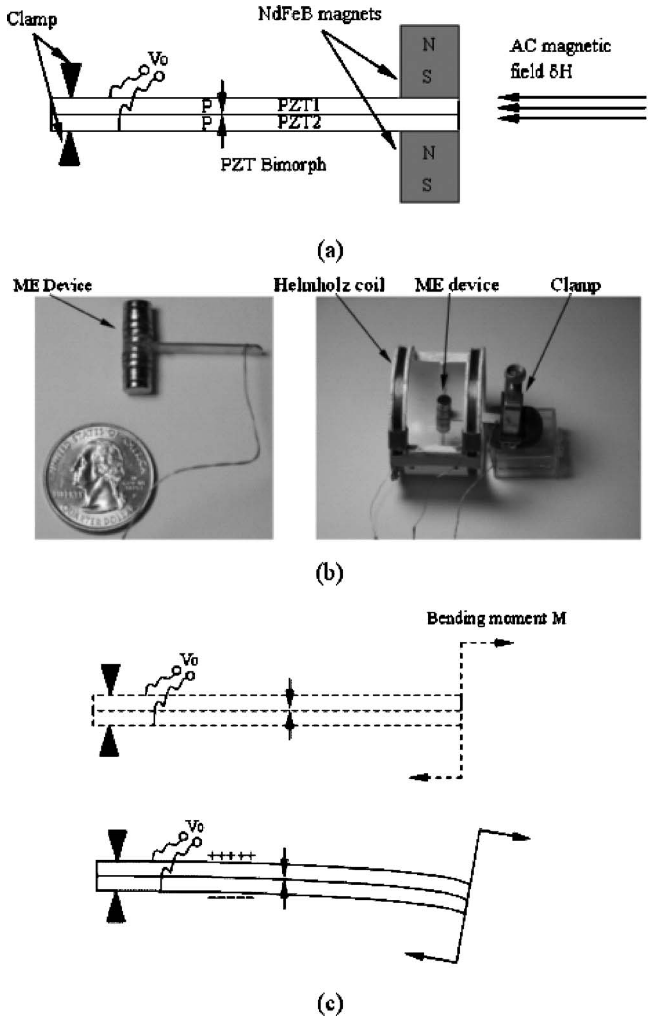

FIG. 1. (a) Structure of NdFeb/PZT-bimorph/NdFeb; (b) photograph of prototype device and testing; and (c) illustration of the working principle.

In Fig. 2, we show the ME coefficient as a function of frequency for $10 < f < 500$ Hz, performed using the prototype shown in Fig. 1(b). In this figure, it can be see that ME voltage coefficients as a high as $\alpha_{ME} = 16$ V/cm Oe can be obtained at subresonant frequencies of $f \approx 10$ Hz. Under EMR conditions, the ME voltage coefficient was enhanced to ~250 V/cm Oe at a first order bending mode frequency of ~60 Hz. The corresponding ME charge coefficients were 62 nC/cm Oe at 10 Hz and 960 nC/cm Oe at the first bending mode. These values are larger than the highest value ever reported for a ME laminate, which was $\alpha_{ME} \approx 10.5$ V/cm Oe for Metglas/PZNPT composites. The large values for our PZT bimorph are due to the strength of the NdFeB permanent magnets placed on the free end of the cantilever, which when acted upon by external magnetic fields will induce large mechanical forces. It must be noted that these large effects are not uniform along the length of the PZT bimorph, but rather limited to the region closest to the clamped end of the cantilever.[15]

Our findings show several simple insights into ME effects in layered composites. First, magnetostrictive layers are not necessarily required to achieve giant ME coefficients. Rather, a simple piezoelectric cantilever with attached permanent magnets on the free end will induce large voltages (and charges) in response to external magnetic fields. Second, the resonance enhancement of the ME effect can be dramatically shifted to lower frequencies by use of a clamped-free bending mode, which can be even further reduced by a tip mass loading method. This makes feasible dramatic enhancements of ME effects (over narrow bandwidths) at extremely low frequencies.

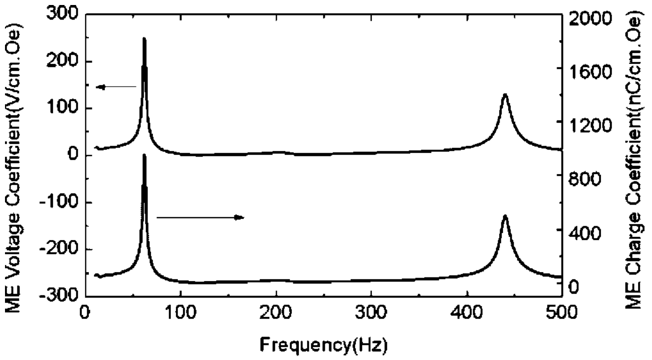

FIG. 2. Frequency dependence of (a) the ME voltage coefficient and (b) the ME charge coefficient.

In summary, we have found large apparent ME effects in simple PZT bimorphs with attached NdFeB magnets. A tip mass loading method was used to further reduce the frequency of a resonant bending mode. Our results show giant ME effects of ~16 V/cm Oe or 62 nC/cm Oe at low subresonant frequencies (~10 Hz), and ~250 V/cm Oe or 960 nC/cm Oe at the first bending mode frequency (~60 Hz).

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