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Giant resonant magnetoelectric effect in bi-layered Metglas/Pb(Zr,Ti)O_3 composites

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In this paper, giant resonant magnetoelectric (ME) effect in an unsymmetrical bi-layered Metglas/Pb(Zr,Ti)O_3 ME composites with multi-push pull configuration that can be significantly tuned was investigated experimentally and theoretically. The actual measured and predicted results present the similar resonant frequency shifting behaviors for such ME composites: The resonant frequency can be varied from 70 Hz to 220 Hz by tip mass loading, where the ME voltage coefficients were over 250 V/cm-Oe. Moreover, the giant frequency-tunable resonant effect allowed us to design a 60 Hz magnetic field energy harvester to be capable of harvesting energy generated by electronic instruments working on a 60 Hz ac power supply. © *2012 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4765724]

I. INTRODUCTION

The magnetoelectric (ME) effect is a change in electric polarization under magnetic field, or conversely a change in magnetization with applied electric field.[1,2] To date, giant ME coupling effects have been found in engineered ME composites, where ferroelectric and ferromagnetic properties are coupled through strain across an interface between magnetostrictive and piezoelectric layers.[3] Recently, there have been many investigations on developing multifunctional devices based on ME composites,[4,5] and studying the influences of environmental conditions on devices' performances.[6]

However, one of the biggest challenges for practical application of such devices has been the ME coefficient α_{ME}, which limits the performances of the ME devices. Thus, it is highly desirable to enhance the value of α_{ME} in order to optimize the property of ME devices. Recent investigations have found driving ME composites under resonant frequency (f_r) can improve α_{ME} dramatically and improve the sensitivity of ME magnetic sensor greatly.[7] The benefit, however, is only useful for a very narrow responsive frequency bandwidth rendering a greatly reduced applications. In order to apply the resonant ME effect at various frequencies, some approaches have been studied to tune the resonant frequency of ME composites.[8–10] In the prior investigations, however, the restrictive experimental conditions were required in these researches, such as double-side clamped edges. Otherwise, the resonant ME coefficients were not impressive which limit the performances of devices as well. Thus, giant resonant ME effect that can be tuned easily is highly desirable.

Here, we present a simple approach to tune the resonance frequency (f_r) of Metglas/Pb(Zr,Ti)O_3 (PZT) bi-layer composites without losing the value of α_{ME} greatly. Investigations show that bi-layered Metglas/PZT composites with multi-push pull configuration have giant resonant ME coefficients of α_{ME} >400 V/cm-Oe. Moreover, by loading tip mass on two edges of composites, resonant frequency of f_r was shifted from 70 Hz to 220 Hz easily, which will enable the design of devices working at various frequencies. A theoretical model for bi-layered ME composites was developed to describe the resonant frequency tunability with tip mass. The predicted results match the experimental data well. Based on great tunability of resonant ME effect, a 60 Hz magnetic energy harvester was developed which can capture 60 Hz magnetic energy generated by electronic instruments operating on the ac power supply.

II. EXPERIMENTAL DETAILS

To fabricate bi-layered Metglas/PZT laminates, we obtain commercially available PZT fibers from Smart Materials (Florida, USA) and Metglas foils from Vitrovac Company (Germany). During fabrication, five pieces of 180 μm thick piezoelectric fibers were oriented along the long axes to form a layer that was in total 10 mm wide and 40 mm long. Then, two interdigited (ID) Kapton®-based electrodes were bonded to the top and bottom surfaces of the piezoelectric layer in a multi push-pull mode configuration.[11] Five Metglas foils of 80 mm in length and 10 mm in width were bonded together, and subsequently laminated to only the bottom surface of the PZT fiber layer to form a bi-layered bending mode structure.

III. RESULTS AND DISCUSSIONS

First, the shift in f_r with tip mass weight was measured using an impedance analyzer (Agilent 4294 A). Tip masses were added to the two edges of the bi-layered composites, as shown in the insert of Figure 1(a). Commercial permanent magnets D41 with mass of 0.377 g from K&J Magnetics (USA) were used as the tip mass. Using small magnets can provide the tip mass and the DC bias at the same time. Thus, there is no necessary to apply the external DC magnetic field in measurement. Accordingly, the resonant frequency measured by the impedance analyzer was a compositive effect of magnetomechanical resonance (MMR) in Metglas and electromechanical resonance (EMR) in the piezo-layers, as shown in Figure 1(a). One can see that the fundamental resonant frequency was observed at $f = 215$ Hz without loading of a tip mass. The value of f_r was then decreased dramatically to about 74 Hz by continuously adding more tip mass.

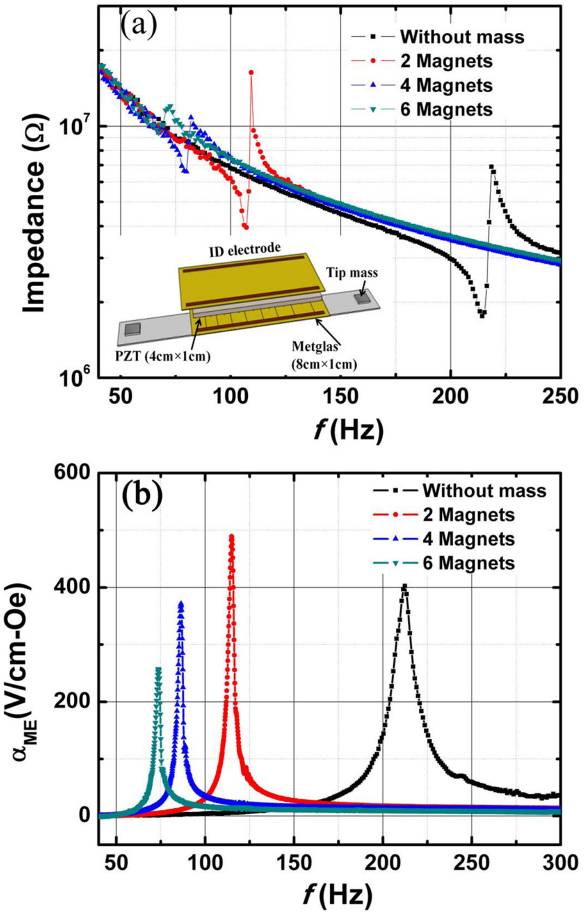

FIG. 1. (a) Impedance spectra of Metglas/PZT bending laminates with various tip masses and (b) ME voltage coefficients for Metglas/PZT laminates as a function of frequency with various tip masses. The inset is a schematic of the bending mode laminates.

Next, the ME voltage coefficient α_{ME} for the bi-layered ME composites was measured as a function of frequency. A lock-in amplifier (SR-850) was used to drive a pair of Helmholtz coils, generating an ac magnetic field of $H_{ac} = 0.1$ Oe over a frequency range of $1\ \text{Hz} < f < 300\ \text{Hz}$. The induced voltage from the ME composites was measured by the lock-in amplifier as well. In Figure 1(b), one can see the ME resonant peak positions were well matched to these of impedance peaks (Figure 1(a)). The ME voltage coefficients reached values of $\alpha_{ME} \geq 400$ V/cm-Oe at $f_r = 215$ Hz without tip mass, consistent with previous reports.[7] The resonant peak positions then exhibited significant tunability on loading with tip mass: shifting from 75 Hz to 215 Hz. Furthermore, α_{ME} was increased to 500 V/cm-Oe with 2 magnets load but decreased to 380 V/cm-Oe and 260 V/cm-Oe with 4 and 6 magnets load, respectively. However, the values of α_{ME} at resonant frequencies were still much larger than the values of the prior reports.[8,10]

A theoretical model for ME bending mode laminates was then developed to predict the behavior of the laminates. Figure 2 describes the model of the bi-layered structure: To simplify the model, a 2-D bar was used to describe the mechanical performance of the ME bi-layer structure. The x_1-axis in Cartesian coordinates is along the length direction of the bar, the x_2-axis is directed across the width, and the x_3-axis is orthogonal to them. It was assumed that the piezoelectric layers were polarized in the x_1 direction and that a magnetic field was incident along the same orientation. During the calculations, only small-amplitude oscillations of the bi-layer were considered.

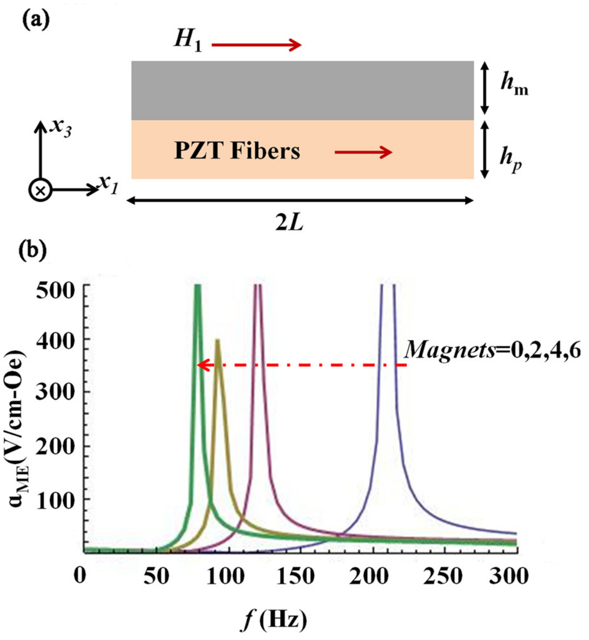

FIG. 2. (a) Theoretical model for magnetoelectric bi-layer laminates and (b) estimated ME voltage coefficients as a function of frequency.

In our theoretical analysis, several assumptions were made. These were that: (i) the length of composites was notably larger than the thickness; (ii) the $L \geq h = h_p + h_m$ boundary conditions between the two layers were ideal; (iii) linear elasticity could describe each layer; (iv) the stains and displacements were small; and (v) the transverse shear stresses on the top and bottom surfaces were zero. In addition, we assumed that Kirchoff's hypothesis was valid for all layers, i.e., the displacements in x_1 and x_3 directions can be represented as follows:

$$\begin{cases} u_1(x_1, x_3) = u(x_1) - x_3 \dfrac{\partial w}{\partial x_1} \\ u_3(x_1, x_3) = w(x_1). \end{cases} \tag{1}$$

The equations for the strain tensor S_{1m} in the magnetostrictive layer (cubic symmetry) and the strain tensor S_{1p} in the piezoelectric one (∞m symmetry) under a magnetic field H_1 and an electric field E_1 were expressed as follows:

$$\begin{cases} S_{1m} = {}^{m}s_{11}{}^{m}T_1 + {}^{m}q_{11}{}^{m}H_1 \\ S_{1p} = {}^{p}s_{11}{}^{p}T_1 + {}^{p}d_{11}{}^{p}E_1, \end{cases} \tag{2}$$

where ${}^{m}s_{11}$ and ${}^{p}s_{11}$ are the elastic compliance tensor components of the magnetostrictive and piezoelectric layers, respectively; and ${}^{m}q_{11}$ and ${}^{p}d_{11}$ are the piezomagnetic and piezoelectric coefficients.

Under the above mentioned assumptions, equations and free-free boundary conditions with a concentrated mass on both ends of the bi-layer, we determined all relevant fields, i.e., stress, strain, magnetic, and electric fields. Finally, under the open circuit condition of

$$\int_{-L}^{L} D_{1p} dx_1 = 0, \tag{3}$$

where, D_{I_p} is the electric displacement. The ME voltage coefficient was determined to be

$$\alpha_{ME} = \frac{E_1}{H_1} = -\frac{{}^{m}q_{11}{}^{p}d_{11}}{{}^{p}s_{11}\varepsilon_{11}}\frac{h_p}{h_p + h_m}\left\{\frac{\gamma_0}{\gamma_0+1}\frac{\tan(\lambda_T L)}{\lambda_T L} - \frac{3}{2}\frac{\gamma_1}{\gamma_2+1}\frac{\sinh(\lambda_B L)\sin(\lambda_B L)}{\lambda_B L[\sinh(\lambda_B L)\cos(\lambda_B L) + \sin(\lambda_B L)\cosh(\lambda_B L)]}\right\}$$
$$\times\left\{1 - K_1^2 + K_1^2\frac{1}{\gamma_0+1}\frac{\tan(\lambda_T L)}{\lambda_T L} + \frac{3}{2}\frac{1}{\gamma_2+1}\frac{\sinh(\lambda_B L)\sin(\lambda_B L)}{\lambda_B L[\sinh(\lambda_B L)\cos(\lambda_B L) + \sin(\lambda_B L)\cosh(\lambda_B L)]}\right\}^{-1}, \tag{4}$$

where, h_m and h_p are the thicknesses of the magnetostrictive and piezoelectric layers; ρ_m and ρ_p are the densities of these two layers. The other notations in Eq. (4) are given by the following expressions:

$$\lambda_T = \sqrt{\frac{\rho\omega^2}{A}};\quad \lambda_B = \sqrt{\frac{\rho\omega^2}{D}};\quad \gamma_0 = \frac{{}^{p}s_{11}}{{}^{m}s_{11}}\frac{h_m}{h_p};\quad \gamma_1 = \frac{{}^{p}s_{11}}{{}^{m}s_{11}}\left(\frac{h_m}{h_p}\right)^2,$$
$$\gamma_2 = \frac{{}^{p}s_{11}}{{}^{m}s_{11}}\left(\frac{h_m}{h_p}\right)^3;\quad A = \frac{h_p}{{}^{p}s_{11}} + \frac{h_m}{{}^{m}s_{11}};\quad D = \frac{1}{3}\left(\frac{h_p^3}{{}^{p}s_{11}} + \frac{h_m^3}{{}^{m}s_{11}}\right),$$
$$\rho = (\rho_p h_p + \rho_m h_m)(1 + m_0);\quad K_1^2 = \frac{{}^{p}d_{11}^2}{{}^{p}s_{11}\cdot\varepsilon_0};\quad m_0 = \frac{m_c}{m_t},$$

where, ω is angular frequency, m_c is the tip mass, and m_t is the mass of ME composites. The material parameters for Metglas and PZT are listed in Table I.

The theoretical ME voltage coefficients for bi-layered Metglas/PZT composites as function of frequency can be established using material parameters given in Table I. Figure 2(b) shows the simulation results of α_{ME} versus frequency for various tip mass loadings. From this figure, one can see that the predictions from the model were in very good agreement with the experimental observations in Figure 1(b). The value of f_r was about 210 Hz without tip mass, which was quite closed to the observed one. Furthermore, a huge resonant peak shift was predicted by the model, whose values were comparable to the experimental data. Thus, our model can provide reasonable estimated values and a sound basis to predict further shifts with additional increasing tip masses.

Based on this tunability of f_r for bending mode laminates, a 60 Hz magnetic field energy harvester was designed with a suitable tip mass. The ME voltage coefficient was found to reach 274 V/cm-Oe at $f = 60$ Hz, as shown in Figure 3(a). The high coupling effect made it possible to more efficiently harvest stray 60 Hz magnetic energy. The output power of the energy harvester was characterized. A lock-in amplifier (SR 850) was used to generate a driving signal for a pair of Helmholtz coils that generated a magnetic field at a frequency of $f = 60$ Hz. A resistance decade box was then directly connected to the ME laminates as an electrical load, and the voltage across it was measured by an oscilloscope. Figure 3(b) shows the output voltage and power as a function of load resistance R_{load}. It can be seen that the normalized voltage reached ∼13 *V*rms/Oe at an optimum R_{load}. Correspondingly, the maximum harvested power output was 16×10^{-6} W/Oe under $R_{load} = 6$ MΩ.

Finally, we used our energy harvester to capture 60 Hz magnetic energy in an open laboratory setting. Figure 4(a) shows a photo of the harvesting system and source. A power cable was placed across the harvester which generated a 60 Hz magnetic field due to a flowing current. Figure 4(b) shows the output voltage from the harvester in the time domain when current was flown through the cable. The output voltage reached 80 mV under open circuit conditions. The period of the signal can be seen to be 16.7 ms, corresponding to 60 Hz. Thus, the test demonstrates the harvester can capture 60 Hz magnetic energy from an ambient environment and convert it to useable electric energy.

IV. SUMMARY

In summary, bi-layered Metglas/PZT ME composites exhibit significant resonant frequency tunability by loading of tip masses. Meanwhile, a theoretical model was developed whose predicts were in agreement with experimental data. Based on the results, a 60 Hz magnetic energy harvester was designed which had $\alpha_{ME} > 270$ V/cm-Oe. The laminated composites were then used to harvest 60 Hz electromagnetic energy. Presently, the optimized output power for this harvester can reach 16 μW/Oe with a 6 MΩ resistance load,

TABLE I. Materials parameters for Metglas, PZT used for theoretical modeling.

Materials	${}^{m}s_{11}$ or ${}^{p}s_{11}$ (10^{-12} m^2/N)	${}^{p}d_{11}$ (10^{-12} C/N)	${}^{m}q_{11}$ (10^{-9} m/A)	$\varepsilon_{11}/\varepsilon_0$	h_p or h_p (10^{-6} m)	$2L$ (m)	Width (m)	ρ_m or ρ_p (kg/m^3)
Metglas[a]	10	…	50.3	…	66	0.06	0.01	7180
PZT[b]	15.3	400	…	1750	180	0.06	0.01	5675

[a] Cited from Ref. 13.
[b] Cited from Ref. 14.

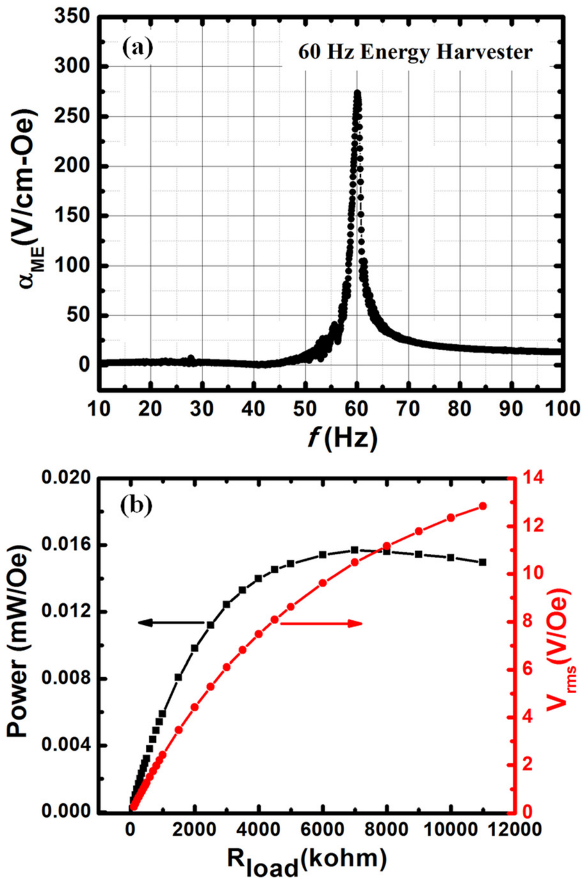

FIG. 3. (a) ME voltage coefficient of 60 Hz magnetic energy harvester as a function of AC magnetic drive frequency and (b) output voltage and power as a function of resistance load at the bending mode resonance frequency.

with the power density of $\geq 200\,\mu$W/cm^3. The power density was found to be limited by the high internal impedance of the ME laminates; however, it can be reduced by using a ME laminates array configuration.[12] Since ME harvesters could be integrated into power source cables or instruments, it could have important applications for harvesting 60 Hz magnetic energy.

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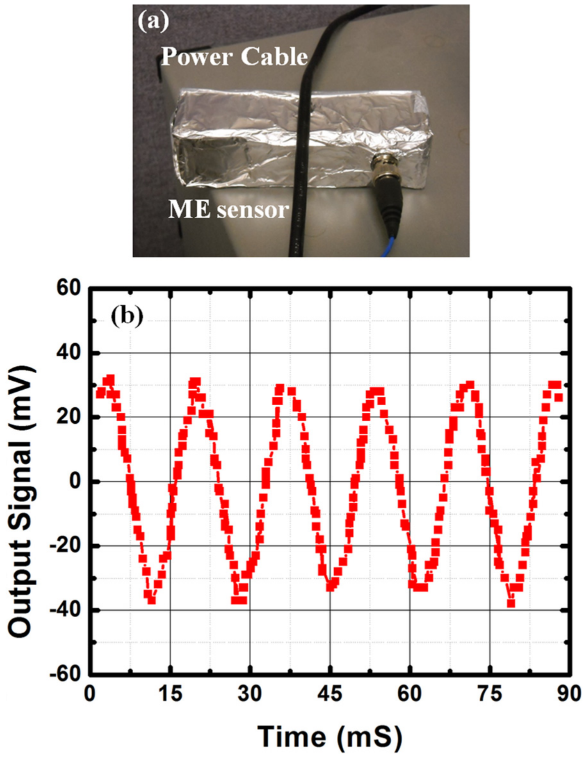

FIG. 4. Demonstration of ability to capture 60 Hz electromagnetic energy by using ME magnetic harvester: (a) photo of experimental setup and (b) output voltage signal in the time domain.

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