Giant resonance frequency tunable magnetoelectric effect in a device of $Pb(Zr_{0.52}Ti_{0.48})O_3$ drum transducer, NdFeB magnet, and Fe-core solenoid

Min Zeng,[1] Siu Wing Or,[2] and Helen Lai Wa Chan[1,a)]
[1]*Department of Applied Physics, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong*
[2]*Department of Electrical Engineering, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong*

(Received 23 March 2010; accepted 17 April 2010; published online 17 May 2010)

Magnetoelectric (ME) effect has been studied in a device of $Pb(Zr_{0.52}Ti_{0.48})O_3$ (PZT) drum transducer, NdFeB magnet, and Fe-core solenoid. A unique ME effect is found to originate from the magnetic force-induced effectively amplified piezoelectric effect. Under the application of a magnet with dimensions of $\phi 22 \times 7.6$ mm^2, a giant ME coefficient of 13.2 V/cm Oe and a power density of 16.4 μW/Oe across a 14 kΩ resistor were obtained at the first order radial resonance frequency of 650 Hz. Importantly, with increasing magnet mass, the resonance frequency decreases, while the resonance ME effect first increases and then decreases, which means a tunable resonance ME effect. © *2010 American Institute of Physics*. [doi:10.1063/1.3428429]

Magnetoelectric (ME) effect, which is an induction of magnetization electric polarization by magnetic field,[1] has attracted considerable research interest because of its potential applications in magnetic field and/or electric current sensors, transformers, energy harvesters, and phase shifters.[2] In the past decades, ME materials have been developed in single-phase materials, multiphase bulk composites, and laminated composites.[2–9] It is known that laminated piezoelectric/magnetostrictive composites have better ME effect than single-phase materials and even multiphase bulk composites. Most previous investigations, focused on laminated composites of magnetorestrictive Terfenol-D and piezoelectric materials (e.g., PZT [$Pb(Zr_{0.52}Ti_{0.48})O_3$] and PMN-PT [$PbMg_{1/3}Nb_{2/3}O_3-PbTiO_3$]), have been considered from polarized/magnetized directions, bonding and geometric aspects, aiming to achieve largest possible transferred stress, and/or piezoelectric effect. Essentially, this ME effect is the magnetostrictive stress-induced piezoelectric effect, in which the role of the magnetostrictive phase can be regarded as a source of mediated mechanical stress.

An extended ME effect is also realizable by a magnetic attractive/repellent force, which acts on a piezoelectric material. Recently, this magnetic force-induced ME effect was reported in the composites of magnet and piezoelectric materials/structures (e.g., PMN-PT single crystal[10] and PZT-bimorph[11]). To obtain high ME effect in magnet/piezoelectric composites, a good piezoelectric voltage/strain coefficient is desirable. In this paper, a PZT drum transducer is used to harvest the magnetic force energy since it has excellent electrical and mechanical performances.[12] The ME effect and power coefficient are studied in a proposed ME device of PZT drum transducer, NdFeB magnet and Fe-core solenoid.

The proposed ME device, as schematized in Fig. 1(a), is comprised of a PZT drum transducer sandwiched between an NdFeB magnet and a Fe-core solenoid in the axial (or the 3) direction. The interfaces are bonded using an insulating epoxy adhesive. Figure 1(b) illustrates the schematic and dimensions of the PZT drum transducer; its preparation was reported in a previous investigation.[13] The NdFeB magnet was commercially supplied in form of a cylindrical slab with the north (N) and south (S) poles normal to their main surfaces and also parallel to the axial direction of the device. The Fe-core solenoid, with 90 turns of Cu wire, was fabricated in-house. In measurement, the input current (I_{in}) was supplied by a dynamic signal analyzer (Ono Sokki CF5220) via a constant-current supply amplifier (AE Techron 7796HF). The induced magnetic field (H_3) was measured on the surface of the magnet by a Hall probe connected to a Gaussmeter (F. W. Bell 7030). The induced voltage (V_{out}) was monitored by the dynamic signal analyzer. An electronic circuit was used to measure the harvested energy. Detailed information on the design and measurement can be also found Ref. 13. In order to investigate the effect of magnet on the ME effect, five magnets, with same cross-section area,

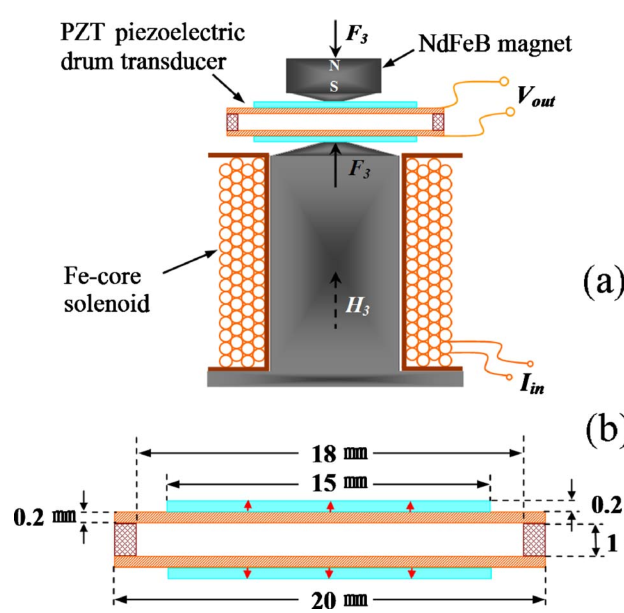

FIG. 1. (Color online) (a) Schematic diagram of the ME device made of PZT drum transducer, NbFeB magnet, and Fe-core solenoid. (b) Dimensions of the PZT drum transducer. Arrows show the polarization direction.

a)Author to whom correspondence should be addressed. Electronic mail: apahlcha@inet.polyu.edu.hk.

TABLE I. Parameters for five different magnets.

	Magnet I	Magnet II	Magnet III	Magnet IV	Magnet V
Diameter (ϕ, mm)	22	22	22	22	22
Thickness (t_m, mm)	1.9	3.8	5.7	7.6	9.5
Induction (B_3, T)	0.36	0.48	0.54	0.62	0.76
Mass (g)	5.4	10.8	16.2	21.6	27

were applied. Related parameters are shown in Table I.

Figure 2 shows the induced voltage (V_{out}) as a function of ac magnetic field (H_3) at a frequency of 100 Hz (subresonance frequency) for different magnets. It is found that V_{out} in the device exhibits good linearity in the whole range of measurement for all magnets. From the slopes of the V_{out}-H_3 plot divided by the thickness (t_p) of PZT disk, the ME coefficient (α_{E}) can be determined. The dependence of α_{E} (solid line) on the magnet mass is plotted in the inset of Fig. 2. It is clear that α_{E} is enhanced with increasing the magnet mass.

The variation in α_{E} with the frequency (f) for different magnets is displayed in Fig. 3. A sharp resonance peak is evident for each magnet. The resonance frequency (f_{r}) and α_{E} exhibit great dependence on magnet mass, as shown in the inset of Fig. 3. It is seen that with increasing magnet mass, f_{r} is shifted monotonously toward the lower frequency side, while α_{E} first increases and then slightly decreases. This is to say, f_{r} in the proposed device is adjustable by simply changing the attached magnet mass, which indicates controllable resonance ME effect.

The ME effect in the proposed ME structure originates from the amplified magnetic force-induced piezoelectric effect in the PZT disks. Theoretically, the ME effect can be predicted from the combination of electromagnetically induced attractive-repellent force effect in the magnet-solenoid assembly and the amplified piezoelectric effect in the drum transducer. Based on the charge model for analyzing the magnetic force between a permanent magnet and a magnetic field,[14] The attractive-repellent force (F_3) in response to H_3 in the magnet, acted on the transducer, can be simply calculated by:

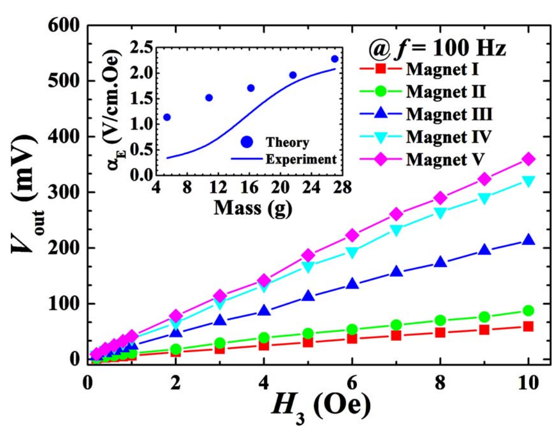

FIG. 2. (Color online) Induced voltage (V_{out}) as a function of αc magnetic field (H_3) at a frequency of 100 Hz for various magnets. The inset presents the comparison between experimental and theoretical ME coefficient (α_{E}) as a function of magnet mass.

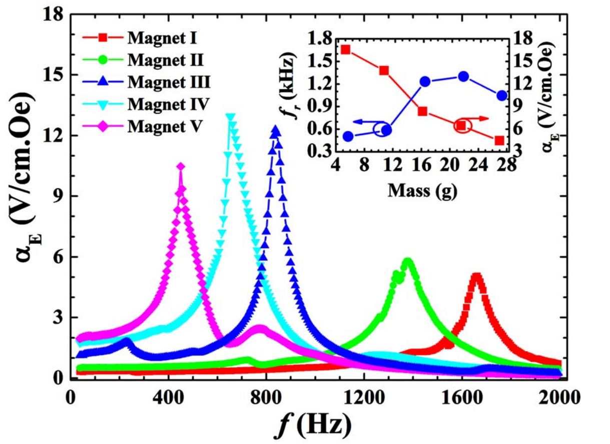

FIG. 3. (Color online) ME coefficient (α_{E}) as a function of frequency (f) for different magnets. The inset shows the dependences of resonance frequency (f_{r}) and α_{E} on magnet mass.

$$F_3 = \frac{10^{-1}}{8\pi} B_3 H_3 A_m, \tag{1}$$

where B_3 and A_m are the surface magnetic induction and surface area of the magnet, respectively. For the drum transducer, the electric field intensity, induced by the F_3, is given by:[15]

$$E_3 = \frac{d_{33}^{\text{eff}} F_3}{\pi r_p^2 \varepsilon_0 (\varepsilon_{33}^T - 1)}, \tag{2}$$

where ε_0 and ε_{33}^T are the vacuum and relative dielectric permittivities of the PZT disks, respectively, r_p is the radius of the PZT disk, and d_{33}^{eff} is the effectively piezoelectric efficient depending on the geometry parameters of the PZT drum transducer.[12] In this case, the measured d_{33}^{eff} values are 28 636 pC/N, which is ~50 times larger than that of PZT disks (592 pC/N). Substituting F_3 from Eq. (1) into Eq. (2), the ME efficient (α_{E}) can be expressed as follows:

$$\alpha_{\text{E}} = \frac{E_3}{H_3} = \frac{10^{-1}}{8\pi^2} \frac{d_{33}^{\text{eff}} B_3 A_m}{r_p^2 \varepsilon_0 (\varepsilon_{33}^T - 1)}. \tag{3}$$

It is clear that α_{E} of the device is proportional to B_3, A_m, and d_{33}^{eff}. The theoretical values (symbols), estimated by substituting the corresponding material parameters into Eq. (3), are shown in the inset of Fig. 2and are in good agreement with the experimental value.

Since the resonance frequency is tunable, for a load-free drum transducer, the resonance frequency of the transducer is related to the flextensional mode and can be estimated by the thin plate vibration theory as follows:[16]

$$f_{\text{r}} = \frac{2\lambda^2}{\pi D_i^2} \sqrt{\frac{\bar{E} t_p^3}{12(1-\bar{\upsilon}^2)\bar{\rho}}} = \frac{2\lambda 2}{\pi d_c^2} \sqrt{\frac{\bar{D}}{\bar{\rho}}}, \tag{4}$$

where t_p is the thickness of the PZT disk, D_i is the inner diameter of the ring, $\bar{Y}$, $\bar{\sigma}$, and $\bar{\rho}$ are the Young's modulus, Poisson's ratio, and weight to surface ratio of the ceramic-metal composite disks, respectively, and λ^2 is constant and depends on the resonance mode, bond type, and even mass loading conditions. The first-order resonance frequency was evaluated to be 25.2 kHz for the load-free PZT drum transducer, which is consistent with the experimental value in Ref. 13. It is important to note that after attaching a magnet,

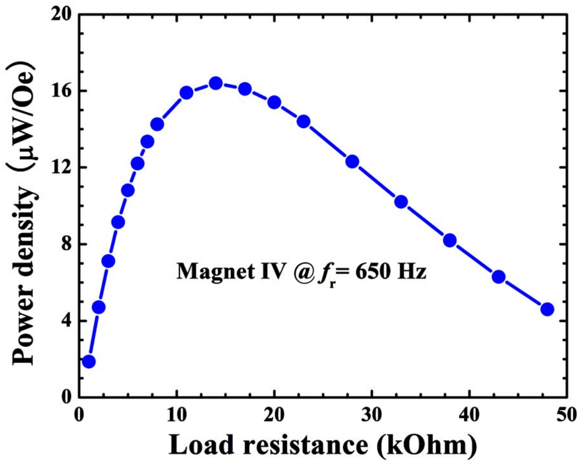

FIG. 4. (Color online) ME output powers density as a function of load resistance at the resonance frequency of 650 kHz for magnet IV.

the mass of the attached magnet and the static magnetic force induced in the magnet-Fe-core assembly, together, act as an external mass loading, which causes f_r to dramatically shift toward the low-frequency side, as seen in Refs. 12 and 13.

The proposed ME device also exhibits a giant ME power. Figure 4 shows the output power density as a function of load resistance at the resonance frequency of 650 Hz for magnet IV. It is observed that the output power density first ascends and then declines with increasing load resistance. The maximal output power density of about 16.4 μW/Oe can be obtained from the transducer across a resistance load of 14 kΩ, which is two orders of magnitude large than the previous ME laminates of PZT and Terfenol-D plates.[9]

In summary, a unique ME effect has been experimentally and theoretically reported in a device of PZT drum transducer, NdFeB magnet, and Fe-core solenoid, with well agreement. Two distinct characterizations have been presented as follows: one is the giant ME coefficient achieved by a magnetic force, instead of traditional magnetostrictive phase, the other is adjustable resonance ME effect, used by changing the mass and size of the magnet. The analysis of output power has also demonstrated that the ME device has a potential application for the magnetic energy harvesting.

This work was supported by the Hong Kong Research Grants Council of the HKSAR Government (Grant No. PolyU 5266/08E) and The Hong Kong Polytechnic University (Grant No. 1-BB95).

[1]M. Fiebig, J. Phys. D **38**, R123 (2005).
[2]R. A. Islam, H. Kim, S. Priya, and H. Stephanou, Appl. Phys. Lett. **89**, 152908 (2006).
[3]W. Eerenstein, N. D. Mathur, and J. F. Scott, Nature(London) **442**, 759 (2006); M. Bibes and A. Barthelemy, Nat. Mater. **7**, 425 (2008).
[4]S. Priya, R. Islan, S. X. Dong, and D. Viehland, J. Electroceram. **19**, 147 (2007).
[5]X. Z. Dai, Y. M. Wen, P. Li, J. Yang, and G. Y. Zhang, Sens. Actuators, A **156**, 350 (2009).
[6]M. I. Bichurin, D. A. Filippov, V. M. Petrov, V. M. Laletsin, N. Paddubnaya, and G. Srinivasan, Phys. Rev. B **68**, 132408 (2003).
[7]J. Ryu, A. Vazquez Carazo, K. Uchino, and H. Kim, Jpn. J. Appl. Phys., Part 1 **40**, 4948 (2001).
[8]S. X. Dong, J. Y. Zhai, N. G. Wang, F. M. Bai, J.-F. Li, D. Viehland, and T. A. Lograsso, Appl. Phys. Lett. **87**, 222504 (2005).
[9]P. Li, Y. Wen, and L. Bian, Appl. Phys. Lett. **90**, 022503 (2007).
[10]Y. J. Wang, S. W. Or, H. L. W. Chan, X. Y. Zhao, and H. S. Luo, Appl. Phys. Lett. **92**, 123510 (2008).
[11]Z. Xing, J. Li, and D. Viehland, Appl. Phys. Lett. **93**, 013505 (2008).
[12]C. L. Sun, S. S. Guo, W. P. Li, Z. B. Xing, G. C. Liu, and X. Z. Zhao, Sens. Actuators, A **121**, 213 (2005).
[13]S. Wang, K. Ho Lam, C. L. Sum, K. W. Kwok, H. L. Wa Chan, M. S. Guo, and X. Z. Zhao, Appl. Phys. Lett. **90**, 113506 (2007).
[14]E. P. Furlani, *Permanent Magnet and Electromechanical Device: Materials, Analysis, and Applications* (Academic, San Diego, 2001).
[15]K. Uchino, *Ferroelectric Devices* (Marcel Dekker, New York, 2000).
[16]G. Galiano, N. Lamberti, A. Iula, and M. Pappalardo, Sens. Actuators, A **46**, 176 (1995).