# Giant magnetoelectric effect in magnet-cymbal-solenoid current-to-voltage conversion device

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A giant magnetoelectric (ME) effect is reported in a current-to-voltage (*I*-to-*V*) conversion device formed by sandwiching a PZT piezoelectric cymbal transducer between an NdFeB magnet and a Fe-core solenoid. The observed ME effect results from the direct coupling of the electromagnetically induced attractive-repellent force effect in the magnet-solenoid assembly with the amplified piezoelectric effect in the cymbal transducer. The device exhibits a colossal *I*-to-*V* conversion factor ($S$) of 27.1 V/A with a giant ME coefficient ($\alpha_V$) of 1.24 V/Oe at a low resonance frequency of 2.33 kHz, besides a large $S$ of 0.74 V/A with a high $\alpha_V$ of 34 mV/Oe in the nonresonance frequency range of 40 Hz–1 kHz. A physical model based on the combination of electromagnetomechanics in the magnet-solenoid assembly and amplified piezoelectricity in the cymbal transducer is present to explain the observed ME effect and the resulting *I*-to-*V* conversion in the device. © *2010 American Institute of Physics*. [doi:10.1063/1.3372759]

## I. INTRODUCTION

The magnetoelectric (ME) effect is an electric polarization response in a material when subjected to an applied magnetic field.[1] The effect has attracted considerable research interest in recent years because of its unusual physics and potential applications.[2–9] In single-phase materials, the ME effect is an intrinsic coupling between the magnetic and electric dipoles at atomic level.[2] However, this intrinsic ME effect is generally weak and only obtainable at low temperatures.[3] By contrast, a much stronger ME effect in a wide range of temperature can be acquired in multiphase magnetostrictive-piezoelectric composites using product property.[4] Typical examples include bulk composites of ferrites and $Pb(Zr_{1-x}Ti_x)O_3$ (PZT) ceramics[5,6] and laminated composites of $Tb_{0.3}Dy_{0.7}Fe_{1.92}$ (terfenol-D) alloy and PZT ceramics or $PbMg_{1/3}Nb_{2/3}O_3-PbTiO_3$ (PMN-PT) single crystals.[7–11] In fact, laminated composites have shown stronger ME effect and better property tailorability than the bulk composites.[5–11] Nevertheless, the ME effect in the composites is a result of the mechanically mediated magnetostrictive effect in the magnetostrictive phase and the piezoelectric effect in the piezoelectric phase.[4–11] The magnetostrictive and piezoelectric phases can be regarded as an actuation and a sensing means in the composites, respectively.

Besides utilizing the mechanically mediated magnetostrictive and piezoelectric effects, the extrinsic ME effect can also be realized in multiphase magnet-piezoelectric composites using the direct coupling of the magnetic attractive/repellent force effect in the magnet phase with the piezoelectric effect in the piezoelectric phase.[12–14] The magnet-piezoelectric composites possess two distinct advantages compared to the magnetostrictive-piezoelectric composites.[12–14] First, the replacement of the magnetostrictive material by the magnet makes the resulting composites more cost-effective and manufacturable. Second, no external bias magnet field is required for the magnet-piezoelectric composites, thereby simplifying the structure of the resulting devices.

By extending the idea of the extrinsic ME effect in the magnet-piezoelectric composites, we have developed a promising type of current-to-voltage (*I*-to-*V*) conversion device by bonding a PZT piezoelectric cymbal transducer between an NdFeB magnet and a Fe-core solenoid. Besides, we have found a giant ME effect and a colossal *I*-to-*V* conversion in the device arisen from the direct coupling of the electromagnetically induced attractive-repellent force effect in the magnet-solenoid assembly with the amplified piezoelectric effect in the cymbal transducer. In this paper, we describe the structure and working principle of such an *I*-to-*V* conversion device and report experimentally and theoretically the observed giant ME effect and colossal *I*-to-*V* conversion.

## II. STRUCTURE AND WORKING PRINCIPLE

Figure 1(a) illustrates the schematic diagram and photograph of the proposed *I*-to-*V* conversion device. The device consists of a PZT piezoelectric cymbal transducer sandwiched between an NdFeB magnet and a Fe-core solenoid in the axial (or the 3 or $z$) direction and with their interfaces being bonded using an insulating epoxy adhesive. As shown in Fig. 1(b), the cymbal transducer is composed of a PZT piezoelectric ceramic disk and two truncated conical brass caps arranged symmetrically along the axial direction and

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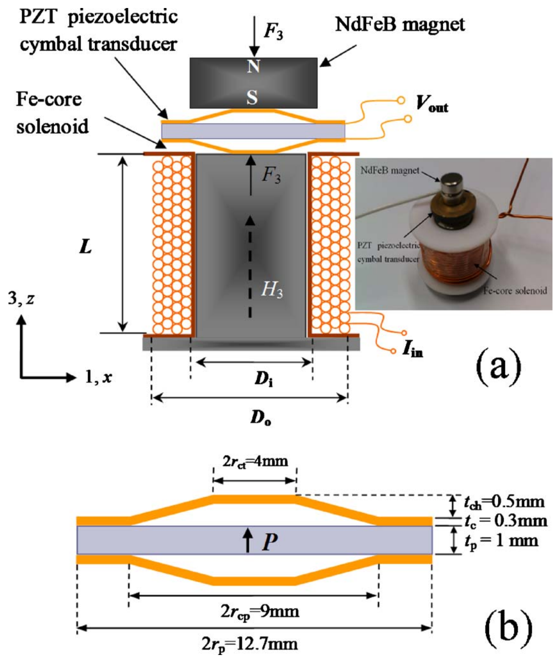


FIG. 1. (Color online) (a) Schematic diagram and photograph of the proposed *I*-to-*V* conversion device. (b) Schematic diagram showing the structure of the cymbal transducer. The arrow *P* denotes the electric polarization direction.

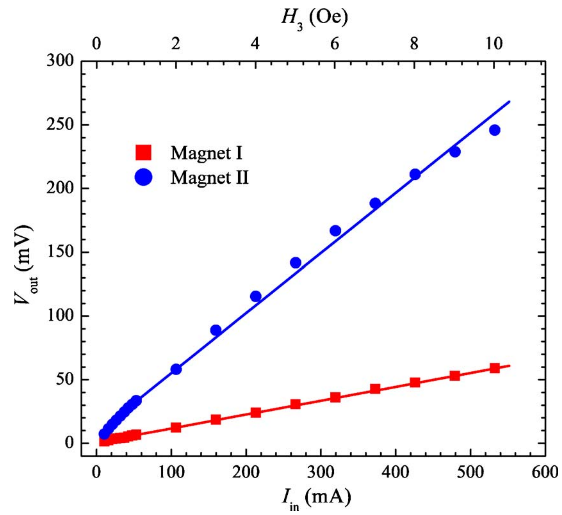


FIG. 2. (Color online) Output voltage ($V_{out}$) as a function of both input current ($I_{in}$) and induced ac magnetic field ($H_3$) for the device with magnets I and II at a frequency of 1 kHz.

bonded using the insulating epoxy adhesive. The PZT disk, with a diameter ($2r_p$) of 12.7 mm and a thickness ($t_p$) of 1 mm, was prepared using soft piezoelectric ceramic powders PKI552 and polarized using the two electroded surfaces normal to its thickness. The use of PKI552 is mainly due to its attractive piezoelectrically induced voltage capability as confirmed by the measured thickness and transverse piezoelectric voltage coefficients ($g_{33}$ and $g_{31}$) of 19.7 and $-8.5$ mV·m/N, respectively, in the PZT disk. The two brass caps, each of 4 mm top-cavity diameter ($2r_{ct}$), 9 mm bottom-cavity diameter ($2r_{cp}$), and 0.5 mm cavity height ($t_{ch}$), were made by die-punching a brass sheet with a thickness ($t_c$) of 0.3 mm. Referring to Fig. 1(a), 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. Two different magnets, namely magnets I and II, were used in turn in the present study in order to investigate their effect on the ME effect and the *I*-to-*V* conversion in the device. Magnet I had dimensions 6 mm(diameter) × 8.5 mm(thickness), mass 1.8 g, and surface magnetic induction ($B_3$) 0.36 T, while magnet II had larger dimensions 14 mm(diameter) × 9.5 mm(thickness), mass 11 g, and surface magnetic induction ($B_3$) 0.58 T. The Fe-core solenoid, with an inner diameter ($D_i$) of 11 mm, an outer diameter ($D_o$) of 16 mm, a length ($L$) of 16 mm, a total of 90 turns ($N$) of Cu wire, and a relative permeability ($\mu_r$) of 5000, was fabricated in-house.

The working principle of our *I*-to-*V* conversion device (Fig. 1) is essentially based on the direct coupling of the electromagnetically induced attractive-repellent force effect ($dF_3/dI_{in}=dF_3/dH_3 \times dH_3/dI_{in}$) in the magnet-solenoid assembly with the amplified piezoelectric effect ($dV_{out}/dF_3$) in the cymbal transducer. In operation, inputting an ac current ($I_{in}$) to the solenoid induces an ac magnetic field ($H_3$) along its axial direction as a result of the electromagnetic effect governed by Ampère's law.[15] This $H_3$ interacts with the magnet to produce an axial attractive-repellent force ($F_3$) for the sandwiched cymbal transducer based on the magnetic force effect.[16] A great portion of this $F_3$ is transformed and amplified by the cavity of the brass caps of the cymbal transducer, resulting in an enhanced radial force ($F_1$). The combination of $F_3$ and $F_1$, upon acting on the central PZT disk, causes it to produce an increased piezoelectric voltage ($V_{out}$) due to the amplified piezoelectric effect.[13]

## III. RESULTS AND DISCUSSION

Figure 2 shows the output voltage ($V_{out}$) as a function of both the input current ($I_{in}$) and the induced ac magnetic field ($H_3$) for the device with magnets I and II at a frequency of 1 kHz. $I_{in}$ was supplied by a dynamic signal analyzer (Ono Sokki CF5220) via a constant-current supply amplifier (AE Techron 7796HF) and monitored by a current probe (Hioki 9273) with a current amplifier (Hioki 3271). $H_3$ was measured on the surface of the magnet by a Hall probe connected to a Gaussmeter (F. W. Bell 7030). $V_{out}$ was acquired by the dynamic signal analyzer with a high input impedance buffer. It is seen that $V_{out}$ of the device with magnet I has a good linear response to both $I_{in}$ and $H_3$ in the whole range of measurement. The *I*-to-*V* conversion factor ($S$) and the ME coefficient ($\alpha_V$), as determined from the slopes of the $V_{out}$-$I_{in}$ and $V_{out}$-$H_3$ curves, are 0.15 V/A and 6.8 mV/Oe, respectively. The device with magnet II possesses an improved $S$ of 0.74 V/A with an increased $\alpha_V$ of 34 mV/Oe. However, there is a slight drop away from the linearity of the $V_{out}$-$I_{in}$ and $V_{out}$-$H_3$ curves in both the small and high ends of $I_{in}$ and $H_3$. The reason may be attributed to the reduced uniformity of distribution of $H_3$ over the increased surface area of magnet II.

Theoretically, $S(=dV_{out}/dI_{in})$ and $\alpha_V(=dV_{out}/dH_3)$ can be described from the combination of the electromagnetically induced attractive-repellent force effect ($dF_3/dI_{in}=dF_3/dH_3$

$\times dH_3/dI_{\rm in})$ in the magnet-solenoid assembly and the amplified piezoelectric effect $(dV_{\rm out}/dF_3)$ in the cymbal transducer. In fact, the electromagnetically induced attractive-repellent force effect originates from the product of the electromagnetic effect governed by Ampère's law $(dH_3/dI_{\rm in})$ in the solenoid and the magnetic force effect $(dF_3/dH_3)$ in the magnet in response of the induced $H_3$. According to Ampère's law, the relation between $I_{\rm in}$ and $H_3$ in the solenoid along the axial (or the 3 or $z$) direction is[15]

$$H_3 = \mu_0 K I_{\rm in}, \quad K = \frac{N}{2L}\left[\frac{L/2+z}{\sqrt{D^2+(L/2+z)^2}} + \frac{L/2-z}{\sqrt{D^2+(L/2-z)^2}}\right], \tag{1}$$

where $\mu_0(=4\pi\times10^{-7}$ H/m) is the permeability of free space, $N$ is the number of turns of Cu wire, $L$ is the length of the solenoid, and $D$ is the mean diameter of the solenoid (Fig. 1). Here, owing to the eddy current effect of Fe-core in the high frequency, e.g., 1 kHz, the effect of Fe-core on $H_3$ is ignored. The attractive-repellent force $(F_3)$ in response to $H_3$ in the magnet can be expressed as[16]

$$F_3 = \frac{10^{-1}}{8\pi} B_3 H_3 A_m, \tag{2}$$

where $B_3$ and $A_m$ are the surface magnetic induction and surface area of the magnet, respectively. For the cymbal transducer, the $g_{33}$ and $g_{31}$ piezoelectric voltage contributions from the PZT disk are combined and mediated by the mechanical transformation/amplification effect in the brass caps to provide an effective piezoelectric voltage coefficient $g_{33}^{\rm eff}$ giving[13,17]

$$g_{33}^{\rm eff} = \beta\left[g_{33} - g_{31}\frac{r_{cp}(r_{cp}-r_{ct})}{t_{ch}(t_p/2+t_c)}\right], \tag{3}$$

where $\beta$ is a constant related to the mass loading of the magnet and the magnetic loading exerted by the attractive force between the magnet and the Fe core of the solenoid (=0.82 for magnet I and 0.76 for magnet II).[17] It is noted that the measured $g_{33}^{\rm eff}$ is 208 mV m/N for magnet I and 193 mV m/N for magnet II, which not only are larger than the $g_{33}$ (=19.7 mV m/N) and $g_{31}$ (=−8.5 mV m/N) of the PZT disk but also agree with the calculated $g_{33}^{\rm eff}$ of 223 mV m/N for magnet I and 207 mV m/N for magnet II based on Eq. (3). Hence, the amplified piezoelectric voltage $(V_{\rm out})$ in the application of $F_3$ is[13]

$$V_{\rm out} = \frac{g_{33}^{\rm eff} F_3}{t_p \pi r_{cp}^2}. \tag{4}$$

Combining Eqs. (1), (2), and (4), $S$ of the device is obtained as

$$S = \frac{V_{\rm out}}{I_{\rm in}} = \frac{V_{\rm out}}{F_3}\frac{F_3}{H_3}\frac{H_3}{I_{\rm in}} = \frac{10^{-1}}{8\pi^2}\frac{\mu_0 K g_{33}^{\rm eff} B_3 A_m}{t_p \times r_{cp}^2}, \tag{5}$$

From Eq. (5), it is clear that $\alpha_V$ has a significant contribution to $S$ and is characterized by

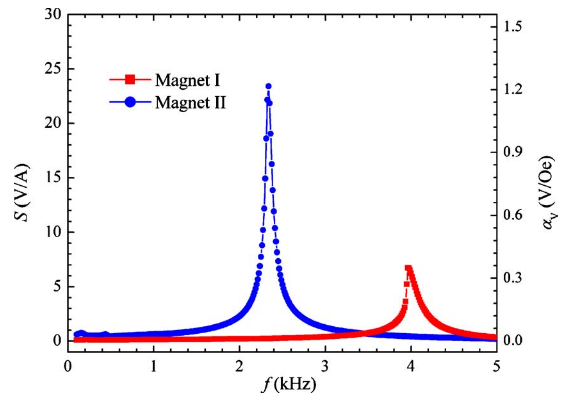


FIG. 3. (Color online) $I$-to-$V$ conversion factor $(S)$ and ME coefficient $(\alpha_V)$ as a function of frequency $(f)$ for the device with magnets I and II.

$$\alpha_V = \frac{V_{\rm out}}{H_3} = \frac{V_{\rm out}}{F_3}\frac{F_3}{H_3} = \frac{10^{-1}}{8\pi^2}\frac{g_{33}^{\rm eff} B_3 A_m}{t_p \times r_{cp}^2}, \tag{6}$$

Substituting the corresponding material and geometric parameters of the device into Eq. (6), $S$ is predicted to be 0.16 and 0.84 V/A and $\alpha_V$ to be 7.5 and 38.2 mV/Oe for magnets I and II, respectively. These theoretical values coincide well with the experimental values in Fig. 2 with $S$=0.15 and 0.74 V/A and $\alpha_V$=6.8 and 34 mV/Oe for magnets I and II, respectively.

Fig. 3 shows the $I$-to-$V$ conversion factor $(S)$ and the ME coefficient $(\alpha_V)$ as a function of frequency $(f)$ for the device with magnets I and II. A large $S$ of 7.9 V/A with a high $\alpha_V$ of 0.36 V/Oe is detected at the resonance frequency of 3.96 kHz for the device with magnet I. For the device with magnet II, a larger $S$ of 27.1 V/A with a higher $\alpha_V$ of 1.24 V/Oe is obtained at a lower resonance frequency of 2.33 kHz. The resonance $\alpha_V$ of 1.24 V/Oe is much higher than the reported $\alpha_V$ in laminated composites.[7–11]

For an unloaded cymbal transducer, its fundamental resonance frequency $(f_{\rm ft})$ corresponds to the first flextensional mode in which all parts of the brass caps move in the same phase and can be estimated by the thin plate vibration theory as follows:[9,13]

$$f_{\rm ft} \propto \sqrt{\frac{Y}{\rho}\left[\frac{1}{r_{cp}^2(1-\sigma^2)} + \frac{1}{r_p^2}\right]}, \tag{7}$$

where $Y$, $\rho$, and $\sigma$ are the density, Young's modulus, and Poisson's ratio of the brass caps, respectively. For our cymbal transducer at load-free condition, $f_{\rm ft}$ is calculated to be 45.2 kHz. It is well known that $f_{\rm ft}$ is proportional to the square root of the inverse of the equivalent mass in the device.[17,18] In current study, $f_{\rm ft}$ was estimated to be 5.34 and 3.28 kHz for magnets I and II loading condition, respectively, which is in agreement with the observed results. The significant difference of the calculated value by Eq. (7) and the observed results in Fig. 3 is originated from the mass loading of the magnet and the magnetic loading of the magnet and the Fe core of the solenoid. It is noted that the enhanced $S$ and $\alpha_V$ in the device with magnet II compared to that with magnet I is mainly attributed to the larger electromagnetically induced attractive-repellent force effect in the assembly of magnet II and solenoid as a result of the larger dimensions and hence surface magnetic induction ($B_3$). Nevertheless, the $S$, $\alpha_V$, and resonance frequency of our device can be easily adjusted by simply changing the magnet.

## IV. CONCLUSION

We have developed a promising type of $I$-to-$V$ conversion device by bonding a PZT piezoelectric cymbal transducer between an NdFeB magnet and a Fe-core solenoid and reported experimentally and theoretically a giant ME effect and a colossal $I$-to-$V$ conversion in the device due to the direct coupling of the electromagnetically induced attractive-repellent force effect in the magnet-solenoid assembly with the amplified piezoelectric effect in the cymbal transducer. The device has showed a colossal $S$ of 27.1 V/A with a giant ME $\alpha_V$ of 1.24 V/Oe at a low resonance frequency of 2.33 kHz, besides a large $S$ of 0.74 V/A with a high $\alpha_V$ of 34 mV/Oe in the non-resonance frequency range of 40 Hz–1 kHz. Interestingly, it can easily adjust $S$, $\alpha_V$, and resonance frequency of the device by changing the associated magnet.

## AKNOWLEDGEMENTS

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