dc magnetoelectric sensor based on direct coupling of Lorentz force effect in aluminum strip with transverse piezoelectric effect in $0.7Pb(Mg_{1/3}Nb_{2/3})O_3-0.3PbTiO_3$ single-crystal plate

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(Presented 21 January 2010; received 31 October 2009; accepted 8 December 2009; published online 15 April 2010)

We report theoretically and experimentally a dc magnetoelectric sensor consisting of a thickness-polarized $0.7Pb(Mg_{1/3}Nb_{2/3})O_3-0.3PbTiO_3$ (PMN-PT) piezoelectric single-crystal plate arranged along the longitudinal direction and sandwiched between a pair of electrically connected aluminum strips. The operation of the sensor is based on the direct coupling of the Lorentz force effect in the aluminum strips in response to an applied dc magnetic field under a reference ac electric current with the transverse piezoelectric effect in the PMN-PT single-crystal plate. The sensor shows a good linear ac electric voltage response to broad ranges of applied dc magnetic field of 0–180 mT and reference ac electric current of 1–100 mA, giving a high and linear current-controlled dc magnetic field sensitivity of 0.23 V/T/A. It also provides the direction information of the applied dc magnetic field. © *2010 American Institute of Physics*. [doi:10.1063/1.3337748]

Magnetoelectric (ME) materials are an important class of multiferroic materials in which an applied magnetic field leads to an electric polarization response and hence an induced electric voltage.[1] Research on ME materials received considerable attention in the past decade due to the tremendous application potential of the materials for passive, solid-state ME sensors with improved magnetic field sensitivity of >100 V/T (>10 mV/Oe) and magnetic field range of linearity of >0.01 T (>100 Oe) compared to traditional active Hall sensors.[2–9] In fact, three main types of ME materials have been developed, including single-phase materials, bulk composites, and laminated composites.[2–9] ME sensors based on magnetostrictive-piezoelectric laminated composites resulted in much higher sensitivities than those with single-phase materials or bulk composites.[5–9] Among them, the ones fabricated with laminated composites of $Tb_{0.3}Dy_{0.7}Fe_{1.92}$ (Terfenol-D) magnetostrictive alloy and $0.7Pb(Mg_{1/3}Nb_{2/3})O_3-0.3PbTiO_3$ (PMN-PT) piezoelectric single crystal demonstrated the largest known sensitivities in excess of 3000 V/T (300 mV/Oe) owing to their greatly enhanced product effect of giant magnetostriction in Terfenol-D alloy and colossal piezoelectricity in PMN-PT single crystal through the mechanical mediation.[10]

The ME sensors reported so far are essentially "ac" ME sensors whereby an applied ac magnetic field induces an ac electric voltage on the basis of the coupled dynamics of the constituent phases in the parental ME materials.[2–10] Accordingly, these sensors fall short of any dc or quasi-dc applications such as sensing of magnetic fields or electric currents in dc electric machines and electric vehicles as well as detection of magnetic field anomalies.[11] This deficiency greatly reduces the competitiveness of the ME sensors against traditional Hall sensors.

Following the idea of mechanically mediated product effect in laminated composites, we developed a promising type of "dc" ME sensor by direct-coupling the Lorentz force generated from a pair of electrically connected aluminum strips under an applied dc magnetic field and a reference ac electric current to the sandwiched PMN-PT plate so as to produce a piezoelectric voltage with amplitude linearly proportional to the applied dc magnetic field and with both amplitude and frequency directly controllable by the reference ac electric current. While traditional Hall sensors require a highly stable true dc electric current to give a sufficiently accurate Hall voltage,[12] our dc ME sensor only needs a less demanding reference ac electric current. In this paper, we describe the structure and working principle of such a dc ME sensor and present its dc magnetic field sensing performance at different combinations of applied dc magnetic field and reference ac electric current.

Figure 1 illustrates the diagram and photograph of the proposed dc ME sensor in the Cartesian coordinate system. The sensor is composed of a plate-shaped piezoelectric single crystal PMN-PT arranged along the longitudinal (or 1-) direction and sandwiched between a pair of electrically connected aluminum strips arranged along the lateral (or 2-)

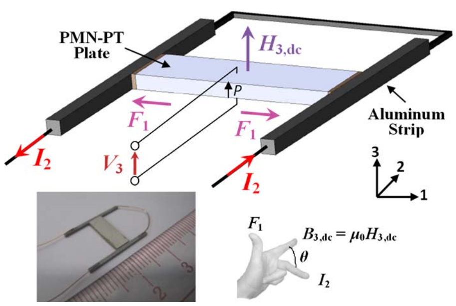

FIG. 1. (Color online) Diagram and photograph of the proposed dc ME sensor in the Cartesian coordinate system. The arrow *P* denotes the electric polarization direction of the PMN-PT plate.

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direction with their interfaces being bonded using an insulating epoxy adhesive. The aluminum strips, having a length of 20 mm and a cross-sectional area of 1×1 mm^2, were cut from a 1 mm thick 7075 aluminum sheet using an electrical discharge machining technique. These aluminum strips had a high electrical conductivity of 47 μS/m and a low relative permeability of unity to facilitate the efficient generation of Lorentz force, besides a high Young's modulus of 75 GPa to ensure the proper transfer of the generated Lorentz force to the sandwiched PMN-PT plate. The PMN-PT plate, with dimensions and crystallographic orientations of $15[100]^L \times 4[011]^W \times 1[0\bar{1}1]^T$ mm^3 (L: length, W: width, T: thickness), an electric polarization along the thickness (or 3-) direction, and full fired silver electrodes on the two major surfaces perpendicular to the thickness direction, was grown and provided by Shanghai Institute of Ceramics, Chinese Academy of Sciences in China. It is noted that the electrodes on the two long sides of the PMN-PT plate were removed to give a slightly reduced electrode length of 14 mm in order to avoid short circuiting the PMN-PT plate by the aluminum strips. The relative permittivity at constant stress ($\varepsilon_{33}^{\mathrm{T}}/\varepsilon_0$) and transverse piezoelectric charge coefficient (d_{31}) of the PMN-PT plate were found to be 3900 and -1746 pC/N, respectively, resulting in a high transverse piezoelectric voltage coefficient ($g_{31}=d_{31}/\varepsilon_{33}^{\mathrm{T}}$) of -50.6 mV m/N.

The working principle of the dc ME sensor (Fig. 1) is essentially based on the direct coupling of the Lorentz force effect in the aluminum strips with the transverse piezoelectric effect in the PMN-PT plate. To impart the Lorentz force effect to the aluminum strips, the dc magnetic field ($H_{3,\mathrm{dc}}$) to be measured is applied in the 3-direction with the reference ac electric current (I_2) applied along the length of the aluminum strips in the 2-direction as shown in Fig. 1. According to the Lorentz force law,[11] and based on Fleming's left hand rule (Fig. 1),[11] a Lorentz force (F_1) in the form of a repellent/attraction force will be generated between the aluminum strips in the 1-direction. This F_1 in turn will extend/compress the sandwiched PMN-PT plate in the 1-direction, making it to produce an ac electric voltage (V_3) across its thickness in the 3-direction as a result of the transverse piezoelectric effect. Mathematically, the relationship of F_1, I_2, and $H_{3,\mathrm{dc}}$ can be expressed in accordance with the Lorentz force law as follows:[11]

$$F_1 = L_{\mathrm{a}}\mu_0 I_2 H_{3,\mathrm{dc}} \sin\theta, \tag{1}$$

where L_{a} is the length of the aluminum strips, $\mu_0(=4\pi\times10^{-7}$ H/m) is the permeability of free space, and θ is the phase angle between I_2 and $H_{3,\mathrm{dc}}$. It is noted from Eq. (1) that $B_{3,\mathrm{dc}}=\mu_0 H_{3,\mathrm{dc}}$ holds true, and the maximization of F_1 occurs when I_2 and $H_{3,\mathrm{dc}}$ are in mutual orthogonal directions so that $\theta=90°$, $\sin\theta=1$, and F_1 is reduced to

$$F_1 = L_{\mathrm{a}}\mu_0 I_2 H_{3,\mathrm{dc}}. \tag{2}$$

For the PMN-PT plate, as it is subject to F_1 in the 1-direction, and since it was thickness polarized in the 3-direction, the constitutive piezoelectric equations are adopted as follows:[13]

$$S_1 = s_{11}^{\mathrm{D}} T_1 + g_{31} D_3, \quad E_3 = -g_{31} T_1 + \frac{1}{\varepsilon_{33}^{\mathrm{T}}} D_3, \tag{3}$$

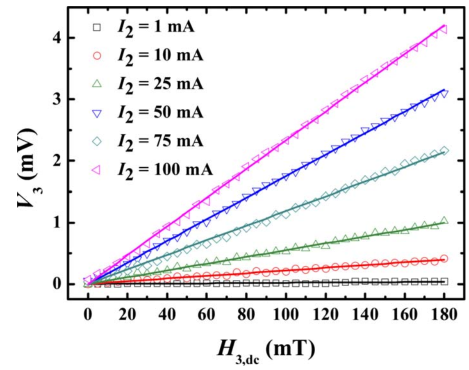

FIG. 2. (Color online) Induced ac electric voltage (V_3) as a function of applied dc magnetic field ($H_{3,\mathrm{dc}}$) for different reference ac electric currents (I_2) at a frequency of 1 kHz. The symbols are the experimental data, while the lines are the linearly fitted lines.

where T_1 and S_1 are the mechanical stress and strain along the length (or 1-) direction, respectively, E_3 and D_3 are the electric field strength and electric displacement along the thickness (or 3-) direction, respectively, g_{31} is the transverse piezoelectric voltage coefficient, s_{11}^{D} is the elastic compliance coefficient at constant electric displacement, and $\varepsilon_{33}^{\mathrm{T}}$ is the dielectric permittivity at constant stress. Combining Eqs. (2) and (3), and setting $D_3=0$ (i.e., open-circuit condition) in Eq. (3), the current-controlled dc magnetic field sensitivity (S) of the sensor, defined as an induced ac electric voltage (V_3) from the PMN-PT plate in response to an applied dc magnetic field ($H_{3,\mathrm{dc}}$) under a reference ac electric current (I_2) to the aluminum strips, is

$$S = \frac{\Delta(\Delta V_3/\Delta H_{3,\mathrm{dc}})}{\Delta I_2} = \frac{\Delta S_{I_2}}{\Delta I_2} = -g_{31}\frac{L_{\mathrm{a}}}{W_{\mathrm{p}}}, \tag{4}$$

where W_{p} is the width of the PMN-PT plate and $S_{I_2}(=\Delta V_3/\Delta H_{3,\mathrm{dc}})$ is the dc magnetic field sensitivity at a given I_2. From Eq. (4), it is clear that S of the sensor depends on L_{a} of the aluminum strips as well as g_{31} and W_{p} of the PMN-PT plate. The use of a piezoelectric material with a higher g_{31} (e.g., our PMN-PT single crystal) is an advantage. Since g_{31} carries a minus sign, S is positive. This suggests that V_3 and I_2 will be in phase for a positive $H_{3,\mathrm{dc}}$ (corresponding to the upward arrow $\uparrow H_{3,\mathrm{dc}}$ shown in Fig. 1) and will be out of phase for a negative $H_{3,\mathrm{dc}}$ (when the upward arrow $\uparrow H_{3,\mathrm{dc}}$ in Fig. 1 becomes a downward arrow $\downarrow H_{3,\mathrm{dc}}$). Hence, our sensor can differentiate the direction of $H_{3,\mathrm{dc}}$. By substituting the corresponding material and geometric parameters into Eq. (4), S of the sensor is predicted to be 0.25 V/T/A (25 μV/Oe/A).

Figure 2 plots the induced ac electric voltage (V_3) as a function of applied dc magnetic field ($H_{3,\mathrm{dc}}$) in the $H_{3,\mathrm{dc}}$ range of 0–180 mT for different reference ac electric currents (I_2) of amplitudes 1, 10, 25, 50, 75, and 100 mA at a frequency of 1 kHz. $H_{3,\mathrm{dc}}$ was supplied by a water-cooled, U-shaped electromagnet (Myltem PEM-8005K) controlled by a dc current supply (Sorensen DHP200–15) and monitored by a Hall probe connected to a gaussmeter (F. W. Bell 7030). I_2 was provided by an arbitrary waveform generator (Agilent 33210A) via a constant-current supply amplifier (AE Techron 7796HF). V_3 was acquired by measuring the associated electric charge (Q_3) using a charge meter (Kister

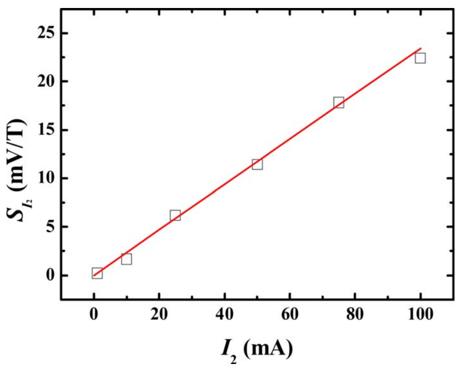

FIG. 3. (Color online) Dependence of dc magnetic field sensitivity at a given I_2 (S_{I_2}) on reference ac electric current (I_2). The values of S_{I_2} (symbol) are obtained from the slope of each $V_3-H_{3,dc}$ curve in Fig. 2, while the line is the linearly fitted line.

5015A1001) using the relation: $V_3=Q_3/C$, where C is the capacitance of the PMN-PT plate and was quantified using a precision impedance analyzer (Agilent 4294A). It is seen that V_3 has good linear responses to $H_{3,dc}$ for different I_2. By linear fitting each of the $V_3-H_{3,dc}$ curves, the dc magnetic field sensitivity at a given I_2 (S_{I_2}), as defined by Eq. (4), is found to be 0.20 mV/T at 1 mA, 2.22 mV/T at 10 mA, 5.51 mV/T at 25 mA, 11.88 mV/T at 50 mA, 17.60 mV/T at 75 mA, and 23.36 mV/T at 100 mA.

Figure 3 shows the dependence of the dc magnetic field sensitivity at a given I_2 (S_{I_2}) on the reference ac electric current (I_2). The values of S_{I_2} are obtained from the slope of each $V_3-H_{3,dc}$ curve as discussed in Fig. 2. It is clear that S_{I_2} increases linearly with the increase in I_2. Based on the slope of the $S_{I_2}-I_2$ curve, the current-controlled dc magnetic field sensitivity (S) of the sensor, as defined in Eq. (4), is determined to be 0.23 V/T/A (23 μV/Oe/A). This experimentally determined S agrees well with the theoretically predicted value of 0.25 V/T/A based on Eq. (4). The results also indicate the large and linear controllability of S_{I_2} and hence V_3 by I_2 for an applied $H_{3,dc}$. In other words, our sensor has the ability to convert a small $H_{3,dc}$ to a relatively large V_3 by using an elevated I_2 to enhance its S_{I_2}.

Figure 4 shows the waveforms of reference ac electric current (I_2) having 100 mA amplitude and 1 kHz frequency and induced ac electric voltage (V_3) when the sensor is used to detect different applied dc magnetic fields ($H_{3,dc}$) of 100 and 150 mT amplitude [Fig. 4(a)] and −100 and −150 mT amplitude [Fig. 4(b)]. Stable signal conversions between $H_{3,dc}$ and V_3 under I_2 are evident. In line with both the theoretical prediction in Eq. (4) and experimental results in Figs. 2 and 3, V_3 increases with the increase in $H_{3,dc}$ for a given I_2. In addition, V_3 and I_2 are in phase when $H_{3,dc}$ is positive [Fig. 4(a)], and they are out of phase when $H_{3,dc}$ is negative [Fig. 4(b)]. This confirms that our sensor is able to differentiate the direction of $H_{3,dc}$.

We developed a dc ME sensor by direct coupling the Lorentz force effect due to an applied dc magnetic field ($H_{3,dc}$) and a reference ac electric current (I_2) in a pair of electrically connected aluminum strips with the transverse piezoelectric effect in a thickness-polarized PMN-PT piezoelectric single-crystal plate bonded between the aluminum strips. The theoretical and experimental results confirmed the

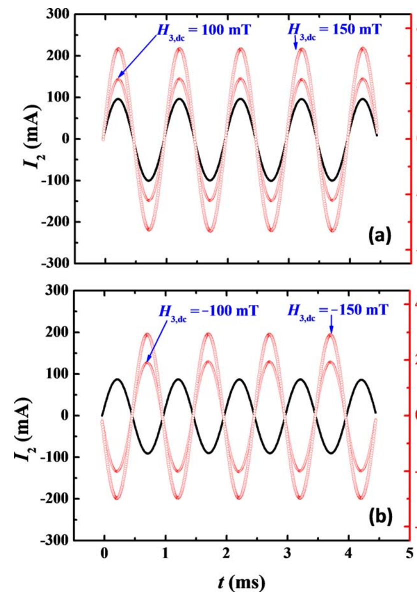

FIG. 4. (Color online) Waveforms of reference ac electric current (I_2) having 100 mA amplitude and 1 kHz frequency and induced ac electric voltage (V_3) under different applied dc magnetic fields ($H_{3,dc}$) of (a) 100 and 150 mT amplitude and (b) –100 and –150 mT amplitude.

existence of a high and linear current-controlled dc magnetic field sensitivity (S) of 0.23 V/T/A in the sensor. By noticing the phase angle between the induced ac electric voltage (V_3) and I_2, it can obtain the direction information of $H_{3,dc}$ by the sensor. Therefore, the sensor has great potential for detecting dc magnetic fields or electric currents crucial to most existing and advanced applications such as in dc electric machines, in electric vehicles, in magnetic anomaly detection, etc. Special attention has to be paid to sensor housing design and signal wiring so as to minimize undesirable electromagnetic interference signals.

This work was supported by the Research Grants Council of the HKSAR Government (PolyU 5266/08E). The authors also thank Professor Haosu Luo of Shanghai Institute of Ceramics, Chinese Academy of Sciences for the supply of PMN-PT single crystal.

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