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Vibrational noise rejection in multilayer structured magnetoelectric sensor

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ABSTRACT

Giant ME effects in laminates have been investigated for highly sensitive low frequency magnetic field sensors. It has been shown in recent years that one of the biggest obstacles for magnetoelectric (ME) sensors achieving high sensitivity at low frequency is the vibrational noise introduced via piezoelectric effect.

This work demonstrates a novel differential technique which has the ability to reject the vibrational noise in a multilayer structured ME sensor. It exhibits an excellent ME effect with a low equivalent magnetic noise floor of 32 $pT/Hz^{1/2}$ at 1 Hz and 3 $pT/Hz^{1/2}$ at 10 Hz, which was very close to the predicted value (27 $pT/Hz^{1/2}$ at 1 Hz and 2.9 $pT/Hz^{1/2}$ at 10 Hz). With respect to the ability to reject the vibrational noise, the external vibrational noise was incredibly attenuated by 91%. These unique properties of the multilayer structured sensor offer potential applications as a precise and sensitive magnetic field detector.

1. Introduction

The magnetoelectric (ME) effect is defined as a variation of dielectric polarization in a material when subjected to an applied magnetic field [1]. Since giant ME effects had been found in piezoelectric/magnetostrictive laminate composites, the ME composites had attracted much attention in recent decades due to the tremendous application for the associated magnetic field sensors, current sensors, energy-harvesting devices, data-storage memory devices and so on [2]. To date, ME laminated composites of magnetostrictive Terfenol-D or Metglas, and piezoelectric $Pb(Zr_{1-x}Ti_x)O_3$ (PZT) and $(1-x)Pb(Mg_{1/3}Nb_{2/3})O_3$–$xPbTiO_3$ (PMNT) have been widely investigated [3–5]. Besides, high curie temperature $0.35Pb(In_{1/2}Nb_{1/2})O_3$–$0.35Pb(Mg_{1/3}Nb_{2/3})O_3$–$0.30PbTiO_3$ single crystal is also being studied [6,7].

The ME coupling of ME composites is realized by a stress mediated interaction between the magnetostrictive phase and the piezoelectric phase. Various operation modes had been studied, including: L–L mode, L–T mode, T–L mode, T–T mode, bending mode, push–pull, etc. [8–12]. For L–T mode laminate, it possesses a large ME charge coefficient and requires smaller dc magnetic biases compared with L–L mode and T–L mode [13]. Recently, a shear mode ME laminate with a giant ME coefficient of 7.5 V/(cm Oe) at low frequency has also been studied [14].

Giant ME effects in laminates have been investigated for highly sensitive low frequency magnetic field sensors [13,15]. However, one of the biggest obstacles for ME sensor achieving high sensitivity and accuracy is the vibrational or acoustic noises introduced via the piezoelectric effect [13]. Unfortunately, the above structures are not capable of solving this issue. A lot of creative works on vibrational noise rejection of ME laminates have been done. Shen et al. had performed a classical differential technique to reject vibrational noise [16]. In addition, a differential-mode vibrational noise cancelation structure had been designed [17]. Yet, rejecting the vibrational noise while not reducing the ME sensitivity is still a major problem to overcome. In addition, signals with different frequency are easy to separate by spectral analysis, extracting the magnetic field signal when its frequency is the same with vibrational signals is another crucial challenge.

In this letter, we focus on small vibrational noise cancelation of ME sensor consisting of two pieces of PIMNT single crystal plates

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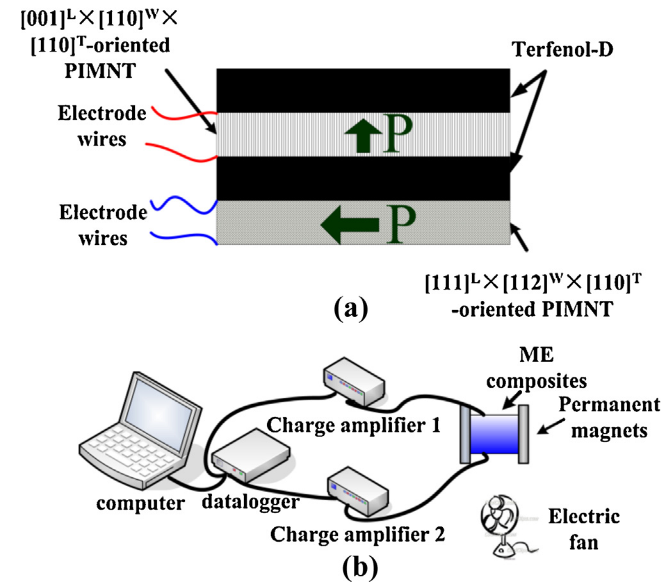

Fig. 1. (a) The schematic diagram of the multilayer structured ME sensor. The output of $[0\,0\,1]^L \times [1\,1\,0]^W \times [1\,1\,0]^T$-oriented PIMNT corresponds to Terminal 1 and $[1\,1\,1]^L \times [1\,1\,2]^W \times [1\,1\,0]^T$-oriented PIMNT corresponds to Terminal 2. The ultimate output of the multilayer ME sensor was obtained by subtracting the two signal channels and (b) the configuration of the experiment.

with different cut. ME properties of the sensor as well as the noise floor has been investigated and analyzed. Phase angle of the output voltages of the two PIMNT plates responding to a vibrational signal was also measured. Furthermore, the ability to reject the vibrational noise was examined. The results show that the proposed ME sensor exhibits an excellent magnetic field detectivity and the ability to avoid vibrational noise.

2. Experimental details

Fig. 1(a) illustrates our proposed multilayer ME sensor which was composed of Terfenol-D alloy and PIMNT single crystals. Two pieces of PIMNT single crystal plates are used in the structure with the cut are $\langle 1\,1\,1\rangle^L \times \langle 1\,1\,2\rangle^W \times \langle 1\,1\,0\rangle^T$ (*L*, length; *W*, width; *T*, thickness) and $\langle 0\,0\,1\rangle^L \times \langle 1\,1\,0\rangle^W \times \langle 1\,1\,0\rangle^T$, respectively. The $\langle 0\,0\,1\rangle^L \times \langle 1\,1\,0\rangle^W \times \langle 1\,1\,0\rangle^T$ (A type) PIMNT, with the dimension of $12^L\,\text{mm} \times 6^W\,\text{mm} \times 1^T\,\text{mm}$ was thickness direction polarized. The $\langle 1\,1\,1\rangle^L \times \langle 1\,1\,2\rangle^W \times \langle 1\,1\,0\rangle^T$-oriented (B type) PIMNT with dimension of $12^L\,\text{mm} \times 6^W\,\text{mm} \times 1^T\,\text{mm}$ was poling along the length direction in silicone oil. The Terfenol-D plates were commercially supplied (Southern Institute of Rare Earth Functional Materials Co., Ltd., China) with the dimension of $12^L\,\text{mm} \times 6^W\,\text{mm} \times 1^T\,\text{mm}$ (*L*, length; *W*, width; *T*, thickness) and with the length direction along the $\langle 1\,1\,2\rangle$ direction. The piezomagnetic coefficient reaches 1.2 ppm/Oe under optimal bias magnetic field of 320 Oe. The fabrication of the multilayer ME laminate is to sandwich the A type PIMNT plate between two Terfenol-D plates, and then attach an B type PIMNT single crystal plate to the bottle of the sandwich structure. Four electrode wires are extracted from the top and bottle surface of each piezoelectric plate. In other words, the proposed structure has two output terminals (the output of A type PIMNT corresponds to Terminal 1, B type PIMNT corresponds to Terminal 2). The output of the multilayer ME laminate was obtained by subtracting the two signal channels. The capacitance (C = 1.31 nF, 1.29 nF) of the two laminates was measured by using an impedance analyzer (Agilent 4294) at 1000 Hz with the corresponding dielectric loss tan δ is 0.8% and 1%, respectively.

Fig. 1(b) is the configuration of the experiment. Raw voltage signals from the channels were linked to the charge amplifiers (Brüel & Kjaer 2635). Then, signals were recorded using a datalogger (National Instrument usb-9162) and uploaded to the computer for post processing. The ultimate output of cut mixed laminate was obtained by subtracting the output of Terminal 1 from the output of Terminal 2 in LabVIEW SignalExpress program. Magnetic test fields were generated using an AC current source (Keithley Model 6221) and a custom-built Helmholtz coil.

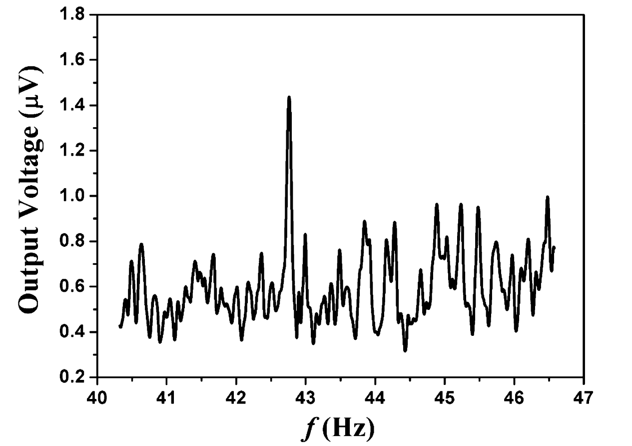

Fig. 2. The magnetic induction caused by the vibrational source. The data are measured using a fluxgate sensor with the responsivity of 100 mV/μT.

A plastic fan with the rotate frequency of 42.75 Hz placed 0.5 m away from was employed as the vibrational noise source in the experiment. The magnetic induction introduced by the fan was evaluated using the fluxgate sensor (Mag-03PSU, Bartington Instruments). The responsivity of the fluxgate sensor is 100 mV/μT and the result is shown in Fig. 2. It can be seen that the response voltage at 42.75 Hz is only 1.5 μV (corresponding to 15 pT). The magnetic noise introduced by the fan can be neglected as compared with the vibrational noise on the ME sample later in this article.

3. Results and discussion

3.1. Equivalent magnetic noise floor

The practical usefulness of a magnetic sensor is determined by the output signal of the sensor in response to an incident magnetic field, and by the equivalent magnetic noise generated in the absence of an incident field. Fig. 3 shows the frequency dependence of the ME charge coefficients. The ME charge coefficients of the

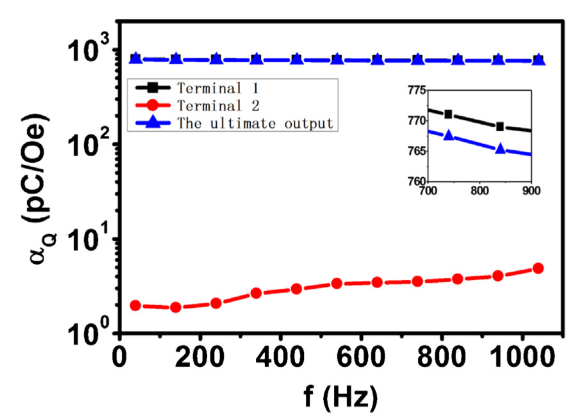

Fig. 3. ME charge coefficients (α_Q) of Terminal 1, Terminal 2 and the multilayer ME sensor for various frequencies (f) of 1–1000 Hz under an optimal bias magnetic field of 320 Oe. The inset shows an explicit scope of the ME charge coefficients (α_Q) of Terminal 1 and the ultimate output of the multilayer ME sensor.