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Electrical resistance load effect on magnetoelectric coupling of magnetostrictive/piezoelectric laminated composite

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ABSTRACT

The effect of electrical resistance load on the magnetoelectric (ME) coupling of laminated composite 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 is investigated at both non-resonance and resonance frequencies. The results show that (i) the ME coefficient and ME resonance frequency increase with the increase in electrical resistance load, and (ii) the maximum ME power occurs in open-circuit condition. The present study provides the basis for the design of ME sensors and their signal-processing and electronic circuits.

1. Introduction

The magnetoelectric (ME) effect is commonly characterized by ME coefficient (α_V) defined as an induced ME voltage by an applied ac magnetic field (dV_{ME}/dH) [1]. The effect has attracted much attention in recent years, not only because of the undiscovered science underpinning the effect, but also due to the tremendous application potential for the associated materials and the resulting devices. Since single-phase ME materials are not suitable for industrial applications due to their generally low ME coefficients [2,3], the development of multiple-phase ME composite materials consisting of magnetostrictive and piezoelectric phases based on extrinsic ME coupling has been the main evolutional tend in the recent decade [4–13].

All the previous investigations on the ME effect and its composites have been mainly focused on sensor applications, aiming to exhibit the bias magnetic field (H_{bias}) and frequency (f) dependences of ME coefficient (α_V) [8]. To enable practical device applications, it is both physically interesting and technologically important to quantitatively characterize the effect of electrical resistance load on the ME coupling for effectively interfacing with the subsequent signal-processing and electronic circuits. In this paper, we investigate the electrical resistance load effect on the ME coupling in a laminated composite formed by $Tb_{0.3}Dy_{0.7}Fe_{1.92}$ (Terfenol-D) magnetostrictive alloy and $0.7Pb(Mg_{1/3}Nb_{2/3})O_3$–$0.3PbTiO_3$ (PMN–PT) piezoelectric single crystal.

2. Experimental details

Fig. 1(a) illustrates the schematic diagram of the measurement principle, while Fig. 1(b) shows the photograph of the fabricated ME laminated composite. The composite was made by sandwiching one thickness-polarized $0.7Pb(Mg_{1/3}Nb_{2/3})O_3$–$0.3PbTiO_3$ (PMN–PT) piezoelectric single-crystal plate between two length-magnetized $Tb_{0.3}Dy_{0.7}Fe_{1.92}$ (Terfenol-D) magnetostrictive alloy plates. The Terfenol-D plates, with dimensions 14^L mm × 6^W mm × 1^T mm (L: length, W: width, T: thickness), were textured with their lengths along the [1 1 2] crystallographic axis. The PMN–PT plate, with dimensions and crystallographic orientations $14[0\,0\,1]^L$ mm × $6[0\,\bar{1}\,1]^W$ mm × $1[0\,1\,1]^T$ mm, was polarized along its thickness direction. Our previous study showed that PMN–PT single crystals with optimal crystal cut using these crystallographic orientations result in ME voltage three times higher compared to those with conventional crystal cut based on the [0 0 1] crystallographic orientation [6]. As shown in Fig. 1(a), an electrical resistance load (R_L) with various resistance values of 1–210 kΩ was connected electrically in parallel with the ME voltage (V_{ME}) output of the composite for the ME property measurement using an in-house automated measurement system. Detail of the measurement system and procedure can be found elsewhere [6].

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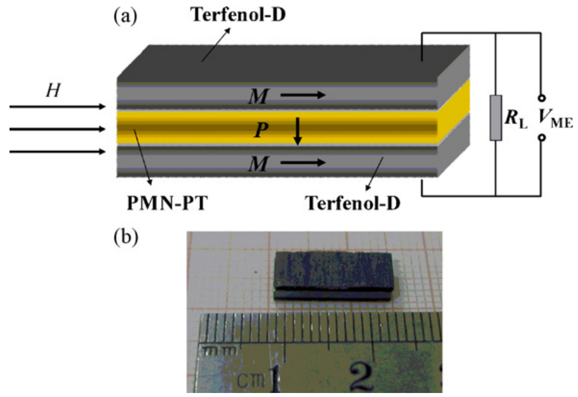

Fig. 1. (a) Schematic diagram of the measurement principle and (b) photograph of the fabricated ME laminated composite and.

3. Results and discussion

Fig. 2 plots the ME coefficient (α_V) as a function of electrical resistance load (R_L) for the ME laminated composite at an applied ac magnetic field (H) of 1 Oe peak, an optimal bias magnetic field (H_{bias}) of 400 Oe, and a frequency of 1 kHz. It is clear that α_V increases with the increase in R_L and reaches ~0.22 V/Oe when R_L is 210 kΩ. The inset shows the dependence of α_V on H_{bias} for the composite in open-circuit condition (i.e., in the absence of R_L). It is seen that α_V attains the maximum value of ~0.32 V/Oe at H_{bias} = 400 Oe, which is essentially related to the maximization of piezomagnetic coefficient ($d_{33,m}$) with respect to H_{bias} in the Terfenol-D magnetostrictive alloy plates [6].

Fig. 3(a) shows the frequency (f) dependence of ME coefficient (α_V) for the ME laminated composite at an applied ac magnetic field (H) of 1 Oe peak and under various electrical resistance load (R_L) values (including the open-circuit condition). In the low-frequency non-resonance range of 1–20 kHz in Fig. 3(b), there is a roll-off in α_V with the decrease in f for various R_L, and the cutoff frequency (f_{cut}) increases with increasing R_L [9]. As H is sinusoidal, f_{cut} can be expressed as $f_{cut} = 1/2\pi\tau$, where $\tau = NRC_0$ is the time constant and R is the parallel resistance of the composite's resistance (R_C), the electrometer's input resistance (R_E), and the electrical resistance load (R_L) [9]. R can be approximately set to R_L since R_L is generally smaller than R_C and R_E. Hence, R increases with the increase in R_L, leading to an increase in f_{cut} as shown in Fig. 3(b). Fig. 3(c) is the zoom-in view of the fundamental shape resonance region of 75–90 kHz. The maximum α_V is found to be ~6.1 mV/Oe at ~83.6 kHz under open-circuit condition. With the increase in R_L, α_V increases gradually while the resonance frequency (f_r) shifts to the higher frequency side and approaches to f_r of the open-circuit condition. The observation is also seen in other materials with piezoelectric element [11].

Fig. 4 shows the resonance frequency (f_r), ME coefficient (α_V), and ME power (P) as a function of electrical resistance load (R_L). The data of f_r and α_V are directly extracted from Fig. 3 at f_r, while that of P is deduced from the relation: $P = V_{ME}^2/R$ at H = 1 Oe peak. f_r increases rapidly for R_L < 8 kΩ and then tends to level off at ~83.6 kHz. The variation of α_V at f_r is similar to that at non-resonance frequency as shown in Fig. 2. P increases initially, reaching the maximum value of ~1.9 mW at R_L = 3.9 kΩ and then decreasing with increasing R_L. The similar electrical resistance load effect has also been observed in other systems with piezoelectric element [11]. Nevertheless, an enhanced P could be obtained if an increased H could be used or composite fabrication technique could be improved.

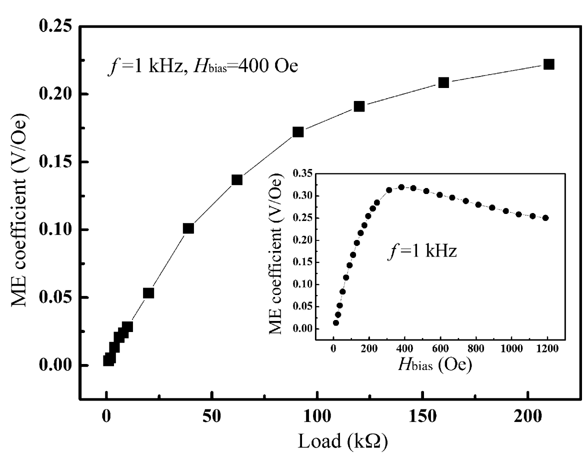

Fig. 2. ME coefficient (α_V) as a function of electrical resistance load (R_L) for the ME laminated composite at an applied ac magnetic field (H) of 1 Oe peak, an optimal bias magnetic field (H_{bias}) of 400 Oe, and a frequency of 1 kHz. The inset shows the dependence of α_V on H_{bias} for the composite in open-circuit condition (i.e., in the absence of R_L).

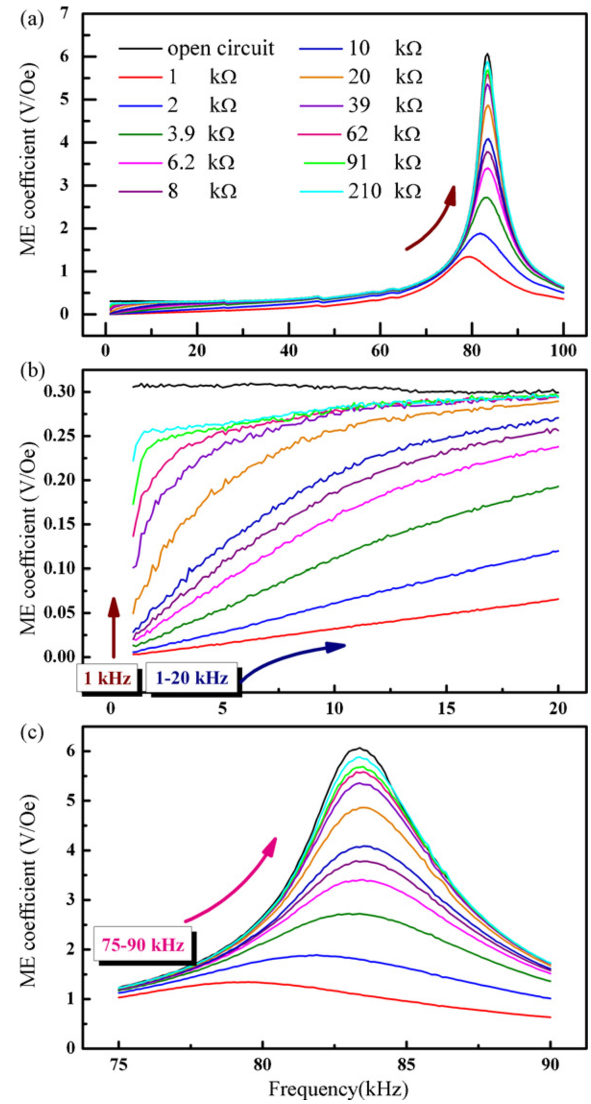

Fig. 3. (a) Frequency (f) dependence of ME coefficient (α_V) for the ME laminated composite at an applied ac magnetic field (H) of 1 Oe peak and under various electrical resistance load (R_L) values (including the open-circuit condition). (b) Zoom-in view for the low-frequency non-resonance range of 1–20 kHz. (c) Zoom-in view of the fundamental shape resonance region of 75–90 kHz.

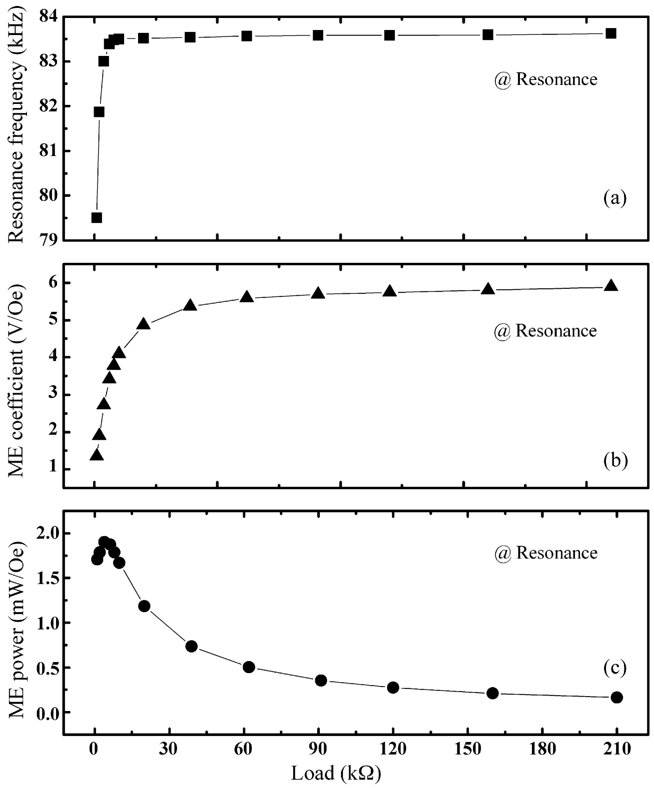

Fig. 4. Resonance frequency (f_r), ME coefficient (α_V), and ME power (P) as a function of electrical resistance load (R_L).

4. Conclusion

We have investigated the electrical resistance load effect on an ME laminated composite of Terfenol-D alloy plates and PMN–PT single-crystal plate in both the non-resonance and resonance frequency ranges. It has been observed that α_V and f_r increase with increasing R_L. Moreover, the maximum P is ~1.9 mW when H of 1 Oe is applied in open-circuit condition and with an optimal H_{bias} of 400 Oe. The results form the fundamental set of data for designing ME sensors and their signal-processing and electronic circuits.

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