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Directional magnetoelectric effect in multi-electrode $Pb(Zr,Ti)O_3$/Ni cylindrical layered composite

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ABSTRACT

Directional magnetoelectric (ME) effect was found in multi-electrode PZT/Ni cylindrical layered ME composite with external magnetic field applied perpendicular to the cylinder axis. The composite with the radially polarized PZT ring was electroplated with four Ni arc layers. Both the ME voltage coefficient and the corresponding phase suggest that the ME effect is omni-directional around the fundamental extensional mode of the PZT ring and directional around the third extensional mode with different magnetic field orientation. ME sensor with this compact structure can be used to determine the magnetic field orientation by measuring the ME voltage amplitude and the corresponding phase.

1. Introduction

Magnetolectric (ME) effect is defined as the influence of magnetic (electric) field on the polarization (magnetization) of a material. In a composite consisting of magnetostrictive and piezoelectric phases, the ME effect is a product property [1]. Multi-phase ME composites exhibit giant ME effect at room temperature with great design flexibility, which is lacking in single phase ME materials. Laminated ME composites show the strongest ME effect and have been extensively studied, having promising applications in sensors, phase shifters, transducers, filters and so on [2–7]. In such laminates the ME coupling is realized by the strain transfer across the interface between the piezoelectric and magnetostrictive phases. Therefore, laminate vibration modes and corresponding strain distribution determine the ME effect [8]. ME laminates with different shapes and configurations have been made. They have different vibration modes, such as bending and radial vibration in disk laminates [9], bending and longitudinal vibration in rectangular composites and torsion vibration in other structures [10–13]. It has been demonstrated that Ni/PZT and Ni/PZT/Ni cylindrical ME laminates made by electroplating have giant ME coupling with radial and axial vibration modes [14,15]. Since ME laminate vibrations are induced by the applied magnetic field, the ME effect is influenced by both the direction and the strength of the magnetic field. For ME laminates applications, especially in magnetic field sensors, the field-direction-dependent ME effect is crucial to treat uncertain magnetic field vector. A few studies have reported anisotropic ME effects in response to magnetic field direction. ME anisotropy results from the piezoelectric, magnetostrictive and/or shape anisotropy [16–19]. However, the investigated ME coefficients are averaged over the whole surface of piezoelectric layer and only a few studies have considered anisotropic ME effects at different positions of the piezoelectric layer.

Moreover, the ME coefficient has been proven to be a complex quantity, resulting from the ME loss, which includes electromechanical, magneto-mechanical and interfacial losses between the piezoelectric and magnetostrictive layers [8,12,20,21]. The phase delay of the ME voltage output with respect to externally applied magnetic field originates from the energy transfer efficiency loss in ME composites. Thus, the ME coefficient phase also reflects the ME characteristics.

In this work the ME voltage coefficient and the corresponding phase of the multi-electrode $Pb(Zr,Ti)O_3$/Ni cylindrical composite in the vertical mode were investigated. The structure consists of an intact PZT ring and four Ni arcs on the inside PZT surfaces. Various vibration modes result in the ME effects of the four arcs having different relationship with the applied magnetic field orientation. The ME coefficient phase showed directionality in high order vibration modes, which is helpful to design ME sensors.

2. Experimental

The multi-electrode $Pb(Zr,Ti)O_3$/Ni cylindrical layered composite, shown schematically in Fig. 1, was prepared by electroplating. The PZT-5H ceramic ring with the dimensions of $\Phi 25 \times \Phi 23 \times 10$ mm^3 was radially polarized. The Ni electrodes on both the inside and outside PZT ring surfaces were equally spaced. They were separated by narrow gaps along the cylinder axis to electrically isolate the electrodes. Four Ni

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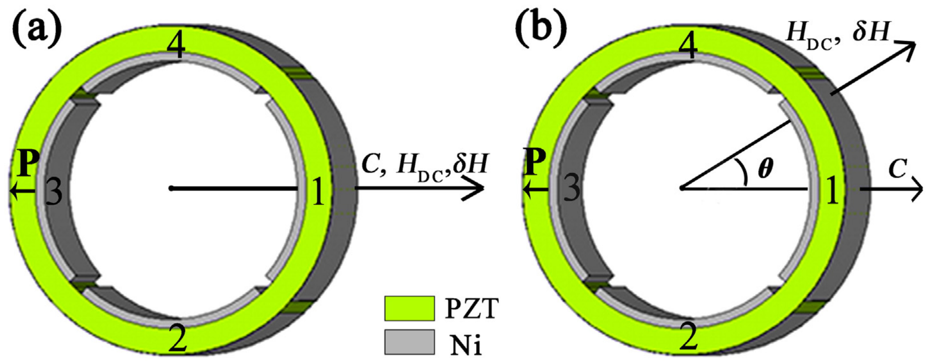

Fig. 1. Schematic illustration of the multi-electrode $Pb(Zr,Ti)_3O$/Ni ring with arrayed Ni arc layers under external magnetic field *H* applied along: (a) the perpendicular bisector *C* of the unit 1 ($\theta = 0°$); (b) an angle θ with respect to *C*. θ denotes the angle between *H* and *C*.

arc layers were electroplated on the inner electrodes simultaneously. The final magnetostrictive Ni thickness was approximately 340 μm. The Ni electroplating bath composition and conditions are described elsewhere [14]. Four ME measurement units (units 1, 2, 3 and 4) are labeled in Fig. 1a. The ME characterization was performed in the ME measurement system, where a DC bias magnetic field (H_{DC}) superimposed with a collinear alternating (δH) magnetic field was applied perpendicular to the cylinder axis (vertical mode). Considering the non-rotational symmetry of the composite, two different measurements were performed with the external magnetic field *H* applied along the perpendicular bisector *C* of unit 1 and at an angle θ with respect to *C*, as shown in Fig. 1b. The ME voltage coefficient was calculated as $\alpha_{E,V} = \delta V / (t_{PZT} \cdot \delta H)$, where t_{PZT} is the PZT thickness and δH is the amplitude of the AC magnetic field generated by the Helmholtz coils. The phase φ between the output ME voltage and the sinusoidal AC magnetic field δH were recorded simultaneously.

3. Results and discussion

Fig. 2a shows the external magnetic field frequency dependence of $\alpha_{E,V}$ and φ for the unit 1 within the 1 kHz to 120 kHz range, while Fig. 2b shows the frequency dependence of $\alpha_{E,V}$ and φ for each of the four units at two resonance regions when $\theta = 0°$. The DC bias magnetic field $H_{DC} = 110$ Oe was applied during all measurements. For units 2, 3 and 4, there are two resonance peaks for the ME voltage coefficient, similar to the unit 1. There is a significant phase shift around each resonance frequency. In previous report of the axial mode, two resonance $\alpha_{E,A}$ peaks of each unit appear at 42 kHz and 59.3 kHz [22]. Here in the vertical mode, the two peaks appear at 42 kHz and 93.7 kHz. The resonance $\alpha_{E,A}$ peaks are near electromechanical anti-resonance frequency (f_a) of the piezoelectric layer [23]. Note that f_a of the radial vibration mode was provided by the manufacturer for the PZT ring as 38.5 kHz. It is quite likely that the first $\alpha_{E,A}$ peak at 42 kHz is associated with the radial

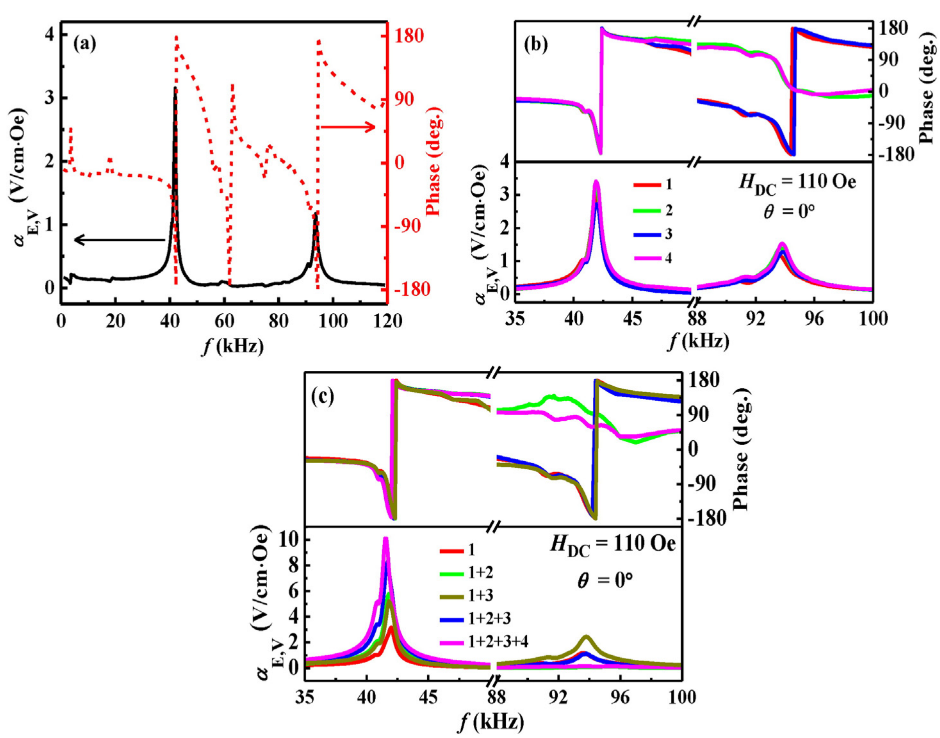

Fig. 2. Frequency dependence of the ME voltage coefficient $\alpha_{E,V}$ and the phase φ for: (a) unit 1 from 1 kHz to 120 kHz; (b) units 1–4 and (c) the four units connected in series sequentially around the resonance regions with $H_{DC} = 110$ Oe and $\theta = 0°$.