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Acoustic wave coupled magnetoelectric effect

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ABSTRACT

Magnetoelectric (ME) coupling by acoustic waveguide was developed. Longitudinal and transversal ME effects of larger than 44 and 6 (V cm^{-1} Oe^{-1}) were obtained with the waveguide-coupled ME device, respectively. Several resonant points were observed in the range of frequency lower than 47 kHz. Analysis showed that the standing waves in the waveguide were responsible for those resonances. The frequency and size dependence of the ME effects were investigated. A resonant condition about the geometrical size of the waveguide was obtained. Theory and experiments showed the resonant frequencies were closely influenced by the diameter and length of the waveguide. A series of double-peak curves of longitudinal magnetoelectric response were obtained, and their significance was discussed initially.

1. Introduction

Magnetoelectric (ME) coupling can be simply realized in layered composites of ferroelectrics and ferromagnets, by using product property of magnetostrictive and piezoelectric effects [1–3]. In layered ME composites, ME signal, which was defined as $\alpha_E = \delta E/\delta H$, is obtained by measuring the voltage between both end-surfaces of the ferroelectric layer when the sample was subjected to a magnetic field. The applied field was usually in two directions, parallel and vertical to the surfaces of the sample, leading to the transverse and longitudinal ME voltage coefficient α_{E31} and α_{E33}, respectively. Both reflected the stretching and flexural effects of the piezoelectric, respectively. Experiments and theory showed that the bending effect of a piezoelectric is larger than its expansion effect due to $d_{33} > d_{31}$ for a given ferroelectric [4–6]. But the α_{E33} observed was commonly far less than α_{E31} in previous literature [7,8]. Investigating its reason, mutual clamping between ferromagnetic and ferroelectric layers due to bonding together may constrain both movement freely, causing the flexural effect of the piezoelectric cannot normally play.

More efficient devices of ME effect could obtain if we can not only give full play to the bending effect of the piezoelectric but also reach the effective magnetoelectric coupling. According to this idea, we developed ME devices based on an acoustic-wave coupling, that is, to connected ferromagnetic and ferroelectric layers with an acoustic waveguide.

2. Sample characterization

The sample under investigated was composed with a disk of $Tb_{1-x}Dy_xFe_{2-y}$ (TDF) and a disk of Pb(Zr, Ti)O_3 (PZT) with a substrate of brass sheet to form a system-on-chip, as well as a wave guide, as shown in Fig. 1, where TDF and PZT disks were taken as the magnetostrictive and piezoelectric phases, respectively. The diameters of both TDF and PZT disks were equal in a sample. The TDF flake was in thickness of 2.0 mm. The sheet of PZT and the brass substrate were in thickness of 0.25 mm, respectively. Two diameters, 8.5 and 10 mm, of DTF and PZT disks were used to prepare samples, respectively. The maximum magnetostriction of the TDF and the polarizing orientation of the PZT were directed to the vertical of their surfaces.

The waveguides were made of plastic rings with the external diameter slightly smaller than that of DTF and PZT disks. The waveguide was bonded with TDF and PZT disks at both ends, respectively, by slow-dry epoxy. And the sample was in the shape of a Cylinder. Three lengths of waveguides were adopted. They were in 2.4, 2.7 and 3.3 mm, respectively.

A bias magnetic field (H_{bias}) and an ac field (δH) were applied along the axial (z) or radial (r) direction of the samples, respectively. δH was about 1 Oe, which was produced by a Helmholtz coil of 4 Ω with applying a function generator (Zhongce Inc, DF1641D). The ME voltage coefficient was calculated according to the relation $\alpha_E = \delta V/t_{PZT}\delta H$, where t_{PZT} is the thickness of the PZT and δV is the end-surface voltage of the PZT disk.

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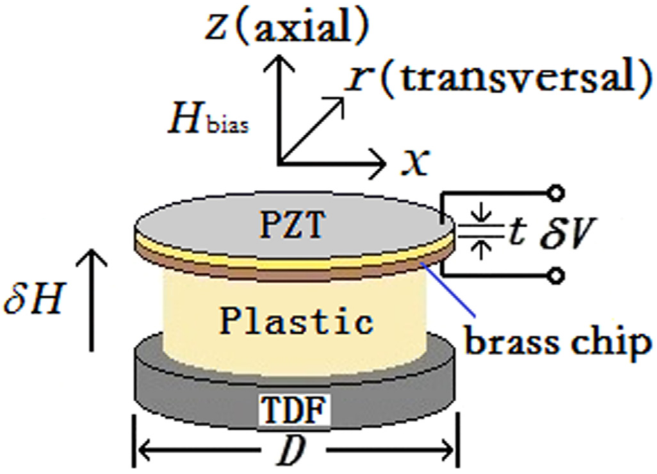

Fig. 1. Schematic diagram of the magnetoelectric device coupled by acoustic wave.

3. Experiments and discussion

Fig. 2 shows the axial ME voltage coefficient $\alpha_{E,33}$ as functions of frequency f of the ac field under a bias magnetic field of 1870 Oe for the samples with different diameters, respectively. It is found that the ME voltage coefficient is very small at lower frequency, then increases with increasing frequency and presents a series of resonant peaks. The strongest resonance locates at the frequency about $f_p = 34$ kHz in the frequency range lower than 100 kHz. Additionally, f_p moves to high frequency with reducing the diameter of the sample, and the ME effects of the devices can exist in a wide range of frequency from 100 Hz to 40 kHz.

The frequency dependence of transversal ME response $\alpha_{E,31}$, namely the ME voltage with the bias field pointed to radial direction, was also measured for the samples at the same ac field as we used in Fig. 2. The results were shown in Fig. 3. It can be seen that the resonant frequencies for the transverse ME couplings were approximately the same as that in the case of axial coupling, but the values of $\alpha_{E,31}$ at resonant frequencies (about 6 V cm^{-1} Oe^{-1}) were much less than those of $\alpha_{E,33}$ (larger than 45 V cm^{-1} Oe^{-1}). This behavior was just opposite to that observed in the test with bonded ME laminates, suggesting the axial coupling plays a major role in the samples. And it is more meaningful to study the axial ME effects for the present system.

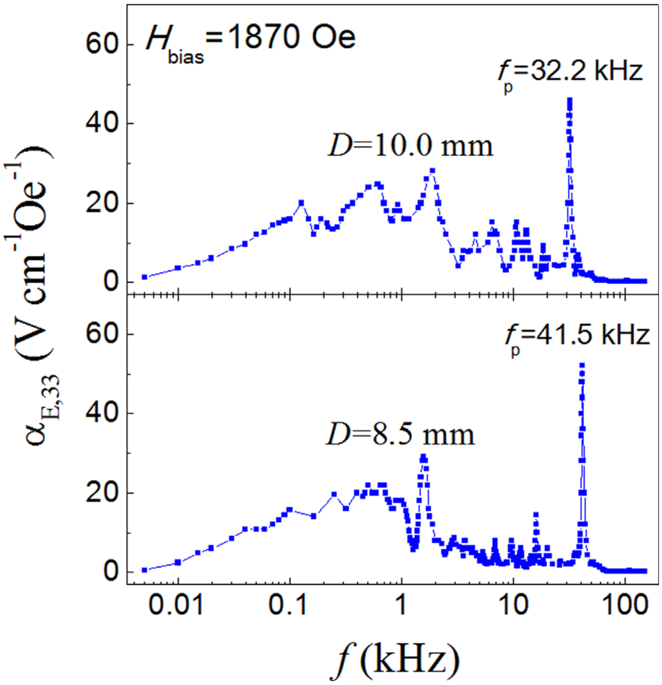

Fig. 2. Axial ME voltage coefficient ($\alpha_{E,33}$) as functions of frequency under a bias field of 1850 Oe for the samples with a wave guide in same length 2.7 mm, and diameters in 10 mm and 8.5 mm, respectively.

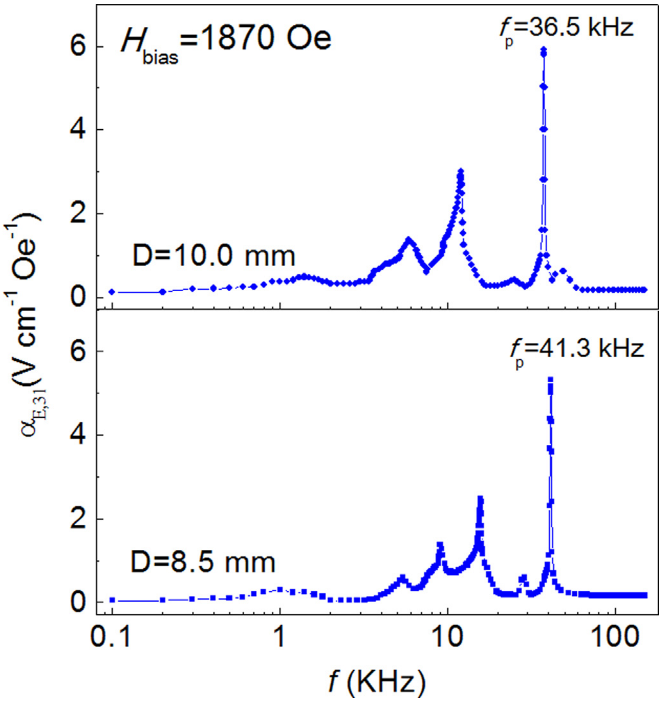

Fig. 3. Transverse ME voltage coefficient ($\alpha_{E,31}$) as functions of frequency under a bias field of 440 Oe for the samples with a same length of wave guide 2.7 mm, and diameters in 10 mm and 8.5 mm, respectively.

According to the acoustics, standing wave can be formed when a traveling acoustic wave propagates in a waveguide. And the wavelength of the former is half of that of the latter. If the length of the waveguide and the wavelength of the standing wave have the relationship of integer times, resonance may take place at both ends of the wave guide. Thus, we have relation $\lambda/2 = nh$ (or $h = n\lambda/2$), $n = 1, 2, 3\ldots$. As the velocity of sound in air is about 348 m/s at room temperature, the resonant frequency $f_p = 174\, n/h$ (or $174\, n/h$). For a 2.7 mm long waveguide, the resonant frequency should be $f_p = 64.44/n$, or 32.22 (kHz) when taking $n = 2$. This value very closes to that of the measured for the sample with the diameter $D = 10$ mm (see Fig. 2). On the other hand, it is well-known that the resonant frequency in a wave guide is strongly influenced by the width or diameter of the waveguide by the relation below [9,10]

$$f_p = 4v/(8h + \pi D). \tag{1}$$

Eq. (1) indicates that the resonance frequency f_p decreases with increasing the waveguide diameter D. It is consistent with our experimental results shown in Figs. 2 and 3.

In addition, the resonance of the PZT chip should also be taken into account when analyzing the resonant frequency of the device. As an electrostatic cavity transducer, the device can be approximated to a spring oscillator when assuming a simple piston resonator surrounded by an infinite rigid baffle. [11] While, the