Adjusting the voltage step-up ratio of a magnetoelectric composite transformer

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A magnetoelectric composite transformer is proposed. The voltage step-up ratio can be adjusted by an applied magnetic field based on the direct and converse magnetoelectric effects. The nonlinear relationship between the voltage step-up ratio and magnetic field is caused by the nonlinear relationship of the magnetoelectric effect in magnetic field.

rosen-type transformer, magnetoelectric effect, magnetostriction, piezoelectricity

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With the development of information technology, materials with good performance and devices with minimal size are highly sought after. The development of new materials and the design of complex composites have become major research topics. Multiferroic materials have attracted increasing interest for their complex properties [1–3]. Magnetoelectric materials exhibit both electric and magnetic properties, and the magnetoelectric effect can be produced by coupling the electric and magnetic properties. Magnetoelectric materials are multifunctional materials, which have potential applications in magnetic sensors, magnetoelectric transducers and data storage devices [4,5]. Many single-phase magnetoelectric materials have weak magnetoelectric coupling and commonly operate at low temperatures [6,7], making them difficult to apply. In contrast, magnetoelectric composites enjoy strong magnetoelectric coupling at room temperature. Moreover, the magnetoelectric coefficients can be adjusted by changing the phase relationships, which is currently attracting the attention of researchers [3]. In recent years, researchers have been optimizing the magnetoelectric output through experimental and theoretical studies. In

particular, laminated magnetoelectric composites exhibit a very strong magnetoelectric coupling around their resonant frequency [8–12], which has been used as an amplifier [13]. A Rosen-type transformer has enhanced the magnetoelectric coefficient of the composite [14,15]. A magnetoelectric device with double output ports was obtained by combining Terfenol-D alloy and a PMN-PT transformer [16]. The key problem is how to use magnetoelectric composites in devices.

The Rosen-type transformer is divided into two basic parts. The input part is polarized across its width and the output part is polarized along its length. When applying an alternating voltage on the input port of the transformer, an amplified voltage was inspired at the output port.

In this study, we propose a composite transformer by combining a magnetostrictive alloy and a Rosen-type transformer. The step-up ratio of the transformer can be adjusted through the direct and converse magnetoelectric effects.

1 Experimental method

A magnetoelectric composite transformer was prepared by

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bonding a Terfenol-D slice and a Rosen-type transformer with epoxy bonder. The Rosen-type transformer was bought from Kong Hong New-Materials Ltd, Xi'an, China. The dimensions of the transformer are 28.2 mm×5 mm×2 mm and it is divided into two parts as shown in Figure 1. The ratio of input to output parts of the transformer is 1:1.13. Terfenol-D with high magnetostriction was supplied commercially (Baotou Rare Earth Research Institute, China) with dimensions of 27.8 mm×4.1 mm×2.51 mm. The composite was cured at 150°C for half an hour under 150 MPa to get good mechanical coupling. For comparison purposes, the Terfenol-D was polished to thicknesses of 2.07, 1.77, 1.52 and 1.3 mm.

The voltage step-up ratio of the magnetoelectric composite transformer was defined by the output voltage (V_{out}) in response to the input voltage (V_{in}), i.e. $t = V_{out}/V_{in}$. The sine voltage V_{in} was applied to the input port of the transformer with a signal generator, and the output voltage V_{out} was measured using an oscilloscope with a 1 M Ω resistance load. Resonance occurs when the driving frequency is near the natural frequency of the magnetoelectric composite transformer and a stronger voltage step-up ratio is achieved. Generally, we used a voltage near the resonance frequency, and studied the transformer properties near that frequency. The magnetoelectric composite transformer was put in a magnetic field. The voltage step-up ratio was measured under various magnetic fields applied along the length of the composite.

2 Results and discussion

Figure 2(a) shows the frequency dependence of the voltage step-up ratio for the pure Rosen-type transformer. Two resonant peaks appear around 59 kHz and 118 kHz, corresponding to the half- and full-wavelength resonant modes. The relative voltage step-up ratio is 75 and 115. Figure 2(b) shows the frequency dependence of the voltage step-up ratio under various magnetic fields for the magnetoelectric com-

Figure 1 Illustration of the magnetoelectric composite transformer. The magnetic field was applied along the length of the transformer.

posite transformer with a Terfenol-D thickness of 2.51 mm. Similarly, two large sharp peaks of voltage step-up ratios appear at 51 kHz and 101 kHz, representing the half- and full-wavelength vibration modes. The step-up ratio without an external magnetic field is 3.1 and 4.2 for the half- and full-wavelength modes. In comparison with the pure PZT transformer, the step-up ratio decreased due to the load of the Terfenol-D plate. After applying the magnetic field, the step-up ratio clearly changed. The step-up ratio peaks decreased and then increased with the magnetic field, while the resonant frequency increased, which was due to the different acoustic velocities of the magnetostrictive Terfenol-D under different magnetic fields [15,17].

The step-up ratios at half- and full-wavelength resonant frequencies share similar characteristics. The Rosen-type transformer commonly works at the full-wavelength vibration mode. Therefore, we studied the step-up ratio characteristics with the magnetic field in the full-wavelength vibration mode. As shown in Figure 3, the step-up ratios with different Terfenol-D thicknesses share similar characteristics with the bias magnetic field. The step-up ratios increase at first and then decrease with increasing magnetic field. Without an external magnetic field, the step-up ratio for the sample with a Terfenol-D thickness of 1.33 mm is 7.7. It changes to 4.2 at 250 Oe and 9.2 at 2500 Oe. The step-up ratio nearly doubles over the magnetic field range of 0–250 Oe. Therefore, we can adjust the step-up ratio by changing the magnetic field. The step-up ratio, under the same magnetic field, increases with decreasing Terfenol-D thickness

Figure 2 Frequency dependence of the voltage step-up ratio of (a) a pure Rosen-type transformer and (b) a magnetoelectric composite transformer under selected magnetic fields.

from 2.51 to 1.3 mm. The step-up ratio, without a magnetic field, is 4.7 for a Terfenol-D thickness of 2.51 mm, and 7.6 for 1.3 mm. The increase nearly doubles. This is because the Terfenol-D is equivalent to a load on the transformer. The smaller load results in a higher step-up ratio. Relatively, the resonant frequency increases with a near linear relationship to the magnetic field except at the low magnetic field levels, which is caused by the complex magnetolectric properties near the resonant frequency [17].

The combining of the direct and converse magnetolectric effects caused the step-up ratio of the magnetolectric composite transformer to be adjusted by the magnetic field. After applying an AC voltage on the input port of the transformer, an amplified signal was produced due to the amplifying effect. At the same time, magnetization is induced due to the converse magnetolectric effect. The magnetization produces a voltage at the output port due to the direct magnetolectric effect, which is superimposed on the amplified signal. Therefore, the step-up ratio of the transformer can be adjusted by the magnetic field because the magnetolectric coupling varies under different magnetic fields.

The magnetization was induced with the piezoelectric material polarized across the width and the magnetostrictive material magnetized along the length. Thus, the converse magnetolectric coefficient is [22]

$$\left. \frac{dH_3}{dE} \right|_{T-L} = \frac{n(1-n)d_{33,m}d_{31,p}}{\mu_{33}^T[(1-n)s_{33}^H(1-k_{33,m}^2) + ns_{11}^E]}, \quad (1)$$

where n is the geometric thickness ratio of the piezoelectric layer to the total thickness of the laminate; s_{11}^E and s_{33}^H are the elastic compliances of the piezoelectric and magnetostrictive layers; $k_{31,m}$ and μ_{33}^T are the electromechanical coefficient and magnetic permeability of piezomagnetic phase under stress; $d_{31,p}$ and $d_{31,m}$ are the piezoelectric and piezomagnetic coefficients. When both the magnetic field and polarized directions are along the length, the direct

magnetolectric coefficient is [22,23]

$$\left. \frac{dE}{dH_3} \right|_{L-L} = \frac{n(1-n)d_{33,m}d_{33,p}}{\epsilon_{33}^E[ns_{33}^E(1-k_{33,p}^2) + (1-n)s_{33}^H]}, \quad (2)$$

where s_{33}^E and s_{33}^H are the elastic compliances of the piezoelectric and magnetostrictive layers; $k_{31,p}$ and ϵ_{33}^E are the electromechanical coefficient and dielectric constant of piezoelectric phase.

Similar to the permittivity and magnetic permeability, the two parameters of the magnetolectric modulus and phasic difference have been used to describe the complete magnetolectric characteristics in the experiments [8,9,15,20]. However, while the magnetolectric modulus was discussed in theory, the phasic difference was not covered [22–25]. In this study, both the magnetolectric modulus and phasic difference are important because the magnetolectric voltage superimposes on the amplifying signal. $d_{31,p}$ and $d_{33,p}$ have opposite signs. There are anti-phasic differences between the input voltage and the voltage produced through the converse and direct magnetolectric effects. Thus, the output voltage reduces after the superimposition of the magnetolectric signal; as a result, the voltage step-up ratio is reduced as shown in Figure 3. Therefore, stronger magnetolectric coupling results in a smaller voltage step-up ratio.

The direct and converse magnetolectric effects share the same characteristics with the increase in the bias magnetic field, i.e., increase and then decrease [8,17–21]. The magnetic field corresponding to the maximum magnetolectric coupling relates to the demagnetization factor or the shape of the magnetic layer. The maximum magnetolectric coupling is at about 250 Oe for the Terfenol-D shape in this study [17]. Therefore, the minimal step-up ratio occurs at a magnetic field of 250 Oe.

3 Conclusions

In summary, a magnetolectric composite transformer was prepared by combining a Terfenol-D slice and a Rosen-type transformer. The voltage step-up ratio of the transformer was adjusted by changing the bias magnetic field based on the direct and converse magnetolectric effects. The dependence of the voltage step-up ratio on the magnetic field shared similar behavior to transformers with different Terfenol-D thicknesses, i.e., decreased at first and then increased with the increase in the magnetic field. The magnetolectric composite transformer provides a method for the application of magnetolectric materials.

Figure 3 Variation of the voltage step-up ratio of the sample and the resonant frequency with magnetic fields for different thicknesses of the Terfenol-D layer.

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