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Bidirectional current-voltage converters based on magnetostrictive/piezoelectric composites

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We report a power supply-free, bidirectional electric current-voltage converter based on a coil-wound laminated composite of magnetostrictive alloy and piezoelectric crystal. An electric current applied to the coil induces a magnetic field, resulting in an electric voltage from the composite due to the direct magnetoelectric effect. Conversely, an electric voltage applied to the composite produces a magnetic induction due to the converse magnetoelectric effect, leading to an electric current from the coil. The converter exhibits excellent linear relationships between current and voltage. Compared with traditional current/voltage converters made by operational amplifiers, the advantages of the proposed device include low cost, no power consumption, and bidirectional conversion. © 2009 American Institute of Physics. [DOI: 10.1063/1.3160739]

Electric current-voltage (I - V) and voltage-current (V - I) converters play an important role in various industrial fields such as power electronics and drives, condition monitoring of electrical power distribution systems, industrial automation, etc. Currently, most of the I - V and V - I converters are based on operational amplifiers (i.e., a class of dc-coupled high-gain electronic voltage amplifiers with differential inputs) so that external power supplies are required to sustain their operations.¹⁻³ Also, these converters can mainly provide unidirectional I - V or V - I conversion. In view of these, power supply-free, bidirectional converters are desirable.

The direct and converse magnetoelectric effects have attracted considerable attention in recent years because of their great potential in realizing power supply-free magnetoelectric devices and core-free electromagnetic devices, respectively.⁴⁻¹⁰ The effects in laminated composites of $\text{Tb}_x\text{Dy}_{1-x}\text{Fe}_{2-y}$ (Terfenol-D) magnetostrictive alloy and $\text{Pb}(\text{Mg}_{1/3}\text{Nb}_{2/3})_{1-x}\text{Ti}_x\text{O}_3$ (PMN-PT) piezoelectric single crystal have been studied, and interestingly large magnetoelectric coefficient ($\alpha_v = dV/dH$) of 384 mV/Oe and converse magnetoelectric coefficient ($\alpha_B = dB/dV$) of 118 mGs/V have been obtained at an optimal bias magnetic field of ~ 350 Oe.¹¹⁻¹³ The direct magnetoelectric effect in the composites have been attributed to the product effect of the direct magnetostrictive effect in the Terfenol-D alloy and the direct piezoelectric effect in the PMN-PT single crystal, while the converse magnetoelectric effect has been ascribed to the product effect of the converse piezoelectric effect in the PMN-PT single crystal and the converse magnetostrictive effect in the Terfenol-D alloy, both mediated by mechanical coupling.⁸⁻¹⁰ In this letter, we report the structure, operating principle, and characteristics of a power supply-free, bidirectional I - V converter based on a Terfenol-D/PMN-PT magne-

toelectric laminated composite wound by a coil.

Terfenol-D ($\text{Tb}_{0.3}\text{Dy}_{0.7}\text{Fe}_{1.92}$) plates of dimensions 12 mm long, 6 mm wide, and 1 mm thick were obtained commercially (Changzhou Wujin Smart Rare Earth Materials Co. Ltd., China). They had their highly magnetostrictive $\langle 112 \rangle$ crystallographic axis in the length direction so that their magnetizations were relatively easy in that direction. PMN-PT single crystal was grown in-house using a modified Bridgman technique.¹⁴ Plate-shaped PMN-PT single crystals with the same dimensions as the Terfenol-D plates were cut from the ingot such that their $\langle 001 \rangle$ and $\langle 110 \rangle$ crystallographic axes were oriented in the length and thickness directions, respectively.^{8,11,15} Polarization was induced in the PMN-PT plates along the thickness direction by immersing the plates in a silicone oil bath with an applied electric field of 1 kV/mm at a temperature of 120 °C for a period of 15 min, and then with a half-reduced electric field of 0.5 kV/mm for natural cooling to room temperature. The piezoelectric coefficient ($d_{33,p}$) of the plates was measured by a Berlincourt d_{33} meter in the thickness direction. Terfenol-D/PMN-PT magnetoelectric laminated composites were fabricated by sandwiching one thickness-polarized PMN-PT plate

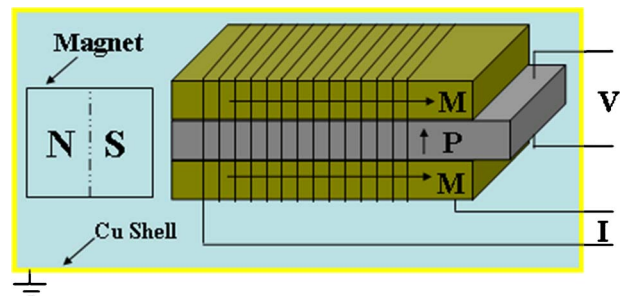


FIG. 1. (Color online) The structure of proposed passive and bidirectional I - V and V - I converter based on laminate ME composite.

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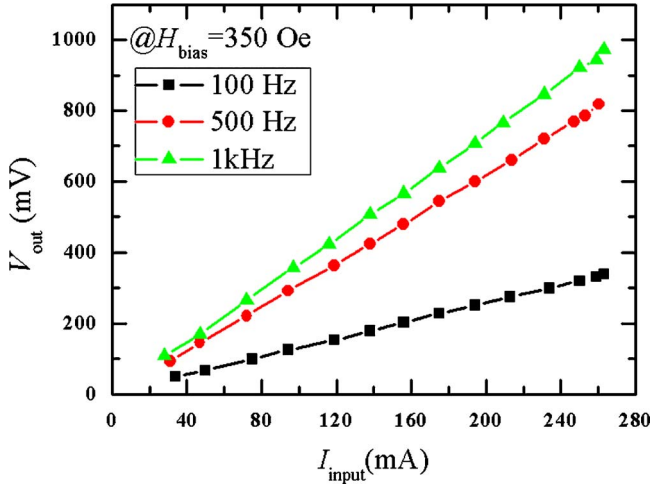


FIG. 2. (Color online) I - V conversion on basis of ME effect of this composite for the proposed I - V and V - I passive and bilateral converter.

between two length-magnetized Terfenol-D plates using silver epoxy (E-Solder No. 3021, ACME Division of Allied Products Co., Connecticut, USA) under a pressure of 10 MPa and at a curing temperature of 60 °C for 6 h to assure good mechanical coupling and strong bonding.

The structure of the proposed converter is shown in Fig. 1. It basically consists of a Terfenol-D/PMN-PT magnetoelectric laminated composite wound by a coil and placed in a Cu shell with a bias magnet. The coil has 20 turns of winding. The bias magnet is capable of providing an optimal bias magnetic field (H_{bias}) of 350 Oe to the composite. The Cu shell is used to provide electric field shielding for the coil-wound composite-bias magnet assembly. The operation of the converter can be described by the I - V and V - I modes separately. For the I - V conversion mode, an electric current (I) applied to the coil induces a magnetic field based on Ampère's law. This magnetic field then results in an electric voltage (V) from the composite due to the direct magnetoelectric effect. For the V - I conversion mode, an V applied to the composite produces a magnetic induction due to the converse magnetoelectric effect. This magnetic induction then leads to an I from the coil based on Faraday's law.

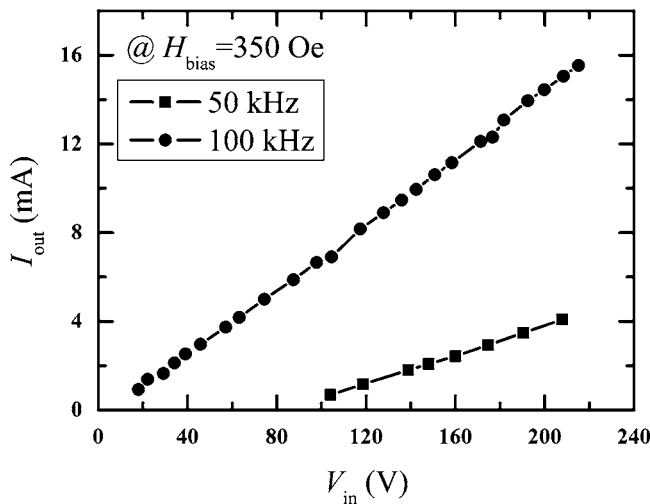


FIG. 3. V - I conversion on basis of the converse ME effect of this composite for the proposed I - V and V - I passive and bilateral converter.

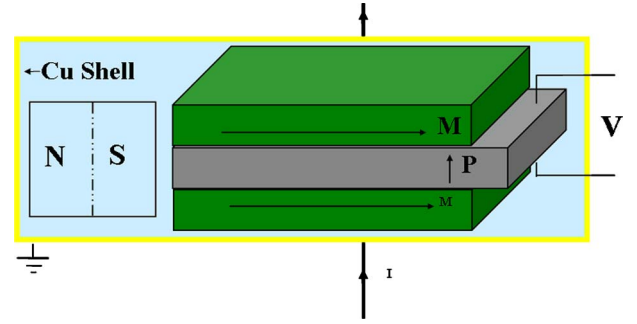


FIG. 4. (Color online) The structure of proposed noncontact and passive I - V converter based on ME composite.

For the V - I measurement, a low-frequency signal generator connected to a power amplifier operating in constant-voltage mode (AE Techtron 7560) was employed to provide an ac input voltage (V_{in}) to the PMN-PT plate, and the output current (I_{out}) induced from the coil was measured by a micro-Ampere meter circuit connected to an oscilloscope. For the I - V measurement, a low-frequency signal generator connected to a power amplifier operating in constant-current mode was used to provide an ac input electric current to the coil, and the output voltage (V_{out}) induced from the PMN-PT plate was measured by an oscilloscope.

Figure 2 shows the measured I - V characteristics of the converter. It is clear that V_{out} has highly linear responses to I_{input} for the measured frequencies, and the I - V conversion efficiency increases with increasing frequency. The conversion coefficient can also be adjusted by changing the bias dc magnetic field.

Figure 3 plots the measured V - I characteristics of the converter. Again, I_{out} demonstrates excellent linear responses to V_{in} for the measured frequencies, and the V - I conversion efficiency increases with increasing frequency. The conversion coefficient can also be adjusted by the change in bias dc magnetic field.

Using this device, we have accomplished an ideal conversion of I - V and V - I . The conversion is bidirectional (saving significant production costs in the final device) and passive (no power consumption). We should note that under ac conditions, due to the product effect of magnetoelectric (ME) effect of piezoelectric/magnetostrictive composite and electromagnetic induction effect of coil, the device can realize bidirectional conversion. Under dc condition, when a dc current was applied on this device, a dc magnetic field will be induced. Due to ME effect, a dc voltage will be obtained. So I -to- V conversion of this device can be realized under dc conditions. However, when a dc voltage was applied on this device, a constant strain will be induced in magnetostrictive layer. The magnetic flux through the coil keeps constant. So V -to- I conversion of this device cannot be realized under dc conditions. The bidirectional nature of the device is true only under ac conditions, although the I -to- V conversion of the device is true under dc conditions.

Piezomagnetism is a linear effect relating mechanical. Magnetostriction (mechanical strain quadratic in the magnetic flux density) is a second order effect. Biased magnetostriction is equivalent to piezomagnetism phenomenologically for excursions about an operating point that are not too large.¹⁶ For the operation of current/voltage converter, biased magnetic field is necessary. To keep linearization, the ac

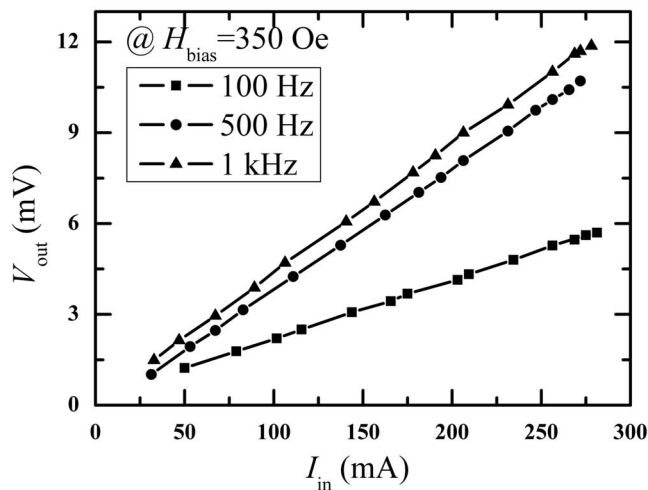


FIG. 5. I - V conversion on basis of ME effect for the proposed noncontact and passive I - V converter.

magnetic field should be much lower than the dc bias (350 Oe). This is one of the limits of the device.

An alternative arrangement for addressing our converter is shown in Fig. 4. The arrangement has most of the advantages of the original setup, i.e., no power consumption, simple structure, and low cost, but added to these advantages is the noncontact mode. While the I -to- V conversion was very easy to arrange and showed an excellent linearity (see Fig. 5), a drawback of this arrangement is that it proved to be very difficult to obtain proper V -to- I conversion with this arrangement. Hence the bidirectional character of the original setup is lost at the expense of the advantage of a noncontact mode of addressing the converter. Ultimately, the intended application field will determine which of the two arrangements is the most appropriate for the application. However, in both arrangements very attractive conversion characteristics are obtained.

In conclusion, a passive and bidirectional current/voltage converter on basis of direct ME and converse ME effect in

piezoelectric/magnetostrictive laminated composites has been fabricated. The advantages include bidirectional conversion, excellent linearity, low cost, and no power consumption. This passive and bidirectional I - V and V - I converter has a wide potential in the field of microelectronics.

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