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Voltage gain effect in a ring-type magnetoelectric laminate

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It has been observed that a ring-type magnetoelectric laminate composite of circumferentially magnetized magnetostrictive Tb₁₋ₓDyₓFe₂ and circumferentially polarized piezoelectric Pb(Zr,Ti)O₃ layers has a large magnetoelectric voltage gain effect, offering potential in high-power miniature transformer applications. © 2004 American Institute of Physics. [DOI: 10.1063/1.1756676]

The magnetoelectric (ME) effect in materials which are simultaneously ferromagnetic and ferroelectric has been a research topic in recent years, due to the potential energy transduction between magnetic and electrical fields. ME materials of single phase, multiple phases, and laminate composites have been reported. Recently, we have developed laminate composite designs that have significantly higher ME coupling effects. However, to date, investigations of ME composites have focused on the ME effect for applications only in magnetic field sensing.

Magneostriuctive Tb₁₋ₓDyₓFe₂ (Terfenol-D) and piezoelectric Pb(Zr,Ti)O₃ (PZT) exhibit high magneto- and electromechanical energy densities, respectively. Accordingly, ME laminates can be operated under high-power drive, producing much stronger ME effects at resonance conditions, as recently shown. In this letter, we report a ring-type piezoelectric/magnetostrictive laminate composite. Our ring-type ME laminate was designed based upon the piezoelectric and piezomagnetic equations of state, in a radial symmetric-mode vibration. Analysis revealed the possibility of a high ME voltage gain, suitable for high-power miniature transformer applications.

Figure 1(a) illustrates the laminate geometry chosen for this investigation. It is a ring-type piezoelectric/magnetostrictive composite design, in which a circumferential-poled piezoelectric ring layer (consisting of m = 4 segments) is sandwiched between two magnetostrictive ring ones that are circumferentially magnetized. The conductive magnetostrictive layers are separated by an insulating piezoelectric one, and thus eddy currents are effectively eliminated if the thickness of the magnetostrictive layers is sufficiently thin. Our ME laminate design differs from previous ones, favoring the circumferential strains along which fields are applied circumferentially.

The working principle is as follows. A harmonic vortex ac magnetic field H₀, excited with a toroidal coil of N turns carrying a current I₀ around the ring, is applied along the circumference of the ring-type laminate, as illustrated in Fig. 1(a). This causes the two magnetostrictive ring layers to shrink/expand in their radial symmetric mode in response to H₀. The magnetostrictive strain then acts upon the piezoelectric ring layer that is bonded between the two magnetostrictive ring ones, causing the piezoelectric ring to strain in the radial symmetric mode, producing a voltage output from each of the four segments of the ring.

Suppose that the input ac voltage applied to the coils is Vₕ and that its frequency is f. Then, a vortex H₀ of the same frequency will be excited along the circumference of the laminated ring. When the frequency of H₀ is equal to the resonance frequency (ωₕ = 2πfₕ) of the ring, the ME coupling effect will be sufficiently strong that the output ME voltage (Vₒ) induced in the piezoelectric layer is much higher than Vₕ. Thus, under resonant drive, our ME laminate will exhibit a large voltage gain, due to the ME effect. We designated this ME voltage gain as MEVG: It is a combinatory effect of electromagnetic, magnetostrictive, and piezoelectric ones. The excited magnetic field fluxes in the ME ring will be continuous vortex fields, and thus the H₀ out of the ring will be localized. This will maximize the voltage and power outputs.

At the radial symmetric mode, the ME voltages induced...
across each segment in the piezoelectric ring layer are equivalent. A magnetoelastoelectric equivalent circuit can be derived by using the piezoelectric and piezomagnetic constitutive equations, by applying Newton’s second law of motion to the laminated ring and by subsequently finding analogous electrical parameters,\textsuperscript{19,20} as shown in Fig. 1(b). The MEVG was determined by analysis of the equivalent circuit of this figure. Assuming that the circuit is unloaded and by applying Ohm’s law, the maximum voltage gain can be estimated as

$$ V_{\text{Gain, max}} = \frac{\varphi_{\text{p}} Q_{\text{mech}}}{2 \pi m C_0 Z_0 \omega_s}; \quad (1) $$

where $Q_{\text{mech}}$ is the mechanical quality factor of the laminate layers, $\varphi_{\text{p}}$ is the elastoelectric coupling factor, $C_0$ is the clamped capacitance of the piezoelectric layer, $Z_0$ is the mechanical impedance of the laminate, and $\omega_s$ is the series resonance frequency (where $\omega_s = \omega_r + \frac{\varphi_{\text{p}}^2}{L_m C_0}$, $\omega_r = \sqrt{1/a}$, and $a$ and $\bar{v}$ are the mean radial and acoustic velocities of the laminated ring). From Eq. (1), it can be seen that the maximum voltage gain at $\omega_s$ is mainly related to the piezoelectric segment of the equivalent circuit in Fig. 1(b), which is because $V_{\text{out}}$ is generated by this segment. The voltage gain is directly proportional to $Q_{\text{mech}}$ and $\varphi_{\text{p}}^2$ in the piezoelectric layer. The purpose of the magnetic section of the equivalent circuit is to transduce the magnetic energy into a mechanical vibration. The piezoelectric one subsequently transduces the vibration to an electrical output.

Calculations were performed using Eq. (1), assuming a Terfenol-D/PZT laminate ring with a mean radius of 9.0 mm, and a total thickness of 6.0 mm (each layer thickness was 2.0 mm). The voltage gain for a laminate with $Q_m = 100$ was estimated to be $\sim 29$. High values of $Q_{\text{mech}}$ in the laminate resulted in higher-voltage gains. Figure 2 shows the calculated voltage gain as a function of drive frequency. The voltage gain predicted by the equivalent circuit method are quite substantial, producing much larger ME voltages than previously reported at lower frequencies.

A ring-type ME laminate with an outer diameter of 25.0 mm, an inner diameter of 12.0 mm, and a thickness of 6.0 mm was fabricated following the illustration shown in Fig. 1(a). Both the piezoelectric and magnetostrictive layers were circumferentially poled and magnetized, respectively. The MEVG was then measured. A voltage generator was used as an input source to the coils, and an oscilloscope was used for monitoring both the input and output voltages. Figure 3 shows the measured voltage gain $V_{\text{out}}/V_{\text{in}}$ of our prototype as a function of the drive frequency $f$. A maximum voltage gain of $\sim 25$ was found at a resonance frequency of 53.3 kHz. This measured value coincided with our predicted one. In addition, at the resonance state, the maximum voltage gain was strongly dependent on an applied dc magnetic bias $H_{\text{dc}}$, due to the fact that Terfenol-D has a large effective piezomagnetic coefficient only under a suitable $H_{\text{dc}}$. In our experiment, the dc magnetic bias $H_{\text{dc}}$ applied to the ring was about 500 Oe.

In transformer application, our ME laminate will not require secondary coils with a high-turns ratio in order to obtain a step-up voltage output, which is needed in conventional electromagnetic transformers. In addition, compared with piezoelectric transformers,\textsuperscript{21} it has a notably wider operational frequency bandwidth. The combination of these advantages offers potential for applications in solid-state transformer devices.

In summary, a large MEVG effect has been found in a ring-type laminate composites of piezoelectric PZT and magnetostrictive Terfenol-D. We believe these results have important ramifications, potentially offering applications in high-power solid-state transformers.

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