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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 $Tb_{1-x}Dy_xFe_2$ and circumferentially polarized piezoelectric $Pb(Zr,Ti)O_3$ layers has a large magnetoelectric voltage gain effect, offering potential in high-power miniature transformer applications. © *2004 American Institute of Physics.*
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The magnetoelectric (ME) effect[1] 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 forms. ME materials of single phase, multiple phases, and laminate composites have been reported.[2–18] Recently, we have developed laminate composite designs that have significantly higher ME coupling effects.[13–15] However, to date, investigations of ME composites have focused on the ME effect for applications only in magnetic field sensing.[6,12,14]

Magnetostrictive $Tb_{1-x}Dy_xFe_2$ (Terfenol-D) and piezoelectric $Pb(Zr,Ti)O_3$ (PZT) exhibit high magneto- and electromechanical energy densities, respectively.[19,20] Accordingly, ME laminates can be operated under high-power drive, producing much stronger ME effects at resonance conditions, as recently shown.[15–17] 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 H_{ac}, excited with a toroidal coil of N turns carrying a current I_{in} 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 H_{ac}. 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 V_{in} and that its frequency is f. Then, a vortex H_{ac} of the same frequency will be excited along the circumference of the laminated ring. When the frequency of H_{ac} is equal to the resonance frequency ($\omega_s=2\pi f_s$) of the ring, the ME coupling effect will be sufficiently strong that the output ME voltage (V_{out}) induced in the piezoelectric layer is much higher than V_{in}. 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 H_{ac} out of the ring will be localized. This will maximize the voltage and power outputs.

At the radial symmetric mode, the ME voltages induced

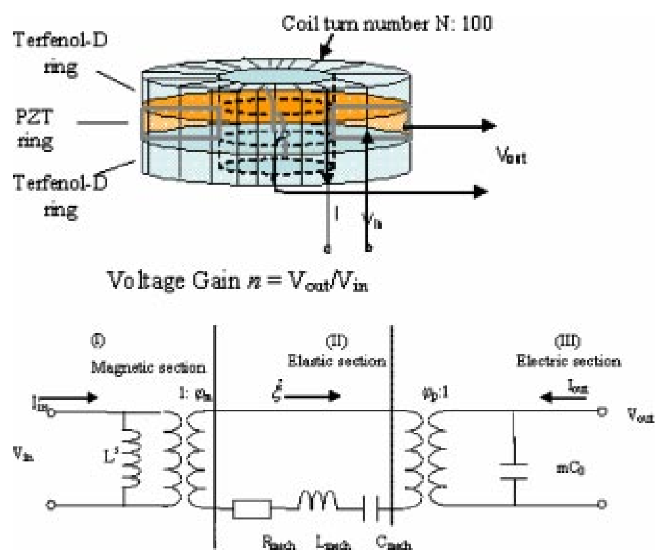

FIG. 1. Magnetoelectric ring-type laminate composite transformer: (a) Schematic illustration of our ring-type ME laminate composite for transformer applications, where the voltage gain is defined as V_{out}/V_{in}; and (b) equivalent circuit for the MEVG effect, where $R_m=2\pi Z_0/Q_m$, $L_m=2\pi a\bar{\rho}A$, and $C_m=1/L_m\omega_r^2$ are the motional mechanical impedance, inductance, and capacitance, respectively; $\varphi_m=2\pi\lambda_{33}/j\omega N$ is the magnetoelastic coupling factor; $\varphi_p=mA_pd_{33,p}/as_{33}^E$ is the elastoelectric coupling factor; and $C_o=(1-k_{33p}^2)wt_p\varepsilon_{33}^T/2\pi a/m$, is the clamped capacitance of each segment in the piezoelectric layer; and $L^s=A_m\mu_{33}^sN^2/\pi a$ is the clamped inductance of the coils around Terfenol-D ring layers.

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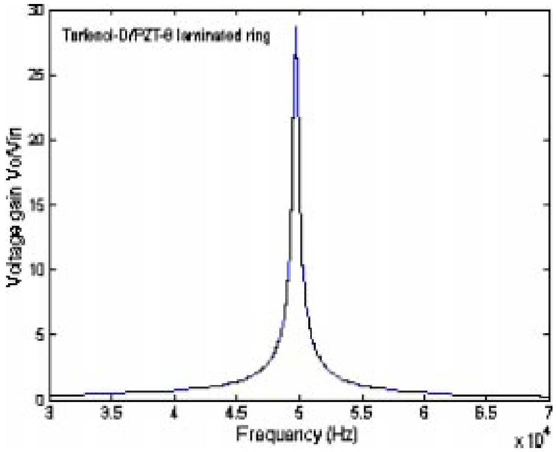

FIG. 2. Calculated MEVG as a function of drive frequency.

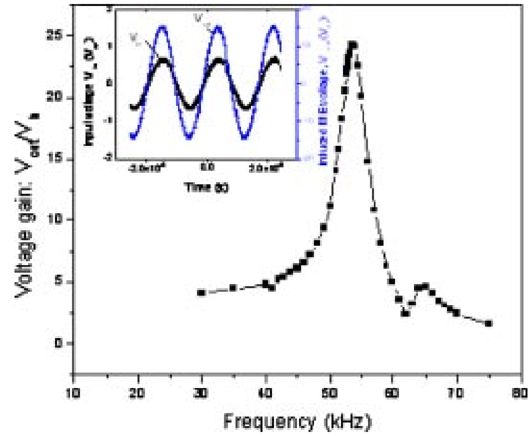

FIG. 3. Measured MEVG as a function of drive frequency.

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,[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

$$V_{\mathrm{Gain,max}}=\frac{\varphi_p^2 Q_{\mathrm{mech}}}{2\pi m C_0 Z_0 \omega_s}; \tag{1}$$

where Q_{mech} is the mechanical quality factor of the laminate layers, $\varphi_{\hat{p}}$ 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 ω_s is the series resonance frequency (where $\omega_s=\omega_r+\varphi_p^2/L_m C_0$, $\omega_r=\overline{\nu}/a$, and a and $\overline{\nu}$ are the mean radial and acoustic velocities of the laminated ring). From Eq. (1), it can be seen that the maximum voltage gain at ω_s is mainly related to the piezoelectric segment of the equivalent circuit in Fig. 1(b), which is because V_{out} is generated by this segment. The voltage gain is directly proportional to Q_{mech} and φ_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 ~29. High values of Q_{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 $V_{\mathrm{out}}/V_{\mathrm{in}}$ of our prototype as a function of the drive frequency f. A maximum voltage gain of ~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_{dc}, due to the fact that Terfenol-D has a large effective piezomagnetic coefficient only under a suitable H_{dc}. In our experiment, the dc magnetic bias H_{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,[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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