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Mechanical loss and magnetoelectric response in magnetostrictive/interdigitated-electrode/piezoelectric laminated resonators

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The mechanical quality factor and the resonant magnetoelectric (ME) response of multi-push-pull mode Metglas/interdigitated (ID)-electrode/Pb(Zr,Ti)O_3 (PZT) ME resonators have been studied as a function of ID-electrode geometry for both sandwich and bimorph configurations. The results show that the mechanical quality factor of the PZT core composite and the effective mechanical quality factor of the ME resonator are increased with increasing ID-electrode spacing. The sandwich resonator was found to exhibit a higher effective mechanical quality factor than the bimorph one. © *2013 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4798300]

The magnetoelectric (ME) effect, which is a cross-correlation between electric and magnetic orders, is an important subject in contemporary condensed-matter science.[1] Although the ME effect itself has a long history,[2] the recent discovery of large ME effects in multiferroic composites by combining magnetostrictive and piezoelectric layer together, where the magnetic and electric properties are mediated via strain across an interface,[2] accelerated their advancement in magnetic sensors and other applications.[2–4] In particular, laminated composites of magnetostrictive Metglas alloys, piezoelectric 0.7Pb($Mg_{1/3}Nb_{2/3}$)O_3-0.3PbTiO_3 (PMN-PT) single crystals or Pb(Zr,Ti)O_3 (PZT) ceramics, and interdigitated (ID)-electrodes operated in a multi-push-pull mode have the highest ME coefficients of $\alpha_E = 52$ V/cm Oe and the lowest equivalent magnetic noise floor of 5.1 pT/$\sqrt{}$Hz at frequency $f = 1$ Hz. However, the quest for ME materials exhibiting even higher magnetic field sensitivities remains a significant challenge.

It has been theoretically and experimentally established that a modulation-demodulation technique can be employed to enhance the magnetic field sensitivity at arbitrary frequencies by utilizing an electromechanical resonance (EMR) gain.[5,6] The enhancement in the magnetic field sensitivity is significantly influenced by the sharpness of the resonance peaks that are determined by the mechanical quality (Q) or loss (Q^{-1}) factors. The Q of ME laminates is determined by the composite components,[7] the polarization distribution of the piezoelectric core,[8] and the boundary conditions.[9] Thus, with regards to modulation technique applications, it is important to characterize the effective mechanical quality factor Q_{eff} of the multi-push-pull mode laminates and the dependence of the polarization distribution that results from the geometry of the ID-electrodes.

Here, the Q_{eff} for multi-push-pull mode laminate composites was systematically investigated for structures having various ID-electrode spacings. The results show that resonators with a sandwich configuration have a higher Q_{eff} than a bimorph one using identical geometries. The value of Q_{eff} increased with increasing ID-electrode spacing, demonstrating that wide spaced resonators with a sandwich structure are better for applications in a modulation-demodulation technique.

A schematic is shown in Figure 1(a) of the core composite in a multi-push-pull modality. It consisted of ID-electrodes with a center-to-center spacing of s that was attached to the top and bottom sides of a $40 \times 10 \times 1$ mm^3 PZT plate (5A1, Smart materials) using epoxy resin. Figure 1(b) presents a photo of core composites for $s = 1$ mm, 1.5 mm, and 1.8 mm. The as-prepared core composites were polarized in a silicon oil bath under an electric field of 1.6 kV/mm at room temperature. The capacitance C_0 of the core composites was then measured at $f = 1$ kHz using an impedance analyzer (Agilent 4294), as summarized in Table I. In order to determine the mechanical quality factor of the core composites (Q_{core}), impedance spectra of the core composites were measured using an impedance analyzer. Three Metglas layers, each of dimensions $80 \times 10 \times 0.025$ mm^3, were then stacked one on top of each other, and a pair of such three-layer Metglas foils was symmetrically bonded to the top and bottom sides of the ID electrode/PZT core composites with epoxy resin (West system 206, USA) using a vacuum bag pressure method.[3] After the properties of the sandwich configuration were characterized, one-of the three-layer Metglas sides was removed to form a bimorph configuration.

Figure 1(c) shows impedance spectra for three core composites with spacing of $s = 1$, 1.5, and 1.8 mm over the frequency range of $1 < f < 100$ kHz. Two longitudinal-extensional resonances (e.g., 1st and 2nd order) can be seen over this frequency range. The resonance f_r and the anti-resonance f_a frequencies of the core composites are summarized within this figure. The mechanical quality factor Q of a piezoelectric vibrator can be expressed as[10]

$$Q = \frac{f_a^2}{2\pi f_r |Z_m| C_0 (f_a^2 - f_r^2)}, \tag{1}$$

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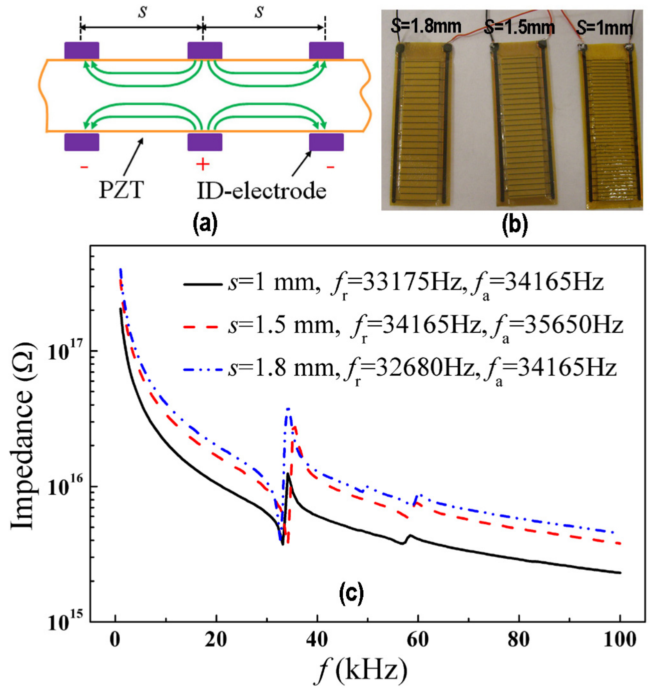

FIG. 1. (a) Illustration of the numerous alternating push-pull mode units, each with length of s. (b) Photographs of the ID-electrode/PZT core composite for ID-electrode spacing of $s=1$ mm, 1.5 mm, and 1.8 mm. (c) Impedance spectra for the three core composites over the frequency range of 1 kHz $< f <$ 100 kHz.

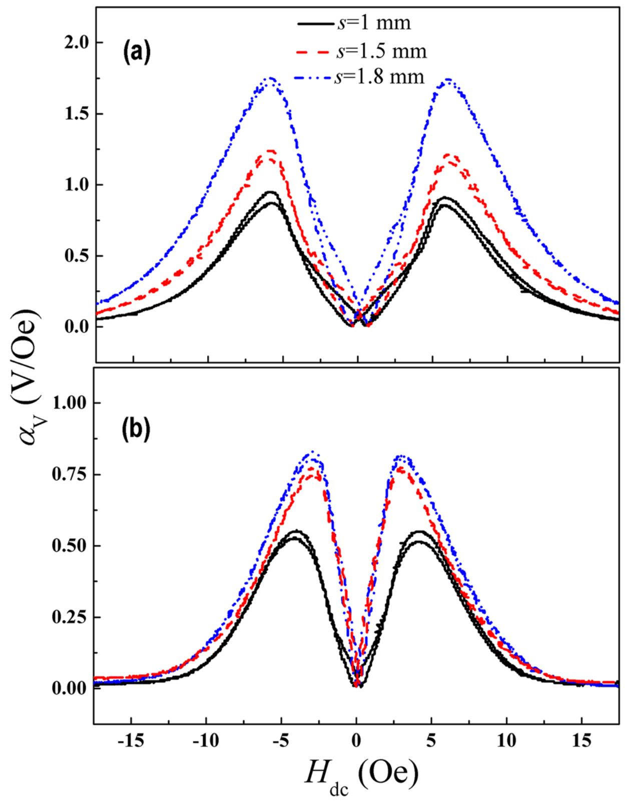

FIG. 2. ME coefficient at 1 kHz for sensors having various spacings as a function of DC magnetic field for (a) sandwich and (b) bimorph configurations.

where C_0 and Z_m denote the quasi-static capacitance and the minimum resonance impedance of a piezoelectric resonator, respectively. Using appropriate parameters for the core composites, the mechanical quality factor Q_{core} for the three core composites can be determined as 29, 32, 37. The enhancement in Q_{Core} with increasing s is due to the increased uniformity of the polarization distribution and a decreased size of a "dead-zone" region.[8]

The ME voltage coefficient α_V for the sandwich (Fig. 2(a)) and bimorph (Fig. 2(b)) configurations was measured as a function of dc magnetic bias H_{dc} in response to an ac magnetic field of $H_{ac}=0.1$ Oe at a drive frequency of $f=1$ kHz using an in-house automated system. For both configurations with various values of s, the functional form of the variation of α_V with H_{dc} was similar to that previously reported for magnetostrictive and piezoelectric laminates.[11–13] For the sandwich structure, the maximum value of α_V near linearly increased with increase of s, resulting in the ME field coefficient α_E (i.e., $\alpha_E=\alpha_V/s$) being a constant in agreement with previous predictions.[14] For the bimorph structure, the maximum value of α_V increased nonlinearly with increase of s. This resulted in a decrease of α_E with increase of s, which is due to the bending mode value of α_E being dependent not only on H_{dc} but also on f.[15] In Figure 2, it can be seen that the optimal value of H_{dc} for the bimorph configuration was notably smaller than that for the sandwich one: this is due to a higher magnetic flux concentration for the three-layer Metglas bimorph configuration than for the six-layer Metglas sandwich one.[16] In each case, the maximum α_V was located near the same optimal H_{dc} for the various values of s, indicating that ID-electrode spacing induced mechanical variations are insufficient to change the required magnetic field for the maximum piezomagnetic coefficient of the Metglas layers.[3]

TABLE I. Resonance properties of the composites and corresponding sandwich and bimorph resonators.

	PZT core composite			Metglas/PZT resonator	
	C_0 (pF)	$\lvert Z_m\rvert$ (Ω)	Q_{Core}	$Q_{eff,1}$	$Q_{eff,2}$
$s=1$ mm	776	3730	29.03	42.4	39.4
$s=1.5$ mm	478	3721	32.11	45.3	44.75
$s=1.8$ mm	397	3905	36.98	56.3	53.6

Figures 3(a) and 3(b) show typical frequency dependencies of α_V for the sandwich and bimorph configuration resonators under the optimal H_{dc}, respectively. For the sandwich configuration, no significant dispersion of α_V was observed, apart from the variations associated with the longitudinal-extensional resonance. However, for the bimorph configuration, in addition to the longitudinal-extensional resonance, several bending-extensional resonances were observed. The right insets in these figures present enlarged views for the longitudinal-extensional resonances for the respective configurations. It is obvious that the resonance value of α_V was enhanced by more than an order of magnitude relative to the nonresonance one for both configurations and for each ID-electrode spacing.

Based on the principle presented in the left inset of Figure 3(a), the effective mechanical quality factor for

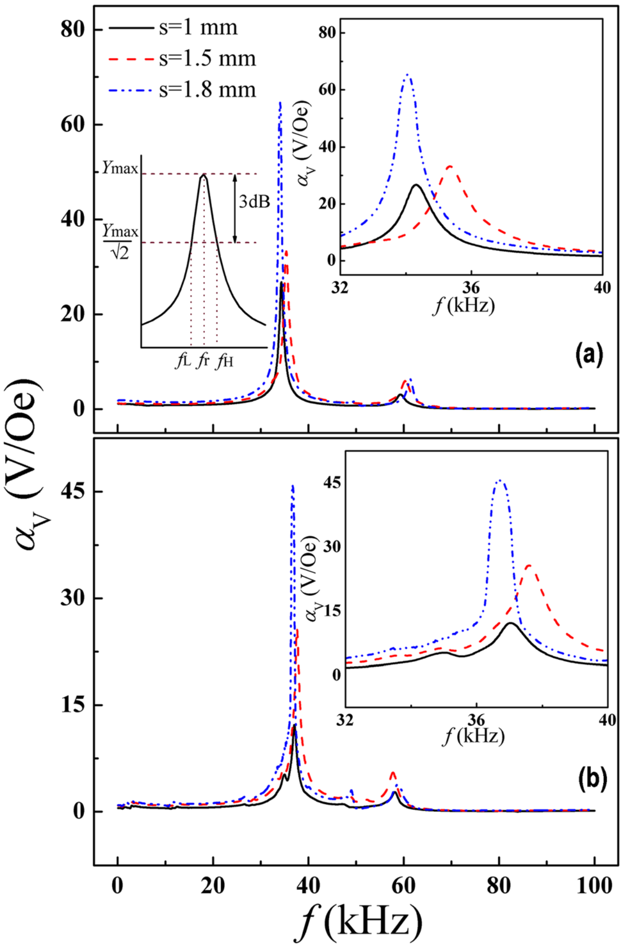

FIG. 3. ME coefficient of sensors with various spacings as a function of frequency under optimal dc magnetic fields for (a) sandwich and (b) bimorph configurations. The left inset of part (a) shows the calculation principle for the mechanical quality factor Q of a piezoelectric resonator (i.e., $Q = f_r/(f_H\text{-}f_L)$, where f_r is the resonance frequency, and $f_H\text{-}f_L$ corresponds the 3 dB frequency bandwidth in the ME curves around the resonance peaks). The right inset of part (a) and part (b) shows close-up views over the frequency ranges of 30 kHz $< f <$ 40 kHz and 32 kHz $< f <$ 42 kHz, respectively.

sandwich ($Q_{eff,1}$) and bimorph ($Q_{eff,2}$) configurations for various values of s was determined, as summarized in Table I. For each spacing, the value of $Q_{eff,1}$ was higher than that of $Q_{eff,2}$. This can be explained by considering the various contributions to the total mechanical loss of the resonators. For a Metglas/PZT-core resonator with a Metglas volume fraction of n, one can regard the total mechanical loss to be mainly contributed by the mechanical loss of the Metglas foils ($1/Q_M$), the loss of PZT core layers ($1/Q_{Core}$) where $Q_M > Q_{Core}$, and the loss at the interface ($1/Q_{int}$) between layers. Thus, the effective mechanical quality factor Q_{eff} of a ME laminated resonator can be expressed as[7,17]

$$Q_{eff} = \frac{1}{nQ_M^{-1} + (1-n)Q_{Core}^{-1} + Q_{Int}^{-1}}. \tag{2}$$

Following Eq. (2), since the Metglas volume fraction n for the sandwich resonator was notably higher than that for the bimorph one, the corresponding value of Q_{eff} for the sandwich configuration was larger than for the bimorph (i.e., $Q_{eff,1} > Q_{eff,2}$). Similarly, for the same configuration, resonators with larger s had higher values of Q_{eff}, as summarized in Table I. For example, $Q_{eff,1}$ of the sandwich configuration increased from 46.4 to 56.3 as s increased from $s = 1$ to 1.8 mm. This change resulted from Q_{Core} increasing with increase of s. Following Eq. (2), for a constant n, the value of Q_{eff} then increased with increasing of Q_{Core}.

In summary, the investigation of the mechanical quality factor of Metglas/PZT-core ME resonators was performed for both sandwich and bimorph configurations. The mechanical quality factor of the PZT core composites composed of ID-electrodes and PZT plates was studied by the analysis of impedance spectra for various ID-electrode spacing. The results show that the ME resonators with a sandwich structure and a large ID-electrode spacing exhibit higher effective mechanical quality factors.

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