Magnetoelectric Bending-Mode Structure Based on Metglas/Pb(Zr,Ti)O_3 Fiber Laminates

Junqi Gao, Ying Shen, Yaojin Wang, Peter Finkel, Jiefang Li, and Dwight Viehland

***Abstract*—A magnetoelectric (ME) bending-mode structure based on Metglas/Pb(Zr,Ti)O_3 fiber laminates has been studied. This bending mode had a fundamental resonance (FBR) of about 210 Hz, which was much lower than that of the longitudinal mode. Near the FBR, the ME voltage coefficient was about 400 V/cm·Oe. Magnetic sensors based on this bending mode had an equivalent magnetic noise floor of $\leq$0.3 pT/$\sqrt{\text{Hz}}$ at $f = 210$ Hz.**

I. Introduction

The magneto-electric (ME) effect is a change in electric polarization under magnetic field, or conversely a change in magnetization with applied electric field [1]. Since 2001, research has focused on engineered ME multiphase systems [2], [3], rather than single-phase systems. Two-phase composites consisting of magnetostrictive and piezoelectric layers have giant ME coefficients [4]–[6], mediated through a magneto-elasto-electric interaction [4]. The ME coefficients (α_{ME}) for laminated composites can reach values of $\alpha_{ME} = 22$ V/cm·Oe at low frequency for long-type three-layer laminates of Metglas (Vitrovac Inc., Hanau, Germany) and Pb(Zr,Ti)O_3 (PZT) fiber layers operated in longitudinal-longitudinal (or L-L) push-pull mode [6]. A gain in α_{ME} occurs near the electromechanical resonance (EMR) of this L-L mode, reaching values as high as 400 V/cm·Oe at $f = fr \approx 30$ kHz [4], [6].

Based on this giant value of α_{ME} for Metglas/PZT laminates, low-frequency passive magnetic sensors have been developed using a charge amplifier detection method [7], [8]. Equivalent magnetic noise floors of about 2×10^{-11} T/$\sqrt{\text{Hz}}$ at $f = 1$ Hz have been achieved, which is quite remarkable given the passive nature of the sensor. Presently, the noise floor is limited by the value of α_{ME}, which is a gain factor in the transfer function between measured voltage and equivalent magnetic noises [9]. As long as the electronic noise of the detection amplifier is a dominant noise source, higher values of α_{ME} for the laminates can result in lower equivalent magnetic noise floors.

Lower equivalent magnetic noise floors might be achieved by utilizing the EMR enhancement of α_{ME} in applications as sensors. Gains in α_{ME} of up to a factor of 100× are feasible at the EMR [6]. However, such EMR gains in L-L mode structures are only possible at high frequencies of $fr \approx 30$ kHz over narrow bandwidths. It would be desirable to shift this gain in α_{ME} to a lower frequency, while limiting the compromise in the bandwidth. Recently, Xing *et al.* developed asymmetric bi-layer ME laminates consisting of Terfenol-D and PZT, which had bending-mode frequencies on the order of several kilohertz [10]. Resonance gains in α_{ME} of 40 V/cm·Oe were found for these asymmetric structures. Furthermore, flexural bending modes for PZT-bimorph cantilevers with attached permanent magnets were also found to have high effective ME coefficients of $\geq$250 V/cm·Oe near a fundamental frequency of several hundred hertz [11]. The fundamental bending frequency in such bi-morph structures is tunable by applying a magnetic field [12]. However, the equivalent magnetic noise floor has not been reported for any of these flexural modes.

Here, we have investigated bending-mode structures for bi-layer Metglas/PZT laminates. Near a fundamental bending frequency (FBR) of 210 Hz, the value of α_{ME} was enhanced by a factor of >10×, compared with a corresponding L-L mode of the same size. Using a charge amplifier detection method, magnetic noise floors of $\leq$0.3 pT/$\sqrt{\text{Hz}}$ were achieved near the FBR, which was about 100× lower than at 1 Hz and about 10× lower than that of L-L mode at the same frequency.

II. Experimental Techniques

We obtained PZT fibers (Smart Materials, Sarasota, FL) and Metglas foils to fabricate laminates. Five pieces of 180-um-thick piezoelectric fibers were oriented along the long axes to form a layer that was, in total, 10 mm wide and 40 mm long. Two interdigited Kapton (DuPont, Wilmington, DE)-based electrodes were then bonded to the top and bottom surfaces of the piezoelectric layer in a multi push-pull mode configuration. To fabricate symmetrical longitudinal mode sensors, three Metglas foils of 80 mm in length and 10 mm in width were first laminated to each other, and subsequently laminated to both the top and bottom surfaces of the PZT fiber layer. To fabricate an asymmetrical bending mode, six Metglas foils of the same size were bonded together, and subsequently laminated to only the bottom surface of the PZT fiber layer. A schematic comparison of the symmetrical L-L and asym-

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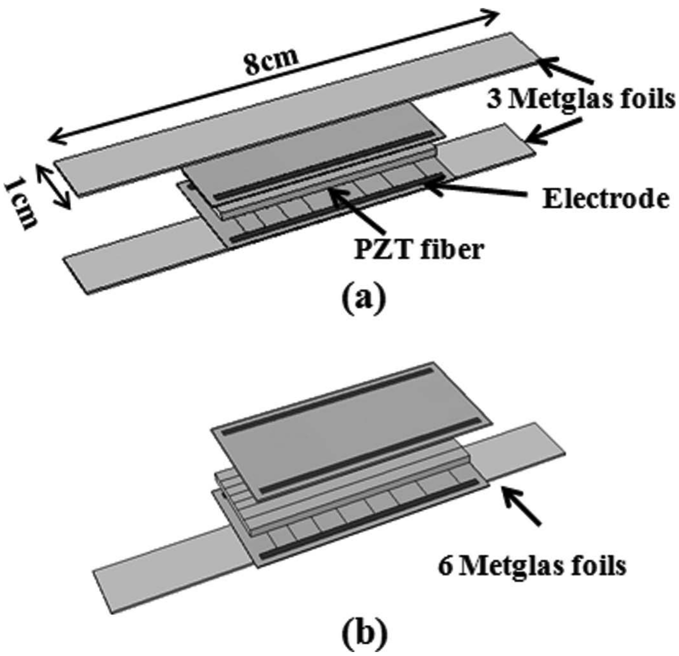


Fig. 1. Schematics of Metglas/PZT ME laminate sensors: (a) L-L mode sensor and (b) bending-mode sensor.

metrical bending modes can be seen in Fig. 1. Because of the symmetric structure of the L-L mode, strains generated by the top and bottom layers of the Metglas are identical under magnetic field, therefore, the L-L mode elongates or shrinks along the horizontal plane; however, the asymmetrical structure undergoes a flexural deformation under magnetic field.

First, α_{ME} for both L-L and bending-mode structures was measured as a function of dc magnetic bias H_{dc}. A lock-in amplifier (SR-850, Stanford Research Systems, Sunnyvale, CA) was used to drive a pair of Helmholtz coils to generate an ac magnetic field of $H_{\mathrm{ac}} = 1$ Oe at a frequency of $f = 1$ kHz. The dc magnetic bias H_{dc} was applied along the long axis of the ME laminates during the test. The α_{ME} as a function of the ac magnetic field frequency was then calibrated through a similar method.

Second, the ac magnetic sensitivity was measured using an operational amplifier-based detection circuit [8]. Helmholtz coils were used to apply a small ac magnetic field along the long axis of the laminates by inputting an ac signal generated by the lock-in amplifier at $f = 210$ Hz. Small permanent dc magnets were attached to the ME laminates along the long axis to bias the laminates to the maximum value of α_{ME}, as identified in the α_{ME}–H_{dc} data of Fig. 2(a). Details of the detection unit can be found in [9]. The noise levels of the detection units and induced ac voltage from the laminates were monitored in the time domain using an oscilloscope (54624A, Agilent Technologies Inc., Santa Clara, CA). Details of the setup and measurement can be found in [13].

Finally, the equivalent magnetic noise floors for both types of ME laminate sensors were measured over the frequency range of $10^2 < f < 10^3$ Hz. During the tests, the ME sensors were placed in a magnetically shielded chamber to reject environmental magnetic noise. A dynamic signal analyzer (SR-785, Stanford Research Systems) was used to measure the noise power density of the ME sensors in volts per square-root hertz. We then used the following sensor transfer function to convert the noise floor in volts per square-root hertz to that in teslas per square-root hertz [9]:

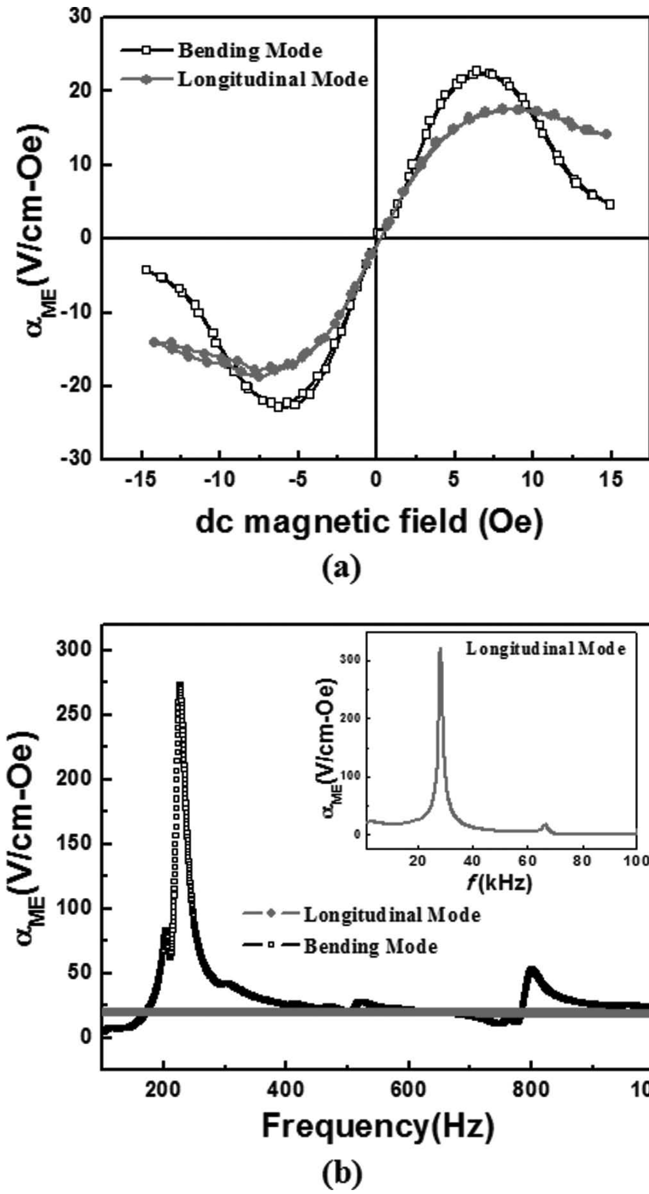


Fig. 2. ME voltage coefficients of L-L and bending-mode ME laminates: (a) α_{ME} as a function of dc magnetic bias H_{dc} at $f = 1$ kHz, and (b) α_{ME} as a function of ac magnetic drive frequency. The insert shows α_{ME} for the L-L mode for $10^3 < f < 10^5$ Hz.

$$\text{conversion factor (V/T)} = \frac{\alpha_{\mathrm{ME}}(\mathrm{pC}/10^{-4}\mathrm{T})}{\text{gain of amplifier (pC/V)}}$$

$$\text{noise floor } (\mathrm{T}/\sqrt{\mathrm{Hz}}) = \frac{\text{noise floor } (\mathrm{V}/\sqrt{\mathrm{Hz}})}{\text{conversion factor}}. \tag{1}$$

Over the frequency range of $10^2 < f < 10^3$ Hz, the gain factor of the amplifier in volts per picocoulomb was 1 V/pC [9].

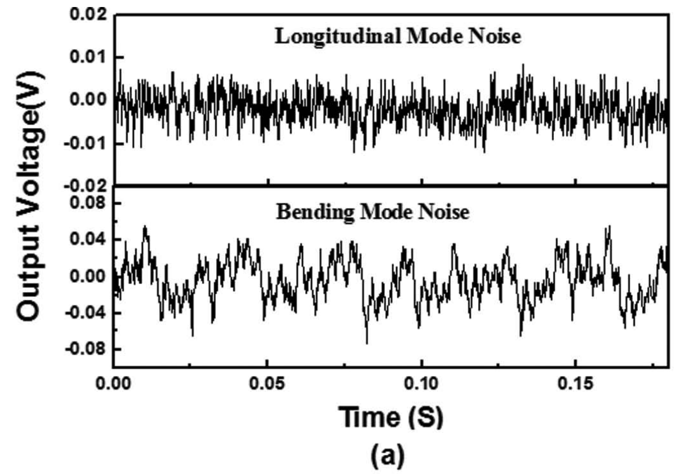
III. Results and Discussions

Fig. 2(a) indicates that the α_{ME} for the two modes exhibited similar trends with increasing H_{dc}. At a frequency of 1 kHz, the maximum value of α_{ME} for the bending mode was 24 V/cm·Oe, which was a little larger than the 20 V/cm·Oe for the L-L mode. The higher ME coupling effect comes from the higher strain for the bending mode compared with the longitudinal mode [12].

Fig. 2(b) shows α_{ME} as a function of the ac magnetic field frequency. In this figure, we can see a notable difference in α_{ME} between the L-L and bending modes over the frequency range of 10^2 Hz $< f < 10^3$ Hz. The value of α_{ME} for the L-L mode was nearly constant over this frequency range at 20 V/cm·Oe. However, the bending mode exhibited a strong EMR enhancement at 210 Hz, achieving values of $\alpha_{\mathrm{ME}} = 400$ V/cm·Oe. This demonstrates that α_{ME} at the FBR for the bending mode can be improved by a factor of 20×, relative to the value for the L-L mode at the same frequency. The insert in Fig. 2(b) shows α_{ME} for the L-L mode sensor as a function of frequency, where the EMR frequency can be seen to be about 30 kHz, as previously reported [6].

Fig. 3(a) shows the noise levels of the L-L and bending-mode ME sensors under $H_{\mathrm{ac}} = 0$ Oe. In this figure, one can see that the peak-to-peak value of the noise for the L-L mode sensor was about 25 mV, which was smaller than that of the bending value of 80 mV. An applied H_{ac} was then modulated to keep the peak-to-peak value of the output voltage constant at about 50 mV for the L-L and 160 mV for the bending-mode sensors, which corresponded to a constant SNR = 2 for both cases. This was done to compare the ac magnetic field sensitivities for different laminates under the same condition. Fig. 3(b) shows the ac magnetic sensitivity at 210 Hz. In this figure, one can see that the ac magnetic field sensitivity for the bending mode was about 0.05 nT at 210 Hz, which was about a factor of 10× lower than that of the L-L mode at the same frequency.

Fig. 4 shows the equivalent magnetic noise floor spectra for both L-L and bending modes. In this figure, we can observe that the noise floor for the L-L mode sensor was constant at about 5 pT/$\sqrt{}$Hz over the frequency range of 100 to 1000 Hz: the consistency was due to the frequency independence of α_{ME}. In this same figure, the magnetic noise floor for the bending-mode sensor can be seen to depend dramatically on frequency. In particular, near the FBR at 210 Hz, the noise floor decreased to 0.3 pT/$\sqrt{}$Hz, which was a direct consequence of the FBR-enhanced α_{ME}. Comparisons of the data in Fig. 4 will show that the magnetic noise floor of the bending was decreased by 1) a factor ~100× at 210 Hz, relative to that of 1 Hz; and 2) a factor of ~20× at 210 Hz, relative to the of the L-L mode at the same frequency. At frequencies below the FBR, the noise floor of the bending mode was higher that of the L-L by a factor of 4 to 5×, but at frequencies greater than the FBR, the noise floors were nearly equivalent at a value of 5 pT/$\sqrt{}$Hz. These results may indicate that the bending-



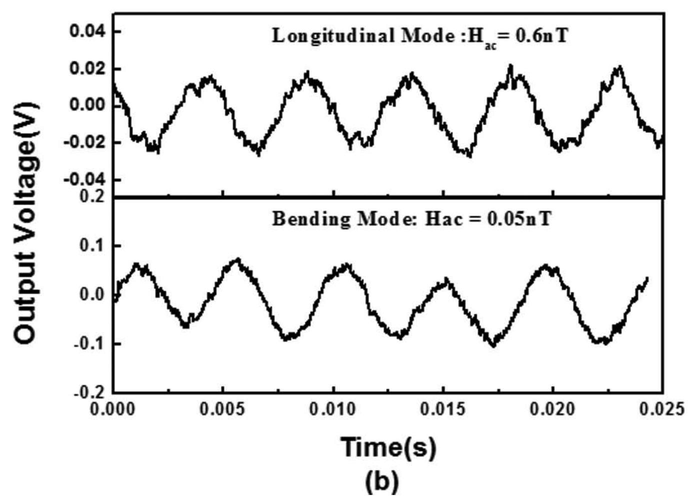


Fig. 3. (a) Noise levels for the L-L and bending-mode sensors, and (b) ME output voltage as a function of time for the L-L and bending-mode sensors. The corresponding peak-to-peak ac field sensitivities are listed in the figures.

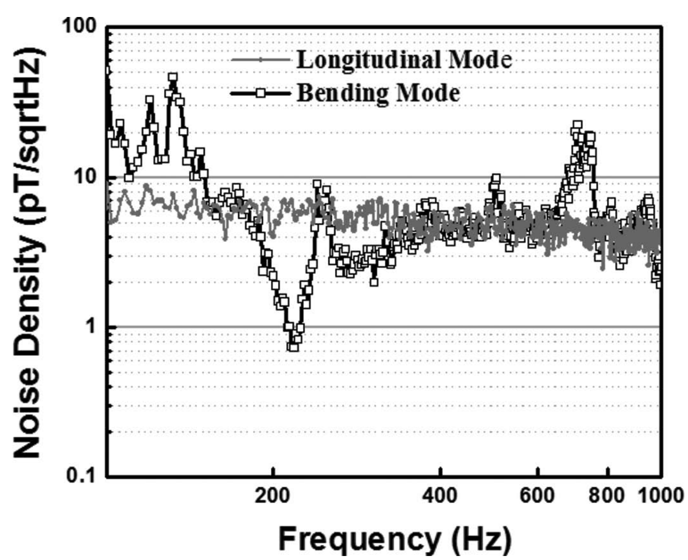


Fig. 4. Equivalent magnetic noise spectra for the L-L and bending-mode sensors for $10^2 < f < 10^3$ Hz.

mode laminates are more sensitive to low-frequency vibrations which are environmental noise sources than the L-L laminates, but, because of the dramatic increase in α_{ME} near the FBR, the SNR was enhanced.

Bending-mode sensors based on Metglas/PZT laminates hold promise for applications in extremely low ac magnetic field detection in this specific frequency range because of higher ac magnetic field sensitivity and lower noise floor in the FBR range compared with L-L mode sensors. Moreover, it is possible to design bending-mode sensors with different FBR frequencies by using some techniques described in [12], which can extend the practical application space for bending-mode sensors.

IV. Summary

In summary, we have developed a bending-mode structure for Metglas/PZT fiber laminate ME sensors. Using this structure, a fundamental resonance frequency of about 210 Hz can be obtained, which has an enhancement in the ME voltage coefficient to $\alpha_{\mathrm{ME}} \geq 400$ V/cm·Oe. The equivalent magnetic noise floor for this bending-mode sensor was about 0.3 pT/$\sqrt{\mathrm{Hz}}$. Our findings thus demonstrate that bending-mode ME sensors have the potential to significantly outperform L-L mode sensors over a 50 Hz bandwidth around their fundamental bending frequency.

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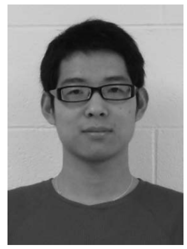

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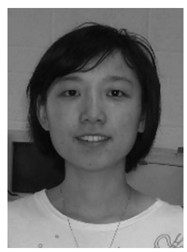

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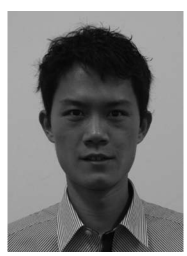

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