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Dependence of magnetic field sensitivity of a magnetoelectric laminate sensor pair on separation distance: Effect of mutual inductance

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The effect of mutual inductance on the performance of a pair of Metglas/Pb(Zr,Ti)O_3 laminate magnetoelectric (ME) sensors has been studied. The effective value of the ME coefficient (α_{ME}) for the laminates was reduced when the distance between was < 40 mm. Separating the two laminates by distances of > 40 mm, the effect of mutual inductance was small. The laminates exhibited the maximum values of α_{ME}. The ME sensor unit with two laminates connected in parallel had higher magnetic field sensitivities. © *2012 American Institute of Physics*. [doi:10.1063/1.3684986]

I. INTRODUCTION

The magnetoelectric (ME) effect—the induction of magnetization by an applied electric field (E) or a polarization by an applied magnetic field (H)—has been of recent research interest, due to potential applications in magnetic sensors.[1–4] The ME effect in laminate composites is known to be much higher than in single phase and particulate composites, due to a combination of magnetostrictive and piezoelectric effects of individual layers.[2,5] Application of magnetic field to the laminates produces an elastic strain in the magnetostrictive phase that is stress coupled to that of the piezoelectric one, resulting in an induced voltage. Such laminates enable one to detect magnetic fields on the order of 0.1 nanotesla (nT) at room temperature at 10 Hz with a simple charge amplifier detection method.[6]

In recent years, different combinations of relative directions of the magnetization and polarization of various magnetostrictive and piezoelectric phases have been reported.[7–10] It has been found that tri-layer Metglas-piezoelectric transducer (PZT)-Metglas structures with a multi-push-pull mode have very high ME voltage coefficients α_{ME} and magnetic field sensitivities. By using an improved lamination process and Metglas with an enhanced magnetostriction, the value of α_{ME} has been increased to 21.6 V/cm Oe, which is the highest value reported for PZT fiber ME laminates.[11] To achieve higher values of α_{ME}, several approaches have been used, which are: (i) piezoelectric single crystal fibers[5] and (ii) stacking of N numbers of ME laminates, which has been predicted in parallel connection to increase the signal-to-noise ratio (SNR) by a factor of $\sqrt{N}$.[12] However, there have been no experimental reports of an increase in the SNR for arrays of Metglas-PZT-Metglas ME laminate sensors.

This letter reports a study of the effect of distance between a pair of Metglas-PZT-Metglas ME laminate sensors, which comprise a ME array. We show here an optimum distance that is important for the application of ME sensor units to have higher values of α_{ME}. This enhanced performance at an optimum distance is due to flux concentration effects, i.e., the sensors in the pair have mutual inductance effects. Also, the magnetic field sensitivity has been increased by 1.27× for such a pair of ME sensors connected in parallel.

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II. EXPERIMENTAL DETAILS

A 40 mm × 10 mm PZT bundle in the center of the laminate consisted of five 40 mm × 2 mm PZT fibers (Smart Materials, Sarasota, FL) oriented along the *x*-axis (length direction). Two interdigitated Kapton electrodes were bonded to the top and bottom surfaces of the piezoelectric bundle with epoxy resin (Stycast 1264, USA). Three 80 mm × 10 mm Metglas foils were then laminated to both the top and bottom surfaces of the interdigitated electrode/PZT core composite with a different epoxy resin (West System 105/206, USA). More detailed information of the lamination process can be found in Ref. 11.

III. RESULTS AND DISCUSSION

In the application of magnetic materials with very high permeabilities, magnetic flux concentration effects can be quite significant.[6,13] The permeability of Metglas is $\mu_r > 45\,000$. Clearly, the magnetic flux density can vary for each Metglas foil, due to the effect of mutual inductance when two foils are placed at different distances with respect to each other, as shown in Fig. 1(a). Finite element simulation using *MAXWELL 13.0* was performed for Metglas foils of the same dimensions as our laminates. We show simulation results in Fig. 1(b) of the flux density for one Metglas foil when another identical foil was placed nearby it at various distances (i.e., center of one Metglas foil to another). The external magnetic field was 0.1 Oe. As can be seen, when the distance between the two Metglas foils was 20 mm, the magnetic flux density at the center region (–20 mm to 20 mm), where the Kapton/PZT core composite was bonded, was the lowest. The flux density became higher in this region as the spacing between the two foils was increased. When the distance was 40 mm and 50 mm, the flux density was nearly equal, which means that mutual inductance between foils is small. Such an effect depended on the size of the sensors. For sensors with various dimensions, the distance at which the

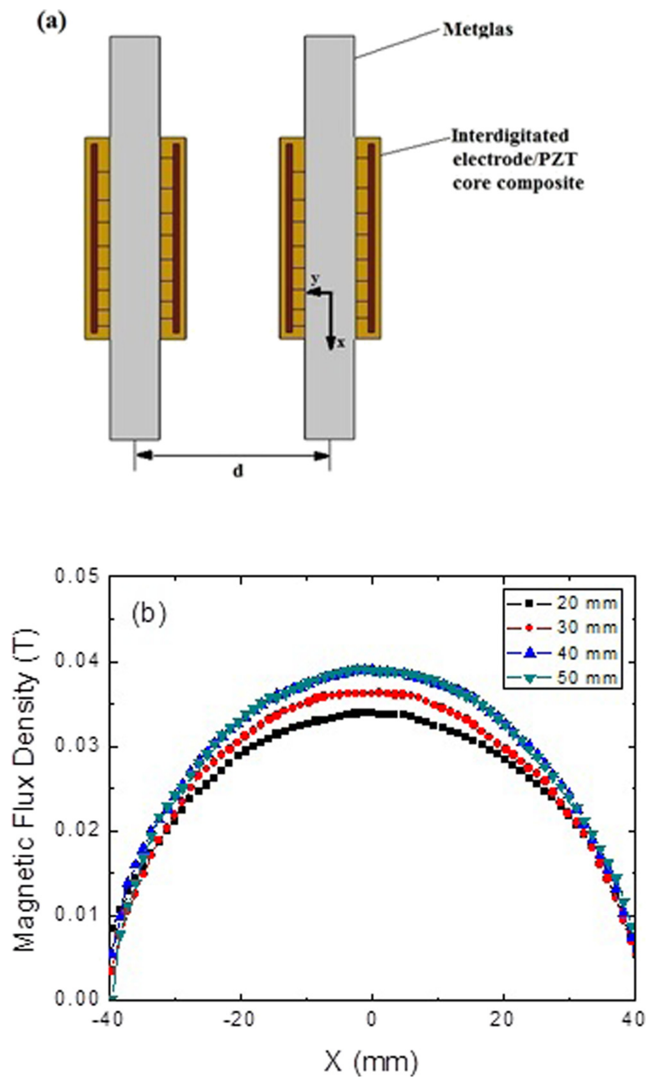

FIG. 1. (Color online) (a) Schematic representation of a pair of Metglas/PZT L-L mode ME laminates separated by a distance d. (b) Magnetic flux density of the Metglas foil along the x-axis (length direction) at $y = 0$, $z = 0$ (the origin was at the center of the Metglas foil) when another identical foil was placed at various distances from it. The external magnetic field was 0.1 Oe.

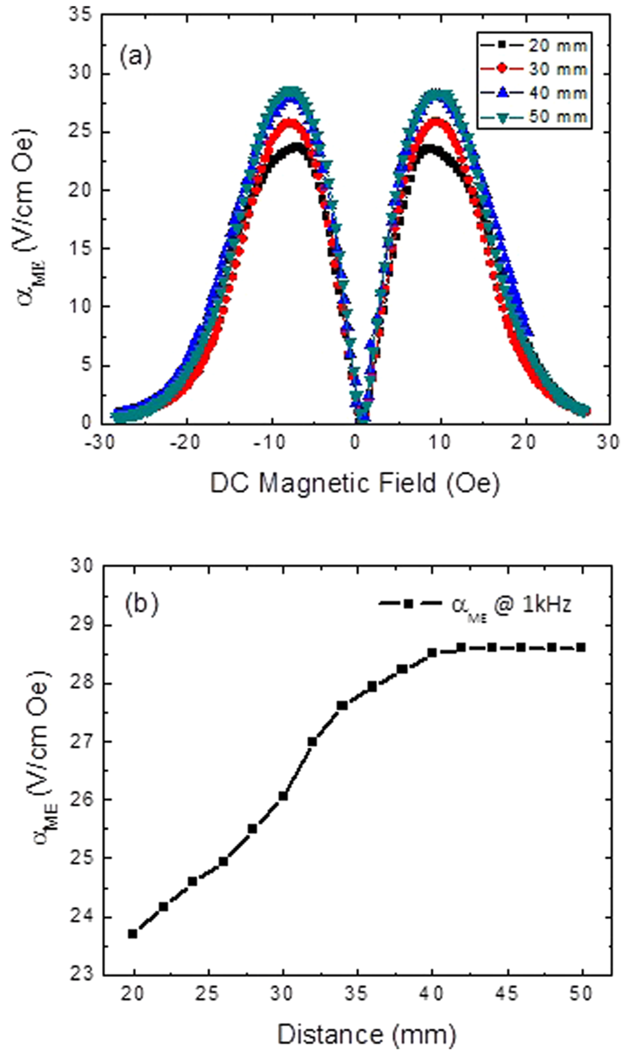

FIG. 2. (Color online) (a) The value of α_{ME} as a function of dc bias field for one Metglas/PZT laminate when another one was placed at different distances from it. (b) The maximum value of α_{ME} as a function of distance between two Metglas/PZT laminates. The data were measured at 1 kHz and $H_{ac} = 0.1$ Oe.

effect of mutual inductance can be neglected should be different.

When the distance separating the two ME laminates was changed, the value of α_{ME} also varied; this is due to changes in the magnetic flux density in the Metglas foil. The value of α_{ME} was measured using a lock-in amplifier (SR-850) in response to a pair of Helmholtz coils driven at an ac magnetic field of $H_{ac} = 0.1$ Oe at a frequency of $f = 1$ kHz. The two laminates were placed on a horizontal plane, separated by different distances within the Helmholtz coil. As shown in Fig. 2(a), the value of α_{ME} was largest when the laminates were separated from each other by at least 40 mm. The maximum value of α_{ME} was then 28.5 V/cm·Oe under a DC bias of 8.86 G. When the distance between these two laminates was < 40 mm, the value of α_{ME} was reduced, for example, at 20 mm, the maximum value of α_{ME} was 23.6 V/cm·Oe under a DC bias of 8.90 G, a 17% reduction with respect to that at 40 mm. Figure 2(b) shows the maximum value of α_{ME} as a function of distance between two Metglas/PZT laminates. In this figure, one can see that the maximum value of α_{ME} increased as the distances between the two laminates was increased. When the distance was > 40 mm, the maximum value of α_{ME} was the same as for each sensor with an infinite separation.

A pair of Metglas/PZT laminates connected in parallel was then packaged with a simple low-noise charge amplifier having a gain of 5.18 V pC^{-1} over the frequency range of $0.1 < f < 100$ Hz (designed by SAIC), which we designated as a ME sensor unit. The unit was placed inside a high-mu-metal magnetic shielding chamber and connected to a dynamic signal analyzer to measure the noise voltage and output signal. The magnetic field sensitivity can be expressed as

$$\text{Magnetic field sensitivity} = \frac{H_{ac-f}}{V_{ME-f}} \times SNR \times V_{noise}, \quad (1)$$

where H_{ac-f} is the ac magnetic field generated by the Helmholtz coil, V_{ME-f} is the ME output voltage of the ME sensor

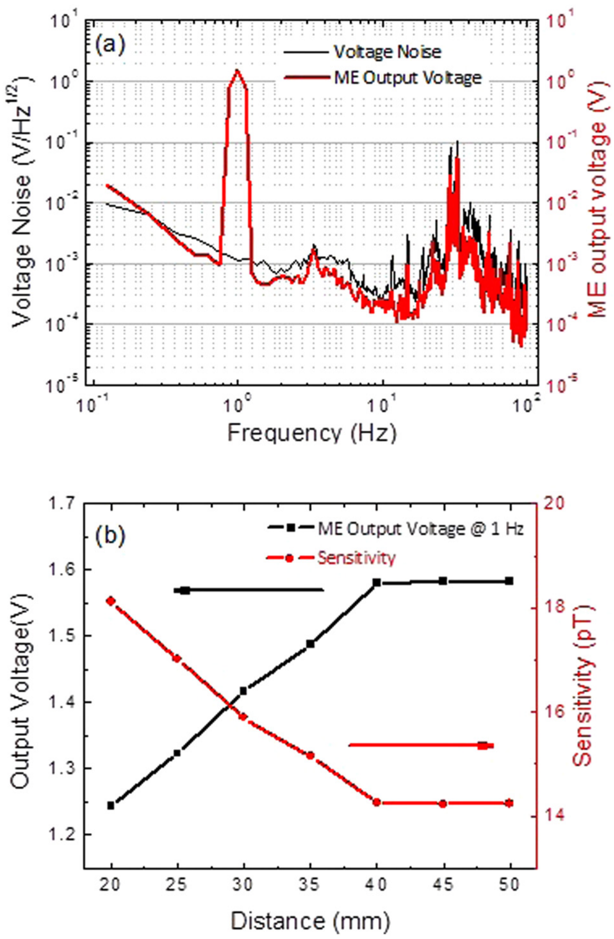

FIG. 3. (Color online) (a) ME output signal of the ME sensor unit and background voltage noise in the absence of intentional excitation. (b) The output signal and sensitivity of the sensor unit when the two laminates were placed at various distances. The incident AC magnetic field was 10 nT at 1 Hz.

unit, $SNR = 2$, and V_{Noise} is the voltage noise at the frequency of interest.

Figure 3(a) shows the voltage noise spectrum over the frequency range of $0.125 < f < 100$ Hz, which also contained an output signal in response to a 10 nT incident AC magnetic field at 1 Hz, when the two laminate were 40 mm from each other. The output of the sensors was 1.58 V, and the background voltage noise at the corresponding frequency was 1.13×10^{-3} V/Hz$^{1/2}$. From Eq. (1), the magnetic field sensitivity of this pair of Metglas/PZT laminate sensors was 14.2 pT at 1 Hz. In Fig. 3(b), the output voltage and magnetic field sensitivity of the sensor pair in response to $H_{ac} = 10$ nT is shown when the laminates were placed at various distances. The output voltage increased with increasing distance between laminates; correspondingly, the sensitivity also improved. When the distance was > 40 mm, the sensors had a maximum output voltage and the highest magnetic field sensitivity (14.2 pT), a 27% increase, relative to a distance of 20 mm.

IV. SUMMARY

An optimization of the distance between a pair of Metglas-PZT-Metglas ME laminates has been performed to achieve enhanced values of α_{ME}. Units of two laminates have quite high magnetic field sensitivities of 14.2 pT when the distance between the laminates is > 40 mm. Our findings demonstrate the effect of geometrical arrangement of sensor pairs in arrays. Mutual inductions can have important effects. To achieve sensor units which have the highest gain and sensitivity, these considerations should be taken into account.

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