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Small dc magnetic field response of magnetoelectric laminate composites

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We have found that small long-type magnetoelectric (ME) laminate composites of magnetostrictive $Tb_{1-x}Dy_xFe_{2-y}$ and piezoelectric $Pb(Zr,Ti)O_3$ are quite sensitive to small dc magnetic field (H_{dc}) variations, when driven by a constant ac magnetic field. The sensitivity limit is $H_{dc} < 10^{-3}$ Oe (10^{-7} Tesla) using a constant amplitude low frequencies drive, and $H_{dc} < 10^{-4}$ Oe (10^{-8} Tesla) under resonant drive. In addition, an unusual ME switching effect—a 180° phase shift—was observed, in response to changes in the sign of a small H_{dc}. *© 2006 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. Previous reports about ME effects have focused on the ac magnetic field (H_{ac}) response of single phase and multiphase laminate ME materials.[2–17] However, magnetic sensors for applications in magnetic anomaly detection[13] require high sensitivity to near-dc frequencies. Previously,[14] we reported a ME multilayer composite for low-frequency H_{ac} signal detection, with working frequencies as low as 5×10^{-3} Hz. In this case, a constant dc magnetic bias (H_{dc}) was applied along the length axis of the laminate, and small variations in H_{ac} detected. However, as is well known, the ME effect is a strong function of H_{dc}.[2–17] Thus, using a constant H_{ac} drive, ME laminates have the potential to be used for small H_{dc} signal detection.[18] Here, we will show that longitudinally magnetized and transversely polarized (or L-T) laminates of $Tb_{1-x}Dy_xFe_{2-y}$ (Terfenol-D) and piezoelectric $Pb(Zr,Ti)O_3$ (PZT) have: (i) An ability to detect small H_{dc} variations; and (ii) posses an unusual ME switching effect—an 180° phase change—in response to changes in the sign of a small H_{dc}.

Our dc magnetic sensor consisted of a L-T mode ME laminate and a coil wrapped around it that carried a small ac current I_{ac}, as shown in Fig. 1. The laminate configuration is similar to that of a prior report,[11] but its dimensions were notably smaller ($2.5\times2.5\times14$ mm^3). The working principle for H_{dc} signal detection is as follows: (i) A small constant ac magnetic field drive of $0.01 < H_{ac} < 1$ Oe was used to excite the laminate into vibration along its length axis, via the attached coils; and (ii) small variations in H_{dc} were detected as small induced voltage changes. Prior experimental studies[2–17] have shown a linear relationship between the ME voltage coefficient α_{ME} and an applied dc magnetic bias H_{dc} over the range of $0 < H_{dc} < 300$ Oe. Measurements of the ME voltage induced by variations in an external H_{dc} were performed in a magnetically shielded environment made of μ-metal, using a lock-in method. A small I_{ac} from the lock-in was used as an input to the coils about the laminate, exciting a small but constant H_{ac}. Experiments were performed at a lower-frequency (10^3 Hz) drive of 1 Oe; and at higher frequencies ($\sim8\times10^4$ Hz) under resonant drive conditions of $H_{ac}=0.1$ Oe, where a significant gain in the ME effect is known.[19] The dc magnetic signal is coupled to the ac voltage response; as for $0 < H_{dc} < 300$ Oe, the ME voltage coefficient (α_{ME}) is known to be linearly proportional to H_{dc} ($\alpha_{ME}=aH_{dc}$, where a is a constant). Accordingly, this is an unusual magnetic sensor as variations in a dc signal (H_{dc}) can be detected as changes in an ac response (V_{ac})—enabling sensitivity at near-static frequencies.

Figure 2 shows the induced ME voltage as a function of H_{dc} for an L-T laminate: (a) -300 Oe $< H_{dc} < 300$ Oe, at $f=10^3$ Hz and $H_{ac}=1$ Oe; and (b) -30 Oe $< H_{dc} < 30$ Oe, under a resonant drive ($\sim8.4\times10^4$ Hz) of $H_{ac}=0.1$ Oe. It can be seen that: (i) The induced ME voltage is a linear function of H_{dc} in both cases; and (ii) that $dV_{ME}/dH_{dc}=0.23$ mV/Oe at 10^3 Hz and $H_{ac}=1$ Oe, but is enhanced to ≈1.2 mV/Oe at $H_{ac}=0.1$ Oe under resonant drive. These results clearly demonstrate that dc magnetic fields can be detected by ac voltage changes induced across the PZT layer. The sensitivity to small variations in H_{dc} can clearly be enhanced by a resonance signal gain. In addition, the right-hand axis of Fig. 2 shows an unexpected 180° phase shift upon reversal of the sign of H_{dc}. Such reversals were found under small dc magnetic field changes ($H_{dc}=\pm15$ Oe), as shown in the inset of Fig. 2(a).

Figure 3 shows the sensitivity limit of an L-T ME laminate to small dc magnetic field variations, while under resonant drive. It can be seen that H_{dc} signal changes as small as 0.1 m Oe (10^{-8} Tesla) can be repeatedly detected. We estimate the signal-to-noise ratio as ~10 in these data, indicating the feasibility to detect dc magnetic field variations in the $\sim10^{-5}$ Oe ($\sim10^{-9}$ Tesla) range. Furthermore, we note that this sensitivity limit could be further enhanced by replacing the piezoelectric PZT layer with a

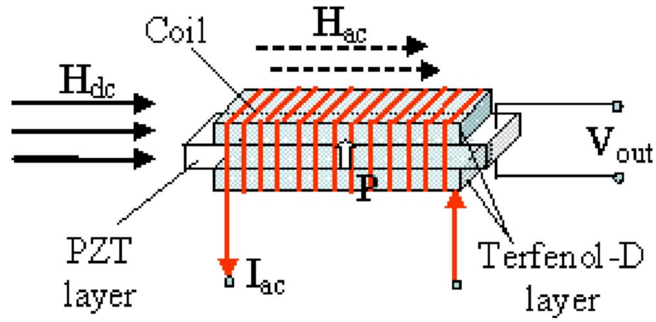

FIG. 1. (Color online) Illustration of our dc magnetic sensor, which is a L-T mode trilayer laminate of Terfenol-D/PZT/Terfenol-D.

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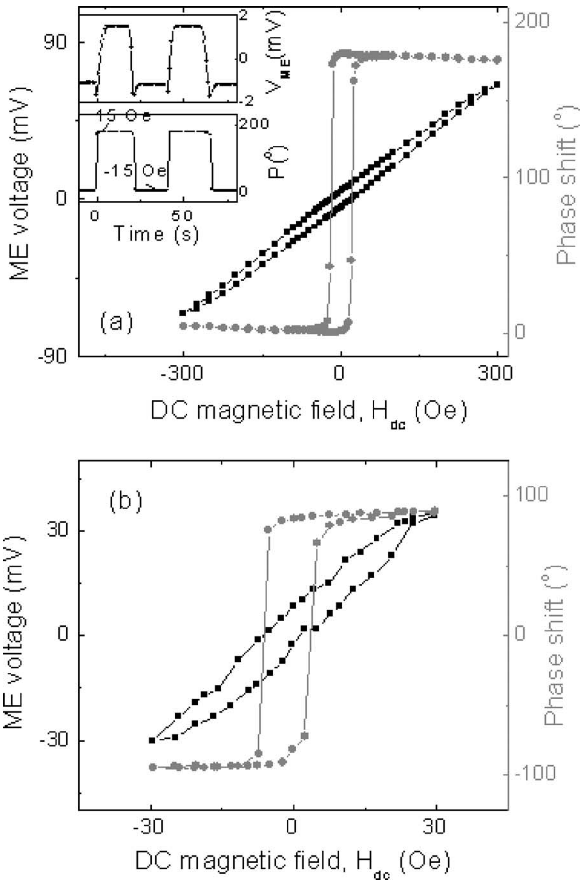

FIG. 2. Induced dc ME voltage response and phase shift of a L-T ME laminate as a function of dc magnetic field for (a) $-300\ \text{Oe} < H_{dc} < 300\ \text{Oe}$, at $f=10^3$ Hz, and a constant ac drive of $H_{ac}=1$ Oe; and (b) $-30 < H_{dc} < 30$ Oe, under a resonant drive of $H_{ac}=0.1$ Oe. The inset in (a) shows responses of ME voltage V_{ME} and phase P to small step changes of dc magnetic field ($H_{dc}=\pm 15$ Oe).

$Pb(Mg_{1/3}Nb_{2/3})O_3-PbTiO_3$ one, and/or by using longitudinal-longitudinal or other complex laminate configurations.[11,15]

In summary, we have found that ME laminates under a constant drive of $H_{ac}=1$ Oe can detect small changes in an external dc magnetic field of $H_{dc} \leq 10^{-4}$ Oe (10^{-8} Tesla). This is an unusual sensor in that variations in H_{dc} are detected as: (i) Changes in an ac voltage; and (ii) changes in sign of a small H_{dc} result in an 180° phase shift. We recognize that such dc magnetic sensors have potential for magnetic recording: in this case, domain orientation differences could be very sensitively read as an 180° shift in an induced voltage.

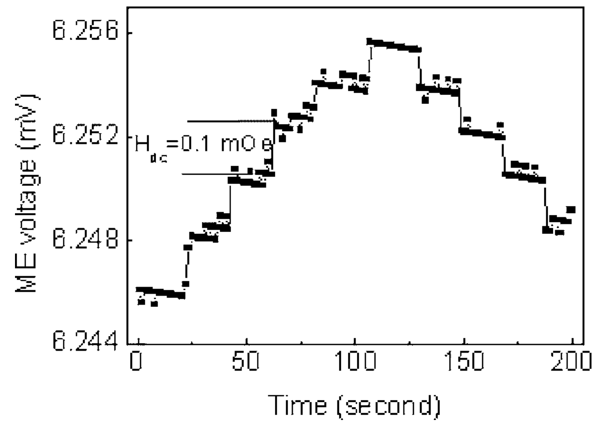

FIG. 3. Sensitivity limit of small dc magnetic field changes for the L-T laminate, while under constant resonant drive ($f_0=84$ kHz, $H_{ac}=71$ mOe).

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