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Detection of pico-Tesla magnetic fields using magneto-electric sensors at room temperature

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The measurement of low-frequency (10^{-2}–10^3 Hz) minute magnetic field variations (10^{-12} Tesla) at room temperature in a passive mode of operation would be critically enabling for deployable neurological signal interfacing and magnetic anomaly detection applications. However, there is presently no magnetic field sensor capable of meeting all of these requirements. Here, we present new bimorph and push-pull magneto-electric laminate composites, which incorporate a charge compensation mechanism (or bridge) that dramatically enhances noise rejection, enabling achievement of such requirements. © *2006 American Institute of Physics*.
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New sensors are needed for the detection of low-frequency minute magnetic field (H) variations in applications ranging from non-invasive neurological interfaces for quadriplegics,[1,2] to magnetoencepthalogy[3,4] and magnetic anomaly detectors.[5] These applications require sensitivity to minute (10^{-12} Tesla), low frequency (10^{-2}–10^3 Hz) magnetic field variations in a time-domain mode without signal averaging. In addition, in order to be deployable, new magnetic field sensor technologies need to operate at 300 K, be passive, and quite small. No known sensor can meet all of these stringent requirements.

The best magnetic field sensors are superconducting quantum interference devices (or SQUIDs).[6] The highest sensitivities (at 1 Hz) of low-temperature ($T<4$ K) and high-temperature ($T<77$ K) SQUIDs are about 10^{-15} Tesla/Hz$^{1/2}$ (Ref. 7) and 5×10^{-14} Tesla/Hz$^{1/2}$,[8] respectively. These sensitivities are achievable only in the best shielded rooms, under cryogenic operating conditions, and using a sensing current of 15 mA. Another important type of magnetic field sensor is the giant magnetoresistance (or GMR) spin valve.[9] At 300 K, the best sensitivity is $\sim4\times10^{-10}$ Tesla/Hz$^{1/2}$ (1 Hz) for $I=1$ mA. Thermal or shot-noise is the limitation. At 4.2 K, the sensitivity is increased to $\sim4\times10^{-11}$ Tesla/Hz$^{1/2}$. Recently, enhanced $1/f$-noise rejection has been achieved by hybridizing a GMR sensor with a superconducting flux-to-field transformer.[10] The best sensitivity is $\sim10^{-12}$ Tesla/Hz$^{1/2}$ at 77 K and $\sim3\times10^{-13}$ Tesla/Hz$^{1/2}$ at 4.2 K, using sensing currents of 5 mA and 15 mA, respectively. Recently, a chip-size atomic magnetometer has been reported[11] that is low-power consuming and has sensitivity as low as 5×10^{-11} Tesla/Hz$^{1/2}$ at 10 Hz.

The magneto-electric (ME) effect offers an alternative *passive* approach to magnetic field sensing at room temperature. It involves the direct conversion of an input magnetic field H to an electric voltage V.[12–14] The ME effect is largest for composites consisting of piezoelectric and magnetostrictive layers laminated together, in either longitudinal-transverse (*L-T*) (Refs. 15–19) or longitudinal-longitudinal (*L-L*) vibration modes.[18,19] An input H-field strains magnetostrictive layers that are elastically coupled to piezoelectric ones, which subsequently transduces the applied stress to a voltage via piezoelectricity. Using signal averaging to assist in noise rejection, it has been shown feasible to detect magnetic field variations as low as $\sim10^{-11}$ Tesla at a drive frequency of $f=10^3$ Hz.[20] However, in applications, noise rejection by signal averaging also limits detection of anomalies. In particular, pyroelectric currents from the $Pb(Zr_{1-x},Ti_x)O_3$ (PZT) layer can be quite significant at low frequencies, on the order of ~100 μC/m^2 K. For example, a temperature fluctuation of $\Delta T=0.1$ °C in a PZT layer of dimensions 1×0.2 cm^2 would generate a noise-equivalent charge of $\sim10^{-11}$ C. Clearly, low-frequency thermal fluctuations present serious equivalent-noise limitations to ME sensors.

However, we have mitigated the low frequency thermal-noise limitations by developing identical piezoelectric layers which are (i) mechanically disconnected; (ii) thermally connected (i.e., packaged together); and (iii) electrically connected in reverse. Figure 1 illustrates the laminate configurations which we have developed that achieve these requirements, which are (a) a two-element piezoelectric bimorph, and (b) a push-pull laminate configuration. The samples were made of Terfenol-D and PZT layers, which were attached to each other using a hard epoxy. The bimorph laminate was consisted of two PZT plates ($13\times6\times0.5$ mm^3) and one Terfenol-D plate ($13\times6\times1$ mm^3), and the push-pull laminated consisted of one PZT plate ($16\times6\times2$ mm^3) and two Terfenol-D plates ($14\times6\times1.2$ mm^3). For these two configurations, thermal noise acts on small neighboring elements similarly; consequently, any temperature changes generate an equal and compensating charge in the mechanically disconnected layer, resulting in enhanced noise rejection. The ability of the bimorph to reject pyroelectric noise is illustrated in Fig. 1(c), which shows the pyroelectric current as a function of temperature for (i) a bimorph, consisting of two PZT layers; and (ii) a corresponding unimorph of the same geometry, but consisting of a single PZT layer. It can be seen that the bimorph configuration reduces the pyroelectric current by a factor of $\geqslant10\times$. Then, for both configurations we established (i) that the ME voltage coefficient is frequency independent over $10^{-2}<f<10^3$ Hz; (ii) that the induced ME voltage is linear with respect to H_{ac}; and (iii) that we could capture the time domain response of the laminate to an H_{ac}. These measurements were done using an op-amp with a high input resistance to collect the charge from the laminates induced by

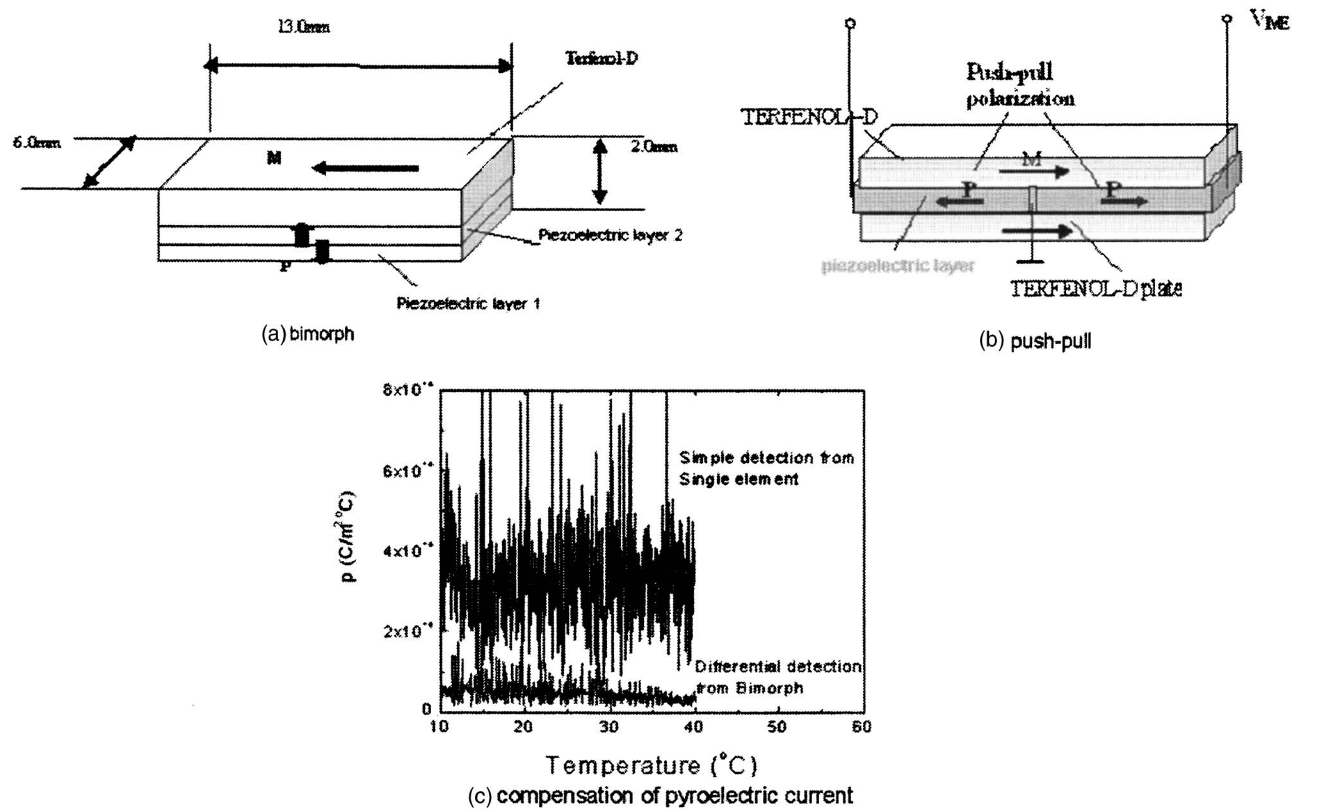

FIG. 1. Schematic view of our magneto-electric (a) bimorph and (b) push-pull laminate composite magnetic field sensors. A magnetic field is sensed by straining magnetostrictive Terfenol-D layers that are epoxied to piezoelectric $Pb(Zr_{1-x}Ti_x)O_3$ ones, which subsequently converts the stress into a voltage via piezoelectric effect. In these two designs, enhanced signal to noise ratio is achieved by the back-to-back configurations of the piezoelectric layers, which rejects thermal noise. In (c), we illustrate the rejection in the pyroelectric current achieved by using the bimorph construction, relative to a unimorph of the same geometry.

H_{ac}. During measurement, a dc magnetic bias of 400 Oe was applied along the length of the laminate using permanent magnets.

First, we present the noise spectra for the bimorph construction, as given in Fig. 2. These measurements were performed at room temperature, in a magnetically shielded environment made of nickel and cobalt alloy, and that had a noise rejection capability of $\sim 10^5$, and by using a simple high-input resistance op-amp operated in a time-domain capture mode. Data are only shown for the low frequency range of $f < 10$ Hz, due to the low inertial resonance frequency of a bimorph. In this figure, the sensitivity limit to minute magnetic field variations can be seen to be about 2×10^{-11} Tesla/Hz$^{1/2}$ (rms) at 1 Hz, where the noise floor has $1/f$ dependence. The noise-equivalent charge was $\sim 10^{-16}$ C (1 Hz). In this figure, we also provide the corresponding data for a unimorph ME laminate, which had a sensitivity limit of about 10^{-9} Tesla/Hz$^{1/2}$ (rms) at 1 Hz and a noise-equivalent charge of $\sim 10^{-14}$ C. Comparisons of the results for the bimorph and unimorph clearly demonstrate the importance of lowering the pyroelectric noise-floor of the PZT layer.

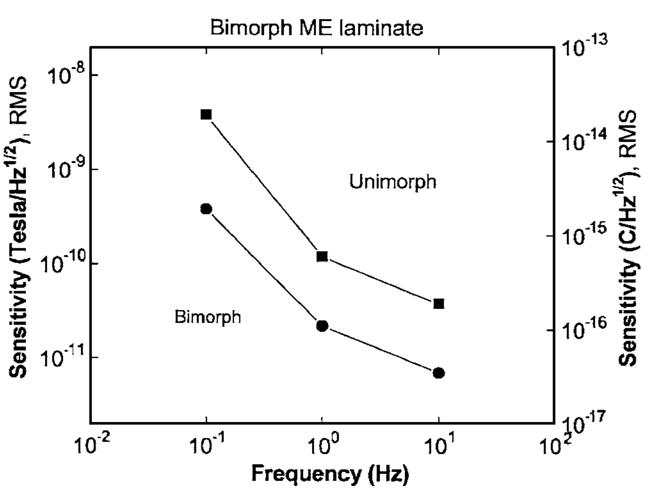

FIG. 2. Noise spectra, given in Tesla/Hz$^{1/2}$ on the left-hand side and Coulombs/Hz$^{1/2}$ on right-hand, for the bimorph ME laminate. These data were taken at 300 K, using a high-input resistance op-amp. The sensitivity limit was about 2×10^{-11} Tesla/Hz$^{1/2}$ (or 2×10^{-16} C/Hz$^{1/2}$) at 1 Hz. We show corresponding data for the unimorph laminate, in order to demonstrate the enhanced noise rejection of the thermal noise by differential detection.

Next, in Fig. 3, we present the noise spectra for the push-pull laminate. Data are shown over a frequency range of $0.1 < f < 10^5$ Hz. The low frequency data were taken using a high-resistance input op-amp, whereas the high frequency data were taken by a voltage method. At 1 Hz, the sensitivity limit to minute magnetic field variations was about 3×10^{-11} Tesla/Hz$^{1/2}$ (rms), and its noise-equivalent charge on the order of 10^{-15} C. With increasing frequency, the noise floor was dramatically lowered, reaching about 2×10^{-15} Tesla/Hz (rms) at the resonance frequency of the laminate ($\sim 10^5$ Hz).

Finally, in Fig. 4, we illustrate the high sensitivity of a time-domain response to a magnetic input signal of $H_{ac} = 2.4 \times 10^{-11}$ Tesla (rms). The results show the voltage response of the push-pull laminate under resonance drive (7.75×10^4 Hz), where the drive is shown beneath the response. At this minute field, the ME response had an ex-

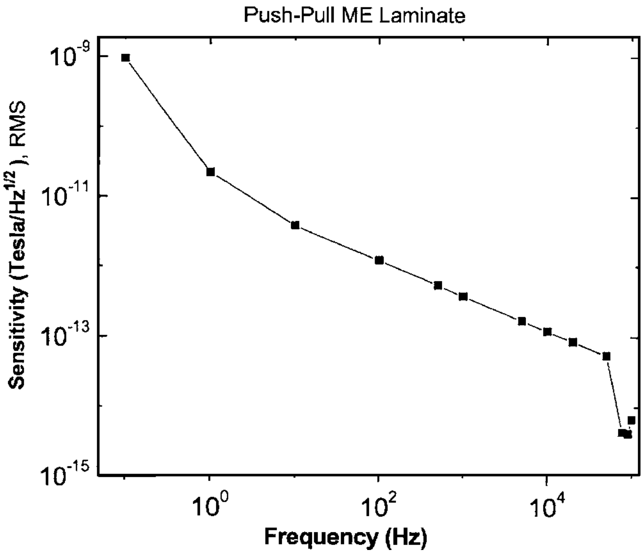

FIG. 3. Noise spectra, given in Tesla/Hz$^{1/2}$, for the push-pull ME laminate. These data were taken at 300 K. The low frequency data was taken using a high-input resistance op-amp to collect charge, whereas the high frequency was taken using a voltage method. The sensitivity limit was about 2×10^{-11} Tesla/Hz$^{1/2}$ (or 2×10^{-16} C/Hz$^{1/2}$) at 1 Hz, and about 2×10^{-15} Tesla/Hz$^{1/2}$ at 78 kHz.

tremely clean waveform. These results clearly demonstrate extreme sensitivity limits of between pico- and femto-Tesla over a broad frequency range, which can be captured in the time domain. The popcorn noise results from the frequency response limitations of the high-input resistance op-amp operating in a time-domain mode.

We summarize our findings as follows: We have developed new ME laminate composite configurations which reject pyroelectric noise. This results in a dramatic lowering of the noise floor. In so doing, we achieve a sensitivity limit to minute magnetic field variations of about 2×10^{-11} Tesla/Hz$^{1/2}$ (@1 Hz) when operated at 300 K. This sensitivity limit is an order of magnitude better than the best previously reported for a GMR spin valve operated at 300 K and 1 mA, which is about 4×10^{-10} Tesla/Hz$^{1/2}$ (@1 Hz).[9] Our bimorph and push-pull ME laminates do not have as high a sensitivity as that of a hybrid GMR-superconducting

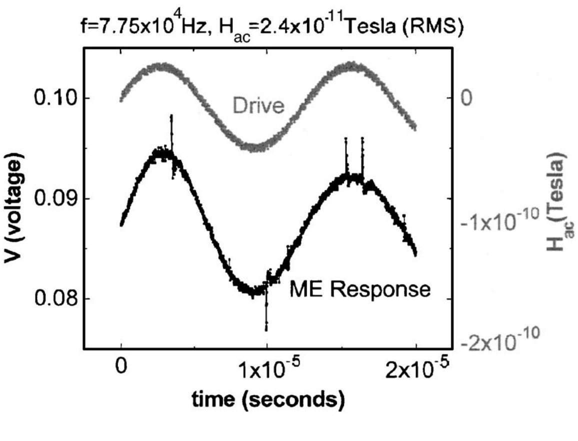

FIG. 4. Time-domain response to a minute magnetic field of $H_{ac}=2.4\times10^{-11}$ Tesla (rms) for the push-pull laminate at 7.75×10^{4} Hz.

sensor operated at 77 K and 5 mA,[10] which is 10^{-12} Tesla/Hz$^{1/2}$ (@1 Hz). However, our bimorph and push-pull ME sensors (i) are entirely passive; (ii) operate at room temperature, rather than under cryogenic conditions, making it suitable for long-term deployment in non-invasive neurological/biological applications and magnetic anomaly detection; (iii) are small, robust, and simple to operate; in addition to being (iv) extremely sensitive and responsive to minute magnetic signals over a broad bandwidth.

Ultimately, we recognize that further significant enhancements in the sensitivity limits of ME laminates are feasible. First, in the case of the push-pull laminate, the extreme enhancement ($\sim10^{-15}$ Tesla/Hz$^{1/2}$) under resonant drive is nearly equivalent to that offered by a SQUID sensor operated a 4 K and 15 mA.[6–8] Second, more sophisticated design configurations of unimorph, bimorph, and other miniature structures are possible to more fully compensate noise contributions to the total charge, via tuning of various electrical parameters within and between layers.

Clearly, ME laminates offer much potential for low-frequency (10^{-2}–10^{3} Hz) detection of minute magnetic fields (10^{-12} Tesla or below), at room temperature, in a passive mode of operation, such combinations of characteristics are not available in any other magnetic sensor.

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