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Phase-sensitive dc magnetometer based on magnetic–electromagnetic–magnetostrictive–piezoelectric heterostructure

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A phase-sensitive dc magnetometer is developed by combining a pair of permanent magnets, an electromagnetic coil, and a magnetostrictive–piezoelectric laminate in one direction to form a four-phase magnetic–electromagnetic–magnetostrictive–piezoelectric heterostructure. The dc magnetic field sensing in the magnetometer is based on the detection of the phase difference between the off-resonance magneto-electric voltage manipulated by the dc magnetic field to be measured and the resonance electric current referenced at zero dc magnetic field, both under a preset bias magnetic field. The theoretical and experimental results confirm a high and linear dc magnetic field sensitivity of $-0.21^\circ$/Oe over a positive and negative dc magnetic field range of $\pm 150$ Oe with a small nonlinearity of 1.7%. The magnetometer has the ability to determine dc magnetic field direction and its sensitivity is independent of zero-field resonance electric current amplitude. © 2017 Author(s). All article content, except where otherwise noted, is licensed under a Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/). [http://dx.doi.org/10.1063/1.4975133]

I. INTRODUCTION

Magnetometers based on an extrinsic magnetoelectric (ME) effect in magnetostrictive–piezoelectric (MS–PE) laminates have stimulated considerable scientific research interest and technological development opportunity in the past decade owing to their promising features of passive sensing, high sensitivity, low noise, and wide bandwidth in comparison with conventional Hall-effect and magnetoresistance magnetometers.\textsuperscript{1,2} In fact, the magnetic field sensing in most ME magnetometers is built on an extrinsic ac ME effect in which the magneto-mechano-electric coupling between the constituent MS and PE phases of the laminates is achieved dynamically under an applied ac magnetic field,\textsuperscript{3,4} and the resulting magnetometers are classified as ac ME magnetometers.\textsuperscript{5–8} The principal limitation in these ac ME magnetometers is their inability to measure dc magnetic fields because the extrinsic ac ME effect as characterized by an ME voltage or charge response is generally weakened by the decay of PE charge with time in the PE phase below 100 Hz.\textsuperscript{1–3}

Recently, a current-mode dc ME magnetometer was proposed based on an ac electric current-controlled, dc magnetic field-induced Lorentz force effect in a conductive–PE heterostructure with or without dc magnetic biasing.\textsuperscript{5,6} An ac electric current-controlled dc magnetic field sensitivity of 3–170 $\mu$V/Oe/A was obtained for dc magnetic fields up to 2 kOe under an ac control current of $\leq 300$ mA at $<15$ kHz. More recently, a voltage-mode dc ME magnetometer was suggested based on an ac electric voltage-driven, dc magnetic field-tuned resonance dc ME effect in a transformer-like PE–MS heterostructure.\textsuperscript{7,8} An ac electric voltage-controlled dc magnetic field sensitivity of \footnote{Author to whom correspondence should be addressed: eeswor@polyu.edu.hk}
–0.6 to –1.3 mV/Oe/V was acquired in a dc magnetic field range of 0–400 Oe at an ac driving voltage of ≤5 V at ~120 kHz. So far, the reported dc ME magnetometers fully rely on the detection of the amplitude of their ac electric voltage output to quantify the strength of the dc magnetic field input, and their sensitivities have the direct dependence on the amplitude of the ac control current or driving voltage. These amplitude-dependent detection techniques are liable to small-signal-induced inaccuracy and large-signal-induced nonlinearity and power consumption. By utilizing an output–input phase differencing technique, it would be possible to develop a phase-sensitive dc ME magnetometer with an amplitude-independent sensitivity and a high linearity.

In this paper, we report theoretically and experimentally a phase-sensitive dc ME magnetometer having a MS–PE laminate wound with an electromagnetic (EM) coil and sandwiched between a pair of permanent magnets in one direction to give a four-phase magnetic–EM–MS–PE heterostructure. Instead of detecting the ac electric voltage amplitude with respect to the dc magnetic field strength, our magnetometer detects the phase difference between the dc magnetic field-manipulated off-resonance ME voltage output from the MS–PE laminate of the heterostructure and the zero-field resonance electric current input to the EM coil of the heterostructure, both under a bias magnetic field preset by the permanent magnets to the heterostructure. As a result, our magnetometer exhibits a high and linear dc magnetic field sensitivity of –0.21 °/Oe, a two-sided measurement range of ±150 Oe, and a small nonlinearity of <2% under a small zero-field resonance electric current of 0.5 mA at 115.8 kHz and a low bias magnetic field of 150 Oe.

II. STRUCTURE AND WORKING PRINCIPLE

Figure 1(a) shows the schematic diagram and prototype of the proposed phase-sensitive dc magnetometer in the form of a four-phase magnetic–EM–MS–PE heterostructure. The heterostructure was fabricated by winding an EM coil on a MS–PE laminate, and the coil-wound MS–PE laminate was bonded by a pair of permanent magnets at its two ends. The MS–PE laminate was prepared by bonding a Pb(Zr, Ti)O$_3$ (PZT, CeramTec P8) PE ceramic plate of 12 mm length ($l$), 6 mm width ($w$), and 1 mm thickness ($t$) between two [112]-textured Tb$_{0.3}$Dy$_{0.7}$Fe$_{1.92}$ (Terfenol-D, Baotou Rare Earth) MS alloy plates of the same dimensions in the thickness direction. The polarization ($P$) direction of the PE ceramic plate and the magnetization ($M$) direction of the MS alloy plates were oriented along their thickness and length directions, respectively. The EM coil was formed by winding two layers of AWG#26 enameled copper wire in the clockwise direction to give a total of 64 turns ($n$), with

![FIG. 1. (a) Schematic diagram and prototype of the proposed phase-sensitive dc magnetometer. (b) Dynamic magneto-mechano-electric equivalent circuit of the magnetometer.](image-url)
each layer comprising 32 turns. The two permanent magnets were length-magnetized NdFeB slabs having 4 mm length, 8 mm width, and 4 mm height. These permanent magnets were able to preset an average bias magnetic field of 150 Oe along the length of the MS–PE laminate for enabling a two-sided measurement of dc magnetic fields up to ±150 Oe and an ability to determine the direction of dc magnetic fields.

The working principle of the phase-sensitive dc magnetometer in Fig. 1(a) can be described by the biasing of the heterostructure with a bias magnetic field \( (H_B = 150 \text{ Oe}) \) preset by the permanent magnets, and on the basis of this \( H_B \) and the natural resonance frequency of the heterostructure without the dc magnetic field to be measured \( (f_{00} \equiv f_r \text{ at } H_{dc} = 0 \text{ Oe under } H_B) \), the detection of the phase difference \( (\theta = \theta_{\text{ME}} - \theta_p) \) between the off-resonance ME voltage \( (V_{\text{ME}}) \) output from the MS–PE laminate of the heterostructure under the manipulation of \( H_{dc} \) to be measured and the resonance electric current \( (I_{00}) \) input to the EM coil of the heterostructure at zero \( H_{dc} \). In more details, the heterostructure is preset to have built-in magnetic biasing by \( H_B (=150 \text{ Oe}) \) to produce a MS strain \( (\lambda_0) \) and hence an elastic modulus \( (E_0) \) and \( f_{00} \) in the absence of both \( I_{00} \) and \( H_{dc} \). By inputting a small-signal \( I_{00} \) into the EM coil, a small-signal resonance magnetic field \( (H_{00}) \) is generated along the length of the heterostructure and to vary about \( H_B \) at \( f_{00} \) in accordance with Ampère’s law. The heterostructure is excited by this \( H_{00} \) to resonate at its \( f_{00} \), thereby producing a resonance ME voltage \( (V_{\text{ME}0}) \) with its phase angle \( (\theta_{\text{ME}0}) \) leading that of \( I_{00}(\theta_{I_0}) \) by \( 90^\circ \) (i.e., \( \theta_0 = \theta_{\text{ME}0} - \theta_p = 90^\circ \)) in light of the resonance ME effect in the MS–PE laminate. In the presence of a positive/negative \( H_{dc} \), the initially preset \( \lambda_0 \) and hence \( E_0 \) and \( f_{00} \) are manipulated by \( H_{dc} \) with respect to \( H_B \) (i.e., \( H_B \pm H_{dc} \)), giving a larger/smaller \( \lambda \) and hence a smaller/larger \( E \) and a lower/higher \( f_r \) based on the negative \( -\Delta E \) effect intrinsic in all MS materials and devices.\(^{5,6}\) This, in turn, alters \( V_{\text{ME}0} \) to become \( V_{\text{ME}} \) with respect to \( I_{00} \), leading to a larger/smaller amplitude \((|V_{\text{ME}}|)\) as well as smaller/larger \( \theta_{\text{ME}0} \) and \( \theta \).

Figure 1(b) illustrates the dynamic magneto-mechano-electric equivalent circuit of the magnetometer in Fig. 1(a). The equivalent circuit consists of three sections, namely the resonance electric current input (reference) section, the dc magnetic field manipulation section, and the ME voltage output section. In the resonance electric current input section, the generation of \( H_{00} \) at \( f_{00} \) by \( I_{00} \) in the EM coil and the coupling of the generated \( H_{00} \) to the MS–PE laminate in the dc magnetic field manipulation section are modeled by a \( I_{00} \)-dependent magneto-mechanical transformer \((\Phi_m)\) and a coil resistor \((R_C)\) connected in parallel with a coil parasitic capacitor \((C_C)\).\(^9\) In the dc magnetic field manipulation section, the excitation of the MS–PE laminate by the coupled \( H_{00} \) at \( f_{00} \) under \( H_B \) preset by the permanent magnets and the manipulation of \( H_{dc} \) with respect to \( H_B \) are modeled as a characteristic acoustic impedance of the MS–PE laminate in the presence of \( H_B \) \((Z_0)\) in series with two characteristic acoustic impedances caused by the manipulation effect of \( H_{dc} \) \((Z_{dc})\) and the mass loading and damping effects of the EM coil and the permanent magnets \((Z_{\text{MLD}})\) so that the effective characteristic acoustic impedance \((Z_{\text{eff}})\) is the sum of \( Z_0 \), \( Z_{dc} \), and \( Z_{\text{MLD}} \).\(^{10}\) In the ME voltage output section, the output of \( V_{\text{ME}} \) due to the off-resonance ME effects with the \( H_{dc} \) manipulation is modeled by a mecanoelectric transformer \((\Phi_p)\) in parallel with a clamped capacitance \((C_0)\).\(^{11}\) Since the phase shift caused by \( R_C \) and \( C_C \) is a constant and can be compensated by a zeroing compensation means in practice (see Eq. (6) and Sec. III for further explanation), \( R_C \) and \( C_C \) can be neglected from the equivalent circuit. Physically, \( Z_{\text{eff}}, \Phi_m, \Phi_p, \) and \( C_0 \) can be expressed as follows:

\[
Z_{\text{eff}} = Z_0 + Z_{dc} + Z_{\text{MLD}}; Z_0 = -\frac{1}{2} j \frac{\rho}{s_0} \tan^{-1} \left( \frac{\pi f_l \sqrt{\rho s_0}}{s_0} \right) \tag{1}
\]

\[
\Phi_m = 2 \pi r d_{33,010} \frac{H_B}{s_0}; H_{00} = \frac{n I_{00}}{l} \tag{2}
\]

\[
\Phi_p = \frac{w d_{31,01} \rho}{s_0} \tag{3}
\]

\[
C_0 = \frac{w f_l}{l} e_{33}^T (1 - k_{33}^2) \tag{4}
\]

where \( \rho = (2 \rho_m + \rho_p)/3 \) and \( s_0 = 3 s_{11}^E H_{1330} / (s_{11}^E + 2 s_{33}^H) \) are the density and \( H_B \)-preset compliance of the MS–PE laminate, respectively; \( d_{33,010} \) and \( s_{33}^H \) are the \( H_B \)-preset piezomagnetic and compliance
coefficients of the MS phase, respectively; $e_3^{T}$, $d_{31,p}$, and $k_{31}$ are the permittivity, piezoelectric, and electromechanical coupling coefficients of the PE phase, respectively.\textsuperscript{12,13} By solving the equivalent circuit in Fig. 1(b), the $H_{dc}$-manipulated resonance frequency ($f_r$) of the heterostructure can be expressed as

$$f_r = \frac{1}{2l} \sqrt{\xi \rho (\frac{3e_1^{T}H_{33}^{H}}{E_{11}^{s} + 2s_{33}^{H}})}$$

where $\xi$ is a constant (=1.77 in our case) for accounting the contribution of $Z_{MLD}$ and $s_{33}^{H}$ is the $H_{dc}$-manipulated compliance coefficient of the MS phase. The $H_{dc}$-manipulated phase difference ($\theta$) between $\theta_{V_{ME}}$ and $\theta_{I_0}$ can be expressed as

$$\theta = \arctan \left( \frac{f_{0}/f_r}{1 - (f_{0}/f_r)^2} \right) + \varphi_0$$

where $\varphi_0$ is introduced to include the phase shift caused by $R_c, C_c$ as well as any other nonlinearity and uncertainty in practice. The value of $\varphi_0$ can be compensated by a zeroing compensation means to be described in Sec. III. It is noted that $\theta$ is a nonlinear and implicit function of $H_{dc}$ in Eq. (6). The tremendous slope of arctan function when $f_{0}/f_r$ is close to unity gives an approximately linear response of $\theta$ with respect to $H_{dc}$. Therefore, the dc magnetic field sensitivity ($S_\theta$) of the magnetometer can be quantified by the slope of the $\theta$ versus $H_{dc}$ plot as

$$S_\theta = \frac{d\theta}{dH_{dc}}.$$  

It is interesting to note that $\theta$ in Eqs. (6) and (7) is independent of $I_0$. This independence can effectively minimize the small ac current and voltage amplitude-induced inaccuracy as well as the large ac current and voltage amplitude-induced nonlinearity and power consumption intrinsic in the previously reported current- and voltage-mode dc ME magnetometers, respectively.\textsuperscript{5–8}

### III. EXPERIMENTS

Figure 2 illustrates the schematic diagram of the experimental setup for the evaluation of the phase-sensitive dc magnetometer at room temperature ($\sim 20^{\circ}$C). The evaluation involves: 1) applying a swept sinusoidal electric current ($I$) of controlled amplitude (i.e., 0.5 and 1 mA peak) to the EM coil of the heterostructure in the vicinity of resonance of 113–119 kHz, and 2) measuring the corresponding $V_{ME}$ output from the MS–PE laminate of the heterostructure at discrete frequency ($f$) intervals of 100 Hz/step under the manipulation of various $H_{dc}$ from –150 to 150 Oe along the length of the heterostructure, to give the $f$ dependence of both amplitude ($|V_{ME}|$) and phase angle ($\theta_{V_{ME}}$) of $V_{ME}$ at various $H_{dc}$ and $I$. The swept sinusoidal $I$ was provided by a constant-current supply amplifier (Techron 7572) connected to an arbitrary waveform generator (Agilent 33210A) and was monitored by a current probe and its amplifier (HIOKI 3271). The monitored $I$ was fed into a lock-in amplifier (SRS SR865) with a phase compensation for $\varphi_0$ in Eq. (6), if any. The $H_{dc}$ manipulation was generated using a pair of Helmholitz coils under the control of a dc current supply (RIGOL...
IV. RESULTS AND DISCUSSION

Figure 3(a) shows the measured $f$ dependence of $|V_{\text{ME}}|$ in the vicinity of resonance of 113–119 kHz at various $H_{\text{dc}}$ from −150 to 150 Oe under two different $I$ of 0.5 and 1 mA peak. For $I = 1$ mA and $H_{\text{dc}} = 0$ Oe (i.e., the curve with large black solid square), the heterostructure is found to resonate at $f_0 = 115.8$ kHz with $|V_{\text{ME}}| = 1.2$ mV. An increase/a decrease in $H_{\text{dc}}$ from 0 Oe shifts the resonance curves in such ways that their $|V_{\text{ME}}|$ appear on the higher/lower $|V_{\text{ME}}|$ side while their $f_0$ occur on the lower/higher $f$ side. This is a valid evidence of the $H_{\text{dc}}$-manipulated resonance ME effect in the heterostructure described in Secs. I and II. In other words, an increase in $H_{\text{dc}}$ from 0 to 150 Oe will manipulate the initially $H_B$-preset $\lambda_0$ and hence $E_0,f_0$, and $V_{\text{ME0}}$ to become a larger $\lambda$ and hence a smaller $E$, a lower $f_0$, and a higher $|V_{\text{ME}}|$ in accordance with the decreasing trend in the negative $\Delta E$ effect.$^5,6$ The situation is reversed upon the reversal of $H_{\text{dc}}$ from 0 to −150 Oe. Now, if $I$ is set as $I_0$ with $f_0 = 115.8$ kHz, an increase/a decrease in $H_{\text{dc}}$ from 0 Oe will increase/decrease the value of $|V_{\text{ME0}}|$ to become $|V_{\text{ME}}|$ (along the dash line) as a result of the shift in resonance curves. This suggests the existence of a direct relationship between $|V_{\text{ME}}|$ and $H_{\text{dc}}$ on $I_0$. When $I$ is reduced to 0.5 mA, all the $|V_{\text{ME}}|$ spectra exhibit very similar quantitative trends to those at $I = 1$ mA, except that their $|V_{\text{ME}}|$ values are half-reduced at the same $H_{\text{dc}}$. The observation indicates the dependence of the amplitude of $I_0$ on the sensitivity of our magnetometer if $|V_{\text{ME}}|$ is used to quantify $H_{\text{dc}}$. Having been described in Sec. I, the use of the amplitude-dependent detection technique, as in the reported current- and voltage-mode dc ME magnetometers,$^3,6$ will lead to the deficiencies of amplitude-dependent sensitivity, small-signal-induced inaccuracy, and large-signal-induced nonlinearity and power consumption. By contrast, the shift in $f_0$ with $H_{\text{dc}}$ provides an essential indication for realizing amplitude-independent sensitivity, high linearity, and low power consumption in our magnetometer by utilizing an output–input phase differencing technique through the detection of $\theta$ ($= \theta_{V_{\text{ME}}} - \theta_{I_0}$), instead of $|V_{\text{ME}}|$.

Figure 3(b) shows the measured and calculated $f$ dependence of $\theta_{V_{\text{ME}}} - \theta_I$ in the vicinity of resonance of 113–119 kHz at various $H_{\text{dc}}$ from −150 to 150 Oe under two different $I$ of 0.5 and 1 mA peak. The calculation was performed by substituting $f_0 = 115.8$ kHz obtained in Fig. 3(a) and supplier-provided material parameters (i.e., $\rho_m = 9200$ kg/m$^3$, $\rho_p = 7600$ kg/m$^3$, $s_{33}^{H} = 32.1 + 6.4 \times 10^{-3} \cdot H_{\text{dc}}$ pm$^2$/N, and $s_{11}^{H} = 7.28$ pm$^2$/N) into Eqs. (5) and (6). The measured and calculated $\theta_{V_{\text{ME}}} - \theta_I$ spectra

![Diagram](image-url)
under two different $I$ overlap fully with each other, elucidating a practically viable measurement of $H_{dc}$ by detecting $I$-independent $\theta_{\text{ME}} - \theta_{l}$. For a given $I$, the measured and calculated spectra also agree well with each other, confirming the validity of our physical model in Sec. II. In fact, the $\theta_{\text{ME}} - \theta_{l}$ spectra essentially follow the arctan trends for all $H_{dc}$ in that their slopes give an approximately linear response of $\theta$ with respect to $H_{dc}$ when $f_{0}/f_{r}$ is close to unity. Considering the case of $H_{dc} = 0$ Oe (i.e., the curve with black solid square), the heterostructure resonates at $f_{0} = 115.8$ kHz with $\theta_{\text{ME,0}} - \theta_{l,0} = 90^\circ$.

Applying a positive/negative $H_{dc}$ will shift $f_{r}$ to the lower/higher $f$ side (Fig. 3(a)), giving rise to the corresponding shift in $\theta_{\text{ME,0}} - \theta_{l,0}$ to become $\theta = \theta_{\text{ME,0}} - \theta_{l,0}$ (along the dash line). This reflects the presence of a direct relationship between $\theta$ and $H_{dc}$ on $f_{0}$.

Figure 4 plots the measured $|V_{\text{ME}}|$ and $\theta$ in the $H_{dc}$ range of $\pm 150$ Oe for two different $I_{0}$ of 0.5 and 1 mA peak, both at $f_{0} = 115.8$ kHz. The lines are the fitted lines to the measured data.

![Figure 4](image_url)  

FIG. 4. Measured (symbols) $|V_{\text{ME}}|$ and $\theta$ in the $H_{dc}$ range of $\pm 150$ Oe for two different $I_{0}$ of 0.5 and 1 mA peak, both at $f_{0} = 115.8$ kHz. The lines are the fitted lines to the measured data.

V. CONCLUSION

We have developed a phase-sensitive dc ME magnetometer based on a four-phase magnetic–EM–MS–PE heterostructure and evaluated theoretically and experimentally its working principle and characteristics. The results have confirmed a unique detection of the phase difference ($\theta = \theta_{\text{ME}} - \theta_{l,0}$) between $V_{\text{ME}}$ output and $I_{0}$ input, both under the manipulation of $H_{dc}$ to be measured and a $H_{B}$ preset in the heterostructure. The magnetometer has demonstrated a high and linear $S_{\theta}$ of $-0.21^\circ$/Oe, a two-sided $H_{dc}$ measurement range of $\pm 150$ Oe, and a small nonlinearity of 1.7% under a small $I_{0}$ of 0.5 mA at $f_{0}$ of 115.8 kHz and a low $H_{B}$ of 150 Oe. By contrast, the amplitude-dependent detection has resulted in two different $S_{|V_{\text{ME}}|}$ of 0.53 and 1.06 $\mu$V/Oe with increased nonlinearities of 3.5 and 2.3% for $I_{0}$ = 0.5 and 1 mA, respectively, giving a $I_{0}$-dependent $S_{|V_{\text{ME}}|}$ of 1.06 $\mu$V/Oe/mA, in the same $H_{dc}$ range. This phase-sensitive dc ME magnetometer is capable of broadening the scientific and technological scopes of ME magnetometers in general, and dc ME magnetometers in specific.
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