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High sensitivity magnetic sensor consisting of ferromagnetic alloy, piezoelectric ceramic and high-permeability FeCuNbSiB

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ABSTRACT

A high sensitivity magnetoelectric (ME) composite sensor employing a type of ferromagnetic constant-elasticity alloy (FeNi-FACE), piezoelectric Pb(Zr,Ti)O_3 (PZT-8H) and high-permeability FeCuNbSiB ($Fe_{73.5}Cu_1Nb_3Si_{13.5}B_9$) is developed. The FeCuNbSiB ribbon with the high permeability serves as the dynamic driver to increase the effective piezomagnetic coefficient d_{33} of the FeNi-FACE. At the same time, the FeCuNbSiB/FeNi-FACE/PZT-8H/FeNi-FACE/FeCuNbSiB (FeFPFFe) composite sensor exhibits a higher effective mechanical quality factor (Q_m), which is ~7.7 times higher than that of Terfenol-D/PZT-8H/Terfenol-D (MPM) sensor. As the ME voltage at resonance is directly proportional to the product of piezomagnetic coefficient and Q_m, a stronger ME effect can be achieved. The experimental results show that the resonance ME voltage coefficient (MEVC) of the FeFPFFe sensor at H_{dc} = 119 Oe achieves 4.367 V/Oe, which is ~1.41 times higher than that of FeNi-FACE/PZT-8H/FeNi-FACE (FPF) sensor. Furthermore, $\partial V_{ME}/\partial H_{dc}$ for the FeFPFFe sensor achieves ~22.5 mV/Oe at H_{dc} = 31 Oe under resonant drive conditions of H_{ac} = 0.1 Oe, which is ~20 times higher than that of the previous reported Terfenol-D/Pb(Zr,Ti)O_3/Terfenol-D composite transducer. Thus the FeFPFFe sensor has highly sensitive ac or dc magnetic field sensing.

1. Introduction

Since Ryu et al. reported a new magnetostrictive/piezoelectric laminated composite which has the much higher ME voltage coefficient (i.e., $\partial V_{ME}/\partial H_{ac}$) than former particulate magnetoelectric composites and single-phase magnetoelectric materials, this feature has provided to be a novel method for detecting a low magnetic field with very high sensitivity [1]. Recent studies on the ME effect have suggested the possibility of fabricating ac magnetic field sensors with high performance [2–5]. Special features are their passive natures, their capabilities to detect magnetic fields at very low frequencies, their large dynamic ranges with linear responses and the great ME voltage coefficient (MEVC) at the resonant frequency. However, the performances of the ME sensor in detecting dc magnetic field are deficient. The reported ME voltage sensitivity to dc magnetic fields (i.e., $\partial V_{ME}/\partial H_{dc}$) of a Terfenol-D/Pb(Zr,Ti)O_3/Terfenol-D composite transducer only retains 1.2 mV/Oe under the resonant drive [6]. When it comes to the applications, the magnetic sensor for magnetic anomaly detection requires the strictly high sensitivity to dc magnetic field. This deficiency greatly reduces the competitiveness of the ME sensors against traditional magnetic sensors.

The sensitivity of Terfenol-D/Pb(Zr,Ti)O_3/Terfenol-D composite transducer in the literature [6] is considerably small for dc field sensing, which results from the rather low effective mechanical quality factor Q_m in the composite transducer ranging from 49.9 to 100 [7]. Hence, we fabricate a new magnetic sensor from the ferromagnetic alloy (FeNi-FACE), PZT-8H and FeCuNbSiB, as shown in Fig. 1. The Q_m of the sensor is significantly enhanced because of the high mechanical quality factor in the FeNi-FACE, FeCuNbSiB and PZT-8H. Although the piezomagnetic coefficient (d_{33} = 0.75 nm/A) [8] of FeNi-FACE is much smaller than that of giant magnetostrictive materials Terfenol-D, FeCuNbSiB acts as the dynamic driver to enhance the effective piezomagnetic coefficient of the FeNi-FACE. In this case, a high sensitivity to small variations in both ac and dc magnetic fields can be obtained, since ME voltage gain is directly proportional to the product of the piezomagnetic coefficient and Q_m. Our experimental results show that the proposed composite sensor increases the ME voltage sensitivity to dc magnetic fields by a factor of around 20 compared with that in the literature [6] and enhances the ME voltage sensitivity to ac magnetic fields by a factor of around ~1.41 compared with FPF sensor.

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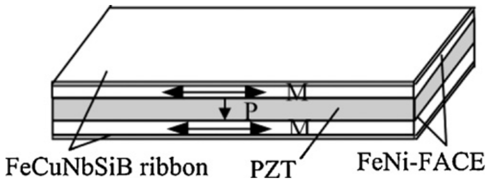

Fig. 1. Schematic illustration of the configuration of the FeFPFFe sensor.

2. Experiment

To fabricate the ME sensor sample, the FeNi-FACE plate, PZT-8H plate and FeCuNbSiB ribbon plate are dipped in organic impregnant to clean. Then the sample is prepared by stacking and bonding the multiple plates with an insulated epoxy adhesive. The sample is cured at 80 °C for 1 h under the load to provide a strong bond between the layers. PZT-8H is produced by China Electronics Technology Group Corporation no. 26 Research Institute. The FeCuNbSIB ribbon is produced by Foshan Huaxin Microlite Metal Co., Ltd, China (International standard trademark 1K107). The FeNi-FACE alloy is produced by Chongqing Instrument Material Research Institute, China. Table 1 summarizes the material characteristics of FeCuNbSiB and FeNi-FACE.

In our experiments, the dc bias magnetic field applied to the FeFPFFe composite sensor is generated by a pair of annular permanent magnets (Nd–Fe–B), and measured by a Gauss meter. Both the ac magnetic field and the dc magnetic bias are parallel to the longitudinal direction of the device. For detecting the ME voltage, the ac magnetic field is generated by applying a sine signal to the solenoid. The induced ME voltage V_{ME} across the two electrodes of the PZT plate is measured by an oscilloscope (Tektronix, TDS2022B). The ME voltage coefficient is calculated according to $\alpha = \partial V_{ME}/\partial H_{ac}$. All the experiments are carried out at room temperature and ambient pressure.

3. Structure and principle of composite magnetic sensor

Fig. 1 shows the configuration of a FeFPFFe composite sensor consisting of magnetostrictive FeNi-FACE, piezoelectric PZT-8H and high-permeability FeCuNbSiB layers. The sizes of the FeNi-FACE, PZT-8H and FeCuNbSiB layers are 12 mm × 6 mm × 0.6 mm, 12 mm × 6 mm × 0.8 mm and 12 mm × 6 mm × 30 μm, respectively. Magnetostrictive FeNi-FACE and FeCuNbSiB layers are magnetized in the longitudinal (length) direction and piezoelectric PZT layer is poled in the transverse (thickness) direction. When a magnetic field is applied to the FeFPFFe sensor, the FeCuNbSiB layer produces a strain due to its magnetostrictive properties, which induces a stress on the FeNi-FACE owing to the stress–strain coupling of the interlayers. Although the saturation magnetostriction coefficient λ_s of FeCuNbSiB layer is only 2.7 ppm [9–11], the magnetic permeability of FeCuNbSiB layer (μ_r > 100,000 at 1 kHz) directly affects its effective piezomagnetic coefficient according to $d_{33} = \mu_r S_{33} \lambda$, where S_{33} is the elastic compliances [12]. And the high permeability causes its large effective piezomagnetic coefficient due to a low saturation field [12,13], producing the large magnetostrictive strain. Hence, the stress exerted on FeNi-FACE layer by the FeCuNbSiB layer can be calculated as follows:

$$\sigma = \frac{2E_f t_f E_t \Delta\varepsilon}{(1-\nu)(2E_f t_f + E_t t_t)}, \tag{1}$$

where E, t, and υ are the elastic modulus, thickness, and poisson's ratio, respectively. The subscript t and f mean FeNi-FACE and FeCuNbSiB respectively. And $\Delta\varepsilon$ is the magnetostrictive strain of the FeCuNbSiB layer. This additional stress can induce a mechanical strain in FeNi-FACE, resulting in the increase of effective piezomagnetic coefficient for FeNi-FACE. As the MEVC at low frequency α_{low} is directly proportional to the piezomagnetic coefficient d_{33} [14], a high α_{low} can be obtained.

For the ME laminated composite, based on the magneto-elasto-electric equivalent circuit method, the MEVC at resonance can be given as [7]

$$\alpha_r = \left|\frac{\partial V_{ME}}{\partial H_{ac}}\right| = \frac{8Q_m}{\pi^2}\alpha_{low}, \tag{2}$$

where V_{ME} is the induced ME voltage across the thickness of the PZT-8H layer under the drive of H_{ac}. From Eq. (2), it is known that the MEVC at resonance depends on α_{low}. Since α_{low} is directly proportional to the piezomagnetic coefficient of the magnetostrictive material [14], Eq. (2) can be rewritten as:

$$\alpha_r = \left|\frac{\partial V_{ME}}{\partial H_{ac}}\right| \propto \frac{8Q_m d_{33}}{\pi^2}. \tag{3}$$

Because of the high mechanical quality factor in the FeCuNbSiB, PZT-8H and FeNi-FACE [8], the FeFPFFe sensor is expected to show the high effective mechanical quality factor Q_m as the Q_m of the FeFPFFe sensor can be given by [7]

$$\frac{1}{Q_m} = \frac{n_1}{Q_{mag}} + \frac{n_2}{Q_{piez}} + \frac{n_3}{Q_{fe}}, \tag{4}$$

where Q_{mag}, Q_{piez} and Q_{fe} are the effective mechanical quality factor of the magnetostrictive FeNi-FACE layer, piezoelectric PZT-8H layer and the FeCuNbSiB layer, respectively. n_1, n_2 and n_3 are the volume ratio of the magnetostrictive FeNi-FACE layer, the piezoelectric PZT-8H layer and the FeCuNbSiB in the laminate, respectively.

According to Eq. (3), the MEVC at resonance is directly proportional to the product of the piezomagnetic coefficient of magnetostrictive layer and the Q_m. Hence, the higher piezomagnetic coefficient d_{33} and Q_m will obviously result in the higher MEVC of the FeFPFFe sensor at resonance. Correspondingly, the ME sensitivity (under resonant drive) to H_{ac} is increased. In this case, a constant dc magnetic bias (H_{dc}) is applied along the length axis of the laminate, and small variations in H_{ac} can be detected. However, the ME effect is also a strong function of H_{dc}. Thus, under a constant H_{ac} drive, ME composite sensor can detect small H_{dc} signal.

The dependence of the ME effect on H_{dc} results from the piezomagnetic coefficient dependence on H_{dc}. In this manner, the dependence of the MEVC on H_{dc} at resonance can be obtained by the derivative of Eq. (3) with respect to H_{dc}, given as

$$\frac{\partial \alpha_r}{\partial H_{dc}} \propto \frac{8Q_m}{\pi^2}\frac{\partial d_{33}}{\partial H_{dc}}. \tag{5}$$

Assuming the induced ME voltage has a linear relationship with H_{ac} at the resonant frequency; Eq. (5) can be rewritten as:

$$\frac{\partial V_{ME}}{\partial H_{dc}} \propto \frac{8Q_m}{\pi^2} H_{ac} \frac{\partial d_{33}}{\partial H_{dc}}. \tag{6}$$

From Eq. (6), the ME sensitivity at resonance to H_{dc} is directly proportional to Q_m. The FeFPFFe composite sensor with the high Q_m is used for dc magnetic field sensing, which will provide the high sensitivity.

Clearly, the FeFPFFe composite sensor has higher sensitivity to small variations in both ac and dc magnetic fields due to the higher product of effective piezomagnetic coefficient d_{33} of the FeNi-FACE and the effective Q_m of the new composite.

Table 1
The material characteristics of FeCuNbSiB and FeNi-FACE.

Material	λ_s (ppm)	Q_{mag}	μ_r	ρ (kg/m^3)	S_{33} ($\times 10^{-12}$ m^2/N)
FeCuNbSiB	2.7	1000	>100,000	7250	5.2
FeNi-FACE	11	2282	30	8000	5

4. Results and discussion

The MEVCs as a function of H_{dc} for the FPF composite and FeCuNbSiB/PZT-8H/FeCuNbSiB (FePFe) composite sensor at a frequency of f = 1 kHz and a drive of H_{ac} = 1 Oe are presented in Fig. 2.

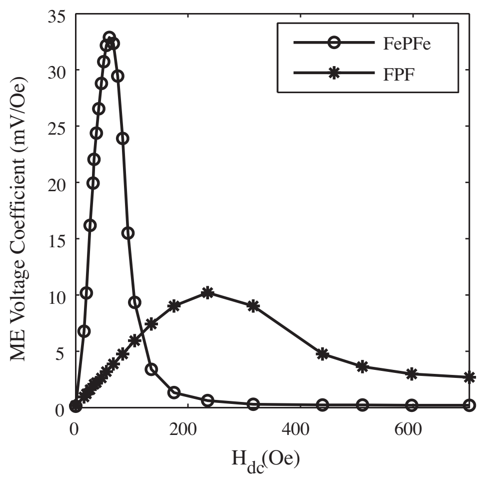

Fig. 2. The ME voltage coefficient as function of dc magnetic field for FPF and FePFe composite sensor at low frequency f = 1 kHz and a constant ac drive of H_{ac} = 1 Oe.

From this figure, it can be seen that with the increase of the dc magnetic filed, the MEVC for FPF composite sensor achieves a maximum of 10.13 mV/Oe at H_{dc} = 235 Oe, then decreases slowly. In contrast, the MEVC for the FePFe composite sensor increases in a approximately linear manner with increasing H_{dc} over the range $0 < H_{dc} < 60$ Oe and gradually reaches the maximum value of 32.89 mV/Oe. With the further increase of the magnetic field, the MEVC decreases gradually. This phenomenon can be understood as a result of the strong relation between the MEVC at low frequency α_{low} and the piezomagnetic coefficient d_{33} ($d\lambda/dH$) of the FeCuNbSiB ribbon, $\alpha_{low} \propto d_{33}$. As mentioned previously, the high permeability of the FeCuNbSiB ribbon causes its large piezomagnetic coefficient at the lower dc magnetic biases, producing the large magnetostrictive strain and ME effect. Taking the advantage of the FeCuNbSiB, a new ME sensor employing magnetostrictive FeNi-FAC, FeCuNbSiB and piezoelectric PZT-8 is fabricated. When FeNi-FACE and FeCuNbSiB layers are bonded by an epoxy adhesive, FeCuNbSiB acts as the dynamic driver to produce the stress on the FeNi-FACE. The additional stress can induce a mechanical strain in FeNi-FACE, resulting in the increase of effective piezomagnetic coefficient for FeNi-FACE [15]. Hence, a higher MEVC for FeFPFFe sensor can be obtained, as shown in Fig. 3. We observe that the maximum MEVC for FeFPFFe sensor achieves 12.216 mV/Oe at H_{dc} = 272 Oe, which is increased by factor of ~1.21 times compared with FPF sensor and the peak position of the MEVC is shifted to a

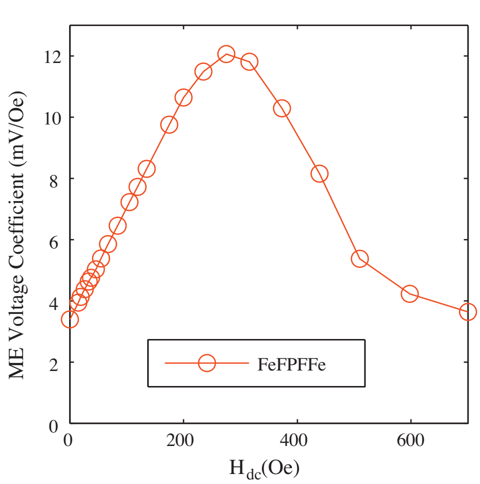

Fig. 3. The ME voltage coefficient as function of dc magnetic field for FeFPFFe sensor.

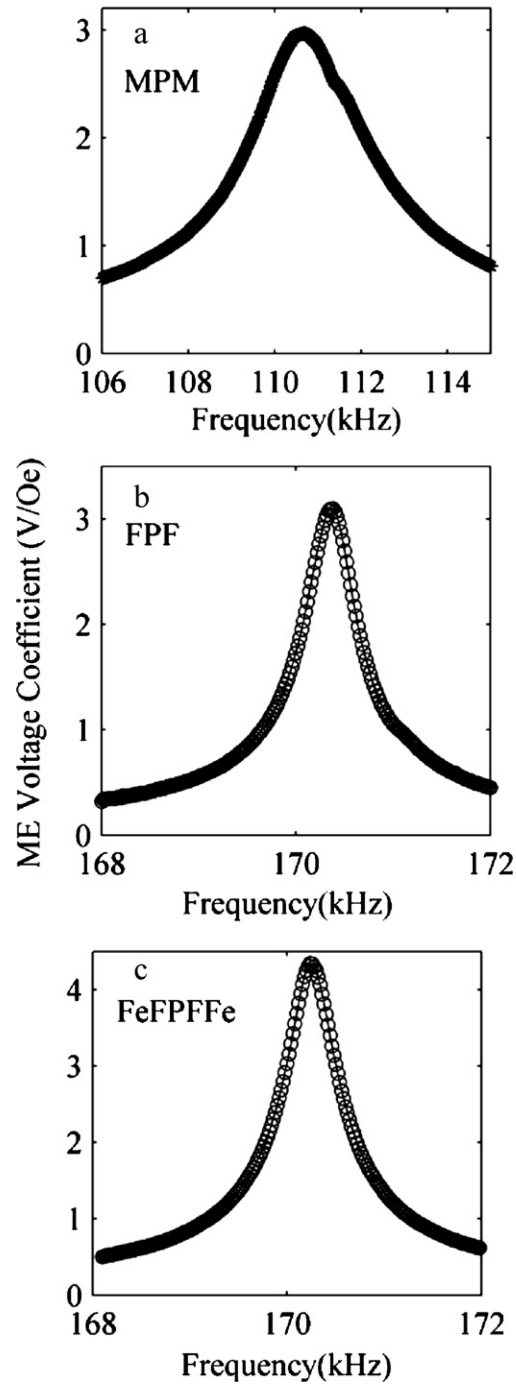

Fig. 4. The maximum ME voltage coefficient as a function of frequency near resonance (a) for the MPM sensor, (b) for the FPF sensor, and (c) for the FeFPFFe sensor.

higher magnetic field. Our experimental results are in good agreement with the theoretical predictions. Obviously, increasing the effective piezomagnetic coefficient of FeNi-FACE by incorporating FeCuNbSiB layers offers an approach to enhance the MEVC α_{low}.

Fig. 4 shows the maximum MEVCs as a function of frequency for MPM, FPF and FeFPFFe sensor near resonance. The data in Fig. 4(a) for the MPM sensor shows the MEVC increases with frequency to a maximum of 2.97 V/Oe at resonance under H_{dc} = 200 Oe. And the resonance frequency f_r is 110.699 kHz and a 3 dB frequency bandwidth Δf is 2.4 kHz. Accordingly, the effective mechanical quality factor of the laminate is $Q_m = f_r/\Delta f$, then Q_m = 46.125 can

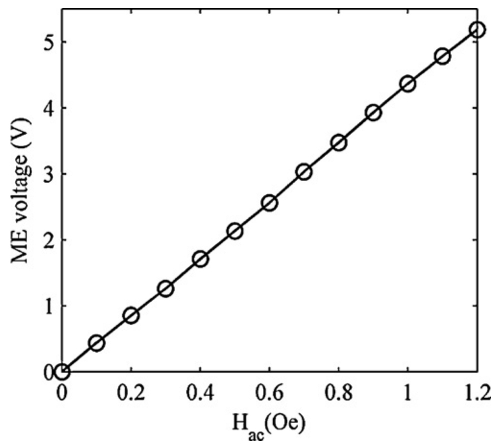

Fig. 5. The ME voltage responding to ac magnetic field H_{ac} at resonance.

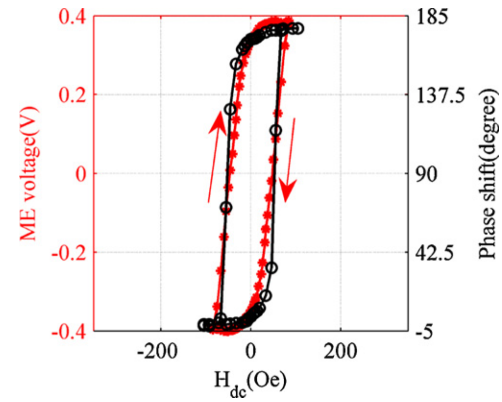

Fig. 6. Resonant ME voltage and phase shift responding to dc magnetic fields.

be obtained. Fig. 4(b) illustrates the MEVC spectrum of the FPF sensor near resonance. From the figure, the resonance occurs at the higher frequency $f_r = 170.38$ kHz due to the lower elastic compliance of FeNi-FACE ($S_{33} = 5.2 \times 10^{-12}$) compared with Terfenol-D ($S_{33} = 42.53 \times 10^{-12}$). And the Q_m of the FPF sensor achieves 354.96, which is ~7.7 times higher than that of the MPM sensor. Although the piezomagnetic coefficient of FeNi-FACE is much smaller than that of Terfenol-D, the higher maximum MEVC of FPF sensor achieves 3.101 V/Oe under $H_{dc} = 316$ Oe, compared with the MPM sensor. As mentioned previously, this is because of the higher Q_m of the FPF sensor at resonance. Fig. 4(c) shows the MEVC spectrum of the FeFPFFe sensor near resonance. From the figure, we obverse that the maximum MEVC of FeFPFFe sensor is 4.367 V/Oe under $H_{dc} = 119$ Oe and the Q_m is calculated as 354.625. The MEVC of the FeFPFFe sensor is ~1.41 times higher than that of the FPF sensor. This may result from the increase in the effective piezomagnetic coefficient d_{33} of the FeNi-FACE caused by the FeCuNbSiB layer acting as the dynamic driver, even though the values of their Q_m are nearly equal. The expression in Eq. (3) gives better physical explanations on these results, thus it is reasonable that the higher product of the piezomagnetic coefficient and Q_m results in the higher MEVC of the FeFPFFe sensor at resonance, compared with FPF and MPM sensor.

By incorporating a high-permeability FeCuNbSiB layer into FPF laminate, a higher MEVC can be achieved. The result unambiguously demonstrates that the FeFPFFe sensor is promising for the small H_{ac} signal detection. Fig. 5 shows the induced ME voltage of the FeFPFFe sensor at the resonant frequency as a function of ac magnetic field under a dc magnetic field $H_{dc} = 119$ Oe. This figure reveals that the induced ME voltage has a linear relationship with H_{ac} at the resonant frequency. Hence, Eq. (3) can be rewritten as

$$V_{ME} \propto \frac{8Q_m}{\pi^2} H_{ac} d_{33}. \qquad (7)$$

From Eq. (7), the value of the ME voltage varies with the ac magnetic biases, Q_m and d_{33}. The ME voltage at the resonance of FeFPFFe sensor is significantly notable because of the increase in the effective piezomagnetic coefficient of FeNi-FACE, compared with FPF sensor. From the ME voltage output the MEVC at resonance can be calculated as 4.367 V/Oe, which indicates that the sensor has an ability to detect low ac magnetic field strength. In this case, the FeFPFFe sensor provides direct conversion of ac magnetic-field into an electrical signal.

Fig. 3 indicates that the MEVC at the low frequency strongly depends on H_{dc}, which can be traced to the different domain magnetizing behaviors under various values of H_{dc} [10]. Thus, the FeFPFFe sensor is potential for small H_{dc} detection under a drive of H_{ac} with the constant magnitude and frequency. Fig. 6 shows the ME voltage as a function of H_{dc} for the FeFPFFe sensor under the resonance frequency $f_r = 170.24$ kHz and $H_{ac} = 0.1$ Oe. From the figure, the induced ME voltage for the FeFPFFe sensor has an almost linear response to the applied dc magnetic field in the ascendent edge of $-84 < H_{dc} < 0$ Oe and in the descendent edge of $0 < H_{dc} < 84$ Oe. And we observe a sharp (step-like) phase shift from 180° to 0° corresponding to the sign reversal of H_{dc} from a positive value to a negative one, as shown on the right-hand axis of Fig. 6. The phase shift reveals the tendency of applied dc field variation. In addition, the value of $\partial V_{ME}/\partial H_{dc}$ for FeFPFFe sensor is calculated from the slope of the ME voltage V_{ME} versus H_{dc} curve. The maximum value is calculated as ~22.5 mV/Oe at $H_{dc} = 31$ Oe, which is about 20 times higher than that of the Terfenol-D/Pb(Zr,Ti)O_3/Terfenol-D laminated transducer in the literature 6. As mentioned previously, this can be ascribed to the high Q_m of the FeFPFFe sensor, resulting in a high ME sensitivity to H_{dc}. Furthermore, the maximal value of $\partial V_{ME}/\partial H_{dc}$ is observed at 31 Oe. This is because of a jump effect, as previously reported in literature [16]. The action of an applied field along the longitudinal-axis direction seemingly induces the magnetization vector of the magnetic domains to change from its initial orientation that is perpendicular to the longitudinal-axis (due to a preload) to being parallel to the direction along which H_{dc} is applied. When the applied H_{dc} increases to 31 Oe, it is near the so-called “burst region”, and the rotation of the magnetic domains is at a maximum. Correspondingly, the ME sensitivity (under resonant drive) to H_{dc} reaches the maximum.

The variation in output voltage for a step-change in dc magnetic field at resonant frequency is investigated, as show in Fig. 7.

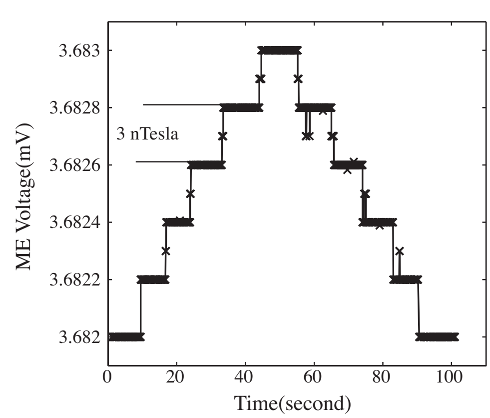

Fig. 7. Sensitivity limit of small dc magnetic field for the FeFPFFe sensor, taken under a constant $H_{ac} = 8$ m Oe at resonant frequency.

The results show that the sensor can distinguish small dc magnetic fields of 3nT under a resonant excitation H_{ac} = 8 m Oe. This also indicates that the FeFPFFe sensor has an ultra-high sensitivity to small dc magnetic field variations.

5. Conclusion

In summary, a magnetoelectric sensor based on FeFPFFe laminates is designed, fabricated and characterized. The configuration with higher permeability FeCuNbSiB is to increase ME coupling and keep its size small. As a result, the high sensitivity to small variations in both ac and dc magnetic fields can be achieved owing to the increase in the effective piezomagnetic coefficient d_{33} of the FeNi-FACE by bonding additional high-permeability FeCuNbSiB layer and the high effective mechanical quality factor $Q_{m,}$ of the FeFPFFe sensor. The MEVC at resonance achieves 4.367 V/Oe and the ME sensitivity to dc magnetic field arrives at ∼22.5 m V/Oe under the resonance frequency f_r = 170.24 kHz and H_{ac} = 0.1 Oe. Furthermore, the sensor can distinguish small dc magnetic fields of 3nT under a resonant excitation H_{ac} = 8 m Oe. Thus the FeFPFFe sensor is potential for highly sensitive dc or/and ac magnetic field detection.

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