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Dynamic Magnetostriction Characteristics of an Fe-Based Nanocrystalline FeCuNbSiB Alloy

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The dynamic magnetostriction characteristics of an Fe-based nanocrystalline FeCuNbSiB alloy are investigated as a function of the dc bias magnetic field. The experimental results show that the piezomagnetic coefficient of FeCuNbSiB is about 2.1 times higher than that of Terfenol-D at the low dc magnetic bias H_{dc} = 46 Oe. Moreover, FeCuNbSiB has a large resonant dynamic strain coefficient at quite low H_{dc} due to a high mechanical quality factor, which is 3-5 times greater than that of Terfenol-D at the same low H_{dc}. Based on such magnetostriction characteristics, we fabricate a new type of transducer with FeCuNbSiB/PZT-8/FeCuNbSiB. Its maximum resonant magnetoelectric voltage coefficient achieves ~10 V/Oe. The ME output power reaches 331.8 μW at an optimum load resistance of 7 kΩ under 0.4 Oe ac magnetic field, which is 50 times higher than that of the previous ultrasonic-horn-substrate composite transducer and it decreases the size by nearly 86%. The performance indicate that the FeCuNbSiB/PZT-8/FeCuNbSiB transducer is promising for application in highly efficient magnetoelectric energy conversion.

Keywords: nanocrystalline FeCuNbSiB alloy, magnetostrictive material, piezomagnetic coefficient, magnetic permeability, magnetoelectric effect

1. Introduction

Magnetostriction is a property of ferromagnetic materials that causes them to change their shapes or dimensions during the process of magnetization [1]. Generally, materials with large magnetostriction are used in transducers, sonar and actuator devices [2-4]. Since the rare-earth iron alloy Terfenol-D ($Tb_xDy_{1-x}Fe_y$) exihibits a giant magnetostrictive characteristic and a good magneto-mechanical coupling factor, it has recently become an attractive topic for transducer applications. However, its quite low relative permeability (~3-10) and serious magnetic flux leakage result in a small piezomagnetic coefficient d_{33} ($d\lambda/dH$) for Terfenol-D under a low H_{dc} [5]. Because of this, it is difficult to realize a highly efficient micro-transducer with Terfenol-D. An Fe-based nanocrystalline material, FeCuNbSiB ($Fe_{73.5}Cu_1Nb_3Si_{13.5}B_9$), exhibits high flexibility, a good mechanical quality factor (Q_m > 1000) and high magnetic permeability (μ_r > 100 000 (f = 1 kHz)) [6-10]. Although FeCuNbSiB possesses an extremely low magnetostriction ($\lambda_s \approx 2.7$ ppm) compared with the conventional rare-earth iron alloy Terfenol-D ($\lambda_s \approx 1000$ ppm), the superior magnetostrictive characteristics at low magnetic field due to the high magnetic permeability and mechanical quality factor is rather promising for magnetostriction-based applications with low field. This great advantage has not been taken into account in the prior studies.

In this paper, we discuss the magnetostriction characteristics of the Fe-based nanocrystalline alloy FeCuNbSiB as a function of the dc bias magnetic field. The high permeability causes the high effective piezomagnetic coefficient d_{33} ($d\lambda/dH$) under a low H_{dc} due to a low saturation field [11]. At the same time, the high mechanical quality factors also lead to the large resonant dynamic strain coefficient d. Hence we fabricate a new magnetoelectric (ME) transducer employing the magnetostrictive material FeCuNbSiB and the piezoelectric material PZT-8 to obtain a high ME voltage coefficient (MEVC) and a high ME power output. The experimental results show that the ME transducer exhibits a superior ME output power density.

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2. Experiments

The experimental data are obtained from the commercially available Fe-based nanocrystalline FeCuNbSiB alloy, produced by the Foshan Huaxin Microlite Metal Co., Ltd, China (International standard trademark 1K107). For comparison, Terfenol-D produced by the Gansu Tianxing Rare Earth Functional Materials Co., Ltd., China is also prepared. Table 1 summarizes the material characteristics of FeCuNbSiB and Terfenol-D. The piezomagnetic coefficients ($d\lambda/dH$) of the FeCuNbSiB and the Terfenol-D are investigated as a function of dc bias magnetic field with a strain-gauge method. The static magnetic field H is generated by a pair of annular permanent magnets (Nd-Fe-B), and then the corresponding magnetostriction λ is measured with a search coil wrapped around the samples and a strain-gauge attached to the center of the samples. The magnetic field H is aligned parallel to the longitudinal direction of the samples so that the measured λ is essentially the longitudinal magnetostriction.

When the frequency approaches a critical value, causing the magnetostrictive material to resonate in its longitudinal direction, the amplitude of the magnetostrictive strain increases abruptly [1]. The magnetostrictive properties of FeCuNbSiB and Terfenol-D at their resonant frequencies are investigated using a Laser Doppler Vibrometer (Polytec MSV-400, Germany) [12].

The ME transducer employing Fe-based nanocrystalline FeCuNbSiB alloy ribbons and piezoelectric PZT-8 is fabricated, as shown in Fig. 1. The FeCuNbSiB/PZT-8/FeCuNbSiB (FPF) transducer is a sandwich of one PZT-8 layer (12 mm × 6 mm × 0.8 mm) bonded between two FeCuNbSiB layers (12 mm × 6 mm × 0.18 mm). The dimensions of the FeCuNbSiB ribbon are 12 mm in length, 6 mm in width, and 30 μm in thickness. The FeCuNbSiB layer is prepared by stacking and bonding six FeCuNbSiB ribbons. The ME transducer is bonded using an insulated epoxy adhesive, and cured at 80 °C for 1 h under the stress load. The FeCuNbSiB layers are magnetized along the longitudinal direction, and the piezoelectric PZT-8 layer is polarized in its thickness direction. When an external magnetic field (including dc bias magnetic field and ac alternating magnetic field) is applied along the longitudinal direction, a strain will be generated in the magnetostrictive FeCuNbSiB layers by the magnetostrictive effect that is transferred to the bonded piezoelectric PZT-8 layer owing to the stress-strain coupling of the interlayers. Then, the ME voltage is generated by the piezoelectric effect. In our experiment, both the ac magnetic field and dc magnetic bias are parallel to the longitudinal direction of the transducer. The dc bias magnetic field is generated by a pair of annular permanent magnets (Nd-Fe-B), and measured using a Gauss meter. The ac alternating magnetic field is also generated by a long straight solenoid, at the center of which the ME transducer is placed. The induced ME voltage is measured by a DSP lock-in amplifier system (Stanford, SR830).

The ME output power is evaluated by measuring the voltage across the parallel resistor with the piezoelectric element PZT-8, as shown in Fig. 2. The output power is calculated by $P = V^2/R_{\mathrm{load}}$, where V is the ME voltage across the load resistor R_{load}.

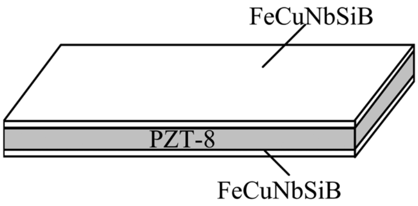

Fig. 1. Schematic diagram of the FeCuNbSiB and PZT-8 composite transducer.

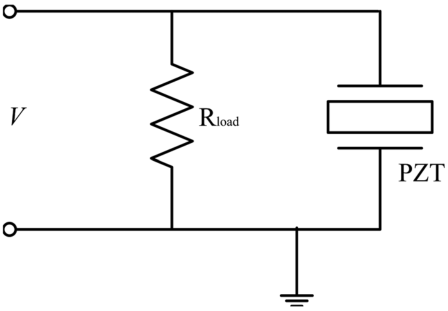

Fig. 2. The circuit for measuring the ME output power.

Table 1. The material characteristics of FeCuNbSiB and Terfenol-D.

Material	Magnetostriction (ppm)	Electrical resistivity (μΩ·cm)	Relative permeability	Density (g/cm^3)
FeCuNbSiB[a]	2.7	130	> 100 000	7.25
Terfenol-D[b]	1000	58	< 10	9.25

[a] Cited from Foshan Huaxin Microlite Metal Co., Ltd., China.

[b] Cited from Gansu Tianxing Rare Earth Functional Materials Co., Ltd., China.

3. Results and Discussion

Fig. 3 shows the magnetostriction as a function of H_{dc} for the Fe-based nanocrystalline FeCuNbSiB and the Terfenol-D. The effective piezomagnetic coefficients are calculated by using the slope of strain-magnetic field (λ–H) curves measured with a strain-gauge method, as shown in Fig. 4. Note that the FeCuNbSiB exhibits a high piezomagnetic coefficient at low H_{dc}. In a small dc magnetic bias range of $0 < H_{dc} < 105$ Oe, the effective piezomagnetic coefficient d_{33} of FeCuNbSiB is greater than that of Terfenol-D. The d_{33} of FeCuNbSiB achieves ~4.08 nm/A, which is ~2.1 times greater than that of Terfenol-D under $H_{dc} = 46$ Oe. This can be attributed to the higher magnetic permeability of the FeCuNbSiB alloy. The magnetostriction λ of a magnetostrictive material can be given as [13],

$$\lambda = \frac{3\lambda_s\mu_r^2}{2M_s^2}H^2, \tag{1}$$

where μ_r is the weak-field relative permeability of the magnetic material, which is constant under small H_{ac}. λ_s and M_s are the saturation magnetostriction and saturation magnetization, respectively; H is the external applied magnetic field. When the applied H_{ac} is much smaller than the superimposed applied dc magnetic bias H_{dc}, the corresponding piezomagnetic coeffcient can be calcuated by the differentiation of Eq. (1) with respect to H, given as

$$d_{33} = \frac{d\lambda}{dH} = \frac{3\lambda_s\mu_r^2}{M_s^2}H \tag{2}$$

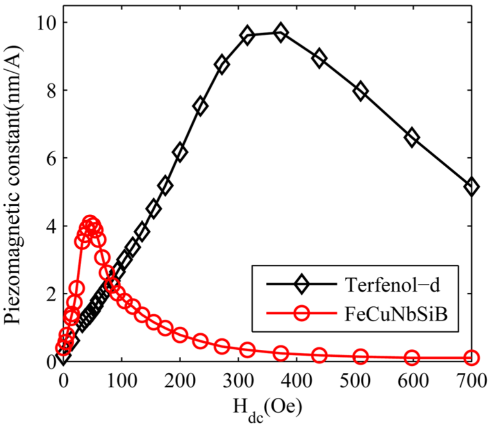

Fig. 4. (Color online) The effective piezomagnetic coefficients d_{33} as a function of H_{dc} for the FeCuNbSiB and Terfenol-D alloys.

From Eq. (2), the piezomagnetic coefficient d_{33} is directly proportional to the saturation magnetostriction and the square of the magnetic permeability. The saturation magnetostriction λ_s of Terfenol-D is 1000 ppm, which is far higher than the saturation magnetostriction of FeCuNbSiB ($\lambda_s = 2.7$ ppm). However, the giant magnetostrictive material Terfenol-D has a quite low relative magnetic permeability ($\mu_r < 10$) [5], correspondingly this results in a lower effective piezomagnetic coefficient at low H_{dc}. The extremely high relative magnetic permeability of FeCuNbSiB ($\mu_r < 100\ 000$ (f = 1 kHz)) dramatically reduces the saturation field, thus a high effective piezomagnetic coefficient d_{33} ($d\lambda/dH$) at low H_{dc} can be achieved.

Fig. 5 shows the resonant dynamic strain coefficients d as a function of H_{dc} for FeCuNbSiB and Terfenol-D. It is found that in the small dc magnetic bias range of $0 < H_{dc} < 200$ Oe, the effective dynamic strain coefficient d of

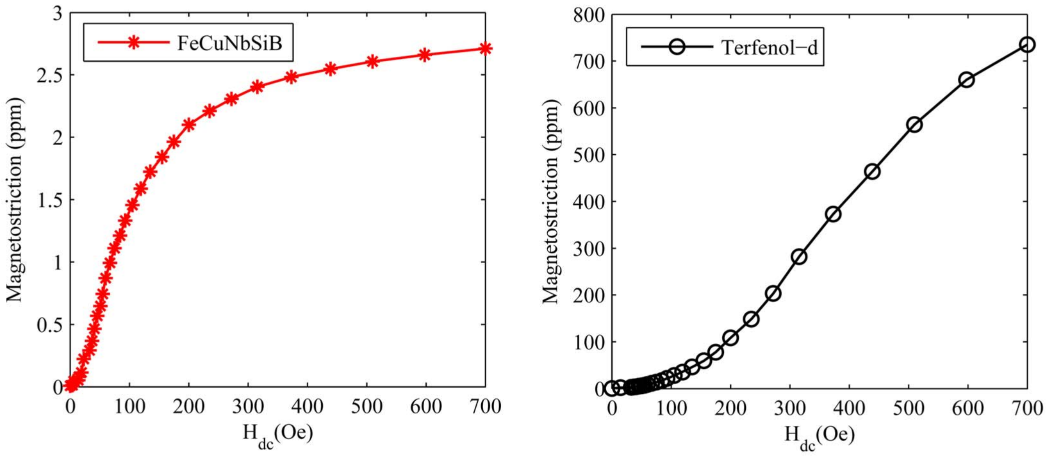

Fig. 3. (Color online) The longitudinal magnetostrictions as a function of H_{dc} for the FeCuNbSiB and Terfenol-D alloys.

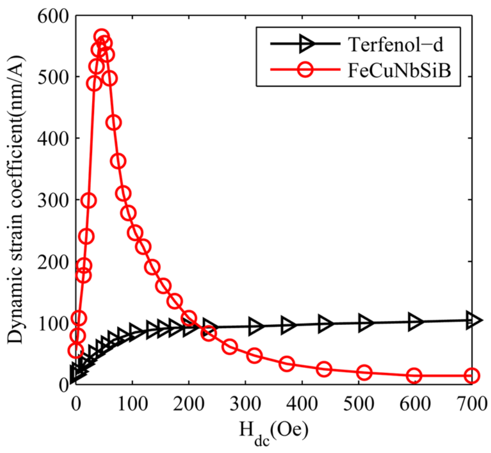

Fig. 5. (Color online) The dynamic strain coefficients d as a function of H_{dc} for the FeCuNbSiB and Terfenol-D alloys.

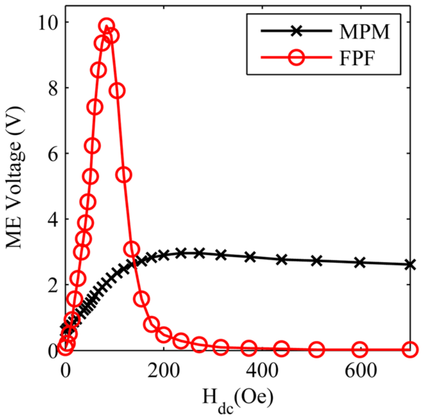

Fig. 6. (Color online) Resonant ME voltages of the MPM transducer and the FPF transducer responding to dc magnetic bias H$_{dc}$ under an ac magnetic field of 1 Oe amplitude.

FeCuNbSiB is about 3-5 times higher that of the Terfenol-D. In addition, the maximum value of d achieves ~108.05 nm/A under $H_{dc} = 700$ Oe for Terfenol-D; whereas the corresponding value for FeCuNbSiB is ~565.18 nm/A under $H_{dc} = 46$ Oe. The dynamic strain coefficient at resonance is notably high as the resonant dynamic strain coefficient is directly proportional to the effective mechanical quality factor, Q_m, of FeCuNbSiB, *i.e.*, $d \approx Q_m d_{33}$. In other words, the dynamic strain coefficient at resonance is magnified by a factor of Q_m, compared with the piezomagnetic coefficient. The mechanical quality factor of the FeCuNbSiB ($Q_m > 1000$) is far greater than that of Terfenol-D ($Q_m < 40$). Correspondingly, it is easy to understand that FeCuNbSiB exhibits a larger dynamic strain coefficient. This result also demonstrates the potential of FeCuNbSiB as a superior magnetostrictive material for ME transducers under low H_{dc}. In this manner, the ME transducer is fabricated by bonding the FeCuNbSiB and the PZT-8 together to obtain a high ME voltage coefficient (MEVC) and a high ME power output. For such a laminated ME transducer, based on the magneto-elasto-electric equivalent circuit method, the MEVC at resonance can be derived as [14].

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

where V_{ME} is the induced ME voltage across the thickness of the PZT-8 layer under the drive of H_{ac}, Q_m is the effective mechanical quality factor of the laminated ME transducer. From Eq. (3), the MEVC is directly proportional to the product of the effective piezomagnetic coefficient and the mechanical quality factor. Therefore, the MEVC at resonance is expected to be very high due to the high dynamic strain coefficient of FeCuNbSiB.

The resonant ME voltages as a function of H_{dc} for the Terfenol-D/PZT-8/Terfenol-D (MPM) transducer and the FeCuNbSiB/PZT-8/FeCuNbSiB (FPF) transducer under an ac magnetic field of 1 Oe are shown in Fig. 6. This indicates that with the increase in the dc magnetic field, the ME voltage for the MPM transducer achieves a maximum of 2.97 V at $H_{dc} = 235$ Oe, then decreases slowly. In contrast, the ME voltage for the FPF transducer increases in an approximately linear manner with the increase in H_{dc} over the range $0 < H_{dc} < 84$ Oe and gradually approaches the maximum ME voltage of about 10 V. Such variation can be understood as a result of the strong relation between the ME effect and the magnetostriction strain of a magnetostrictive material. In addition, with a further increase in the magnetic field, the ME voltage of the FPF transducer decreases gradually and

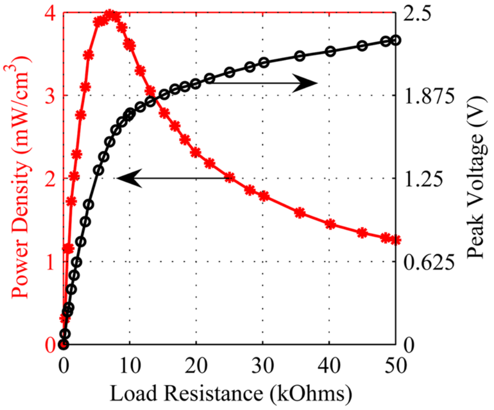

Fig. 7. (Color online) ME voltage and output power density as a function of load resistance of the FPF transducer operating at resonance.

falls to zero at a magnetic field of 316 Oe due to the magnetostriction saturation tendency at high magnetic field ($d\lambda/dH = 0$). The calculated maximum MEVC for FPF at resonance is 10 V/Oe (125 mV/cm Oe) at $H_{dc} = 84$ Oe, which is ~3.3 times higher than that of the MPM transducer (2.97 V/Oe at $H_{dc} = 235$ Oe) and ~3.77 times higher than that of the reported longitudinal-transverse mode Terfenol-D/$Pb(Mg_{1/3}Nb_{2/3})O_3$-$PbTiO_3$ laminate composites [15]. As mentioned previously, this is because the high magnetostriction strain of FeCuNbSiB leads to a large ME voltage coefficient. Obviously, this feature enables the FPF composite transducer to possess more highly efficient magneto-electric energy conversion ability around its resonance.

The ME output power density and ME voltage as a function of load resistance at resonance frequency are shown in the Fig. 7. Under an ac magnetic field of 0.4 Oe, the maximum ME voltage the transducer can achieve is 2.35 V. Correspondingly, the maximum output power is 331.8 μW at the optimum load resistance of 7 kΩ in this case, which is 50 times higher than that of ultrasonic-horn-substrate composite transducer of Terfenol-D and multiple PZT plates [16] and it decreases the size by nearly 86% compared with the latter. The ME power density is calculated by $P_d = P/V_{ol}$, where $V_{ol} = 0.835$ mm^3 is the volume of the FPF transducer. In this case, the corresponding ME output power density achieved is 3.98 mW/cm^3. This indicates that the FPF transducer is promising for highly efficient ME energy conversion and the fabrication of micro-transducers.

4. Conclusion

We investigate the dynamic magnetostriction characteristics of FeCuNbSiB alloy relative to the dc bias magnetic field (H_{dc}). And due to the high permeability and mechanical quality factors, FeCuNbSiB displays a significantly high dynamic strain coefficient at low dc magnetic biases compared with Terfeonl-D. In turn, the ME transducer made from FeCuNbSiB and piezoelectric PZT-8 demonstrates a strong ME coupling at resonance. The resonant MEVC achieves 10 V/Oe and the ME output power density reaches 3.98 mW/cm^3 under an ac magnetic field of 0.4 Oe. These properties are promising for ME energy conversion applications.

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