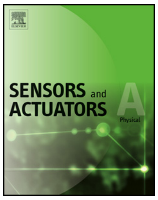
Sensors and Actuators A 214 (2014) 149–155

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

journal homepage: www.elsevier.com/locate/sna



Shear-mode self-biased magnetostrictive/piezoelectric laminate multiferroic heterostructures for magnetic field detecting and energy harvesting

Jitao Zhang, Ping Li*, Yumei Wen, Wei He, Aichao Yang, Caijiang Lu

Research Center of Sensors and Instruments, College of Optoelectronic Engineering, Chongqing University, Chongqing 400044, China

ARTICLE INFO

Article history:
Received 5 December 2013
Received in revised form 26 April 2014
Accepted 26 April 2014
Available online 2 May 2014

Keywords:
Self-biased magnetoelectric effect
Magnetostrictive/piezoelectric laminate composite
Multiferroic heterostructures
Magnetoelectric sensor
Energy harvesting

ABSTRACT

We report on a shear-mode off-antiresonance and antiresonance magnetoelectric (ME) responses in $Tb_{0.3}Dy_{0.7}Fe_{1.92}$/Pb(Zr, Ti)$O_3$/$SmFe_2$ laminate multiferroic heterostructures for magnetic detecting and energy scavenging without bias field. A negative shear force as well as large internal anisotropic field is provided by $SmFe_2$ plate due to its ferromagnetic and magnetostrictive properties, while the Terfenol-D plate provides a positive shear force to provoke a higher shear–stress transfer. Consequently, stronger ME coupling with a value of 2.24 V/Oe is obtained to be generated from the proposed architecture in the absence of the applied dc magnetic field. Experimental results exhibit an approximately linear sensitivity curve under off-antiresonance and antiresonance conditions, and the minimum stepped variations of input ac magnetic field as low as 2.43×10^{-8} T can be clearly distinguished under 111.5 kHz. In addition, a maximum power of 0.323 μW with a 2.6 MΩ load resistance in series connected to the ME laminate under the conditions of no bias can be achieved. These properties demonstrate that such a miniature multimode ME device is capable of weak magnetic field detecting and spatial magnetic energy scavenging by removing the requirement of dc bias field.

1. Introduction

Magnetoelectric (ME) coupling with the coexistence of two distinct phases (magnetostrictive and piezoelectric materials) presents valuable degree of freedom for their promising applications, such as magnetic sensors [1–3], energy harvesters [4,5], current sensors [6], microwave antiresonance devices [7] and magnetoelectric random access memories [8]. Intrinsic ME effects are initially found in single-phase ME compounds (e.g., Cr_2O_3 and $BiFeO_3$), but the low Curie temperature and weak ME coupling restrict their applications at room temperature [9]. Over the last decades, the investigation of ME effects has focused on bulk laminates and thin films in various operational modes with different polarized/magnetized directions [10,11], and the maximum ME voltage coefficient of 737 V/cm·Oe has been reported in composite of $(Fe_{90}Co_{10})_{78}Si_{12}B_{10}$/AlN at its antiresonance conditions up to now [12]. It is established that the maximum ME coupling is achieved under its antiresonance frequency [13]. Therefore, the enhancement of ME voltage in antiresonance conditions can be used as magnetic field sensing (or energy harvesting) which requires higher sensitivity (or higher efficiency), but this advantage can be obtained only in the benefit of an applied external magnetic field with typical value of ~400 Oe [14], the requirement of external magnets may occupy additional space and interfere with neighboring sensors. In view of this, subsequent attempts have been performed through various methods to decrease the required bias field while keeping the optimum performances of the ME laminates [15–18]. Recently, Mandal et al. first presented a self-biased ME heterostructure in composite of compositionally stepped ferrites and piezoelectric plates, this technique opens a new perspective about the ME coupling without the permanent magnets [16]. Yang et al. realized the self-biased ME effects in a bending mode trilayer laminate of NKNLS-NZF/Ni/NKNLS-NZF by changing the electrical connections [17,18]. Taking advantage of the presence of two (or more) magnetostrictive phases with difference in magnetic susceptibilities and coercivity, the realization of self-biased ME composites with various materials have been reported by several research groups [19–22]. In order to avoid the occurrence of atomic interfacial inter-diffusion and thermal expansion in multilayer magnetostrictive phases, the self-biased ME effects in homogeneous ME composites operating in *L-T* mode are realized [23–26]. For example, at the co-fired temperature of 930 °C,

---

* Corresponding author. Tel.: +86 23 65105517; fax: +86 23 65105517.
E-mail addresses: liping@cqu.edu.cn, pingli@ucla.edu (P. Li).

http://dx.doi.org/10.1016/j.sna.2014.04.037

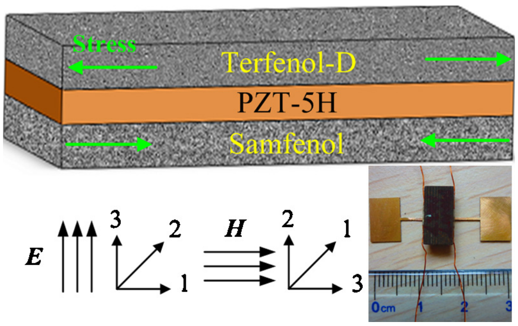


Fig. 1. Schematic diagram and photograph of the proposed ME transducer.

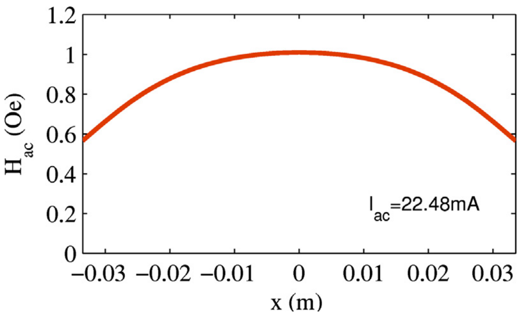


Fig. 2. Magnetic field distribution of the solenoid.

the realization of maximum ME coupling at zero bias in NCZF/PMN-PT laminate is documented by Yan et al. [27] Apart from magnetic field detecting, the ME composites and the ME cantilevers have been attempted to use in the field of vibration energy harvesting [28–31]. Specifically, in the semiring-type or ring-type ME transducers, the bias field is difficult to be superimposed due to their compact designs [32]. However, the permanent magnets are indispensable in these schemes to provoke the optimum performances of the ME laminates, which will dramatically increase the size and decrease the signal-to-noise ratio. Therefore, the magnets can be removed if the key transducer component is replaced by the self-biased ME laminates for magnetic sensing and energy harvesting in practical applications.

In this study, we present a self-biased trilayer ME laminate heterostructure consisting of positive/negative giant magnetostrictive materials (GMMs) and piezoelectric ceramics for magnetic-sensing and energy-harvesting applications. Strong magnetoelectric couplings are obtained to be generated from the proposed structure just under the applied ac magnetic field. Large remnant magnetostriction is provided by the negative giant magnetostrictive material $SmFe_2$ due to its large intrinsic anisotropic field, and the $SmFe_2$ plate also provides the negative strain with piezoelectric plate. In order to acquire a higher shear–stress transfer, Terfenol-D plate is attached the other side of the piezoelectric plate to generate a positive strain. Consequently, compared with the previously reported architectures, the proposed shear-mode ME laminate exhibits a higher non-zero ME voltage and a maximum power under load resistance without bias.

2. Experiment and analysis

The device prototype is a trilayer ME laminate composed of piezoelectric ceramic PZT-5H plates, positive/negative GMMs Terfenol-D ($Tb_{0.3}Dy_{0.7}Fe_{1.92}$) plates and Samfenol ($SmFe_2$) plates, and its schematic diagram and photograph are illustrated in Fig. 1. The positive GMM Terfenol-D plate (Gansu Tianxing Rare earth Functional Materials Co., Ltd., China) exhibits a large saturation magnetostriction ~1600 ppm with its easy-magnetized crystallographic axis [1 1 0] along the longitudinal direction. The negative GMM Samfenol with compositions of $SmFe_2$ (Baotou Research Institute of Rare Earths, China) has a giant negative saturation magnetostrictive coefficient ($\lambda_s \approx -1258$ ppm at 300 K) with its easy-magnetized crystallographic axis [1 1 1] along the longitudinal direction, and the positive/negative GMM plates all have dimensions of 12 mm × 6 mm × 1 mm. The piezoelectric ceramic PZT-5H plate (Zibo Bailing Functional Ceramic Co., Ltd, China) with dimensions of 12 mm × 6 mm × 0.8 mm is selected as the piezoelectric phase due to its large shear-mode piezoelectric constant ($d_{15} = 741$ pC/N). $SmFe_2$ plate plays two key roles in this composite: (i) it serves as piezomagnetic phase providing a negative shear force; (ii) it can provide an internal field to bias the ME composite due to its ferromagnetism with obvious hysteresis and large remnant magnetostriction oriented the direction [1 1 1] of easy-magnetization axis. To fabricate the sample of the proposed trilayer laminates, the GMM plates are dipped into acetone to remove the surface oxidation layer at first, and then the sample is bonded together with GMMs and PZT-5H plate by epoxy adhesive. Finally, the sample is cured at 80 °C for 4 h under load to provide a strong bond between layers. A rectangular copper stick with dimensions of 13 mm × 0.5 mm × 0.2 mm is fabricated as the mechanical anchor for simply supported boundary of middle clamping, and the ME sample with symmetrically attached the mechanical anchor is located in the middle of a solenoid. The solenoid coil (length $L = 6.7$ cm, radius $R = 2.05$ cm) with 245 turns is excited by a signal generator (Tektronix Model AFG3021B) with peak-to-peak current of 22.48 mA to generate an ac field H_{ac} with amplitude of 1 Oe, and its magnetic field distribution at random position within the length ($|x| < 3.35$ cm) is illustrated in Fig. 2. We can see that the value of the magnetic field in the region $|x| < 12$ mm is nearly uniform and approximately equal to 1 Oe, and reliable results are achieved in the benefit of this generated uniform magnetic field. A pair of disk-type NdFeB permanent magnets (commercial brand N50) is used to provide the dc magnetic field. Induced ME voltage is filtered first by using a low-noise preamplifier (Stanford Model SR560) before being sent to the data acquisition board (National Instruments Model PCI-6115) which uses LabVIEW VI programs. Magnetic properties of the magnetostrictive layer are measured by using a vibrating sample magnetometer (Lake Shore Cryotronics Model VSM 7410).

Due to the existence of distinct remnant magnetization in $SmFe_2$ plates, the dynamic behavior of the plate can be described by remnant piezomagnetic effects, and the remnant piezomagnetic coefficients ($d_{33,m}$) can be assumed to be constant [26]. Therefore, for modeling the presented ME device, which can be simplified as an in-plane, two-dimensional object with the assuming that the length much larger than its thickness. The polarization (P) and magnetization (M) directions are assigned to 1-direction and 3-direction of the coordinate system, and the piezomagnetic and piezoelectric constitutive equations are expressed as [33,34]

$$S_{3,m} = s_{33}^{H} T_{3,m} + d_{33,m} H_3, \tag{1a}$$

$$B_3 = d_{33,m} T_{3,m} + \mu_{33}^{T} H_3, \tag{1b}$$

$$S_{5,p} = s_{55}^{D} T_{5,p} + g_{15,p} D_1, \tag{2a}$$

$$E_1 = -g_{15,p} T_{5,p} + \beta_{11}^{T} D_1, \tag{2b}$$

where H_3 and B_3 are the applied magnetic field strength and magnetic induction along the length direction, respectively; $S_{3,m}$ and $T_{3,m}$ are the strain and stress along the length direction of the magnetostrictive plate, respectively; $d_{33,m}$ and μ_{33}^{T} are the elastic compliance coefficient at constant magnetic field strength, piezomagnetic coefficient, and magnetic permeability at constant stress, respectively. E_1 and D_1 are