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High sensitive nonlinear modulation magnetoelectric magnetic sensors with a magnetostrictive metglas structure based on bell-shaped geometry

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ABSTRACT

In this paper both linear and nonlinear magnetoelectric (ME) effects have been investigated intensively. In order to obtain magnetic amplification, we fabricated 3 multi-push–pull mode magnetoelectric laminated composites metglas/PMNT/metglas based on dumbbell-shaped metglas. The linear magnetoelectric charge coefficient is enhanced to 2600 pC/Oe at 2 Hz based on dumbbell-shaped metglas and it increases as the end-flange width of the dumbbell-shaped metglas increases at 2 Hz, respectively. Based on these 3 ME composites, we establish an active mode nonlinear modulation system for ME magnetic sensor, the sensitivity of which are enhanced to 80, 100 and 102 pT/$\sqrt{\text{Hz}}$ at 1 Hz for the composites with the end-flange width 20, 15 and 10 mm, respectively, via nonlinear ME modulation method. Strain distribution simulations illustrate the theoretically accurate amplification of the dumbbell-shaped geometry. The center strains of 3 dumbbell-shaped metglas decrease as the width of end-flanges decreases

1. Introduction

In recent years, the magnetoelectric (ME) effect has attracted increasing interest from the viewpoint of the physics underlying the coupling between ferromagnetic and ferroelectric orders, as well as the potential for applications in novel multifunctional devices [1,2]. Although the ME effect was first observed in single phase material (e.g., Cr_2O_3), the laminated composites consisting of the magnetostrictive layer (e.g., Terfenol-D and Metglas) and the piezoelectric layer [e.g., $Pb(ZrTi)O_3$ (PZT) and $xPb(Mg_{1/3}Nb_{2/3})O_3$-$(1-x)PbTiO_3$ (PMNT)] have attracted much attention due to the strong coupling effect between the magnetostrictive phase and the piezoelectric phase, which derive large ME coupling effect at room temperature, especially in laminated structure composites, and have great potential to be applied as high sensitive magnetic sensors, electrical current sensors, etc. [3–7]. Therefore, ME effect is a product effect of magnetostrictive and piezoelectric effect, as well as a product effect of a coupling effect of magnetism, elasticity and electricity, in which elasticity acts as a bridge [8].

Working as magnetic sensors, ME composites have been investigated for nearly 20 years and a great improvement has been achieved, in which magnetic sensitivity based on linear ME effect has been improved about several orders of magnitudes [9]. Meanwhile, plenty of new kinds of magnetostrictive materials (e.g., Gafenol and metglas) and piezoelectric materials [PMNT and $(1-x-y)Pb(In_{1/2}Nb_{1/2})O_3$–$yPb(Mg_{1/3}Nb_{2/3})O_3$–$xPbTiO_3$ (PIMNT) etc.] have been used in ME composites, while many new kinds of ME structures have been designed simultaneously, such as longitude–transverse (L–T) laminated structure and multi-push-pull structure based on magnetostrictive material Terfenol-D or metglas [10–12]. New kinds of piezoelectric and magnetostrictive materials and structures make ME coefficients improved tremendously [13–16]. Based on a cantilever structure, Liu et al. have obtained a giant ME electric field coefficient of about 16,000 V/(cm Oe)at the resonant frequency of 5 Hz, using a multi-push–pull core epoxied to the bonding side [17]. A multi-push–pull mode ME composite consisting of PMNT and metglas, fabricated by Wang et al., exhibits an ultrahigh magnetoelectric charge coefficient (2680 pC/Oe), ultralow loss (0.8%) and capacitance (340 pF) at quasi-static frequency range. The parameters result in very low theoretical equivalent magnetic noise to 4.2 pT/$\sqrt{\text{Hz}}$ and an experimental equivalent magnetic noise to 5.1 pT/$\sqrt{\text{Hz}}$ at 1 Hz [18]. Li et al. obtained a ME coefficient as high as 3756 pC/Oe at 1020 Hz based on multi-push–pull structure, using high curie temperature relaxor ferroelectric single crystal PIMNT [19]. Many novel structures have also been investigated to enhance the ME response. A magnetostrictive metglas shaped in a dumbbell-shaped geometry

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was proposed by Wang et al. to improve the linear ME coefficients [20]. However, Wang et al. only investigated linear magnetoelectricity of the ME structure based on dumbbell-shaped metglas. If the structure is used in nonlinear magnetoelectricity and nonlinear ME magnetic sensor, a larger ME amplification will be obtained, which will be discussed in this paper.

So far, extensive effort has been made to improve the properties of linear ME effect, but there still exist some obstacles for this kind of magnetic sensors to detect weak quasi-static or DC magnetic signal [21]. In fact, passive mode can hardly be utilized to measure DC magnetic field because it can only response to AC magnetic field. Even the passive ME magnetic sensors are subjected to quasi-static magnetic signal, such as 1 Hz or below, its detectivity declines sharply because of the low frequency ambient mechanical vibration, electromagnetic perturbation and thermal noise [22]. Each of above reasons hinders passive ME sensors developing tremendously. In fact, ME effect is a nonlinear effect and its working optimal magnetic field bias is close to 0 [21,23]. In ME effect, electric response is related to not only one-order magnetic signal, but also high-order magnetic signals, such as 2-order magnetic signals [24]. Frequency modulation, in which low frequency signal is transferred to high frequency modulation signal to shield low frequency electromagnetic and mechanic perturbation, was introduced in active mode ME magnetic sensor to detect quasi-static and DC weak magnetic field via nonlinear ME effect. Since the introduction of frequency modulation method in magnetoelectric magnetic sensor, several years has been spent in improving the detectivity of DC and quasi-static weak magnetic field. Zhuang et al. obtained a high sensitivity, as high as 70pT/$\sqrt{\text{Hz}}$ at 1 Hz, via a piezoelectric-to-piezoelectric modulation method [22]. Liu et al. fabricated excellent nonlinear ME sensors, sensitivities of which at 10 mHz, 100 mHz, and 1 Hz could as low as be 200, 150, and 20 pT, respectively [25]. Huong Giang et al. even used nonlinear modulation to prepare a geosensors with a resolution in the order of 10^{-4} Oe without amplification, making ME laminates configuration a potential sensor for applications in novel smart compasses and global positioning devices [26].

2. Nonlinear magnetoelectric effect and magnetic flux concentration effect

In this paper, based on magnetic flux concentration effect, we have designed the magnetostrictive material metglas into a dumbbell shape to obtain magnetic amplification to enhance the ME nonlinearity and to improve sensitivity of active mode ME magnetic sensor. In ME effect, linear ME charge coefficient can be expressed as

$$\alpha_Q = \frac{dQ}{dH_{AC}} \tag{1}$$

If magnetic flux concentration is considered, the magnetic induction will be higher in the center of the metglas than that in the end-flange of the metglas, and the H'_{AC} is not the original H_{AC} generated by coils. It is obvious that the H'_{AC} is larger than H_{AC}. We can introduce an amplification factor β, a function of the geometry of metglas. Then let $H'_{AC} = \beta H_{AC}$. Therefore,

$$\alpha'_Q = \frac{dQ}{dH_{AC}} = \frac{\beta dQ}{dH'_{AC}} = \beta\alpha_Q \tag{2}$$

And the 2-order ME charge coefficient can be expressed as,

$$\alpha_Q^{non} = \frac{d\alpha_Q}{dH_{AC}} \tag{3}$$

Therefore, when the amplification factor β is taken into consideration, the α'^{non}_Q in dumbbell-shaped metglas will be,

$$\alpha'^{non}_Q = \beta^2\alpha_Q^{non} \tag{4}$$

We designed a dumbbell shape geometry for magnetostrictive phase to utilize the magnetic flux concentration effect, which made $\beta>1$. β of dumbbell-shaped metglas was larger than that of the rectangular one, making the nonlinear ME property enhanced and sensitivity of the modulated nonlinear ME magnetic sensor higher evidently [27].

3. Experiments and results

The proposed ME laminated composite was composed of dumbbell-shaped mono-layer metglas and piezoelectric core composite consisting of five PMNT fibers (Shanghai Institute of Ceramics, Shanghai, China), each with dimensions of $40 \times 2 \times 0.2$ mm^3, interrogated by a pair of Kapton interdigitated (ID) electrodes. The Kapton films were attached to both the top and bottom surface of the PMNT fibers, using an epoxy resin to obtain a multi-push–pull geometry, as shown in Fig. 1(a) and (b). The ID electrodes were 0.5 mm in width, and the center-to-center

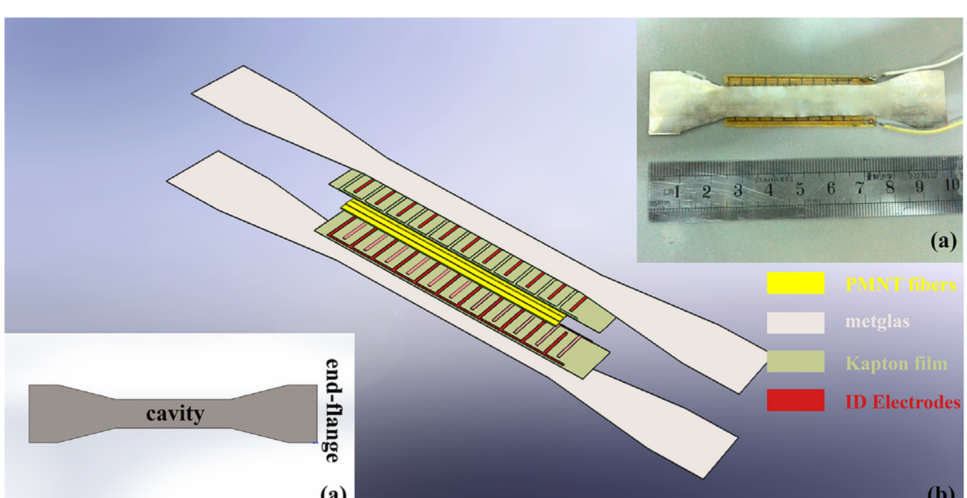

Fig. 1. (a) and (b) show the photograph and the schematic of the multi-push–pull ME laminated composite based on dumbbell-shaped metglas, respectively; (c) shows the schematic of the dumbbell-shaped metglas.