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Research Article

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Magneto-Mechano-Electric (MME) Energy Harvesting Properties of Piezoelectric Macro-fiber Composite/Ni Magnetoelectric Generator

Abstract: Asymmetric and symmetric magnetoelectric (ME) laminates structures of piezoelectric macro-fiber composite (MFC)/nickel (Ni) were fabricated and investigated their ME and magneto-mechano-electric (MME) energy harvesting responses to an applied magnetic/mechanical stimulations. Both the structures strongly revealed the dependence of ME voltage coefficient (α_{ME}) on applied magnetic field directions with an important feature of a zero-bias field ME response. This is much more beneficial for designing the magnetic field sensors. The fabricated MFC/Ni structures exhibited good energy harvesting response to applied simultaneous magnetic/mechanical vibrations of lab magnetic stirrer. The electric power was successfully harnessed from magneto-mechanical stimulations; the resulting potential and power were up to ~20 V_{p-p} and ~6 μW respectively, which are quite enough power to light a commercial red LED with traditional rectifier circuit and capacitor. Hence, the present MFC/Ni ME generators provide their future feasibility having self-biasing feature for designing the magnetic field sensors as well as for powering small consumer electronic devices and wireless sensor network systems by exploiting mechanical/magnetic stimulations from surrounding.

Introduction

Magnetoelectric (ME) laminate/layered constituents are the present and next generations favorable candidates for magnetic field sensors, gyrators and energy harvesters due to its effective giant ME response and multifunctional behavior than single phase and particulate composite structures, hence gained certain attention for the researchers of ME society today (Nan et al. 2008; Zhai et al. 2008; Liverts et al. 2011). Recently, ME materials have successfully proved their efficiency for generating the power to an applied magnetic/mechanical stimulations with high output voltage characteristics (Kambale et al. 2013; Zhou, Apo, and Priya 2013; Ju et al. 2013). In such piezoelectric/magnetostrictive coupled systems, the stress/strain transfer between the two phases plays a vital role during the ME interaction as well as energy harvesting performance, which is significantly affected by the structure of the composite. Thus, ME effect is a *magneto-elasto-electric* effect (Yang et al. 2010; Kambale, Jeong, and Ryu 2012).

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The strength of the ME effect is determined by the product of piezoelectric (d_{ij})/piezomagnetic ($q_{ij} = d\lambda_{ij}/dH$, $\lambda_{ij} \sim$ magnetostriction strain) coefficients. To achieve the inducible ME voltage coefficient (α_{ME}), as magnetostriction strain is generally too small at around zero magnetic field, external magnetic *dc* bias should be applied to invoke large piezomagnetic response (Dong et al. 2006). Therefore, to implement the ME materials in realistic applications, the need of an external magnetic bias seems to be a significant disadvantageous, which hinders their practical operation on thick or thin film platform as well as increases the device size with an electromagnet interference. But recently some research groups were succeeding to achieve good ME response at zero magnetic *dc* bias i.e., self-biased ME materials using Ni plate (Yang et al. 2010; Zhou et al. 2012; Li et al. 2013).

Dong et al. and others provided the systematic investigation and theoretical approach for the effective ME coupling modes and effect of demagnetization factor (reduction of the magnetic field within the magnetostrictive layer) on the magnitude of α_{ME} (Liverts et al. 2011; Dong, Li, and Viehland 2004; Cui and Dong, 2011). Among the different operational modes of ME measurement, the L-T (longitudinally magnetized-transversely polarized) mode is very easy to fabricate and yield 5–7 times higher ME output than T-T (transversely magnetized-transversely polarized) mode (Zhai et al. 2008; Dong, Li, and Viehland 2004). Therefore, it is indispensable to design ME structures with self-biasing feature having specific coupling mode of operation (*magnetic field direction*) to reveal better ME response at low frequency (~100 Hz); can be further implemented for magnetic field sensor devices as well as for energy harvesting purpose to generate the power.

Here, ME laminate structures with asymmetric (bilayer) and symmetric (trilayer) modes were designed by incorporating piezoelectric macro-fiber composite (MFC) as a piezoelectric layer and Ni as a magnetostrictive layer and investigated their ME responses with different magnetic field directions. How an effective magnetic field direction as well as demagnetization factor affects the ME response along with specific structure design for magnetic field and energy harvesting purpose is discussed in this article. Furthermore, the ability of designed ME laminates for inducing power to an applied magneto-mechanical vibrations was tested on laboratory magnetic stirrer. We believe that in future this approach is intriguing for designing ME magnetic field sensors and energy harvesters to yield maximum power density in response to magnetic/mechanical stray vibrations.

Experimental details

Asymmetric, the bilayer of Ni/MFC, and symmetric, the trilayer of Ni/MFC/Ni, ME laminates were fabricated by using a MFC-PZT 5A piezoelectric fibers operating in d_{31} mode (Model: M2814-P2, Smart Materials, Dresden, Germany) and Ni plate (99.9%, thickness ~ 0.25 mm, Alfa Aesar, Ward Hill, MA). The Ni plates having dimension of $30^{\mathrm{L}} \times 17^{\mathrm{W}} \times 0.25^{\mathrm{T}}$ mm^3 were bonded on the active surfaces of the MFC layer using 3M™ Scotch-Weld™ Epoxy Adhesive DP-460 EG. The MFC/Ni laminate assembly was cured at 60°C for overnight. The schematic representation of the designed ME laminates is shown in Figure 1(a–c). The magnetostriction coefficient (λ_{ij}) measurement of the Ni plate was carried out by performing standard strain gauge technique. A strain gauge of 350 Ω (FLA-5-350-1LS, Tokyo Sokki Kenkyujo Co. Ltd.) was used for the magnetostriction measurement. The gauge was glued to the Ni plate with an M-Bond 200 adhesive and the magnetostriction measurements were carried out along the *in-plane (length)* and *out-plane (width)* direction as shown in Figure 1(d). The saturated in-plane λ_{11} is found to be negative with a magnitude of −40 ppm, whereas the out-plane λ_{12} is found to be positive with a magnitude of +20 ppm. Thus, $|\lambda_{12}| \sim 0.5|\lambda_{11}|$, the observed results are in well agreement with the reported one (Sreenivasulu et al. 2011). This behavior is mainly ascribed to the contraction–expansion phenomenon of the Ni plate to an applied magnetic field.

The value of α_{ME} was measured using a lock-in amplifier (SR-850, Stanford Research Systems, Inc., Sunnyvale, CA) in response to a pair of Helmholtz coils driven at an *ac* magnetic field of $H_{ac} \sim 0.5$ Oe at a frequency of $f \sim 1$ Hz and 1 kHz (off resonance). A *dc* magnetic field was applied by a large electromagnet driven by lock-in amplifier in anticlockwise direction sweep (high field > low field > high field). The ME coefficient was calculated based on, $\alpha_{\mathrm{ME}} = \delta V/(t_p\text{-MFC} \cdot \delta H)$. Where tp-MFC is thickness of MFC. The α_{ME} measurements were performed along length (direction 1), width (direction 2) and thickness (direction 3) directions of the structures (inset Figure 2). The feasibility of energy harvesting response from MFC-Ni laminates was partially tested using stray magnetic vibrations by shaking (up and down) the permanent bar-shaped Nd magnet ($H \sim 200$ Oe) around the structures. The induced output voltage from MFC-Ni structures was monitored by a digital oscilloscope with internal impedance of 1 MΩ. Further by using laboratory magnetic stirrer, we tested the magneto-mechano-electric (MME) energy harvesting response from the MFC-Ni structures, recorded the induced voltage

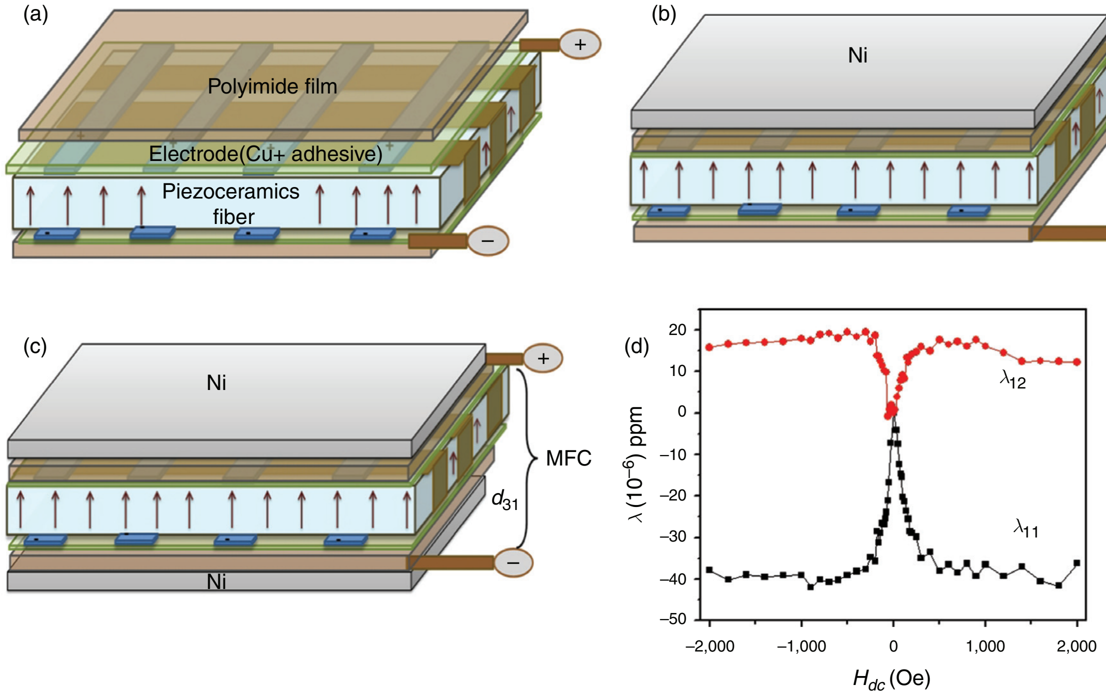

Figure 1 Schematics of (a) Transverse "d_{31}" Macro-fiber composite, (b) Asymmetric MFC/Ni laminate structure, (c) Symmetric Ni/MFC/Ni laminate structure, and (d) Magnetic field dependence of magnetostriction (λ_{ij}) for Ni

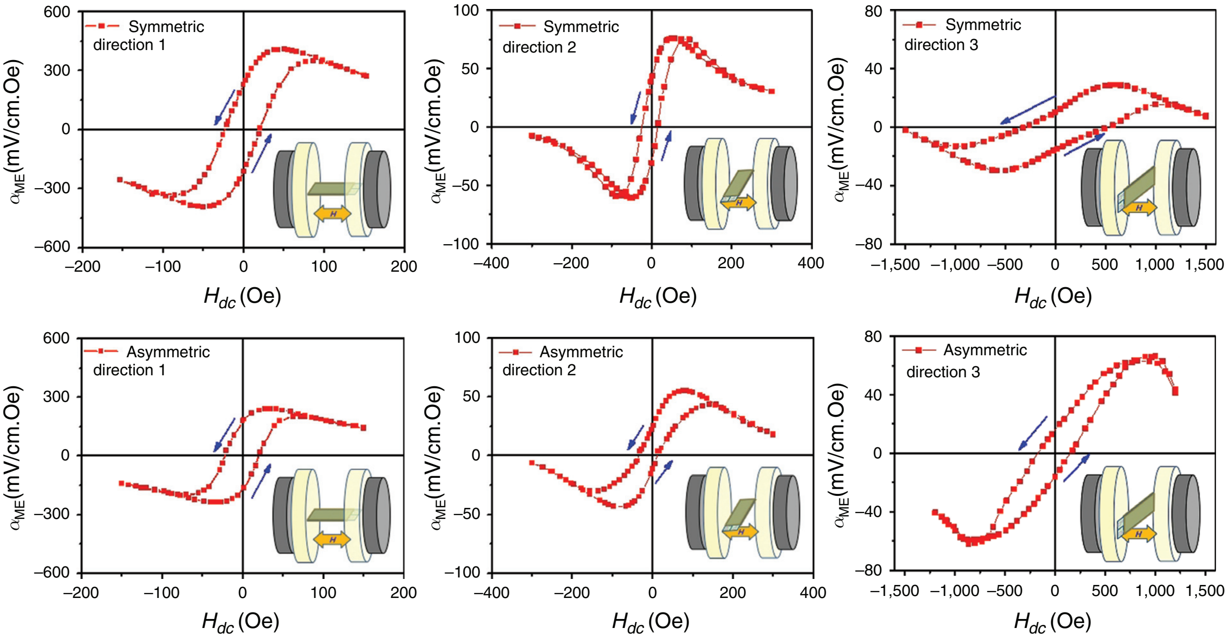

Figure 2 Magnetoelectric response (α_{ME}) of symmetric and asymmetric Ni/MFC laminate structure as a function of H_{dc} @ 1 kHz

across the structures due to summation effect of magnetic/mechanical stimulations. The stirring speed (approximately 50 ~ 60 Hz) was adjusted to show maximum open-circuit voltage from the samples. It could be assumed that at the stirring speed mechanical resonance of the samples were achieved. The output voltage from the structure is then passed to rectifier circuit, which is composed of 4 diodes in the form of a full bridge. After rectifying, the output power flows through a regulation circuit, including a charging capacitor of 10 μF (350 V) and load resistances. Various load resistances were used in order to characterize the performances of the device. The powers (P) under different load resistances R_L were calculated using the formula $P = V^2/R_L$, where V is the output *dc* voltage.

Results and discussion

As MFC is a piezoelectric fiber plate has inbuilt ability to generate the electric voltage/power to an applied mechanical vibrations. It is known that MFC is very attractive for low-frequency vibration energy harvesting application due to its flexibility. Alternatively, magnetostrictive materials also have high energy densities and magneto-mechanical coupling factors. Hence selection of a suitable piezoelectric/magnetostrictive material is an important factor for designing ME generators to produce high ME output voltages, as the strain in piezoelectric material can be maximized with the aid of magnetostrictive material. Therefore, when attaching the magnetostrictive Ni metal on the top of MFC, magnetic signal in addition to the mechanical vibration can be also converted as an electric power through ME coupling. The mechanism of direct ME coupling for magnetostrictive-piezoelectric structures is very much straightforward. An input magnetic field deforms the magnetostrictive layer generating the strain that is elastically coupled to piezoelectric ones, which subsequently transduces the applied stress to a voltage via piezoelectricity (Yang et al. 2010). Thus, magnetostrictive deformation of magnetostrictive layer is the cause for inducing the voltage in piezoelectric layer and vice versa. This magnetostrictive strain is anisotropic, dependent significantly upon the direction along which the magnetic field is applied. The proper structure design for magnetic field sensor and piezoelectric vibrational energy harvesting application along with affecting/useful factors, viz. demagnetization factor, effective operational magnetic field direction and self-biasing feature are discussed as follows.

ME interaction

Structures design and operation mode

The dependences of the α_{ME} on the bias field H_{dc} at $f = 1$ kHz and 1 Hz of H_{ac} for asymmetric (Ni/MFC) and symmetric (Ni/MFC/Ni) ME laminates with different operation modes are shown in Figures 2 and 3 respectively. The ME interactions for symmetric structures were found much stronger than the asymmetric structures, i.e. α_{ME} in an asymmetric structure is approximately half of that in a symmetric structure with same constituents. This result agrees with those from earlier experiments conducted by others (Zhang et al. 2007; Shi et al. 2013; Pan et al. 2009). Moreover, the ME interactions of both structures are found to be significantly dependent on the direction of applied magnetic bias. It is well-known that the ME coupling is directly proportional to the piezomagnetic coefficient, i.e. $q_{ij} = d\lambda_{ij}/dH$ not on the magnetostriction coefficient (λ_{ij}) value (Zhou, Apo, and Priya 2013). Aforementioned the magnetostriction coefficient (λ_{11}) measured along the length side (in-plane) of the Ni plate is twice than that of the magnetostriction coefficient (λ_{12}) measured along the width side (out-plane) of the Ni plate. Therefore, along in-plane, i.e. direction 1 the magnitude of α_{ME} is greater than that of out-plane directions 2 and 3.

Since asymmetric ME structure possesses the bending strains/flexural deformation associated with them in an applied magnetic field (Shi et al. 2013; Mandal et al. 2010; Petrov et al. 2009; Yang et al. 2009). Such flexural

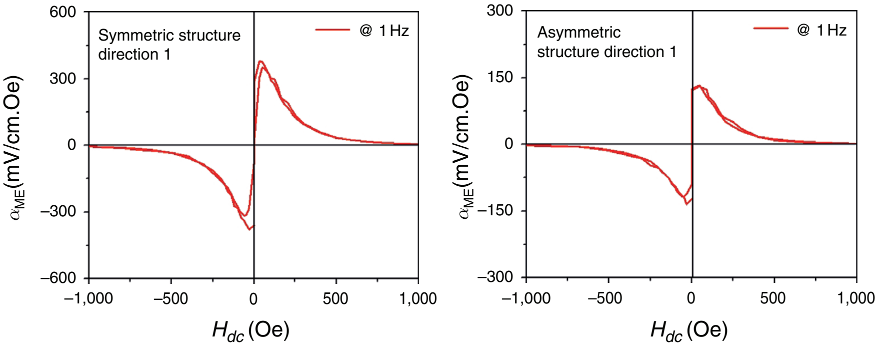

Figure 3 Low-frequency magnetoelectric response (α_{ME}) of asymmetric and symmetric Ni/MFC laminate structure as a function of H_{dc} @ 1 Hz

deformations mainly arise from the differences in elastic stiffness/Young's modulus of the piezoelectric MFC and magnetostrictive/magnetic phases, Ni of the ME constituents which leads to the distortions of the piezoelectric layer and hence reduces the strength of ME interactions (Yang et al. 2009). Because, for present bilayer structure, the magnetostrictive extension of the Ni induces not only the uniform elongation along the direction of the applied magnetic field but also a flexural deformation due to asymmetric stress mismatch as like well-known occurrence of bending in thermo bimetals; therefore, the flexural deformation resulting from the magnetostrictive strain mismatch significantly weakens the contribution of the extensional deformation in the asymmetric ME composite, resulting in a reduction of ME coefficient. Also, it should be considered that an asymmetric structure comprises inseparable vibrational bending noise as well as the signal bending having no vibration noise cancellation ability (Xing et al. 2009). Consequently, the associated flexural deformation and noises weakened the ME effect of present asymmetric MFC-Ni laminate. Instead, the bending strains (flexural deformation) are absent in symmetric structures lead to the reduction of the in-plane strain and maximize the out-of-plane strain (Mandal et al. 2010). In addition, symmetric configuration has a built-in ability to cancel vibrations in the bending mode (Xing et al. 2009). As a result, for Ni-MFC-Ni symmetric structure the induced surface strains on top and bottom surface of Ni plates are equal and in opposite directions, therefore the inner MFC layer constrains the extensional deformation of the two Ni layers equally and cancels the bending mode vibrations.

For a given shape/size of the magnetostrictive material, there is a principal magnetostrictive direction is allied along the maximum dimension direction of the structure called as magnetostrictive strain mode with maximum magnetostrictive strain (Pan et al. 2009). Thus, for rectangular plate geometry, the entire dimension changes (strains) due to the magnetostrictive effect are larger in the plane of the plate (when the magnetic field is applied in the longitudinal direction) than in the transverse out-of-plane (width and thickness) direction, since the in-plane dimension is larger. Therefore, for the magnetostrictive layer plate geometry, the longitudinal in-plane line magnetostriction will be much higher than the out-plane transverse one, so the maximum of α_{ME} is larger and the corresponding *dc* magnetic field is lower and according shifts toward the higher field (Pan et al. 2009). Similar results were observed in the present work. Apart from this it should be also noted that the present ME structures comprise the piezoelectric fibers, i.e. MFC; the interdigitated electrodes of MFC deliver the electric field required to activate piezoelectricity in fibers to invoke the stronger piezoelectric effect along the length (effective in-plane poling direction) of the fibers (Kovalovs, Barkanov, and Gluhihs 2007). Thus, the piezoelectric fiber effects which are much more effective along the length of the fibers should be considered for present structures though they are of d_{31} type.

Shape demagnetization effect

Demagnetization factor describes the reduction of the magnetic field within the magnetostrictive layer during operation; it seems to be strongly affect the magnetostrictive response of the magnetic phase of ME structure and hence affect the ME interaction. As seen from Figure 2, the observed values of α_{ME} for symmetric structure with directions 1 (length), 2 (width) and 3 (thickness) are 407, 76 and 29 mV/cm · Oe at 50, 75 and 650 Oe magnetic *dc* bias respectively. Also, for asymmetric structure the observed values of α_{ME} with directions 1, 2 and 3 are 241, 55 and 63 mV/cm · Oe at 30, 80 and 820 Oe magnetic *dc* bias respectively. Thus, the measured α_{ME} values for both asymmetric and symmetric structures are strongly found to be dependent on the direction of applied magnetic field, i.e. in-plane (along length) and out-plane (along width and thickness). The difference of such ME coupling response as well as magnetic *dc* bias of the samples with different in-plane and out-plane sizes originates from the shape demagnetization effect (Liverts et al. 2011; Cui and Dong, 2011; Pan et al. 2008). Relative to 1 and 2 directions, the thickness (3) direction did not saturate until $H_{dc} \sim 800$ Oe; this is due to the higher demagnetization factor associated along this direction.

Thus, α_{ME} depends on in-plane sizes due to shape demagnetization effect and is expressed as (Pan et al. 2008),

$$\alpha_{\mathrm{ME}} \propto (1+\beta)/N \qquad [1]$$

where $\beta \approx \sqrt{N_1/N_2}$ is the magnetostriction factor for a given shape magnetostrictive material, N (N_1 or N_2) is the demagnetization factors. The demagnetization factor along the length (L) is $N_1 \sim 2t/\pi L$, while along width (W) is $N_2 \sim 2t/\pi W$ at fixed thickness t is taken in the account. Thus, here the laminate structure is of rectangular shape and for which the $N_2 > N_{1;}$ eventually α_{ME} for direction 2 case is smaller than direction 1 (Aharoni et al. 1998). Large demagnetization will result in a weak effective magnetic induction in the magnetic phase and thus in turn it will result in a weak ME coupling (Dong and

Zhai, 2008). Thus, the present results for both Ni/MFC and Ni/MFC/Ni revealed the higher magnitude of α_{ME} for direction 1 operational mode than directions 2 and 3 mode due to small demagnetizing effect (strong magnetic flux) as well as effective in-plane piezoelectric properties of MFC.

Self-biased ME effect

Recently, self-biased ME effect defined as "remnant ME coefficient (α_{MER}) at zero H_{dc}" is one of the important topic of research for the potentiality of ME materials for magnetic field sensor as well as ME energy harvesting applications. ME effects at zero magnetic bias is interesting and it is experimentally proved by some research groups recently (Yang et al. 2010; Zhou et al. 2012; Li et al. 2013; Mandal et al. 2010). At present we also claim the self-biased ME effect for our designed asymmetric and symmetric Ni-MFC ME laminates. Careful observation of Figure 2 illustrates that at zero magnetic bias, there is some value of α_{ME}. Both the structures, i.e. Ni/MFC and Ni/MFC/Ni showed the hysteretic nature of α_{ME} during H_{dc} sweep (anticlockwise direction, high field > low field > high field) with a large magnitude of α_{ME}. This hysteretic nature is originated from Ni (Zhou et al. 2012). For symmetric structure, the observed values of α_{MER} along directions 1, 2 and 3 are 250 mV/cm · Oe (62% of its maximum α_{ME}), 44 mV/cm · Oe (59% of its maximum α_{ME}) and 10 mV/cm · Oe (34% of its maximum α_{ME}), respectively. On the other hand, for asymmetric structure the observed values of α_{MER} along directions 1, 2 and 3 are 178 mV/cm · Oe (74% of its maximum α_{ME}), 26 mV/cm · Oe (47% of its maximum α_{ME}) and 16 mV/cm · Oe (25% of its maximum α_{ME}), respectively. Thus, the MFC-Ni ME laminate system exhibited self-bias ME response revealed linear ME voltage coefficient dependence on the applied magnetic field, which makes them as a promising candidate for magnetic field sensor applications without *dc* magnets for the bias field.

ME harvester

Subsequently, the ME laminates comprise the piezoelectric/magnetostrictive phases are very much suitable candidates for vibrational-to-electricity power generators, i.e. energy harvester. Thus, the energy harvesting on which many researchers have an eye can consider the ME structures to harvest the power from additive magnetic/mechanical vibrations for various applications such as wireless sensor networks, environmental monitors and medical implants (Kambale et al. 2013; Zhou, Apo, and Priya 2013). Thus, the ME (piezoelectric/magnetostrictive) harvesters can generate power with additive sources like mechanical vibration and magnetic vibration and will enhance the power density as well as time efficiency of the harvesters.

The energy harvesting performance for the designed asymmetric (Ni/MFC) and symmetric (Ni/MFC/Ni) laminate structures was tested with surrounded stray magnetic vibration produced by shaking the permanent bar-shaped Nd magnet near the structures (up and down) in Figure 4(a). During measurements, the structures were completely attached to the supporting table with the tape; for asymmetric structure the measurements were carried out in both attached and suspended configurations. For the suspended configuration, one end side of the sample was clamped by Teflon fixture and the samples were like a cantilever. Figure 4(b) shows the induced signal (approximately) from the designed structures due to magnetic vibrations; conversely, it is observed that the asymmetric Ni/MFC structure exhibited high efficiency for generating the voltage (attached ~ 2–3 V, suspended ~ 12–14 V) across the MFC than symmetric Ni/MFC/Ni structure (attached ~ 0.2–0.4 V). Also Figure 3(b) reveals that when the magnet moves up and down near the structure then the corresponding induced voltage across changes its sign/magnitude. When magnetic magnet approaches toward the structure then negative voltage was observed, when magnet goes away from the structure then positive voltage was observed. This behavior can be assumed to spring/buckling effect generated by magnetic vibrations as well as by Ni plate on MFC layer. Thus, these results give a clear cut indication of effect of magnetic vibrations (ME coupling) on the induced voltage across MFC piezo fibers. Therefore, the present structures with self-biasing feature were further tested to explore their efficiency of MME energy harvesting to an applied simultaneous mechanical and magnetic vibrations on laboratory magnetic stirrer.

The energy harvesting response (induced open circuit voltage) of the designed asymmetric and symmetric MFC-Ni structures due to magneto-mechanical vibrations of magnetic stirrer as a function of time, peak $H \sim 200$ Oe is illustrated in Figure 5. It is observed that the asymmetric Ni/MFC structure exhibited high efficiency for generating the voltage (attached ~ 1.57 V, suspended ~ 4 V) across the MFC than symmetric Ni/MFC/Ni structure (attached ~ 0.7 V). These results are in good agreement with that of data represented in Figure 4(b). For this experiment, the frequency generated (mechanical vibrations) is assumed to be 50 ~ 60 Hz. Since the output was an *ac* signal, it has to be rectified to obtain a *dc* voltage for use as a power

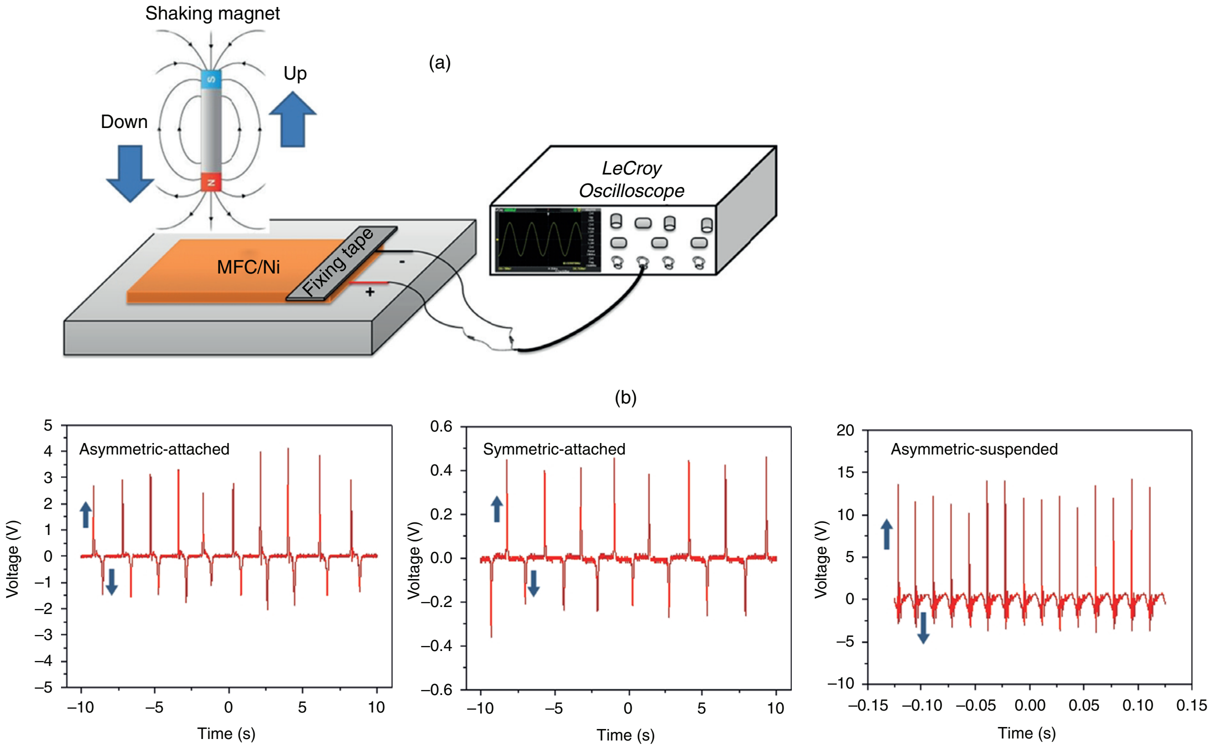

Figure 4 (a) Schematic showing the testing of the induced signal from the structure to stray magnetic vibrations produced by shaking the magnet around the structure. (b) Voltage induced by stray magnetic vibration across Ni/MFC asymmetric and symmetric structures as a function of time

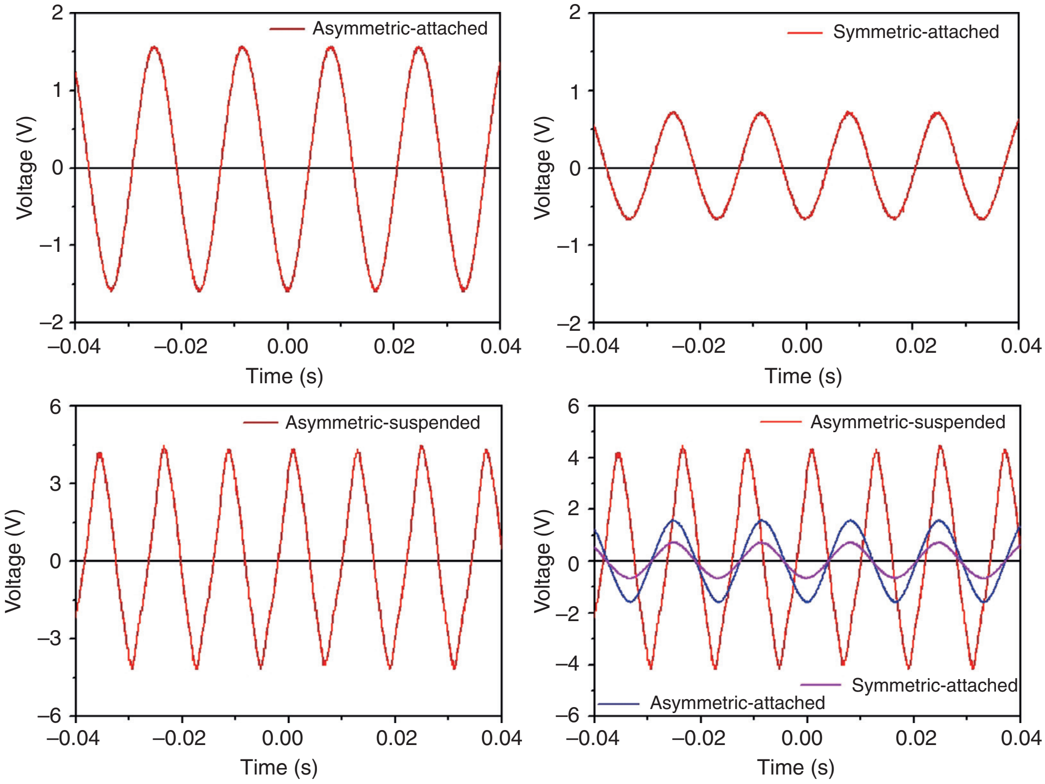

Figure 5 Open-circuit voltage induced due to mechanical and stray magnetic vibrations of magnetic stirrer across Ni/MFC asymmetric and symmetric structures as a function of time

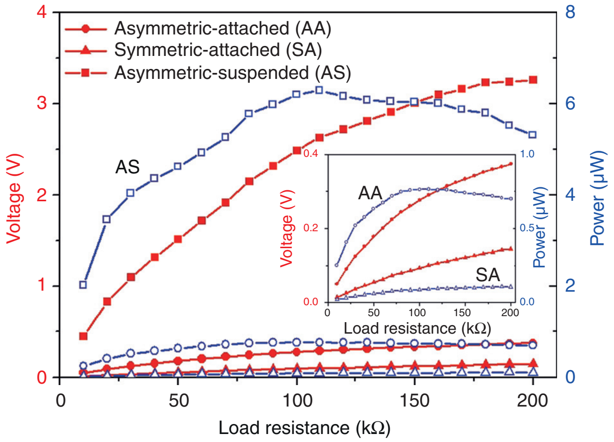

Figure 6 Measured rectified voltage and power induced due to mechanical and stray magnetic vibrations of magnetic stirrer across Ni/MFC asymmetric and symmetric structures as a function of time

source which can be used for a load or battery. The generated voltage and calculated power of the piezoelectric MFC fibers due to magneto-mechanical vibration is shown in Figure 6 as functions of various resistive loads. The asymmetric Ni/MFC structure exhibited high efficiency for generating the power (attached ~ 0.75 μW, suspended ~ 6.2 μW) across the MFC than symmetric Ni/MFC/Ni structure (attached ~ 0.1 μW). The output power is found to be various with resistive load and attains a maximum value at particular load resistance, i.e. its matching impedance of the piezoelectric MFC fibers.

The results of ME interactions and energy harvesting response of symmetric and asymmetric structure are opposite. ME interactions are already discussed, but the energy harvesting response of asymmetric MFC/Ni bilayer is two to three times more than that of trilayer Ni/MFC/Ni symmetric structure. This is what expected from the Ni/MFC structure as the flexural strain (bending strain/vibration) is associated with the asymmetric structure (Xing et al. 2009) which results into the larger thickness shear deformation; by using piezo-material featuring high coupling coefficient along the flexural mode (Rakbamrung et al. 2010) can generate high voltage/power output under lower excitation frequencies and load resistances than symmetric. Thus, it can be predicted that our designed Ni-MFC laminate structures can be suitable candidates for possible applications in self-biased magnetic field sensors with in-plane mode and as well as potential energy harvesters with asymmetric (unimorph) mode in future.

Conclusion

In summary, for magnetic field sensor and piezoelectric vibration energy harvesting applications, the proper materials structure design and coupling modes for getting better performance have explained for designing the symmetric Ni/MFC/Ni and asymmetric Ni/MFC ME laminate structures. Both structures revealed the strong self-biasing feature of ME coupling along with their feasibility for energy harvesting from magneto-mechanical vibrations. The Ni/MFC/Ni structure showed high magnitude of α_{ME} than Ni/MFC; this is due to the better magnetic field sensitivity and small demagnetization factor of Ni/MFC/Ni structure. Conversely, Ni/MFC structure in flexural mode showed better energy harvesting response than Ni/MFC/Ni structure due to the effective bending. Thus, for future designing of ME magnetic field sensors and energy harvesters, the symmetric and asymmetric structures can be employed respectively with effective (in-plane) coupling directions.

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