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Anisotropic self-biased dual-phase low frequency magneto-mechano-electric energy harvesters with giant power densities

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We report the physical behavior of self-biased multi-functional magneto-mechano-electric (MME) laminates simultaneously excited by magnetic and/or mechanical vibrations. The MME laminates composed of Ni and single crystal fiber composite exhibited strong ME coupling under $H_{dc} = 0$ Oe at both low frequency and at resonance frequency. Depending on the magnetic field direction with respect to the crystal orientation, the energy harvester showed strong in-plane anisotropy in the output voltage and was found to generate open circuit output voltage of 20 V_{pp} and power density of 59.78 mW/Oe^2 g^2 cm^3 under weak magnetic field of 1 Oe and mechanical vibration of 30 mg, at frequency of 21 Hz across 1 MΩ resistance. [http://dx.doi.org/10.1063/1.4870116]

Energy harvesting implies generation of electrical energy from ambient energy sources such as light, rf radiations, heat, vibration, or magnetic field. In recent decade, energy harvesting technologies have drawn considerable attention due to their promise for multiple applications such as low-power electronics including wireless sensors, data transmitters, digital controllers, and medical implants.[1–5] Recently, these applications desire a cost-effective self-powering mechanism instead of battery which could be prohibitively expensive to recharge or replace.[6,7] The development of energy harvesters to extract kinetic energy from low frequency (<100 Hz) vibrations has received much attention due to the universal presence of mechanical vibrations. There are variety of methods to convert the low frequency mechanical energy into electrical energy, however, as the dimension approaches smaller than 1 cm^3, piezoelectric mechanism becomes relevant as it provides the optimum combination of energy density and efficiency.[8,9] Most of the low frequency piezoelectric energy harvesters reported in literature have cantilever-based configurations that meet the frequency requirement through complex beam patterns (such as zigzag) but have challenges in terms of output power and bandwidth. These challenges should be resolved in order to open the pathway for their adoption in the above mentioned applications.

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The mechanical stress in piezoelectric materials along the cantilever beam is non-uniform and depends upon the bending vibration modes.[10] This stress-distribution can be modulated by attaching the magnetostrictive layers in a configuration where piezoelectric materials are mechanically coupled with the magnetostrictive materials.[11,12] Magnetostrictive materials have higher energy density and magnetomechanical coupling effect, thus, it can generate higher stress to deform the piezoelectric materials through small input strains.[13–17] In addition, the magnetostrictive effect of magnetostrictive phase can be utilized to harvest energy from low frequency stray magnetic fields available from nearby current sources. This simultaneous harvesting of vibration and magnetic energies can improve the relative power density of the mechanical energy harvesters. The combined piezoelectric and magnetostrictive layered structures, referred to as magnetoelectric (ME) composites, are subject of investigation in this paper.

Recently, efforts have been made to utilize the ME composites to harvest energy from mechanical vibration[13–17] as well as magnetic field.[18,19] Most of these proposed harvester structures utilize $Pb(ZrTi)O_3$ (PZT) based polycrystals or single crystal as piezoelectric materials which are extremely brittle and cannot sustain harsh vibration conditions and shocks. Moreover, these ME composites require external magnetic bias to obtain optimum ME sensitivity, which is a significant disadvantage as it reduces the volumetric power density and increases the noise. An optimum solution to these problems will be self-biased and flexible ME energy harvester. The ME composites with piezoelectric ceramic fibers can offer a promising alternative where they combine the advantages of the large piezoelectric constants of ceramics with the mechanical flexibility of polymers.

Advancing this concept, we report a dual phase (vibration and magnetic) magneto-mechano-electric (MME) energy harvesting device fabricated from magnetostrictive Nickel (Ni) metal shims laminated with single crystal fiber composite (SFC) with anisotropic transverse piezoelectric properties. Two different SFCs with orientation along the [001] or [011] direction in thickness of single crystal fiber were chosen for the comparative study. The fibers were flexible and exhibited high transverse piezoelectric coefficient d_{ij} and electromechanical coupling factor k_{ij}. Particularly SFC with [011]-orientation had unique anisotropic transverse piezoelectric properties, i.e., $d_{32} \approx -3d_{31}$, and $s_{11}^{p} \neq s_{22}^{p}$ that provides an exceptional opportunity for achieving large changes in planar uniaxial anisotropy.[17] This enables the harvester to trap the mechanical energy in bi-axial transverse in-plane directions. In conjunction, nickel (Ni) plays an important role in achieving the self-biased ME response. It exhibits low field magnetic hysteresis and non-zero piezomagnetic coefficient at zero DC bias.[17]

The schematic of the MME energy harvesters is illustrated in Fig. 1(a) and the fabricated prototype is shown in Fig. 1(b). The ME laminates were prepared by laminating [001] and [011]-oriented SFCs along the thickness direction with dimensions of 40 (length) × 20 (width) × 0.20 (thickness) mm^3 (active piezoelectric area was 28 × 14 mm^2) (Ceracomp Co. Ltd., Cheonan, Korea) on the top of the Ni plate with the dimensions of 90 (length) × 20 (width) × 0.25 (thickness) mm^3. The electrodes of the SFC were applied on both sides of the fiber thickness direction surface (planar electroding). Three different types of crystallographic orientation, i.e., [011]-d_{32}, [011]-d_{31}, and [001]-d_{31}, were selected for comparison as shown in Fig. 1(a). The Ni and SFC were bonded by epoxy adhesive (West system 206/105, USA) and cured overnight at room temperature. The proof mass of 2 g permanent magnet was placed on the tip of the MME laminate structure. No proof mass was used for ME coupling measurements. To characterize the harvester under the dual-phase mode, the MME laminate cantilever was simultaneously excited by an AC magnetic field (H_{ac}) generated by the Helmholtz coil and a mechanical oscillation generated by the shaker. The ME coefficient (α_E) was measured in the L-L mode (longitudinally magnetized and longitudinally poled) configuration with sample located in the center of the Helmholtz coil. The induced ME voltage was monitored using a lock-in amplifier. For the vibration test, the MME cantilever was mounted on an LDS shaker (Bruel and Kjaer North America, Inc.) using a custom clamp. The mechanical excitation (acceleration, g, as well as frequency, f) was generated by the shaker using a function generator embedded in spectral analyzer (SigLab, Model 20-42) and high power amplifier (Hewlett-Packard 6862A). The shaker base acceleration and displacement at the free end of the harvester were monitored by a low mass accelerometer (PCB U352C22) and a laser vibrometer (PDV 100, Polytech, Inc.). All the signals, including the output from laser vibrometer, power spectrum of acceleration, the transfer

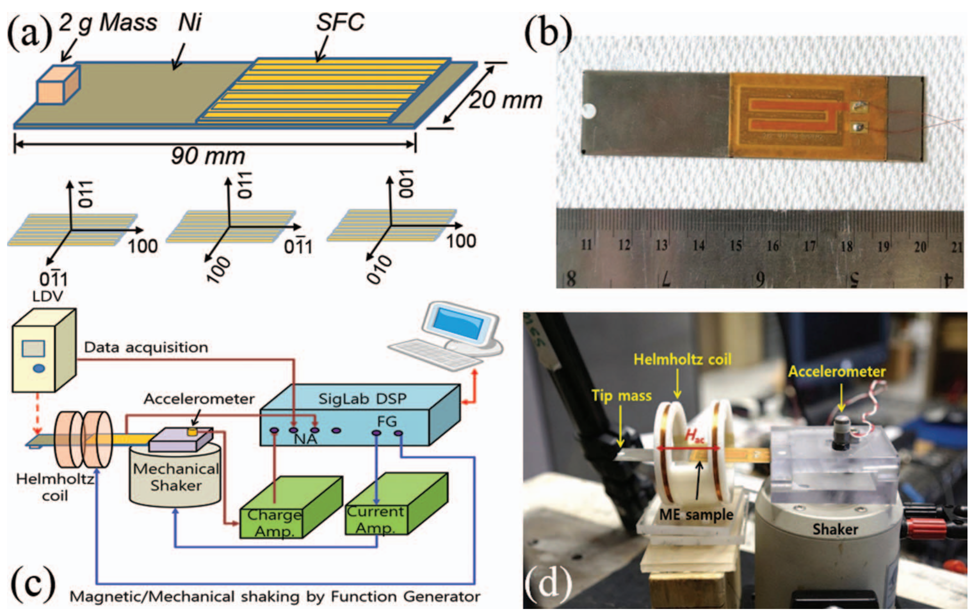

FIG. 1. Schematic diagram showing (a) Ni/SFC MME composites with different orientations of SFC, (b) prototype of Ni/SFC magnetoelectric composite, (c) schematic of the Ni/SFC dual-phase MME harvester, and (d) the experimental setup for characterization.

function from base acceleration to tip mass acceleration, and the output voltage of the harvester, were collected by spectral analyzer. Schematic diagram and experimental setup for characterization are presented in Figs. 1(c) and 1(d), respectively.

Figure 2(a) shows the ME voltage coefficients, α_E as a function of H_{dc} for Ni/ SFC laminates with [001]- and [011]-oriented SFCs, measured at an off-resonance frequency of 1 kHz. For laminate with [011]-orientation, α_E was measured for two different crystallographic directions with H//[100] (d_{32}) and H//[0$\bar{1}$1](d_{31}). For all the samples, α_E exhibited a typical H_{dc} dependence showing a sign change with respect to the reversal of H_{dc} direction. The H_{dc} dependence of α_E is correlated with the magnetic-field dependency of the piezomagnetic coefficient, q_{ij}, i.e., $d\lambda_{ij}/dH_j$, where λ_{ij} is the magnetostriction in the i-axis for H applied along the j-axis.[20] The most significant observation, however, was the hysteretic behavior of the structures during H_{dc} sweep, which results in nearly optimum α_E values at zero bias field ($H_{dc} = 0$ Oe). This can be attributed to the hysteretic magnetic behavior of the Ni foil. Nickel foil was found to possess macrosized domains with long range ordering which resulted in the larger coercive field. Once the magnetic domains were reoriented, it required higher field to achieve the random state resulting in larger hysteresis in the magnetization curve which resulted in the asymmetry in the magnetostriction.[21] The magnitude of the self-biased ME voltage coefficient was tuned by taking into account the size dependent demagnetization effect.[21–23] It is important to note that the self-biasing behavior observed in the present laminates is unique and intrinsic to the laminate structure in contrast to the other self-biased laminates where external grading[24,25] or exchange biasing techniques[26] were used, which are rather complex in fabrication and implementation.

The laminates with [011]-oriented SFCs showed strong anisotropic behavior in magnitude with α_E values of 1.2 V/cm Oe and 0.6 V/cm Oe for laminate with [011]-d_{32} and laminate with [011]-d_{31} SFC, respectively. However, for laminate with [001]-orientations the magnitude of α_E was 0.62 V/cm Oe irrespective of the magnetic field direction. It is also noteworthy that the maximum value of 1.2 V/cm Oe for [011]-d_{32} SFC laminate is about 2 times larger than that of the Ni/[011]-d_{31} SFC and Ni/[001]-d_{31} SFC laminates. The larger magnitude of α_E for [011]-d_{32} SFC laminate can be attributed to the large piezoelectric coefficient, d_{32} of Ni/[011] SFC laminate along [100] direction compared to the d_{31} of other two laminates. Moreover, the anisotropy in the magnitude of α_E for the Ni/[011] SFC laminates with d_{32} and d_{31} directions can be attributed to the anisotropic piezoelectric

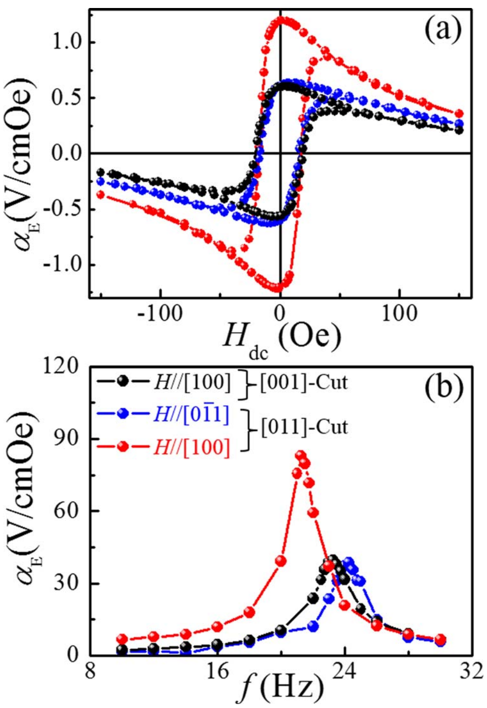

FIG. 2. (a) H_{dc} dependence of α_E at a frequency $f = 1$ kHz, (b) frequency dependence of α_E for Ni/[001]-d_{31} SFC, Ni/[011]-d_{31} SFC, and Ni/[011]-d_{32} SFC self-biased laminates under zero biased conditions ($H_{dc} = 0$ Oe).

properties of [011]-oriented SFC, i.e., $d_{31} \neq d_{32}$ and $s_{11}^p \neq s_{22}^p$. On the other hand, for laminate with [001]-oriented SFC one can expect the same magnitude of α_E values along different in-plane H-directions due to the isotropic behavior of the [001]-oriented SFC.[27]

Figure 2(b) shows the frequency dependence of bending mode α_E for the laminates in the frequency range of 20–35 Hz under zero-biased condition ($H_{dc} = 0$ Oe). All the laminates showed single electromechanical resonance ME peak corresponding to the fundamental bending vibration mode. For the laminates with [011]-oriented SFC the ME peaks were observed at 21 Hz and 24 Hz for d_{32} and d_{31} directions, respectively, with α_E values of 82.9 V/cm Oe and 38.5 V/cm Oe. Similarly for laminate with [001]-oriented SFC the electromechanical resonance was observed at 23 Hz with α_E of 39.4 V/cm Oe. These values were indeed very large at such low resonance frequencies. Moreover, for the former case the peak magnitude of α_E was different for the two configurations. The ME coupling for Ni/[011]-d_{32} SFC laminate was higher than that for Ni/[011]-d_{31} SFC laminate and Ni/[001]-d_{31} SFC laminate, which was consistent with the α_E (H_{dc}) data. It is important to note that the ME peaks were observed at very low frequencies, especially for Ni/[011]-d_{32} SFC laminate, which can be attributed to the large elastic compliance of the [011]-oriented SFC along [100] direction as the resonance frequencies are generally inversely proportional to the square root of the average elastic compliance.[28]

Next we studied the energy harvesting response of the designed MME cantilevers at the bending resonance of the laminates under zero biased conditions. The energy harvesting response was studied under three different conditions: (a) under only a stray magnetic excitation ($H_{ac} = 1$ Oe), (b) under only a stray vibrational excitation (30 mg), and (c) under both stray magnetic and vibrational excitations (1 Oe + 30 mg). Figure 3(a) shows the voltage induced at the bending mode by an applied magnetic field of $H_{ac} = 1$ Oe, without any mechanical vibrations for all the three MME cantilevers. The inset shows the time varying voltage signal at the respective bending modes of the cantilevers at the resonance frequency. The output voltages under the open circuit conditions were 4.69 V_{pp}, 2.17 V_{pp}, and 2.22 V_{pp}, respectively, for Ni/[011]-d_{32} SFC cantilever, Ni/[011]-d_{31} SFC cantilever, and Ni/[001]-d_{31} SFC cantilever at their respective bending resonance frequencies.

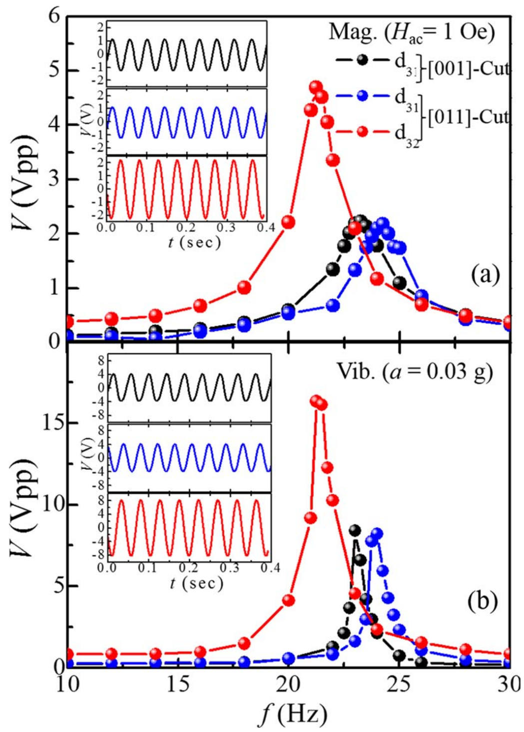

FIG. 3. Open circuit voltage output of the Ni/SFC MME harvesters as a function of frequency under (a) magnetic field condition of $H_{ac} = 1$ Oe, (b) vibration condition of $a = 30$ mg (inset: the time varying open circuit voltage at respective resonance frequencies).

Figure 3(b) shows the voltage induced at the bending modes by applying mechanical vibration with an acceleration of 30 mg without any magnetic field. The output voltages under the open circuit conditions were found to be 16.32 V_{pp} (or 544 V_{pp}/g), 8.2 V_{pp} (or 273 V_{pp}/g), and 8.4 V_{pp} (or 280 V_{pp}/g), respectively, for Ni/[011]-d_{32} SFC cantilever, Ni/[011]-d_{31} SFC cantilever, and Ni/[001]-d_{31} SFC cantilever. As expected in both the cases, Ni/[011] d_{32}-SFC showed the maximum V_{pp} consistent with the ME coupling data. Moreover the bending mode frequencies matched well with that of ME coupling data. We found that the output voltage increased as a function of both acceleration and AC magnetic field[29] in accordance with the behavior of piezomagnetic and piezoelectric coefficient. But neither high acceleration nor high AC magnetic field is desirable under practical scenario, thus the characterization of the harvester was limited to low magnitudes and emphasis was laid upon understanding the dual phase coupling.

Next, we investigated the ability of the MME harvesters to simultaneously harvest both magnetic and mechanical energies by exciting the cantilevers with stray magnetic field and mechanical vibration simultaneously at the resonance frequency. Figure 4 shows the voltage induced under in-phase magnetic field of $H_{ac} = 1$ Oe and a mechanical vibration of amplitude 30 mg. The output voltages were enhanced relative to the single sources through additive effect from magnetostrictive and piezoelectric contributions. The maximum of 20 V_{pp} (666 V_{pp}/g Oe) was observed for the Ni/[011]-d_{32} SFC harvester, which is equal to the sum of two individual contributions (16.32 V_{pp} at 30 mg and 4.69 V_{pp} at 1 Oe). Similarly the output voltages of 11.04 V_{pp} (368 V_{pp}/g Oe) and 11.44 V_{pp} (381 V_{pp}/g Oe) were observed for Ni/[011]-d_{31} SFC cantilever and Ni/[001]-d_{31} SFC cantilever, respectively. The power, P, of all the energy harvesters was calculated at an external load of 1 MΩ by using the relation $P = V_{RMS}^2/R$ and correspondingly, power densities at different excitations by taking into account the total volume (0.88 cm^3, including the tip mass) of the MME harvesters as shown in Fig. 5. As expected, Ni/[011]-d_{32} SFC harvester showed large power densities at all the three excitations. The power densities under magnetic, mechanical, and dual-phase (magnetic + mechanical) excitations for Ni/[011]-d_{32} SFC were found to be 2.75 μW/Oe^2 cm^3, 42.46 mW/g^2 cm^3,

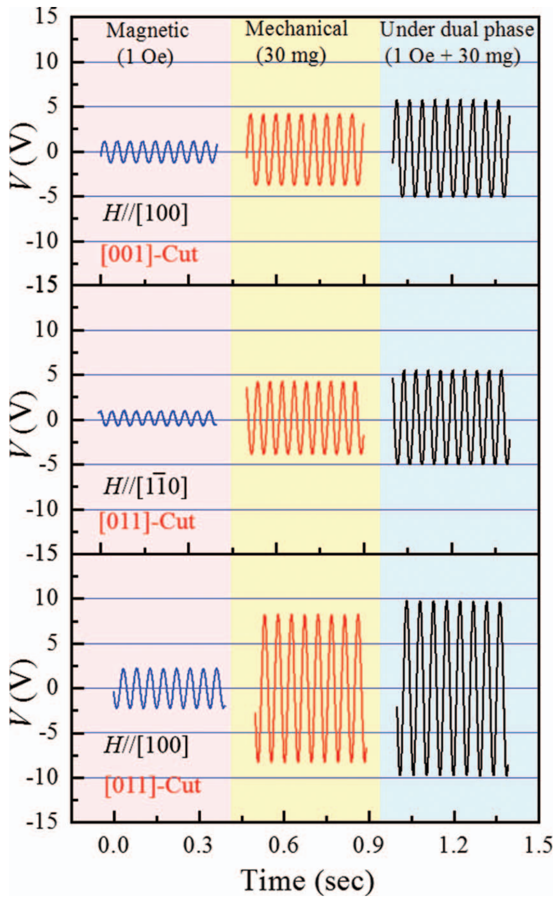

FIG. 4. Open circuit voltage output as a function of time for the dual-phase MME harvesters working under both mechanical and magnetic conditions at respective resonance frequencies.

and 59.78 mW/Oe^2 g^2 cm^3. It is important to note that P varies with H_{ac} and acceleration, a by square relation ($P \propto H_{ac}{}^2$ and $P \propto a^2$).[30,31] Here, the value of 59.78 mW/Oe^2 g^2 cm^3 observed under dual-phase excitation is indeed very large considering the very small magnitudes of magnetic and mechanical excitations and comparatively much higher than those of other reported dual-phase energy harvesters.[18,22] Moreover unlike output voltage, the power densities under dual phase excitation are not only additive but also showed large synergic enhancement of 40.8%, 70.5%, and 86.7%, respectively, for Ni/[011]-d_{32} SFC cantilever, Ni/[011]-d_{31} SFC cantilever, and Ni/[001] d_{31}-SFC cantilever. The additive effect of the MME harvesters is related to the combinatory effect of two mechanisms. First, an ambient AC magnetic field H_{ac} applied along the longitudinal direction of the MME composite cantilever generates a magnetic force moment $M = 2V_m J_r H_{ac}$ at the tip-magnet on the cantilever beam, resulting in a bending vibration of the MME composite cantilever. During this process, the ambient magnetic energy is transferred into the mechanical energy of the MME composite cantilever subsequently inducing the voltage outputs.[31] Second, under mechanical vibration a bending motion can be excited that results in induced voltage output (in-phase with the magnetic excitation) due to the direct piezoelectric effect. Both the excitations simultaneously enhance the bending stress on the MME composite cantilever resulting in the enhancement of the voltage outputs. The criterion for the optimum response through these two simultaneous mechanisms requires phase matching of the magnetic and mechanical excitation.

Above mentioned results clearly demonstrate that the coexistence of small AC magnetic field (only 1 Oe) excitation with mechanical (only 30 mg) excitation can greatly enhance the power densities of the energy harvesters even under zero-biased conditions. This is a significant advancement towards the miniaturization of the energy harvesters. In particular, Ni/[011]-d_{32}-oriented SFC

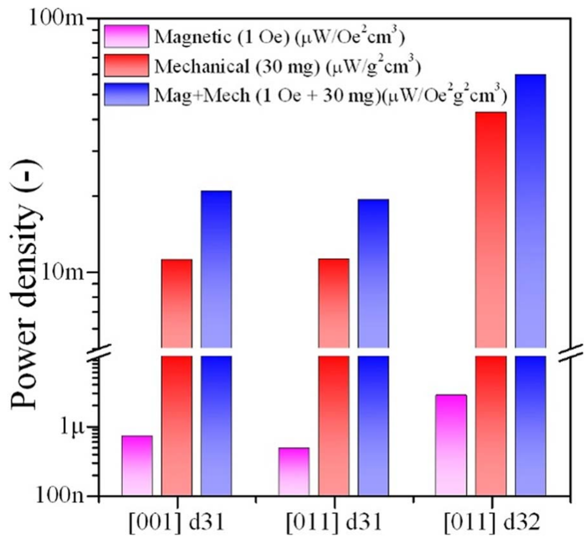

FIG. 5. Comparison between the power densities of MME harvesters at single excitations and dual phase (magnetic + mechanical) excitations.

cantilever can have a unique capability of harvesting energy from both the in-plane axis of the cantilever (bi-axial, anisotropic) with different magnitude. A large enhancement in the output voltages and power densities was obtained under dual-phase excitations and showed a much larger magnitude than that of the other multimode MME harvesters[18,23] reported in literature. Our harvester structures have the capability to extract energy from very weak mechanical vibrations (only 30 mg) and/or weak magnetic fields (only 1 Oe) present in the ambient environment through combinatory effect.

In conclusion, we characterized the ME coefficients and showed the low frequency energy harvesting capability of the self-biased laminates under individual external AC magnetic field and mechanical vibration and also dual phase energy harvesting when both the excitations were present. The ME laminates showed comparatively large values of α_E at zero bias ($H_{dc} = 0$ Oe) both at low and resonance frequency in comparison to the other self-biased ME laminates. The Ni/[011]-d_{32} SFC energy harvester showed giant output voltage of 20 V_{pp} (666 V_{pp}/g Oe) and power density of 59.78 mW/Oe^2 g^2 cm^{3}when it was operated under the dual-phase mode (magnetic + vibration). The self-biasing, biaxial (anisotropic), dual-phase energy harvesting properties make the Ni/[011]-oriented SFC MME harvester promising for developing power source for the wireless sensor networks and portable electronics.

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