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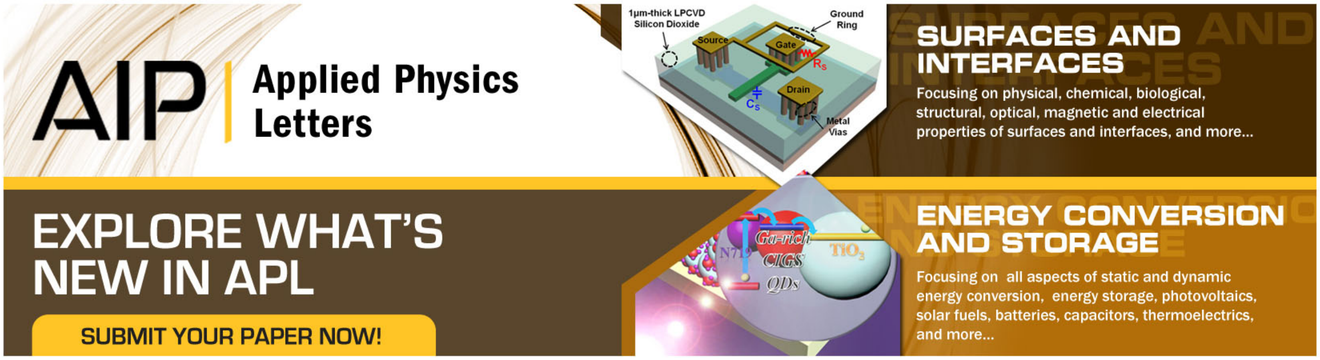

APPLIED PHYSICS LETTERS **101**, 123903 (2012)

Multi-resonant energy harvester exploiting high-mode resonances frequency down-shifted by a flexible body beam

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We describe a mechanical vibration-based energy harvester deploying a flexible body beam to lower the spring constant of the device so that high-mode resonant frequencies are shifted down into a useable frequency range under natural environmental conditions. Whereas conventional cantilevers feature a single resonant frequency within this range, the proposed device generates multiple high-mode resonant frequencies in close proximity to form a wider operational bandwidth that is over 400% wider than that of conventional cantilever-type energy harvesters. © *2012 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4754147]

In recent years, energy harvesters have gained significant attention as portable power sources for self-sustainable wireless sensor networks.[1–4] Many researchers[4–10] have suggested various types of energy harvesters that harness different energy sources (ambient light, heat, and mechanical vibration). Among these energy harvesters, vibration-based piezoelectric energy harvesters are promising because of advantages such as high energy densities and ease in fabrication. In a typical piezoelectric energy harvester, the piezoelectric material is attached to a simple structure such as a cantilever.[8–10] However, conventional cantilever-type energy harvesters generate power from only a limited vibrational frequency range around the first-mode resonant frequency, as higher-mode resonances with smaller displacements occur in an excessively high frequency range. Therefore, conventional cantilever-type energy harvesters can exploit only their first resonance mode. This inherent limitation results in a narrow operational frequency range and may generate insufficient power from ambient environmental vibrations. Previous studies have attempted to remedy this limitation by widening the bandwidth and tuning the operational frequency.[11–22] Generator arrays or nonlinear characteristics are used to broaden bandwidths,[11–17] and additional loading forces are employed for tuning the operational frequency of devices.[18–22] However, these solutions only focus on the first resonance mode, ignoring the other higher mode resonances. This is because higher mode resonances are found at higher frequencies corresponding to smaller displacements and are more difficult to exploit.

Our proposal follows a new methodology that uses these higher mode resonances but also shifts down their frequencies to a vibrational range accessible under normal environmental conditions. To meet this objective, a flexible body beam is deployed that modulates the high-mode bending motion resonances. We fabricated a prototype to demonstrate its potential by measuring the output voltage under various practical frequency ranges.

Our device consists of two parts: a cantilever comprising a piezoelectric material (PZT) and a flexible body beam (Fig. 1(a)). The cantilever assumes the role of a power generator by engendering power when bending-motion resonance is induced. The flexible body beam induces additional bending motions in the generator and controls the resonant frequencies of the total system. In conventional single cantilever-type energy harvesters, of the various resonance modes, the high-mode bending-motion resonances are generated at much higher frequencies unattainable in most vibratory environments.[23,24] These high resonance frequencies, of course, can be lowered by controlling the device stiffness, although rigid piezoelectric ceramic materials, such as PZT, attached to a cantilever make adjusting frequencies difficult.

In contrast, in our device, the flexible body beam can control the resonant frequencies independently because this

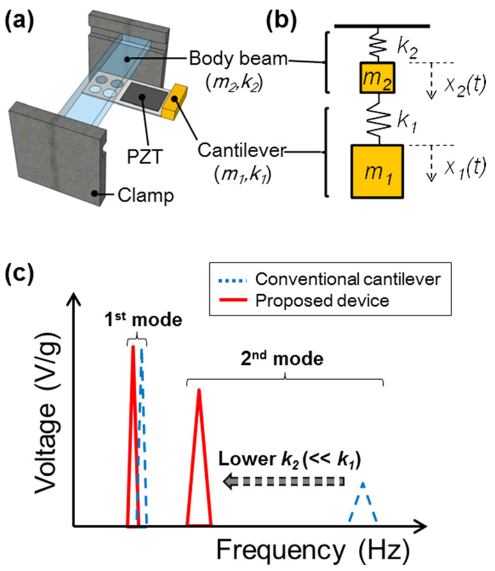

FIG. 1. Multi-resonant energy harvester: (a) schematic, (b) simplified mechanical model, (c) expected output characteristics.

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beam is detached from the PZT. Hence, when it vibrates, the beam easily induces additional bending motions. In other words, this separated beam couples to high-mode resonances shifting their frequencies down to practical environmental frequency ranges. Moreover, owing to its flexibility, the body beam at resonance can generate large bending-motion displacements of the attached cantilever. Therefore, we can obtain large bending-motion resonances that are adjustable within our device. To ascertain its viability qualitatively, we modeled the device as a simplified mass-spring system, illustrated in Fig. 1(b). Assuming the masses have only one-dimensional movement, the two fundamental resonant frequencies (ω_1, ω_2) of the system can be expressed as

$$\omega_1^2,\omega_2^2=\frac{1}{2}\left\{\frac{(k_1+k_2)m_2+k_2m_1}{m_1m_2}\right\}\mp\frac{1}{2}\left[\left\{\frac{(k_1+k_2)m_2+k_2m_1}{m_1m_2}\right\}^2-4\left\{\frac{(k_1+k_2)k_2-k_2^2}{m_1m_2}\right\}\right]^{\frac{1}{2}} \qquad (1)$$

where m_1 and m_2 represent the effective masses of cantilever and body beam, respectively, and k_1 and k_2 are the respective spring constants. From Eq. (1), with constants m_1, m_2, and k_1 remaining fixed, changing the beam's spring constant (k_2) is a means to freely adjust the resonant frequencies of the total system. Therefore, for the output characteristics, the operating frequencies of our energy harvester using high-mode resonances is expected to be shifted down to a practical ambient frequency range with an extremely small beam spring constant k_2 (Fig. 1(c)).

To predict the characteristics of our energy harvester, we performed an FEM simulation using COMSOL. The resonances, which can induce bending motions to the cantilever, were observed producing two representative bending-motion resonant frequencies (Fig. 2). As we expected, the smaller beam spring constant k_2 results in lower resonant frequencies and the frequency change is notable in the second-mode resonant frequency compared with that for the first mode. In the FEM simulation, we confirmed that we can localize the first two resonant modes for our device within an environmental frequency range using an extremely low value for the beam spring constant.

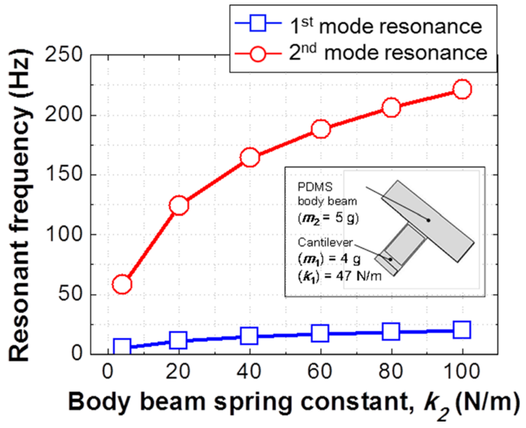

FIG. 2. Multi-mode resonant frequencies of the energy harvester as a function of the flexible body beam spring constant, obtained by FEM simulation.

To investigate the concept in practice, a special material polydimethylsiloxane (PDMS) was used for its extremely low stiffness factor. A body beam of PDMS has a very low Young's modulus (E of 360–870 kPa) compared with usual cantilever materials of metal (E of 69–200 GPa). The fabricated device consisted of an iron proof mass (3 g) and an aluminum cantilever beam ($40(L) \times 20(W) \times 3(T)$ mm^3, $E = 76$ GPa) connected to the PDMS body beam ($80(L) \times 20(W) \times 3(T)$ mm^3, Sylgard 184; Dow corning). A piezoceramic sheet ($28(L) \times 18(W) \times 0.5(T)$ mm^3, $E = 66$ GPa, PSI-5A4E, Piezo-Systems) was mounted on the cantilever using epoxy bond (Fig. 3(a)). For performance comparison, a second device, of conventional cantilever-type, was fabricated with the same proof mass (3 g) and aluminum cantilever ($40(L) \times 20(W) \times 3(T)$ mm^3, $E = 76$ GPa) (Fig. 3(b)). Each device was mechanically shaken to provide harmonic excitations. A nominal acceleration was applied and measured using an accelerometer; the voltage response generated by the piezoceramic sheet was measured using an oscilloscope. Finally, all measured open-circuit voltage values were normalized using the actual acceleration measured at the base of the vibrator, because the vibrator itself can change the base accelerations.

The frequency responses of the open-circuit voltage generated by our device and the conventional cantilever-type energy harvester are shown in Fig. 4(a). The conventional cantilever-type device showed only a single voltage peak at 37 Hz within the 100 Hz range and values agree with the FEM simulation (first resonant frequency: 41 Hz, second resonant frequency: 642 Hz). In contrast, our device, with a flexible 6-cm PDMS body beam, featured within the 100 Hz range two resonant frequencies of 10 Hz and 88.1 Hz with open-circuit voltages of 8.3 V/g and 1.85 V/g, respectively.

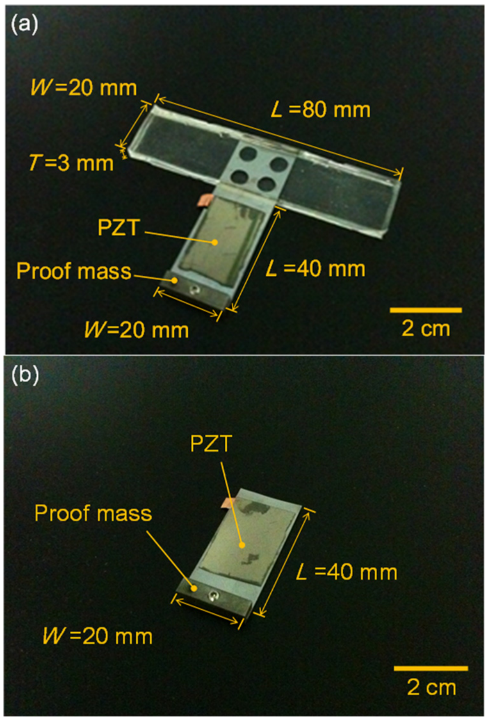

FIG. 3. Photographs of (a) our fabricated energy harvester and (b) a conventional cantilever-type energy harvester.

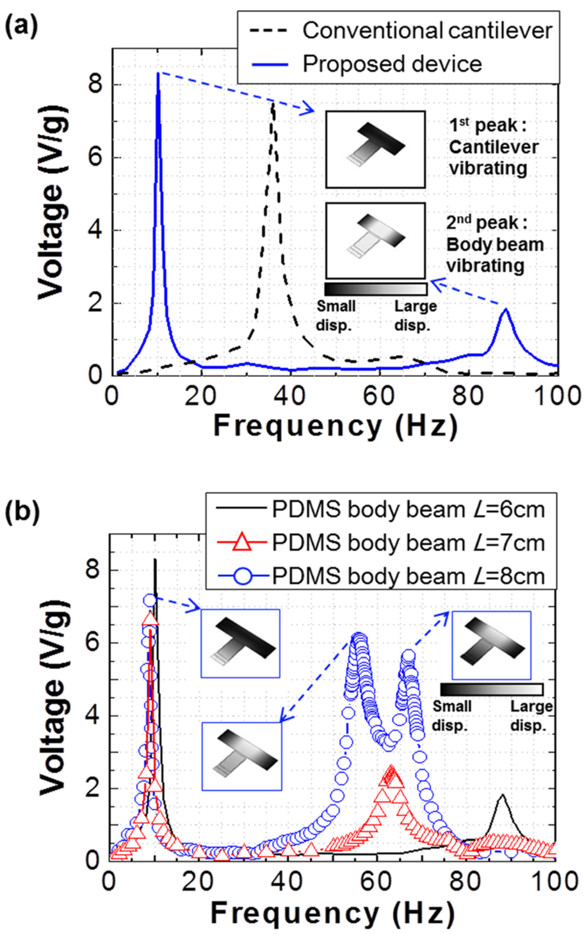

FIG. 4. Measured frequency response of our energy harvesters; insets are the relative displacements at resonance from FEM simulations: (a) the conventional cantilever device has a single voltage peak (dash line, 7.5 V/g at 35.8 Hz), whereas our device (body beam of $L = 6$ cm) has two voltage peaks (solid line, the first peak: 8.33 V/g at 10 Hz; the second peak: 1.85 V/g at 88.1 Hz). The first peak corresponds to the cantilever fundamental and the second peak from body beam vibration. (b) The generated voltage peaks using an 8 cm long body beam (circles, the first peak: 6.45 V/g at 8.8 Hz; the second peak: 6.12 V/g at 55.8 Hz; the third peak: 5.64 V/g at 67 Hz), a 7 cm long body beam (triangles, the first peak: 6.63 V/g at 9 Hz; the second peak: 2.39 V/g at 63.2 Hz; the third peak: 0.51 V/g at 86 Hz), and a 6 cm long body beam (solid line, same as for (a)).

According to the analysis based upon the FEM simulation, the first resonance peak originated from the PZT cantilever vibration, whereas the second resonance peak arose from a bending-motion vibration of the PZT cantilever induced by a resonance in the body beam.

The resonance frequency characteristics under different PDMS body beam lengths were compared (Fig. 4(b)). As confirmed by FEM simulations, power generation occurred at lower frequency as the body beam had a smaller spring constant; output voltages increased as well because of a larger displacement. Also, harvesting efficiency can grow proportional to $1/\omega^2$ (here ω is frequency of the harmonic vibration).[25] This result shows that resonant frequencies can be down-shifted to a practical vibrational frequency range by introducing a flexible body beam. This feature has not been reported before in vibrational energy harvesters. The device with the longest 8 cm body beam showed notable down-shifted high-mode resonances at 8.7, 55.8, and 67 Hz, respectively (cf. the simulation result of 8, 58, and 66 Hz, respectively). The additional third peak is thought to result from another width-wise vibration in the body beam. Moreover, at higher mode resonances, these high output voltage characteristics stem from additional bending motions of the cantilever which force the attached PZT to operate with a length vibration mode that is the most efficient mode in cantilever-type energy harvesters.[26]

Another important characteristic of this 8 cm body-beam device is its wide operating frequency range. The proximity of its second and third peaks enables broadband energy harvesting. Defined as the frequency band where the output voltage is -3 dB of the peak value, the bandwidth for the conventional cantilever was approximately 4 Hz (dashed line in Fig. 4(a)) and for our device was 17 Hz (circles in Fig. 4(b), 425% wider bandwidth).

In conclusion, a multi-resonant energy harvester that uses multiple resonances has been proposed and investigated. Attached with a flexible body beam, the device generates additional bending motions to augment power generation from couplings to higher-mode resonances. Flexibility in design can shift the multi-mode resonant frequencies down to within a practical environmental vibration range. With a long body beam design, three different output voltage peaks were generated under 100 Hz; the proximity of the second and third peaks help to form a wide bandwidth. We anticipate that our multi-resonant energy harvester with a wider operating frequency range can provide more efficient power generation for a self-sustainable wireless sensor network or a body-area network for wearable computers in the near future.

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