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The aim of this work was to efficiently convert the mechanical vibrations into electrical energy by using direct piezoelectric effect. Most mechanical vibrations occur at low frequencies varying from 50 to 120 Hz. As piezoelectric converters provide maximum energy conversion when their natural frequencies are close to the frequency of the mechanical source, it would be interesting to design piezoelectric con-verters operating at low resonance frequencies. For those reasons, a piezoelectric generator has been developed with multi-cantilever piezoceramics operating at low frequencies. The device was shaped using the tape casting technique followed by a laser cutting process. It was made of six piezoelectric can-tilevers with different lengths and various masses at their free-ends. Its piezoelectric response was char-acterized and analysed. It was shown that it can operate at low and many resonant frequencies. Moreover the frequency bandwidth was widened up to 200% compared to the one obtained from a single cantilever beam. It allowed efficiently exploiting mechanical vibrations of sources exhibiting wide frequency spectrum.

1. Introduction

For the operation of many intelligent systems, it is often necessary to supply electrical energy in a simple, economical and robust way. The multiplication of many kinds of sensors makes the systems more and more complex because of the need for electrical supply through a wired system.

For many applications, energy sources such as vibrational energy of the surrounding mechanical structure should be considered. A piezoelectric transducer could then be suitable since it allows direct and *in situ* conversion of the vibrational energy into electrical energy.

Energy harvesting with piezoelectric materials is a very attractive approach to supply energy to mobile electronic devices and wireless systems. This technique allows converting available mechanical energy into electrical energy with a power in the range from 10^{-6} W to 10^{-3} W.

Thanks to its simplicity, low stiffness and high deformation ability, the piezoelectric cantilever beam is the most commonly used structure for energy harvesting with piezoelectric materials. It usually consists of one or two piezoelectric ceramic layers deposited on either one or both sides of a metal cantilever beam. The first end of this beam is clamped, while the other one remains free. A proof mass can be attached at the free-end. The cantilever dimensions and the proof mass value must be tuned in order to make the energy scavenger more efficient by adjusting its resonant frequency to the peak-power frequency of the vibration source.

Many methods have been reported to increase the harvested energy by piezoelectric materials. They can be divided into two categories. The first one consists of selecting the coupling mode of operation [1–4] because the higher the coupling factor, the higher the energy harvested. The second one consists of changing the device configuration in order to improve the harvested power. Regarding the later procedure, the configuration change is possible by modifying the cantilever geometry (rectangular, triangular, circular, etc.) [5–7], by electrical tuning [8,9], by widening the bandwidth of the generator or most commonly by mechanical tuning [10,11] as it is easier to implement.

The different strategies to widen the energy harvester bandwidth were detailed by Zhu et al. [12].

A summary of previous works about the use of a generator array technique is presented here after. This method consists of a combination of cantilevers (or multi-generators) with different dimensions and/or different proof masses at their free ends. Each

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resonator exhibiting its own resonant frequency, the combination of all of them leads to a wide operational frequency range.

Kim et al. [13] developed and tested a piezoelectric energy-harvesting device based on two cantilevers beams with piezoceramic sheets. It was shown that its frequency bandwidth was significantly greater than a single cantilever-type device.

Shahruz [14] proposed a design and a modelization of a mechanical band-pass filter consisting of beam-mass systems. Each beam was an individual generator exhibiting a resonant frequency depending on the dimensions. It was shown that such an ensemble can be made into a band-pass filter when dimensions of the beams and proof masses values are chosen appropriately. The cantilever beams were made of metal, without any piezoelectric part.

Xue et al. [15] presented an analytical model of a broadband piezoelectric harvester consisting of multiple piezoelectric bimorphs with piezoelectric layers differing in terms of thickness. It was found that the bandwidth of the generator can be widened by connecting multiple piezoelectric bimorphs.

Feng et al. [16] presented a micromachined piezoelectric generator made of four cantilever structures connected in parallel. The dimensions of the generator were 3 mm × 3 mm × 5 mm. The designed generator was targeted at working in a wide mechanical vibrations range from 300 to 800 Hz.

Ferrari et al. [17] developed a piezoelectric multifrequency converter intended for powering autonomous sensors from background vibrations. The generator was composed of three commercially piezoelectric bimorph cantilevers exhibiting different natural frequencies. These cantilevers were 15 mm long, 1.5 mm wide and 0.6 mm thick and masses of 1.4 g, 0.7 g and 0.6 g were fixed at their free ends. The operating frequency of the generator ranged from 100 to 300 Hz.

Sari et al. [18] designed and implemented a micromachined electromagnetic generator with a wide bandwidth. The generator consisted of a series of parylene cantilevers with various lengths ranging from 0.9 to 1 mm and natural frequencies from 4.2 to 5 kHz.

Lin et al. [19] reported a multi-cantilever piezoelectric MEMS generator constituted of four cantilever-type devices made by a silicon process. The prototype device resonated between 237 and 244.5 Hz.

However, it was reported that the fabrication of these kinds of converters is usually difficult and it leads to an increase of the device cost. On the other hand, it was reported in the literature that most of mechanical vibrations in the environment occur at low frequencies and vary between 50 and 120 Hz [20]. According to Roundy et al. [20], the power decreases as frequency increases because the decrease of the input vibration amplitude dominates the increase of the frequency contribution. It is therefore very advantageous to use a piezoelectric converter with a low natural frequency. On the other hand, many mechanical vibrations sources exhibit a variation in their resonance frequency around a peak-power frequency during operation.

So, in order to efficiently exploit such mechanical vibrations, piezoelectric devices should be designed to resonate at the fundamental vibration frequency and to operate at low frequency and on a large band spectrum. The aim of this work was then the elaboration and the characterization of a multi-cantilever converter for energy harvesting operating at low frequencies and exhibiting a wide frequency spectrum. The device was shaped using a tape casting technique followed by a laser cutting process. This later technique was a good way to solve problems encountered in achieving this kind of converters array. This energy harvester was constituted by several PZT-based thick ceramic cantilevers exhibiting different lengths and carrying different masses at their free-ends.

2. Device elaboration

The multi-cantilever device was elaborated by using the tape casting technique followed by a laser cutting process (Fig. 1). The tape casting process was carried out by means of a doctor blade apparatus and it allowed obtaining green tapes showing a length of a few meters and width of 15 cm. The thickness could be adjusted between approximately 40 μm and 1 mm. After drying, the tape could be handled very easily. It consists of a rather compact staking of grains (about 70 wt.%) bound by an organic phase. The slurry composition and the casting procedure were presented in a previous article [21].

After sintering at 1100 °C, silver electrodes, of about 10 μm thick, were deposited on the sample by screen printing and the polarization was performed at 3 kV/mm during 15 min at 50 °C. A post treatment without contact was then carried out by laser cutting. The device was a 150 W Laser Startcut Sc18SN motorised in (x, y) plane, allowing the cutting of plane parts only. The laser cutting could be carried out on unpolarized parts as well as on electroded and polarized ones. The polarization state was shown to be stable during the cutting process for samples with a width greater than or equal to 1 mm. The thickness of the sample to laser-cut must be less than 2 mm. Fig. 2 shows a SEM picture of a laser cutting result obtained on a PZT substrate. The dimension of the laser spot could be tuned from 20 to 80 μm. It was therefore possible to decrease the cutting dimension down to 20–30 μm. This technique made it possible to cut thin and plane parts of polarized PZT. By

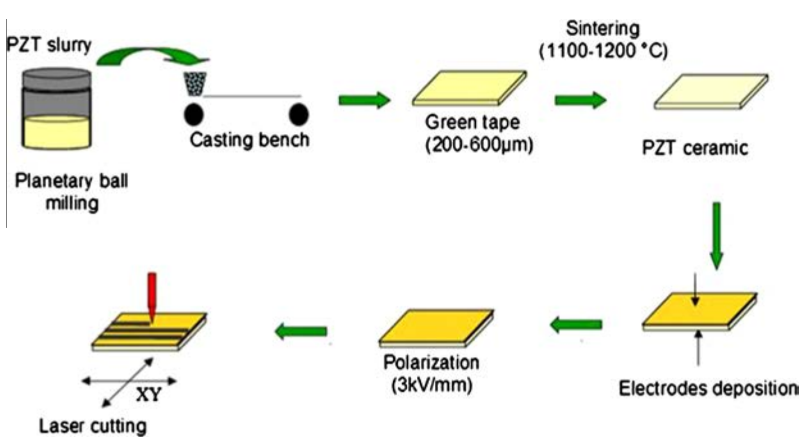

Fig. 1. The different stages of the elaboration process.

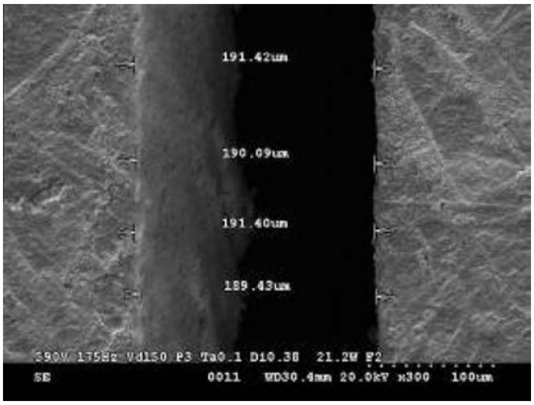

Fig. 2. Cut out realised on a PZT sample.

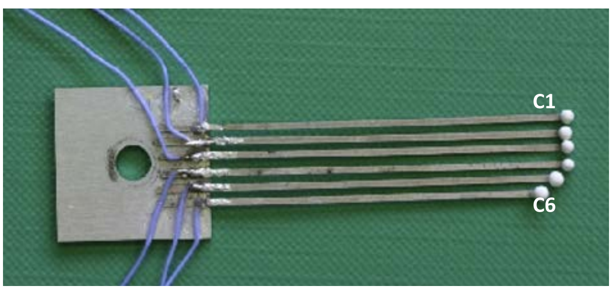

Fig. 3. Sensor made of cantilevers with different lengths.

Table 1
Sensor characteristics.

Cantilever	C1	C2	C3	C4	C5	C6
Length (mm)	46.0	46.0	46.5	46.5	45.5	44.0
Proof mass (mg)	10	10	9	9	11	12
Output voltage without proof mass (V)	1.56	1.48	1.36	1.36	1.40	1.50

this way, piezoelectric devices with different lengths, widths and shapes could be designed with high accuracy.

The sensor presented in this paper was made of PZT-based multi-cantilever exhibiting different lengths and different proof masses at their tips (Fig. 3). The cantilevers were from 44 to 46.5 mm long, 1 mm wide and 300 µm thick. The different parameters are reported in Table 1.

3. Characterization

The experimental set-up was built with a 3B Scientific U56001 vibration generator which was used as a source of mechanical vibrations as shown in Fig. 4. A function generator was used as an electrical supplier to drive the vibration generator. For all measurements, the sinusoidal supply voltage was kept constant at a value of 2 V peak-to-peak. One end of each piezoelectric cantilever was clamped to the mounting pin of the vibration generator and the frequency could vary over the range from 0 up to 20 kHz. The free-end proof masses allowed tuning resonant frequencies. A Polytec Portable Digital Vibrometer (PDV 100) was mounted on a bar above the piezoelectric cantilevers and allowed measuring vibration velocity. The output voltage and vibration velocity were measured on an oscilloscope. All data were measured through an acquisition card with LabVIEW software.

To characterize this multi-cantilever device, the output voltage of each cantilever was first measured separately and then the output voltage of all cantilevers electrically connected in parallel was measured. Measurements were performed at the 1st and at the 2nd resonance modes, without any proof masses at cantilevers tips and also with different proof masses. In order to compare results obtained in the different cases, all measurements were normalized in order to compensate the frequency dependence of the vibration generator by dividing the output voltage by the actual velocity of the source.

4. Results and discussion

Fig. 5 shows the vibration velocity of the source, the vibration velocity at the tip of the first cantilever (C1) and the output voltage of this cantilever depending on frequency. These results were obtained for the 1st resonance mode, with a proof mass of 10 mg. The cantilever tip exhibited a vibration magnitude more than 10 times larger than the source one. It was also shown that the vibration source presents a maximum velocity at about 47.5 Hz. The measure of the tip velocity showed a saturation which corresponded to the maximum velocity (500 mm/s) that could be detected by the vibrometer.

The normalized voltage of each cantilever at 1st resonance mode without proof masses is presented in Fig. 6. It can be noted that frequency bandwidths at half maximum were between 5 and 7 Hz.

Output voltages of all cantilevers without proof masses were similar. They were between 1.36 and 1.56 V_{pp}.

The voltage variation vs. frequency when cantilevers were in parallel connexion at the 1st mode of resonance is presented in Fig. 7. Two curves are presented: either with or without proof masses.

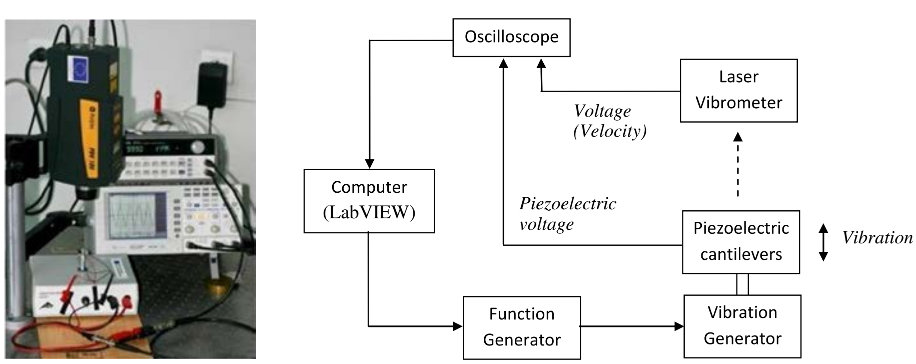

Fig. 4. A photo of experimental set-up (on the left) and the block diagram (on the right).

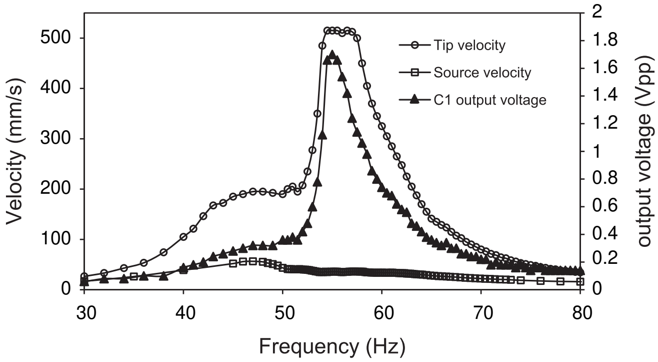

Fig. 5. Output voltage of C1 and vibration velocities of the vibration source and at the tip of C1.

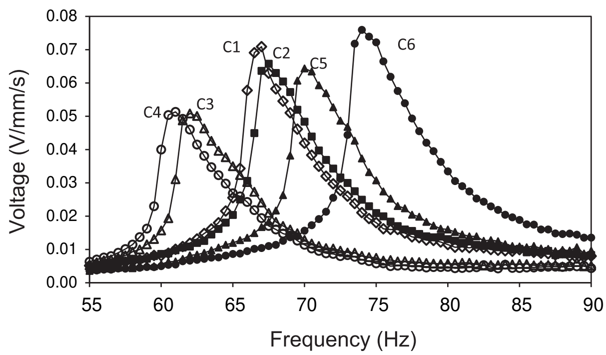

Fig. 6. Output voltages of each cantilever at 1st resonance mode without any masses at their free-ends.

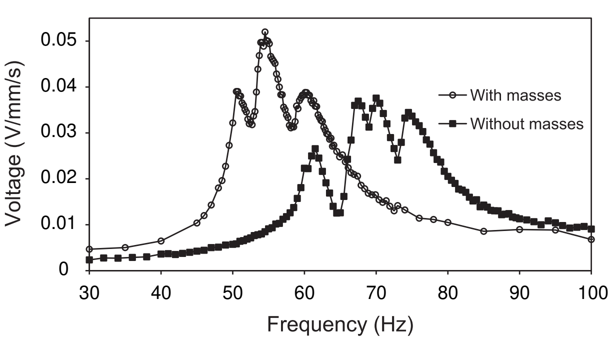

Fig. 7. Output voltage at 1st resonance mode when all cantilevers are in parallel electrical connexion.

The proof masses values were between 8 and 12 mg. They were chosen in order to obtain resonant frequencies relatively close to each others. The multi-cantilever device exhibited a larger frequency spectrum than any of the cantilevers measured separately. Its bandwidth at half maximum was larger than 15 Hz. The same result was obtained for the 2nd resonance mode (Fig. 8). The different cantilevers lengths and proof masses at their free-ends make the multi-cantilever a multi-frequency device. It was thus possible to exploit mechanical vibrations characterized by different peak-power frequencies or by a wide bandwidth.

As demonstrated by Ly et al. [22], it could be seen that for the same vibration velocity, the output voltage at the 2nd resonance mode was slightly higher than the one obtained at the 1st resonance mode. Moreover the voltage value increased with the use of proof masses.

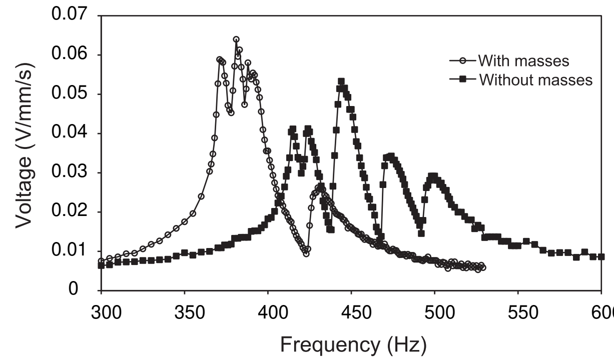

Fig. 8. Output voltage at 2nd resonance mode when all cantilevers are in parallel electrical connexion.

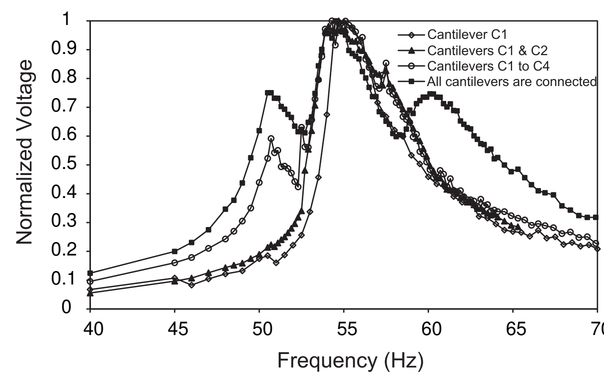

Fig. 9. Normalized output voltage at 1st resonance mode of different cantilever configurations, showing the frequency bandwidth as a function of the number of connected cantilevers.

Table 2
Comparison of bandwidth value according to the number of connected cantilevers.

	1 Cantilever (Hz)	2 Cantilevers	4 Cantilevers	6 Cantilevers (Hz)	Δf (%)
1st mode	~5	~7 Hz	~10 Hz	~15	200
2nd mode	~20	Not measured	Not measured	~35	75

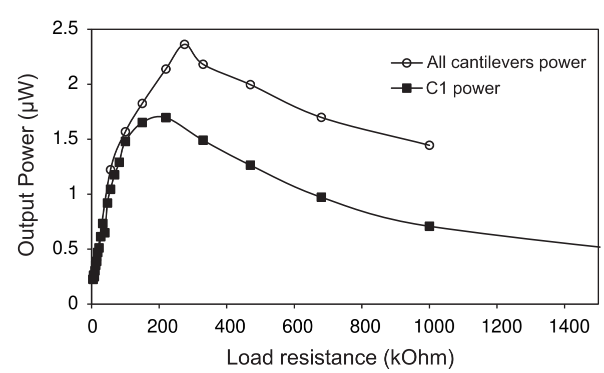

Fig. 10. Output power vs. load resistance at 1st resonance mode.

Fig. 9 shows a comparison of the device bandwidth (at the 1st resonance mode) when two, four or all cantilevers were in parallel connection. It shows that the bandwidth at half maximum increased when increasing the number of connected cantilevers.

The values of the frequency bandwidth according to the number of connected cantilevers at 1st and 2nd resonance modes are reported in Table 2. For the 2nd mode, bandwidth values were measured either for one cantilever or when all cantilevers were connected. It was shown that the bandwidth of the array was increased by 200% for the 1st mode and by 75% for the second mode when compared to a single cantilever.

Fig. 10 shows the evolution of power according to the load resistance at the 1st resonance mode (54.5 Hz) and a source velocity of 35 mm/s. When all cantilevers were in parallel electrical connexion, the maximum output power was about 2.5 μW when the load resistance was about 275 k Ohm. The power was increased by 39% when compared to the power of a single cantilever.

This generated power was relatively low because cantilevers were designed to enhanced bandwidth. In order to improve power, cantilevers lengths and proof masses should be tuned to have identical individual resonance frequencies.

To overcome this drawback, individual rectifiers could be implemented in order to cumulate the output powers of all cantilevers and avoid the power transfer between the individual cantilevers. The output power could also be improved by increasing the proof masses values.

5. Conclusion

For many applications, energy sources such as vibrational energy of the surrounding mechanical structure should be considered. A low frequency and wideband piezoelectric converter was developed by elaborating a ceramic-based cantilevers device using tape casting and laser cutting. The laser cutting process, made it possible to develop devices with various shapes and sizes quite easily.

It was shown that the frequency bandwidth could be widened to 200% for the 1st resonance mode and up to 75% for the 2nd resonance mode by using a multi-cantilever device and could be tuned by adding proof masses. This band-pass could be further improved by increasing the cantilevers number and by fine tuning of the cantilevers dimensions and the proof masses. It was 2.5 μw and it could be improved by increasing the cantilevers number. This power could be also improved by tuning cantilevers lengths and proof masses to have identical individual resonance frequencies. An adapted electrical circuit should be developed in order to optimize and to store the harvested energy. Such generators could be used to efficiently exploit mechanical energy provided by vibration sources with different peak-power frequencies.

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References

[1] B.S. Lee, S.C. Lin, W.J. Wu, X.Y. Wang, P.Z. Chang, C.K. Lee, Piezoelectric MEMS generators fabricated with an aerosol deposition PZT thin film, J. Micromech. Microeng. 19 (2009) 065014.
[2] W.J. Choi, Y. Jeon, J.H. Jeong, R. Sood, S.G. Kim, Energy harvesting MEMS device based on thin film piezoelectric cantilevers, J. Electroceram. 17 (2005) 543–548.
[3] A. Hajjaji, D. Guyomar, S. Touhtouh, S. Pruvost, Y. Boughaleb, M. Rguiti, C. Courtois, A. leriche, K. benkhouja, Nonlinearity and scaling behavior in a soft lead zirconate titanate piezoceramic, J. Appl. Phys. 108 (2010) 064103.
[4] A. Hajjaji, G. Guyomar, S. Pruvost, S. Touhtouh, K. Kaori, Y. boughaleb, Temperature/electric field scaling in ferroelectrics, Phys. B – Condens. 405 (2010) 2757–2761.
[5] L. Mateu, F. Moll, Optimum piezoelectric bending beam structures for energy harvesting using shoe inserts, J. Intel. Mater. Syst. Str. 16 (2005) 835–845.
[6] S. Roundy, E.S. Leland, J. Baker, E. Carleton, E. Reilly, E. Lai, B. Otis, J.M. Rabaey, P.K. Wright, V. Sundararajan, Improving power output for vibration-based energy scavengers, IEEE Pervas. Comput. 4 (2005) 28–36.
[7] H.W. Kim, A. Batra, S. Priya, K. Uchino, D. Markley, R.E. Newnham, H.F. Hofmann, Energy harvesting using a piezoelectric "cymbal" transducer in dynamic environment, Jpn. J. Appl. Phys. 1 (43) (2004) 6178–6183.
[8] W.J. Wu, Y.Y. Chen, B.S. Lee, J.J. He, Y.T. Peng, Tunable resonant frequency power harvesting devices, Proc. SPIE 6169 (2007) 55–62.
[9] A. Cammarano, S.G. Burrow, D.A.W. Barton, A. Carrella, L.R., Clare tuning a resonant energy harvester using a generalized electrical load, Smart Mater. Struct. 19 (2010) 055003.
[10] C. Peters, D. Maurath, W. Schock, F. Mezger, Y. Manoli, A closed-loop wide-range tunable mechanical resonator for energy harvesting systems, J. Micromech. Microeng. 19 (2009) 094004.
[11] M. Wischke, M. Masur, F. Goldschmidtboeing, P. Woias, Resonance tunability of clamped-free piezoelectric cantilevers, J. Micromech. Microeng. 19 (2009) 125020.
[12] D. Zhu, M.J. Tudor, S.P. Beeby, Strategies for increasing the operating frequency range of vibration energy harvesters: a review, Meas. Sci. Technol. 21 (2010) 022001.
[13] I.H. Kim, H.J. Jung, B.M. Lee, S.J. Jang, Broadband energy-harvesting using a two degree-of-freedom vibrating body, Appl. Phys. Lett. 98 (2011) 214102.
[14] S.M. Shahruz, Design of mechanical band-pass filters for energy scavenging, J. Sound Vib. 292 (2006) 987–998.
[15] H. Xue, Y. Hu, Q.M. Wang, Broadband piezoelectric energy harvesting devices using multiple bimorphs with different operating frequencies, IEEE T. Ultrason. Ferr. 55 (2008) 2104–2108.
[16] G.H. Feng, J.C. Hung, Optimal FOM designed piezoelectric microgenerator with energy harvesting in a wide vibration bandwidth, in: Proc. 2nd IEEE Int. Conf. on Nano/Micro Engineered and Molecular Systems (16–19) January 2007, Bangkok, Thailand) pp. 511–514.
[17] M. Ferrari, V. Ferrari, M. Guizzetti, D. Marioli, A. Taroni, Piezoelectric multifrequency energy converter for power harvesting in autonomous microsystems, Sensor. Actuat. A – Phys. 142 (2008) 329–335.
[18] I. Sari, T. Balkan, H. Kulah, An electromagnetic micro power generator for wideband environmental vibrations, Sensor. Actuat. A – Phys. 145–146 (2008) 405–413.
[19] S.C. Lin, B.S. Lee, W.J. Wu, C.K. Lee, Multi-cantilever piezoelectric MEMS generator in energy harvesting, IEEE Int. Ultrason. Symp. Proc. 1 (2009) 755–758.
[20] S. Roundy, P.K. Wright, J. Rabaey, A study of low level vibrations as a power source for wireless sensor nodes, Comput. Commun. 26 (2003) 1131–1144.
[21] M. Rguiti, S. Grondel, F. El Youbi, M. Lippert, C. Courtois, A. Leriche, Optimized piezoelectric sensor for a specific application: detection of Lamb waves, Sensor. Actuat. A – Phys. 126 (2006) 362–368.
[22] R. Ly, M. Rguiti, S. D'Astorg, A. Hajjaji, C. Courtois, A. Leriche, Modeling and characterization of piezoelectric cantilever bending sensor for energy harvesting, Sensor. Actuat. A – Phys. 168 (2011) 95–100.