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A Nonlinear Energy Harvester by Direct Printing Technology

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Abstract

This paper presents an energy harvester based on a bistable clamped-clamped beam to collect energy from wideband vibrational sources at low frequencies. The device exhibits a nonlinear dynamic behaviour which can be described by a double well bistable potential with a switching threshold and two stable equilibrium states. The beam switching is activated by environmental vibrations. The mechanical-to-electrical energy conversion is performed by a screen printed piezoelectric layer electrically connected using InterDigiTed Electrodes (IDT) realized by the inkjet printing of a silver based solution on a flexible PET (PolyEthyleneTerephthalate) substrate through a cheap commercial EPSON® inkjet printer. Main advantages of the proposed approach are related to the wide frequency band assuring high device efficiency and low cost technologies adopted to realize both electrodes and the piezoelectric layer.

Keywords: Nonlinear Energy Harvesting; Bistable Systems; Wideband Vibrations; Direct Printing; Piezoelectric Materials;

1. Introduction

In the last few decades, there has been a rapid development in the field of portable, small-scale and low-power electronic devices, including wireless electronics, mobile systems, wireless sensor networks and wearable electronics. These devices need continuous and reliable electric power sources and scientific research has recently focused on energy harvesting solutions to provide an autonomous solution to power up them by exploiting the energy scavenged from their operating environment. Among different solutions, environmental mechanical vibrations play a major role because they represent one of the most ubiquitously available sources that can potentially deliver a significant amount of energy [1].

Traditional energy harvesters are based on linear resonant mechanical structures, e.g. cantilever beams, eventually coupled with inertial masses and often exploit a piezoelectric mechanical-to-electrical conversion mechanism. Although such devices are really efficient when stimulated close to their resonance frequency, the need for harvesters able to scavenge energy more efficiently from wideband

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vibrational sources pushes the development of different solutions exploiting nonlinear mechanisms, such as clamped-clamped beams and compliant mechanisms [2]. In fact, it has been demonstrated that bistable systems, under proper conditions, can provide better performances, compared to linear resonant oscillators, in terms of the amount of energy extracted from vibrations having a wide spectrum [3].

Plastic or polymeric substrates represent one of the most suitable choices for the realization of flexible structures as they are cheap and compatible with direct printing technologies. In fact, direct printing technologies have been intensively studied in the last years because they represent a fast and low cost strategy that could replace, in specific contexts, traditional fabrication techniques (e.g. sputtering and lithography) both in the mass production for industries and in the rapid prototyping for the research and academic laboratories. Among direct printing techniques, more attention has been essentially reserved to screen printing and inkjet printing, in the realization of printed devices [4].

Screen printing is a technique requiring the use of a mask that acts as stencil while inkjet printing consists in the deposition of a layer of functional ink that can be easily deposited on the substrate in defined patterns without the need of masks. This reduces time, costs and waste of materials. Moreover, deposition in inkjet printing is contactless and makes it compatible with different kinds of substrates, such as PET. Depending on the ink to be deposited and on its compatibility with printing heads, very cheap commercial inkjet printers can be adopted, lowering fabrication costs. Some of the functional inks used are PEDOT-PSS and Polyaniline (PANI), to implement functional layers in sensors, and aqueous dispersions of metal nano-particles (in particular silver), to realize conductive electrical connections.

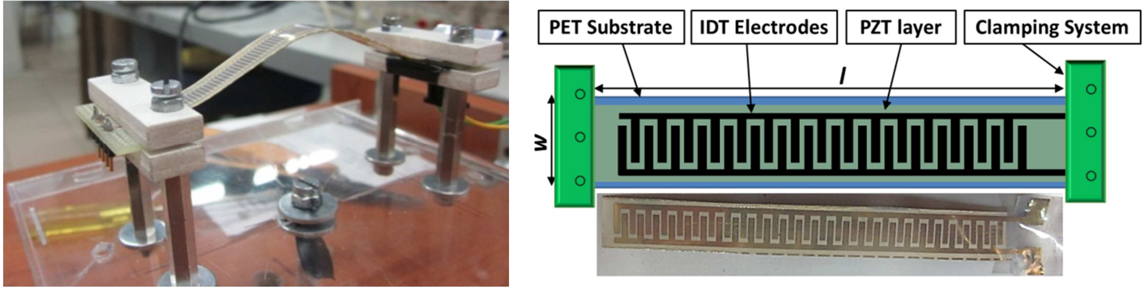
Many examples in the literature adopt a mixed approach for the realization of low cost devices by direct printing technologies: conductive structures (such as wires, coils, capacitor electrodes) are usually implemented by screen printing technology while polymer layers (such as PEDOT-PSS for resistive patterns) and functional layers (such as PANI for gas sensors) are successively deposited by low cost inkjet printers. Some examples are resistors and electrodes realized by PEDOT-PSS on PET [5], PANI based devices for the detection of ammonia [6], ZnO thin films based gas sensor [7] and strain gauges [8].

This paper presents the rapid prototyping of an energy harvester of centimeter size exploiting the bistable dynamics and assuring a wide bandwidth at low frequencies and a high device sensitivity. Low cost strategies based on direct printing technologies are adopted to reduce both costs and realization time.

2. The device prototype

The device consists of a PET (PolyEthylene Terephthalate) substrate, about 100 μm thick, that implements a clamped-clamped beam. On the top of this beam, a layer containing two pads and two InterDigiTed Electrodes (IDT) has been realized by inkjet printing a conductive pattern of the silver nano-particles solution "Metalon® JS-B15P" by Novacentrix, through a cheap commercial EPSON® inkjet printer. IDT fingers width, length and thickness are about 200 μm, 5 mm and 200 nm, respectively, while the track spacing is about 300 μm. The IDT electrically connect the piezoelectric layer realized by screen printed lead zirconate titanate (PZT) films with a final thickness of about 25 μm. After the deposition, the PZT layer is poled applying an electrical field of about 2MV/m. Due to the electrodes geometry and the poling direction, the piezoelectric element works predominantly in the mode 33. A clamping system allows for both fixing of the beam ends and pads connection. Fig. 1a shows a picture of the realized prototype and Fig. 1b reports a diagram (not in scale) of the device compared with a picture of the beam.

When a suitable precompression DY is applied by the clamping system to both beam ends, the clamped-clamped beam exhibits a bistable behaviour due to the buckling. An upper and a lower stable equilibrium positions appear having a distance DX. An increase of DY results in an increase of DX. In order to achieve commutations between these stable states, a force F having amplitude larger than a certain threshold (imposed by the bistability) must be applied approximately at the center of the beam in its out-of-plane direction. In this case, this force is given by the product of the acceleration coming from external vibrations and of the beam mass (which can be increased by placing a proof mass at the center of the beam). Strains due to the beam commutations are converted into an output voltage by the PZT layer. An increase of the distance between stable states *DX* leads to a growth of both the output voltage and the force amplitude required for commutations.



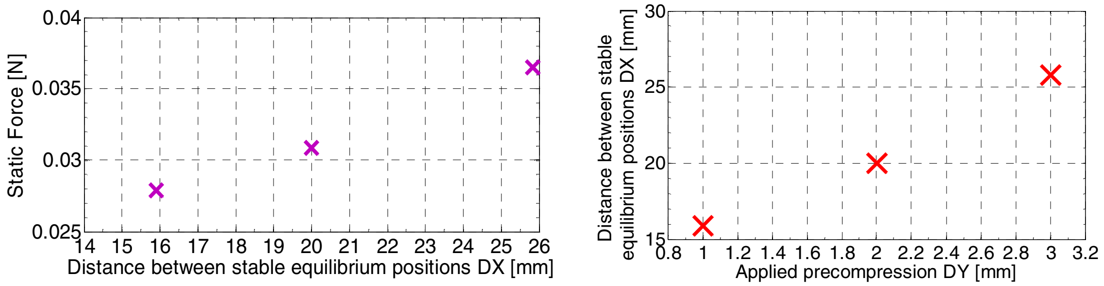
(a) (b)

Fig. 1. (a) The real prototype; (b) Diagram of the device structure and of its layers together with a picture of the device.

In order to define the beam length *l* and width *w*, the beam precompression *DY,* a suitable design flow has been adopted. First of all, the amplitude of accelerations from target input vibrational sources must be taken into account; then, the amount of the proof mass *m* can be (optionally) chosen on the basis of the required distance *DX* between stable states and, finally, the required precompression *DY* is evaluated.

3. Results and conclusions

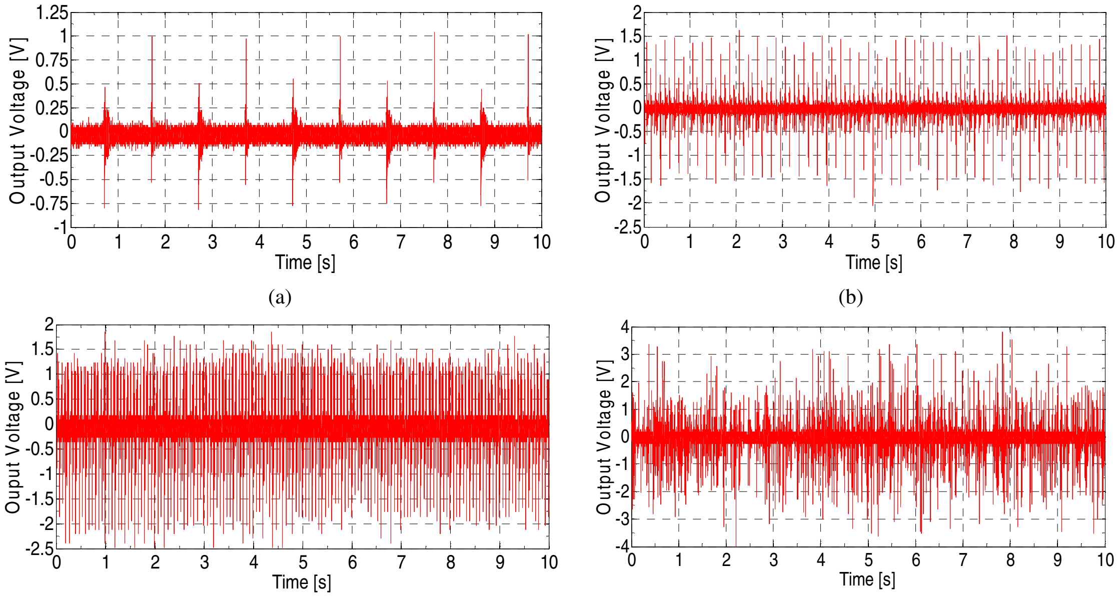
Several tests have been performed to define the device mechanical behaviour and to assess the relationships among device parameters useful for the definition of the geometry in the design flow. Results of the experimental mechanical static characterizations are shown in Fig. 2; results refer to a beam having a length *l* of 9 cm, a width *w* of 1 cm and a mass of 420 mg. No proof mass is applied.



(a) (b)

Fig. 2. (a) Results of the experimental characterization of the relationship between the distance between stable equilibrium states *DX* and the static force required to get a commutation between stable equilibrium states when no proof mass is applied. (b) Results of the experimental characterization of the relationship between *DX* and the required beam precompression *DY*.

In order to assess the expected dynamic behaviour of the device, several mechanical stimuli, generated by a shaker and having the waveform of a periodic burst (train of pulses of finite duration) with a fixed frequency and a defined amplitude, able to make the device switching between its stable equilibrium states, have been applied as input. Output voltages generated with no electrical loads have been measured and are shown in Fig. 3 for different frequencies of the input burst. The working frequency band of the device is estimated around 70 Hz.



(a) (b)

(c) (d)

Fig. 3. Signals generated by the piezoelectric conversion without an electrical load. The mechanical source is a periodic burst (train of pulses of finite duration) with a defined amplitude and a frequency of: a) 1 Hz, b) 10 Hz, c) 30 Hz and d) 70 Hz.

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