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# A diode-less mechanical voltage multiplier: A novel transducer for vibration energy harvesting

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ABSTRACT

This paper addresses the general area of electrical power collection and storage from vibrations. Energy harvesting from vibration sources through piezoelectric transduction is emerging as an interesting option for powering autonomous devices. In this research area, voltage multipliers are usually adopted to boost the voltage in order to reach a suitable level for the load circuits; these kind of devices are normally composed of diodes and capacitors in particular configurations.

The novel approach proposed in this paper is called “All Mechanical Vibration Piezo-Electric Voltage Multiplier”; it allows the multiplication of the voltage produced by a piezoelectric transducer and it is based on a series of capacitors and mechanical switches (cantilever beams and stoppers) suitably connected. A suitable arrangement of switches, capacitors and piezoelectric transducers will result into the proposed mechanical voltage multiplier structure; no diodes are required and no control circuit is needed to allow the system to work. In this paper the working principle is introduced together with analytical models and numerical simulations. Experimental results are also reported to further confirm the validity of the proposed strategy: they have been obtained by using a macro-scale laboratory prototype.



## 1. Introduction

Energy harvesting is one of the hottest topic addressed by the scientific community in the last years as alternative power supply for electrical devices, due to the large improvement in wireless and low-power technologies [1,2]. Several strategies for scavenging energy have been proposed based on solar [3], thermal [4,5], biochemical [6], vibrational sources [7] in order to give autonomy to electrical devices like wireless sensors. Vibrational sources are abundant in a lot of environments, rich of energy and exploitable in order to implement a transduction from mechanical to electrical power [8–11]. Transduction strategies have been investigated and developed, such as piezoelectric [12], electrostatic [13] and electromagnetic [14]: among these piezoelectric approaches have usually shown better performance than the others [7]. Furthermore, different solutions have been proposed in order to intercept vibrations and electro-mechanical devices have been designed, simulated and implemented to achieve this goal [15–17]. The development of micro and nano machining techniques has quickly led to the fabrication of smaller and smaller devices to be adequately power supplied; in this context, the “power section” dimensions should be compatible with the device's size with a consequent drastic drop of the electrical power levels of the transducers. This condition strongly restricts the use of the classical approaches to rectify the alternating voltages provided by the transducer and also to store the harvested energy: in particular the use of diodes, widespread in classical solutions (i.e. full bridge rectifiers, voltage multipliers), is not compatible with low voltage small harvester because there is a threshold to be overcome, typically 0.7–0.8 V, that can be reduced, to about 0.1 V with “active approaches” [18], but not removed. Several strategies have been developed in order to rectify the voltage avoiding the use of diodes, as authors propose in Ref. [19], where the rectified output voltage reaches a steady-state value ideally equals to the rms (root means square) value of the input one; in this case, a mechanical switches system has been implemented using a nonlinear bistable approach, with very good performances in terms of widespread large frequency response.

As it is shown in Ref. [20] the voltage output can be both incremented and rectified through a synchronized mechanism based on inductor, switch and full diode bridge, moreover in Ref. [21] authors propose an improvement of this latter approach, which shows better performances in presence of random vibrational inputs, that represent the largest number of occurrences in nature.

In this paper a novel strategy for rectifying and multiplying an alternate voltage by avoiding the use of diodes is proposed with application to vibration energy harvesting. The proposed device

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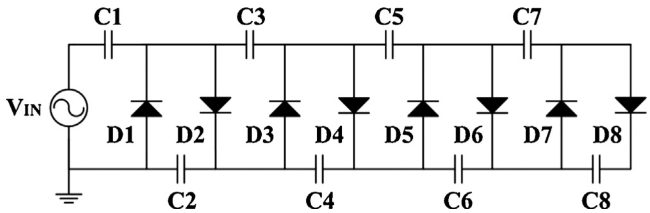


**Fig. 1.** Electrical schematic of the classic diode based voltage multiplier, also called Villard cascade.

architecture is based on the classical charge pump, however here the diodes are replaced by couples of mechanical switches driven by an external vibrational input so no active elements are required. The system allows for voltage boost also in the case of very weak voltages gathered from the harvesters thus providing useful signals even in the case of miniaturized devices where the output voltage will be well below the diode threshold. In literature integrated systems including mechanical switches in MEMS technologies have been proposed, for example in Ref. [22] authors show a mechanical rectifier for micro electric generators with detailed description of the fabrication process. The voltage generator is represented by a piezoelectric transducer, embedded into the vibrating cantilevers which deforms according to the vibration. The paper is structured as follows: in Section 2 the working principle and the analytical model will be described and are reported together with the numeric simulations results shown too; in Section 3 the macro-scale laboratory prototype will be described and the experimental results obtained shown together with simulations results in the case of very weak voltages; finally, in Section 4 conclusions and future trends will be provided.

## 2. Working principle, analytical model and simulations results

Voltage rectification is one of the most important issues in a lot of microelectronics and micro-systems applications: usually, a simple voltage rectifying mechanism is not sufficient to satisfy the requirements, especially when a higher level than the simple rms (root means square) input value is required.

Typically, capacitors and diodes suitably interconnected in networks are used in order to obtain the desired multiplication effect. An example is shown in Fig. 1, where a circuital configuration known as Villard Cascade is shown: these kind of solutions are limited by the presence of diode thresholds that must be overcome by the input signal in order to guarantee a correct work. It is clear that in the specific conditions characterized by input voltage signals under diode activation threshold, the classic Villard Cascade approach, based on diodes, is not able to provide any output voltage. Innovative solutions are needed to avoid the use of diodes: starting from this consideration the proposed approach has been developed and will be shown below.

Let us consider a single cell (Fig. 2a) of the network shown in Fig. 1. The basic idea of the novel approach is to replace diodes with a couple of mechanical switches (Fig. 2).

The working principle is based on the anti-phase behavior of the switches, according to the sign of the input voltage, thus emulating diodes behavior: specifically, considering Fig. 2, if $V_{IN}$ is negative, S1 is closed and S2 open as it would be for D1 and D2, while if $V_{IN}$ is positive the two switches will reverse their configuration.

In electromechanical systems, vibrations are often used as energy source; there are several mechanisms used to transform mechanical energy to electrical, for example the piezoelectric transduction Ref. [23], according to which if a piezoelectric transducer is placed into an oscillating systems it provides an alternate voltage source as shown in Fig. 2.

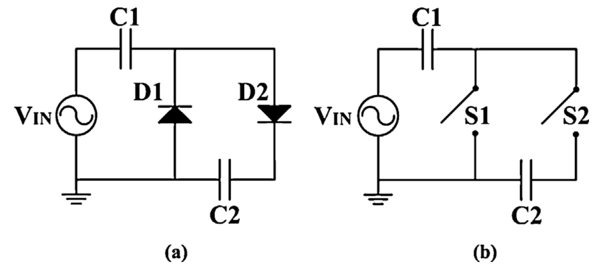


**Fig. 2.** Comparison between the single cell of traditional voltage multiplier (a) and the proposed approach (b): the switches replace the diodes emulating their behavior, but no voltage threshold has to be overcome.

Referring to Fig. 3, if there is no input acceleration the piezoelectric voltage is zero, the switches are open so no current flows through the circuit and no charge appears at the capacitors (Fig. 3a); when an input acceleration occurs, providing a piezoelectric voltage negative, S1 is closed, S2 open and a positive current flows through C1 in the sense of the arrow so C1 is charged with a positive voltage $V_{C1}$ (Fig. 3b). In the following step (Fig. 3c) the piezoelectric voltage is positive, S1 is open and S2 closed so C2 is charged with a positive voltage $V_{C2}$ obtained adding $V_{PZT}$ with $V_{C1}$; finally, in the last step, the input acceleration disappears, both of the switches are open, and a positive voltage is maintained across C2 (Fig. 3d).

The maximum value achievable for $V_{C1}$ is ideally the rms value of the piezoelectric voltage and $V_{C2}$ is $2{\cdot}V_{PZT}$ (rms): connecting $n$ cells in cascade and repeating the same considerations as for the single cell, a $2{\cdot}n{\cdot}V_{PZT}$ (rms) can be obtained (Fig. 4).

The goal of the proposed approach is to realize a 4-stage mechanical voltage multiplier: it is based on the use of 4 cantilever beams with 4 couples of stoppers that implement the mechanical switches and another beam (together with a piezoelectric transducer) used for generating an alternate voltage where each cantilever can be modeled with a second order mass-spring-damper system. In order to implement the synchronization mechanism between every couple of switches (as better explained in Section 3), the beams can be joined by a single mass on their free tips as the schematic system in Fig. 5 shows.

In this case the beams can be considered as 5 parallel springs, each of them characterized by an elastic constant $k_S$, so that in the model it is possible to summarize the 5 beams with a single spring with $k = 5{\cdot}k_S$.

Furthermore the system has been analytically modeled in order to evaluate both the mechanical and the electrical behavior through numerical simulations. As explained before a mass-spring-damper equation has been used to model the mechanical part of the system, capable to oscillate in response to an external mechanical stress (such as a vibrational input); an additional equation has been introduced to take into account the piezoelectric transduction effect, as shown in Eq. (1) [24]:

$$\begin{cases} m\ddot{x} + d\dot{x} + kx + d_{pzt}V_x = F(t) \\ \dot{V}_x = k_{pzt}\dot{\bar{s}} - \Gamma V_x \end{cases} \quad (1)$$

$x$, $\dot{x}$ and $\ddot{x}$ represent displacement, velocity and acceleration of the mass $m$ respectively while $k$ and $d$ the elastic constant and the damping coefficient, $V_x$ and $\dot{V}_x$ are the piezoelectric voltage and its first derivate, $d_{pzt}$, $k_{pzt}$, $\Gamma$, take into account the transduction and in particular are related to the piezoelectric damping effect, the material, the dynamic response respectively, $F(t)$ and $\dot{\bar{s}}$ are the external input mechanical force and the derivate of the strain according to Castigliano's Theorem [25].

In absence of external mechanical input, the mass $m$ lies in the $x = 0$ plane, all the switches are open (OFF) and the piezoelectric transducer doesn't produce any output voltage; when an external