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Energy Harvesting Combining Three Different Sources for Low Power Applications

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Abstract— **Hybrid energy harvesting system combining multiple sources is an alternative solution to harvest energy continuously and to increase the output power to bias the electronic systems. In this work is presented a prototype for harvesting energy, which combined three different sources. It contains a piezoelectric cantilever based on Lead-Zirconate Titanate piezoelectric transducer (PZT) in order to harvest the ambient vibrations, a solar cell for sunlight and an antenna capable to harvest ambient Radio Frequency (RF) energy. The design, implementation and characterization of the circuits for signal conversion from AC to DC for the case of piezoelectric generator, and the RF to DC for the antenna are presented. The RF harvesting circuit operates at 2.4 GHz obtaining a voltage of 71mV. The prototype is capable to generate a maximum DC power around 241.3 mW when the piezoelectric, solar cell and RF devices are connected together. Thus, the output power of this hybrid harvesting circuit is very attractive for low power electronic applications.**

Keywords—piezoelectric; solar; RF; harvesting energy

I. INTRODUCTION

Energy harvesting (EH) is the process of scavenging power from the ambient energy resources [1]. This ambient energy is related to green energy sources such as solar, thermal, wind, vibrations and electromagnetic radiation. The amount of energy transformed from the ambient sources can power up different applications e.g. biomedical devices, sensor nodes, low power consumable electronics and also to recharge batteries. Energy harvesting has received great attention because is a potential solution to realize handheld electronics with long-term operation and also self- powered electronics, eliminating the need of changing batteries frequently or augmenting the battery usage. The devices that harvest energy from the ambient require specific environmental conditions; for instance, solar cells and piezoelectric generators demand sunlight and mechanical vibration, respectively. But, in the case of indoor condition the efficiency of the solar cell decreases [2]. Since these conditions do not exist all the time, the energy harvesters need to transform continuously electricity even for the changes in the environment. The most investigations in the energy harvesting generators have focused on individual conversion mechanisms (electrostatic, piezoelectric, electromagnetic, photovoltaic) however they produced limited output power. For example in the case of Radio Frequency (RF) harvesting circuits the reported amount of power available is very little around of 158 nW at 960MHz [3]. Some solutions at microelectronic level have been proposed combining and selecting multiple sources with the maximum power input or connecting the storage stages of the individual energy sources in series [4, 5]. Other studies have reported hybrid energy harvesting systems combining piezoelectric and electromagnetic micro-generators [6-8] because these mechanisms are suitable for small size harvesters and compatibles with standard microelectromechnical systems (MEMS) manufacturing process. However, until the moment there is not an optimal harvesting energy system and a demand to explore topologies for multiple sources are under study [9].

In this research, an energy harvester prototype is presented, using three sources: piezoelectric, solar and radiofrequency (RF), with the consideration that the prototype must be to self-powered. For each source, its signal conditioning circuits and conversion of energy have been constructed and characterized in order to manage the different environment conditions and to increase the output power of the energy harvesting system.

II. MATERIALS AND METHODS

The harvesting energy using multiple sources consists of four stages: an energy source, the conversion, the adder circuit and the storage energy (battery or supercapacitor), as shown in Fig. 1, which corresponds to the complete power system diagram. The main components for individual sources are:

a) Piezoelectric: AC to DC rectifier and DC-DC converter

b) Solar: DC-DC converter with MPPT control.

c) RF environment: Antenna, matching network, RF to DC converter and doubler

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In the next subsections the details for each source are described.

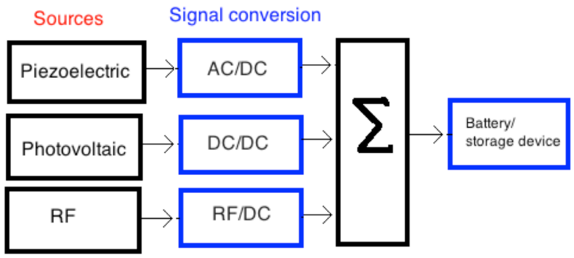

Fig. 1. The Block diagram of the energy harvester, which include piezoelectric, solar and RF input sources. The complete system considers the following stages: source, conversion, addition and storage

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A. Piezoelectric

The vibration can be converted to electrical energy by the piezoelectric mechanism, with employ the mechanical strain of piezoelectric elements under loaded force due to direct piezoelectric effect [4]. Lead Zirconate Titanate (PZT) is one of the most common materials used in the fabrication of piezoelectric harvesting devices since it shows a high efficiency of mechanical to electrical energy conversion [10]. The Fig. 2(a) shows the piezoelectric beam generator (PZT-5H) from piezosystem Inc. used as vibration transducer. For its characterization of the beam, a shaker vibration system was used as a source of mechanical vibration, it is connected to an amplifier and a function generator as is shown in Fig. 2(b). The piezoelectric beam generates a voltage in AC (alternating current- sinusoidal waveform) and the signal is measured using an oscilloscope. Then, a full-wave bridge rectifier based on 1N5820 Schottky diodes is used for the AC signal, and its output is connected to a load resistance (R_L). When resonant vibration is achieved, the piezoelectric source has the maximum output power under the load resistance, and the output power can be determined.

The resonant frequency of the piezoelectric cantilever can be expressed in terms of the elastic module, Y_{11} (N/m^2), an can be determine by (1) [10]:

$$f = \frac{0.16t_h}{L^2}\sqrt{\frac{Y_{11}}{\rho}} \qquad (1)$$

where t_h is the thickness of the beam (0.00051m), L is the length (0.0318 m), W is the width (0.0032m), and ρ is the density of the material (Kg/m^3) respectively.

The complete characterization of the piezoelectric cantilever was performed with an integrated circuit (IC) LTC3588-1 from Linear Technology; it was used as energy harvesting rectification and conversion. The LTC3588-1 integrates a low-loss full-wave bridge rectifier with buck converter to form a complete EH module optimized for high output impedance energy sources such as piezoelectric transducers [11].

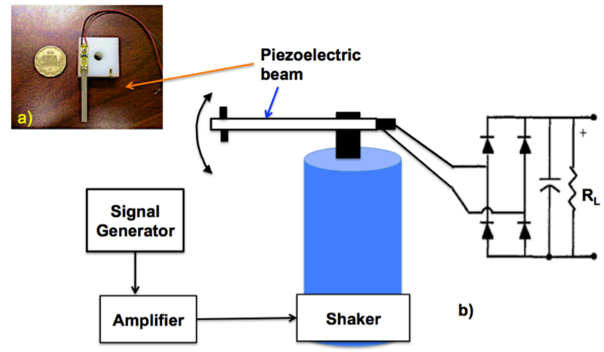

Fig. 2. (a) Piezoelectric cantilever as vibration transducer, (b) the experimental setup for the characterization of EH vibration source.

B. Solar

The solar cell is a device that converts the light into electricity using the photovoltaic effect. The materials used for solar cells include poly-crystalline Silicon (Si), mono-crystalline c-Si, amorphous Silicon (a-Si), Cadmium Telluride, and Copper Indium Selenide-Sulfide. Mono c-Si solar cells are expensive with efficiency around 25% [12]. a-Si solar cells have been reported efficiencies around 7% with the advantage of low cost [2]. In this work a Radio Shack Model 2770051 solar panel was employed as input for the solar source, which is shown in Fig. 3(a). The panel is rated at 4.5 V, 1.5 W [13], the characterization was performed under standard conditions ($1000W/m^2$ at 25C) by a Oriel Sol2A Class ABA Solar Simulator (see Fig. 3b) to obtain from the I-V curve the open-circuit voltage (V_{OC}), short-circuit current (I_{SC}) and the maximum power point (MPP) respectively

The voltage at which the solar cell produces maximum power depends on solar radiation, ambient temperature and device temperature. Typically, the Maximum Power Point control uses an algorithm to search the MPP where a DC-DC converter extracts the maximum power available from a solar cell [14].

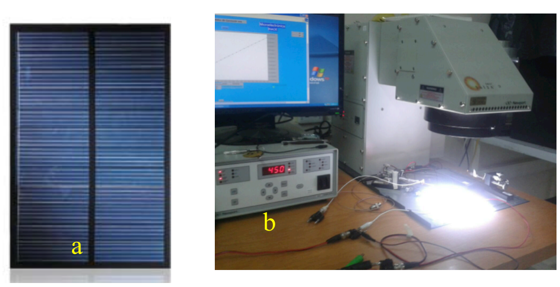

Fig. 3. (a) Solar panel, (b) The solar simulator for its characterization.

In this work the circuit proposed for the solar harvesting energy is showed in Fig. 4. The block diagram include the solar panel, the DC-DC and MPP tracking circuit and the stage to the batteries charger. For power management of the solar panel the DC to DC converter with integrated maximum power point control model LTC3105 from linear technology was selected, due to this is a complete single chip solution for energy harvesting from single photovoltaic cells [14]. In addition, its integrated low voltage start-up at 225mV operation ensure optimal energy extraction, it allows direct operation from relatively high impedance of solar cells and can be used to directly power circuitry or for charging energy storage devices.

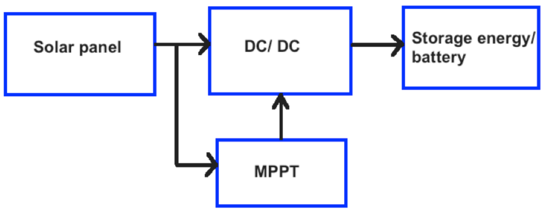

Fig. 4. Architecture for the solar EH module

C. *RF harvesting*

Currently, the use of wireless systems has increased due especially to the use of mobile phones and Wi-Fi networks which results in the increasing of radiating power. But the Radio Frequency (RF) energy radiation is also emitted by other sources such as radio and TV broadcasting, satellite communications. Due to the availability of these RF electromagnetic sources, the energy can be collected and rectified into electrical energy to power electronics devices, it is known as RF energy harvesting [15]. The most of communication systems are in the range from 75 MHz to 3.0 GHz, including TV, FM Radio, mobile phones and Wi-Fi. The 2.4GHz band was selected due to the availability in the ambient. The EH-RF system consists of an antenna, which is used to pick up the radiation signal from the source (e.g. mobile phone telecommunication tower, etc.). Then, the RF signal is rectified to DC signal by the diodes. This power conditioning is used to deliver the energy to the load.

In this work, the architecture for the EH-RF circuit is proposed with the block diagram showed in Fig.5; it is to be made of an antenna, a voltage doubler circuit used to convert the RF to DC voltage; impedance matching network which performs impedance transformation to ensure maximum power delivery.

A matching network is designed to match the impedance of the antenna to 50 ohms at 2.4GHz. Fig. 6(a) shows the lumped elements matching network. The matching network consists of a 3.3nH inductor and a 150pF capacitor. The capacitor is connected in parallel with the antenna ports.

The RF to DC design is based on the Villard voltage doubler circuit, taking in account a 7-stage Schottky diode voltage doubler circuit in order to increase the output voltage [16]. This voltage doubler circuit is shown in Fig. 6(b), it was fabricated using Schottky diode HSMS-2850 from Avago technologies. The features of these diodes are low forward voltage, low substrate leakage and very fast switching [17].

The antennas used for RF Harvesting system were a microstrip patch antenna [18] and microstrip bowtie antenna [19]. Patch antenna and bowtie antenna were designed and fabricated on the substrate Rogers 4003C with relative permittivity (ε_r) of 3.4, and with a thickness of 1.6mm. The central frequency of the antennas is 2.4GHz. Besides the characteristic impedance (Z_o) is 50Ω for both antennas. Fig. 7 shows a picture of the antennas employed for the RF Harvesting system.

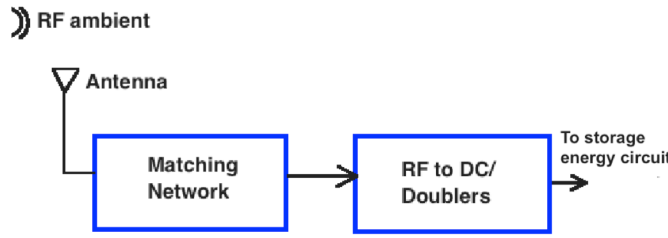

Fig. 5. Block diagram of the EH-RF module

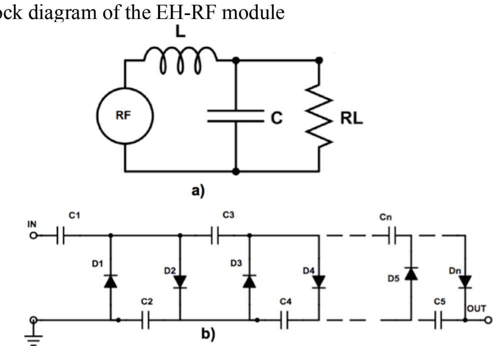

Fig. 6. Circuits for RF signal conditioning: (a) The Matching network circuit, (b) RF to DC converter and doubler stages.

D. *Connecting multiple sources and the storage stage*

To achieve a self-powered energy harvester prototype, the output of solar panel is used to bias an operational amplifier (OA), due to this source is who delivers most power from the three individual sources proposed in this work. The OA is connected in a voltage adder circuit based on non-inverting configuration; it is showed in Fig. 8. The adder is implemented for combining multiple inputs of the different energy harvesting sources into a single output voltage; all the values of the resistors were set at 100Ω. The OA model OPA170 from Texas instrument was selected due the features such as: single-supply, low-noise operational amplifier with the ability to operate on supplies ranging from + 2.7V to 36V, for portable and battery-powered applications [20].

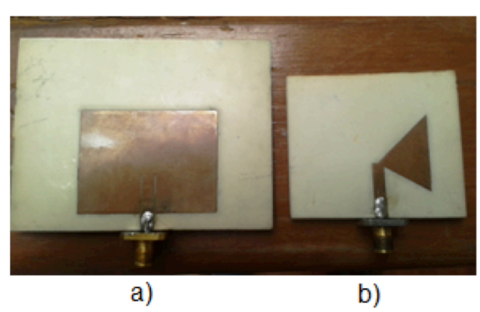

Fig. 7. Front view of a) Microstrip patch antenna, b) Microstrip bowtie Antenna

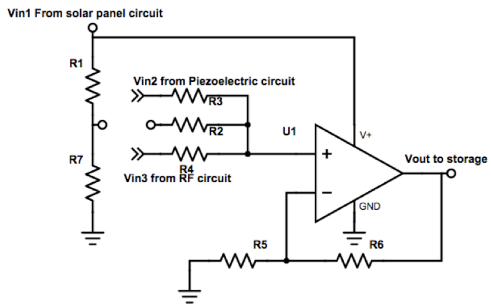

Fig. 8. The adder circuit for connecting multiple sources.

The output of the adder is connected to the storage stage. In this case, rechargeable batteries were chosen and the charging module was implemented using a simple Li-Ion batteries charger IC from Linear Technology's LTC4071, which requires only one external resistor to form a complete and compact charger solution, the device protects batteries and charges from previously unusable very low current, intermittent or continuous charging sources [21], the implemented circuit is shown in Fig. 9. In addition, the batteries could be considered as backup for the initial operation of the harvester prototype circuit in case of insufficient input power.

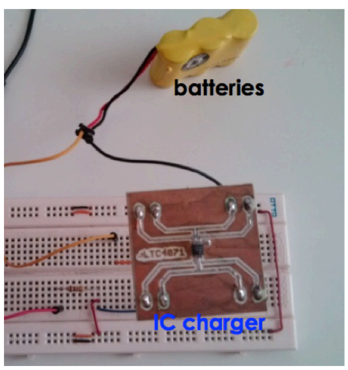

Fig.9. Application of the charger circuit with IC- LTC4071

III. RESULTS

The energy harvester prototype consists of a set of energy sources and its units as was showed in Fig. 1, each unit includes an ambient power source, the signal conversion and power circuits. In this section is presented the implementation for each energy source unit using commercial devices, including the printing circuit board for each IC´s. Firstly, the individual sources have been characterized using piezoelectric, solar panel, and RF antenna respectively. Then the complete system was tested in terms of the output voltage; in the following subsection are described the results including the voltage measured in the batteries.

A. vibration source

The experimental setup used to determine the frequency response and the output voltage is shown in Fig. 10. In order to obtain the output power and the voltage generated by the piezoelectric cantilever, it was evaluated using the AC to DC rectifier. The optimal resistance load, was found by varying it in steps of 10 KΩ to obtain the maximum dissipated power, using the relationship $P=V_{RMS}^2/R_L$.

The resonant frequency of the piezoelectric harvesting device under 1g of vibration resulted about 200 Hz as is shown in the inset of Fig. 11; the value is closed to the 234Hz obtained with (1). The output voltage was around 9.1V AC rms, which provided an output power equal to 0.4mW as is shown in Fig. 11. When the AC signal goes trough the rectifying and DC-DC circuit the maximum output voltage was equal to 2.1V at resonant frequency of 200 Hz, therefore the output power at was 240μW when the load resistance is 15KΩ.

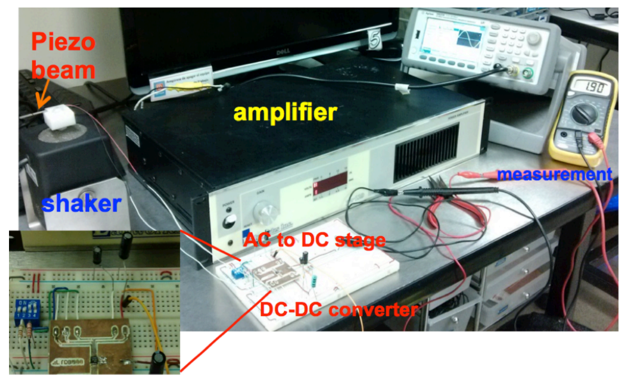

Fig.10. Experimental setup for the piezoelectric harvester, indicating the elements in the characterization and the cantilever beam, the scale of the measurement is in Volts.

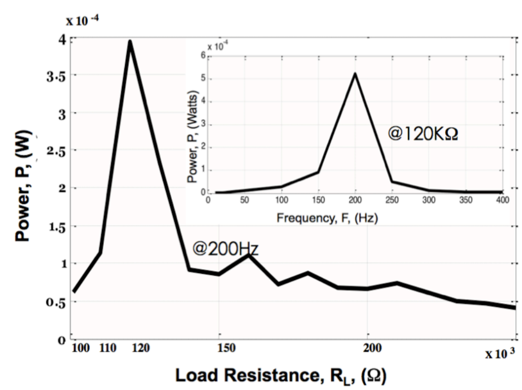

Fig.11. Characteristics of piezoelectric cantilever Power *vs* load resistance; the inset shows the optimal vibration frequency at 200Hz

Regarding, to the resonant frequency, the most reported works for vibration sources have showed high resonant frequencies around 500Hz [22]. Therefore the piezoelectric cantilever beam selected in this work is very promising for low power applications operating at low resonant frequency as the environment vibration sources.

B. Photovoltaic source

In order to determine the real values for Radio Shack (Model 2770051) solar panel used in this work, the I-V (current-voltage) and the power characteristics were measured and plotted, as is shown in the Fig. 12. The V_{OC} of the solar panel was 5V, which is consistent with the technical datasheet 4.5V [13]; the maximum current at short circuit was 210mA. In Fig. 12, the blue plot shows the Maximum Power Point (MPP), which resulted at 0.65W, it data is below to the advertised in datasheet referred at 1.5 W, it may be due to the losses of series connection of the cables. These values were considered for the circuit design. The experimental implementation for the solar EH module is showed in Fig. 13(a-c), and the regulated voltage was at 4.5V; it is taken to bias the OA and also into a voltage divider as input of the solar source to the adder circuit.

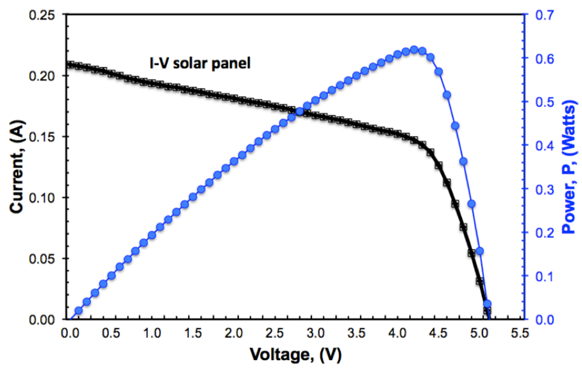

Fig. 12. The I-V characteristic for the solar panel, and the blue plot shows the maximum power point reached at 4.5V

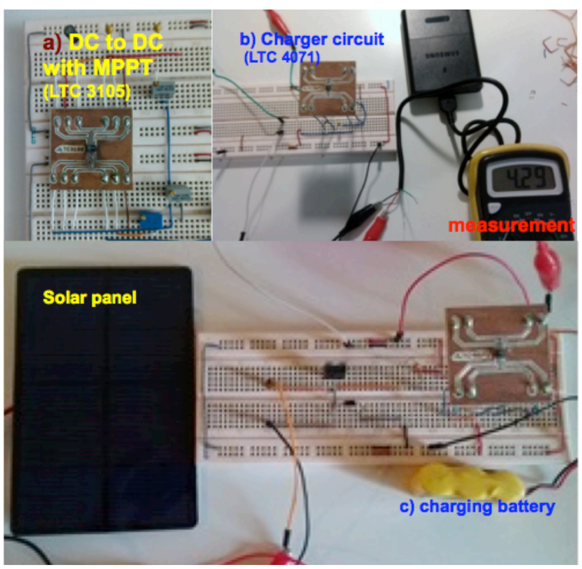

Fig.13. Solar panel unit: a) DC-DC with integrated MPPT circuit, b) battery charger circuit, c) view of complete module

C. RF source

The characteristic of the matching network connected to the anntena was measured using EXA signal analyzer model N9010A from Agilent techonologies. Fig. 14(a) shows the implementation of the matching network which is connected to the antenna. Fig. 14(b) shows the signal spectrum at 2.4GHz for -52.3dBm, it measurement corroborated the optimal desgin proposed at 50Ω for the RF antenna.

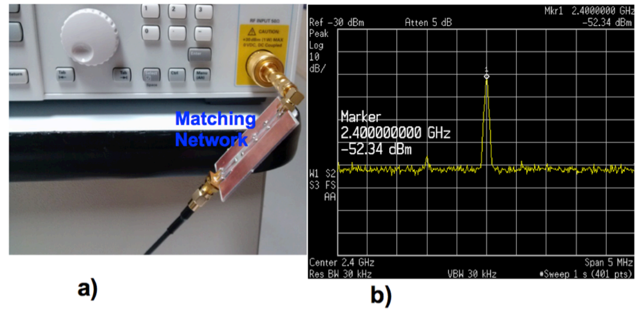

Fig. 14. (a) Matching Network circuit connected to signal analyzer, (b) antenna signal spectrum measured at 2.4GHz

In Fig. 15(a) is observed the three main components implemented for RF-EH: B (bowtie) antenna, the matching network circuit and the RF to DC doubler. Fig. 15(b) presents the measurement using a RF synthesizer HM8135 (from Rohde & Schwarz) as the RF source that transmits at a power of -40 dBm at 2.4 GHz, the maximum DC output voltage was 71 mV, using a R_L=1KΩ the output power is 5.0μW.

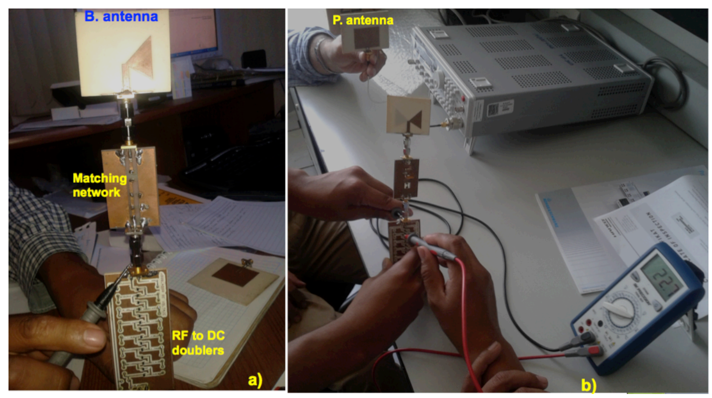

Fig. 15 (a) Photograph of the RF harvesting energy system, (b) measurement of the DC voltage after the signal is converted; the scale of voltmeter is in mV

D. Performance of complete system

TABLE I. COMPARISON WITH SYSTEMS BASED ON MULTIPLE SOURCES

No. of sour	*Types of sources*	*Output voltage (Volts)*	*Power (mW)*	*Ref.*
3	Thermal, Solar, Piezoelectric	1.8 regulated	T=1.3 S=5 Pz=0.5	[4]
2	Solar, wind	S=4.1 W=2.7	~80mW	[23]
3	Piezoelectric, Solar and RF	S=2.1 Pz=2.0 RF=71.1mV	241.3mW	This work

In Table 1 is presented a comparison with other related works [4, 23] that use multiple energy sources; the prototype developed here resulted with a higher power and it is due to the incorporation of the solar panel that delivers the highest power of the three sources, taking in account that its operation will be under ideal conditions of the spectral irradiance. The operation of the complete system is shown in Fig. 16, the total output voltage was at 4.17V, and it can provide self-operation for the system with the advantage to operate under different ambient conditions and providing enough energy for low power electronics applications. The maximum voltage for charging the batteries was reached after 240 min. In Table II is presented the power requirements for some low power electronic devices, it suggest that is possible to bias some of those with the harvesting energy prototype.

TABLE II. POWER REQUIREMENTS OF LOW POWER ELECTRONIC DEVICES

Electronic application	*Power consumption*
Cardiac pacemaker	15-50μW
Blood pressure sensor	<10 μW
Hearing aid	1mW
MP3 player	80-150mW
Watch	10 μW
Smart phone (GSM call)	820mW
WSN	100 μW

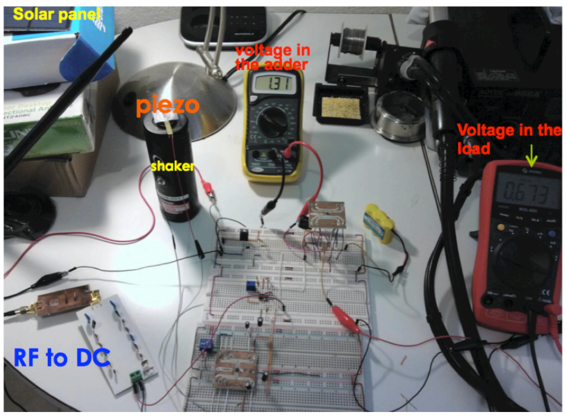

Fig. 16. The energy harvester prototype with multiple sources, the two measurements are in the load and the adder respectively

IV. CONCLUSIONS

In this work was demonstrated an energy harvester prototype with the signal conditioning and conversion that manage properly the energy. Our prototype can power electronics devices with a 241mW of power consumption like medical sensor and microcontrollers. The measurement of the RF power at 2.4Ghz is very low in comparison with solar and vibration sources, however it is distributed in the RF ambient and it is very attractive for the increasing in the wireless communication systems. For the three modules of the harvesting energy with the obtained DC power is possible the autonomous operation of the prototype and some low power electronics applications.

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REFERENCES

[1] S. Chalasani, J. M. Conrad, "A Survey of Energy Harvesting Sources for Embedded Systems," in Proceedings of the IEEE Southeastcon 2008, 3-6 April 2008, pp. 442-447.

[2] H. Yu, Q. Yue, and H. Wu, "Power management and energy harvesting for indoor photovoltaic cells system," Mechanic Automation and Control Engineering (MACE), 2011 Second International Conference on, 2011, pp. 521–524.

[3] S. H. Nasab, M. Asefi, L. Albasha, and N. Qaddoumi, "Investigation of RF Signal Energy Harvesting," Active and Passive Electronic Components, vol. 2010, Article ID 591640, 2010.

[4] Bandyopadhyay and A. P. Chandrakasan, "Platform architecture for solar, thermal and vibration energy combining with MPPT and single inductor," in VLSI Circuits (VLSIC), 2011 Symposium, Jun. 2011, pp. 238-239.

[5] H. Lhermet, C. Condemine, M. Plissonnier, R. Salot, P. Audebert, and M. Rosset, "Efficient power management circuit: From thermal energy harvesting to above-IC microbattery energy storage," IEEE J. Solid-State Circuits, vol. 43, no. 1, pp. 246–255, Jan. 2008.

[6] P. G.Jones, M. J. Tudor, S. P. Beeby and N. M. White, "An electromagnetic, vibration-powered generator for intelligent sensor systems", Sensors Actuators A Vol. 110 pp. 344-349, Feb. 2004.

[7] P. Mitcheson, P. Miao, B. Start, E. Yeatman, A. Holmes and T. Green, "MEMS electrostatic micro-power generator for low frequency operation", Sensor Actuators A, Vol. 115, pp. 523-529, Sept. 2004.

[8] B. Yang, C. Lee , W. Loon Kee and S. P. Lim, "Hybrid energy harvester based on piezoelectric and electromagnetic mechanisms", J. Micro/Nanolith. MEMS MOEMS. 9(2), 023002, April 2010.

[9] S. Bandyopadhyay and A. P. Chandrakasan, "Platform architecture for solar, thermal, and vibration energy combining with MPPT and single inductor, IEEE J. of Solid-State Circuits, vol. 47, no. 9, pp. 2199-2214, Sept. 2012.

[10] R. Ambrosio, A. Jimenez, J. Mireles, M. Moreno, K. Monfil and H. Heredia, "Study of Piezoelectric Energy Harvesting System Based on PZT", Integrated Ferroelectrics, Vol. 126, pp. 77-86, Jun. 2011.

[11] Linear Technology. LTC3588-1 - Nanopower Energy Harvesting Power Supply. http://cds.linear.com/docs/en/datasheet/35881fb.pdf, 2015

[12] A. Blakers, N. Zin, K. R. McIntosh and K. Fong "High Efficiency Silicon Solar Cells", Energy Procedia, Vol. 33, pp. 1–10, 2013.

[13] Radioshack 2770051 solar panel. http://radioshack.com/radioshack-1-5w-solar-panel-4-5v/2770051.html, 2015.

[14] N. Bourgoine, "Harvest Energy from a Single Photovoltaic Cell", Journal of Analog Innovation, Vol 21, no.1, pp. 2-6, April 2011.

[15] S. Hemour and K. Wu, "Radio-Frequency Rectifier for Electromagnetic Energy Harvesting: Development Path and Future Outlook", Vol. 102, Proceedings of the IEEE , pp. 1667-1691, No. 11, Nov. 2014.

[16] N. M. Din, C. K. Chakrabarty, A. B. Ismail, K. K. A. Devi and W. Y. Chen,"Design of rf energy harvesting system for energizing low power devices", Progress In Electromag. Research, Vol. 132, pp. 49-69, 2012.

[17] HSMS-285x Series, Surface Mount Zero Bias Schottky Detector Diodes (data sheet), http://www.avagotech.com/docs/AV02-1377EN, 2015.

[18] C. A. Balanis, "Antenna Theory: Analysis and Design", 3a ed. Wiley. 2005.

[19] M. A. Rahim, M. A. Aziz and C. Goh, "Bow-tie microstrip antenna design," IEEE 7th Malaysia International Conference on Communication, vol.1, 2005.

[20] Texas Instrument, single-supply, low-power operational amplifier , www.ti.com/lit/ds/sbos598a/sbos598a.pdf, 2015.

[21] Linear Technology, LTC4071 Li-Ion/Polymer shunt battery charger system with low battery disconnect, http://cds.linear.com/docs/en/datasheet/4071fc.pdf, 2015.

[22] R. Xu, A. Lei , C. Dahl-Petersen, K. Hansen, M. Guizzetti, K. Birkelund, E. Thomsen and O. Hansen, "Screen printed PZT/PZT thick film bimorph MEMS cantilever device for vibration energy harvesting", Sensors Actuators A Vol.188 pp. 383-388, 2012.

[23] C. Park and P. H. Chou, "AmbiMax: Autonomous Energy Harvesting Platform for Multi-Supply Wireless Sensor Nodes", in Sensor and Ad Hoc Communications and Networks, 2006. SECON '06, Reston VA, 28-28 Sept, pp 168-177,. 2006.