Flexible Hybrid Solar/EM Energy Harvester for Autonomous Sensors

Apostolos Georgiadis, Ana Collado, Selva Via, Cesar Meneses

Centre Tecnologic de Telecomunicacions de Catalunya (CTTC), Castelldefels, Barcelona, 08860, Spain

***Abstract* — A flexible electromagnetic (EM) / solar energy harvester is proposed that finds application in low power energy autonomous wireless sensor networks and RFID-enabled sensors. A low cost, compact and conformal harvester is implemented on a flexible polyester (PET) substrate combining a rectenna for EM harvesting and a flexible amorphous silicon solar cell for solar energy harvesting. A compact design is achieved by placing the solar cell on top of the radiating element. A coplanar UWB monopole antenna is designed and a rectifying network is optimized using harmonic balance in order to maximize the rectenna efficiency for low power electromagnetic signals in the GSM-850 and GSM-1900 frequency bands. The solar cell is integrated on the surface of the UWB antenna and electromagnetic simulation is used to optimize its location and the required DC interconnects in order to minimize the performance degradation of the antenna. Measured results of the performance of the hybrid energy harvester are presented showing good agreement with simulation.**

***Index Terms* — energy harvesting, rectenna, solar cell, flexible substrate, PET, UWB monopole, harmonic balance.**

I. Introduction

The new paradigm in wireless communication systems points towards ubiquitous sensor networks employing highly efficient, environmental friendly, and energy autonomous nodes. The use of low cost, flexible substrate materials together with low cost fabrication techniques provide a platform for integrating sensors and electronics implementing RFID-enabled sensor nodes [1]. Within this context, the design of a compact and conformal harvesting unit that provides complete autonomy to the sensor nodes becomes a critical issue. In order to maximize the amount of harvested power the use of hybrid harvesters is considered. In this work a low cost, flexible hybrid electromagnetic (EM) and solar harvester is proposed, able to provide sufficient energy to power commonly used commercial motes.

Wireless power transfer has been proposed in the past utilizing directive rectennas and high power transmission, however new applications have recently emerged by focusing on employing low profile, non-directive rectennas optimized to harvest energy from low power, ambient electromagnetic signals from existing employed communication systems and other RF/microwave sources [2]. In this work, a rectenna based on an ultrawideband (UWB) monopole is proposed, fabricated on low cost flexible PET substrate. In order to maximize the RF-to-DC conversion efficiency a printed matching network is used to provide conjugate matching in two commonly used frequency bands for mobile telephony. Alternatively, a reconfigurable matching network may also be employed, which, combined with some type of spectrum sensing capability, can lead to a smart EM harvesting system implementation.

In the proposed design the antenna and the solar cell share the same area, allowing for a more compact design. Such solar-antenna systems have been initially proposed for micro-satellite applications [3], however the recent interest in energy harvesting systems emerges as an additional promising application. The use of a flexible amorphous silicon solar cell proposed in this work, maintains the flexibility of the structure and its conformal placement capability.

Electromagnetic (EM) simulation is used for the design of the radiating structure and modeling of the solar cell [4]. In addition, EM simulation is used to optimize the placement of the DC interconnects required for the solar cell in order to minimize their effect on the antenna performance. The Thevenin equivalent of the antenna is then imported in a harmonic balance optimization [5] in order to design the rectenna circuit and maximize the RF-to-DC conversion efficiency in the desired frequency bands. A prototype has been fabricated and measurements demonstrate the performance of the harvester in good agreement with simulation. The proposed system may further be combined with a flexible capacitor (or battery) energy storage system in order to obtain a complete implementation of the energy harvesting and storage unit using flexible materials suitable for applications where conformal implementation is highly desirable such as for example (but not limited to) on-body communication systems.

II. EM Energy Harvester Design

Due to the limited amount of available energy from ambient EM energy sources, the combined recycling of energy from different frequencies is a must. Towards this objective the use of UWB or multiband rectennas that can capture communication signals from several frequency bands is introduced here.

The proposed design for the EM energy harvester can harvest energy from the GSM-850 and GSM-1900 frequency bands. It is based on the use of a 0.7GHz - 6 GHz UWB

978-1-61284-757-3/11/$26.00 C2011 IEEE

antenna, together with a rectifying circuit that converts the input RF signal into DC power. The selected material for implementing the rectenna system was a 75um thick flexible polyester (PET) substrate Akaflex PCL3-35/75 um with $\varepsilon = 3.3$ and $\tan\delta = 0.08$.

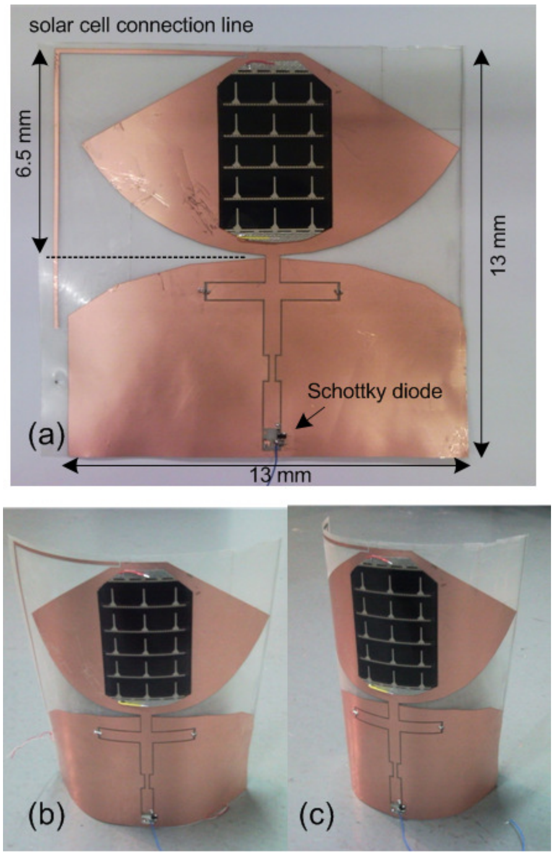

Fig.1. Designed and implemented hybrid solar/EM energy harvester. a) top view, b) bended structure with radius r =10cm , c) bended structure with radius r = 7cm.

A. UWB antenna and solar cell

The selected topology for the designed antenna was a printed monopole structure with a circular base and a centered feed line (Fig.1). The design was made in coplanar waveguide technology to overcome fabrication limitations when using microstrip technology with the selected substrate. In addition, coplanar waveguide technology requires only one metal layer, and therefore maintains the flexibility of the structure.

The monopole antenna was designed using a finite element based EM simulator. Starting from a circular disc and semi-circular disc implementation, the size of the radiating structure was minimized and a sector like structure was selected, eliminating the areas of the structure where the field distributions were weaker. In order to integrate the solar cell on the radiating structure, it was necessary to additionally include in the design one DC interconnect line (Fig. 1a). The number of required DC interconnects was minimized by using the conducting part of the antenna as the ground terminal of the solar cell element. The positive DC terminal of the solar cell is connected to a DC line from the top of the sectoral structure (Fig. 1), which was found using EM simulation to have the minimum effect in the antenna performance.

The designed antenna presents good input matching from 0.75GHz to 6GHz (Fig.2) and a gain value of approximately 0dB at 0.85GHz and 3.4 dB at 1.85GHz. Fig. 3 shows the simulated and measured evolution of the gain along the frequency band of the antenna. The measured radiation patterns corresponding to the E-plane and H-plane at 1.85GHz are shown in Fig. 4.

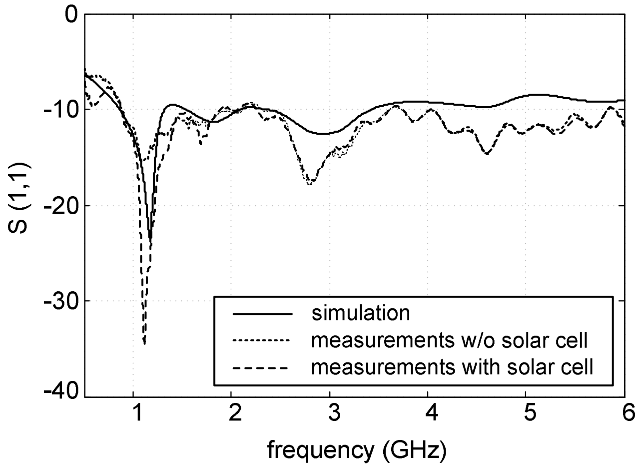

Fig. 2. Input S-parameters of the UWB radiating element.

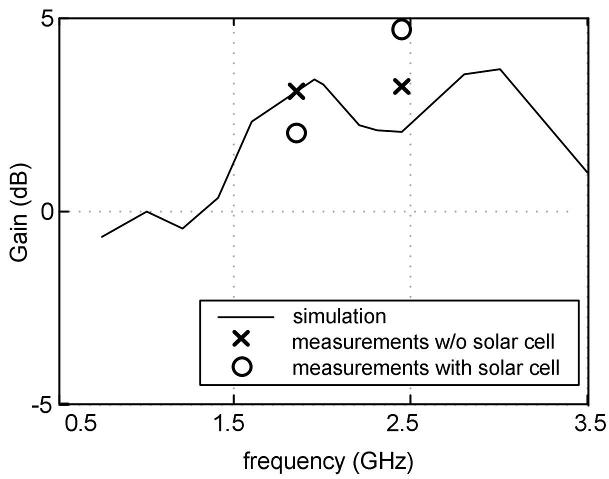

Fig. 3. Simulated and measured antenna gain with and without the solar cell.

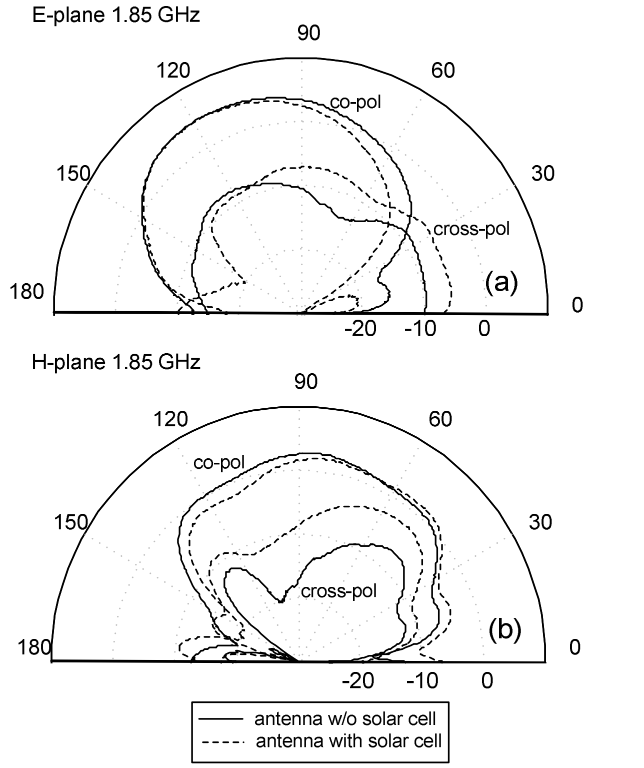

Fig. 4. Gain radiation patterns for the UWB antenna and for the combination antenna/solar cell at 1.85 GHz (a) E-plane radiation patters (b) H-plane radiation patterns.

B. Multiband rectifier circuit

The efficiency of rectenna systems is strongly dependent on the input RF power. In order to maximize the RF to DC conversion efficiency high Q narrow band matching networks are preferred over low Q wideband ones. As a result a multiband rectifier design was selected over an UWB one. In order to demonstrate the concept the GSM-850 and GSM-1900 bands were chosen.

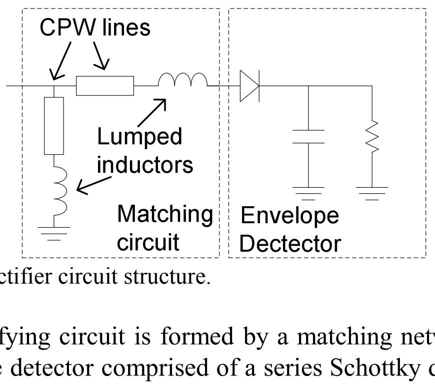

Fig. 5. Rectifier circuit structure.

The rectifying circuit is formed by a matching network and an envelope detector comprised of a series Schottky diode and a shunt capacitor. The DC output voltage is taken from a resistive load R_L. The circuit schematic of the rectifier is shown in Fig. 5, whereas an implemented prototype can be seen in Fig. 1 together with the radiating structure. The selected rectifying element was a silicon Schottky diode (Skyworks SMS7630). The matching network has to be optimized in order to match the output impedance of the antenna to the rectifying circuit load. In the simulation the Thevenin equivalent of the antenna in the receiving mode is used, comprised of the impedance of the antenna in the transmitting mode calculated by the EM simulator and a series voltage source whose value can be evaluated for an incoming wave using reciprocity theory [5,6]. The matching network was implemented in coplanar waveguide technology (Fig.1).

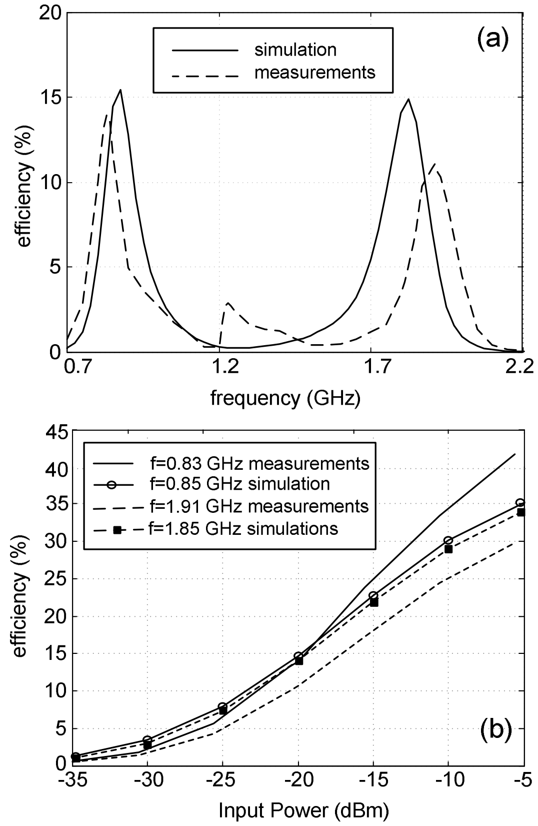

Fig. 6. Multiband rectifier performance (a). Efficiency versus frequency for P_{in}=-20 dBm. (b) Efficiency versus input power for the peak efficiency frequencies.

In order to obtain a rectifier with multiband efficiency, a multiple goal harmonic balance simulation was used by introducing two goals, that impose a minimum value of efficiency at 0.85GHz and 1.85GHz calculated as in (1). Then, the matching network parameters were optimized in order to fulfill these goals.

$$\eta(\%) = \frac{P_{DC}}{P_{av}} \cdot 100 = \frac{V_{DC}^2 / R_L}{P_{av}} \cdot 100 \qquad (1)$$

$$P_{av} = \frac{V_{in}^2}{8 \cdot \mathrm{real}(Z_{in})}$$

where Z_{in} is the input impedance of the antenna element.

Fig. 6 shows the performance of the designed multiband rectifier circuit both in simulation and measurements. Fig.6a shows the evolution of the efficiency versus frequency for a fixed received input power of P_{in}=-20dBm and Fig.6b shows the efficiency versus the received input power level for the frequencies where there is maximum in the efficiency (Fig.6a).

III. Hybrid Solar/EM Energy HArvester

In order to preserve the flexibility of the proposed harvester, the solar cells that are integrated with the multiband EM energy harvester were selected to be flexible amorphous silicon (a-Si) solar cells. The used solar cells were SP3-37 flexible solar panels with Voc=4.1 V and Isc=30 mA and dimensions 37x50mm.

A compact design is achieved by placing the solar cell on the surface of the radiating element. The performance of the EM energy harvester is preserved by integrating the solar cell on the areas of the radiating element where the fields are weak. Fig. 1b. and 1c, demonstrate the fact that the flexibility of the structure is maintained with the introduction of the solar cell.

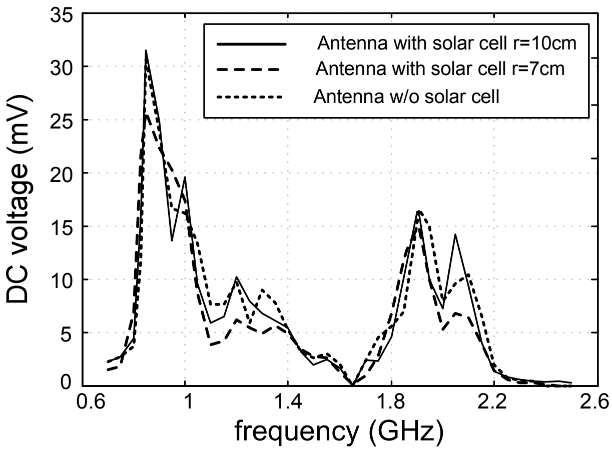

Fig. 7. Solar/EM energy harvester measured performance. DC voltage at the output of the rectifier.

A prototype of the antenna with the solar cell integrated was fabricated and tested. The input S-parameters of the fabricated prototype are shown in Fig. 2, where it is verified that the integration of the solar cell has a minimum effect. Fig. 3 also shows measured gain of the antenna with the solar cell, demonstrating the fact that proper placement of the cell has a minimum effect in the antenna performance and in some cases may lead to a gain improvement. Due to lack of a required standard antenna at 0.85 GHz, it was not possible to measure the gain of the prototype at this frequency. Fig. 4 shows the measured E-plane and H-plane radiation patterns of the solar antenna prototype at 1.85 GHz, showing a reduction of 1dB in the gain of the structure when integrating the solar cell.

Finally, the evolution of the obtained DC voltage from the EM energy harvester was measured versus frequency, with and without the integration of the solar cell. Fig. 7 shows a comparison of the measured DC voltage for the structure without the solar cell, and with the solar cell bended with a radius of 10 cm (Fig.1b) and with a radius of 7 cm (Fig.1c). One can see that the performance is minimally affected both by the placement of the solar cell and by the bending of the flexible structure.

IV. Conclusion

A flexible hybrid solar/EM energy harvester is proposed for its use on recycling environmental energy. A low cost PET substrate was used for the rectenna and an a-Si solar cell resulting in an inexpensive and flexible structure demonstrating good performance. A compact topology that integrates the solar antenna onto the radiating element and an optimized design of a multiband rectifier circuit using harmonic balance simulations are proposed.

Acknowledgement

This work was carried out in the framework of COST Action IC0803 (RFCSET). This work was also supported by the Marie Curie project SWAP, FP7-PEOPLE-2009-IAPP 251557, the Spanish Ministry of Science and Innovation project TEC2008-02685/TEC, and grants PTQ-06-02-0555 and PTQ-08-01-06432.

References

[1] R. Vyas, V. Lakafosis, A. Rida, N. Chaisilwattana, S. Travis, J. Pan, M.M. Tentzeris, "Paper-Based RFID-Enabled Wireless Platforms for Sensing Applications," IEEE Trans. Microw. Theory Tech., , vol.57, no.5, pp.1370-1382, May 2009.

[2] J. A. Hagerty, F. B. Helmbrecht, W. H. McCalpin, R. Zane, and Z.B. Popovic, "Recycling ambient microwave energy with broadbandrectenna arrays," IEEE Trans. Microw. Theory Tech., vol. 52, no. 3,pp. 1014–1024, Mar. 2004.

[3] M. Tanaka, R. Suzuki, Y. Suzuki, K. Araki, "Microstrip antenna with solar cells for microsatellites," IEEE International Symposium on Antennas and Propagation (AP-S), vol. 2, pp. 786-789, 20-24 June 1994.

[4] S. Vaccaro, J.R. Mosig, P. de Maagt, "Two advanced solar antenna "SOLANT" designs for satellite and terrestrial communications," IEEE Transactions on Antennas and Propagation, vol.51, no.8, pp. 2028- 2034, Aug. 2003

[5] A.Georgiadis, G. Andia-Vera, A. Collado "Rectenna design and optimization using reciprocity theory and harmonic balance analysis for electromagnetic (EM) energy harvesting," IEEE Antennas and Wireless Propagation Letters, vol. 9, pp. 444-446, 2010.

[6] V. Rizzoli, G. Bichicchi, A. Costanzo, F. Donzelli, and D. Masotti,"CAD of multi-resonator rectenna for micro-power generation," in Proc. EuMC, Rome, Italy, Oct. 2009, pp. 1684–1687.