Marcelo PEROTONI*, Jorge TOMIOKA*, Walter SILVA*, Douglas CAMPOS, Kenedy dos SANTOS**, Danilo ALMEIDA****

UFABC (*), IFBA (**), Brasil

doi:10.15199/48.2020.11.20

UHF Energy Harvesting based on a reflector-backed bowtie antenna

***Abstract**. This article covers the use of a bowtie planar antenna for energy harvesting, covering the range between 900 MHz and 1000 MHz. The same converter circuit was compared connected to a wire dipole antenna, with the same size of the bowtie. Co and cross polarizations of the incoming wave were tested. The inclusion of a reflector to both dipole and bowtie was evaluated, and it proved superior performance in terms of sensitivity.*

***Streszczenie.** Przedstawiono planarną antene zbierającą energię w paśmie 900 MHz do 1000 MHz. Antena ma kształt in rozmiar uszki (bowtie). Antena jest podłączona do podwajacza na pięcia bazującego na diodzie Schottky. (**Antena UHF typu bowtie zbierająca energię**)*

Keywords: RF energy harvesting, bowtie antenna, electromagnetic simulation, detector.
Słowa kluczowe: antena zbierająca energie, bowtie antena (antena w kształcie muszki).

Introduction

Using an RF electromagnetic wave as source to generate DC power is an attractive alternative to situations such as those with wireless sensor networks [1]. The use of frequencies in the mid-UHF range was employed in several different energy harvesting systems, for instance, a folded dipole for IoT (Internet of Things), with maximum efficiency centered at 918 MHz [2]. An 866 MHz capacitively loaded printed monopole antenna, employing a five-stage diode multiplier achieved a peak of 53% efficiency [3]. A single diode connecting both halves on a reflector-backed bowtie antenna was used for the frequency of 2.45 GHz [4] without the use of matching network or filtering. The same approach of a single diode connecting both halves of a bowtie antenna was employed on a 2.3 GHz array [5]. Another work reports on a bowtie antenna used to harvest solar energy at wavelengths of 37.5 μm, using a metal-insulator-metal diode [6]. Instead of a single antenna, an array using bowtie antennas at the frequency of 1800 MHz resulted in better efficiency collecting the incoming RF energy [7]. For low power wave densities illuminating the rectenna, a situation that typically results in lower converter efficiencies, a 900 MHz printed dipole with reduced size resulted in 47% efficiency for RF power densities of 2.1 $\mu W/cm^2$ [8]. A miniature 3-layer planar inverted F antenna, with central frequency of 915 MHz achieved peak efficiency reaching 70%, with applications in deep-brain stimulation [9]. A modified bowtie antenna with four petals to harvest both polarizations and an additional auxiliary geometry aimed to size reduction achieved a peak efficiency of 65 % at the frequency of 800 MHz [10].

This work presents the use of a bowtie antenna directly connected to a voltage doubler circuit, based on Schottky diodes. As a baseline for comparison a wire dipole is used, with the same length of the bowtie and using the same converter circuit. The system was also measured backed by a metallic reflector, and comparisons are shown to illustrate the effects on the collected DC voltage, sensitivity and efficiency. The frequency range of 900 MHz to 1 GHz was chosen in this investigation due to the large number of devices available and also due to less critical construction and layout requirements. This frequency range also has a large number of existing carriers from mobile phone services, especially in urban environment [11], which can be used as a source for harvesting.

Circuit Description

A Hitachi 1SS106 Schottky diode (package DO-35) was used, which does not have a simulation model. Given the lack of computer evaluation, the circuit input impedance was not estimated, therefore no matching network was employed. The lack of matching network helped keep the circuit as simple as possible – the antenna was directly connected to the voltage doubler. Fig. 1 shows the circuit schematic, the 100 nF capacitor and 0.1 mH inductors complement the voltage doubler circuit, whose values were found after tests with other available commercial components. A similar investigation was performed at the frequency of 866 MHz to design an optimized loop antenna, with additional short-circuited loops, to be directly connected to the rectifier circuit [12], where in contrast to this present work the diode had a computer model available that was used in a Harmonic Balance analysis.

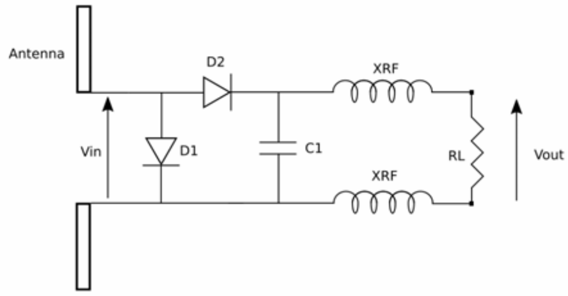

Fig.1. Circuit schematic of the voltage doubler and the antenna.

The efficiency of the rectifier isolated, defined as the power ratio between the DC and RF levels, is measured by connecting the converter circuit input to an RF generator instead of the antenna, and evaluating the DC output voltage across the load. It is worth mentioning that the used diode, by itself, presents a rectification efficiency of 70% according to the device datasheet. Both frequency and input power levels were swept, whose results area shown in Fig. 2 for the load resistances of 1320 Ω, 4.62 kΩ, 31 kΩ and 182 kΩ. These resistor values were chosen to be randomly distributed across a range of possible loads. It can be seen that the efficiency increases with lower load resistances and it peaks for frequencies close to 920 MHz, for the four different cases. Increasing the efficiency at low power levels is a usual problem for this class of application, addressed specifically by means of methods such as the use of two printed low pass filters that avoid re-irradiating higher order harmonics created by nonlinearities of the diode [13]. The use of a wideband matching network can also provide larger efficiencies, such as 64% [14], 68% for -5dBm RF input power [11], or 65% [10], at expenses of larger areas and higher complexity.

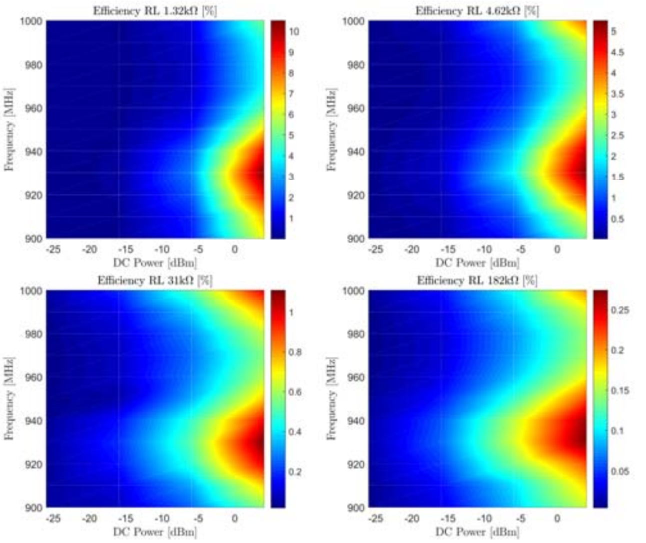

Fig.2. Circuit efficiency for R_L =1.32 kΩ (top left), 4.62 kΩ (top right), 31 kΩ (bottom left) and 182 kΩ (bottom right).

Antenna Design

The planar bowtie antenna was designed to resonate in the middle of the chosen band. For the sake of comparison, a dipole antenna was built with the same length as the bowtie, built with a wire with diameter of 1 mm. It has to be stressed that the concept of resonance is not of paramount importance for this case since the circuit input impedance is generally far from a purely 50 Ω resistive value. In the next step, a metallic reflector was kept 50 mm away from the antennas, with a rectangular shape of 215 mm vs. 870 mm. The distance between both reflector and radiant elements was smaller than the usual quarter wavelength (5 cm vs. 30 cm), due to mechanical constraints and also in order to keep small dimensions. Fig. 3 shows the FEKO simulated (using the Method of Moments solver) results for the bowtie antenna, with and without reflector. It can be seen that the inclusion of the reflector has an effect of generating a slight mismatch on the resonant point, moving it away from the 50 Ω.

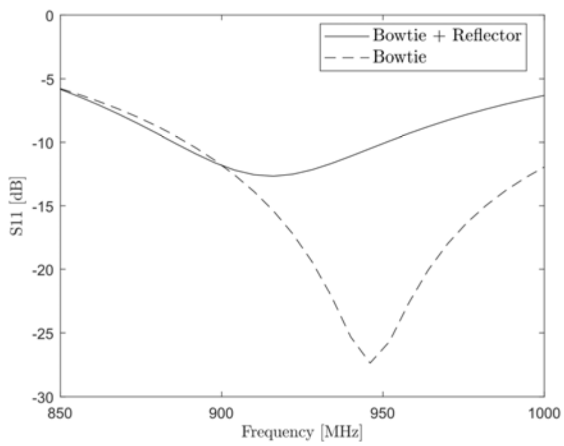

Fig.3. Computed return loss (S11) for the bowtie antenna, with and without reflector.

Integration and efficiency tests

The circuit was built in a compact form on a PCB board (dimensions 24 x 6 mm^2) in order to minimize parasitics in the RF part. Fig. 4 shows the bowtie antenna (total length 109 mm, width 40 mm), cut from Copper foil, integrated to the voltage doubler, alongside to the open waveguide used to excite it. The rectenna was laid out on a 5 cm-thick styrofoam board as to mechanically support it and as a separation to the metallic reflector.

Fig.4. Computed return loss (S11) for the bowtie antenna, with and without reflector.

The rectennas were tested placed one meter away from an open waveguide antenna, connected to a generator set to its maximum power (20 dBm). The following tests were performed: measurement of the voltage on the particular load of 31 kΩ with and without reflector, shown in Fig. 5 (co-polarization) and Fig. 6 (cross-polarization). It can be seen that the reflector helps increase the DC voltage developed on the load, for both dipole and bowtie cases. For the sake of cross-polarization, in contrast to antennas designed to operate in communication channels, the ability to pick up incoming RF energy for all polarizations is positive for energy harvesting purposes. The bowtie with the reflector showed the best for both orthogonal polarizations.

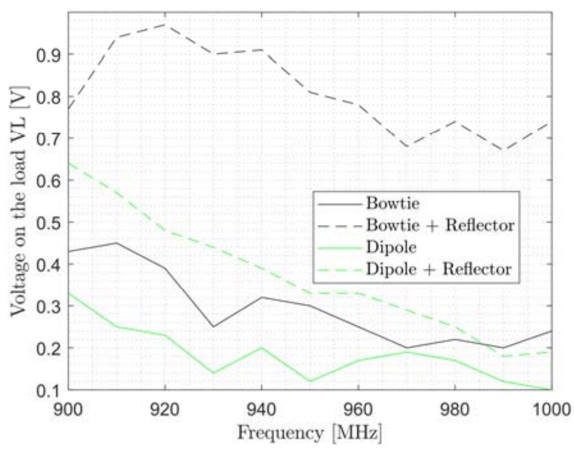

Fig.5. Voltage on the load, co-polarization.

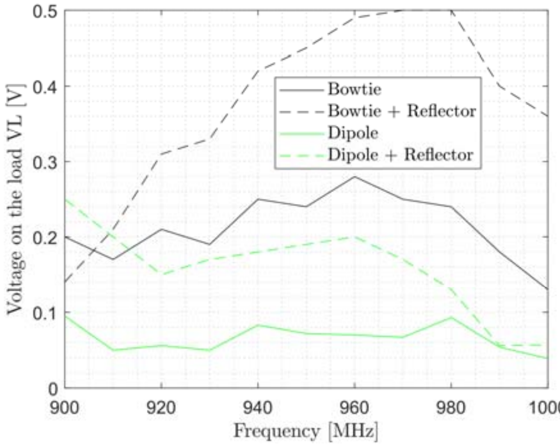

Fig.6. Voltage on the load, cross-polarization.

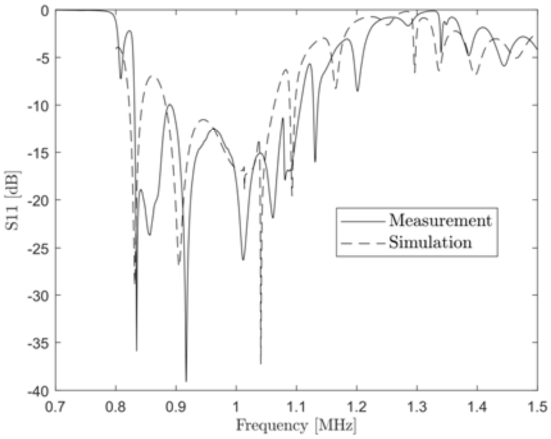

Fig.7. Open waveguide, measured and simulated return loss.

The measurement of the efficiency (relation of the DC and incident RF powers) is not trivial [13], due to the difficult in the precise determination of the RF incident level right on the rectenna position. For instance, the Friis formula can be used in case the antenna gain is known, and that demands the impedance mismatches being properly addressed, with the risk that if they are not part of the energy left in reflections would be unaccounted for and considered as effectively absorbed in the load. Here the impedances are not known, given the lack of computer simulation of the converter circuit. For this matter, an open waveguide set as transmitter was used as reference antenna, whose response and behavior were numerically predicted. Instead of the efficiency, the rectenna sensitivity parameter s was computed, defined as the ratio between the DC power on the load and the field density (Poyinting vector) on the rectenna position:

$$s = \frac{P_{DC}}{P_{RF}} = \frac{\frac{V^2}{R_L}}{\frac{(E^2)}{\eta_0}} \quad (1)$$

where V is the DC voltage measured on the load resistor; E the field numerically computed at the point where the rectenna is and η_0 is the free space impedance (377 Ω). The unit of s is m^2 (surface) – as it grows larger more DC power the rectenna can generate after converted from the picked up incoming RF wave. To address the electric field on the rectenna a full-wave 3D simulation was used, containing the open waveguide and its coax probe. The consistency of the transmitter antenna numerical model can be checked on the comparison between the measured and computed S11 curves, shown in Fig. 7. It can be seen that for both cases the return loss is below 10 dB across the frequency range of interest. The good results from the impedance correlation can then be extended with confidence to the acquired electric field amplitude.

The sensitivity measurement was performed with the RF generator set with a power P_{gen} of 20 dBm, to account for the losses due mismatch, the effective RF power P_{eff} was computed as:

$$P_{eff} = P_{gen}\left(1 - |S11|^2\right) \quad (2)$$

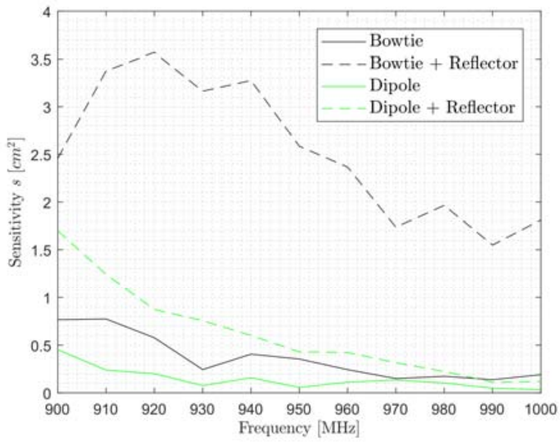

Fig.8. Sensibility s for the co -polarized case.

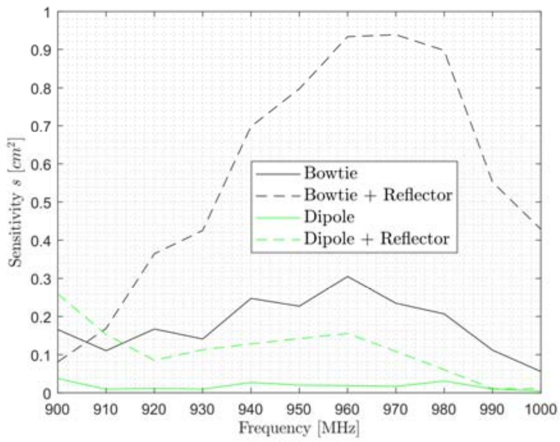

Fig.9. Sensibility s for the cross -polarized case.

With the S11 parameter taken from the measurement at the frequency points were the DC power was measured across the 900 MHz to 1 GHz range, in steps of 100 MHz. Since for these frequency points the S11 was below -10 dB the difference between the generator power and effective radiated power was less than 10%. The electric field E computed by the simulation package was then re-scaled to correspond to an excitation power of P_{eff}, sampled at the point in space where the rectenna is (1 meter from the aperture center), which corresponds to approximately 8.4 μW/cm^2 according to the simulation, whereas other similar studies used higher power densities such as 80 μW/cm^2 [3] and 60 μW/cm^2 [10]. Fig. 8 and Fig. 9 show, respectively, the computed sensitivity for the co and cross polarizations. It can be seen that the inclusion of the reflector indeed helps capture more of the incoming RF field. Besides that, the larger area of the bowtie in contrast to the dipole converts a larger part of incoming orthogonal polarizations, which is relevant for cases when signals from mobile phone carriers, for instance, are to be harvested. Since the multi-path energy is usually larger than that of direct line-of-sight (Rayleigh Channel type), the electric field orientation will also come in multiple polarizations due to the reflections and diffractions the channel usually imposes on the rays.

Conclusion

This article covered a bowtie antenna used as a rectenna for energy harvesting, with and without a reflector, in the range of 900 MHz to 1 GHz, illuminated with power densities around 8.4 μW/cm^2. A dipole antenna was used as a baseline for comparison. Since the Schottky diodes do not have available computer model, a direct connection from the antenna to the voltage doubler was employed. Computer simulation was used to help determine the system sensitivity, which showed best results for the bowtie with reflector, for either co and cross polarized signals.

Acknowledgements

The authors thank the Pro-Rectory for Research, Graduate and Innovation (PRPGI) and the Federal Institute of Education, Science and Technology of Bahia for their financial support

Authors*: Prof. Marcelo Bender Perotoni, Prof. Jorge Tomioka, Prof. Walter Silva, CECS UFABC, Av. dos Estados 5001,09210-580 Santo Andre, Brazil, emails: marcelo.perotoni@ufabc.edu.br, jorge.tomioka@ufabc.edu.br, prof.walterjs@gmail.com. Prof. Kenedy M. dos Santos (kenedy.marconi@gmail.com), Douglas Campos (douglas.ocampos97@gmail.com) and Danilo Brito (danilobrito@ifba.edu.br) are with IFBA, Vitoria da Conquista, BA, 45078-900, Brazil.*

REFERENCES

[1] Vecchio A.: Adaptability in wireless sensor networks, 15th IEEE Int. Conf. Electron. Circuits Syst. ICECS, 2008.

[2] Khang S. T., Yu J. W., Lee W. S.: Compact folded dipole rectenna with RF-based energy harvesting for IoT smart sensors. *Electron. Lett*., 51(12), pp. 926-928, Dec 2015.

[3] Monti G., Congedo F., Donno D., Tarricone L.: Monopole-Based Rectenna for Microwave Energy Harvesting of UHF RFID Systems. *Prog. Electromagn. Res. C.* , 31, pp. 109-121, 2012.

[4] Tran M., Nguyen C.: A new rectenna circuit using a bow-tie antenna for the conversion of microwave power to DC power. *Microw. Opt. Technol. Lett.* , 6(11), pp. 655-656, 1993.

[5] Basta N. P., Falkenstein E. A., Popovic Z.: Bow-tie rectenna arrays. IEEE Wirel. Power Transf. Conf. WPTC, 2015.

[6] Sabaawi A. M. A., Tsimenidis C. C., Sharif B. S.: Bow-tie nano-array rectenna: Design and optimization. Proc. 6th Eur. Conf. Antennas Propagation, EuCAP , 2012.

[7] Salsabila S., Setiawan A. D., Charisma A., Najmurrokhman A., Munir A.: Design of printed bowtie dipole array antenna for rectenna application. ICWT 2017 3rd Int. Conf. Wirel. Telemat., 2017.

[8] Okba A., Takacs A., Aubert H.: 900 MHz Miniaturized Rectenna. IEEE Wirel. Power Transf. Conf. WPTC, 2018.

[9] Hosain M. D. K., Kouzani A. Z., Samad M. F., Tye S. J.: A miniature energy harvesting rectenna for operating a headmountable deep brain stimulation device. *IEEE Access.*, 3, pp. 223-234, 2015.

[10] Monti G, Congedo F.: UHF Rectenna using a bowtie antenna. *Prog. Electromagn. Res. C.* ; 26, pp. 181–192, 2012.

[11] Kawahara Y., Tsukada K., Asami T. : Feasibility and potential application of power scavenging from environmental RF signals. IEEE Antennas Propag. Soc. AP-S Int. Symp., 2009.

[12] Visser H. J., Keyrouz S., Smolders A.B.: Optimized rectenna design. Wirel. Power Transf. ; 2(1), pp. 44–50, 2015.

[13] Riviere S, Alicalapa F, Douyere A, Lan Sun Luk JD.: A compact rectenna device at low power level. *Prog. Electromagn. Res. C.* 16, pp. 137–146, 2010.

[14] Delong B. J., Lee C. W. L., Kiourti A., Venkatakrishnan S. B., Volakis J. L.: Wireless Energy Harvester from 700-900 MHz. United States Natl. Comm. URSI Natl. Radio Sci. Meet. (USNC-URSI NRSM), 2018.