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Bio-inspired Fractal Rectenna for RF Energy Harvesting at 2.45 GHz ISM Band

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1. Abstract

In this article, a bio-inspired fractal antenna with rectifying circuit is presented over FR-4 substrate for 2.45 GHz ISM band applications. The antenna offers a wide bandwidth (800MHz) over the central frequency. The whole design is based upon the micro-strip transmission line geometry. At the backside of the structure, defected ground plane paves the new way for introducing one design parameter for the radiator. Further, an efficient rectifying circuit is proposed with high frequency Schottky diode and stub loaded impedance matching network. This work also covers circuit modeling of the entire system. The rectifier circuit exhibits maximum conversion efficiency of ~ 80.59% while applying +20 dBm inputs.

2. Introduction

With the explosive growth in integrated circuit and embedded system technology, self-sustaining low power hungry devices suitable for IoT(Internet of Things), RFID(radio frequency identification systems), smart cities, wearable electronics, wireless sensor networks(WSN), smart health monitoring, non-accessible sites for military usages, etc have attracted notable attention in the last decade. At present, the power requirement of these devices positioned at far/remote places is accomplished generally using traditional dry cell or battery. Once exhausted these DC power sources are immediately replaced with new one. This is itself a tedious job in addition to being hazardous to the environment. Hence, there is a need of green solution of this battery. Energy harvesting wherein the abundantly available energy is absorbed by several means and thereafter converted into DC power source for powering the device is the most suitable to the currently raised burning issue. There are various sources of ambient energy in abundance, like-Sun, wind, tide, piezoelectric vibration, EM-wave, etc [1]. Among them, the energy with EM wave is most easily available resources and it is abundantly available due to explosive growth of mobile communication, and many other wireless communications like-WiFi, WLAN, Bluetooth, FM-radio, etc in modern era. Hence, it can be used as a primitive resource.

Radio frequency energy harvesting, and wireless power transferring methods have gained wide recognition over a decade ago in the process of enabling battery-free wireless networks [2]. 'Rectenna' is the backbone of such system. The performance of the system depends on the quality of the 'rectenna' developed for it. This kind of antenna is able to catch the EM waves from the surroundings. Whenever it receives a signal, it generates oscillating charges that moved through attached fluctuations to a DC current. The throughput of the system solely depends upon the AC/DC conversion. The term 'rectenna', describing an antenna connected to rectifier for harvesting RF power, emerged and powering autonomous drones [3-10]. As the time progress towards revolution in wireless communication, power consumption of semi-conductor devices and wireless sensors nodes continuously scales down. It becomes more feasible to power sensor nodes using ambient radio frequency energy harvesters. The possible sources of RF energy in ambient are Bluetooth, GSM, FM radio, UWB, WLAN, WiFi, etc.

Researchers are implementing various bio-inspired geometries (either from animal /plant kingdom) in the antenna field to improvise various performance metrics of the radiator. Animal-inspired antenna implements either the shape of internal organs or external body parts, which work equivalently as that of antenna in wireless system viz. bat's ear [11], hearing mechanisms of some insects [12], and wasp's curved antenna [13], etc. Plant-body inspired antenna, either uses stem, leaf, flower) or the entire plant body [14-15].

This paper presents the design of a novel bio-inspired antenna for RF energy harvesting system. A binary tree-shaped architecture is implemented for the current design. The operating frequency is chosen as 2.45 GHz (ISM-band). Similarly, a rectifying circuit is also designated for the same antenna circuit. The whole design is exercised on FR-4 substrate. In the subsequent sections, detailed analysis is chalked out.

3. RECTENNA DESIGN

3.1 Principle of operation

Rectenna mainly consists of harvesting circuit, DC power source, storage unit, and low power μp and transceiver. The efficiency of energy harvester depends upon the performance of individual blocks, such as: antenna, rectifier, and power management unit. There is an impedance matching network between the antenna and rectifier circuit, which delivers maximum power from source to load. Generally, it consists of inductive and capacitive elements [16-17].

3.2 Antenna and Rectifier design

An antenna with a layout area of 10×10 cm^2 is proposed here for the WPT system. The antenna shows a bandwidth of 800 MHz (2.1 GHz to 2.9 GHz). The radiating element is a U-Shaped tree like structure. The length of the binary tree is about half wave length at the central frequency. The width is taken less than 0.02 λ_B, where λ_B is wavelength of central frequency f_B. The length of the antenna is given by the equation (1).

$$L_B = \frac{\lambda_g}{2} = \frac{c}{2f_B\sqrt{\frac{\varepsilon_r+1}{2}}} \quad \ldots\ldots. (1)$$

The base line structure is modified tree geometry with initial U-like structure. For each iteration, four copies of U-shaped branches are created. The Hausdorff dimension will be [18],

Where, [R= reduction factor, n= no. of iterations.]

$$d = \frac{\ln(n)}{\ln(2R)} = \frac{\ln(4)}{\ln(2)} = 2 \quad \ldots\ldots. (2)$$

The fractal tree can be generated by a recursive formula,

$$a_n = a_{n-1} + 2^n \qquad\qquad (3)$$

3.3 Rectifier circuit design

ADS2020 [19] is used as circuit simulator for evaluating the rectifier circuit with impedance matching network. The rectifier design starts with BAT15-03W [20] diode. It is a silicon low barrier N-type device with an integrated guard ring on-chip for over-voltage protection. An easy implementation of the network is accomplished utilizing planar transmission lines considering Z_{Ant}=50.27 +j×0.5 Ω and Z_{Diode}=56.05+j×468.95 Ω). Transient analysis of the circuit is evaluated and the layout of the same is shown in Fig.1 (b).For the layout purpose, the chip resistor and capacitors are chosen. For making the ground connection at one of the common terminal, plated through via-holes are used.

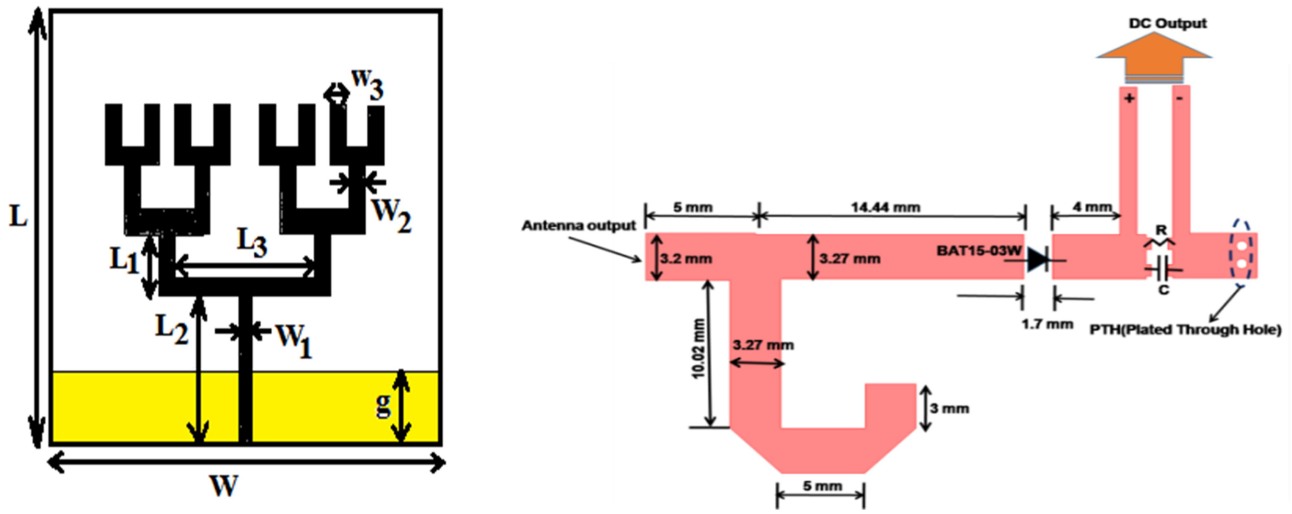

Fig.1: (a) Antenna architecture, (b)Layout of the rectifier circuit including matching network

3.4 CIRCUIT MODELING

The whole module can be electrically modeled with three different segments, as shown in Fig.2. The antenna alone can be expressed in terms of a tank circuit (parallel RLC network), assuming the dominant mode as TE_{10}. The resonant frequency of the antenna is governed by L_{10} and C_{10}, whereas R_{10} determines bandwidth of the same. The feedline is symbolically expressed with the series combinations of R_f and L_f. 'R_f' determines the conductor loss, whereas the current crowding effect is represented by L_f. After the antenna, impedance matching network (IMN) is connected, which is realized here with the L-network of the planar transmission lines. This IMN is responsible for transferring maximum power from the antenna terminal to the rectifier circuit. The rectifier circuit consists of BAT-15 diode and loading network (R_{Load} and C_{Load}).The complete package of the diode can be thought as a combination of several parasitic inductances (L_p) and capacitances (C_p) along with actual diode. The adjoining portion of the transmission line is represented by R_s and L_s, which indicates the source of finite conductor loss.

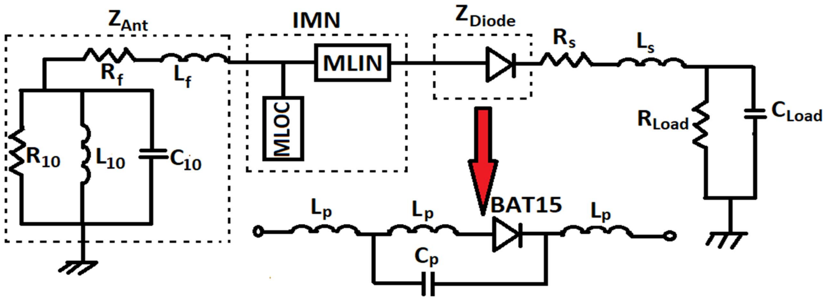

Figure 2. Electrical equivalent circuit

3.5 SIMULATED RESULTS

The proposed fractal inspired tree-shaped is simulated in CST Microwave Studio [21]. Simulated radiation characteristics of the proposed antenna are depicted in Fig.3 (a) and (b), which describes well the directive property. Current distribution of the radiator at the operating frequency is shown in Fig.3(c).

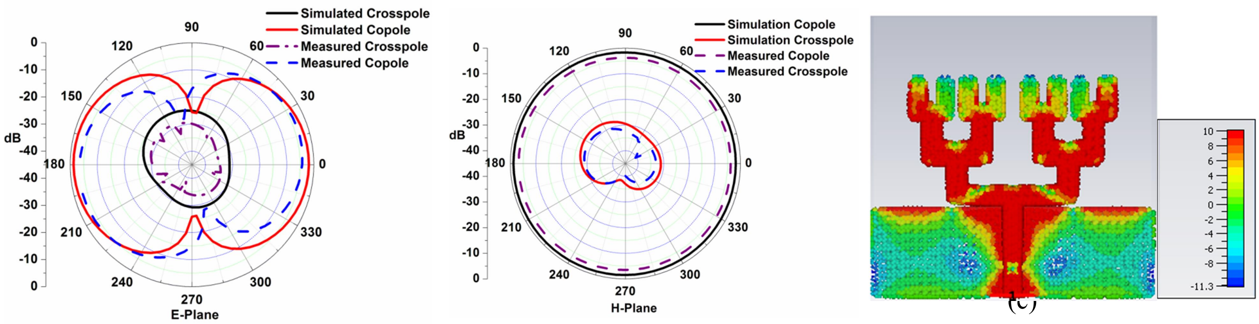

Figure 3. Far-field radiation pattern of the antenna (a) E-plane (b) H-plane (c) Current distribution @ 2.45 GHz

It is observed that, the current is concentrated on the main patch and edge of the ground plane. A better than 35 dB return loss is observed for the said antenna. On the contrary, based on ADS simulation of the whole rectifier circuits the transient responses of the input and output voltages are captured as shown in Fig.4 (a) and (b). An RF source of 50Ω internal impedance is used at input terminal of rectifier. As is evident from Fig.4 that, DC voltage of around 2.789V comes out at the output terminal of rectifier. The efficiency of rectifier as function of input RF power is shown in Fig.4 (c).

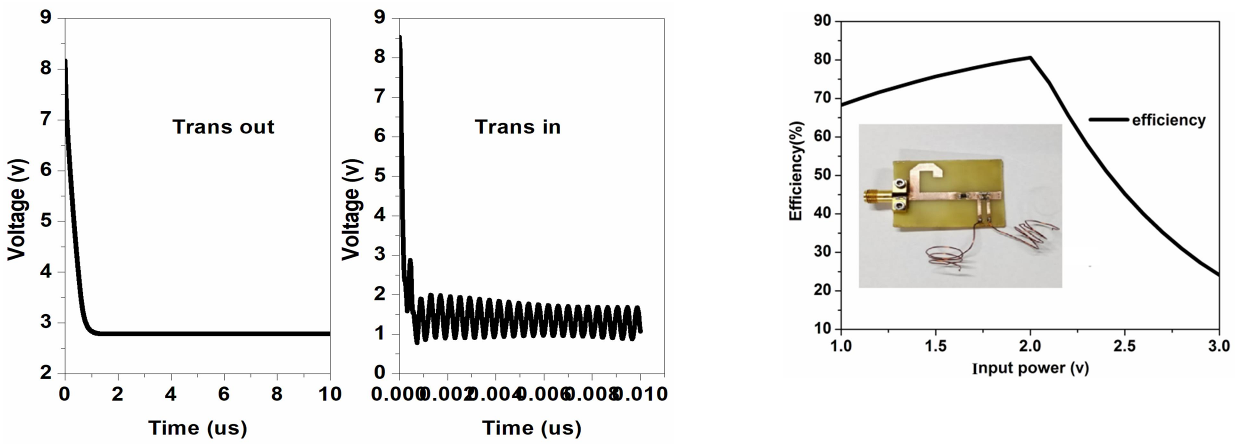

Figure 4. Transient voltage at the (a) output and (b) input terminal of the rectifier (c) Conversion Efficiency of Rectifier

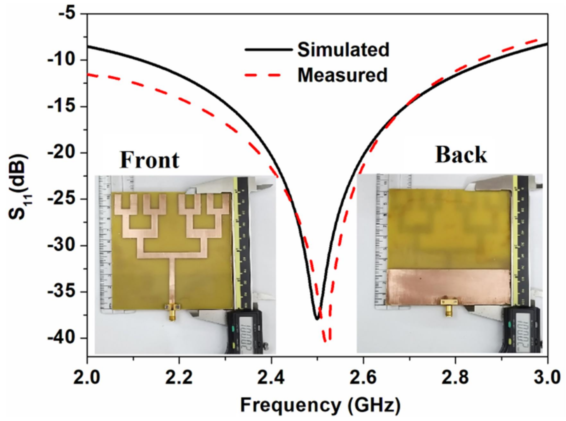

Figure 5. Return loss profile of the proposed antenna

3.6 FABRICATION AND MEASUREMENT

The designed antenna and rectifier have been fabricated on 1.6mm thick FR-4 substrate. Standard photo etching technique is adopted for PCB realization.

Fig.5 (a) compares the impedance matching profile at antenna port for simulated and experimental value. It also captures the photograph of the fabricated prototypes. For measuring the scattering parameter of the antenna, we use R&S make ZVA-40 Vector Network Analyzer (VNA) and measurement set-up is shown Fig.5 (b). And, to check the rectifier efficiency the power of the input RF signal is varied. The output of the same is measured correspondingly for different power levels. Digital multi-meter (DMM) is used to measure the DC voltage at the output of the rectenna across its load (R_L=1kΩ). We observe the output voltage with different input power levels and notice that at -20dBm, -10dBm, 0dBm and 10dBm of input power the output voltages are 3mv, 8mv, 13mv and 50mv, respectively.

4. Conclusion

This article covers the design and development of a rectenna circuit for RF energy harvesting. The centre frequency of operation is at 2.45 GHz(ISM-band). Back bone of the circuit is a novel bio-inspired antenna realized on a single-layer PCB-substrate using the standard photolithography and wet etching chemistry. Further, an impedance matching network along with rectifying circuit makes it a viable solution for RF to DC conversion. Inverted J-shaped open stub matching makes the circuit suitable for miniaturized version. Experimental study was conducted to evaluate the various performance metrics of the rectenna circuit. Easy design approach implementing bio mimicry, simple fabrication method, and finally an efficient circuit realization are the novelty of this current research work. Additionally, an attempt to model the whole circuit electrically makes the proposed work more attractive.

Ref	Frequency (GHz)	Types of Antenna used	Substrate with thickness	Antenna Dimension (mm^2)	Bandwidth (MHz)	DC Conversion Efficiency
3	2.45	A planar multi layer fabric patch antenna	Polyester felt (Ɛr=1.2) with 1.65 mm	60×54	100	33.6%
4	0.79-0.96 1.71-2.17 and 2.5-2.69	Two Annular Slots	Paper (Ɛr=2.55) with 0.37 mm	110×110	17, 46, 19	57%
8	0.868	Small Loop Antenna	GML 1000 (Ɛr=3.05) with 0.5 mm	219×219	60	40%
9	GSM-1.8 UMTS-2.1	Yagi Antenna array	RT/Duroid 5870 (Ɛr=3.05) with 62-mil	190×100	400	40 %
17	GSM-0.9 GSM-1.8 UMTS-2.1	Dual port Microstrip patch	RT/Duroid 5880 (Ɛr=2.2) with 62-mil	200×175	100 in each band	40 %
This work	2.45	Bio Inspired fractal patch	FR4 (Ɛr=4.4) with 1.6 mm	100×100	800	80.59 %

Table-1. Comparison Table with proposed rectenna and some other related work

References

1. Tran, LG., Cha, HK. & Park, WT. RF power harvesting: a review on designing methodologies and applications. *Micro and Nano Syst Lett* **5,** 14 (2017). https://doi.org/10.1186/s40486-017-0051-0
2. N. Shinohara, "Trends in Wireless Power Transfer: WPT Technology for Energy Harvesting, MIlimeter-Wave/THz Rectennas, MIMO-WPT, and Advances in Near-Field WPT Applications," in*IEEE Microwave Magazine*, vol. 22, no. 1, pp. 46-59, Jan. 2021, doi: 10.1109/MMM.2020.3027935.S. -E. Adami *et al.*, "A Flexible 2.45-GHz Power Harvesting Wristband With Net System Output From −24.3 dBm of RF Power," in *IEEE Transactions on Microwave Theory and Techniques*, vol. 66, no. 1, pp. 380-395, Jan. 2018, doi: 10.1109/TMTT.2017.2700299.
3. V. Palazzi *et al.*, "A Novel Ultra-Lightweight Multiband Rectenna on Paper for RF Energy Harvesting in the Next Generation LTE Bands," in *IEEE Transactions on Microwave Theory and Techniques*, vol. 66, no. 1, pp. 366-379, Jan. 2018, doi: 10.1109/TMTT.2017.2721399.
4. C. Song *et al.*, "Matching Network Elimination in Broadband Rectennas for High-Efficiency Wireless Power Transfer and Energy Harvesting," in *IEEE Transactions on Industrial Electronics*, vol. 64, no. 5, pp. 3950-3961, May 2017, doi: 10.1109/TIE.2016.2645505.
5. C. Song *et al.*, "A Novel Six-Band Dual CP Rectenna Using Improved Impedance Matching Technique for Ambient RF Energy Harvesting," in *IEEE Transactions on Antennas and Propagation*, vol. 64, no. 7, pp. 3160-3171, July 2016, doi: 10.1109/TAP.2016.2565697.
6. H. Miyagoshi, K. Noguchi, K. Itoh and J. Ida, "High-impedance wideband folded dipole antenna for energy harvesting applications," *2014 International Symposium on Antennas and Propagation Conference Proceedings*, 2014, pp. 601-602, doi: 10.1109/ISANP.2014.7026794.

7. M. Stoopman, S. Keyrouz, H. J. Visser, K. Philips and W. A. Serdijn, "Co-Design of a CMOS Rectifier and Small Loop Antenna for Highly Sensitive RF Energy Harvesters," in *IEEE Journal of Solid-State Circuits*, vol. 49, no. 3, pp. 622-634, March 2014, doi: 10.1109/JSSC.2014.2302793.
8. H. Sun, Y. Guo, M. He and Z. Zhong, "A Dual-Band Rectenna Using Broadband Yagi Antenna Array for Ambient RF Power Harvesting," in *IEEE Antennas and Wireless Propagation Letters*, vol. 12, pp. 918-921, 2013, doi: 10.1109/LAWP.2013.2272873.
9. M. Wagih, A. S. Weddell and S. Beeby, "Rectennas for Radio-Frequency Energy Harvesting and Wireless Power Transfer: A Review of Antenna Design [Antenna Applications Corner]," in *IEEE Antennas and Propagation Magazine*, vol. 62, no. 5, pp. 95-107, Oct. 2020, doi: 10.1109/MAP.2020.3012872.
10. A. Flint. A biomimetic antenna in the shape of a bat's ear. IEEE Antennas and Wireless Propagation Letters. 2006;5(1):145-147. DOI: 10.1109/LAWP.2006.873940
11. Nader Behdad, Mudar A. Al-Joumayly and Meng Li. Biologically Inspired Electrically Small Antenna Arrays With Enhanced Directional Sensitivity. IEEE Antennas and Wireless Propagation Letters . 2011;10:361-364. DOI: 10.1109/LAWP.2011.2146223
12. Khabat Ebnabbasi. A Bio-Inspired Printed-Antenna Transmission-Range Detection System. IEEE Antennas and Propagation Magazine. 2013;55(3):193-200. DOI: 10.1109/MAP.2013.6586661
13. Xiao-Feng Bai, Shun-Shi Zhong and Xian-Ling Liang. Leaf-shaped monopole antenna with extremely wide bandwidth. Microwave and Optical Technology Letters. 2006;48(7):1247-1250. DOI: 10.1002/mop.21668
14. B. Biswas, R. Ghatak and D. R. Poddar, "A Fern Fractal Leaf Inspired Wideband Antipodal Vivaldi Antenna for Microwave Imaging System," in IEEE Transactions on Antennas and Propagation, vol. 65, no. 11, pp. 6126-6129, Nov. 2017, doi: 10.1109/TAP.2017.2748361.
15. B. L. Pham and A. Pham, "Triple bands antenna and high efficiency rectifier design for RF energy harvesting at 900, 1900 and 2400 MHz," *2013 IEEE MTT-S International Microwave Symposium Digest (MTT)*, 2013, pp. 1-3, doi: 10.1109/MWSYM.2013.6697364.
16. S. Shen, C. Chiu and R. D. Murch, "A Dual-Port Triple-Band L-Probe Microstrip Patch Rectenna for Ambient RF Energy Harvesting," in *IEEE Antennas and Wireless Propagation Letters*, vol. 16, pp. 3071-3074, 2017, doi: 10.1109/LAWP.2017.2761397.
17. K. J. Vinoy, J. K. Abraham and V. K. Varadan, "On the relationship between fractal dimension and the performance of multi-resonant dipole antennas using Koch curves," in IEEE Transactions on Antennas and Propagation, vol. 51, no. 9, pp. 2296-2303, Sept. 2003, doi: 10.1109/TAP.2003.816352.
18. ADS2020 ; www.keysight.com
19. BAT15-03W Diode datasheet; https://www.infineon.com/dgdl/Infineon-BAT15-03W-DS-v01_00-EN.pdf?fileId=5546d46265f064ff01663896078c4e80
20. CST Microwave Studio ; www.cst.com