Microstrip-based Patch Array with rectenna architecture for radio frequency energy harvesting at 2.45 GHz ISM band

Harsh Anand Singh* (1), Manas Aggarwal(2), Ayan Karmakar (3), Keka Biswas (4), Bobby (5), Balaka Biswas (5)
(1) UIET, Punjab
(2) Jawaharlal Nehru University, Delhi
(3) Semi-Conductor Laboratory (SCL), Chandigarh
(4) Megnadh Saha Institute of Technology, Kolkata.
(5) Indian Institute of Science Education Research (IISER), Mohali

Abstract

In this article, a microstrip-based patch array antenna with rectifying circuit is presented over FR-4 substrate for 2.45 GHz ISM band applications. The antenna offers high gain of around 7 dBi with bandwidth of around 131 MHz over the central frequency. Corporate feeding network is adopted here. Further, an efficient rectifying circuit with 80.6 % efficiency is proposed with BAT-15 high frequency diode and inverted-J shaped stub loaded impedance matching network. This work also covers the electrical equivalent circuit modelling of the entire circuit. The performance metrics of the whole network are analyzed.

1. INTRODUCTION

Presently, the power requirement of the devices positioned at far places is accomplished generally using standard cell or battery. Once exhausted these DC power sources are immediately replaced with new one. This itself is a tedious job in addition to being hazardous to the environment. Hence, there is a need of sustainable or green solution of this battery. There are various sources of ambient energy, like-Sun, wind, tide, piezoelectric vibration, EM-wave, etc [1]. Among them, the energy associated with EM-wave or RF energy source is most easily available resources and it is abundantly available due to explosive growth of mobile communication, WiFi, TV users, etc in modern era. Hence, it can be used as a primitive resource for EH system in current scenario.Radio frequency energy harvesting have gained wide recognition over a decade ago in the process of enabling battery-free wireless networks[2]. Rectifying antenna or in short 'Rectenna' is the backbone of such system. This kind of antenna basically picks up the electromagnetic waves from the surroundings. Whenever it receives a signal, it generates oscillating charges that moved through attached fluctuations to a direct electric current. The throughput of the system solely depends upon the ac-to-dc conversion. The term 'rectenna', describing an antenna connected to rectifier for harvesting RF power, emerged and powering autonomous drones [2-6].

Fig.1 shows the possible sources of RF energy in ambient.
This paper presents the design of a single element patch antenna for RF energy harvesting system, and further extending the same concept for array realization. The operating frequency is chosen as 2.45 GHz, popularly designated as Industrial, Scientific and Medical(ISM) band. Similarly, a rectifying circuit is also designated for the same antenna circuit. In the subsequent sections, detailed analysis is chalked out.

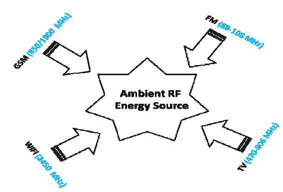


Fig.1: Available RF energy sources in ambient

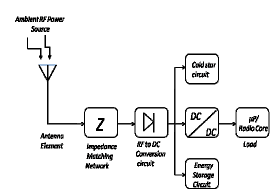


Fig.2: Generalized architecture of RF energy harvester

2. RECTENNA DESIGN

5.1 Principle of operation of Rectenna

Rectenna mainly consists of RF harvesting front end, DC power source, storage unit, and low power microprocessor and transceiver. Fig.1 depicts the architecture of an RF energy harvester. The efficiency of such system depends upon the performance of individual blocks, such as the antenna, rectifier, and power management unit. There is an impedance matching network between the antenna and rectifier circuit. The role of this network is to deliver maximum power from source to load. Generally, it consists of inductive and capacitive elements [7-14].

5.2 Antenna Design

The objective of this part is to design a single inset-fed microstrip patch antenna and then extend it to develop a 2×2 array network using corporate feeding topology which is illustrated below. To design the patch antenna some parameters are rudimentary such as: frequency of operation, dielectric property of the substrate and its height.

For the present case, we proceed with frequency of 2.45 GHz using 1.6 mm thick FR-4(ϵ_r=4.4, tan δ =0.002) substrate. The patch length (L) and width (W) are calculated using the following mathematical equations [13],

$$W = \frac{1}{2f_r\sqrt{u_0\varepsilon_0}}\sqrt{\frac{2}{\varepsilon_{reff}+1}} = \frac{c}{2f_r}\sqrt{\frac{2}{\varepsilon_{reff}+1}} \quad (1).$$

$$L = L_{eff} - 2\Delta l \quad (2).$$

Where, 'c' is the velocity of light in vacuum, ϵ_r is the permittivity of the substrate, f_r is the resonant frequency, h is the height of the substrate and, ε_{reff} is the effective dielectric constant.

After designing the single element, it is targeted to develop 2×2 linear broadside array, suitable to provide high gain for radio frequency energy harvesting. Corporate feeding topology is adopted here to make the architecture more compact. Fig.3 depicts the array network, which consists of four unit radiating patches separated by $0.75\lambda_g$. The optimized length and width of the single patch are coming around 29 and 28.7 mm, with a feeding line width of 2 mm.

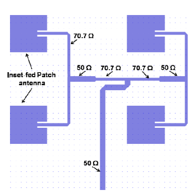


Fig.3: Layout of array antenna with corporate feeding network

5.3 Design of Rectifier circuit

Agilent ADS2020 [14] is used a base-line circuit simulator for evaluating the rectifier circuit with impedance matching network. The rectifier design starts with M/s Infineon made BAT15-03W[25] RF Schottky diode. It is a silicon low barrier N-type device with an integrated guard ring on-chip for over-voltage protection. Its low barrier height, low forward voltage and low junction capacitance make it a suitable choice for mixer and detector functions even up to 12 GHz. The specification of the diode is summarized in Table-2.Extracting the input impedance of the antenna (Z_{Ant}=50.27 +j×0.5 Ω) and impedance of the diode used (Z_{Diode}=56.05+j×468.95 Ω) at 2.45 GHz make the designer capable to propose various types of matching networks, as summarized in Fig.4[15]. The values of the circuit elements in these networks are not feasible practically. Hence, an easy implementation of the network is accomplished utilizing planar transmission lines (microstrip). Fig.5 depicts the rectifying circuit, whereas Fig.6 demonstrates the procedure to find out the input impedance of the high frequency diode. Transient analysis of the circuit is evaluated and the layout of the same is shown in Fig.7. For the layout purpose, the chip resistor and capacitors are chosen as per the '0603' package footprint. For making the ground connection at one of the common terminal, plated through via-holes with a diameter of 655 µm are proposed.

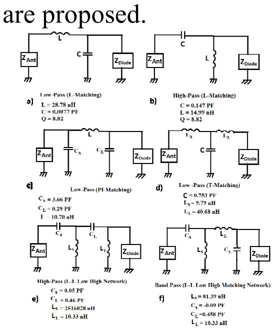


Fig.4: Probable combinations of Impedance matching networks:

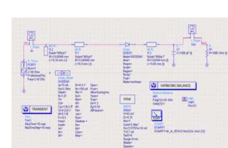
(a) Low-pass (L-matching) ; (b) High-pass(L-matching);

(c) Low-pass(π-matching) ; (d)Low-pass(T-matching);

(e) High-pass (L-L Low high network); (f) Band pass(L-L Low-High network)

Table-1: Properties of Infineon BAT15-03W high frequency diode of SOD323-package

S/N	Parameter	Value
1	Reverse saturation current(I_s)	74 nA
2	Diode resistance(R_s)	5 Ω
3	Emission coefficient(N)	1.07
4	Zero-bias junction capacitance(C_{j0})	138.5 fF
5	Junction potential(V_j)	0.224 V
6	Grading coefficient(M)	0.138
7	Forward-biased depletion capacitance(F_c)	0.5
8	Reverse breakdown voltage(B_v)	6.4 V
9	Current at reverse breakdown voltage(I_{bV})	100 µA
10	Reverse breakdown ideality factor(N_{bV})	1
11	Saturation current temperature exponent(X_{ti})	1.5
12	Energy gap(Eg)	0.59 eV



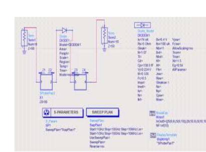
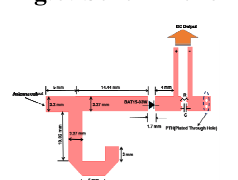


Fig.5: Complete schematic view of rectifier circuit

Fig.6: Schematic to find out the input impedance of the diode



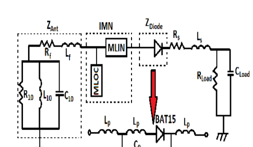


Fig.7: Layout of the rectifier circuit including matching network

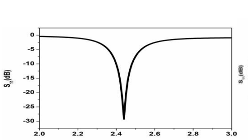
Fig.8: Electrical equivalent circuit

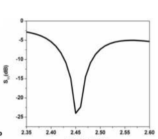
3. CIRCUIT MODELLING

The whole 'Rectenna' module can be electrically modelled with five different segments, as shown in Fig.8. 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 feed-line of the antenna circuit 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.

4. SIMULATED RESULTS

The proposed array is simulated in Ansys HFSS [16] suite using finite element method. The design parameters are optimized and thereafter the optimized return loss at 2.45 GHz are shown in Fig.9 and 10. It can be observed that, around 170 MHz (2380 -2550 MHz) bandwidth is achieved with single element, whereas array profile is offering a bandwidth of 131 MHz (2420 MHz to 2551 MHz). Simulated radiation characteristics of the array are depicted in Fig.11, which describes well the directive behaviour of the structure.





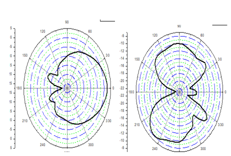
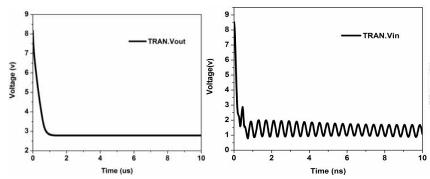


Fig.9 : Return loss characteristics of the patch antenna

Fig.10 : Return loss profile of array structure

Fig.11: Far-field radiation pattern of the antenna array in (a) H-plane and (b) E-plane.

On the other hand, based on Keysight's ADS simulation of the whole rectifier circuit the transient responses of the input and output voltage are captured as shown in Fig.12.



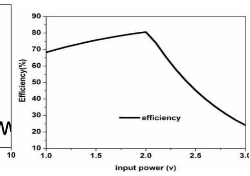


Fig.12: Transient voltage at the (a) input and (b) output terminal of the rectifier

Figure 13: Conversion Efficiency of Rectifier

An RF source of 50Ω internal impedance is used at input terminal of rectifier. As is evident from Figure 12 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 Figure 13

From Fig.13, it can be inferred that the rectifier circuit has the highest efficiency of ~80.593% when input RF power is 20dBm.

5. FABRICATION AND MEASUREMENTS

The designed antenna and rectifier have been fabricated on 1.6 mm thick Fr-4 substrate. The fabrication process is obtained using the standard photo-etching techniques for PCB realization. Fabricated prototypes are shown in Fig.14. For measuring the scattering parameter of the antenna, we use R&S make ZVA-40 Vector Network Analyzer (VNA). 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). Table-3 summarizes the output voltage and power levels for different input power ranges. It can be observed that, a maximum output power obtained is 0.016 mW against an input of +10 dBm RF signal. Fig.15 pictorially expresses the agreement and deviation of the simulated and measured return loss performance of the proposed antenna.

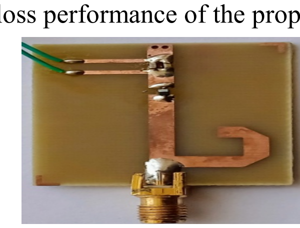


Fig.14: Fabricated prototype of (a) rectifier and (b) antenna array

Table-2: Variation of output voltage and power levels for different input signal power

Input signal Power(RF/AC)	Output voltage(DC)	Output power(DC)
-20 dBm/ (0.01 mW)	2 mV	0.00004 mW
-10 dBm/ (0.1 mW)	9 mV	0.00081 mW
0 dBm/ (1 mW)	14 mV	0.00196 mW
+10 dBm/ (10 mW)	40 mV	0.01600 mW

6. 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 microstrip-based array 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. Experimental study was conducted to evaluate the various performance metrics of the rectenna circuit. Easy design approach, 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.

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