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Ambient RF-Power Harvesting Using Compact Multi-Band Rectenna Embedded with Triple Meander Slots

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Abstract—*This work presents the design of compact multi-band Rectenna (rectifying circuit+antenna) embedded with triple meander slots for RF energy harvesting from various bands. This design is initiated by the construction of dual V-slots fed by Grounded Co-planar Waveguide (GCPW) for the frequency of 2.4 GHz. Multi-bands are obtained by embedding the triple meander lines around the dual V-slots on the rectangular patch. The designed antenna has a good return loss, greater than -25 dB in all bands. Input and output matching networks are designed to match the GCPW and rectifier circuit where voltage-doubler principle is used. GCPW lines are used due to the ease of integration with active and passive elements which makes it ideal for designing a rectifier circuit. The overall idea is to establish the Rectenna using low-mass hardware that performs at low incident power densities at multiple frequencies, with the fixed dc load. This rectenna has been designed for high mw-dc conversion efficiency.*

Keywords: *rectenna, GCPW, meander slots, voltage-doubler, mw-dc conversion efficiency*

1. INTRODUCTION

With the recent increase in RF-energy wastage across the spectrum, the use of rectifying antennae has become clearly viable. Various wireless applications inject a great amount of EM energy into the environment – energy, which can be reused, if recovered properly. This has paved way for technology which can be used to harvest this stray energy. Since microwave power transmission technology is also becoming one of the most promising charging methods for electronic devices such as wireless sensors, RFID [1], the need for efficient rectennas has increased which can utilize the aforementioned stray RF energy.The rectifying antenna, or rectenna, design basically consists of three elements: antenna, matching network, and rectifying circuit. From the architecture's point of view, the selection of antenna has a great effect on the size and the order of the system's complexity.

Different kinds of rectennas have been reported since the first rectenna presented by Brown in 1963 [2]. Various transmission lines have been, over the years, to design the rectifying circuits, such as microstrip lines, coplanar striplines (CPS) and coplanar waveguides (CPW). CPW transmission lines have several advantages, such as low dispersion, low radiation loss and avoidance of ground vias. Since the impedance bandwidth of the receiving antenna limits the operation bandwidth of the rectenna, a Grounded Coplanar Waveguide (GCPW) structure was introduced to provide wide bandwidth and simple impedance matching network.

In this paper, a novel multi-band rectenna using GCPW and dual V-slots along with Meander lines is proposed as a receiving antenna, for the frequency range of 850 MHz to 8 GHz. A triple-meander slot technology is implemented here to obtain multiple frequency bands [3]. Meander lines allow small size of antennas, wideband and ability to operate in multiple frequencies. The rectifier contains a Schottky Diode which, based on the Voltage-Doubler principle, converts the received RF energy to dc power which is further used for various target applications[4]. In the original model with only the V-slots, a single frequency band was obtained. Upon introducing meander lines, multiple spectral bands were obtained.

2. DESIGN OF MULTI-BAND RECTENNA

The GCPW rectifying antenna, operates in multiple frequency bands, and is designed using a 0.8mm thick RT/duroid substrate with a relative permittivity of 2.2 and a loss tangent of 0.001.A resistive load is terminated at the end to extract the dc power.

A. Design of Patch Antenna with Dual V-Slots

The proposed antenna originally consists of two V-slots on either side of the feed line. The copper material has a thickness of 35 µm. The rectifier section and the receiving antenna are directly matched using the GCPW structure [6]. Additionally, this structure also has a ground plane on the back of the antenna.

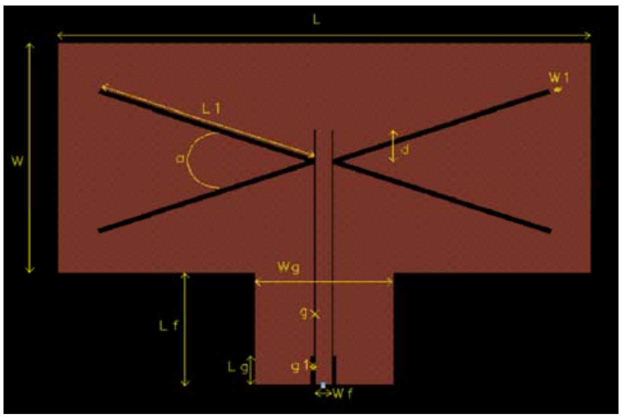

Fig. 1: Layout of receiving antenna with dual V-slots. Parameters are W_s=97mm, L_s=125mm, W=55mm, L=110mm, W_1=1.2mm, L_1=50mm,W_f=3.5mm, L_f=27mm, W_g=30mm, L_g=7mm, a=40°, d=7mm, g_1=1mm, g=0.2mm, d=25mm.

The frequency of operation is dependent on the slot length, L_1. This frequency is centered at 2.4 GHz is $0.408\lambda_0$. By tuning the length *d*of the CPW stub, the input impedance of the receiving antenna is matched to 50 Ω.

The simulated result of $|S_{11}|$ is found to be -25 dB at 2.45 GHz as plotted in fig.2.

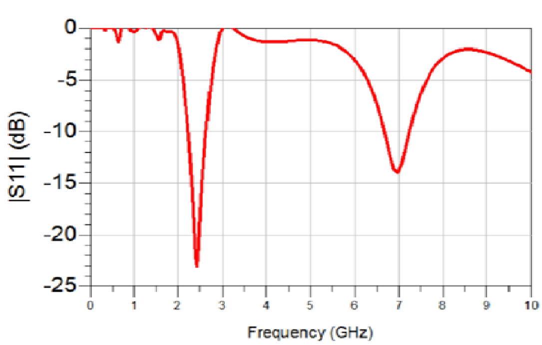

Fig. 2: Return loss of receiving antenna with only dual V-slots

B. Design of Patch Antenna with Triple Meander Lines

The meander lines implemented are used to obtain multiple frequencies. The dimensions of these lines control the range of frequency bands that are obtainable.

The width of the meander line is calculated as:

$$W = \frac{c}{2f_0\sqrt{\frac{\varepsilon_r+1}{2}})}$$

And the length of the meander line is calculated as:

$$L_{eff} = \frac{c}{2f_0(\sqrt{\varepsilon_{eff}})}$$

The triple meander slot concept is implemented around the V-slots to facilitate the generation of multiple bands. Two meander lines are embedded on either side of the V-slots while the third one is placed on top, above the feed line.

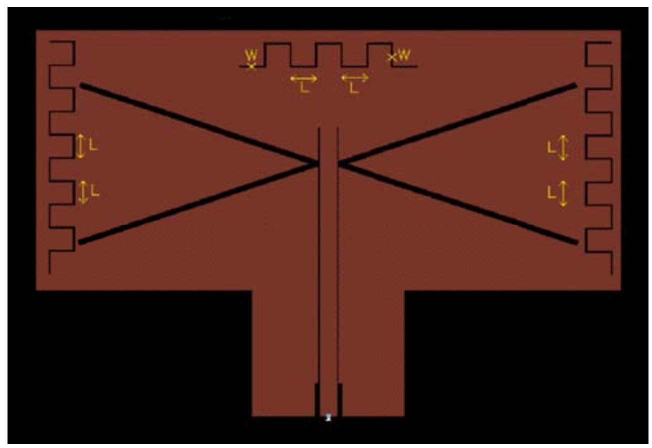

Fig. 3: Structure of receiving antenna with dual V-slots and Triple Meander lines

Upon implementation, the simulated results showed the generation of three other bands apart from the original center frequency.

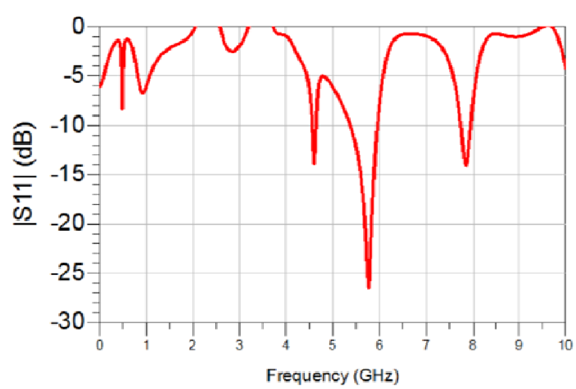

Fig. 4: Simulated results for receiving antenna with dual V-slots and Triple Meander lines.

C. Design of Rectifier

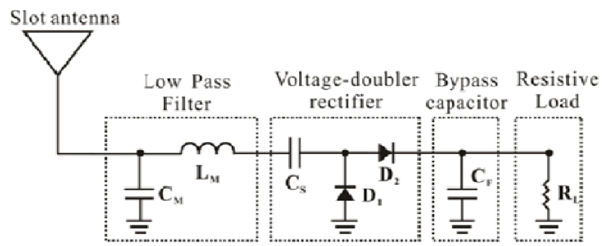

Fig. 5: Configuration of a general rectifier layout.

The multi-band rectifying circuit is show below. This design avoids the use of ground vias.

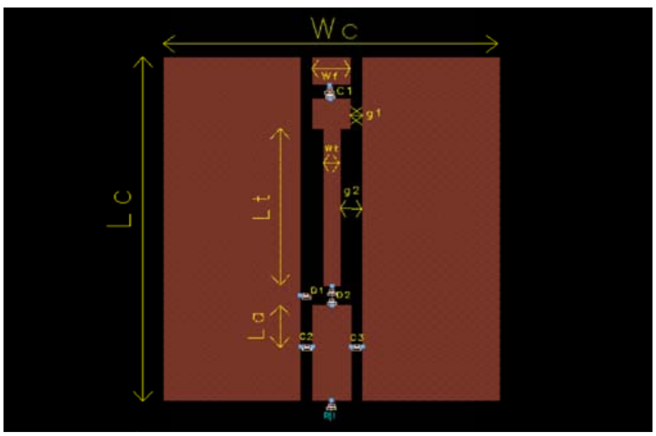

Fig. 6: Configuration of proposed rectifier: W_c=30mm, L_c=35mm, L_t=16mm, L_a=4mm, W_f=3.5mm, W_t=1.5mm, g_1=1mm, g=2mm.

The rectifier section contains capacitors and diodes which are connected in a series-parallel network. The configuration of the Schottky diode used here is HSMS-2862. This series-parallel connection of the diodes is packaged into a single SOT-23.

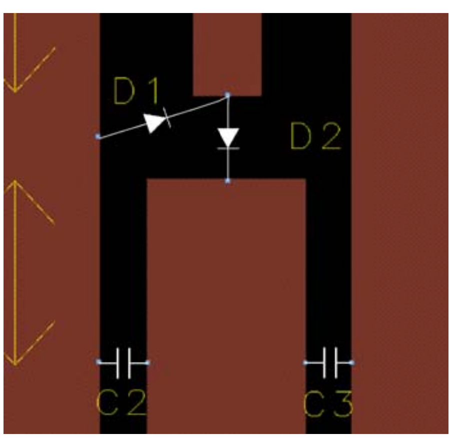

Fig. 7: Layout of the rectifier section in-detail.

A value of 5 pF is adopted for capacitor C_1which is used to prevent short-circuit of the direct current path between the antenna and rectifier. The pair of capacitors, C_2 and C_3, with values 33.5 pF and 23.5 pF, are shunted across the GCPW line to act as the dc-pass filter. The input impedance matching network is realized by adjusting W_t, L_t and the gap g_2. The circuit is terminated with a resistive load of 50 Ω.

D. Design of Multi-Band Rectenna

The layout of the multi-band rectenna with the dual V-slots after embedding the Triple Meander slots and integrating the rectifier is shown below in Fig.8.

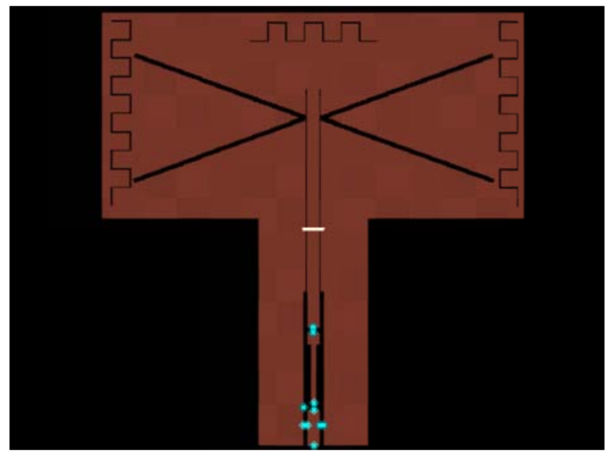

Fig. 8: Layout of multi-band rectenna with dual V-slots and Triple Meander slots.

The simulated results after integrating the multi-band antenna with the rectifier circuit yields the frequency bands as shown below in Fig.9:

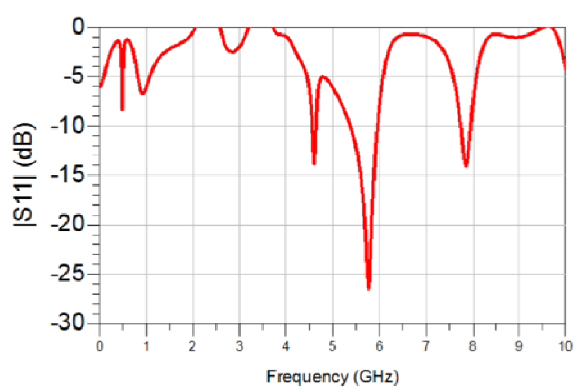

Fig. 9: Simulated results for multi-bandrectenna with dual V-slots and Triple Meander lines.

The frequency bands obtained in the simulated results range from 850 MHz to 8 GHz. The return losses for the respective bands are as shown below:

Frequency Band (GHz)	Application	Return Loss (dB)	Gain	Directivity
0.850	GSM	-27	4.48	6.95
1.7-2.1	Secure Military Comm.	-10.2	3.93	5.52
3-3.6	WiMAX	-15	6.96	8.23
5.4-7.8	UWB Application	-44	9.60	10.74

Due to the increased amount of ambient RF energy in these spectra, the energy that can be harvested in each band like GSM and WiMAX can be rectified and used to power different applications like Wireless Sensors for uninterrupted monitoring of various Agricultural aspects like crops.

E. Rectenna Efficiency

The efficiency of the rectenna system is basically equivalent to its transfer function. The general definition of any efficiency (η) used hereafter is the ratio of the output power P_{out} over the input power P_{in},

$$\eta = P_{out}/P_{in} (1)$$

The conversion efficiency (η) of the whole system is the DC power at the receiver end over the AC input power captured by the system (antenna). This efficiency is strongly dependent on the power density (P_d) distributed across the receiver aperture. The maximum incident power density can be expressed as:

$$P_d = P_t G_t / 4\pi R^2 \quad (2)$$

Where P_t is transmitted power, G_t and G_r are the gains of the transmitter and receiver antennas, and R is the distance. The effective area A_{eff} for antenna is given as:

$$A_{eff}=\lambda^2 G_r / 4\pi \quad (3)$$

Therefore, we can use eqns. (2) and (3) to obtain the power received by antenna as:

$$P_{in}= P_d * A_{eff} \quad (4)$$

As the output of the rectenna is DC power, the output power we can obtain from the output voltage generated on the load resistance by:

$$P_{out} = V^2_{out,DC} / R_{load} \quad (5)$$

Therefore, from eqns (1), (4) and (5) the conversion efficiency can be obtained by:

$$\eta = (V^2_{out,DC} / R_{load}) / (P_d * A_{eff})$$

Simulation of the rectenna through Advanced Design System yields a general efficiency of 76.40% as shown below:

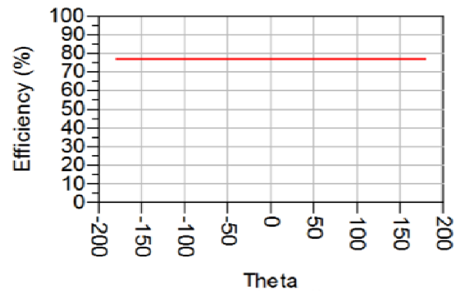

Fig. 10: General Efficiency of simulated Multi-Band Rectenna

3. CONCLUSION

In this paper, a compact linearly-polarized multi-band rectenna embedded with dual V-slots and triple meander slots was designed for harvesting the ambient RF energy in various frequency bands like GSM, WiMAX and most UWB applications. The designed antenna has a good return loss greater than -25dB and a general efficiency of 76.40% is achieved.Nowadays, in low power RF energy harvesting, as the need of RF to dc conversion has become the challenging criteria, this study can be treated as a pointed attempt in this respect. Agilent Advanced Design System was used to perform all simulations.

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