Small Low Power Rectenna for Wireless Local Area Network (WLAN) Applications

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***Abstract* ─** In this paper, a novel design of small low power rectenna operating on WLAN band with high harmonic rejection is presented. By using rotated E-shaped strip in the radiating patch, a new resonance at lower frequency (2.4 GHz) can be achieved. Also, by cutting a rectangular slot with protruded interdigital strip inside the slot in the feed line, a frequency band-stop performance can be achieved. The proposed structure has a major advantage in high harmonic rejection. The rectenna with integrated monopole antenna can eliminate the need for a Low Pass Filter (LPF) placed between the antenna and the diode as well as produce higher output power, with maximum conversion efficiency of 74% using a 1 KΩ load resistor at a power density of 0.3 mW/cm².

***Index Terms* ─** Wirless Power Transmiton System, Rectifier-Antenna (Rectenna), Protruded Interdigital Strip.

I. INTRODUCTION

The evolution of the wireless power transmission system has required simple configuration, light and easy integration with Monolithic Microwave Integrated Circuits (MMICs) and narrowband antennas for the special system application [1]. Recently, considerable research efforts have been directed toward low-profile, low-power, energy efficient, and self-sustainable sensor networks aiming to harvest ambient energy from vibrations, solar energy, as well as microwave energy from existing employed communication networks [2]-[4]. The initial development of rectenna focuses on its efficiency for great power reception and conversion. But in the last few years, excluding high power applications, wireless power transfer has been often used in microwave radiation with relatively low power densities [5,6]. This approach offers the possibility to use the rectenna as an energy module in a WSN. Indeed, the rectenna efficiency at low power level is an important feature (0 dBm, and 10 dBm), because it would allow one to power a node or a tag located far away from the RF transmitting source. For this purpose, we must take into account several considerations, such as the size, and good conversion efficiency.

During the last years, there are various antenna designs, which enable antennas with low profile, lightweight, flush mounted, and WLAN devices. These antennas include the Planar Inverted-F Antennas (PIFAs) [7], printed dipole antenna [8], the chip antennas [9], and the planar monopole antennas [10]. However, up to now, a printed antenna that has T-shaped notch configuration has not been reported. Rectifying antenna (rectenna), which can convert RF energy to DC power, plays an important role in free space Wireless Power Transmission (WPT). Over the last century, the development of rectenna for Space Solar Power Transmission (SSPT) [11] as well as WPT [12] had great achievement with specific functions, and the applications; e.g., actuator [13] or wireless sensors [14]. The typical rectenna in the prior literatures [15] basically consists of four elements: antenna, Low Pass Filter (LPF), diodes, and RC filter. The initial development of rectenna focuses on its directivity and efficiency for great power reception and conversion; hence, large array was usually adopted for microwave power reception.

In this letter, we propose a novel a microstrip rectenna with harmonic rejection property. By

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using rotated E-shaped strip in the radiating patch, a new resonance at lower frequencies (2.4 GHz) can be achieved. Also, by cutting a rectangular slot with protruded interdigital strip inside the slot in the feed line, a frequency band-stop performance can be achieved. In the proposed rectenna structure, the design of the antenna is first presented followed by the rectifier circuit optimization and measurements. Finally, the complete rectenna performance is evaluated. This structure has a major advantage in providing tighter capacitive coupling to the line in comparison to known radiating patch [11]. In the proposed configuration, a pair of gap distances are playing important role in the radiating characteristics of this antenna, because it can adjust the electromagnetic coupling effects between the interdigital radiating patch and the microstrip transmission line.

II. RECTENNA DESIGN AND CONFIGURATION

The presented miniature packaged rectenna with the integrated band-reject filter is shown in Fig. 1, which is printed on an FR4 substrate of thickness 0.8 mm, permittivity 4.4, and loss tangent 0.018. The proposed rectenna structure consists of a microstrip monopole antenna for radiating element, an integrated band-reject filter, and a rectifier with DC filter and matching circuit for active part. The filter is used to reduce the out of band harmonics generated by the rectifying Schottky diode. An HSMS-2862 microwave Si Schottky detector diode pair was used to design the rectenna. The width of the 50-Ω microstrip line is fixed at 1.5 mm. The matching circuit to the left and right of the device controls the degree of reflection. On the other side of the substrate, a conducting ground plane is placed. In addition, to satisfy the efficiency requirement, the microstrip strips are fixed to a suitable electrical length, taking the calculated phases of the rectifier and passive antenna into consideration [7]. The proposed antenna is connected to a 50-Ω SMA connector for signal transmission.

In rectenna design, the antenna and rectifier circuits are typically designed separately. The antenna is designed using Electromagnetic (EM) simulation, and its parameters are then included in a nonlinear circuit simulation tool such as a Harmonic Balance (HB) simulator used to design the rectifier [5]. In this work, the complete antenna Thevenin equivalent circuit in the receiving mode is computed including the open-circuit voltage and incorporated in the harmonic balance analysis to optimize the rectenna parameters [7]. The equivalent circuit parameters can be efficiently calculated from the antenna analysis in the transmit mode using commercial EM simulators. This allows one to directly include the input power density and incoming wave direction in addition to the antenna impedance matrix in the rectenna design. The method is demonstrated by designing a dual-polarized aperture-coupled patch rectenna that has a compact size due to the use of a cross slot at the patch surface [8]. Preliminary details of the proposed rectenna design without utilizing the complete Thevenin equivalent circuit of the antenna are given in [9]. The aperture-coupled feeding structure makes the design suitable for implementation on flexible or textile-based substrates. Additionally, the method can be easily extended to rectenna array configurations.

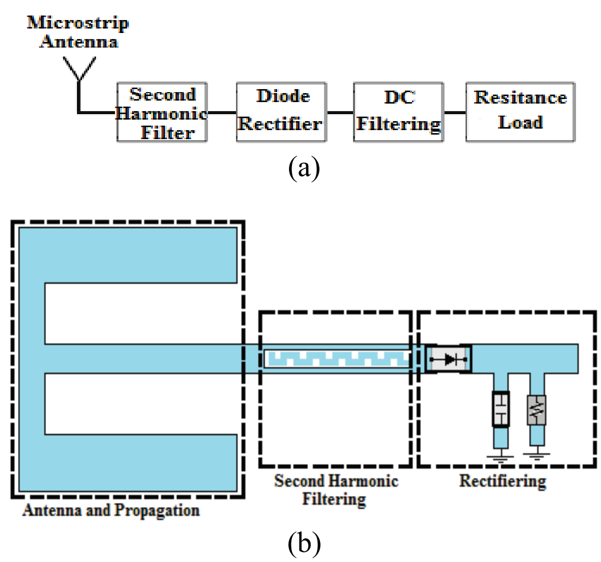

Fig. 1. Schematic of proposed rectenna with filter: (a) simplified block diagram, and (b) realized microstrip structure.

A. Antenna and defected microstrip line design

The presented small monopole antenna fed by a microstrip line is shown in Fig. 2, which is printed on an FR4 substrate of thickness 0.8 mm, permittivity 4.4, and loss tangent 0.018. The proposed monopole antenna structure consists of a rotated E-shaped radiating patch, a 50 Ω microstrip feed line with a rectangular slot with an interdigital strip protruded inside the slot, and a ground plane. The proposed antenna is connected to a 50- Ω SMA connector for signal transmission.

Regarding Defected Microstrip Structures (DMS), the creating slots in the microstrip feed-line provide an additional current path. Moreover, this structure changes the inductance and capacitance of the input impedance, which in turn leads to change the bandwidth. The DMS applied to a microstrip line causes a filtering characteristic of the structure transmission with a filter frequency controllable by changing the shape and size of the slot [3]. In this structure, the protruded interdigital strip perturbs the resonant response and also acts as a half-wave resonant structure. At the notch frequency, the current flows are more dominant around the protruded interdigital strip, and they are oppositely directed between the protruded strip and the microstrip feed-line [4]. As a result, the desired high attenuation near the notch frequency can be produced.

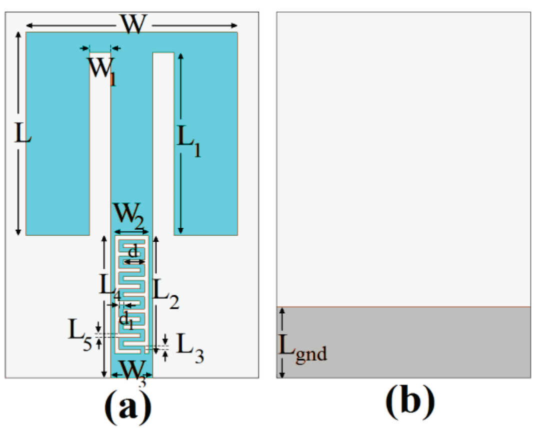

Fig. 2. Geometry of proposed microstrip-fed monopole antenna: (a) top view, and (b) bottom view.

The proposed DMS with their equivalent circuit models are shown in Figs 3 (a) and (b), respectively, which is printed on a FR4 substrate of thickness 0.8 mm. This defected structure on the feed-line will perturb the incident and return current and induce a voltage difference on the ground plane and microstrip feed-line. These two effects can be modeled as a series LC circuit, such as band-stop filter response due to its frequency response [9]. Figure 4 shows the effects of the rectangular slot with an interdigital strip protruded inside the rectangular slot, on the return loss in comparison to the same antenna without it. It can be observed in Fig. 4, that by using a rectangular slot with an interdigital strip protruded inside the slot with variable dimensions in the microstrip feed-line, a band-stop performance can be created.

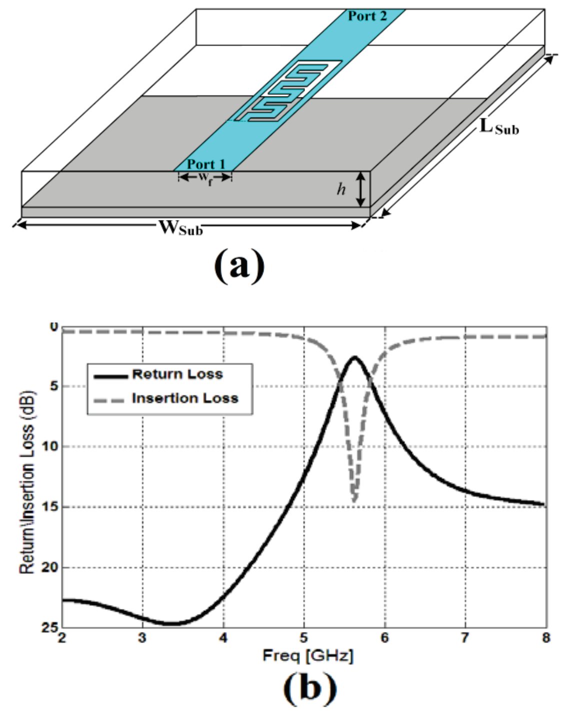

Fig. 3. (a) Geometry of the proposed Defected Microstrip Structure (DMS), and (b) simulated return/insertion loss characteristics for the proposed defected microstrip structure.

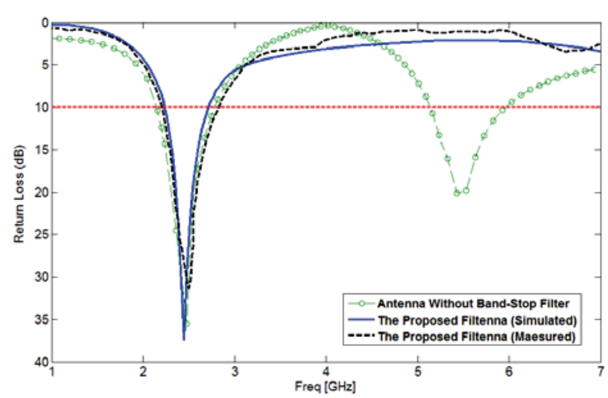

Fig. 4. Return loss comparisons for the ordinary rotated E-shaped antenna and the proposed antenna.

In order to understand the phenomenon behind this new resonance and out of band harmonic generation, the simulated current distributions on the top layer for the proposed antenna are shown in Fig. 5. As shown in Fig. 5 (a), at the first resonance frequency (2.4 GHz) the current mainly concentrates on the rotated E-shaped strip in the radiating patch, and also as shown in Fig. 5 (b), at the notch frequency (5.5 GHz) the current flows are more dominant around of the protruded interdigital strip. As a result, the desired high attenuation near the notch frequency can be produced [3]-[5].

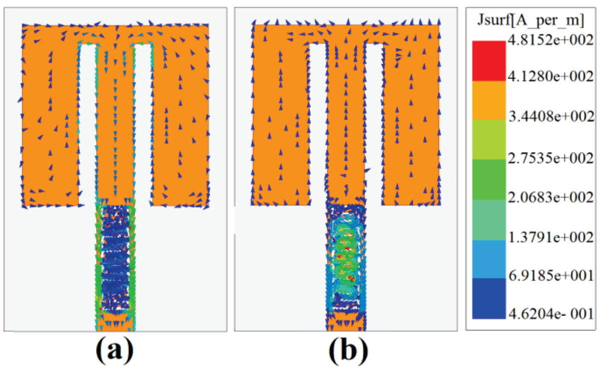

Fig. 5. Simulated surface current distributions on the radiating patch: (a) at the first resonance frequency (2.4 GHz), and (b) the second resonance frequency (5.5 GHz).

B. Rectifier design

In this study, the Schottky diode is used in the rectification of RF energy for the rectenna. The Schottky diode is used mainly because of its low turn on voltage and low junction capacitance characteristics, which enables it to work at the high frequencies required. The circuit diagram of rectifier is given in Fig. 6, while component values are summarized in Table 1. Dimensions of the resonators and the matching network were optimized using Agilent's Advanced Design System (ADS) in conjunction with the Electromagnetic (EMDS) Simulation tool to get the required oscillation frequencies for dual-band operation. At a maximum distance of 2 m, output dc voltage of over 2 V at the lower frequency band and over 1 V at the higher frequency band can be achieved [9]. Figure 7 shows return loss in dB versus frequency for the deigned rectifier.

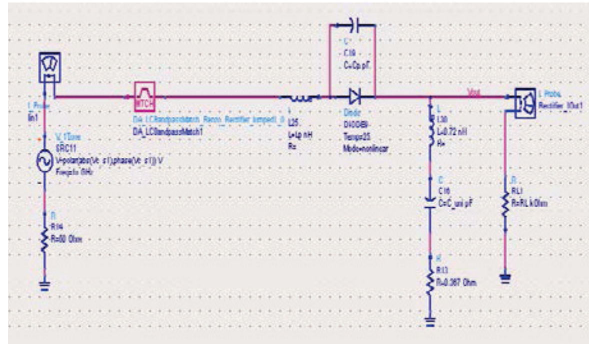

Fig. 6. Circuit diagram of the proposed rectifier circuit.

Table 1: Rectifier circuit dimensions and component values

Param.	R_L	L_2	L_1	C_{uni}
Value	1.1 KΩ	3.93 nH	2.01 nH	3.01 pF

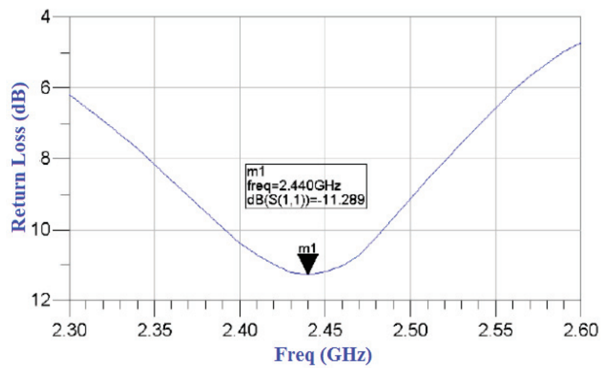

Fig. 7. Return loss versus the frequency.

III. RECTENNA PERFORMANCE

The receiving antenna and rectifying are connected by SMA connectors as shown in Fig. 8. It contains a linearly polarized monopole antenna designed at 2.4 GHz by using HFSS software [16]. The rectenna contains one HSMS2860 commercial Schottky diodes in a SOT23 package. The zero bias junction capacitance Cj0 is 0.18 pF and the series resistance Rs is 5 V. The experiments have been carried out in anechoic chamber. The transmitting antenna is a standard linear polarized horn with gain G_t of 12 dB. The rectenna is located at the distance *r* of 50 cm, which is the far region of the horn.

In general, the overall efficiency of a rectenna is defined as a ratio of DC power to incident RF power as below:

$$\eta_0 = \frac{V^2 / R_{Load}}{P_A}. \tag{1}$$

The measured overall efficiency is shown in Fig. 8. In the power density range (0-0.25 mW/cm²), the measured rectenna efficiency is above 72% from 0.2 mW/cm² power density over a 1 KΩ load resistance. The measured results show that the efficiency increases when the power density increases. In applications, the antenna and rectifying circuit can be integrated directly on one substrate by omitting SMA connectors. Without the loss of SMAs, the efficiency would be higher.

The output DC voltage has been measured against power density from the Friss transmission equation:

$$P_r = \left(\frac{\lambda}{4\pi r}\right)^2 P_t G_t G_r, \tag{2}$$

where P_t is the transmitting power; G_r is the receiving antenna gain, λ is the free space wavelength at 2.42 GHz. The rectenna is illuminated by a linearly polarized incident plane wave of 20 V/m (0.10 mW/cm²) at its broadside. On the transmitter side, we have used a 30 dB gain power amplifier at 2.4 GHz connected to a signal generator. The output DC voltage across the resistor load has been measured by a voltmeter.

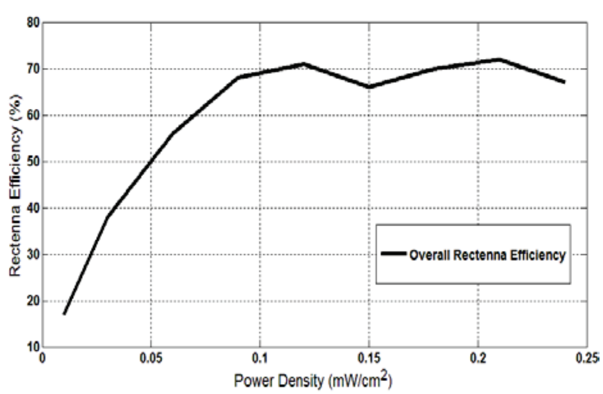

Fig. 8. Measured rectenna efficiency against power density.

The measured output DC voltages are shown in Fig. 9. In the power density range (0-0.3 mW/cm²), the measured output DC voltage is 2.9 V over a 1 KΩ optimized load resistance. The measured results show that the output voltage increases when the power density increases.

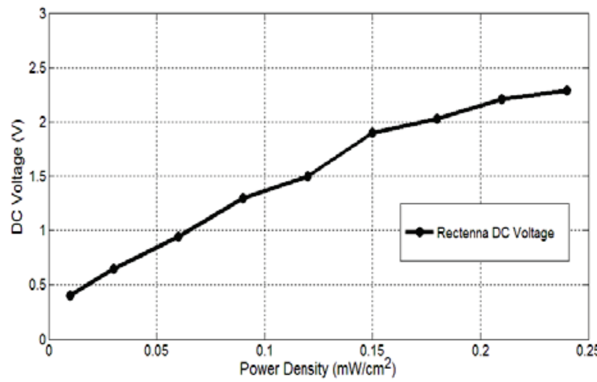

Fig. 9. Measured DC voltages against power density.

IV. CONCLUSION

As presented above, a novel design of rectenna with a series diode circuit topology is an interesting subject for WLAN applications. By using rotated E-shaped strip in the radiating patch, a new resonance at lower frequencies (2.4 GHz) can be achieved. Also, a rectangular slot with protruded interdigital strip inside the slot in the feed line is used to reject the second harmonic. No input low pass filter is needed; thus, reducing the insertion losses and the dimensions of the circuit. The oscillator design based on the AIA concept has been shown to provide an efficient and successful method for designing high efficiency and compact systems. The rectifying circuit has been optimized at 2.4 GHz for an input power of 10 dBm. The rectenna exhibits a measured efficiency of 72% at 0.24 mW/cm² power densities and an output DC voltage of 2.39 V.

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