Design of a 5.8-GHz Rectenna Incorporating a New Patch Antenna

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***Abstract*—This paper presents a rectifying antenna (rectenna) designed in a finite ground coplanar waveguide (FG-CPW) circuit. The new rectenna element is based on a new patch antenna and a new band-stop filter, in the form of compact CPW resonant cell (CCRC), located between the antenna and the rectifying diode. The novel coplanar patch antenna with about 9-dBi gain is proposed for the rectenna. The CCRC is adopted to suppress the second harmonic from radiation. With the use of this band-stop filter, a radio-frequency-to-direct-current (RF-to-dc) conversion efficiency of 68.5% using a 270-Ω load resistor is obtained.**

***Index Terms*—Coplanar waveguide (CPW) band-stop filter, coplanar waveguides, rectenna, wireless power transmission.**

I. Introduction

Rectennas, for receiving and converting the microwave power to dc power, have received much attention lately in the development of the wireless power transmission. Different rectenna designs have been demonstrated for the transmission of electrical power over free space. In addition, the application of this technology can be used in radio-frequency identification (RFID).

Rectennas using different kinds of antenna have been proposed in the last few years. Printed dipole rectennas [1]–[3], rectennas designed with harmonic-rejecting circular-sector antenna [4] and a dual-frequency circularly polarized rectenna [5], have been demonstrated. Moreover, rectenna arrays were investigated for rectifying larger amount of RF power. Broadband rectenna arrays using spiral antennas [6] and circularly polarized dual-rhombic-loop rectenna arrays [7] have also been introduced. Antenna array is an effective means to increase the receiving power for rectification. However, a tradeoff arises between the antenna size and the radiation gain.

In this paper, an antenna that has a high radiation gain and yet is compact in size is proposed for the rectenna. Its characteristics are comparable to that of a two-element antenna array, but an extra feeding network is not required. The rectenna, depicted in Fig. 1, is a finite ground coplanar waveguide (FG-CPW) structure that is employed in a rectenna design for the first time. The design also includes a compact CPW resonant cell (CCRC) filter for improving the performance of the rectenna.

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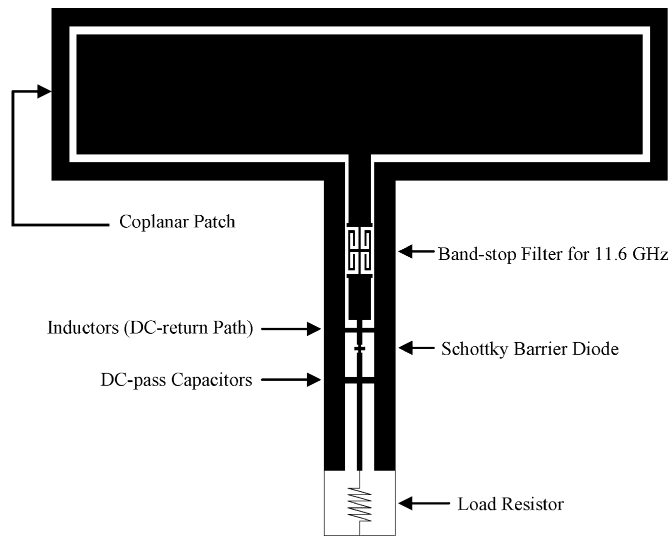

Fig. 1. Circuit configuration of the FG-CPW rectenna.

II. Rectenna Element Design

The FG-CPW rectenna is fabricated on a 0.7572-mm-thick RT/Duroid 6002 substrate with a dielectric constant of 2.94. The main components are shown in Fig. 1. The full-wave electromagnetic simulator, IE3D [11], is used to design the antenna and the CCRC filter. The patch antenna receives RF power at 5.8 GHz, which is then transmitted through the CCRC to an Agilent surface mount microwave Schottky barrier diode (HSMS-8202) for power rectification. The second harmonic power generated by the nonlinear rectifying diode is blocked by the CCRC from radiating through the antenna. A resistive load is finally attached to extract the dc power.

A. FG-CPW Fed Patch Antenna Design

The newly proposed antenna, depicted in Fig. 2(a), employs the structure of a FG-CPW, which not only maintains the advantages of conventional CPW, but also is much more compact due to the great reduction in size of the CPW ground. In order to produce the unidirectional radiation and to increase the antenna gain, an extra ground plane is located behind the antenna to reduce the back radiation, causing the broadside radiation into one direction.

A two-element microstrip antenna array has been designed in Fig. 2(b) to compare the size and the performance of our proposed antenna. The proposed one possesses a smaller size, which is about 75% of that of the array. The measured return loss and radiation gain of the proposed patch antenna are shown

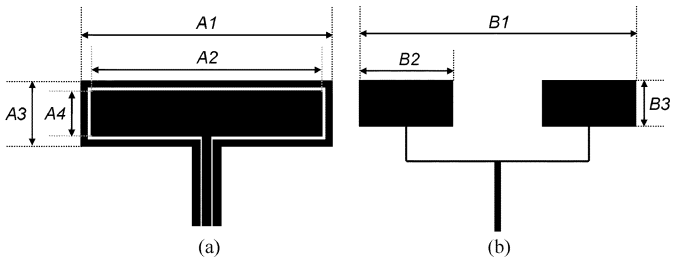

Fig. 2. (a) Configuration of a one-element FG-CPW rectenna: $A1 = 79$ mm, $A2 = 73$ mm, $A3 = 21$ mm, and $A4 = 14.55$ mm. (b) Configuration of a two-element microstrip patch antenna: $B1 = 86.3$ mm, $B2 = 29.3$ mm, and $B3 = 14.55$ mm.

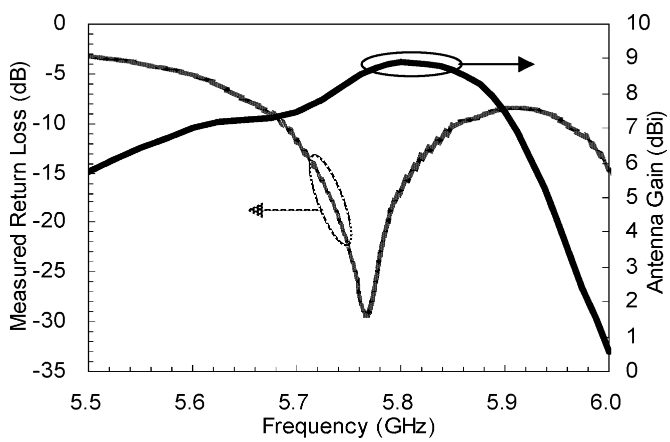

Fig. 3. Measured return loss and radiation gain of the antenna.

in Fig. 3. The return loss is found to be better than 15 dB at 5.8 GHz, with 3% bandwidth at 10-dB return loss. In addition, the radiation efficiency of our antenna attains a maximum value of 90% at the operating frequency, while that of a conventional patch is 89.4%. More important, the measured antenna has a gain of 9 dBi, which is as high as that of the array, but with a more compact circuit area.

Fig. 4 shows the measured radiation pattern in the H-plane and E-plane. The results reveal that the radiation beam of the H-plane is much narrower than that of the E-plane. Small variation exists along the H-plane copolarized radiation pattern. The phenomenon can be analyzed by using the current distribution along the coplanar patch.

Current distribution along the FG-CPW fed patch antenna at the resonant frequency point of 5.8 GHz is illustrated in Fig. 5. Most of the current concentrates on the two sides of the antenna. Like the current distributed in a two-element antenna array, the current at both sides flows in the same direction with the same phase. Due to the similarity of the current distribution, the proposed FG-CPW fed antenna has the same effect as a two-element array. Therefore, without using an extra feeding network and sacrificing the gain, our proposed antenna exhibits characteristics similar to that of an antenna array.

B. Coplanar Patch Incorporating CCRC

The compact microstrip resonant cell (CMRC) pattern was first proposed in [10], exhibiting a distinctive stopband effect. The newly proposed CCRC as shown in Fig. 6 was adapted to suit the structure of FG-CPW. It is aimed to pass the 5.8 GHz

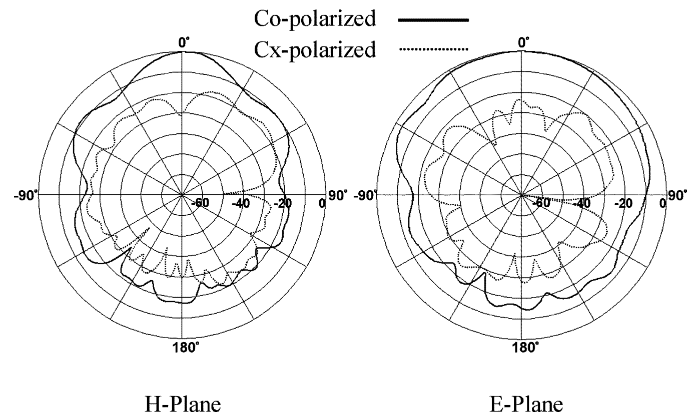

Fig. 4. Measured H-plane and E-plane radiation patterns.

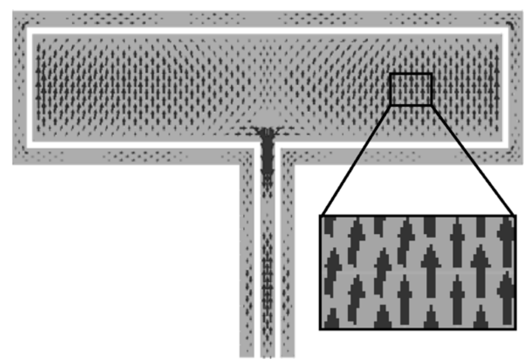

Fig. 5. Current distribution at 5.8 GHz along the coplanar patch.

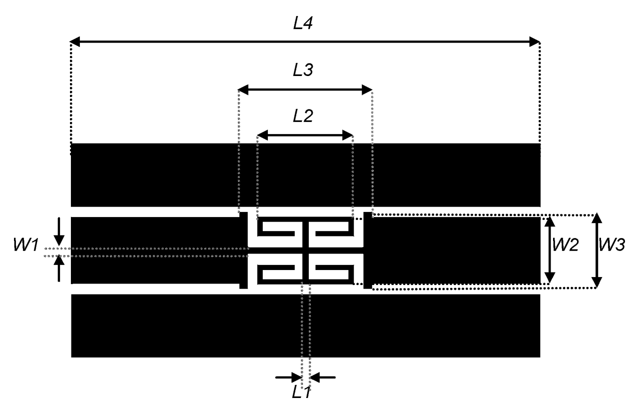

Fig. 6. CCRC structure: $W1 = 0.25$ mm, $W2 = 2.9$ mm, $W3 = 3.3$ mm, $L1 = 0.3$ mm, $L2 = 4.8$ mm, $L3 = 6.6$ mm, and $L4 = 23.4$ mm.

from the FG-CPW fed antenna to the rectifying device and block the second harmonic at 11.6 GHz flowing from the rectifying device to the antenna. The dimensions of the filter are chosen to be neatly fitted into the FG-CPW feeding line widths of both the antenna and the following rectifying circuit. Fig. 7 shows the measured S-parameters of the CCRC structure with a 45% (-10-dB) stopband from 8.7 to 13.5 GHz and good passband at 5.8 GHz. The generated second harmonic signals, which are at 11.6 GHz, can therefore be effectively prevented from radiation.

Frequency responses of the antenna alone and the antenna integrated with filters are shown in Fig. 8 for comparison. It is worthwhile to mention that the return loss of the second harmonics for the antenna with CCRC is found to be better than -0.4 dB at 11.6 GHz, while the return loss is as poor as -8 dB

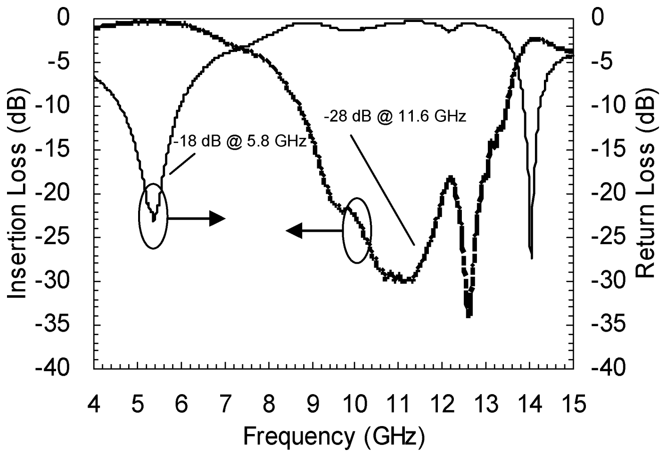

Fig. 7. Measured performance of the CCRC.

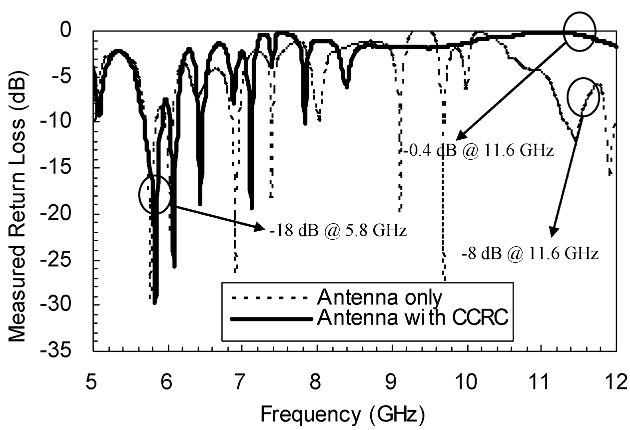

Fig. 8. Measured frequency responses of the antenna and the antenna with filter.

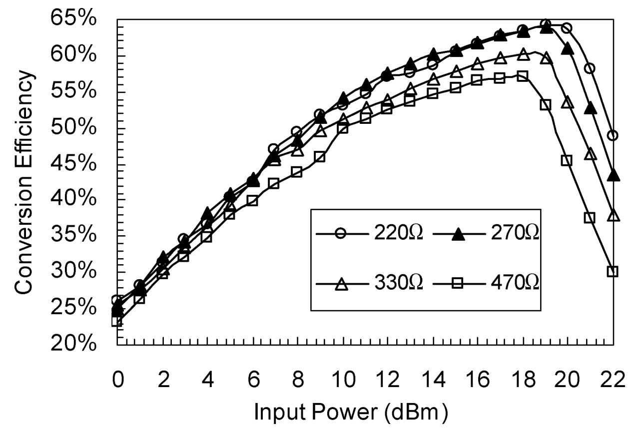

Fig. 9. RF-to-dc conversion efficiency versus input power for various resistive loading.

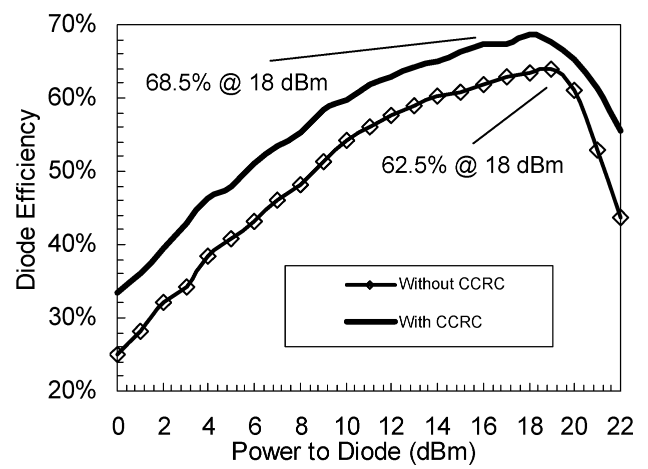

Fig. 10. RF-to-dc conversion efficiency versus input power for 270-Ω-loaded rectenna with and without CCRC.

without CCRC. In addition, it is found that good return loss of the antenna at 5.8 GHz, with better than −25 dB, can still be obtained after integrated with the CCRC. It can be shown that the CCRC effectively passes the fundamental and blocks the second harmonics.

C. RF-dc Rectifying Circuit

A Schottky barrier diode HSMS-8202 is chosen for the rectifying circuit. Owing to the series connection of the diode, a pair of 33-nH inductors is shunted across the FG-CPW line at the input of the diode to act as a dc return path. At the output, a dc pass filter is formed from a shunt 47-pF capacitors pair. It is designed to readily reflect the RF energy back to the diode for rectification. The distance between the capacitors and the diode is adjusted to optimize the conversion efficiency.

III. Rectenna Measurements

The RF-to-dc conversion efficiency measurement of the rectenna is performed in an anechoic chamber. The measurement setup refers to the approach in [2]. A standard gain horn antenna is used for transmitting power at 5.8 GHz. The distance between the antenna and the horn for measurement is 2.3 m. The conversion efficiency is defined as

$$\eta = \frac{P_{\mathrm{dc}}}{P_{\mathrm{to\ diode}}} \times 100\%. \tag{1}$$

As shown in Fig. 9, our rectenna without the CCRC is first tested under different resistor values. A peak efficiency of 62.5% at 18-dBm input power is obtained using a 270-Ω load. With this load resistance value fixed, Fig. 10 shows a 6% efficiency improvement after introducing the CCRC.

IV. Conclusion

A novel finite group coplanar waveguide (FG-CPW) high-gain rectenna element has been developed which has the conversion efficiency of 68.5% at 5.8 GHz with an input power of 18 dBm. The antenna proposed for this rectenna possesses the characteristics of a two-element array but with a smaller size. It not only has the similar radiation pattern, but also radiates with a higher gain of 9 dBi. The proposed compact CPW resonant cell (CCRC), which is used as an input band-stop filter, effectively suppresses the second harmonic radiation. In addition, by incorporating the CCRC, an enhancement of 6% is achieved for the RF-to-dc conversion efficiency. A conversion efficiency of 68.5% is finally obtained.

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