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A CIRCULARLY POLARIZED RECTENNA WITH LOW PROFILE FOR WIRELESS POWER TRANSMISSION

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Abstract—A novel circularly polarized microstrip rectenna operating on C-band with low profile is proposed. The input and output match networks of the rectifying circuit are realized by $\lambda/4$ microstrip lines and open stubs with the harmonics being inhibited. The circularly polarized receiving antenna is a truncated-corner square patch fed by microstrip line with DGS (Defect Ground Structure) for suppressing high order harmonics further. The voltage of 4.34 V on the load of 298 Ω is measured and the overall RF-DC conversion efficiency of 68.4% is obtained. This kind of rectenna can be extended to large arrays for wireless power transmission applications.

1. INTRODUCTION

The technology of microwave power transmission (MPT) has been developed since the solar power satellite plan was proposed to solve the global energy crisis in 1960s [1]. A rectenna, which is used to convert the microwave power to the direct current power, is one of the key components of the MPT system. The first rectenna was designed by Brown in 1963 [2]. With the development of microwave devices and planar printed technologies, it is possible for rectennas to obtain high RF-DC (Radio Frequency-Direct Current) conversion efficiency with thin depth and light weight. MPT technology can be used as a kind of source supply without wire, which has been finding potential applications in many areas, such as RFIDs (Radio Frequency IDentifications, pipeline robots, wireless sensors and actuating smart materials, etc. [3–5].

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Circularly polarized (CP) rectennas have been noticed because they could output constant DC power at random polarization angles. Coplanar Stripline (CPS) is a good choice of the feedline or the transmission line because it is convenient for an active device being integrated without any via holes. The high rectifying efficiencies of 81% and 76% were obtained in [6, 7]. To match the rectifying circuits of CPS structures, the receiving antennas were dual-rhombic loop and dual-patch, respectively in [6, 7]. In both of the rectennas, the antennas were followed by bandpass filters so the whole sizes of rectennas were large.

The microstrip line is more general in microstrip antenna design. A linearly polarized dual-frequency rectenna using two slot rings fed by a microstrip line as the receiving antenna was proposed in [8]. RF-DC conversion efficiencies of 65% and 46% were obtained at 2.45 GHz and 5.8 GHz, respectively. A circularly polarized rectenna with RF-DC conversion efficiency of 75% was obtained at 9.98 GHz [9], in which the receiving antenna was a double-layer patch fed by a microstrip line through a cross slot.

In general, the rectifying circuit is composed of a rectifying diode, an input and output matching networks, a bandpass or lowpass filter, and a DC-pass filter [6–9]. In this paper, a novel circularly polarized rectenna with low profile is developed. The harmonics suppression characteristic are realized by the receiving antenna with DGS and the input and output match networks of the rectifying circuit with $\lambda/4$ microstrip lines and open stubs, which are designed especially at C-band. The bandpass or lowpass filter could be omitted, and the rectenna would be compact. It is convenient for this kind of rectenna with microstrip line structure to be extended to large arrays for high power transmission applications.

2. RECTIFYING CIRCUIT

The schematic diagram of the proposed rectifying circuit is shown in Fig. 1. The input impedance match network consists of two $\lambda/4$ microstrip lines and an open stub working at C-band. This sort of match network is sensible to the operating frequency, so the effect of the high harmonics incurred by the diode is low. The DC-pass filter is composed of a chip capacitor and $\lambda/4$ microstrip line, which smoothes the DC voltage and reutilizes harmonics energy. The DC power is collected by a resistive load.

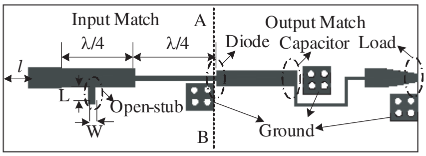

Figure 1. Structure of the rectifying circuit.

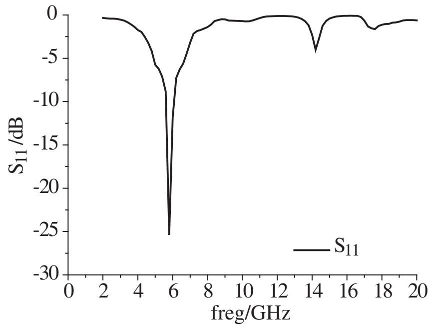

Figure 2. S_{11} curve of rectifying circuit.

2.1. Rectifying Diode

The diode used in the circuit is the M/A COM flip-chip schottky diode MA4E1317, which has the equivalent circuit parameters as follows, series resistance $R_S = 4\,\Omega$, zero-bias junction capacitor $C_{j0} = 0.02\,\text{pF}$, built-in turn-on voltage $V_{bi} = 0.7\,\text{V}$, and breakdown voltage $V_B = 7\,\text{V}$. The rectifying circuit is etched on the substrate of FR4 with the relative dielectric constant ε_r of 2.55, the thickness of 0.8 mm, and the $\tan\delta$ of 0.002.

Based on the analysis of ADS software, this rectifying circuit has the maximum RF-DC conversion efficiency when the load is $320\,\Omega$, and the diode input impedance is $(230 + j18)\,\Omega$.

2.2. Input Match Network

To match the input impedance of diode with the source impedance of $50\,\Omega$, two-step $\lambda/4$ microstrip lines are designed. The open-stub microstrip line merged with matching network can suppress the third-order harmonic wave back to the rectifying diode by adjusting the length L and width W. The return loss of rectifying circuit is presented in Fig. 2 when the input power is 110 mW. At 5.8 GHz, the circuit is well matched with $50\,\Omega$, and S_{11} is -25.4 dB. S_{11} values at 11.6 GHz and 17.4 GHz are -0.146 dB and -1.529 dB, respectively. It shows that the second and third-order harmonics are suppressed effectively.

2.3. DC-pass Filter

The DC-pass filter consists of a chip capacitor and $\lambda/4$ microstrip line. The capacitor is used to smooth the DC voltage and isolate the fundamental and high order harmonics power from the resistive load. For the fundamental wave and high order harmonics, the impedance of the capacitor is little, so the capacitor can be considered as short. Z_{in} on AB plane is expressed as:

$$Z_{in} = j\tan(\beta l) = j\tan\left(\frac{n\pi}{2}\right) \tag{1}$$

The first, second, third, ..., orders harmonics wave are presented when $n = 1, 2, 3, \ldots$. Even order harmonics can pass through DC-pass filter when $n = 2, 4, 6, \ldots$, and the average voltage of load is zero. When the diode is turn-on, the impedance of diode is little, so the even order harmonics are circled between diode and capacitor and can be rectified. Odd order harmonics can be stopped by the capacitor because the impedance is infinite when $n = 1, 3, 5, \ldots$. Consequently, the third-order harmonic is bounced between the matching network and dc-pass filter and rectified once again.

A general chip capacitor with the value of 47 pF is used in the DC-pass filter. The DC-pass filter with a $\lambda/4$ microstrip line (λ is the wavelength at 5.8 GHz) rejects all of the microwave energy from passing the load resistor. Proper distance between the diode and capacitor is crucial for maximizing the conversion efficiency. Rectifying efficiency can be improved by turning the length of $\lambda/4$ microstrip line on a small scale.

The measured S_{11} and S_{21} values of capacitor are shown in Fig. 3. The insertion losses at 5.8 GHz, 11.6 GHz and 17.4 GHz are 19 dB, 7 dB and 19 dB, respectively. The return loss is about -2 dB at 5.8 GHz. It is obvious that the fundamental and harmonic waves are reflected effectively.

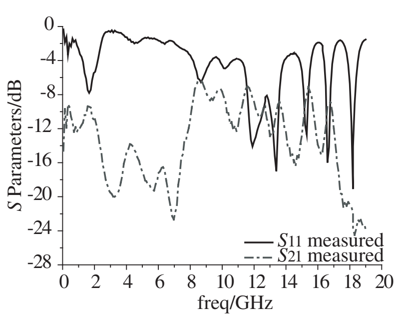

Figure 3. Measured return and insertion loss of capacitor with balun.

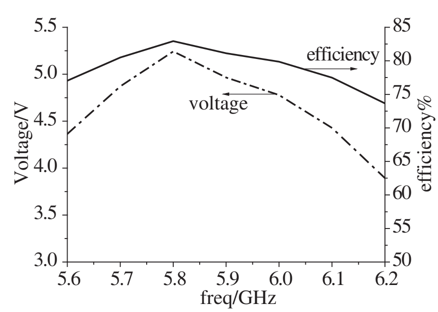

Figure 4. Simulated efficiency and output voltage versus frequency.

The DC voltage amplitudes, fundamental frequency and high order harmonics on diode and load are presented in Table 1. The odd order harmonics voltage can be suppressed below 0.1 V by the DC-pass filter, and the even order harmonics voltage is below 0.01 V while the DC voltage is 5.352 V.

2.4. Rectifying Circuit

The rectifying circuit shown in Fig. 1 is simulated by ADS. The simulation efficiency and output voltage versus frequency are shown in Fig. 4. The highest conversion efficiency is 81.4% on the load of 320 Ω at 5.8 GHz. The voltages from 5.7 GHz to 6.1 GHz are above 4 V. The bandwidth of conversion efficiency over 75% is 300 MHz (from 5.7 GHz to 6 GHz). Theoretically, the diode voltage should not be designed to 3.5 V because the breakdown voltage could not exceed 7 V. However, the breakdown voltage of rectifying diode is testified to achieve around 11 V.

Figure 5 shows the simulated conversion efficiency versus the input power. The highest efficiency of 81.4% occurs at an input power of 110 mW. The conversion efficiency increases gradually with the input power when the input power is less than 110 mW. The efficiency drops down rapidly when the input power is more than 110 mW because the diode voltage has exceeded the breakdown voltage. Between 30 mW and 135 mW input power, the efficiency exceeds 70%.

Table 1. Voltage amplitudes of DC and harmonics on diode and load.

Frequency/GHz	0	5.8	11.6	17.4	23.2	29
V_{diode}/V	5.352	7.851	0.067	2.008	0.018	0.68
V_{dc}/V	5.352	0.076	0.004	0.006	0.0008	0.001

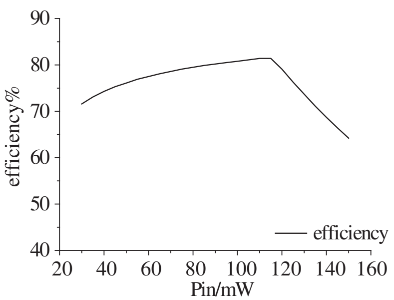

Figure 5. Simulated conversion efficiency versus input power.

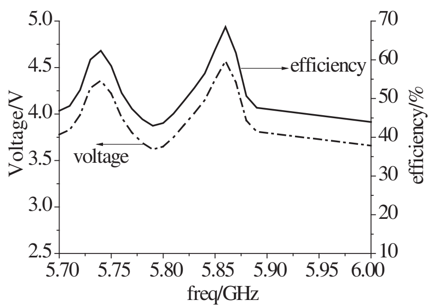

Figure 6. Measured efficiency and DC voltage versus frequency.

Agilent 83623L is used as the microwave source. The DC voltage V_D on the load R_L is measured by a voltage meter. The conversion efficiency of the circuit can be calculated by Equation (2).

$$\eta = \frac{P_{out}}{P_{in}} = \frac{V_D^2}{R_L P_{in}} \tag{2}$$

where, P_{out} and P_{in} are the output DC power and incident RF power, respectively.

It has been found in the experiment that this rectifying circuit has the highest voltage of 4.57 V at 5.86 GHz on the load of 298 Ω when input power is 102 mW. The RF-DC conversion efficiency reaches 68.5%. The output DC voltage and conversion efficiency versus frequency are shown in Fig. 6. The voltage is more than 3.5 V from 5.7 GHz to 6 GHz. The difference between the simulated and experimental results lies on the parameters of the diode provided by the company, the welding positions of the diode and capacitor, and measurement errors, etc.

3. CIRCULARLY POLARIZED ANTENNA

The proposed circularly polarized antenna with harmonics suppression is shown in Fig. 7. The circular polarization operation is realized by the truncated-corner patch. Harmonics suppression characteristic is carried out by the DGS of dual dumbbell below the microstrip line on the ground.

The antenna has been etched on a FR4 substrate with the thickness of 1.5 mm, the relative dielectric constant ε_r of 2.55 and

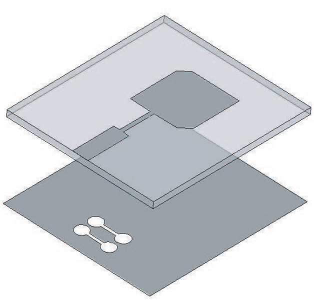

Figure 7. Circularly polarized truncated-corner patch antenna.

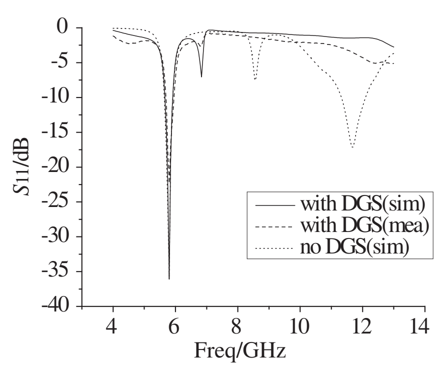

Figure 8. Return loss curves vs. frequency of the CP antenna.

the $\tan\delta$ of 0.002. The antenna's return loss with and without DGS is shown in Fig. 8. It is obvious that the high order harmonics are inhibited effectively. Fig. 8 also plots the measured curve, which is in good agreement with the simulated one. The return loss is -30 dB at 5.8 GHz and about -3 dB at 11.6 GHz. Fig. 9 shows the experimental and simulated AR (Axial Ratio). The minimum AR is 1.0 dB. The bandwidth of AR less than 3 dB is 1.37% from 5.78 GHz to 5.84 GHz on the main direction. The measured gain is 6.5 dB at 5.8 GHz operating frequency.

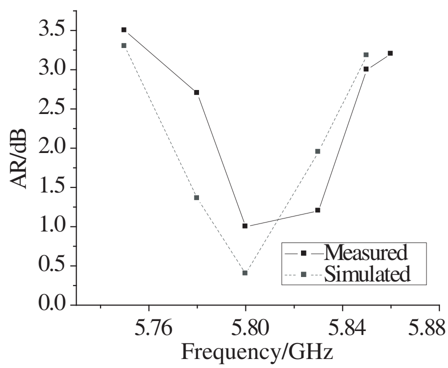

Figure 9. AR vs. frequency of the CP antenna.

4. MEASUREMENT OF RECTENNA

The receiving antenna and rectifying are connected by SMA connectors as shown in Fig. 10. The experiments have been carried out in a chamber. The transmitting antenna is a standard linear polarized horn with gain G_t of 16.6 dB. The rectenna is located at the distance r of 72 cm, which is the far region of the horn. The receiving microwave power of the rectenna is calculated by the Friis transmission formula

$$P_{RM} = \left(\frac{\lambda}{4\pi r}\right)^2 P_t G_t G_r \tag{3}$$

where P_t is the transmitting power; G_r is the receiving antenna gain; λ is the free space wavelength at 5.8 GHz. So the RF-DC conversion efficiency is calculated by formula (4).

$$\eta_r = \frac{V_D^2}{R_L}\left(\frac{4\pi r}{\lambda}\right)^2 \frac{1}{P_t G_t G_r} \tag{4}$$

The overall RF-DC conversion efficiency of rectenna versus frequency is illustrated in Fig. 11. The voltage of 4.34 V is obtained, and the highest conversion efficiency reaches 68.4% on the load of 298 Ω at 5.86 GHz, which is exactly the value of the rectifying circuits in Fig. 6. Comparing Fig. 11 with Fig. 6, it can be found that the second higher DC voltage at about 5.73 GHz in the rectenna has disappeared, because the center operation frequency of the receiving antenna is 5.8 GHz.

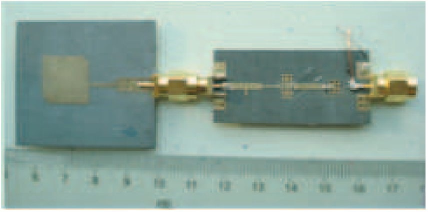

Figure 10. Picture of rectenna.

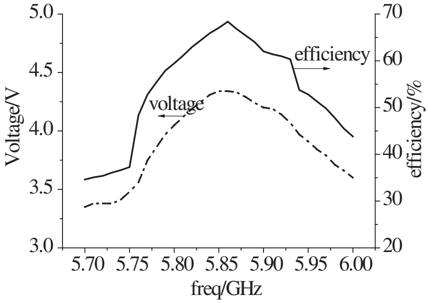

Figure 11. RF-DC efficiency of rectenna versus frequency.

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.

5. CONCLUSION

A novel compact rectenna with circular polarization operation has been developed. The truncated-corner patch antenna achieves the harmonics suppression characteristic by a microstrip feedline with DGS. This receiving antenna has 6.5 dB gain and 1.0 dB AR with the second harmonic being limited within −3 dB. The harmonics are suppressed further by the input and output match networks of the rectifying circuit being designed especially at C-band. A RF-DC conversion efficiency of 68.4% has been measured on the load of 298 Ω at 5.86 GHz. This kind of compact rectenna with low profile can be applied to RFID and wireless sensor. It also can be extended to large array easily for high power applications.

ACKNOWLEDGMENT

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REFERENCES

1. Glaser, P. E., "An overview of the solar power satellite option," *IEEE Trans. MTT*, Vol. 40, No. 6, 1230–1238, 1992.
2. Brown, W. C., "Experiments in the transportation of energy by microwave beam," *IRE International Convention Record*, Vol. 12, No. 2, 8–17, 1964.
3. Brown, W. C., "An experimental low power density rectenna," *IEEE MTT-S Digest*, 197–200, 1991.
4. Mohammod, A., G. Yang, and R. Dougal, "A new circularly polarized rectenna for wireless power transmission and data communication," *IEEE Antennas and Wireless Propagat. Lett.*, Vol. 4, 205–208, 2005.
5. Lim, S., K. Leong, and T. Itoh, "Adaptive power controllable retrodirective array system for wireless sensor server applications," *IEEE Transactions on Microwave Theory and Techniques*, Vol. 53, No. 12, 3735–3743, 2005.
6. Berndie, S. and K. Chang, "5.8-GHz circularly polarized dual-rhombic-loop traveling-wave rectifying antenna for low power-density wireless power transmission application," *IEEE Transactions on Microwave Theory and Techniques*, Vol. 51, No. 5, 1548–1553, 2003.
7. Ren, Y.-J. and K. Chang, "5.8-GHz circularly polarized dual-diode rectenna and rectenna array for microwave power transmission," *IEEE Transactions on Microwave Theory and Techniques*, 1–8, 2006.
8. Ren, Y.-J., M. F. Farooqui, and K. Chang, "A compact dual-frequency rectifying antenna with high-orders harmonic-rejection," *IEEE Transactions on Antennas and Propagation*, Vol. 55, No. 7, 2110–2113, July 2007.
9. Yang, X.-X., J.-S. Xu, D.-M. Xu, and C.-L. Xu, "X-band circularly polarized rectennas for microwave power transmission applications," *Journal of Electronics*, Vol. 25, No. 3, 389–393, 2008.