Circularly Polarized Rectifying Reflectarray Antenna at C-band

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Abstract

In this paper, circularly polarized rectifying reflectarray antenna has been proposed. Cylindrical dielectric resonator (CDRA) antenna is used to exhibit left-hand and right-hand circular polarizations. As well, the antenna operates in a linear polarization mode on the basis of the bias states of two PIN diodes. The antenna is used to feed the reflectarray to increase its gain in a certain direction. A single piece of dielectric material sheet is divided into 17x17 unit-cell elements to build up the reflectarray. Each unit cell has four circular holes of equal diameters and is supported on the perfect conducting ground plane. The total phase variation of 360o is achieved as the hole radius is varied. Full-wave analysis using the finite integration technique is used to calculate the radiation characteristics of the reflectarray with its feed. The reflectarray is designed at 5.8 GHz at C-band to concentrate the incident waves on the receiving antenna. It is lite weight, small size and low cost. Rectifying circuit components composed of a matching network, two-stage voltage doubling circuit, DC-pass filter and a resistive load are designed. Based on the analysis of ADS software, this rectification circuit has the maximum conversion efficiency of 71% at 5.8 GHz on the load of 1200-Ω.

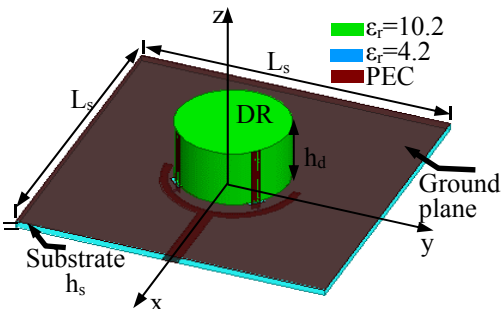
1. Introduction

The Microwave power transmission (MPT) technology can be used as a kind of source supply without wire. MPT has applications in energy harvesting [1], radio frequency identification (RFID) [2] and wireless sensor networks [3]. A rectenna is a fundamental component in microwave power transmission systems. A rectenna usually contains a receiving antenna and a rectifier circuit. It is capable of capturing the microwave energy from surrounding environments and converting the RF power into useful DC energy. Various types of rectenna have been developed for different applications as described in [4]. To design a miniature rectenna, the size of the antenna part has to be reduced, then the rectifier and the antenna are of similar size and are located very close together. Several array types of rectennas have been studied with high gain property to achieve a long distance wireless power transmission (WPT). Experimental study of a large antenna array is depicted in [5]. A highly efficient rectenna array at 5.87 GHz, comprising of 1000 dipole elements has been designed in [6]. However, in the array rectenna design, there are several problems, such as: the relatively high loss of array feeding networks, difficulty in feeding network design, thus causing lower rectenna array performance. Recently, rectenna systems using reflectarrays instead of array antenna elements have been demonstrated. The reflectarray is used for concentrating the incident waves on the receiving antenna. Due to the high gain property of the reflectarray, the combined rectenna array can be expected to achieve higher output power with a smaller area. An 8×1 rectenna array is designed as a feed antenna of the reflectarray in [7]. The reflectarray consists of rectangular dipoles as its radiating elements. A high gain rectenna combined with a microstrip reflectarray is presented in [8]. In general, the circularly polarized (CP) antenna has been chosen widely because of its robustness against environmental interference. Circularly polarized rectennas have constant DC output power at random polarization angles irrespective of the rotation of the rectenna [9].

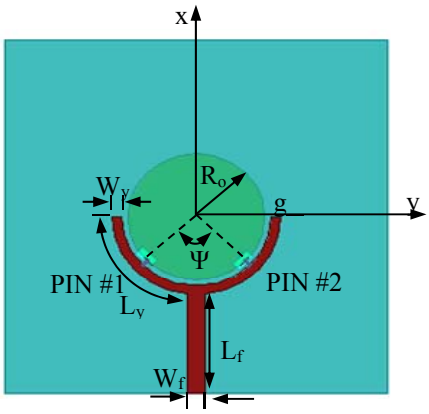
In this paper, a high gain circularly polarized rectifying antenna combined with reflectarray for 5.8 GHz to generate DC energy is proposed. This presents a novel combined rectenna with a circularly polarized reflectarray for high gain. This kind of the combined rectenna system will potentially have higher output power level and conversion efficiency. The reduced size of the antenna at this frequency leads higher density of rectenna per unit area.

3. Antenna Design

The circularly polarized antennas are preferable in rectenna systems to remain the power transfer efficiency unchanged with the rotating of the rectenna. Circularly polarized cylindrical dielectric resonator antenna (CDRA) is proposed in this paper. The detailed structure of the circularly polarized CDRA is shown in Fig.1. A curved Y-shaped feed line is printed on a dielectric substrate with an arm length L_s = 25.8 mm, ε_r =4.2 (FR-4), and thickness of h_s =0.68 mm. A ground plane with the same dimensions of the substrate is used to support a CDRA of a radius r =5.4825 mm, a height h_d =6.02 mm and dielectric constant ε_{rd} =10.2. Two rectangular strips are used for feeding the antenna with dimensions 0.69 × 6.71 mm^2. The two strips are symmetric around y-axis.



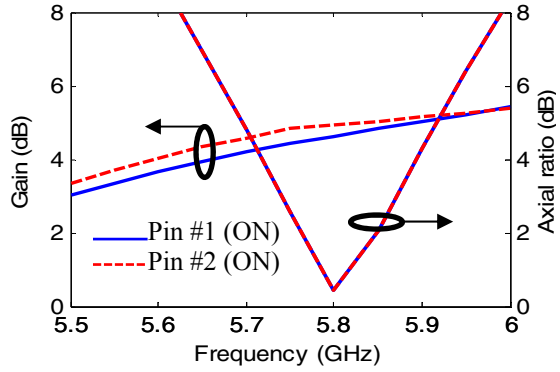
a.



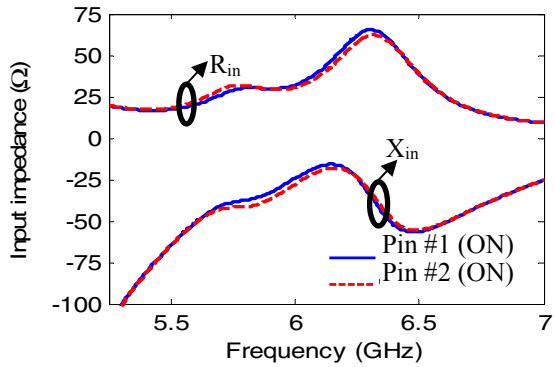
b.

Figure 1: The detailed structure of circularly polarized CDRA with y-shape microstrip feed line with L_s=25.8 mm, h_s =.688 mm, R_o=5.4825 mm, h_d=6.02 mm, L_f=6.48 mm, L_y=10.13 mm,W_f=1.29 mm, W_y=.645 mm, g=.3175 mm, and Ψ=90◦.

The curved Y-shaped feed line and the two strips are connected with two PIN diodes (HSMP-3860). The two strips and the curved Y-shaped feed line is electrically connected or disconnected depending on the on/off-states of the PIN diodes. The PIN diode is represented by a resistor of 1.5 Ω in the forward bias state and a capacitor of 0.2 pF in the reverse bias state. Figure 2a shows the axial ratio and the gain of the proposed antenna when the PIN diode (1) is in the off-state and PIN diode (2) is in the on-state. The positions of the PIN diodes are obtained by changing the angle between the two diodes. The optimized value of Ψ = 90º is used to obtain a good circular polarized at 5.8 GHz. Fig. 2b shows the input impedance of the antenna versus the frequency. The gain is 4.91 dBi at the operating frequency. The radiation patterns in E- / H- plane for the antenna when the PIN diode (1) is in the off-state and PIN diode (2) is in the on-state are shown in Fig. 3a. The AR is less than 3 dB from 5.74 GHz to 5.87 GHz and the minimum is 0.41 dB at 5.8 GHz. When the PIN diode (1) is in the on-state and PIN diode (2) is in the off-state, the radiation patterns in E- / H- plane for the antenna are shown in Fig 3b. Note that the effects of dielectric and metallic losses and thickness of the metallic layer are considered in the simulation of the antenna. The antenna has the advantages of compact size, left-hand, right-hand circularly polarized and linearly polarized characteristics can be obtained.

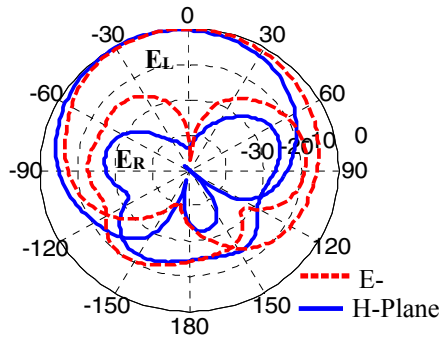


a.

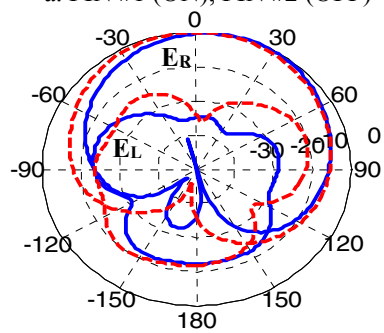


b.

Figure 2 :a. Antenna gain and axial ratio of DRA versus frequency. b. Antenna input impedance versus frequency.



a. PIN #1 (ON), PIN #2 (OFF)



b PIN #1 (OFF), PIN #2 (ON).

Figure 3: Radiation patterns of CDRA antenna at 5.8GHz.

4. Reflectarray Design

The reflectarray is made from one piece of dielectric material sheet; with a perforated dielectric and completely eliminating all the rest of the dielectric materials. The perforations result in modifying the effective dielectric constant of the dielectric material. The simplicity of the

structure makes it practical in terms of reduced weight and profile, low-cost fabrication and high gain. The reflectarray is composed of 17×17 unit-cell elements and is covering an area of 525.3×525.3 mm^2 in x-y plane. The configuration of the proposed unit cell is shown in Fig. 4. The unit-cell element of the reflectarray consists of a square cell, with length L_c = 30.9 mm, and substrate thickness H_c = 25 mm with ε_r = 8.9. Each unit cell has four circular holes of equal diameters and is supported on the perfect conducting ground plane. The relationship between variable hole radius and the reflection coefficient phase at 5.8 GHz was determined using the finite integration technique. The unit cell achieves reflection coefficient phase variation from 0° to 360° as shown in Fig 4. The focal length–to-diameter ratio F/D for the reflectarray is optimized for lower side lobe levels and highest reflectarray gain. In this analysis F/D=1 is considered. Computed radiation pattern of the reflectarray in 3D plot at 5.8 GHz is shown in Fig. 5. The symmetrical gain patterns for the reflectarray is obtained due to the symmetry of the arrays about the x- and y-axis. The reflectarray has a gain of 20.4 dBi at the operating frequency and 1-dB gain bandwidth of 3.21 % is achieved over the band from 5.715 GHz to 5.896 GHz. Of course, a larger number of cells can be used to get higher gain. However, it is the computing facilities which limited the number of cells to 17×17. To avoid incident field blockage, the reflectarray is designed to have an offset feed with θ_o =22° as shown in Fig.6.

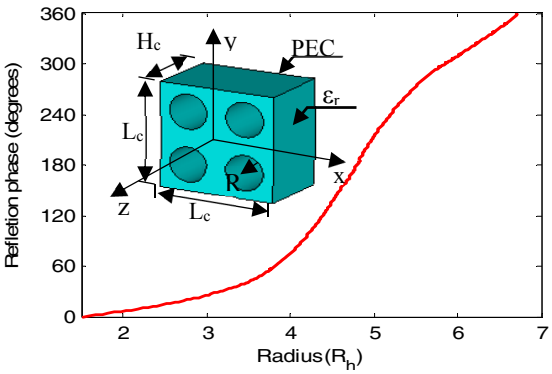


Figure 4: The 3-D structure of the unit-cell element and the variation of reflection coefficient phase versus the hole radius of the perforated unit-cell element.

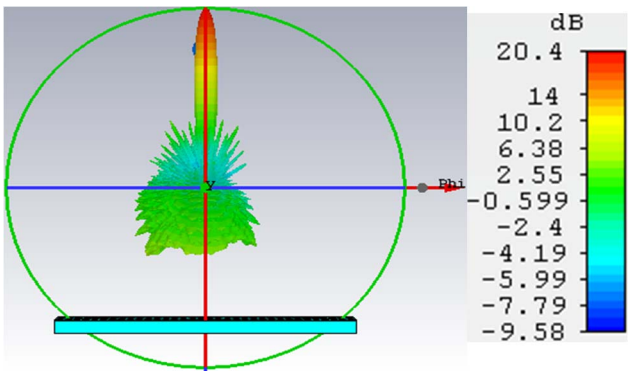


Figure 5: The 3-D gain radiation pattern for center fed reflectarray at 5.8GHz.

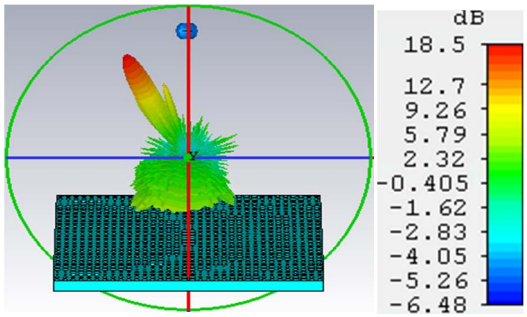


Figure 6: The 3-D gain radiation pattern for offset fed reflectarray, θ_o = 22° and ϕ_o=0.

5. Rectenna Design

In general, the rectifying circuit consists of an impedance matching circuit for delivering the maximum power, a rectifying element (diode) to perform the RF to DC conversion, a DC- pass filter for smoothing the ripple of output DC and a load (resistor) [14]. The rectifying circuit is etched on the substrate of FR4 with dielectric constant εr of 3.38, the thickness of 0.508 mm and the tan δ of 0.0027. In this paper, two-stage voltage doubling circuit (four diodes) is considered. The packaged Schottky diode HSMS-2862 of Avago Technologies is used. The equivalent circuit parameters of the diode are series resistance RS= 6 Ω, zero-bias junction capacitance C_j=0.18 pF, built-in turn on voltage V_F=0.3 V and breakdown voltage V_B=7 V. The diode is a nonlinear device, so the power conversion efficiency is sensitive to the frequency and the input power. The voltage doubling circuit is simulated and analyzed by Agilent Advanced Design System (ADS) software. DC-pass filter with single radial stub and pair radial stubs have angles of 50°, 70°, 70° is designed. The DC-pass filter is used to reject any RF signals and smooth the generated DC voltage. The magnitude of the transmission coefficient S_{21} of the DC-pass filter versus the frequency is shown in Fig.7. The filter is used to block the fundamental frequency, the second, and the third harmonics lower the transmission coefficient S21 below -12 dB. The final values of the fundamental, the second, and the third harmonics are -55.44 dB, - 20.05 dB and 34.03 dB, respectively. The input impedance of the rectifying circuit with frequency at 10 mW input power is shown in Fig.8. Also, the input impedance versus the input power at 5.8 GHz is depicted in Fig. 9. The real part of the input impedance is changed from 3.77 to 18.9 Ω while the imaginary part is varied from 8.11 to 23.24 Ω as the input power is varied from 5 mW to 100 mW. To ensure maximum power transfer, a good impedance matching network has to be realized between the antenna and the rectifier input. The matching technique was designed by way of conjugate matching between the input impedance of the antenna and that for the rectifying circuit in order to improve the conversion efficiency. Figure 10 shows the complete circuit of the rectenna. The output voltage and the conversion efficiency versus the input power at 5.8 GHz are depicted on Fig.11. The conversion efficiency of 71% is achievable over an input power range from 25 mW to 80 mW. The DC output voltage is 7 Volt at 60 mW input power.

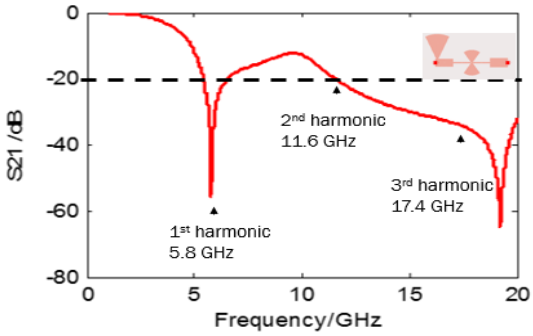


Figure 7: S_{21} of the dc filter simulated by ADS.

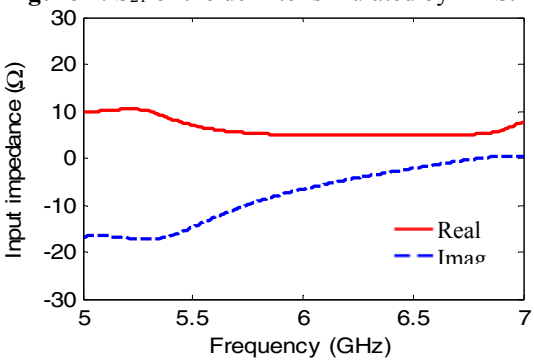


Figure 8: Input impedance of rectifying circuit versus frequency at input power=10 mW.

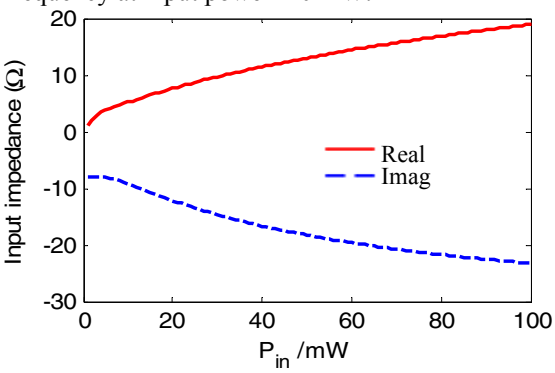


Figure 9: Input impedance of rectifying circuit versus the input power at f=5.8 GHz.

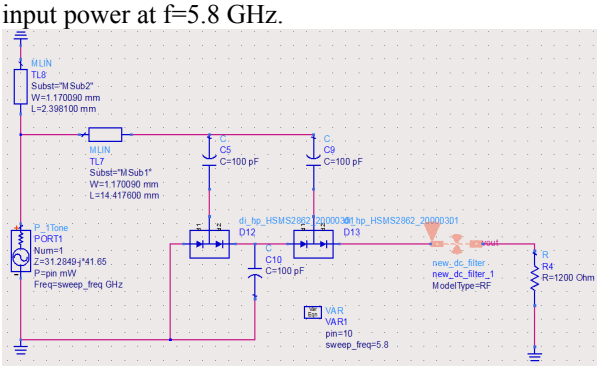


Figure 10: Simulation model of rectenna by ADS.

6. Conclusions

In this paper, a high gain rectenna combined with a reflectarray is presented to achieve a long distance WPT, higher out DC power level and conversion efficiency, and reduced receiving areas. Center fed and offset fed reflectarray system are investigated. The radiation characteristics of the feed antenna and the reflectarray are investigated using the full-wave analysis. The rectifying circuit is simulated by ADS. The highest conversion efficiency reaches 71% on the load of 1200 Ω. The maximum output DC voltage of 8.66 V is obtained.

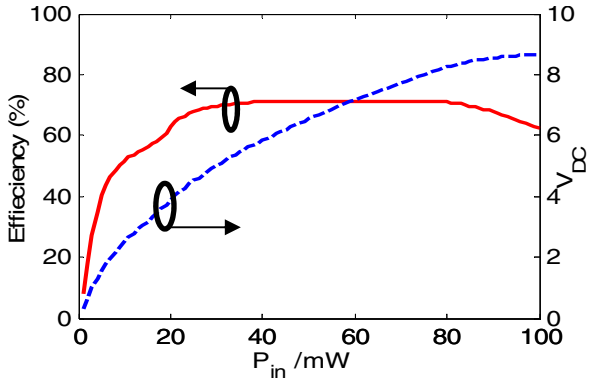


Figure 11: Simulation output voltage and efficiency with the input power.

7. References

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