2005

A New Circularly Polarized Rectenna for Wireless Power Transmission and Data Communication

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Abstract—**Small distributed wireless sensors are becoming very important in many aspects of our lives. While low data rate passive sensors operate with little energy there is a need for moderate to high data rate distributed sensors for infrastructure monitoring and other applications. Such sensors will require their batteries or onboard capacitors to be charged when depleted for proper operation. In this letter, we propose a circularly polarized (CP) microstrip patch antenna that can function as a WLAN antenna in the 5.15–5.35 GHz and as a rectenna at 5.5 GHz.**

Index Terms—**Antenna, rectenna, sensor, wireless.**

I. INTRODUCTION

RECENTLY, considerable emphasis has been placed on studying the quality and safety issues of our nation's transportation infrastructures [1]–[3]. A careful evaluation of the life span and current condition of steel reinforcement tendons inside the concrete covering of a bridge is crucial to ensure public safety. The solution for this problem calls for the deployment of miniaturized embedded sensors within the bridge structure itself during the construction process. An RFID (radio frequency identification) type passive sensor utilizes a narrowband tank circuit. Thus, the presence of other metallic objects can cause a significant frequency shift as a result of which the sensor may not operate properly. Also, due to the availability of low power, only a very limited amount of data transmission is possible. In contrast, a 5–6 GHz WLAN type sensor is not limited in data rate and does not have the constraints of a narrowband *LC* tank circuit. However, for proper functioning of the circuitry there must be a mechanism to: 1) remotely charge the transceiver battery or capacitor as needed, and 2) send and receive data in between the embedded sensor and the interrogator.

Detecting cracks or deformations in the structure can be achieved by employing active acoustic wave transducers [1]. This information then must be sent to an appropriate destination. Traditionally, a mobile test unit (MTU) will perform the function of the interrogator. We propose that in addition to data telemetry the MTU will also deliver microwave power to the embedded wireless sensor. The power will be received and converted to dc using an on-board rectenna [4]–[6]. In
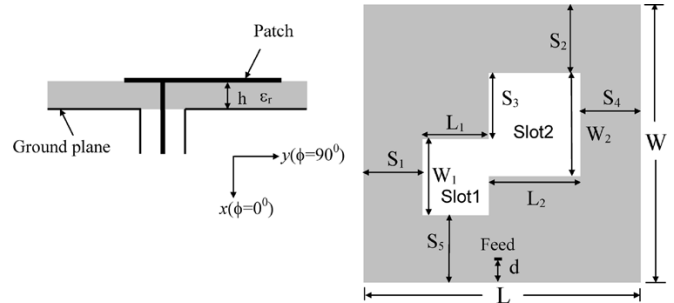
Fig. 1. Antenna geometrical configuration; cross section and top view. Antenna parameters: $L = 14.8$ mm, $W = 14.8$ mm, $L_1 = 4.1$ mm, $L_2 = 5.2$ mm, $W_1 = 5.45$ mm, $W_2 = 5.8$ mm, $S_1 = 2.75$ mm, $S_2 = 3.25$ mm, $S_3 = 2.85$ mm, $S_4 = 2.75$ mm, $S_5 = 3.25$ mm, $d = 2.83$ mm, $h = 3.175$, $\varepsilon_r = 2.2$.

the future instead of MTUs one can envision stationary in-situ supervisory control sensors (installed on the surface and not embedded) in the vicinity of the embedded sensors, which will perform the functions of data communication and power delivery. Such in-situ sensors can send information to the highway administration on a continuous basis.

Recent research has shown that there are certain benefits to use circularly polarized (CP) antennas with sensors [7], [8]. Circularly polarized antennas will essentially help obtain the same dc voltage irrespective of the rotation of the rectenna. In this paper, we introduce a circularly polarized microstrip patch antenna which can function as a rectenna for wireless battery charging at 5.5 GHz and data telemetry in the 5.15–5.35 GHz WLAN band. Our proposed antenna is only 14.8 mm by 14.8 mm by 3 mm in size which can be readily integrated within a sensor circuit board.

II. GEOMETRY OF THE CIRCULARLY POLARIZED PATCH ANTENNA

The geometry of the proposed antenna along with its parameters is shown in Fig. 1. The antenna was initially designed and developed on 3.175-mm thick Duroid 5880 ($\varepsilon_r = 2.2$) substrate and fed by a coaxial probe. Before fabrication the antenna characteristics were optimized for wide return loss and circular polarization bandwidth by conducting a parametric study using Ansoft HFSS. The antenna design is based on our previous work presented in [9], [10]. The two slots positioned along the left diagonal of the microstrip patch generate right-hand circular polarization (RHCP). Positioning the slots along the right diagonal generates left-hand circular polarization (LHCP).
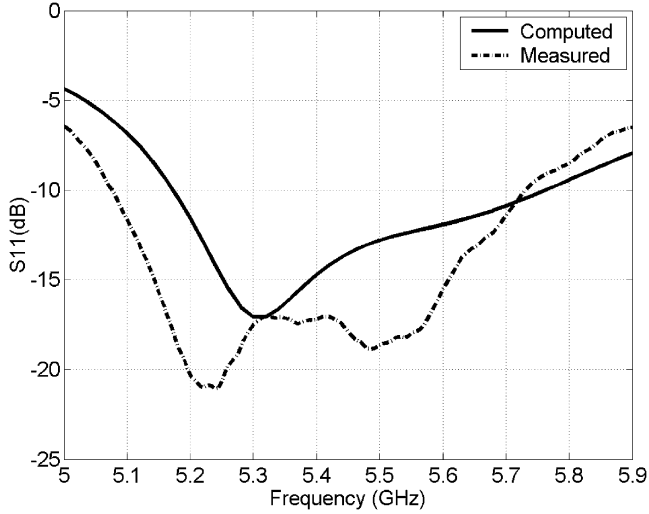
Fig. 2.   Computed and measured return loss versus frequency for the proposed antenna on 3.175-mm-thick Duroid 5880 substrate.
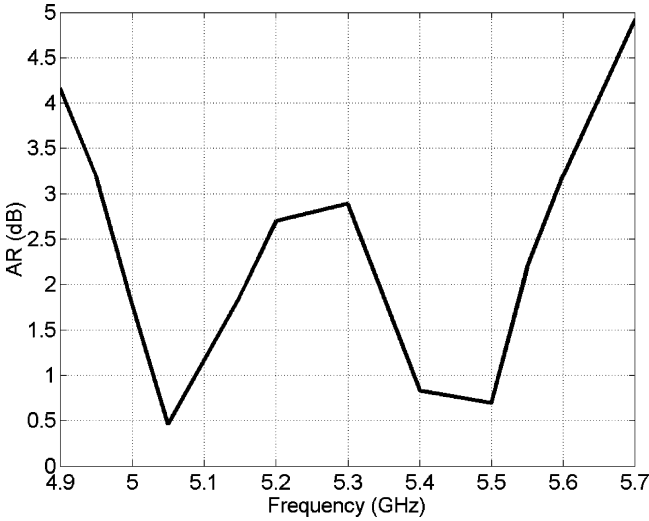

Fig. 3.   Computed axial ratio of the proposed antenna on 3.175-mm-thick Duroid 5880 substrate.

III. RESULTS

A. Antenna Characteristics

Computed and measured S_{11} (dB) data for the proposed antenna on 3.175-mm thick Duroid 5880 substrate are shown in Fig. 2. These data are generally in good agreement. Computed and measured bandwidths within $S_{11} \leq -10$ dB are 11% and 12%, respectively. It is clear that the measured antenna prototype supports operation in the 5.15–5.35 GHz WLAN frequency bands.

Computed axial ratio data (at boresight) for this antenna are shown in Fig. 3. The 3 dB axial ratio bandwidth extends from 4.96 to 5.59 GHz (12.1%), which is very good for a single-fed microstrip patch. The antenna is right-hand circularly polarized for the 5.15–5.35 GHz WLAN data communication. It is also circularly polarized for the 5.5 GHz wireless power transmission scheme. Computed normalized radiation patterns of this antenna at 5.5 GHz are shown in Fig. 4(a) and (b). The antenna was placed on a 40 mm by 40 mm ground plane. The E_{θ} and
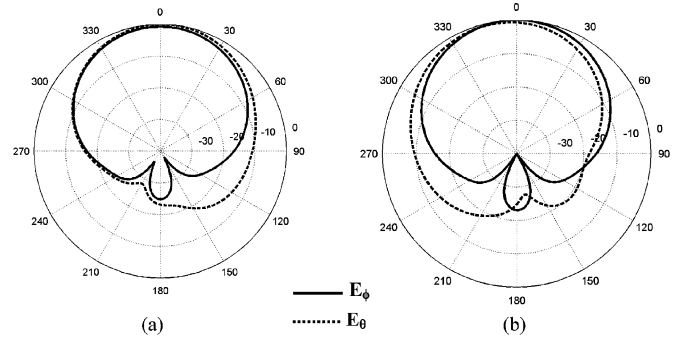

Fig. 4.   Computed normalized radiation patterns of the proposed antenna on 3.175-mm-thick Duroid 5880 substrate at 5.5 GHz. (a) $\phi = 0°$. (b) $\phi = 90°$.
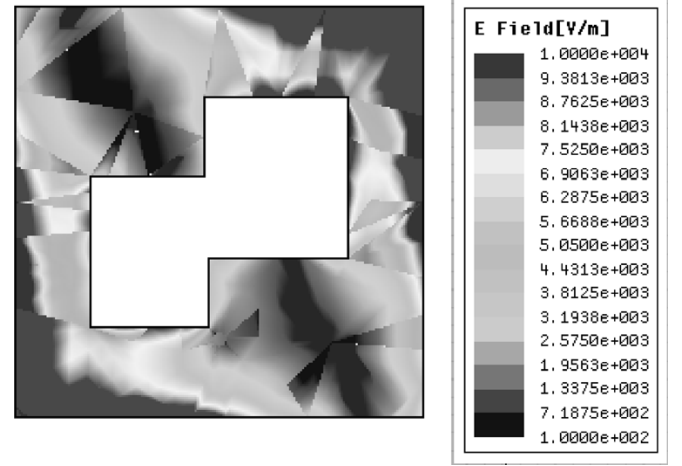

Fig. 5.   Computed E field distribution of the proposed antenna on 3.175-mm-thick Duroid 5880 substrate at 5.5 GHz.

E_{ϕ} components are very close to each other in magnitude as expected. The peak gain of the antenna is 8 dBi RHCP at 5.5 GHz. The front to back ratio is 20 dB or better.

Computed E field distributions of the proposed antenna are shown in Fig. 5. Stronger fields are concentrated close to the feed with a clockwise rotation sense. The two slots create unequal lengths for two separate current paths. These current paths correspond to two hybrid operating modes which result in good return loss and axial ratio performance. This was also confirmed when E-field animation was observed in HFSS. This particular geometry with its slot orientation results in right-hand CP. If a mirror image case is considered, left-hand CP will result with stronger field concentration along the other diagonal.

B. Rectenna Fabrication and Testing

There has been considerable research work on rectennas for space and satellite applications [4]–[6]. Recently there has been some focus to power wireless embedded sensors using rectennas [8]. Our proposed circularly polarized microstrip patch antenna described above was used to design and develop a rectenna to demonstrate wireless power beaming at 5.5 GHz. The circuit diagram of the rectenna along with its components is shown in Fig. 6. A photograph of the fabricated prototype rectenna is also shown in Fig. 7. The test setup used to measure the rectenna performance characteristics is depicted in Fig. 8. A 5.3–5.9 GHz amplifier with 7 W output power was
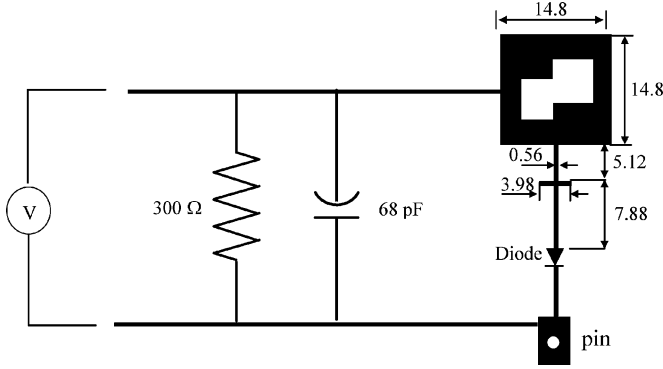
Fig. 6. Geometry and circuit diagram for the proposed rectenna consisting of an M/A com diode, CP antenna, and other passive components.
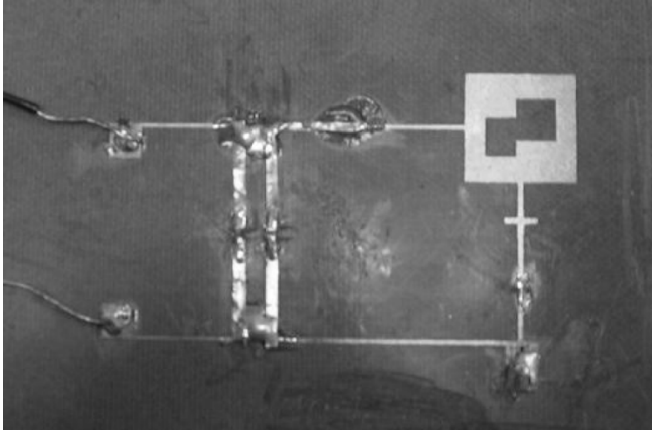

Fig. 7. Photograph of the fabricated and measured rectenna.
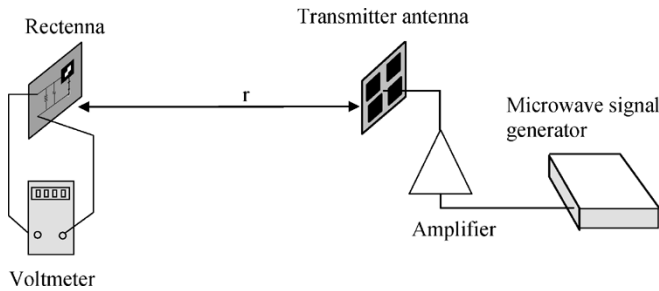

Fig. 8. Rectenna measurement setup.

used with the signal generator. The amplifier was connected to a four-element linearly polarized microstrip array antenna with gain 7.6 dBi. The distance between the transmitter and the rectenna is r. For rectification, a high efficiency M/A COM detector diode MA4E1317 was used.

The width of the microstrip transmission line was chosen based on the input impedance of the diode (172 Ω). The line length was so chosen as to achieve a good impedance match between the diode and the antenna. The bottom side of the diode was connected to a wide stub which was shorted to the ground plane using a via. The converted dc was collected from the left edge of the patch in order to avoid direct interference with the incident waves. A 68 pF capacitor and a 300 Ω load resistor, R_L were used to maximize the dc voltage output.
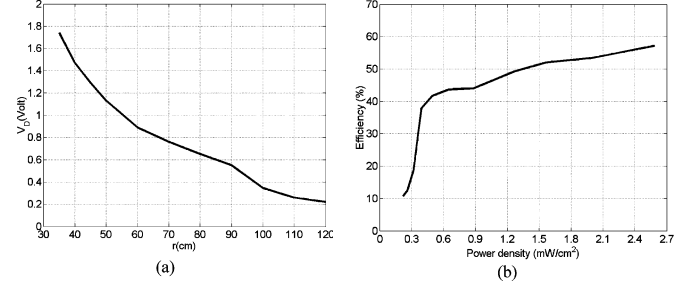

Fig. 9. Measured output voltage V_D and convesion efficiency of the CP rectenna at 5.5 GHz. (a) Distance versus output voltage V_D. (b) Power density versus conversion efficiency; $R_L = 300 \ \Omega$, $C = 68 \ pF$.

The conversion efficiency for the CP rectenna can be calculated by [11]

$$\eta_R = \frac{\frac{V_D^2}{R_L}}{P_t G_t G_r \left(\frac{\lambda_0}{4\pi r}\right)^2 L_{pol}}$$

where P_t and G_t represent the transmit power and the gain of the transmitting array, G_r represents the gain of the rectenna, V_D is the voltage across the load resistor R_L of the rectenna. The distance between the transmitter and the rectenna is r. The transmitter array and the CP rectenna has a polarization mismatch loss taken care of by the term L_{pol}. For this case, L_{pol} can be calculated as $L_{pol} = |\rho_w \cdot \rho_a^*|^2 = |\hat{a}_x \cdot (1/\sqrt{2})(\hat{a}_x + j\hat{a}_y)|^2 = 1/2$ [11]. The power density, P_D at the location of the rectenna is given by $P_D = P_t G_t / 4\pi r^2$ [8].

The performance of the rectenna was measured at 5.5 GHz. Measured diode voltage, V_D and conversion efficiency are shown in Fig. 9(a) and (b), respectively. Clearly with increasing distance V_D decreases. For instance, 1.74 V dc was received for $r = 35$ cm. From Fig. 9(b), it is clear that maximum conversion efficiency of 57.3% is achieved when incident power density is 2.55 mW/cm^2.

IV. CONCLUSION

A circularly polarized microstrip patch antenna is introduced that can function as a WLAN antenna in the 5.15–5.35 GHz and as a rectenna at 5.5 GHz. Two rectangular slots properly positioned along the diagonal of the square patch antenna create two hybrid operating modes which operate very close in frequency and hence help achieve wide axial ratio bandwidth. Antenna designed on Duroid 5880 substrate with single feed provides a return loss bandwidth of 12.4% and axial ratio bandwidth of 12.1%, respectively. Using the proposed CP patch a rectenna was fabricated and tested at 5.5 GHz providing a conversion efficiency of 57.3% for a load resistance of 300 Ω.

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