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Miniature Circularly Polarized Rectenna With Reduced Out-of-Band Harmonics

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***Abstract*—Wireless embedded sensors are becoming increasingly important for many safety critical applications. Sensor batteries or capacitors must be charged as needed in order to achieve high data rate communications. A miniature circularly polarized rectenna operating at 5.5 GHz is introduced which, with the help of an integrated band-reject filter, reduces out-of-band harmonic emission significantly. The rectenna has a conversion efficiency of 74% with more than 50 dB out-of-band harmonic suppression at 11 GHz.**

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

I. Introduction

RECENTLY there is a growing concern on the safety and security aspects of our nation's civil infrastructures [1]–[3]. Routine monitoring of the health of infrastructures requires embedded sensors that can transmit and receive data either on a continuous basis or as needed. In contrast with RFID type passive sensors all high data rate active embedded sensors must be supplied with power wirelessly [4]–[6] to maintain continuous communication between the sensor and a supervisory controller. Miniature rectennas which can receive wireless power as well as send and receive data are critical for such applications. For rotating platforms circularly polarized rectennas help achieve the same dc voltage irrespective of the rotation of the rectenna. Earlier, we proposed a wideband circularly polarized microstrip patch rectenna which can support data telemetry in the 5.15–5.35 GHz and wireless power beaming at 5.5 GHz [6].

It is well known that a rectifying diode being a nonlinear device generates higher order harmonics when an incident microwave signal passes through it [4], [7]. Particularly the microstrip patch antenna being a resonant element will re-radiate the high frequency harmonics. These undesired harmonic emissions may cause electromagnetic interference to nearby circuits and antennas. To prevent the higher order harmonics, specifically the strong second harmonic, a band-reject filter is designed and integrated with our proposed rectenna. The band-reject filter is designed to pass 5.5 GHz from the antenna to the diode and block the harmonic at 11.0 GHz from entering the antenna from the diode. The new rectenna contains a CP patch on one side of the substrate backed by the band-reject filter on the other side.

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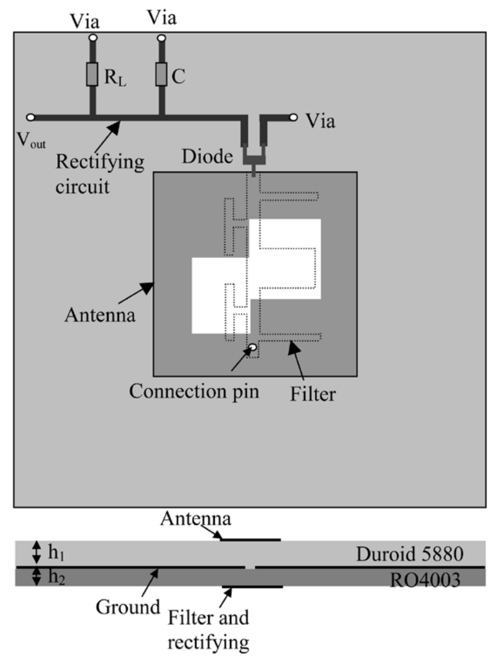


Fig. 1. Miniature rectenna with filter.

The complete rectenna is a miniature element measuring only 40 mm by 40 mm by 4.7 mm.

II. Antenna and Diode Characteristics

A schematic diagram of the proposed circularly polarized rectenna with integrated band-reject filter is shown in Fig. 1. A detailed description of the antenna design and characteristics of a simple rectenna are available in our earlier work [6], [8]. The integrated band-reject filter is used to reduce the out-of-band harmonic generated by the rectifying schottkey diode. The proposed design consists of a two-layered structure. The circularly polarized microstrip patch antenna is printed on a 3.175-mm-thick Duroid 5880 ($\varepsilon_r = 2.2$) substrate. The integrated band-reject filter is printed on a 1.524-mm-thick RO4003 substrate ($\varepsilon_r = 3.38$) on the back side of the antenna. The diameter of each connecting via is 0.5 mm. The two slots positioned along the left diagonal of the patch generate right-hand circular polarization (RHCP). The dimensions of the microstrip patch antenna are 14.8 mm by 14.8 mm. Other antenna parameters, such as slot length, width, and feed position are available in [8].

We use an HSMS-2862 microwave Si Schottky detector diode pair for our rectenna design. The equivalent circuit of a single diode is described in [9] which consists of $R_s = 6.0\ \Omega$, $C_{j0} = 0.18$ pF, $V_{bi} = 0.65$ V, $V_B = 7$ V. The single diode efficiency

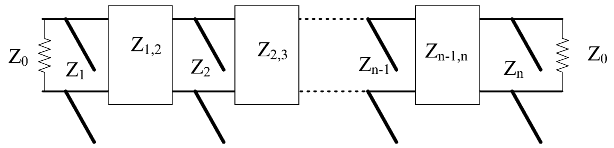


Fig. 2. Transmission line network representation of band-reject filter with open-circuited stubs.

η_D and input impedance Z_D can be calculated using equations described in [9]. For $V_D = 3.5$ V and $R_L = 300\ \Omega$, the input impedance of this diode, Z_D is $158 + j92\Omega$. Because the two diodes in the diode pair are in parallel, the input resistance is half of a single diode, 79 Ω, which is very close to the characteristic impedance (83 Ω) of the microstrip line used to design the filter.

III. Results

Fig. 2 shows a transmission line network of a band-reject filter with open-circuit stubs, where the shunt quarter-wavelength, open-circuited stubs are separated using unit elements that are also quarter wavelength long at the stopband frequency [10]. The filter's performance is dependent on the characteristic impedances Z_i and $Z_{i,j}$ of the stubs and unit lines.

For miniaturization we chose to design a three-element filter. The Z_i and $Z_{i,j}$ values can be calculated by [10]

$$Z_1 = Z_0\left(1+\frac{1}{\alpha g_0 g_1}\right) \quad Z_2 = \frac{Z_0 g_0}{\alpha g_2} \quad Z_3 = \frac{Z_0 g_0}{g_4} \tag{1}$$

$$Z_{1,2} = Z_0\left(1+\alpha g_0 g_1\right) \quad Z_{2,3} = \frac{Z_0 g_0}{g_4} Z_0\left(1+\alpha g_3 g_4\right). \tag{2}$$

For a Chebyshev lowpass filter prototype with 0.05 dB passband ripple, the element values of the lowpass prototype are $g_0 = g_4 = 1.0$, $g_1 = g_3 = 0.8794$, and $g_2 = 1.1132$.

$$\Omega = \Omega_c \alpha \tan\left(\frac{\pi}{2}\frac{f}{f_0}\right) \quad \alpha = \cot\left[\frac{\pi}{2}\left(1-\frac{f_2-f_1}{2f_0}\right)\right] \tag{3}$$

where Ω and Ω_c are the normalized frequency variable and the cutoff frequency of a lowpass filter, f_0 is the midband frequency, α is the coefficient in the frequency mapping function and f_1 and f_2 are the cutoff frequencies for the band-reject filter. Considering $f_1 = 6.5$ GHz, $f_2 = 15.5$ GHz, and $f_0 = 11$ GHz, the parameter α can be calculated from (3). The corresponding characteristic impedances are calculated from (1) and (2) considering a 1.524-mm-thick RO4003 ($\varepsilon_r = 3.38$) substrate

$$Z_1 = Z_3 = 124\ \Omega \quad Z_2 = 60\ \Omega \quad Z_{1,2} = Z_{2,3} = 83\ \Omega.$$

The widths of the stubs and the unit lines were calculated as

$$W_1 = W_3 = 0.45 \text{ mm} \quad W_2 = 2.4 \text{ mm}$$
$$W_{1,2} = W_{2,3} = 1.25 \text{ mm}.$$

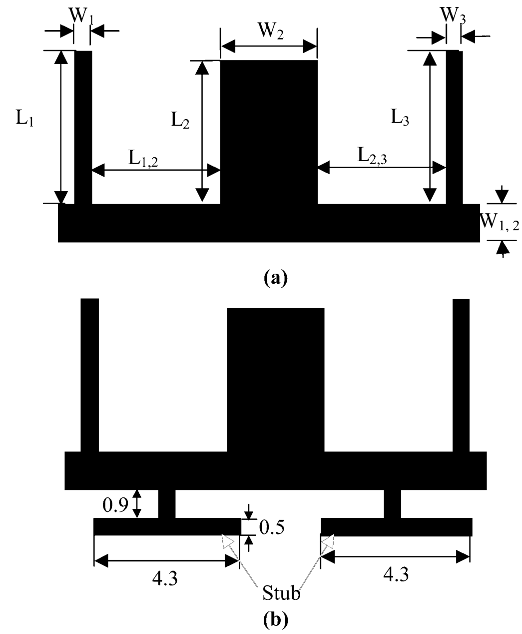


Fig. 3. Geometry of (a) band-reject filter 1 and (b) band-reject filter 2 (unit: mm).

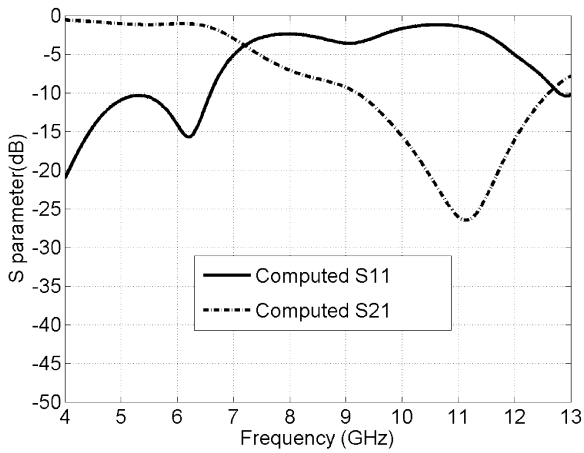
The equivalent lengths of the stubs and the unit lines are quarter wavelength long at 11 GHz and are given here

$$L_1 = L_3 = 4.3 \text{ mm} \quad L_2 = 4.0 \text{ mm}$$
$$L_{1,2} = L_{2,3} = 3.5 \text{ mm}.$$

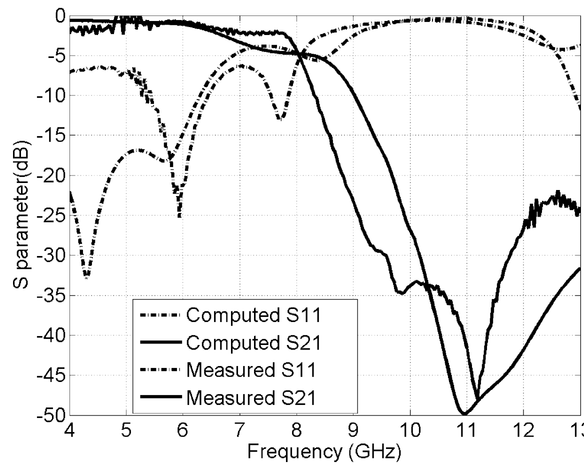
The geometry of this microstrip line filter is shown in Fig. 3(a). Simulated S-parameter data from HFSS are shown in Fig. 4(a). It can be seen that this filter has a small insertion loss (less than 1 dB) at 5.5 GHz and a reasonable out-of-band rejection (about 25 dB) at 11 GHz. This isolation can be further improved by adding two quarter wavelength long stubs which represent the new filter illustrated in Fig. 3(b). Performance of the new filter is shown in Fig. 4(b). The computed and measured insertion loss data are generally in good agreement. There is some discrepancy between the computed and measured S_{11} data particularly at the low frequencies, which may have been caused due to fabrication imperfections. Clearly the insertion loss at 5.5 GHz is good. The isolation at 11 GHz has improved considerably (50 dB).

Besides blocking the harmonic frequency from the diode, this proposed filter, when integrated with the RHCP antenna, also blocks the potential resonance of the antenna from 9 to 16 GHz. Fig. 5 shows the simulated return loss of the RHCP antenna with and without the filter. Clearly, after using the filter, the antenna resonance near 11 GHz has disappeared even while its return loss bandwidth at 5.5 GHz is unchanged.

The performance of the rectenna was measured in the far-field by performing a radiated test. Considering the largest dimension of the transmit array antenna the far-field distance calculated using $2D^2/\lambda$ was 35 cm. On the transmitter side we used a 7 W power amplifier transmitting at 5.5 GHz. It was connected to a signal generator, and 9.4 dBi gain linearly polarized microstrip patch array. The rectenna was positioned at a distance r away from the transmitter, and the converted dc voltage was measured using a voltmeter. Photographs of the proposed



(a)



(b)

Fig. 4. S-parameters of (a) filter 1 and (b) filter 2.

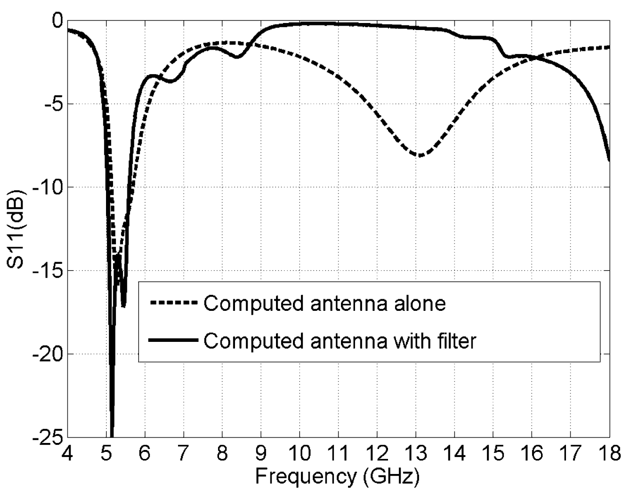
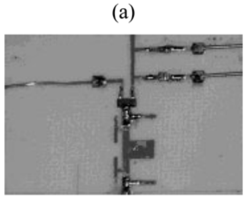


Fig. 5. Return loss characteristics of the antenna with and without the band-reject filter.

(a)



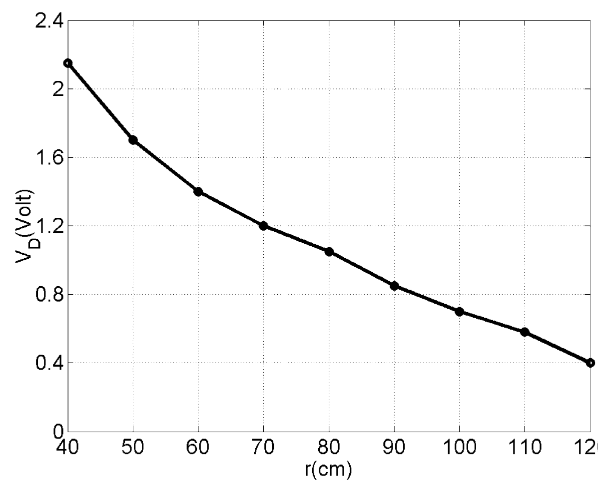
(b)

Fig. 6. Photographs of the miniature rectenna with filter: (a) front; (b) back.

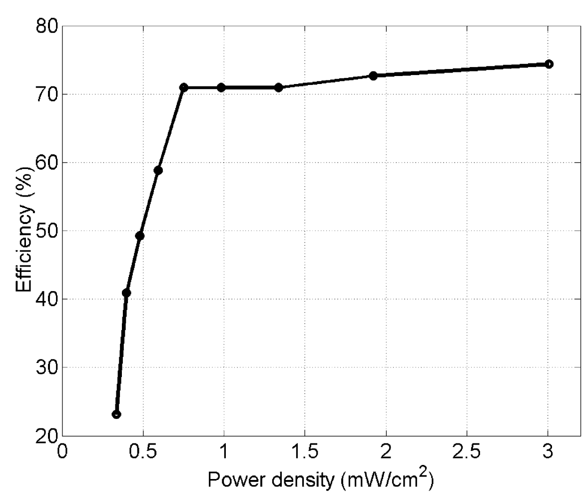
rectenna are shown in Fig. 6(a) and (b), respectively, illustrating the circularly polarized patch antenna and the band-reject filter on the top and bottom layers.

The conversion efficiency of the CP rectenna can be calculated from the measured diode voltage as [4]

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



(a)



(b)

Fig. 7. Measured output voltage, V_D versus distance and (b) conversion efficiency versus power density at 5.5 GHz.

where P_t represents the transmit power, G_t and G_r represent the gain of the transmitting array antenna and the gain of the rectenna, respectively. The $L_{\rm pol}$ term in (4) represents the polarization loss factor between the linearly polarized transmitter array and the circularly polarized rectenna which is 0.5 here.

The efficiency is normally plotted as the function of the incident power density at the rectenna which is calculated as $P_D = \left(P_t G_t / 4\pi r^2\right)$.

The rectenna conversion efficiency was measured, where transmit antenna gain $G_t = 9.4\ \mathrm{dBi}$ (gain of microstrip patch array), transmit power $P_r = 7$ W, load resistance $R_L = 300\ \Omega$ and receive antenna gain $G_r = 7.6\ \mathrm{dBi}$ (gain of circularly polarized rectenna). The output dc voltage and conversion efficiency of this rectenna are shown in Fig. 7. The maximum output voltage V_{out} is 2.15 V at a distance of 40 cm, and the highest conversion efficiency is 74%. The conversion efficiency curve represents a slight anomaly at a single point at around 0.75 $\mathrm{mW/cm^2}$, which may have occurred due to the improper alignment of the transmit antenna with respect to the rectenna. At power densities higher than 0.75 $\mathrm{mW/cm^2}$, the conversion efficiency is nearly constant.

IV. Conclusion

A miniature packaged rectenna is proposed which, with the help of an integrated band-reject filter, prevents the out-of-band harmonic generated from the diode from being radiated by the antenna. The circularly polarized rectenna operates at 5.5 GHz and has a conversion efficiency of 74%. The antenna can be used for microwave power reception at 5.5 GHz and for data communication within 5.15–5.35 GHz.

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