A Novel Dual Frequency Rectenna for High Efficiency Wireless Power Transmission at 2.45 and 5.8 GHz

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***Abstract* — A dual frequency printed dipole rectenna has been developed at 2.45 and 5.8 GHz (ISM bands) for the wireless power transmission. For operating at dual band, a new dual frequency uniplanar printed dipole antenna and a novel coplanar stripline (CPS) filter are developed. A device nonlinear analysis is used to select the diode with low junction capacitance to reduce the effect of frequency dependence. The measured conversion efficiencies achieved at free space are 84.4 and 82.7 % at 2.45 and 5.8 GHz, respectively. The measured results agree very well with the theoretical analysis.**

I. INTRODUCTION

Various kinds of rectennas have been developed since Brown demonstrated the dipole rectenna using aluminum bars to construct the dipole and the transmission line [1]. He also presented the thin-film printed-circuit dipole rectenna [2] with 85 % of conversion efficiency at 2.45 GHz. Linearly polarized printed dipole rectennas were developed at 35 GHz in [3] and [4] with the conversion efficiency of 60 % and 70 %, respectively. 5.8 GHz printed dipole rectenna was developed in 1998 [5] with a high conversion efficiency of 82 %. Microstrip patch dual polarized rectennas were also developed at 2.45 [6] and 8.51 GHz [7]. Recently, a circularly polarized rectenna, which does not require strict alignment between transmitting and receiving antennas, was developed at 5.8 GHz [8] with the conversion efficiency of 60 %.

Several operating frequencies of the rectenna have been considered and investigated. Components of microwave power transmission have traditionally been focused on 2.45 GHz and recently moving up to 5.8 GHz, which has a smaller antenna aperture area than that of 2.45 GHz. Both frequencies have comparably low atmospheric loss, cheap components availability, and reported high conversion efficiency.

This paper presents a new dual frequency rectenna operating at both 2.45 and 5.8 GHz (ISM bands) simultaneously. If the rectenna operates at dual band, it can be used for power transmission at either frequency depending upon power availability. A diode parameter, giving high conversion efficiency and insensitive to the operating frequency, is discussed. To prevent the higher order harmonics re-radiation generated by the diode, a novel coplanar stripline (CPS) lowpass filter integrated with two additional open-ended T-strip CPS bandstop filters is designed.

II. ANTENNA AND FILTERS DESIGN

The structure of rectenna is illustrated in Fig. 1.

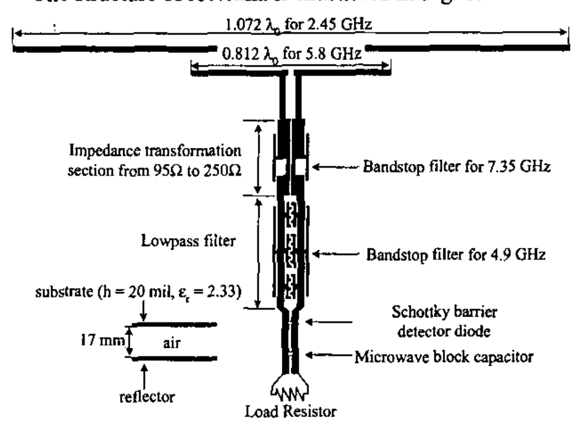

Fig. 1. Circuit configuration of the dual frequency rectenna. The circuit is separated from a reflector plate at a distance of 17 mm.

The rectenna consists of a receiving dual frequency dipole antenna, a coplanar stripline (CPS) input lowpass filter, two CPS bandstop filters, a rectifying diode and a microwave block capacitor. The antenna receives the transmitted microwave power, and the input lowpass and the bandstop filters pass 2.45 and 5.8 GHz but block the higher order harmonics, produced from the diode, from re-radiation. The microwave block capacitor passes DC signal, but blocks all high frequency signals to prevent them from leaking to the load resistance. Consequently, all microwave signals, including fundamental and harmonics, are confined between the input filters and microwave block capacitor. Consequently, the conversion efficiency is improved.

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All the circuit simulations including dual frequency dipole antenna, CPS lowpass filter and open-ended T-strip CPS bandstop filters are designed using IE3D [9] software, which uses moment method for full wave electromagnetic simulation. A 20 mil RT/Duroid 5870 substrate with a dielectric constant 2.33 is used for the dual frequency rectenna design.

A. Dual Frequency Antenna Design

The CPS dipole dual frequency antenna with a reflector plate is designed for 2.45 and 5.8 GHz. This type of dual frequency antenna was introduced in [10]. In [10], the antenna radiates bi-directionally and has a double-sided structure with a microstrip feed operating at 2.4 and 5.2 GHz.

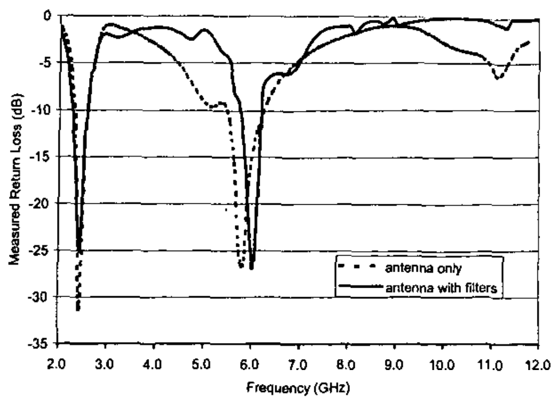

Fig. 2. Measured frequency responses of the antenna and the antenna with filters. Good return loss is achieved at both 2.45 and 5.8 GHz.

The new rectenna has a uniplanar structure, which has the advantage of convenient device mounting. A reflector plate is required for the uni-directional radiation/reception and it also increases antenna gain.

For dual band operation, the reflector plate's distance is optimized with IE3D in order to produce good radiation patterns and similar gains for both frequencies. The reflector plate's distance is optimized at 17 mm which is about 0.14 λ_0 of 2.45 GHz and 0.32 λ_0 of 5.8 GHz.

Measured frequency response of the antenna is shown in Fig. 2. This measurement was performed using the wideband CPS-to-microstrip transition reported in [11] which has a less than 3 dB insertion loss and better than 10 dB return loss from 1.3 GHz to 13.3 GHz. Measured return losses for antenna only are better than 30 and 25 dB at 2.45 and 5.8 GHz, respectively. Return losses at second order harmonics are found to be around 8.6 and 3 dB at 4.9 and 11.6 GHz, respectively.

B. Coplanar Stripline Lowpass Filter integrated with Bandstop Filters

CPS lowpass filters and bandstop filters are previously reported in [12-14]. However, the structure of reported lowpass filters are complex and design methods are not clear.

New simple coplanar stripline (CPS) lowpass filter and bandstop filters are designed and shown in Fig. 3. For the lowpass filter, the capacitances take place at interdigital fingers and the CPS transmission lines work as the inductors. With this structure, the lowpass filter can be easily designed using the prototype of the desired filter type with the chosen cutoff frequency. The lowpass filter has a cutoff frequency of 7 GHz to pass 2.45 and 5.8 GHz and to reject 11.6 GHz, which is second order harmonic of 5.8 GHz.

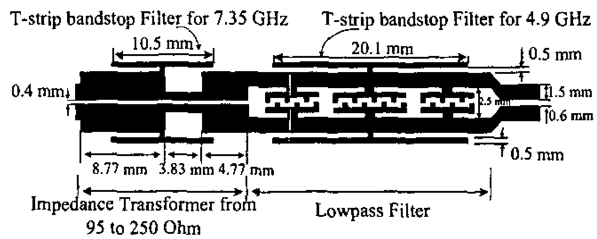

Fig. 3. The structure of coplanar stripline lowpass filter with bandstop filters.

However, the lowpass filter will pass the second order harmonic of 2.45 GHz at 4.9 GHz and the third order harmonic level at 7.35 GHz will not be deeply suppressed.

New open-ended T-strip CPS bandstop filters, placed outside of the CPS strips, are developed for rejecting the second and the third order harmonics of 2.45 GHz at 4.9 and 7.35 GHz, respectively.

An impedance transformation section consisting of two CPS step discontinuities as shown in Fig. 3, is designed and optimized by IE3D [9] to transform antenna's input impedance of 95 Ω to the CPS characteristic impedance of 250 Ω.

According to Fig. 2, the second (4.9 GHz) and the third (7.35 GHz) harmonics of 2.45 GHz, and the second (11.6 GHz) harmonic of 5.8 GHz are well suppressed, which shows good bandstop performance of the designed filters.

C. Dual Frequency Antenna integrated with Filters

For comparison, frequency response of the antenna integrated with filters is also shown in Fig. 2. Measured return losses of 15.1 and 18.2 dB are achieved at 2.45 and 5.8 GHz, respectively. Measured return losses at the second harmonics of 2.45 and 5.8 GHz are found to be 1.58 and 0.2 dB at 4.9 and 11.6 GHz, respectively. This shows that the lowpass filter integrated with two additional bandstop filters effectively block the second order harmonics at both frequencies.

Dual frequency antenna is measured at an anechoic chamber. Good radiation patterns are observed at both frequencies. Measured E-plane gains of 5 and 5.4 dBi are achieved at 2.45 and 5.8 GHz, respectively. Radiation patterns at second order harmonics are also measured and shown in Fig. 4. The second order harmonic radiation gains at 4.9 and 11.6 GHz are -10 and -15 dBi, respectively. Since the gains for the fundamental frequencies at 2.45 and 5.8 GHz are 5 and 5.4 dBi, the corresponding suppressions are about 15 and 20.4 dB, respectively.

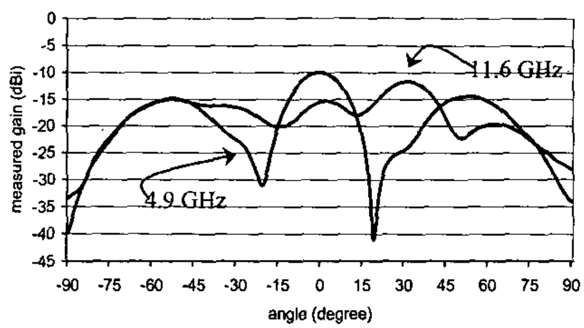

Fig. 4. Radiation patterns at second harmonic frequencies. Measured gains of –10 and –15 dBi are achieved at 4.9 and 11.6 GHz, respectively.

III. Diode Analysis

A diode analysis is used to achieve high RF-to-DC conversion efficiencies at both frequencies. RF-to-DC conversion efficiency (η_d) and input impedance (Z_d) of the diode can be calculated from the closed form equations in [5]. RF-to-DC conversion efficiency is frequency dependent of ωC_j. A small value of diode junction capacitance (C_j) will reduce the effect of frequency dependence on the conversion efficiency. To have a small value of C_j, a packaged diode is not suitable. From the above analysis, a flip-chip type GaAs Schottky barrier diode (MA4E1317) is selected as a rectifying device. The diode has a standard built-in voltage (V_{bi}) and breakdown voltage (V_{br}) of 0.7 and 7 V, respectively. Measured V_{br} is around 12 V and maximum output DC voltage (V_0) is about 6 V. The zero bias junction capacitance (C_{j0}) is 0.02 pF with a series resistance (R_s) of 4 Ω.

Using closed form equations in [5], RF-to-DC conversion efficiency (η_d) and input resistance of the diode (R_d) can be calculated in terms of load resistance (R_L) at 2.45 and 5.8 GHz, as shown in Fig. 5. In Fig. 5, very little difference in conversion efficiency is observed between 2.45 and 5.8 GHz. This is due to the low zero bias junction capacitance (C_{j0}) of the diode. Since C_{j0} is low, corresponding C_j is also low [5].

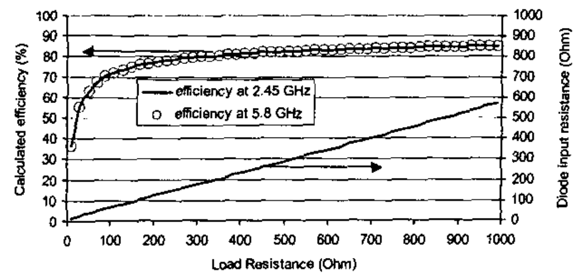

Fig. 5. Diode (MA4E1317) RF-to-DC conversion efficiency analyses in terms of the load resistance (R_L) and the diode input resistance (R_d) at 2.45 and 5.8 GHz. Diode parameter values of V_{bi}, V_0, and V_{br} are 0.7, 6 and 12 V, respectively. The zero bias junction capacitance (C_{j0}) of 0.02 pF, and a series resistance (R_s) of 4 Ω are used for the analyses.

IV. Rectenna Measurements

The rectenna is measured in free space. Conversion efficiency of the rectenna is represented as

$$\eta = \frac{P_{DC}}{P_{received}} \times 100\ (\%) \quad (1)$$

where P_{DC} is DC power produced at the load resistance (R_L) of the rectenna and $P_{received}$ is power received at antenna of the rectenna. $P_{received}$ can be calculated from the Friis transmission equation [5]. Parameters for calculating $P_{received}$ of the dual frequency rectenna are displayed in Table I. A standard gain horn antenna is used for transmitter.

TABLE I
RECEIVED POWER CALCULATION PARAMETERS FOR THE DUAL FREQUENCY RECTENNA.

Frequency	λ_0 (cm)	Far field (cm)	G_r (dBi)	G_t (dBi)	A_e(cm^2)
2.45 GHz	12.2	87.1	5	14.5	37.7
5.8 GHz	5.1	48.5	5.4	17.6	7.4

Because of the diode dimension, CPS strip width (s) is fixed to 0.6 mm and corresponding characteristic impedance is 184 Ω. The diode input impedance is matched to this impedance of 184 Ω, which corresponds to a load resistance of 310 Ω as determined in Fig. 5. This gives around 82 % target efficiency.

Measured rectenna efficiencies are shown in Fig. 6. High efficiencies of 84.4 and 82.7 % are measured at 2.45 and 5.8 GHz, respectively, with the load resistance of 310

Ω. Experimental efficiencies follow closely with the theoretical efficiency calculations. Received power at each highest efficiency points are 89.84 and 49.09 mW corresponding to power densities of 2.38 and 8.77 mW/cm^2 at 2.45 and 5.8 GHz, respectively, as shown in Fig. 6.

Considering the antenna's effective areas (A_e) listed in Table I, the required power density of 5.8 GHz is around 5.1 times larger than that of 2.45 GHz to achieve 80 % efficiency.

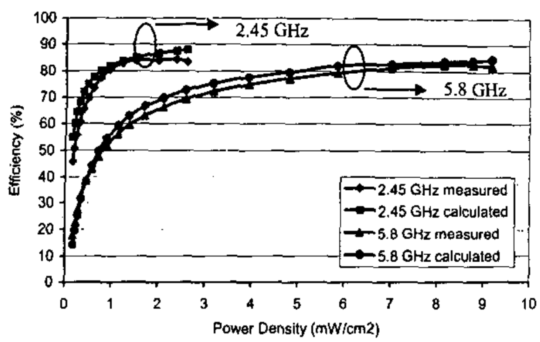

Fig. 6. RF-to-DC conversion efficiency for dual frequency rectenna.

V. Conclusions

A dual frequency rectenna operating simultaneously at 2.45 and 5.8 GHz has been developed. New dual frequency printed dipole antenna is developed integrated with novel CPS filters. The combination of lowpass filter and bandstop filters effectively block the higher order harmonic re-radiations. A low C_{j0} of the diode is desired to have frequency insensitive high RF-to-DC conversion efficiency. High conversion efficiencies of 84.4 and 82.7 % are achieved at 2.45 and 5.8 GHz, respectively. The dual frequency rectenna should have many applications in wireless power transmission.

Acknowledgement

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