A HIGH CONVERSION EFFICIENCY 5.8 GHZ RECTENNA

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ABSTRACT

A high efficiency rectenna element has been designed and tested at 5.8 GHz for applications involving microwave power transmission. The dipole antenna and filtering circuitry are printed on a thin duroid substrate. A silicon Schottky-barrier mixer diode with a low breakdown voltage is used as the rectifying device. The rectenna element is tested inside a waveguide simulator and achieves an RF to DC conversion efficiency of 82% at an input power level of 50 mW. The antenna and circuit design is based on a full-wave electromagnetic simulator.

I. INTRODUCTION

The rectenna is coined from the words "rectifying" and "antenna." This receiving antenna efficiently converts microwave power into direct current (DC) power. A rectenna is a fundamental component in microwave power transmission systems. Microwave power transmission has applications in solar power satellites, remotely powered vehicles, and powering high altitude communication and surveillance platforms [1], [2].

Components for microwave power transmission have traditionally been focused at 2.45 GHz due to its low attenuation through the atmosphere, low cost technology base, and location at the center of an ISM band. The next higher ISM band is centered at 5.8 GHz. This frequency is appealing for beamed power transmission due to smaller component sizes and a greater transmission range over 2.45 GHz. The efficiency at which rectennas convert the microwave energy into DC is the rectenna's critical figure of merit. Aluminum bar-type rectennas developed in the 1970's achieved conversion efficiencies greater than 90% at 2.45 GHz [3]. Later, a thin-film class of rectenna design was developed at 2.45 GHz where conversion efficiencies of 85% were achieved [4].

The first C-band rectenna achieved a 70% overall efficiency and a 80% conversion efficiency at 5.87 GHz [5]. These efficiencies were measured in a waveguide simulator with a input power level approximately 700 mW per element. This C-band rectenna used a printed dipole that fed into a Si Schottky diode quad bridge. However, little information is provided on the design of the matching circuit between the dipole antenna and the diode.

In testing rectennas in a waveguide simulator, an overall efficiency(η_o) and a conversion efficiency, (η_c) are defined as

$$\eta_o = \frac{\text{DC Output Power}}{\text{Incident RF Power}}$$

$$\eta_c = \frac{\text{DC Output Power}}{\text{Incident RF Power - Reflected RF Power}}$$

Measurements performed in a waveguide simulator can accurately monitor reflected power.

The rectenna element developed in this paper operates efficiently (>80%) at much lower incident power levels of 30 to 60 mW. This characteristic has two important applications in microwave power beaming systems: 1) power can be converted efficiently at the edge of the rectenna where power densities are lower than the center elements, and 2) power can be converted efficiently when the transmission distance is large and power density is low.

II. RECTENNA ELEMENT DESIGN

The structure of the printed rectenna element is shown in Figure 1. The entire element is composed of a two plane format where the printed rectenna circuit is placed horizontally to a metal reflecting plane. The horizontal dipole antenna and coplanar stripline (CPS) transmission lines are printed on one side of 10 mil Rogers 5880 duroid (ε_r = 2.2). A low pass filter composed of three printed strips on the opposite side of the coplanar stripline (CPS) transmission lines passes the operating frequency of 5.8 GHz and rejects higher order harmonics produced by the rectifying diode. The filter also transforms the input impedance of the dipole antenna to the input impedance of the diode. A 47 pF chip capacitor is used to effectively short the RF energy and pass the DC power to a resistive load. The chip is also used to maximize the diode's conversion efficiency. The distance between the diode and the chip constitutes an inductance which tunes the capacitance of the diode. The resistive load typically 1.2 to 1.3 times the diode input resistance is then placed at the output CPS terminals [6]. Both the low pass filter and the chip output capacitor are used to store RF energy during the off period of the diode. A reflecting metal plane is then placed behind the substrate typically $0.2\lambda_o$.

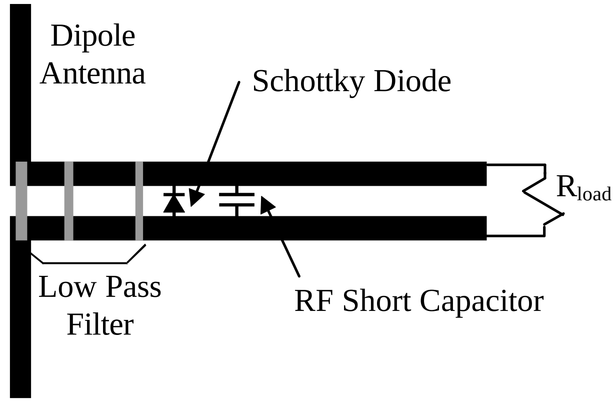

Fig. 1. 5.8 GHz rectenna element.

A commercially available full wave electromagnetic simulator, IE3D, was used to design the dipole, CPS, and low pass filter [7]. The steps taken to design the rectenna begin at the dipole. The length and input resistance of the resonant dipole were first simulated to be approximately 26.5 mm and 92 Ω, respectively. The gap between the dipole terminals is determined by the characteristic impedance of the CPS. This gap is designed to accommodate the size of the diode package. Using IE3D, the calculated characteristic impedance for a 2.1 mm gap and 1.6 mm wide strips is 254 Ω. The diode input impedance is taken to be 254 Ω to reduce the loss associated with the built-in voltage of the diode. The low pass filter is designed to pass 5.8 GHz and transform the 92 Ω dipole impedance to the 254 Ω diode impedance. IE3D was used in an iterative process to correctly size the three low pass filter strips and the spacing between the strips to achieve this characteristic. The efficiency loss caused by the built-in voltage (V_b) drop across the Schottky barrier is approximately given by [3]

$$Loss = \frac{V_b}{V_{dc} + V_b}$$

where V_{dc} is the voltage measured across the resistive load. Forcing the diode input impedance to be large will decrease the loss associated with V_b.

A M/A-COM Si Schottky diode (MA40150-119) used for X-band mixer applications is the rectifying device. The measured built-in and breakdown voltages at 10 μA are 0.224 V and 4.44 V, respectively. This low breakdown voltage limits the diode's power handling capabilities.

III. MEASUREMENTS

A waveguide simulator was designed to test and monitor the rectenna element. The short dimension of a standard WR 137 waveguide was expanded to equal the wide dimension. Thus, the rectenna is placed in a square opening (3.485 cm x 3.485 cm). Based on the cutoff frequency of the WR 137 waveguide and the operating frequency of 5.8 GHz, the angle of incidence is calculated to be 47.9° from boresight [6]. Thus, the rectenna efficiency proves to be very non-directional. In applications where the rectenna is placed on a moving target, this aspect allows the rectenna to receive power efficiently at various angles of incidence.

Figure 2 shows the measurement setup. The HP 83622A synthesized sweeper provides the input RF power and allows the power and frequency to be varied. In addition to built-in isolators of the sweeper, a coaxial isolator provides additional protection from the reflected energy. A coax to waveguide adapter is used to connect to a waveguide slotted line to monitor the reflected RF power. VSWR measurements by a voltmeter are taken using the mounted detector on the carriage. The waveguide expander transitions from WR 137 waveguide to the square output of the waveguide simulator. The rectenna element is placed between the waveguide expander and a square waveguide. This square waveguide houses an adjustable reflecting plane to tune the rectenna element.

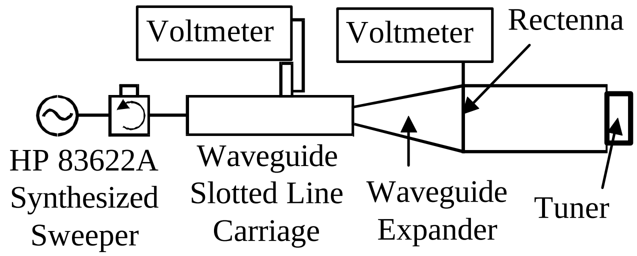

Fig. 2. Measurement setup.

Figure 3 shows overall and conversion efficiencies of the rectenna using a 326 Ω resistor load. A placement of 11.1 mm (0.21 λ_o) measured between the back of the substrate and the reflected plane resulted in the highest rectenna efficiency. A maximum conversion efficiency of 82% is achieved at an input power of 50 mW. The differences between the overall efficiency and conversion efficiency indicate very little power is reflected from the measurement system.

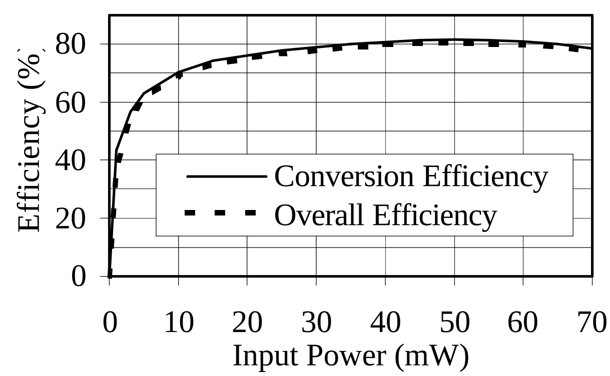

Fig. 3. Rectenna performance at 5.8 GHz with a 326 Ω load.

Figure 4 shows the effects of varying the resistive load on the rectenna at 5.8 GHz. The range of loads used indicate very small changes in conversion efficiency. Overall efficiency was also monitored but again there was little difference from conversion efficiency. Thus, the rectenna element converts power efficiently when the load varies by± 10%.

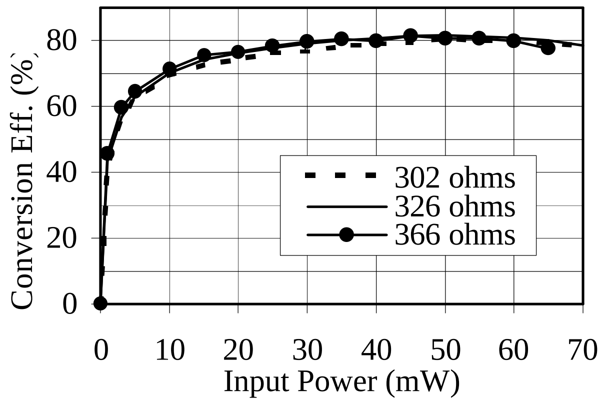

Fig. 4. Conversion efficiency comparison.

Figure 5 shows the rectenna conversion efficiency when the frequency is varied at a constant input power of 55 mW. Changes in frequency influences rectenna performance by electrically changing the dipole impedance and reflecting plane spacing. A maximum conversion efficiency of 81% occurs at 5.775 GHz. The efficiency remains above 75% over the entire ISM band located between 5.725 GHz to 5.875 GHz.

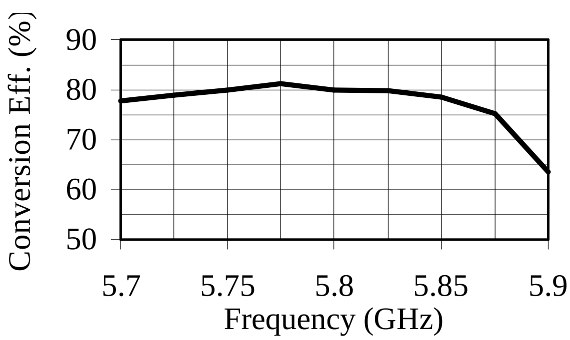

Fig. 5. Frequency variation.

IV. CONCLUSIONS

A rectenna element has been developed which has the highest recorded conversion efficiency of 82% at 5.8 GHz with an input power of 50 mW. The circuit design was based on electromagnetic and circuit analysis and accurately tested in a closed environment.

V. ACKNOWLEDGMENTS

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