AN EXPERIMENTAL LOW POWER DENSITY RECTENNA

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ABSTRACT

The paper describes the design and performance of a 2.45 GHz rectenna that absorbs small amounts (milliwatts) of microwave power at incident power density levels that are 10,000 times lower than those normally used, and then, after a microwave impedance step up of 50, converts it into DC power at useful voltage levels. Several useful applications are discussed.

THE TECHNOLOGY OF THE LOW POWER DENSITY RECTENNA

The rectenna is the receiving device in a beamed microwave power transmission system that absorbs the incident microwave power and converts it by rectification into DC power. The rectenna is well developed at incident microwave power density levels of 500 watts per square meter and a corresponding DC power output density level of 400 watts per square meter.[1,2,3] By comparison the subject of this paper is a rectenna that was developed to operate efficiently with an incident microwave power density of as low as 50 milliwatts per square meter, a factor 10,000 times less.[4] The resulting experimental rectenna is shown in Figure 1.

In addition to low power density operation it was desired to use the power output from the rectenna to operate a solid state device for which the nominal operating voltage was assumed to be about five volts. But it was also desired to hold the microwave power collected to a minimum, thereby, demanding that the effective load on the rectenna be a high impedance. This, in turn, required that an impedance transforming device be used to step up the voltage at the 50 ohm output impedance level of the collecting antenna to a high microwave voltage input to the rectification circuit. The quarter wavelength transformer used for this purpose achieved an impedance transformation of 50 with a resulting step up of 7 in voltage. The half wave rectification circuit effectively adds another step up of two in impedance to achieve an overall step up in impedance of 100 and a step up in voltage of 10.

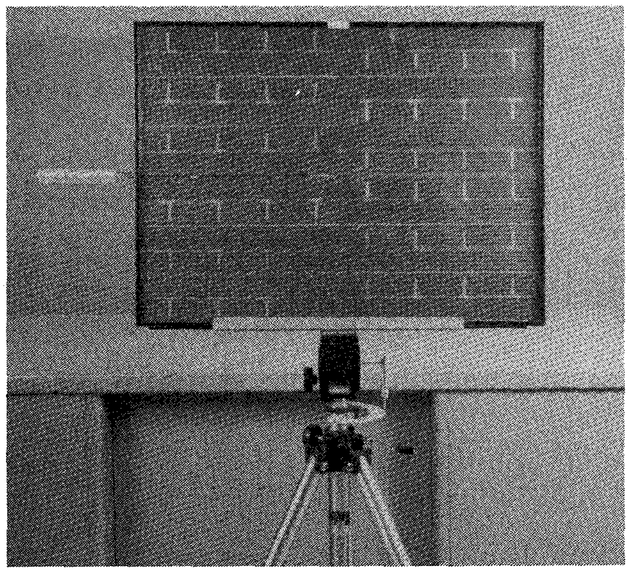

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Figure 1. The 48 element, low microwave-power-density rectenna set up for testing.

To achieve efficient operation at low power densities it was necessary to abandon the standard rectenna design in which there was a separate rectifier in each microwave collecting element, usually a half wave dipole. The collecting aperture then becomes a broadside array, so that the non-directive properties of the conventional rectenna are lost. However, several advantages are gained: (1) an adequate filter may now be inserted to suppress harmonic radiation to any degree required, (2) the number of diodes used is greatly reduced , (3) the diodes are used at a power level where their efficiency is maximized, (4) the antenna array can now be used as either a transmitter or receiver, and (5) the terminal impedance of the antenna can be designed to be 50 ohms for use with standard test equipment and components.

The broadside array consists of a foreplane and a reflecting plane which is about one fifth of a wavelength behind the foreplane. The foreplane is fabricated by printed circuits on both faces of a laminate material. If the dipole

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is visualized as consisting of two legs, then one set of legs for all the dipoles is on one face and the other set on the other face. The foreplane consists of 48 dipole receiving elements and the transmission lines which connect them to the output terminal. The details of the microwave circuit configuration for the foreplane are explained in the caption of Figure 2.

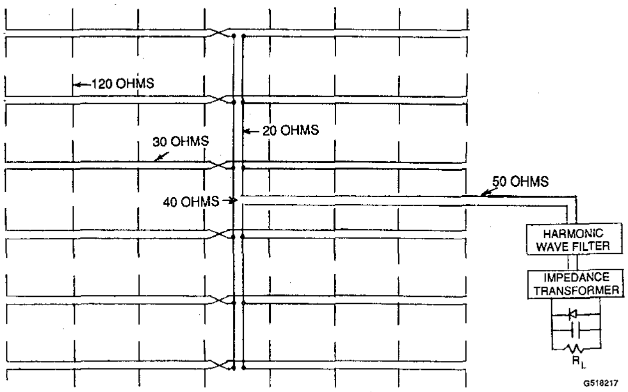

Figure 2. The electrical schematic for the 48 dipole rectenna. Each dipole has an impedance of about 120 ohms. In each row two sets of four diodes are each connected in parallel to a 30 ohm transmission line. The 30 ohm transmission lines are connected in series to give 60 ohms. Three such rows are connected in parallel to match an impedance of 20 ohms. Another group of three rows, similarly connected, are connected in series to produce an output impedance of 60 ohms.

The filter section, the impedance transformer, and the rectification section are shown in more schematic detail in Figure 3. The various impedances in Figure 3 are defined and quantified as follows. The antenna impedance Za is that seen at the coaxial terminal of the antenna, approximately 50 ohms. The low pass filter section has a characteristic impedance of 50 ohms. The quarter wavelength impedance transformer has a characteristic impedance of 350 ohms to boost the impedance to a level of 2500 ohms at its output. The half wave rectifier makes the load resistance RL of 5000 ohms appear as 2500 ohms in the rectifier circuit, thereby matching the antenna output to the useful load RL.

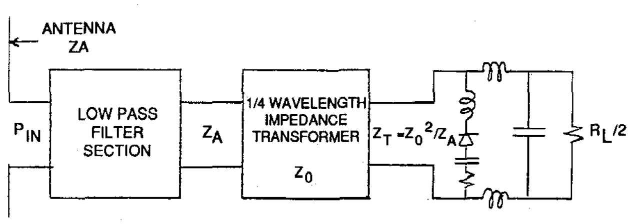

Figure 3. Schematic of the impedance transformation and rectification functions.

A cutaway view of the cartridge that contains the impedance transformation and rectification functions is shown in Figure 4. The transformer is a quarter wave length of a two wire transmission line with an air dielectric. The diode in the rectification circuit is a silicon Schottky barrier diode with a zero bias capacitance of one picofarad. The rectification circuit is tuned with a sliding capacitor which has a dual function. One function is to act as a bypass capacitor with low impedance of a few ohms at the fundamental frequency of 2.45 GHz, thereby effectively serving as a microwave short to establish the equivalent inductance value of the shorted transmission line. (See the capacitor in Figure 3). The other function is to prevent power at the fundamental and harmonic microwave frequencies from reaching the DC bus.

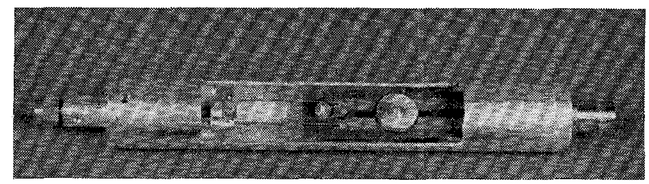

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Figure 4. Cutaway view of the impedance transformation and rectification cartridge.

The performance of the impedance transformation and rectification cartridge is shown in Figure 5. A typical DC power output of 10 milliwatts and a DC voltage of 7 is achieved into a load resistance of 5000 ohms with an input microwave power level of 20 milliwatts. Efficiencies of about 50% are obtained. These efficiencies are considerably lower than the 85% to 90% efficiency of the standard rectenna (1) but it should be noted that at a DC output level of 5 volts, the 0.7 volt drop across the Schottky barrier accounts for a power and efficiency loss of 14%. In addition the diode has excessive internal resistance which can be removed by redesigning the diode.

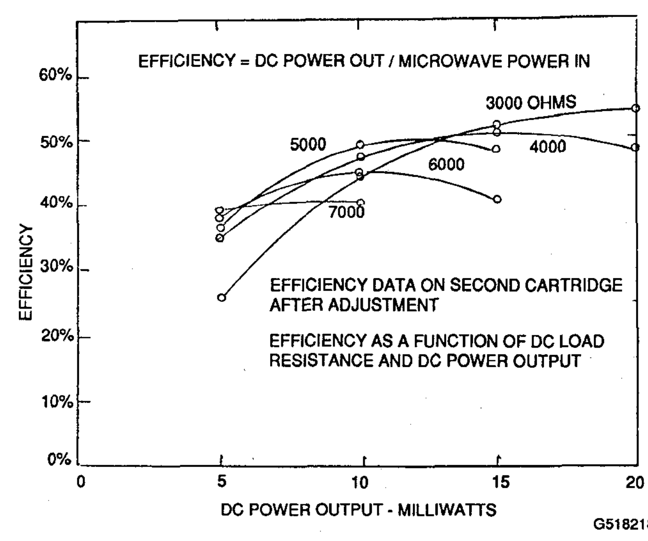

Figure 5. Performance chart of the impedance transformation and rectification cartridge. Output voltage can be obtained from the square root of the product of the DC load resistance and the power output. For example, at 10 milliwatts output into a load resistance of 5000 ohms, the DC voltage will be 7 volts.

The suppression of the radiation of harmonic frequencies is always desirable and perhaps necessary in many applications. For this purpose, a low pass filter was designed for the suppression of harmonic frequencies while retaining a very low insertion loss at the fundamental frequency of 2.45 GHz. To evaluate the design an 8 section filter was constructed, as shown in Figure 6. The total attenuation of the low pass filter for the second harmonic was 104 dB and the total insertion loss at the fundamental or microwave beam frequency at 2.45 GHz was only 0.4 +/ -0.05 dB. Attenuation of the third and fourth harmonics was not measured but the theoretical prediction would be for even greater attenuation at the third harmonic and about the same for the fourth harmonic. The performance of one section of the low pass filter as derived from the performance of the 8 section filter is shown in Figure 7 and compared with a theoretical prediction of behavior.

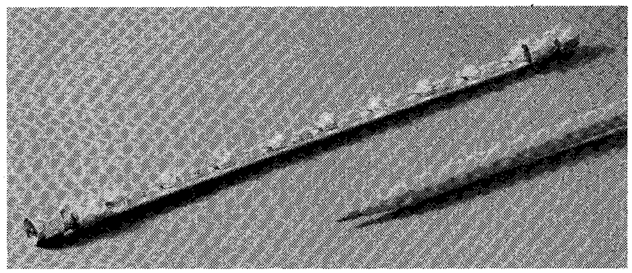

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Figure 6. View of the 8 section low pass filter with 104 dB of 2nd harmonic attenuation with insertion loss of 0.4 dB or 8% at 2.45 GHz input frequency.

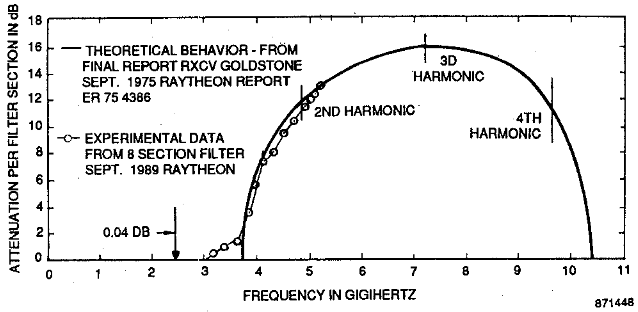

Figure 7. Performance of a single section of the 8 section filter as derived from the overall performance as shown in Figure 6. Experimental data is compared with the theoretical prediction of the filter's performance.

The overall efficiency of the rectenna consists of the product of: (1) the efficiency of the broadside array to capture the microwave energy and transport it to the output terminal, and (2) the efficiency of the impedance transformation and rectification cartridge. The efficiency of the cartridge has been given in Figure 5. A discussion of the testing and efficiency of the broadside array follows.

The testing and evaluation of the broadside array consisted of two parts. The first part was using it as a transmitting array and noting its input match and the antenna patterns around both axes. The second part was immersing it into a microwave power beam and noting its collection efficiency.

In the transmission mode, the reflections from two broadside antennas of slightly different design that were made from slightly different laminates were measured. One had a power reflection of 2% while the other had a reflection of 10%. The antenna patterns around vertical and horizontal axes were found to agree closely with the expected patterns for uniform illumination.

When immersed in the microwave beam the absorbed power of the antenna was only about half (45%) of the incident microwave power on the antenna. It was estimated that the losses consisted of: (1) 15% from I^2R losses in the internal transmission lines, (2) 14 % loss caused by failure to introduce side lobes back into the uniform illumination pattern, and (3) 20% loss caused by lack of phase and amplitude coherency across the radiating surface as measured by a probe held in close proximity to each dipole. These inefficiencies when taken together reduce the efficiency of the aperture to 58%. In addition there may be an efficiency factor related to edge effects around the aperture.

APPLICATIONS

There are a number of potential applications for the new technology which will convert microwave power at very low levels into DC power at useful voltage levels. One application is for a transponder in a communications or sensor system in which the interrogating transmitter also supplies power to the transponder. Even though the incident microwave power level is very low, the rectified DC energy can be accumulated over long periods of time in capacitors or batteries to provide substantial amounts of stored energy for those short periods of time when substantial power levels are needed. Application areas would be where the transponder is inaccessible to replace batteries and where solar or other light is not available for photovoltaic power supplies.

An important high-microwave-power-density spinoff of this technology, that is already being used for demonstrations of beamed microwave power transmission at the Center for Space Power at Texas A&M University, is a new rectenna format specifically for space use in which the inherent "nondirectivity" of the standard rectenna is preserved around one axis of the rectenna but not the other. The rectenna shown in Figure 1 can be converted into such a format by terminating each row of the antenna with a rectifier. Such rectennas can be used without compromise for Earth to space transmission systems where all elements, the satellite as well as the transmitter , are located in the equatorial plane.[5] For those systems, non-directivity is required in the West to East direction but not North to South. The benefits derived from this arrangement are that many less diodes are used, they are used at higher efficiency levels, and there is ample opportunity to put in adequate filters for harmonic and intermodulation suppression.

ACKNOWLEDGMENTS

The author acknowledges the NASA and Raytheon support in this development.

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