2.45 GHz Rectenna Designed for Wireless Sensors Operating at High Temperatures

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Abstract

High temperature wireless sensors that operate at 500°C are required for aircraft engine monitoring and performance improvement. However, even if the sensor output data is transmitted wirelessly to a receiver in the cooler part of the engine, and the associated cables are eliminated, DC power cables are still required to operate the sensors and power the wireless circuits. To solve this problem, NASA is developing a rectenna, a circuit that receives RF power and converts it to DC power. In this paper, we report the first rectenna designed for 2.45 GHz operation at high temperatures. The circuit consists of a microstrip dipole antenna, a stripline impedance matching circuit, a stripline low pass filter, an n-type, 4H SiC Schottky-barrier diode, and a capacitor integrated on an alumina substrate. Experimental characterization of the rectifying diode has been completed through 400°C. At 3.0 GHz and 300°C, the maximum measured output power of the rectenna is 275 mW and the peak efficiency is 47 % of the room temperature value.

Keywords: SiC, diode, rectenna, high temperature.

I. Introduction

Temperature, pressure, and chemical sensors that operate at high temperatures (500°C and above) are required for aircraft engine development and monitoring during flight. Additional interest exists in high-temperature electronics for use in the harsh environments of interplanetary exploration, telemetry during mining operations and oil exploration, and in conjunction with advanced systems for consumer automobiles [1-3].

For aircraft engine monitoring during flight, there is an additional need to minimize the aircraft weight. MEMS sensors of all types have been developed that significantly reduce the weight of the sensors, but cables are still required to extract data and bring power to the sensors. A NASA program (Ultra-Efficient Engine Technology program) managed at NASA Glenn Research Center is developing high temperature wireless sensors that operate at 500°C for placement in aircraft engines. These sensors would replace currently used hard-wired sensors and lead to a substantial reduction in mass. However, even if the sensor output data is transmitted wirelessly to a receiver in the cooler part of the engine, and the associated cables are eliminated, DC power cables are still required to operate the sensors and power the wireless circuits.

A rectenna is a circuit that captures Radio Frequency (RF) energy and converts it to DC power through a simple circuit consisting of an antenna and a rectifying circuit [4]. Rectennas have been developed primarily for microwave power transmission from space platforms, which is summarized well in [5], but there has been some development of rectennas for providing power for sensors [6]. Impressive efficiencies and power have been reported from these rectennas. For example, a 9 element array has achieved 78% RF to DC power efficiency and 0.86 W DC power at 5.8 GHz [7] and a single element has achieved 84 % efficiency and 90 mW DC power at 2.45 GHz [8]. However, to date, no high temperature rectennas have been reported.

In this paper, we report the first rectenna designed for 2.45 GHz operation at high temperatures. Thus, once integrated with a MEMS sensor and a wireless transmitter, all cables to the sensor will be eliminated. The diode characteristics as a function of temperature, the rectenna design, and the rectenna performance as a function of temperature are described.

II. Circuit Description

Figure 1 shows the main components of the rectenna circuit. A half-wave dipole antenna is connected to a low-pass filter that is used to prevent higher-order harmonics generated by the non-linear rectifying diode from being re-radiated by the circuit. In this rectenna design the dipole, filter, and coplanar stripline are patterned in gold on a 660-μm alumina substrate. The diode is placed in shunt across the coplanar stripline and rectifies the incoming microwave power. A capacitor acts as a DC-pass

filter by collecting RF energy when the diode is in the on state and storing charge when the diode is off. Finally, a resistor is placed across the output terminals to act as a load for measuring output DC power.

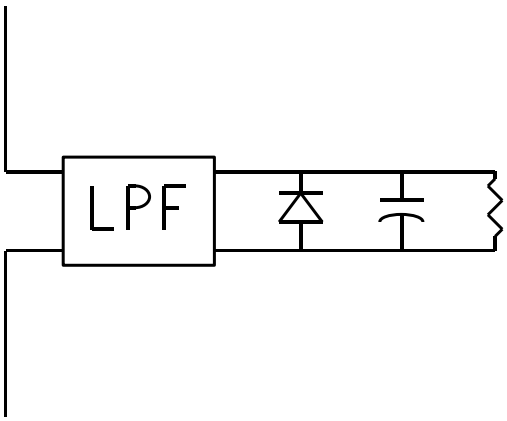

Figure 1. The main components of the rectenna circuit include the dipole antenna, low-pass filter, rectifying diode, DC-pass capacitor, and load resistor.

A. Dipole and Low-Pass Filter

The dimensions of the dipole antenna and the low-pass filter were optimized using the Sonnet EM simulation software. The half-wave dipole antenna was designed to operate at 2.45 GHz. During initial simulations, the antenna was placed too close to the boundary planes, effectively making the dipole electrically shorter than anticipated. The dipole, as fabricated, is operated at 3.0 GHz. The low-pass filter was based on a 5th-order Chebyshev coplanar design by Uysal and Ng [9], and was designed to have a cutoff frequency of 4.0 GHz. The filter uses alternating high- and low-impedance sections of transmission line (equivalent to series inductances and shunt capacitances, respectively) to simulate the reactive elements. The layout and simulated response of the filter are shown in Figures 2 and 3. The correctly simulated and measured response of the combined filter and dipole is shown Figure 4.

B. Rectifying Diode

A Schottky-barrier diode fabricated on n-type 4-H silicon carbide (SiC) substrate is the rectifying device [10]. This device has a vertical structure consisting of a 0.1-µm-thick gold Schottky-barrier and is 50 µm in diameter. The diode has a 100 µm x 100 µm anode contact pad fabricated on a layer of insulating spin-on-glass (annealed at 350°C) for wire-bonding or on-wafer probing.

Figure 2. Layout of the 5th-order Chebyshev coplanar low-pass filter.

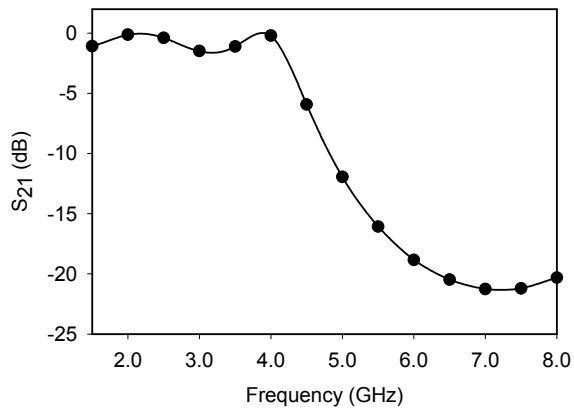

Figure 3. Frequency response of the low-pass filter, simulated using Sonnet EM software.

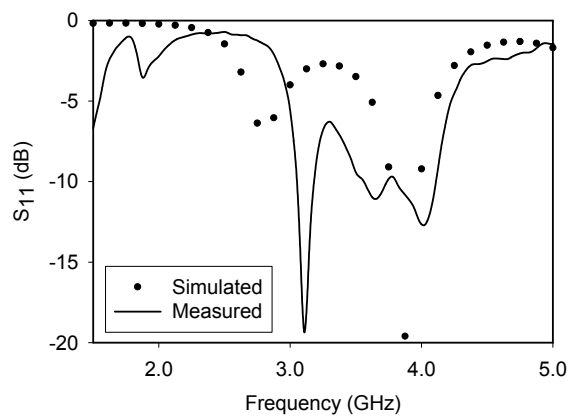

Figure 4. Simulated and measured reflection coefficient of the combined low-pass filter and half-wave dipole antenna.

At room temperature, the measured built-in (V_{bi}) and breakdown (V_{br}) voltages are approximately +2.2 V and –40 V, respectively. As will be discussed in the next section, the built-in voltage typically decreases after one heating cycle to about +1.2 V. The breakdown and built-in voltages limit the maximum DC output voltage as:

$$V_{DC} < \frac{|V_{br} + V_{bi}|}{2} \qquad (1)$$

thus, for the SiC Schottky diode used here, the maximum expected V_{DC} is about 19 V at room temperature [11]. However, driving the diode to this voltage limit may cause damage if a large reverse bias current flows through the device.

The diode's series resistance, R_s, is determined from the current-voltage (*I-V*) curve when the diode is forward biased and is

approximately 15 Ω at room temperature for this device. This resistance reduces the efficiency of the diode by absorbing power during the conducting portion of the charging cycle.

C. DC-Pass Filter

The DC-pass filter used is a 56-pF chip capacitor by ATC Microcap. The DC leakage was measured to be better than 0.5 mA/V at 500°C.

D. DC Load

The DC load resistor can reside externally or be integrated within the rectenna circuit. An external variable resistor is used in this experiment to allow the DC load to be tuned during rectenna operation. Output DC power is accurately measured by measuring the voltage across this resistor. With the load resistor set at 200 Ω, the maximum DC power limit is 1.8 W, assuming a maximum room temperature V_{DC} of 19 V for the SiC Schottky diode.

III. Experimental Results

DC current-voltage (*I-V*) measurements are recorded for a typical diode at temperatures (in order) of 30, 100, 200, 300, 400, 350, 250, 150, and 65°C and the diode parameters V_{br}, R_s, and V_{bi}, are extracted from the measured data. As shown in Figure 5, the magnitude of the reverse breakdown voltage is stable as the temperature rises to 200°C, then drops with further increases in temperature.

The series resistance is calculated as the inverse of the slope of the diode's *I-V* curve as it becomes linear in the forward-bias region. As shown in Figure 6, the series resistance is constant at 15 ± 3 Ω across the entire temperature test range for two sequential heating cycles. The built-in voltage is also measured for two heating cycles. During the first heating cycle, the value of V_{bi} decreases from 2.2 V at room temperature to 0.4 V at 400°C. When the device cools, the built-in voltage only rises to 1.3 V. A second heating cycle kept the built-in voltage in the 0.4 to 1.3 V range, as shown in Figure 7.

Using these measurements of the breakdown and built-in voltages give an indication of the limits of DC performance at temperature by the relationship described in Equation 1. At 400°C, the maximum DC voltage is about 1.3 V, resulting in a maximum output power of 8.5 mW into a 200 Ω load.

To characterize the RF-to-DC efficiency of the diode at room temperature, a 56-pF chip capacitor and a single diode are mounted in shunt across a simple coplanar stripline, and a 200-Ω resistor is connected to load the circuit. Microwave power is applied at 3.00 GHz to the circuit through an end-launch connector while the DC voltage across the resistor is monitored. The DC output power and diode efficiency are shown in Figure 8 as a function of applied microwave power. A peak RF-to-DC efficiency of 20.3 % is achieved at an output power of 819 mW.

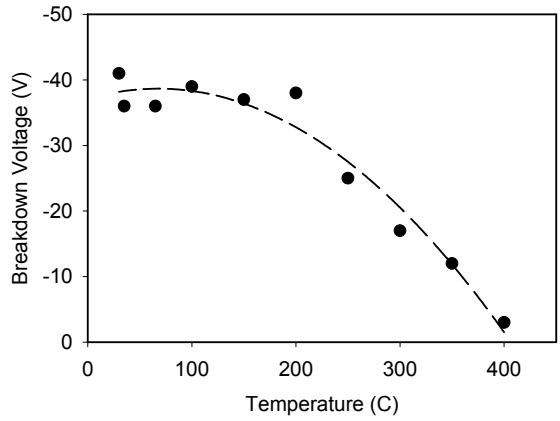

Figure 5. Measured reverse breakdown voltage, V_{br}, as a function of temperature.

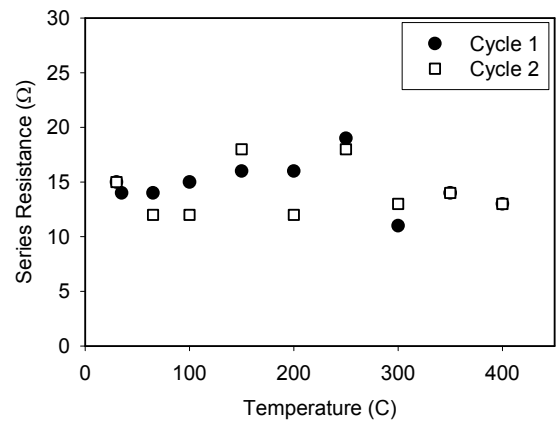

Figure 6. Measured values of series resistance, R_s, as a function of temperature over two sequential heating cycles.

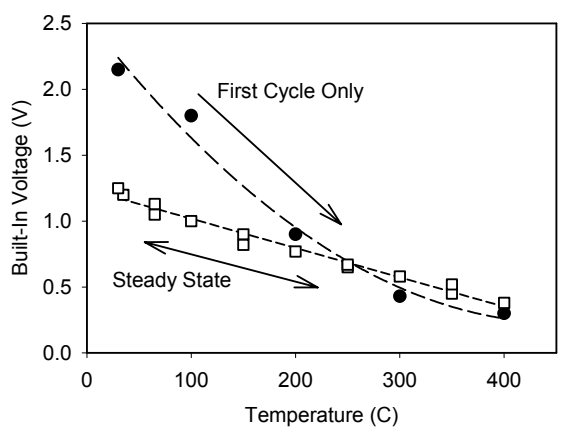

Figure 7. Measured built-in voltage, V_{bi}, as a function of temperature for two sequential heating cycles. The upper curve (black circles) occurred as the device was being heated for the first time. The white squares indicate the values of V_{bi} measured during the subsequent heating cycle.

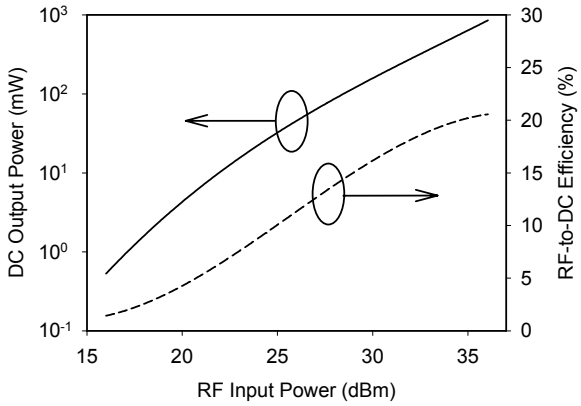

Figure 8. DC output power and RF-to-DC efficiency of the SiC-Schottky diode with power applied at 3.00 GHz through an end-launch connector. The DC load is 200 Ω.

For wireless measurements, a diode is mounted to the rectenna board, 5 mm beyond the low-pass filter, using conductive silver paste. A 56-pF chip capacitor is likewise mounted 5 mm beyond the diode. Gold wirebonds connect the top contact pads of the diode and capacitor across coplanar stripline. A ceramic disc heater, mounted on a 10-cm tall insulating tile, is used as the heating element. The rectenna rests directly on the heater and DC measurements are made with two needle probes at the end of the transmission line. An external variable resistor is used as the DC load. The rectenna and heating stage are aligned at the open end of a WR-430 waveguide, used to feed RF power from the signal generator and amplifier to the device under test. A diagram of the test setup is shown in Figure 9.

The frequency of the RF source is manually tuned to determine that 3.00 GHz is the optimal operating frequency for rectenna as fabricated. With the heater at room temperature, the load resistor is swept from 50 to 1000 Ω at amplifier power levels of 25, 35, and 45 dBm. The total efficiency (the ratio of output DC power to amplifier RF power) is calculated for each resistor value and is plotted in Figure 10. (The efficiency values calculated here are an order of magnitude lower than those shown in Figure 8 when using the end-launch connector. The waveguide and rectenna circuit are not in a closed system, therefore a large amount of RF power is radiated into the surrounding absorbent material instead of being collected by the rectenna's dipole. A measurement using a printed dipole with no rectifying elements showed as little as 10% of the radiated power is actually collected by the dipole antenna.) The optimal resistor value changes as the power level, and therefore the DC bias point of the diode, is changed. The peak efficiency is at 500 Ω for an amplifier power of 25 dBm, 250 Ω for 35 dBm, and 200 Ω for 45 dBm. The load resistor will be fixed at 200 Ω for the remaining measurements to optimized the high power performance of the rectenna.

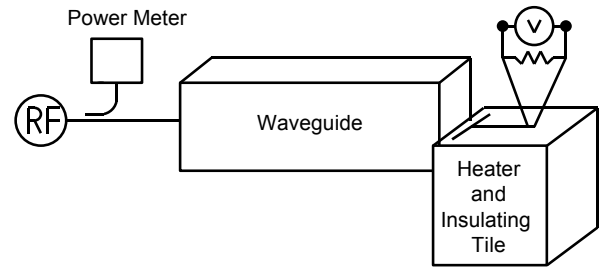

Figure 9. Diagram of the rectenna test setup. The rectenna rests on a ceramic heater and insulating tile, while RF power from the signal generator and amplifier is applied to the circuit through a rectangular waveguide.

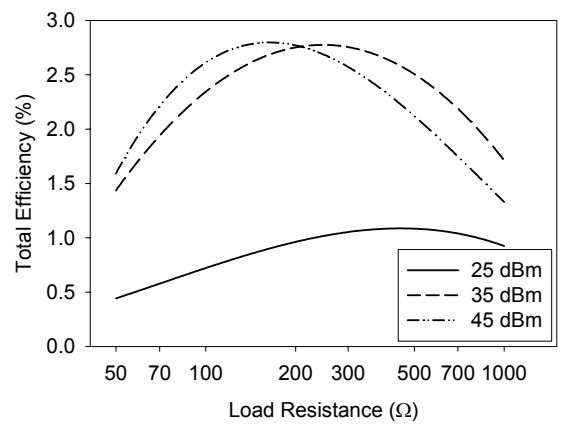

Figure 10. Total efficiency of the rectenna circuit as a function of amplifier power and load resistance at room temperature.

A complete power sweep is performed at room temperature, varying the amplifier power from 17 to 45 dBm in increments of 1.0 dBm. Again, the output voltage is recorded and the efficiency is calculated. The heater temperature is raised to 100, 200, and 300°C and the same data are taken at each temperature. Unfortunately, the rectenna's alumina substrate unexpectedly cracked on the heating stage at 400°C, ending this series of measurements.

The results of these measurements are summarized in Figures 11 and 12. The maximum output powers measured are 773, 556, 454, and 275 mW at temperatures of 30, 100, 200, and 300°C, respectively. Peak efficiencies of 2.63, 2.04, 1.87, and 1.25 % are measured at the four temperatures. The drop in output power and efficiency with increasing temperature is a direct result of the decreasing breakdown voltage described in Figure 5. The load resistance was fixed at 200 Ω during these measurements; however, the ideal value for the

resistive load may have in fact changed due to changes in the diode and capacitor with temperature. We expect that, had the substrate survived for a measurement at 400°C, the measured efficiency would be quite low.

IV. Summary

The first rectenna for use in high temperature applications has been presented. The design and characterization of each element of the rectenna circuit has been described. The SiC Schottky-barrier diode has a peak measured RF-to-DC efficiency of 20.3 % at a DC output power of 819 mW at room temperature. At 300°C, the total efficiency of the rectenna circuit decreases to 47 % of its room temperature value, which is shown to be caused by a decrease in the breakdown voltage of the SiC Schottky-barrier diode. This decrease in breakdown voltage limits the performance of the circuit beyond 300°C.

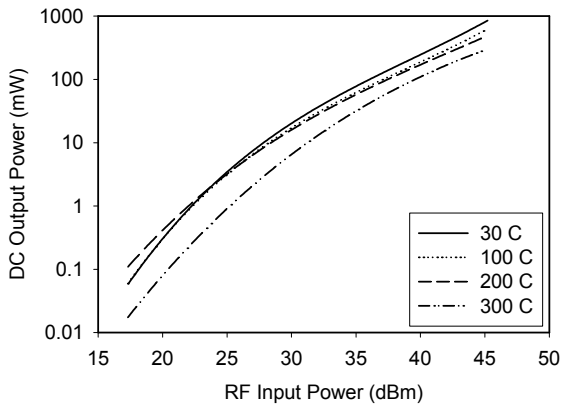

Figure 11. DC output power of the rectenna circuit measured at 30, 100, 200, and 300°C.

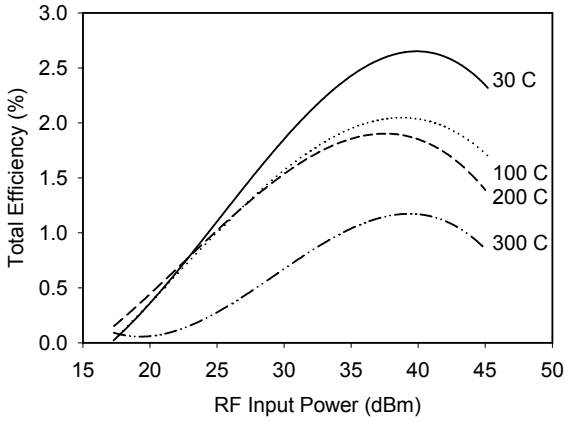

Figure 12. Total efficiency of the rectenna circuit measured at 30, 100, 200, and 300°C.

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