A Conformal 10 GHz Rectenna for Wireless Powering of Piezoelectric Sensor Electronics

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Abstract— **This paper presents the design, implementation and characterization of a rectenna array for wireless powering of sensor electronics for airframe fatigue detection. The rectenna aperture is powered 5 minutes at a time during inspection with a requirement of ±15V at 100mW. The maximum incident RF power is 10mW/cm^2. A single rectenna element at this incident power density has an output power of 5 mW and an estimated efficiency of 50%. Each of the 25 antenna elements has an integrated rectifier, the outputs of which are combined in series to achieve the total required voltage and power at an estimated efficiency of 40%.**

Keywords-component; Rectenna, Rectifying Circuit, Schottky Diode, Piezoelectric Sensors

I. Introduction

The flight environment of an aircraft is very harsh due to large changes in humidity, temperature, pressure, speed, and loading conditions. These effects cause significant stress to the aircraft frame. As a result, corrosion, delamination, cracks, disbonds, and other failures occur once the aircraft is in service for some time. Since early detection of failures in aircraft structures is crucial for aircraft safety, a smart health monitoring system is desired. Using piezoelectric sensors, failures can be detected before they pose a significant risk to the aircraft [1].

A wireless means of actuator excitation, communication, and sensor interrogation has many benefits such as fast inspection, less downtime, labor cost reduction, etc [2,3]. The objective of this research is to develop a prototype system with ultrasonic guided-wave “leave-in-place” passive sensors, an on-board miniaturized antenna, and a multi-channel circuit for data acquisition.

Currently, similar monitoring systems use batteries, magnetic coupling or solar cells to power the sensors and control, data collection and processing electronics [4]. As an alternative to conventional powering methods, this work presents a rectenna array for that provides DC power to the sensors and circuits from incident microwave radiation. This paper summarizes the single rectenna element design, array design, fabrication, and evaluation. Rectennas have been demonstrated for a variety of applications, over a range of frequencies and powers, e.g. [5].

The specifications of the rectenna are derived from the requirements of the sensor system. It requires ± 15V with 100mW of continuous power for 5 minutes in order to complete corrosion inspection. The physical size requirements for the rectenna are an aperature of 15cm by 15cm using as this of a substrate as possible to conform to the shape of the airframe. The environment is controlled during testing; therefore the transmission is only through free space without obstacles between the rectenna and illuminating source. The transmitting antenna is linearly polarized and provides a power density of at most 10mW/cm^2 incident on the rectenna array from a maximum distance of one meter. The block diagram of the system is shown in Fig.1. The rectenna array is designed starting from a single element. The number of elements and their DC connection is determined from the power obtained from the single element and the total requirements.

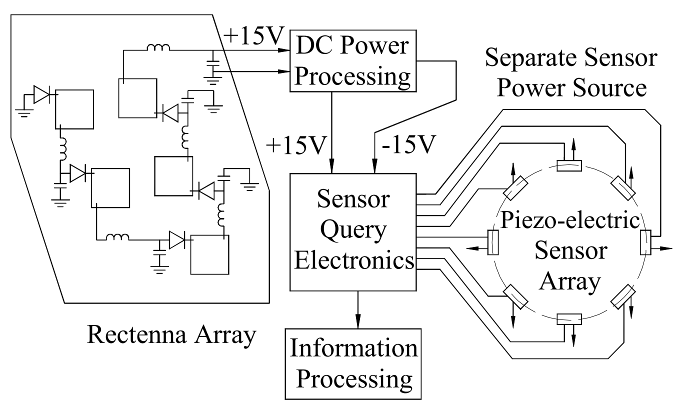


Fig 1. Block diagram of rectenna and sensor system. In the initial test, only the sensor control and processing electronics circuitry is powered by the rectenna.

II. Rectenna Array Design

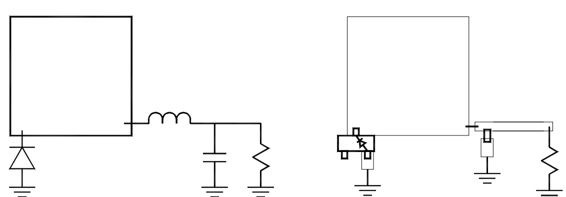
A. Antenna Element Design

For this application, the antenna element is a narrowband, linearly polarized patch antenna at 10 GHz designed for a

0.25-mm thick Rogers Duroid substrate with a permittivity of 2.2. The gain of the patch calculated from its physical area is 1.39 (1.45dB). In a rectenna element, the rectifying diode is connected directly to the antenna, so the radiation pattern cannot be measured at RF. When a feedline is added to the patch, the measured gain is approximately one (0 dB). The thin substrate is chosen because it allows the final rectenna array to be flexible enough to conform to the moderate curve of the airframe while desirable microwave properties are maintained.

B. Single Rectifier/Antenna Element Design

The rectifier diode is an Agilent HSMS-8101 Schottky mixer diode. It was chosen based on its reported performance at 10GHz and its availability. An ADS harmonic balance simulation using the model in Fig. 2a was used to optimize input and output impedances for maximum output voltage and power. The input impedance is found to be purely real. The maximum input impedance value is limited by the highest impedance of a manufactured patch antenna, around 200 Ω near the corner. The output circuit is an LC circuit, used as both the low pass filter and the matching circuit. The matching aspects of this circuit are more critical to the design for optimizing the output power [6]. The single element was simulated without considering connections to other rectenna elements. The maximum efficiency for the ideal circuit is 52% for an input power of 10mW.



(a) (b)

Fig 2. Model for ADS rectenna simulation circuit (a). The simulation uses a Spice model for the diode and models the antenna as an AC power source with a large series. The optimal lumped-element values are determined to be C = 100pF; L = 2.56nH. The lumped elements are soldered in place as shown in (b). The ground symbol indicates a via to the ground plane of the antenna.

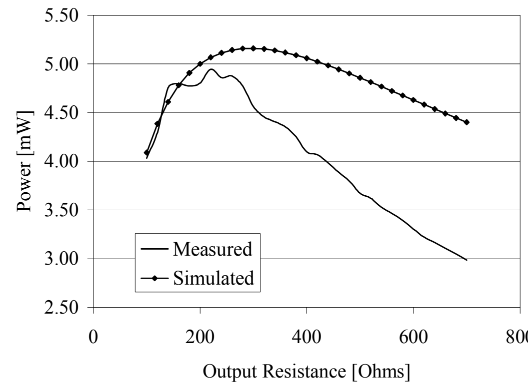
The rectenna element was fabricated using the layout in Fig 4b. A commercial lumped element capacitor and a small 0.24mm diameter wire as the inductor provide the necessary impedance for the output filter. The output voltage is measured across a variable resistor and the DC power is calculated as V^2/R. Figure 3 shows the simulated and measured output voltage versus the output resistance.

C Array Design and DC Power Combining

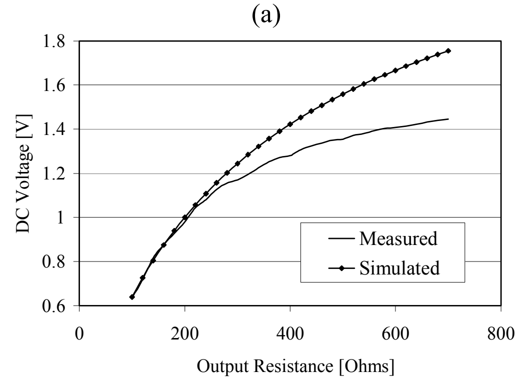
The total number of elements cannot be calculated directly from a single element because the efficiency of a rectenna array is lower than the efficiency of a single element [7]. Therefore, the minimum number of elements is calculated from the specified DC power and the efficiency of a single element. The minimum number of elements is calculated in (1)

$$N = \frac{P_{spec}}{S_{inc} \cdot A_{eff} \cdot \eta} \quad (1)$$

where N is the number of elements, P_{spec} is the specified DC power, S_{inc} is the incident power density, A_{eff} is the effective area of the antenna element and η is the rectification efficiency. Using a rectification efficiency of 50% and an effective area of $1cm^2$, a minimum of 20 elements will be required to provide 100mW.



(a)



(b)

Fig 3. Output power (a) and voltage (b) as a function of output resistance.

Although the overall efficiency depends on how the rectenna elements are connected [8], all 25 elements in this rectenna are connected in series, as shown in Fig. 4, to maximize the output voltage as required by the electronics load. The simulation is modified to reflect the additional reactance from the DC lines between rectenna elements.

Data is reported here for 16, 19 and 25 rectenna elements connected in series. The trend for output power and voltage versus the resistive load is shown in Fig.5. Series connection of 25 elements provides the required 15V output with approximately 100mW of DC power for a 2.4-k Ω load.

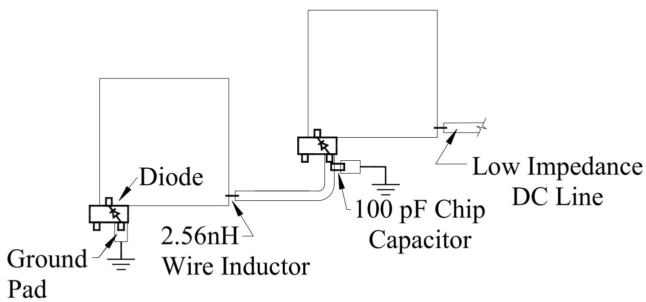
To estimate the efficiency, first the total received RF power must be calculated as:

$$P_{RF} = S_{inc} \cdot A_{eff} \cdot N \qquad (2)$$

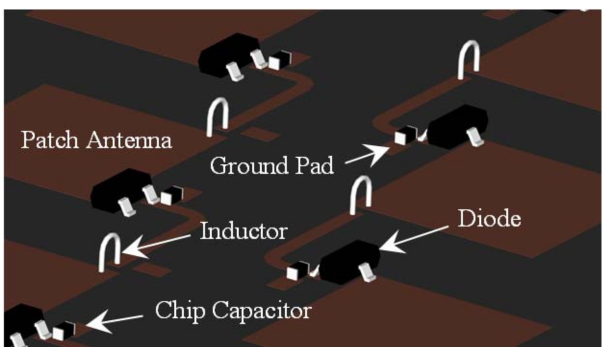
from which the efficiency of the array can be calculated from [9] as

$$\eta = \frac{P_{DC}}{P_{RF}} \qquad (3)$$

In (2) and (3), S_{inc} is the incident power density and P_{DC} is the output DC power.



(a)



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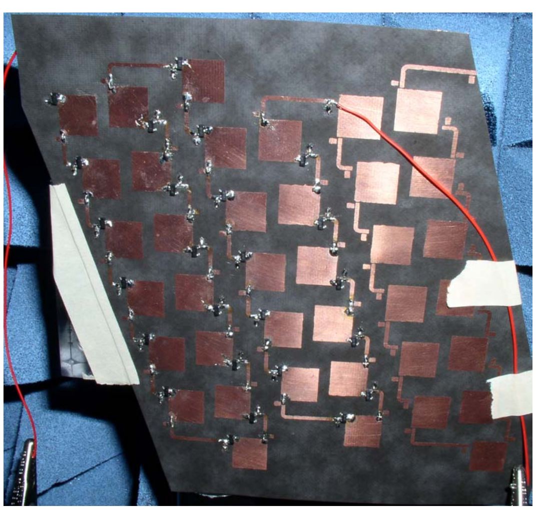
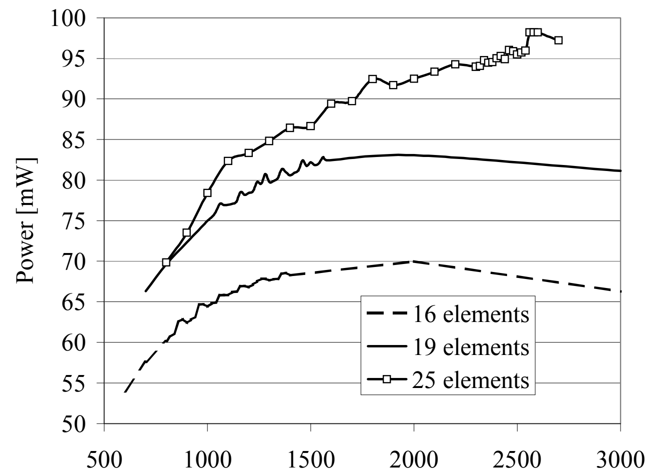


(c)

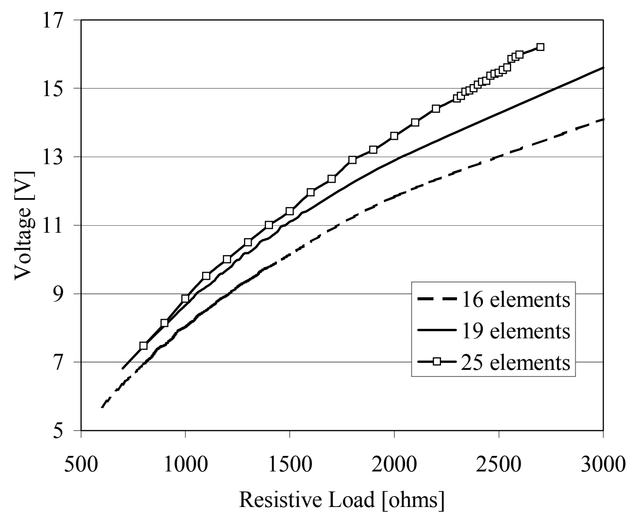
Fig 4. (a) Layout of multiple elements connected in series. (b) A close-up 3D representation of the assembled rectenna elements. (c) Fabricated rectenna array using 25 of 38 elements.

The maximum efficiencies of the 16, 19 and 25 element arrays are 44%, 44% and 39% respectively.

The rectenna array has 38 elements in a total area of 153.3cm^2 (roughly 13.5cm by 14.5cm). Since only 25 elements are required, the array can be populated with more diodes to increase the output power and voltage.



(a)



(b)

Fig 6. Measured DC output power (a) and DC output voltage (b) versus the resistive load.

III. System Integration

The direct output voltage of the rectenna only provides positive or negative voltage and additional circuitry is required to provide both polarities. The Maxim ICL7662 inverter chip is suitable for this application although it has a substantial current requirement (~30-40 mA) in the transient start-up phase. The input power requirement during this phase is almost 200mW, or twice the available output from the rectenna. To solve this problem, a large capacitor (approximately 1mF) is used to store enough energy to compensate for the initial requirements of the inverter chip. Once the inverter is in its normal operating region, the power requirements are very low and its efficiency is close to 98%. The capacitor is charged in an open circuit configuration and then connected to the inverter chip.

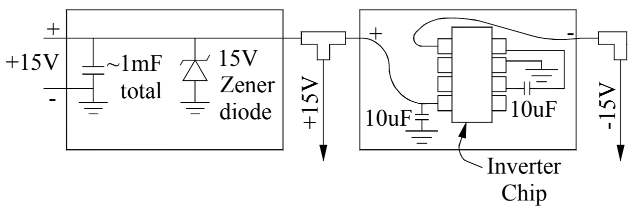


Fig 6. Block diagram of DC power processing to obtain ± 15 V. A 1mF capacitor is added to store enough energy for the transient period of the inverter chip. The Zener diode is added to limit the open circuit voltage.

The positive and negative voltages are used to power the diagnostic system from Intelligent Automation, Inc. The output of the rectenna to the system is tested at decreasing power levels and angles of polarization. The current and voltage are measured for the positive and negative outputs and the total power is reported as the sum of the two outputs. The measurements are performed while the rectenna is powering the diagnostic system. Fig. 7 shows the results of these tests. Below 20mW output power, the inverter chip was operating outside its low power region, thereby drawing too much power and shutting down the system.

IV. CONCLUSIONS AND FUTURE WORK

In summary, the 14cm by 15cm rectenna is able to provide 100mW of continuous power for longer than the required 5 minutes. Using a charge storage capacitor, the rectenna is able to provide up to 200mW of power during the transient turn on period of the inverter. This indicates that the rectenna can also be used in a burst mode that would provide high powers for short duration. A resonant converter with high efficiency can be used to provide the 2-MHz 50-volt bursts required for the piezoelectric transducers, and efforts to integrate this system are under way. Our goal is to have a complete sensor system powered and interrogated wirelessly.

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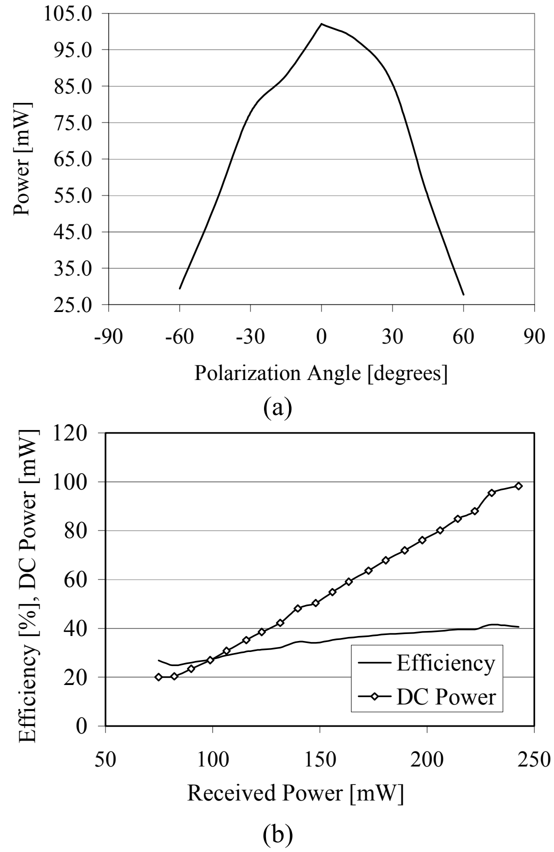

Fig 7. Measured output DC power versus polarization angle (a) and received RF power (b).

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