# RF Energy Harvester in the Proximity of an Aircraft Radar Altimeter

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***Abstract*—This paper presents the design and characterization of a rectenna-based energy harvester for low-power aircraft sensors. The harvester is placed on the aircraft skin in the proximity of the radar altimeter transmit antenna with power densities between 0.04 $\mu\mathrm{W/cm^2}$ to 2.2 $\mu\mathrm{W/cm^2}$ around 4.3 GHz. Several diodes were investigated via source-pull, and the chosen devices integrated with a patch antenna to directly charge a capacitor which serves as the energy storage device. The harvester is able to collect -23.2 dBm of power from an incident power density of 0.65 $\mu\mathrm{W/cm^2}$, and the time it takes the harvester to reach 63% of its open-circuited voltage is characterized for several designs.**

***Index Terms*—Altimeter, Rectenna, Harvester, Low-Power, Sensor.**

## I. INTRODUCTION

Modern aircraft require large numbers of sensors both for sensing within the cabin [1] and for sensing various properties of the aircraft structure itself [2]. For external very low-power structural health sensors, battery replacement is inconvenient and harvesting available RF energy becomes attractive. Low power wireless delivery has been proven extensively in previous work [3], [4], [5], [6], [7] and in this paper, we present an approach to harvesting power in the antenna sidelobes of a radar altimeter [8]. The altimeter antenna is typically a cavity-backed patch mounted flush with the aircraft skin between the front and back landing wheels with a beam pointing towards ground, e.g. [9]. The altimeter transmitter power is usually around 0.5 W and the radar operates in a narrow bandwidth around 4.2-4.4 GHz. A typical radiation pattern, e.g. [9], shows a reduction of power by -13 dB at $\pm 90^\circ$ compared to the power radiated at $0^\circ$ in the far-field E-plane. Therefore, we estimate that in the near field of the altimeter a flush-mounted harvesting rectenna would receive below $2.2\,\mu\mathrm{W/cm^2}$ power density.

The harvesting patch rectenna in this paper is designed for the center of the band at 4.3 GHz, but can easily be scaled. Several diodes were considered for the single-ended low-power rectifier, and after performing source-pull simulations with several diodes and nonlinear models, a choice was made to use the Skyworks SMS7630-061 GaAs Schottky diode. The goal of this work is to demonstrate useful stored energy in a capacitor integrated with the rectenna, and the remainder of the paper details the requirements, design and measured performance.

## II. HARVESTER DESIGN

### A. Altimeter environment characteristics

The frequency of operation of radar altimeters is between 4.2 and 4.4 GHz, typically 150 MHz of bandwidth centered at 4.3 GHz are used [8]. Altimeter antennas are typically mounted flush with the skin of the plane in a radome. The transmitted power of the altimeter ranges from 10 mW to 500 mW [8]. A typical radiation pattern of an altimeter antenna [9] has a gain of around -13 dBi at $90^\circ$, taking this into account the RF power density available 30 cm from the antenna and at $90^\circ$ ranges from $0.04\,\mu\mathrm{W/cm^2}$ to $2.2\,\mu\mathrm{W/cm^2}$.

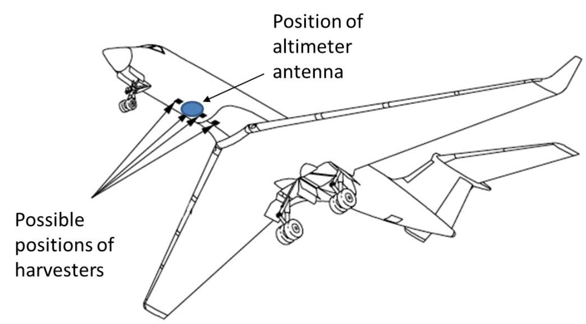



Figure 1: Altimeter radar location on the plane and possible harvester locations around the transmit antenna.

### B. Design requirements

The energy harvester will be placed near the altimeter transmit antenna. The device has to deliver at least $300\,\mu\mathrm{J}$ of energy during a time span of 10 minutes to be able to energize a low power, low duty cycle sensor, resulting in an average power requirement of

$$P = \frac{300\,\mu\mathrm{J}}{600\,\mathrm{s}} = 0.5\,\mu\mathrm{W}$$

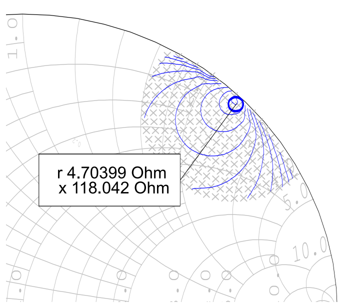
This implies that the average power transfer requirement at the DC side is -33 dBm.

### C. Diode Selection

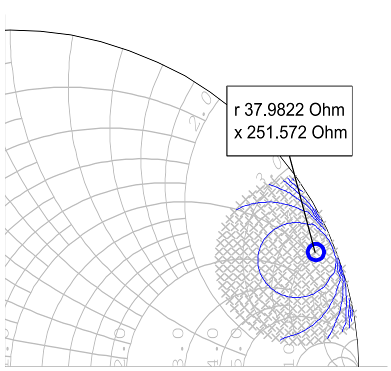
Based on the the average power the rectifier has to provide, a number of commercial diodes were considered and a source-pull simulation was performed in the NI/AWR Microwave Office harmonic balance simulator using available nonlinear models. The optimum RF impedance that needs to be presented to every diode to obtain the highest rectifier efficiency was determined, and the results are summarized in Table I. The devices that require the smallest input power are selected: the Skyworks SMS7621-079 and SMS7630-061 GaAs Schottky diodes. Figure 2 shows the source pull simulation results for both devices. In all cases, the input power is set to obtain the required -33 dBm output power, and the DC load was swept to find the optimum in terms of rectification efficiency.

| Model | Manufacturer | Input Power [dBm] | Optimum Source Resistance [Ω] | Optimum Source Reactance [Ω] |
|---|---|---|---|---|
| SMS7621-079 Modelithics | Skyworks | -20 | 4.7 | 118.0 |
| SMS7621-079 Spice | Skyworks | -21 | 44.1 | 326.0 |
| SMS7630-061 | Skyworks | -23.5 | 38.0 | 251.6 |
| HSCH-5314 | Avago | -16.5 | 52.0 | 307.1 |
| HSMS-286x | Avago | -19.5 | 36.0 | 192.3 |
| MA4E1317 | MACOM | -13.5 | 382.1 | 763.5 |

Table I: Simulation results from the considered diodes listing the RF impedances and input powers needed to get the required -33 dBm of output power at the DC side. The output DC power in all cases is $-33$ dBm at 4.3 GHz



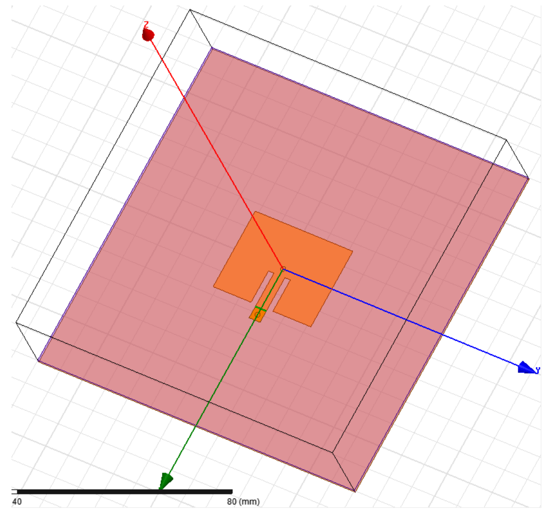

(a)




(b)

Figure 2: Source pull simulations showing the optimal RF source impedance at 4.3 GHz for maximum rectifying efficiency, for (a) Skyworks SMS7621-079 diode (Modelithics model) and (b) Skyworks SMS7630-061 diode (Spice model).

*D. Antenna design*

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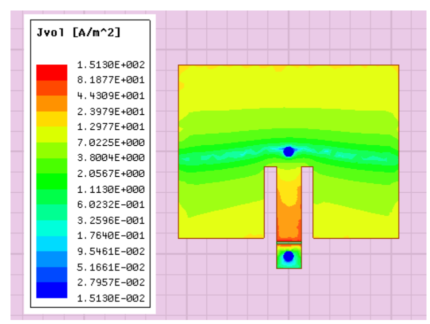


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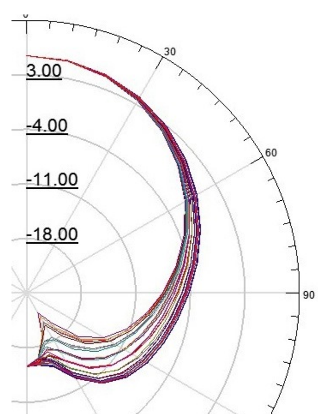


(c)

Figure 3: Antenna design simulations for the SMS7630-061 prototype. (a) Radiating-edge indented feed patch antenna geometry used for the three prototypes with variations on the dimensions to get the desired impedance for every diode. (b) Simulated current distribution on the patch showing the RF null at the DC collection point. (c) E-plane radiation pattern in dBi at 4.3 GHz for different $\phi$ from $0°$ to $360°$.

Three antennas were designed on a Rogers RO4350B™ substrate with 30 mils thickness. Of the three antennas, two are based on the Spice models of both diodes provided by Skyworks and one is based on a sophisticated nonlinear diode model provided by Modelithics for the Skyworks SMS7621-079 diode.

Linearly-polarized patch antennas fed at the radiating edge were designed and simulated using HFSS, all centered at 4.3 GHz. The antenna impedance was designed to match the rectifier complex impedance directly, thus eliminating the need for a matching network. Figure 3 shows the simulations of the designed antenna for one of the devices.

## III. Measurement Results

Three rectennas were built, prototype SMS7630-061 is shown in Figure 4. The center of the patch is an RF short used as an RF isolated point to extract the DC signal from the rectifier without affecting the RF impedance.

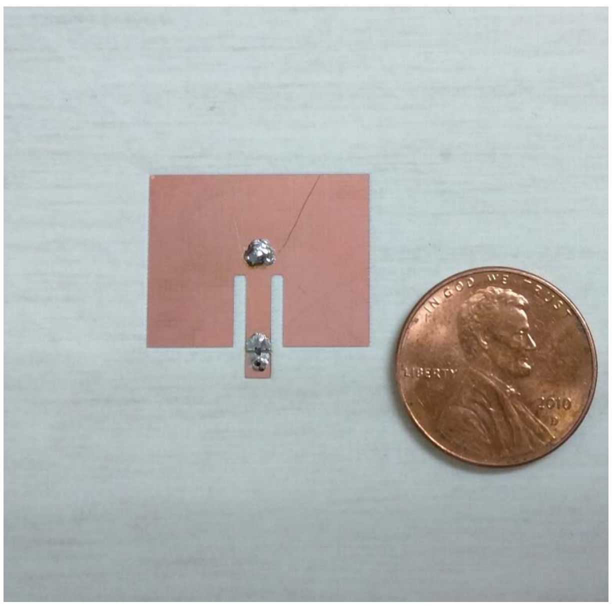

Figure 4: SMS7630-061 rectenna.

Measurements were carried out inside an anechoic chamber with calibrated power densities at the plane of the rectenna of $0.13\,\mu\mathrm{W/cm^2}$ and $0.65\,\mu\mathrm{W/cm^2}$, both within the lower range of the estimated power density in the harvesting environment. Two values of capacitors are used as energy storage devices, $100\,\mu$F and 1 mF. Figure 5 shows the test setup for the measurements.

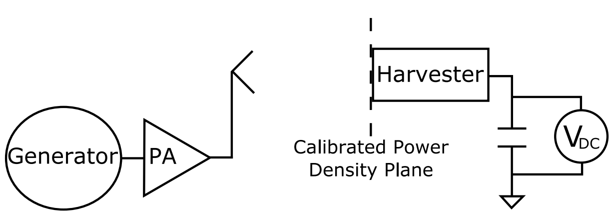


Figure 5: Sketch of far-field test setup for the measurements of the rectenna prototypes.

Figure 6 shows the open circuit voltages for all the prototypes, since prototype SMS7630-061 has the best performance, for reasons explained ahead, measurements at the higher power were only done with this prototype. The open circuit voltage is used to find the resonant frequency of the device and to calculate the stored energy in the capacitor. From the three prototypes SMS7630-061 is the one that resonates closer to the design frequency (at 4.31 GHz), the frequency shift can be attributed to tolerances from both the substrate and the milling process as well as to parasitics. The energies at the peak voltages for all cases are shown in Table II, where for $0.13\,\mu\mathrm{W/cm^2}$ incident power density a $100\,\mu$F capacitor was used while for the $0.65\,\mu\mathrm{W/cm^2}$ incident power density a 1 mF capacitor was used.

| Prototype | Power Density $[\mu\mathrm{W/cm^2}]$ | Capacitance $[\mu\mathrm{F}]$ | Voltage $[mV]$ | Stored Energy $[\mu\mathrm{J}]$ |
|---|---|---|---|---|
| SMS7621-079 Modelithics | 0.13 | 100 | 113 | 0.64 |
| SMS7621-079 Spice | 0.13 | 100 | 77 | 0.30 |
| SMS7630-061 | 0.13 | 100 | 57 | 0.16 |
| SMS7630-061 | 0.65 | 1000 | 218 | 23.8 |

Table II: Measured stored energy at the maximum open circuit voltages.

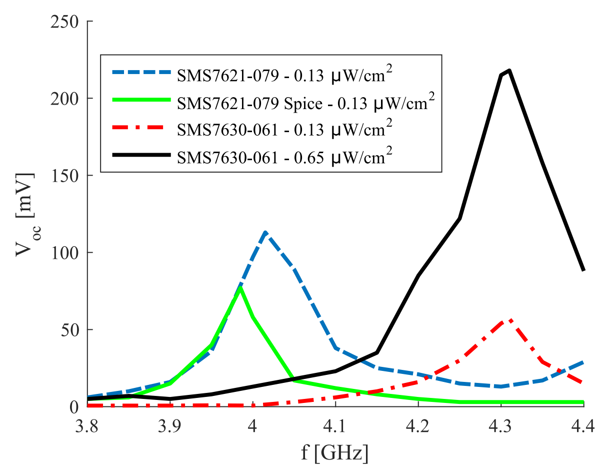


Figure 6: Measured open-circuit voltage of the prototypes.

Open circuit voltage and energy are not enough to characterize the behavior of the devices since the stored energy must be collected in a fixed amount of time, for this reason the time constants of the charging circuits were taken, Figure 7 shows a plot of the time constants for all the prototypes, here again for $0.13\,\mu\mathrm{W/cm^2}$ incident power density a $100\,\mu$F capacitor was used while for the $0.65\,\mu\mathrm{W/cm^2}$ incident power density a $1\,m$F capacitor was used. In Figure 7 can be seen how prototype SMS7630-061 is considerably better and can store the energy in shorter bursts than the other two prototypes.

The average power delivered to the capacitor in one time constant is shown in Figure 8, where it can be seen that the device delivers more than -31.5 dBm in the whole bandwidth of interest, from 4.2 to 4.4 GHz.

## IV. Conclusion

It was demonstrated that a rectenna device can successfully harvest enough energy from a radar altimeter to energize low

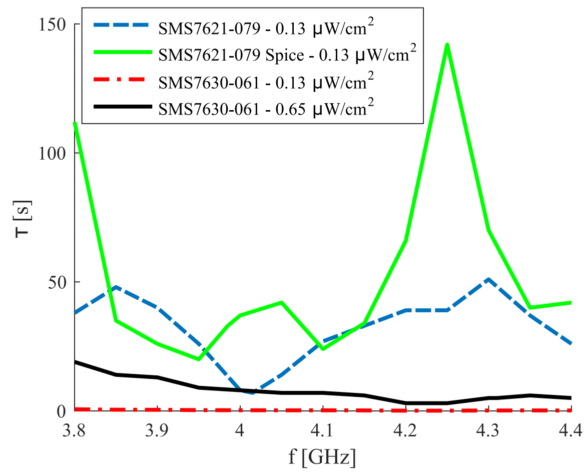


Figure 7: Time constant $\tau$, measured as the time it takes the circuit to reach 63 % of its open-circuit voltage.

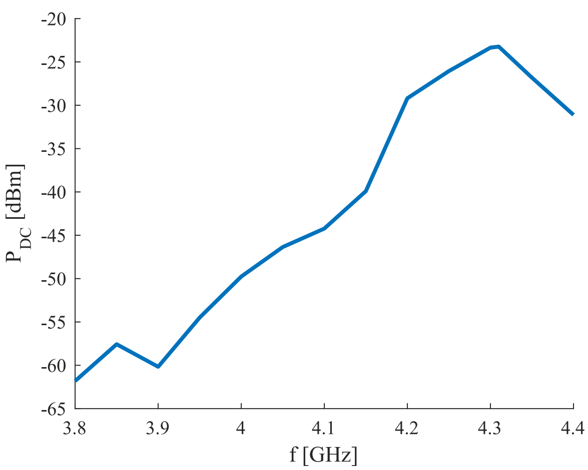


Figure 8: DC Power output for the SMS7630-061 prototype with an incident power density of $0.65\,\mu\mathrm{W/cm^2}$ and loaded with a $1\,m\mathrm{F}$ capacitor.

power/low duty cycle sensors. Measured performance reveals that our prototype is capable of delivering the required DC power at the lower power range of a typical altimeter radar. A bigger array of rectennas can be used to power sensors with higher energy requirements as is shown in [10], [11]. Several diodes were considered and the best performance is given by Skyworks SMS7630-061.

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