

# Harvesting of Aircraft Radar Altimeter Sidelobes for Low-Power Sensors

José Estrada, Philip Zurek and Zoya Popović  
 Department of Electrical, Computer and Energy Engineering  
 University of Colorado, Boulder, CO 80309, U.S.A.

**Abstract**—In this paper a harvesting system for powering low-power sensors from sidelobe power of an aircraft altimeter radar is presented. The rectenna is co-designed using full-wave field simulations and harmonic balance circuit simulations. A harvesting system is demonstrated and can produce a DC output power of  $-21$  dBm from  $2 \mu\text{W}/\text{cm}^2$  incident power density at  $4.3$  GHz. The stored energy is sufficient for low-power sensor operation and validates the rectifier and antenna co-design.

## I. INTRODUCTION

Harvesting RF power from side-lobes of an aircraft altimeter can enable low-maintenance unattended sensing of various quantities relevant to aircraft structural health [1], [2]. Fig. 1 shows a photograph of the aircraft body with the position of the altimeter and potential placement of sensors. Altimeter antenna radiation patterns obtained from the manufacturer [3] show a gain of  $10.4$  dBi in the direction of ground and sidelobes with  $-13$  dBi gain in the direction of the aircraft skin. The RF power density available ranges from  $0.04 \mu\text{W}/\text{cm}^2$  to  $2.2 \mu\text{W}/\text{cm}^2$  at  $4.3$  GHz and a distance of  $30$  cm from the altimeter’s antenna [3], [4], [5]. Low-power structural integrity sensors can be powered by delivering  $300 \mu\text{J}$  of energy every  $10$  minutes. The average power requirement at the DC side is then  $P = 0.5 \mu\text{W}$  ( $-33$  dBm).



Fig. 1. Typical location of the altimeter radar on a commercial aircraft, the red circle shows the location of the altimeter antennas and the green oval is the approximate region where the harvesters can be located.

In this paper, we detail the co-design of the antenna, single-ended diode rectifier, and harvester power management,

following the work in [5]. We experimentally demonstrate integration of a full system capable of harvesting the expected energy, thus validating rectenna design.

## II. RECTENNA DESIGN

The rectenna uses a single SMS7630-061 GaAs Schottky diode as a half-wave rectifier connected in parallel with the antenna. The rectifier is simulated using harmonic balance (HB) source-pull analysis in National Instruments AWR. During the source pull simulations, the RF input impedance at the diode is swept, while the input power and DC load are varied. The contours of constant DC rectified power for a  $5 \text{ k}\Omega$  DC load and at  $-15$  dBm input power are shown in Fig. 2, indicating that the optimal complex antenna impedance under these conditions is  $Z_a = (38 + j252) \Omega$ .

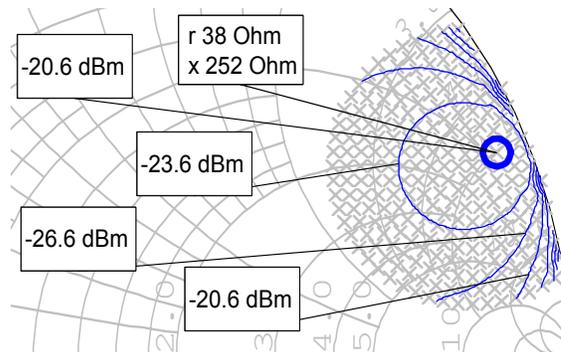


Fig. 2. Rectifier HB source-pull simulation results show contours of constant rectified power, in dBm, for  $-15$  dBm input power and a DC load of  $5 \text{ k}\Omega$  for the Skyworks SMS7630-061 GaAs Schottky diode.

The antenna is a radiating-edge fed linearly polarized rectangular patch antenna on a Rogers RO4350B<sup>TM</sup> substrate, designed for maximum power transfer to the rectifier. Ansys HFSS is used to design the feed point that directly matches the antenna feed point to the diode complex impedance, removing the need for a matching network. Fig. 3 shows the simulation results where the antenna impedance at  $4.3$  GHz is  $Z_a = (30 + j240) \Omega$  with an antenna gain of  $5$  dBi. The rectifier DC collection circuit uses the RF null of the patch as DC-RF isolation, further reducing the size and loss of the rectenna passive circuit. The DC power delivered by the rectenna at  $4.3$  GHz with an incident power density of  $0.65 \mu\text{W}/\text{cm}^2$  is  $-23.2$  dBm

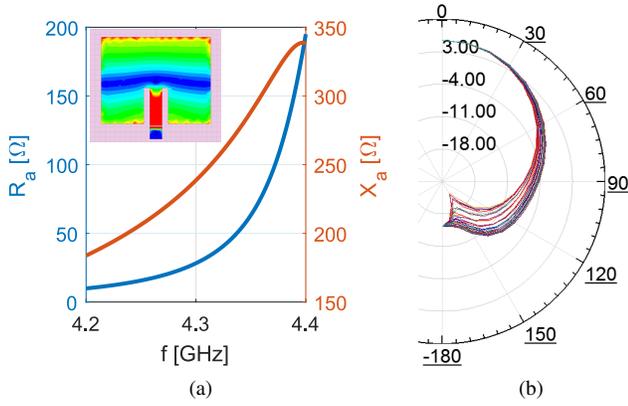


Fig. 3. Antenna simulation results. (a) Antenna impedance showing both real and imaginary part and surface current density amplitude distribution. (b) Radiation pattern in  $\theta$  and for a  $\phi$  sweep.

### III. FULL HARVESTING SYSTEM

The voltage available from a single Schottky diode at low power levels is too small for most electronic functions, so some power management with voltage boosting is necessary. Additionally, when the available RF power varies, the optical DC load varies, so maximum power point tracking can be used to dynamically adapt the load for maximum power extraction [6], commonly used in, e.g., photo-voltaic systems [7]. In our case, the power variation is not substantial and the load seen by the rectifier is not dynamically adjusted but instead is fixed to the experimentally obtained  $20\ \Omega$  optimum DC loading. Using a Texas Instruments BQ25504 PMM chip, the effective resistance seen by the rectifier is set to the optimum value. The BQ25504 chip also has a high efficiency boost converter used to get the voltage level to a more usable 3.2 V. The BQ25504 can efficiently manage microwatts of power and it also has a cold start up operation mode which can start with voltages as low as 330 mV. After the main boost charger turns on and efficient operation begins the system can work with input voltages as low as 80 mV.

A demo for the full harvesting system capable of charging a  $100\ \mu\text{F}$  capacitor (built into the EVM) or a  $200\ \mu\text{F}$  capacitance (a  $100\ \mu\text{F}$  capacitor in parallel with the built in one). A simple efficient circuit also allows the system to be configured to blink an LED for visual demonstration of harvested power. The experimental unit is shown in Fig. 4.

The energies stored in the two capacitors when charged to 3.2 V are  $E_{100} = 512\ \mu\text{J}$  and  $E_{200} = 1024\ \mu\text{J}$ , respectively. The time it takes for the system to fully charge the  $100$  and  $200\ \mu\text{F}$  capacitors from a fully discharged state (from cold-start operation) is 8 and 9 min, respectively. The module starts efficient operation when the output voltage reaches 1.7 V, which occurs after 7 and 8 min for the  $100$  and  $200\ \mu\text{F}$  capacitors, respectively. These measurements are performed with a  $2\ \mu\text{W}/\text{cm}^2$  incident field that is calibrated using an ETS HI-6005 electric field probe.

Another test is performed with an LED as the load. A

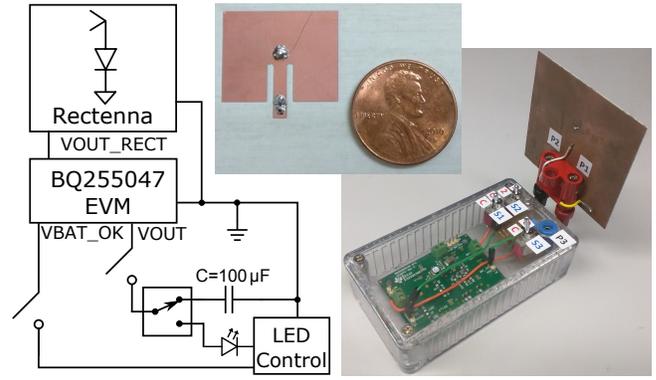


Fig. 4. Harvesting system circuit diagram and photos of both the rectenna and the power management module.

$100\ \mu\text{F}$  capacitor is charged to 3.2 V and then discharged through an LED to 1.8 V. While in efficient operation (the voltage is always above 1.7 V) and for an incident field of  $2\ \mu\text{W}/\text{cm}^2$ , the LED turns on and off with a period of 20 s. Since the voltage drops to 1.8 V after each blink, the energy at the end of the cycle is  $E' = 162\ \mu\text{J}$ . This implies that the energy delivered after each blink is  $\Delta E = 350\ \mu\text{J}$ . The experiment shows that the energy that is specified to be delivered to a sensor every 10 min can be done every 20 s and the average harvested power is:

$$P = \frac{\Delta E}{T} = \frac{350\ \mu\text{J}}{20\ \text{s}} = 7.78\ \mu\text{W} = -21\ \text{dBm}.$$

In summary, the demonstrated energy harvesting from very low incident power levels at 4.3 GHz ( $< 2\ \mu\text{W}/\text{cm}^2$ ) is sufficient to power unattended sensors on an aircraft. These results validate the co-design methodology for the rectenna, which combines full-wave EM modeling and nonlinear circuit simulations.

### ACKNOWLEDGMENT

The authors would like to thank Drs. Authi Narayanan and Alan Keith from Boeing Corporation for advice and support.

### REFERENCES

- [1] B. Strauss, "The onboard commercial aircraft in-flight rf environment - measurements and implications," in *Electromagnetic Compatibility, 2006. EMC 2006. 2006 IEEE International Symposium on*, vol. 1, pp. 234–239, Aug. 2006.
- [2] X. Zhao, H. Gao, G. Zhang, B. Ayhan, F. Yan, C. Kwan, and J. L. Rose, "Active health monitoring of an aircraft wing with embedded piezoelectric sensor/actuator network: I. Defect detection, localization and growth monitoring," *Smart Materials and Structures*, vol. 16, no. 4, p. 1208, 2007.
- [3] [www.ubcorp.com/product/microstrip-raa-ads43010-1a-1ac/](http://www.ubcorp.com/product/microstrip-raa-ads43010-1a-1ac/).
- [4] M. Vidmar, "Design improves 4.3-ghz radio altimeter accuracy," *Microwave & RF*.
- [5] J. Estrada, I. Ramos, A. Narayan, A. Keith, and Z. Popovic, "Rf energy harvester in the proximity of an aircraft radar altimeter," in *2016 IEEE Wireless Power Transfer Conference (WPTC)*, pp. 1–4, May 2016.
- [6] S. Dunbar and Z. Popovic, "Low-power electronics for energy harvesting sensors," *Wireless Power Transfer*, no. 1, pp. 35–43, 2014.
- [7] T. Eswam and P. L. Chapman, "Comparison of photovoltaic array maximum power point tracking techniques," *IEEE Transactions on Energy Conversion*, vol. 22, pp. 439–449, June 2007.