Efficient Broadband RF Energy Harvesting for Wireless Sensors

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Abstract: *This paper presents an approach to wireless power delivery and subsequent power management for low-power batteryless sensors. Broadband multifrequency rectenna arrays which independently receive and rectify two orthogonal wave polarizations provide DC power with decreased variations in a multipath environment. The DC power extracted from 2-18GHz electromagnetic radiation is managed by high efficiency power processing circuitry. Experimental results are presented for an integrated switched capacitor power converter realized in a fully-depleted silicon on insulator (FD-SOI) process.*

Keywords: energy harvesting; scavenging; rectenna; integrated power converter; wireless sensors.

Introduction

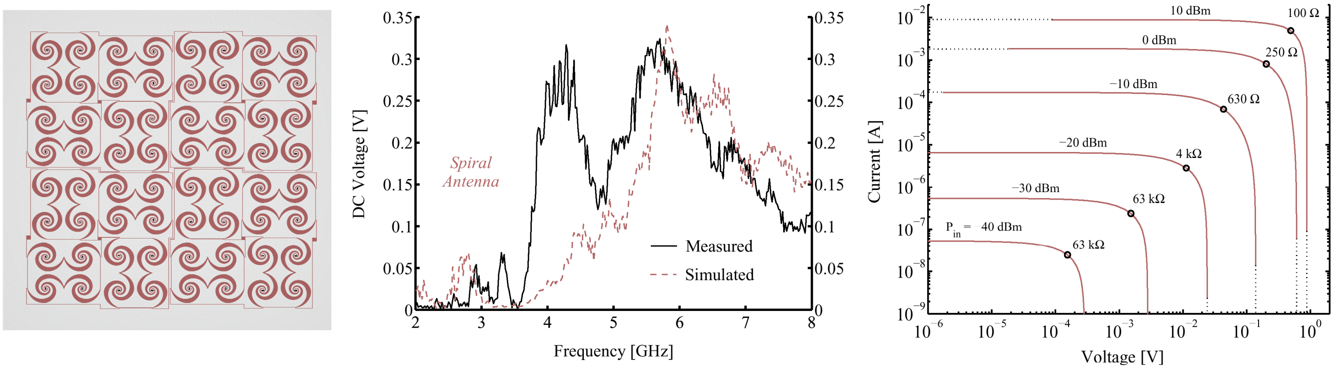
A common challenge in wireless sensors is providing the fundamental resource of power. This is especially relevant to large distributed arrays of miniature sensor devices are envisioned to provide broad and continuous "knowledge" to systems on everything from temperature, humidity and motion to identity, location, hazard and history. Existing technologies, such as RFID tags, generally require very high source energy and operate only over short distances with very low efficiency. In contrast, we present an approach based on broadband RF energy delivery at or below ambient energy levels (or based on stray RF energy), with a broadband receiving antenna and diode rectifier, or "rectenna", coupled to a high efficiency power processor for optimal energy harvesting. The energy is harvested over a period of time and delivered to the sensor load at discrete intervals when sufficient energy is available.

The paper is organized as follows:

- the next section gives a brief description of a dual circularly polarized broadband (2-18GHz) rectenna array optimized for low incident power densities in the range of 1 $\mu W/cm^2$ to 10 mW/cm^2.
- we then discuss the power processing requirements dictated by the statistical DC output power of the rectenna. Experimental results on a custom integrated circuit are shown as a feasibility demonstration of efficient power harvesting even at microwatt levels.
- the last section discusses application examples of RF energy harvesting in wireless sensors.

RF Power Reception and Rectification

To date, wireless power transmission to rectenna elements and arrays have been developed for powering a variety of devices and systems through line-of-sight power beaming at high radiated narrow-band power levels, e.g. [1]. However, for distributed sensors in complex environments such as aircraft and ships, it is likely that radiated power at each frequency will be limited to very low levels and



(a) (b) (c)

Figure 1. Experimental results in wireless power transmission for low broadband radiation: (a) layout of dual-circularly polarized wideband rectenna "wallpaper" array for ambient energy recycling (25 cm x 25 cm), (b) simulated (harmonic balance) and measured rectified voltage as a function of frequency for a circularly polarized spiral rectenna element outside of the array, and (c) simulated current-voltage (I-V) characteristics for the rectenna of (a) over a range of incident power levels with measured peak power points labeled with the optimal equivalent load (in Ohms) [1].

sensor size requirements make large antenna arrays with matching circuitry impractical.

We present a solution for delivering power to wireless sensors using small rectenna elements and arrays, as shown in Fig. 1(a). The designs shown were originally developed for ambient energy recycling in a multi-path statistically varying environment, with a demonstrated efficiency of 20% at low ambient power levels with low reradiated harmonics [2]. In the array in Fig.1(a), each spiral antenna element receives one of two circular polarizations and couples the incident power to a Schottky diode, without any additional matching or harmonic tuning circuitry. The design is based on a source-pull of the diode for a range of power levels and frequencies, which results in a range of impedances that the antenna needs to provide for optimal power delivery to the diode and rectification. Fig. 1(b) shows simulated and measured rectified voltage as a function of frequency for a single spiral element with a feed-line. The simulated curve is a result of full-wave antenna modeling and harmonic balance nonlinear simulations and shows good agreement.

Fig.1(c) shows the simulated current-voltage characteristics for the rectenna of Fig 1(a) over a range of incident power levels with measured maximum power points labeled together with the optimal equivalent load (in Ohms) [2]. These curves are the input data for design of the power management circuitry. The primary challenge for the power processor is to provide optimal loading of the rectenna to maximize the harvested energy and system efficiency.

High Efficiency Power Processing

The primary challenge for the power processor is to continuously extract energy from the rectenna source at the peak power point (labeled with dots in Fig. 1(c)) despite variations in the incident power and rectenna efficiency, while efficiently integrating the energy to a storage element and delivering regulated power to a sensor load. Our solution, shown functionally in Fig. 2, is based on a single energy coupling DC-DC converter that uses either inductive or capacitive elements for internal energy transfer or a combination of the two.

Integrated Converter Design: Integrated power converters at very low power levels are generally limited to low efficiency due to parasitic leakage currents and parasitic capacitance to the substrate. To remove these limitations, we have developed a set of prototype integrated converters for high efficiency energy harvesting using an RF process available through the MIT Lincoln Labs. The process is based on fully-depleted silicon-on-insulator (FD-SOI) with a thick upper metal layer for inductors and a high resistivity substrate. The primary advantages in this process for power processing are reduced parasitic capacitances, which have been measured at up to 1000 times lower than in a traditional CMOS silicon process. Such low parasitics facilitate high efficiency operation, even at very low power levels and frequencies as high as hundreds of kHz (allowing small component sizes). We implemented a custom power converter IC with single and two-stage switched capacitor (SC) circuits, which are predicted to have high efficiency at very low power levels if the parasitic capacitors are small [3-5].

The two-stage SC topology is shown in Fig. 3, where on-chip buffers were provided for each of the switches and external control logic was used to determine the switching configuration. The topology is capable of generating eight distinct power conversion ratios from the input voltage to the output voltage for ratios from one third to three, with a maximum output voltage of 1.5 V due to process limitations. The controller adaptively adjusts the switching frequency and topology to continuously extract the maximum power from the rectenna while storing the harvested energy to the output capacitor. As the output capacitor voltage builds, the converter sequences through topologies to maintain optimal loading of the rectenna and high efficiency.

IC Fabrication and Experimental Results: A CAD image of the fabricated IC is shown in Fig. 4, measuring approximately 2 mm x 2 mm. Experimental results are shown in Fig. 5 with the controller maintaining a fixed input power of 10 µW. Figure 5(a) shows how the switching frequency varies as a function of the output capacitor voltage. As can be seen, the switching frequency rises rapidly output voltage limit of each converter topology. Our control strategy is to monitor the switching frequency during input voltage (or power) regulation and increment to the next higher conversion ratio topology at a

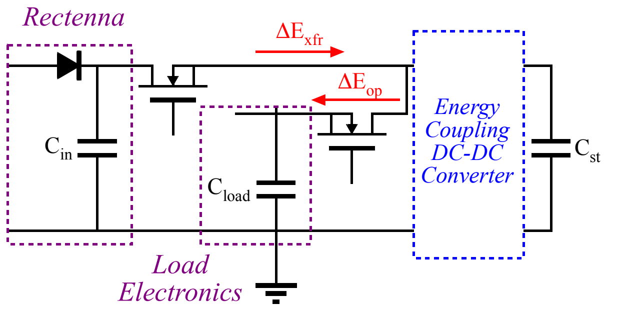


Figure 2. Functional schematic of the energy coupling power converter.

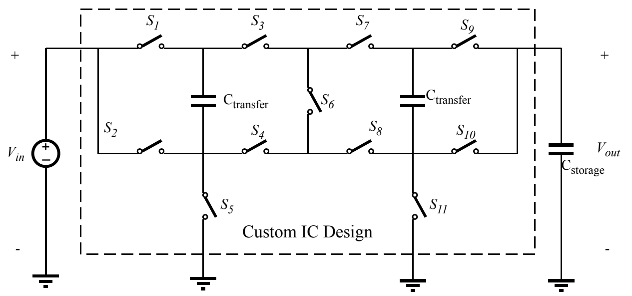


Figure 3. Two-stage switched-capacitor (SC) converter integrated in FD-SOI process

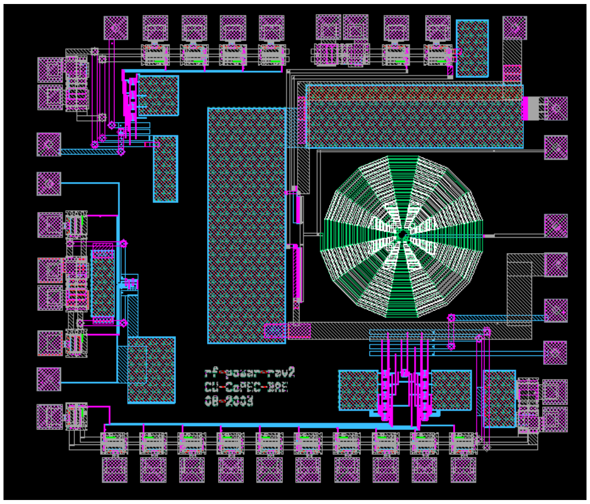
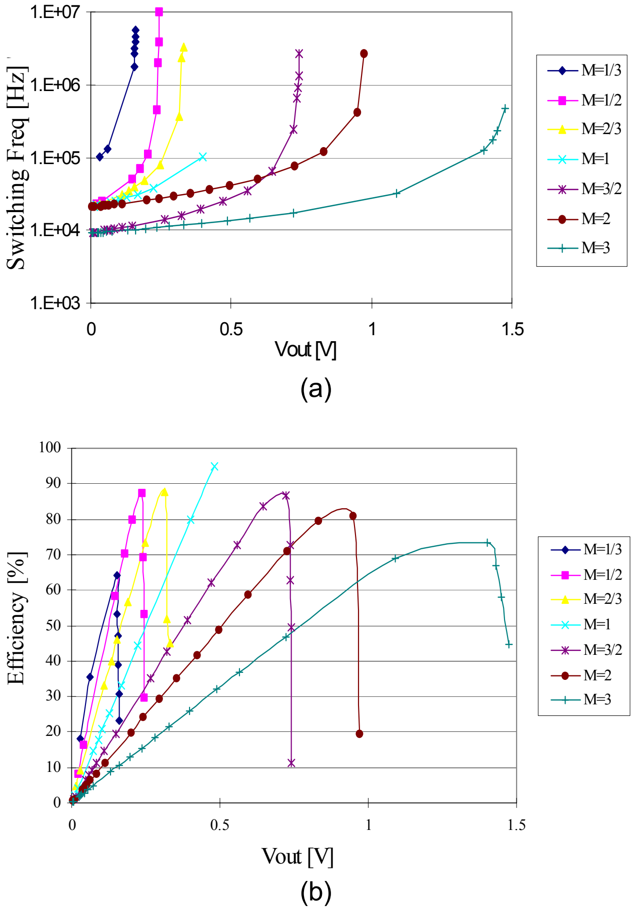


Figure 4. CAD image of integrated power converter in MIT-LL FD-SOI process

programmable frequency limit for each topology. The resulting converter efficiency for each topology is shown in Fig. 5(b), demonstrating the ability to maintain above 70% efficiency over a wide range of output voltages by selecting the appropriate topology as the output voltage varies. These results demonstrate a measured parasitic capacitance to substrate approximately 1000 times lower than in a standard CMOS process, enabling such high efficiency. We are now developing a full demonstration converter with integrated controls and scaled up capacitor and switch values for universal operation from microwatts to milliwatts of input power.

Application Example

Applications for wireless powering fall into several categories: (1) high power, single frequency, single polarization, high directivity for beaming applications; (2) medium power, narrowband, relatively directive, polarized for some sensor applications; (3) broadband, randomly polarized, low varying power levels, and large incoherent apertures for recycling applications and some sensor applications and (4) very small aperture, very low power single or multifrequency polarized for biosensor powering. The rectenna shown in Fig. 1 is designed for case (3) – very low power densities and unknown frequency and polarization of the incident electromagnetic radiation, resulting necessarily in lower efficiency. However, a number of applications make it possible to design narrowband rectennas with higher incident power levels. An example of case (2) above is wireless power delivery to tomographic piezolictric sensors for aircraft wing fatigue inspection [6]. 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. Using piezoelectric sensors, failures can be detected before they pose a significant risk to the aircraft. Currently, these systems use batteries, magnetic coupling or solar cells to power the sensors and control, data collection and processing electronics. A wireless means of actuator excitation, communication, and sensor interrogation has many benefits such as fast inspection, less downtime, labor cost reduction, etc. The wirelessly-powered sensor array is shown in Fig.6. The requirements for powering the driver electronics is ±15V with 100mW, and a rectenna array consisting of patch antennas at 10GHz is chosen due to its low profile, ground plane isolation and filtering effects. It requires a 5-minute illumination from a 1-meter distance with several Watts of radiated power from a 10-GHz source.



(a)

(b)

Figure 5. Experimental results for the integrated power converter while regulating a fixed input power of 10 μW. Results show operating frequency (a) and converter efficiency (b) as a function of output voltage for each of the converter configurations.

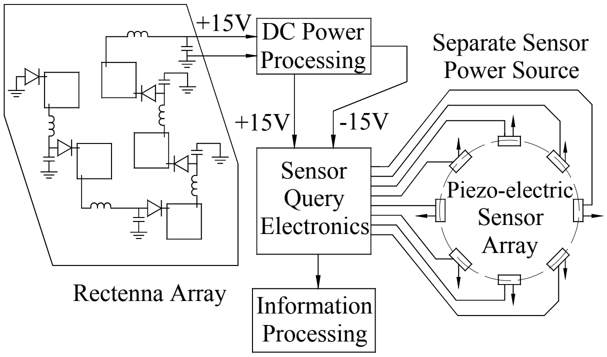


Figure 6. Block diagram of rectenna and sensor system. In the initial test, only the sensor control and processing electronics circuitry is powered by the rectenna.

The most difficult case is when a small aperture is required and only very low power densities are allowed, such as in the case of wireless health monitoring device. The power delivery for such a device includes the rectenna array and ultra-capacitor energy storage on one side and the custom energy harvesting IC and commercial power regulator on the other, harvesting between 10 µW and 1 mW average power. The anticipated power characteristics are shown in Fig. 7, where given the measured efficiency of the rectenna and power converter, and the sensor load requirements, we anticipate a duty cycle of approximately 12% of power harvesting to sensor operation (i.e. it is expected that with every 35 seconds of energy harvesting, sufficient energy will be available for 5 seconds of data recording followed by a brief burst for RF data transmission).

In summary, this paper demonstrates an innovative approach for delivering wireless power to batteryless sensors at very low power levels and high efficiency. The design is based on broadband rectenna elements and arrays and high efficiency power processing circuitry. Hardware examples are given for rectenna design and custom IC-based power processing in advanced FD-SOI process for very low parasitic losses.

Acknowledgements

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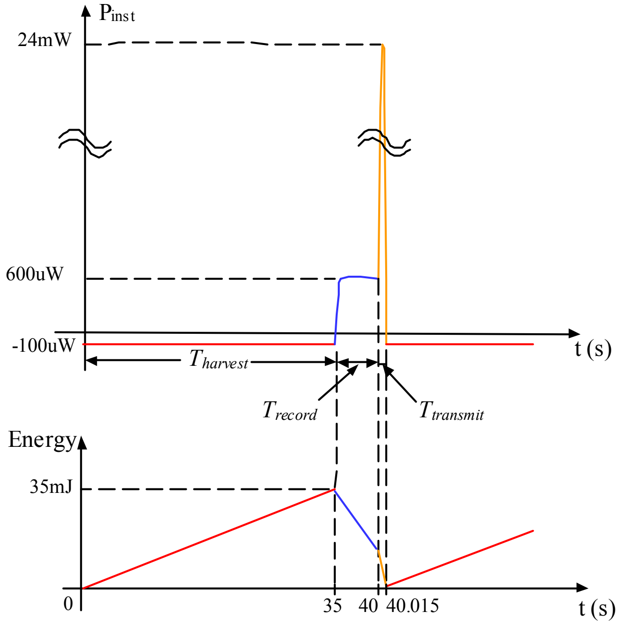

Figure 7. Simulated power characteristics for the example application. Energy is harvested for a period (~35 s), followed by discrete intervals of data recording and burst data RF communication (~5 s).