Wireless Powering for Low-Power Distributed Sensors

Zoya B. Popović[1]

Abstract: In this paper, an overview of the field of wireless powering is presented with an emphasis on low-power applications. Several rectenna elements and arrays are discussed in more detail: (1) a 10-GHz array for powering sensors in aircraft wings; (2) a single antenna in the 2.4-GHz ISM band for low-power assisted-living sensors; and (3) a broadband array for power harvesting in the 2-18GHz frequency range.

Keywords: Rectenna, antenna array, power management, wireless powering.

1 Introduction

Nikola Tesla's United States Patent No. 685,954, dated November 5, 1901 [1], describes a "method for utilizing effects transmitted through natural media." In this patent, Tesla first describes several ways of transmitting electrical disturbances through the natural media: "One of these ways consists of producing by a suitable apparatus rays or radiations – that is disturbances – which are propagated in straight lines through space, directing them upon a receiving or recording apparatus at a distance, and thereby bringing the latter into action. This method has been brought particularly into prominence in recent years through investigations by Heinrich Hertz." Though described in somewhat confusing legal language, it is obvious that the "disturbances" in Tesla's patent are electromagnetic waves. Claim 11 of this patent specifies that the patented method of "…utilizing effects or disturbances transmitted through the natural media from a distant source, which consists in storing in a condenser… electrical energy derived from an independent source, and using, for periods of time predetermined as to succession and duration, the accumulated energy so obtained to operate a receiving device."

What is described above is wireless transmission of energy, storage of the energy in a capacitor and energy management over time. In the past few decades, a considerable amount of work has been done in the area of wireless powering, including inductive powering for short ranges, high power density

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[1]Zoya Popović is the Hudson Moore Jr. Chaired Professor of Electrical and Computer Engineering at the University of Colorado, Boulder, CO, 80303-0425, USA; E-mail: zoya@colorado.edu

directive powering in the microwave frequency range, as well as low-power near-field interrogation with RFID tags, and medium- and low-power density powering of low-power sensors. This is usually accomplished by receiving incident waves with an antenna and rectifying the received RF voltage, Fig. 1. An integrated antenna and rectifier is usually referred to as a rectenna.

Rectification of microwave signals for supplying dc power through wireless transmission has been proposed and researched in the context of high power beaming since the 1950s, and a good review of the history for these types of applications is given in [2]. In microwave power transmission, the antennas have well-defined polarization, and high rectification efficiency is enabled by single-frequency high microwave power densities incident on an array of antennas and rectifying circuits. Applications for this type of power transfer have been proposed for helicopter powering [3], solar-powered satellite-to-ground power transmission [4], inter-satellite power transmission [5] including utility power satellites, mechanical actuators for space-based telescopes [6], small dc motor driving [7] and short range wireless power transfer, e.g. between two parts of a satellite. Both linear [8] [9], dual-linear [6] and circular [10-13] polarization of the receiving antennas were used for demonstrations of efficiencies ranging from around 85-90% at lower microwave frequencies to around 60% at X-band and around 40% at Ka-band [5].
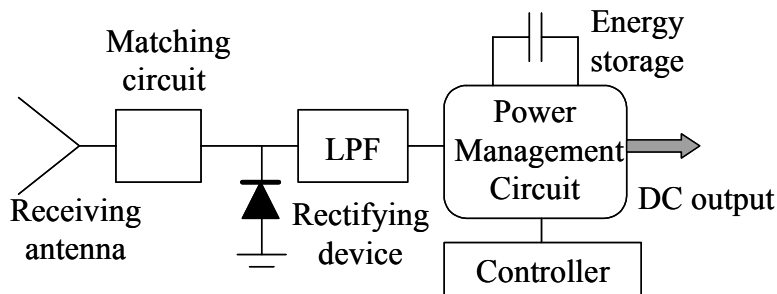

Fig. 1 – *Schematic of a rectenna and associated power management circuit. The incident waves within a certain spectral range are received by the antenna, coupled to the rectifying device (diode in this case), and the low-pass filter (LPF) ensures that no RF is input to the power management circuit. A controller provides input to the power management circuit, which enables storage of the received energy over time, and delivery of DC power at the level and time when it is needed.*

In the above referenced work, rectification is performed for narrowband, essentially single-frequency, incident microwave radiation with relatively high power densities. A survey of the typical power densities associated with high power rectennas is given in [13], along with corresponding rectification efficiencies. Expected power densities 50 meters away from a typical base station

tower operating at 880 and 1990MHz are usually assumed to be around 10^{-4} mW/cm^2. Concerns have been expressed in terms of possible health hazards [14]. In [8] rectification of low power levels was discussed for battery-free transponders, with power densities on the order of 10^{-2} mW/cm^2. Recently, broadband rectification of very low-power incident radiation has been of interest, both for energy harvesting and for powering low-power batteryless sensors.

This paper presents an overview of design, implementation and characterization of rectenna elements and arrays for various applications where the powering range needs to exceed a few meters, and discusses the required energy management that can enable reasonable electronic functions using wirelessly transmitted power.

2 Electromagnetic Environment

There are several distinct scenarios for wireless powering, and the specific design is highly dependent on the incident waves that carry the energy:

− one or more high-directivity narrowband (single frequency) line-of-sight transmitters with well known and fixed polarization and well-known power levels. In this approach, used for power beaming, the efficiency of the rectenna can be very high. A reasonable application is transmitting power from one part of a satellite to another, eliminating heavy and bulky cables.

− one or more medium-power semi-directional transmitters that illuminate a range in space, with multipath present. In this case, the incident power density is known approximately, but there are multipath effects that change polarization and spatial distribution of power density. The transmitters can be single-frequency, multiple-frequency or broadband. An application of this scenario is for powering multiple sensors whose location is not precisely known, e.g. sensors that are placed behind walls or in a manufacturing environment. Another related application is for powering batteryless implanted devices.

− unknown transmitters over a range of frequencies, power levels, generally unpolarized, with varying low-level spatial power densities. The application is energy harvesting or energy scavenging.

This paper deals with the latter two cases, and some specific designs and applications are briefly described in the next sections. This section concludes with a discussion of figures of merit for rectennas and rectenna arrays.

The incident power density on the rectenna, $S(\theta, \phi, f, t)$, is a function of incident angles, and can vary over the spectrum and in time. The effective area

of the antenna, $A_{eff}(\theta,\phi,f)$, will be different at different frequencies, for different incident polarizations and incidence angles. The average RF power over a range of frequencies at any instant in time is given by:

$$P_{RF}(t) = \frac{1}{f_{high} - f_{low}} \int_{f_{low}}^{f_{high}} \int_{0}^{4\pi} S(\theta,\phi,f,t) A_{eff}(\theta,\phi,f) d\Omega df . \tag{1}$$

The DC power for a single frequency (f_i) input RF power, is given by

$$P_{DC}(f_i) = P_{RF}(f_i,t) \cdot \eta\left(P_{RF}(f_i,t), \rho, Z_{DC}\right), \tag{2}$$

where η is the conversion efficiency, and depends on the impedance match $\rho(P_{RF},f)$ between the antenna and the rectifier circuit, as well as the DC load impedance. The reflection coefficient in turn is a nonlinear function of power and frequency. Therefore, in order to find the efficiency of the rectenna, we perform the following measurements:

- illuminate the rectenna from a known distance and incidence angle with a known frequency and power; thus $S(\theta,\phi,f,t)$ is known;

- for each frequency of interest, determine geometrical electrical area of the antenna. This is generally larger than the effective area and therefore overestimates the received RF power;

- measure the DC power as a function of the DC load impedance (resistance);

- calculate the estimated conversion efficiency as P_{RF}/P_{DC}. Since the DC power is measured directly, and the RF power is over-estimated, the resulting efficiency will be an under-estimate.

this process should be done at each frequency in the range of interest. However, DC powers obtained in that way cannot be simply added in order to find a multi-frequency efficiency, since the process is nonlinear. Thus, if simultaneous multi-frequency or broadband operation is required, the above characterization needs to be performed with the actual incident power levels and spectral power density.

3   Example Rectenna Designs

Next, the design and characteristics of several rectenna elements and arrays is overviewed, in the following order:

- a linearly-polarized, single frequency (10GHz) conformal rectenna array for monitoring corrosion in aircraft wings [17];

- a dual-polarized rectenna element for small low-power sensor powering;

–   several broadband arrays for power recycling [13,16].

A. Linearly-polarized medium-power conformal rectenna

The flight environment of an aircraft is very harsh due to large changes in humidity, temperature, pressure, speed, and loading conditions, which can result in corrosion and other failures. Using tomographic piezoelectric sensors, failures can be detected before they pose a significant risk to the aircraft. A wireless means of actuator excitation, communication, and sensor interrogation has many benefits such as fast inspection, less downtime, labor cost reduction, etc. Currently, wireless sensors contain an on-board miniaturized antenna, and a multi-channel circuit for data acquisition. Batteries, magnetic coupling or solar cells can be used to power the sensors, control, data collection and processing electronics. As an alternative to conventional powering methods, a rectenna array was developed that provides DC power from incident microwave radiation.

The specifications of the rectenna are derived from the requirements of the sensor system: ± 15V with 100mW of continuous power for 5 minutes in order to complete corrosion inspection. The physical size requirements for the rectenna are an aperture of 15cm by 15cm using as thin of a substrate as possible to conform to the shape of the airframe. 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 with line of sight. 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.

For this application, the antenna element is a narrowband, linearly polarized patch antenna at 10GHz designed on a 0.25-mm thick Rogers Duroid substrate with a relative permittivity of 2.2. The gain of the patch calculated from its physical area is 1.39 (1.45dB). 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.

The rectifier diode is an Agilent HSMS-8101 Schottky mixer diode. An ADS harmonic balance simulation using the single-patch model in Fig. 2 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 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 10 mW.
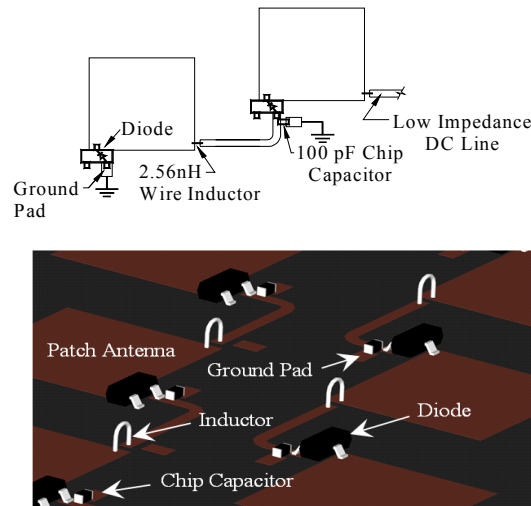
Fig. 1 – *Schematic of two patch rectennas connected in an array (top) and view of the hardware implementation of a portion of the rectenna array (bottom).*

Although the overall efficiency depends on how the rectenna elements are connected [13], all 25 elements in this rectenna are connected in series 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. The trend for output voltage versus the resistive load is shown in Fig. 3. Series connection of 25 elements provides the required 15V output with approximately 100mW of DC power for a 2.4-k Ω load. The estimated optimal efficiencies of 16, 19 and 25-element arrays are 44%, 44% and 39%, respectively. Fig. 4 shows the measured sensitivity of rectified DC power as a function of polarization mismatch between the transmitter and rectenna.
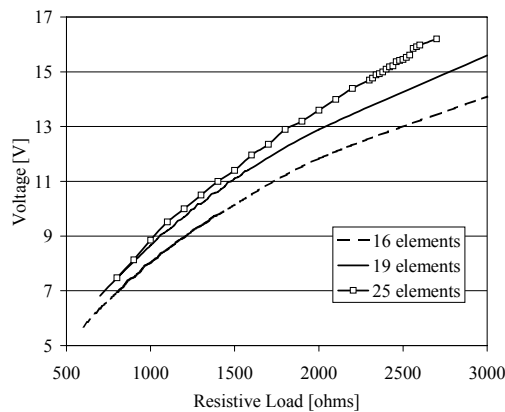

Fig. 3 – *Measured DC voltage as a function of the DC resistive load for three array sizes.*
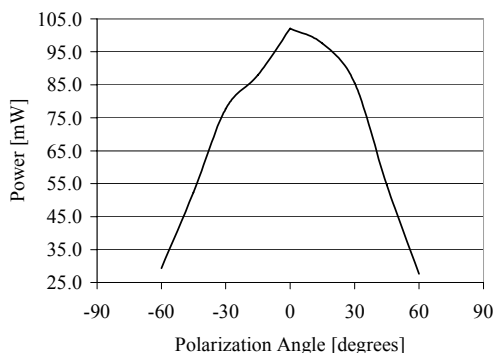
Fig. 4 – *Measured DC power as a function of polarization mismatch between the transmitter and rectenna array. 0 degrees indicates linear polarization match.*
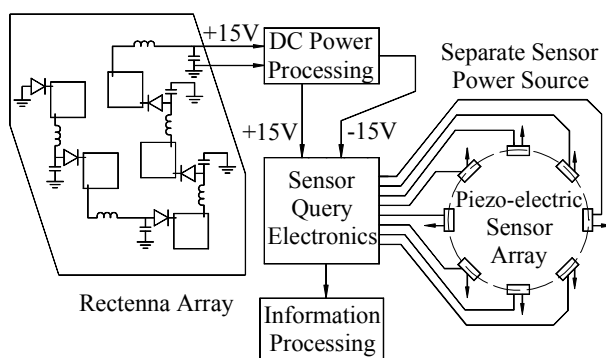

Fig. 5 – *Block diagram of rectenna and sensor system. In the initial test, only the sensor control and processing electronics circuitry is powered by the rectenna.*

The 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 with 98% efficiency is used for this task. The system block diagram is shown in Fig.5.

B. Dual-polarized low-power rectenna element

The un-licensed ISM band around 2.4GHz is an appropriate frequency range for low-power wireless sensor powering. In this case, the application is a human health-function monitoring sensor for senior-citizen assistant living. The wireless sensor contains an accelerometer, temperature sensor and skin conductivity sensor. The sensor and power management circuit is controlled through a low-power microcontroller, and the collected data is transmitted via a commercial low-power ISM band transmitter (from Chipcon).

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In this scenario, the sensor is mobile and therefore the polarization changes. Thus, the rectenna is designed to be dual-polarized with two rectifier diodes. Each diodes rectifies one of the two received polarizations, and the DC signals add. The rectenna is a 19mm x 19mm square patch, with a 6cm x 6cm square ground plane on a Rogers Duroid 6010 substrate (ε_r=10.2, thickness=50mil) chosen to reduce the antenna size. An Agilent HSMS8101 diode is connected at each of the two centers of the two orthogonally-polarized patch radiating edges, Fig. 6a. A via terminates each diode to RF/DC ground, which is structurally isolated from the patch ground plane and interfaces with a PCB layer (behind patch ground plane) through a 2.7-nH inductor.
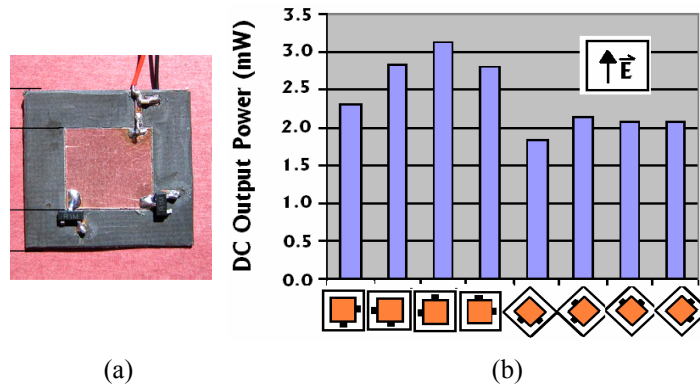

(a)   (b)

Fig. 6 – *Photograph of dual-polarized* 2.4-*GHz patch rectenna (a), and histogram of measured power levels for an incident power level of* $170\mu\mathrm{m/cm}^2$ *for different incident polarization levels (b).*

Fig. 6 shows a histogram of measured power levels for an incident power level of $170\mu\mathrm{W/cm}^2$ for different incident polarization combinations, which will all be present in the multipath environment envisioned in this application. It is interesting to compare these to the results in Fig. 4, which are measured for a similar patch antenna but with a single diode receiving one linear polarization. Not only is the DC power larger in this case, as both polarizations are received and rectified, but the variation of received power is reduced by approximately a factor of two.This rectenna operates with incident power levels as low as $10\mu\mathrm{W/cm}^2$ and is capable of powering a low-power wireless sensor.

B. Broadband rectenna arrays for low-power arbitrarily polarized incident radiation with high power dynamic range

For low power applications, as is the case for collected ambient energy, there is generally not enough power to drive the diode in a high efficiency mode. Furthermore, rectification over multiple octaves requires a different approach from standard matching techniques. In a rectenna application, the antenna itself

can be used as the matching mechanism instead of using a transmission-line or lumped-element matching circuit. The antenna design is therefore heavily dependent on the diode characteristics.
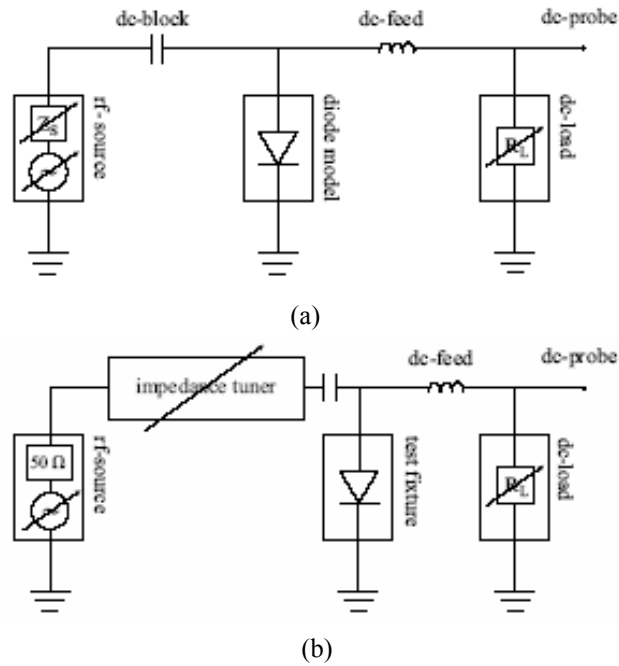

(a)

(b)

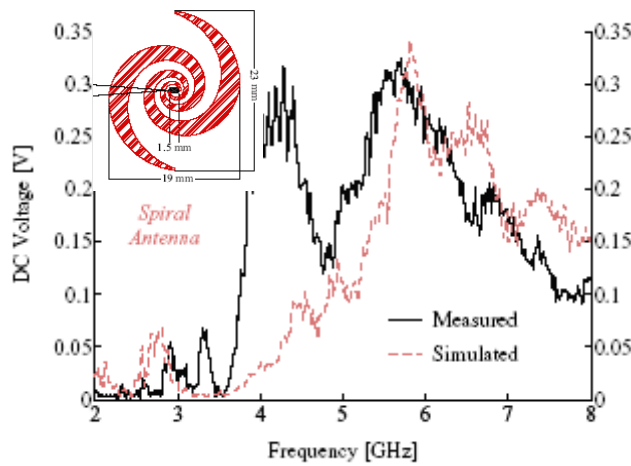**Fig. 7** – *Circuit diagram of the Harmonic Balance simulation (a) and diagram of the equivalent source-pull measurement setup (b).*

Fig. 8 – *Nonlinear harmonic-balance simulation and measurements of theDC rectified voltage response across 60 ohms for the spiral antenna in the inset, over a 4:1 bandwidth.*

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Design of a broadband antenna integrated with a power and frequency-dependent diode impedance is a challenge. A source-pull of the diode is a sweep of RF input source impedance values over a given area of the Smith chart. Fig.8 shows the HB simulation approach using Agilent ADS as well as the measurement approach using impedance tuners. In both simulation and measurements, for a variety of input powers the resulting DC voltage is quantified for each source impedance and plotted on the Smith chart. The region of optimal source impedance is later used for optimizing the antenna design so that the antenna presents the proper equivalent source impedance to the diode. Since the harmonic balance technique calculates the response at all harmonics of the excitation frequency, in the simulation an assumption must be made for the impedance seen by the reflected harmonics, and in the presented case this impedance was set to the impedance of a broadband, self-complementary antenna, 189 ohms. Usually, the optimal source impedance moves counter-clockwise along a constant admittance circle with increasing frequency due to the junction capacitance.

For maximal power transfer, the antenna impedance would match the optimal diode impedance for all frequencies. Since this is difficult to accomplish, a possible sub-optimal approach is to present a constant impedance to the diode by using a frequency independent antenna element. An equiangular spiral was chosen as the array element since it is uniplanar with convenient feed point for diode connection, and can be left or right-hand circularly polarized. A single element was simulated with full-wave CAD tools (Ansoft's *Ensemble* and Zeland's *IE3D*) resulting in a one-port frequency dependent impedance that becomes the diode load in the rectenna. A diode is connected at the antenna feed and the resulting rectenna element performance is shown in Fig. 8. The disagreement around 4 GHz is believed to be caused by the 1-cm long unbalanced coax feed.

A 64-element array of left and right hand circularly polarized spiral elements is designed, so that each spiral element is directly connected to a rectifier diode. Therefore, the RF powers received independently by each element are summed upon rectification as DC currents and/or voltages. A sweep of the input power is performed and the resulting DC output and re-radiated power is quantified. The measurement, Fig. 9, is made with broadside linearly polarized radiation at 3 GHz with incident power densities ranging from tens of nW/cm^2 to $0.1 mW/cm^2$. The rectenna array receives radiation from all directions (there is no ground plane), and in order to measure the re-radiated power at the harmonics, the array was placed half-way between a transmit and receive test antenna, perpendicular to the line-of-sight axis. The DC voltage is measured across a 100-ohm load. The rectification efficiency reaches the 20% range for an incident power density of $0.1 mW/cm^2$ and arbitrary polarization.
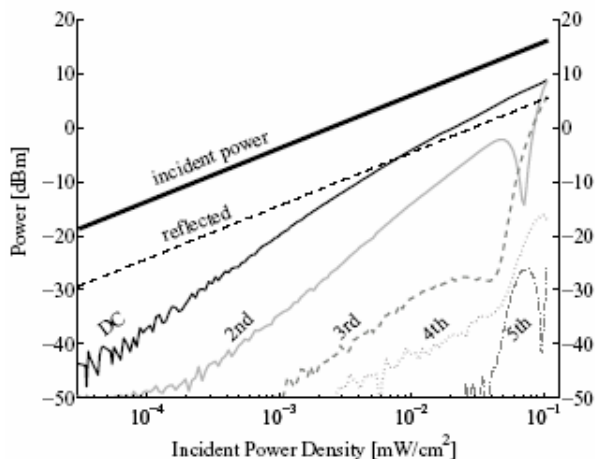
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Fig. 9 – *Measured reflected, rectified, and re-radiated harmonic power as a function of incident power density.*

Also shown in Fig. 9 is the relative amount of reflected power along with the radiated power of the 2nd through 5th harmonics. The reflected power is found from a time-gated s_{11} measurement using a vector network analyzer. The result, consistent with simulation results, indicates that the reflected power varies linearly with input power up to 0.1mW/cm^2. Simulations suggest, however, that the reflections begin to drop as higher power levels are applied and a larger fraction of incident power is converted to DC and power at the harmonics.

The array scaling in size is trivial, since there is not RF feed network, and only the DC output network is required. If space allows, this type of array can be made in the form of wall-paper for collecting as much power as possible. Further, the DC collecting lines can be made to be reconfigurable, so that either current or voltage are summed, depending on the DC load. The spiral array discussed in [13] is dual-circularly polarized, but the same concept of separately rectifying two orthogonal polarizations applies to linear vertical and horizontal polarization. A grid-type dual-linear dense array is shown in Fig.10a. Because of the tight spacing, this array is non-resonant and operated over a 4:1 bandwidth. Such arrays are also conformal and can be made on flexible substrates, as is shown in Fig. 10b where a small spiral array is designed to decorate a coffee cup and provide DC power to a sensor with only $50 \mu \text{W/cm}^2$ incident power density.

4   Conclusion

This paper presents a summary of recent work in rectenna elements and arrays for wireless sensor powering at the University of Colorado. The paper

focused on design and characterization of antennas and rectifiers, but an important part of a wireless powering system is the power management and storage, as shown in Fig. 1. A significant effort has been devoted to that portion of the powering system, as well as integration with the rectenna, and will be the topic of a future paper.

It may be appropriate to conclude with a quote from Tesla's patent mentioned in the introduction: "My invention is particularly useful in connection with methods and apparatus for operating distant receiving devices by means of electrical disturbances produced by proper transmitters and conveyed to such receiving devices through the natural media; but it obviously has a wider range of applicability and may be employed, for example, in the investigation or utilization of terrestrial, solar or other disturbances produced by natural causes." At this time, available solid-state devices (diodes) have finite turn-on voltages, which implies that black-body radiation cannot turn on a diode and Tesla's visionary idea is not practically feasible. However, recent progress on zero-turn on diodes using semiconductor heterostructures, e.g. [18], may turn yet another of Tesla's dreams into engineering reality.
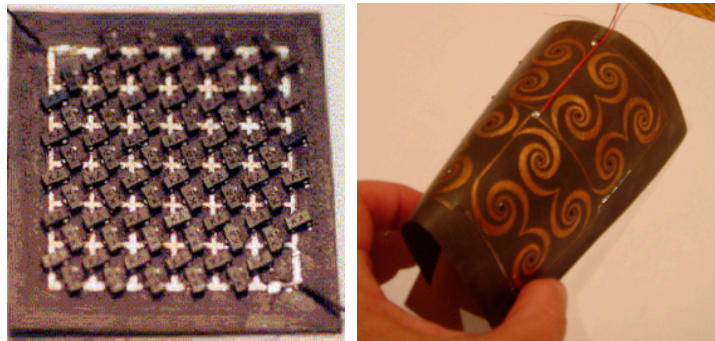

Fig. 10 – *A dense dual-linearly polarized grid-rectenna array*
with an 4:1 operating bandwidth (left) and
a dual-circularly polarized spiral antenna array fabricated on
a flexible conformal substrate and operating between 2 and 18GHz.

5   Acknowledgement

6   References

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