Air-substrate Compact High Gain Rectennas for Low RF Power Harvesting

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***Abstract*—In this paper, we present two integrated rectifier-antennas (rectennas) which maximize received DC power for 1 μW/cm^2 incident power density at 2.45 GHz. One of the rectennas is an air-substrate patch, 58 $\times$ 10 mm^2 in area, with a ground plane that is only slightly larger than the patch and a 3-mm thick air spacer, resulting in a gain of 7.2 dBi. A single diode rectifier is directly matched to the complex antenna impedance in both cases. The second rectenna is a printed version of a coaxial collinear array, 261 mm $\times$ 5 mm in area and a 3-mm air substrate. The two rectennas have comparable antenna gain of 7 dBi, rectified power of 15 to 25 μW and efficiency of 30%.**

air substrate, antenna, CoCo antenna, low power, patch antenna, rectenna, rectifying circuit, RF energy harvesting, Schottky diode, wireless power transfer.

I. Introduction

Miniaturized low power distributed wireless sensors are becoming an enabling technology for diverse applications such as environmental, health [1], structural monitoring [2], [3] as well as industrial automation. Such sensors operate in conditions where it is costly, inconvenient, or impossible to replace a battery, or deliver wired power. In some cases there is no available light, eliminating the possibility of photovoltaics, and low-energy RF harvesting becomes a reasonable choice [4]. In this case, the powering is performed independently of signal transmission, which differentiates it from RFID. Harvesting power from UHF digital TV bands [5] as well as various communication bands [6], [7], [8], [9] has been demonstrated with various rectifier and antenna architectures. Example specifications, e.g. [10], are motivated by commonly used communication, sensing and heating bands around 2.45 GHz [11] which are regulated in terms of allowed radiated power levels. Typical requirements for such sensors are small size, low maintenance and low available power levels, with unknown exact locations while operating in a multipath propagation environment.

The available power density of 1 μW/cm^2 is approximately in the range of power density levels close to cell-phone base-station antennas, e.g. [12]. For autonomous sensor applications, the size of the harvesting device needs to be small in all three dimensions. In this work, one of the dimensions is constrained to less than 5 mm. The small size implies an electrically small antenna, which will affect the system efficiency [13]. The engineering challenge is to design a small harvester which extracts maximum power from an incident wave at 2.45 GHz from an approximately known direction and delivers it to some optimal DC load. An efficiency figure of merit that summarizes the requirements is defined as [10]:

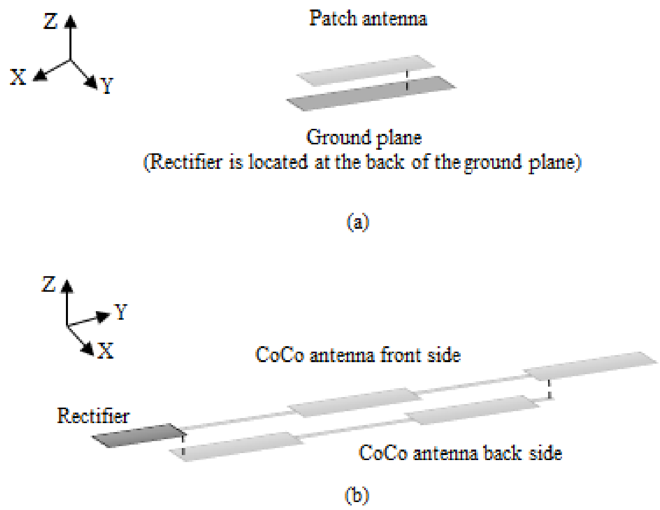

Fig. 1. (a) Layout of air-substrate patch rectenna; top layer is shown on the top and the ground plane layer along with the rectifier circuit feed are shown on the bottom. (b) Layout of CoCo rectenna; top layer along with the rectifier traces is shown on the top and the lower layer is shown on the bottom. The air substrate height for both antennas is 3 mm. Air substrate patch is 58 $\times$ 10 mm^2 in area, with a ground plane that is only slightly larger than the patch. The CoCo rectenna is 261 mm $\times$ 5 mm in area.

$$EFoM = 20\log\left[\frac{p_L}{a_{max}}\right] \quad (1)$$

where p_L is the power across an optimal DC load normalized to 10 μW and a_{max} is the maximal area normalized to 20 cm^2 and defined as the product of the two largest linear dimensions of the harvester. We present two rectennas which maximize the above figure of merit, with different geometrical aspect ratios, shown in Fig. 1.

The rectenna shapes are chosen for placement in different locations for the purpose of powering sensors such as occupancy, humidity and temperature, to provide control data for an energy-efficient home. Both rectennas use air substrates for increased gain. The rectenna in Fig. 1a uses an air-substrate patch with a ground plane that is only slightly larger than the patch, with a directly matched rectifier. This rectenna can be placed on metal objects without its radiation pattern and impedance being significantly affected. The rectenna shown in Fig. 1b uses a printed version of a coaxial collinear (CoCo) array [14] and [15] with a simple single feed where the rectifier is integrated, while allowing increased gain compared to a dipole antenna. This rectenna is long, narrow and omnidirectional in elevation, and can be placed along straight edges such as cabinets or picture frames.

In the next section, the design and simulations of the two high-gain, small antennas from Fig. 1 are described. Both antennas were selected to have high gain for the lowest possible profile, enabled by an air substrate, which slightly increases the length of the antenna but significantly increases the gain, efficiency and bandwidth [16]. The patch and CoCo antenna types are selected for ease of integration with rectifiers. The antennas are operated off resonance in order to facilitate matching to the complex impedance of the rectifiers optimized for peak efficiency at low input power.

II. Air-substrate patch

A patch structure is chosen for its small form-factor, light weight, simplicity and easy integration with a rectifier circuit. The diagram of the air-substrate patch antenna for 2.45 GHz are shown in Fig. 1. The top layer is simply copper and the bottom layer is composed of a ground plane placed on top of the rectifier with 20-mil-thick Rogers4003C substrate. The low-permittivity substrate used for the antenna support is Rohacell 31 LG with a nominal relative permittivity of 1.004. In order to reduce the antenna size and increase the figure of merit given in (1), the ground plane dimensions were reduced as much as possible and the antenna optimized using full-wave simulations (Ansoft HFSS). Increasing the air gap thickness can improve the gain. When increasing the air substrate thickness from 0.2 to 1 mm, the gain of the patch rapidly increases. In order to achieve a high gain and remain within the thickness dimension constraint, a 3 mm air substrate thickness is selected.

The rectifier optimal RF impedance is complex, and therefore in order to reduce the harvester size, the antenna impedance is designed to be matched to the complex impedance of the rectifier and therefore operated at a frequency that is off resonance. The simulated complex antenna impedance at 2.45 GHz is equal to $43 + j141\Omega$.

The gain of the air-substrate patch in two different planes, $\phi = 0°$ and $\phi = 90°$ is shown in Fig. 2 (see Fig. 1 for axis information). At the selected air gap of 3 mm the gain of patch is 7.19 dBi.

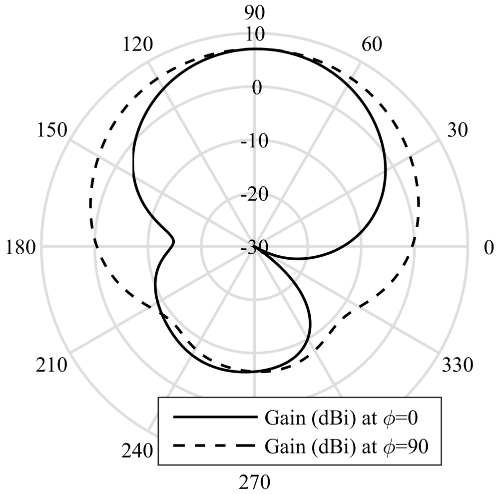

Fig. 2. Simulated gain of the air-substrate patch antenna as a function of θ, for $\phi = 0°$ (solid line) and $\phi = 90°$ (dashed line) along with the simulated gain of the air-substrate CoCo antenna for $\phi = 0°$ (dotted line) and $\phi = 90°$ (dash-dot line) at frequency of 2.45 GHz.

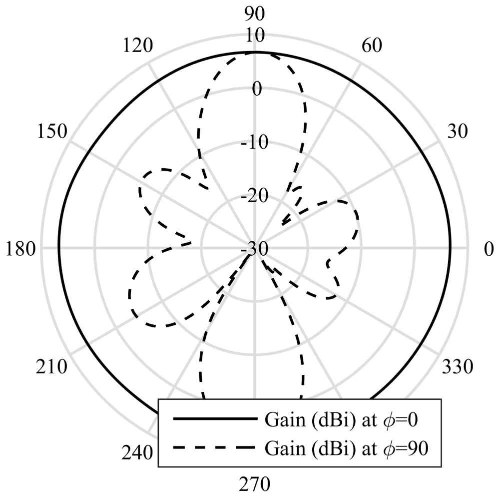

Fig. 3. Simulated gain of the air-substrate CoCo antenna as a function of θ, for $\phi = 0°$ (solid line) and $\phi = 90°$ (dashed line) along with the simulated gain of the air-substrate CoCo antenna for $\phi = 0°$ (dotted line) and $\phi = 90°$ (dash-dot line) at frequency of 2.45 GHz.

III. Air-substrate printed CoCo array

A classical implementation of the CoCo antenna array consists of a sequence of collinear, closely spaced coaxial line segments in which the inner and outer conductors are transposed between segments [17]. In a CoCo antenna, the length of each coaxial line segment is half of a wavelength at the design frequency. As a consequence, the voltage at the antenna feed point is transmitted to each of the line segments. The result in terms of radiation pattern is essentially the same as a collinear array of dipoles driven in phase but without the additional losses and size of a complex feeding structure. These single-feed arrays can also be implemented with non-coaxial printed lines, e.g. [14] and [18], sometimes incorrectly refered to as microstrip [19]. Another interesting example is given in [15], where a printed CoCo antenna is designed for dual band operation (2.4 and 5.8 GHz).

The diagram of the 4-element printed CoCo antenna for 2.45 GHz is shown in Fig. 1b. Two substrate layers with an air

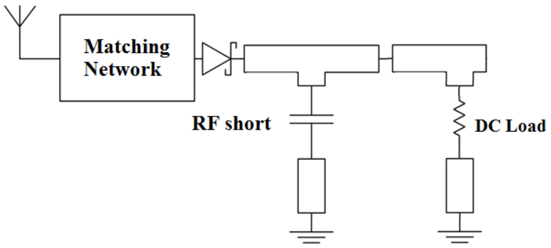

Fig. 4. Block diagram of the rectifier for both rectennas.

gap result in a significant increase in gain without significantly increasing the dimensions of the antenna. The gain improves rapidly as the airgap increases. The asymmetry in the printed lines around the longitudal axis simplifies the connection to the rectifier. Note that the optimum position of the short circuit at the end of the antenna is not in the middle of the last half-wavelength segment as usual. This shift is required because the ground plane of the rectifier affects antenna performance.

Similar to a dipole, there are multiple approximately equally spaced resonances in the impedance as a function of frequency. In addition, near 2.45 GHz the impedance is 23 - j22Ω and does not change very rapidly (in particular the real part). Fig. 3 shows the simulated gain of the CoCo antenna in two planes, ϕ = 0° and ϕ = 90° (see Fig. 1 for axis information) .

IV. Rectifier design

Depending on the input power level, different rectifier circuit topologies such as single series diode, single shunt diode, diode bridge, as well as Villard and Dickson voltage multipliers have been introduced . In this paper, a single series diode rectifier is selected since it tends to have higher efficiency at low input power levels [20]. The selected diode is a packaged Skyworks GaAs Schottky SMS7630-079 [21] and [22] and the nonlinear spice model for the Schottky diode is available from manufacturer. The block diagrams of the rectifiers for the patch and CoCo antennas are illustrated in Fig. 4. At the antenna feed point the diode is matched to the RF complex antenna impedance and the matching network is designed to have minimal loss in order to maintain high efficiency at low input power levels. For the air-substrate patch, the complex antenna impedance is directly matched to the diode complex impedance for optimal rectification efficiency.

The rectifier circuits were simulated in Keysight ADS using the harmonic balance nonlinear simulator with the antenna modeled as a sinusoidal source with an impedance equal to the complex impedance of each antenna. Both antenna and rectifier were tuned slightly to optimize efficiency at an input power of -12.5 dBm that corresponds to 1 μW/cm^2 incident power density, calculated from

$$P_{(dBm)} = 10\log_{10}\left(S_{(\mu W/cm^2)}\lambda^2_{(cm)}/4\pi\right) + G_{(dB)} - 30, \quad (2)$$

considering a gain on the order of of 7 dBi. The impedance matching between the rectifier and the antenna is achieved with lumped components to maintain a small footprint. At the expected -12.5 dBm input power, the simulation predicts 24.6 μW of harvested power at 43.75% efficiency.

Simulated DC harvested power as a function of DC load shows that the optimal DC load is around 1.3 kΩ. The optimal DC load can be any value from around 2 to 4 kΩ, in particular 2.2 kΩ is reasonable since the harvested power does not change much within this range. At -12.5 dBm the efficiency is slightly below 50% and the harvested power is approximately 25 μW. In terms of frequency response, the antenna impedance and harvested power stay reasonably constant if the deviation from 2.45 GHz is not too large.

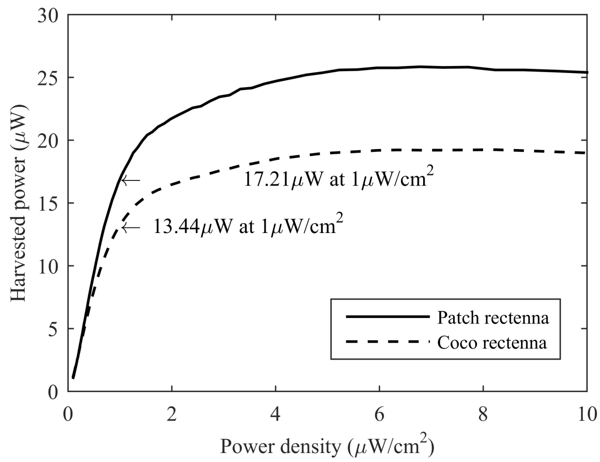

Fig. 5. Measured harvested power of the patch and CoCo rectennas as a function of power density. At the power density of 1 the harvested power for the patch and CoCo rectennas are 17.21 and 13.44 μW, respectively.

V. Integrated Rectenna Experimental Results

Both rectennas are integrated with rectifier circuits. The rectennas were characterized in an anechoic chamber and the power density at the DUT was calculated from the Friis formula. To cover all 360° in azimuth and elevation, the rectenna was flipped on the mounting structure and 180° were measured at a time, resulting in slight misalignment errors.

Fig. 5 shows the measured harvested power as a function of power density for both the patch and CoCo rectennas across DC loads of 1.3 kΩ and 2.2 kΩ, respectively. It can be seen that in both cases the harvested power decreases rapidly with power density for values below 1 μW/cm^2. As the power density increases, the harvested power saturates. Considering the maximum area of the patch and CoCo rectennas, the measured $EFoM$ from (1) are 15.419 and 6.267, respectively.

Fig. 6 shows the power harvested by the patch and CoCo rectennas. In general, these results are consistent with the previously calculated from simulation. In addition, some reflections in the setup could not be eliminated, resulting in increased power at some angles.

VI. Conclusion

In summary, this paper discussed design, implementation, and characterization of two integrated rectennas. The rectennas

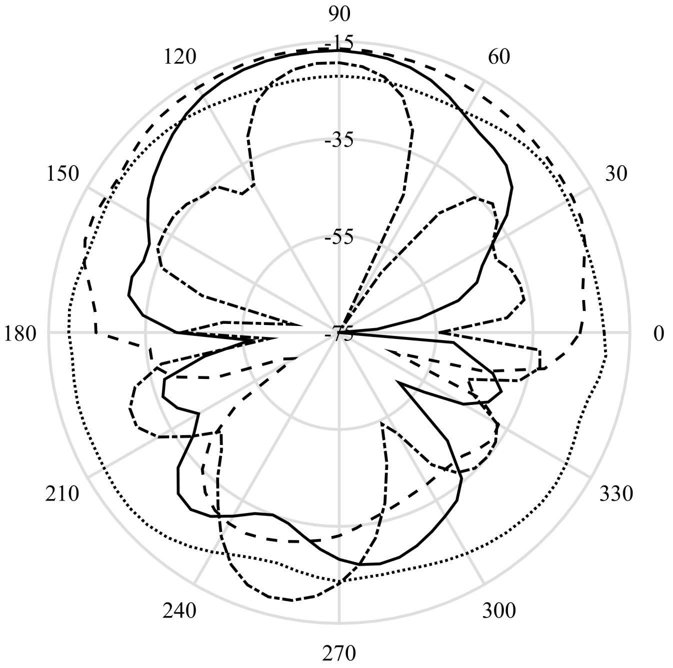

Fig. 6. Measured harvested power of the patch rectenna (dBm) as a function of θ at the incident power density of $1\,\mu$W/cm^2, for ϕ = 0° (solid line) and ϕ = 90° (dashed line) along with the measured harvested power of the CoCo rectenna for ϕ = 0° (dotted line) and ϕ = 90° (dash-dot line) at frequency of 2.45 GHz.

are designed under specific constraints in dimensions. The first rectenna is an air-substrate patch with a reduced-size ground plane. The second rectenna is a printed version of a coaxial collinear array with a single feed point. The rectennas have different form factors and are designed to fit in different locations in a home, e.g. the CoCo antenna fits along straight edges such as picture frames and bookshelves and is omnidirectional in the elevation plane. The patch rectenna can be placed on metal objects such as many appliances, since the miniaturized ground plane provides sufficient shielding. A high gain on the order of 7 dBi, is obtained for these electrically small antennas using the air-substrate technique. The two rectennas provide harvested power in the range of 15 to 25 μW with maximal efficiency of 30% at $1\,\mu$W/cm^2 incident power density.

ACKNOWLEDGMENT

The authors would like to thank Professors Nuno Borges Carvalho and João Nuno Matos from the University of Aveiro, Portugal, Steven Dunbar from TI, Mike Litchfield and Prof. Edward Kuester from the University of Colorado for useful discussions.

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