Inkjet printed 24 GHz rectenna on paper for millimeter wave identification and wireless power transfer applications

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***Abstract*—The use of millimeter wave bands presents an exciting possibility for Radio Frequency Identification (RFID) and wireless power transfer technologies since it allows for low power, low profile yet high performance circuits and provides a larger bandwidth for communication. Furthermore, inkjet printing fabrication permits the fast prototyping of millimeter wave circuits using a variety of low cost and flexible substrate materials. In this work we present the design of a millimeter wave rectenna inkjet-printed on glossy photo-paper substrate and integrating an off-the-shelf Schottky diode. The design has been optimized using harmonic balance optimization combined with electromagnetic simulation in order to maximize the RF-dc conversion efficiency. The simulated rectenna RF-dc efficiency was** 35.2% **for** 15 **dBm input power across an optimal load of** 280 **Ohm.**

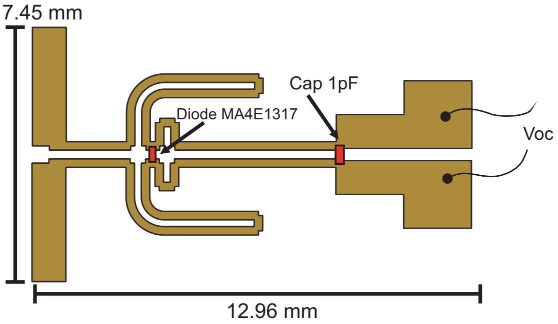

Fig. 1. Circuit layout of the designed rectenna. The rectenna includes just two discrete components in addition to the printed antenna and matching network: a Schottky diode and a capacitor.

I. INTRODUCTION

Today there are many critical applications that require low power and low cost sensing. There is a wide range of wireless sensor nodes and other electronic devices such as Radio Frequency Identification (RFID) that enable users to measure parameters with low power and low cost. Backscatter radio has been progressively utilized as a low-power and low-cost way for internet of things (IoT) applications.

Traditionally RFID systems operate in HF, UHF, or low microwave frequencies but the advantages of operating in millimeter waves have been recognized in [1] where the concept of millimeter wave identification was proposed. Operation in the lower frequency bands is advantageous due to the low cost and low losses of the components but higher frequencies on millimeter-wave (mmWave) bands can offer high operational bandwidth and extremely high transmission data rates [2], [3]. In [3], the ability to transmit Gbps modulation rates using a single transistor millimeter wave backscatter switch was demonstrated.

In order to provide power to the aforementioned devices millimeter wave wireless power transmission has been considered [4]–[6]. In [5], a 24 GHz rectenna has been proposed, for fixed wireless access applications. It achieved 43.6% RF-dc conversion efficiency with output filter of harmonic balance at 500 mW (27 dBm) input power. In [7] a multiband rectenna is presented for radio frequency (RF) energy harvesting placed on board of geostationary satellites. Such rectenna circuits [8] are used for powering autonomous wireless sensors for satellite health monitoring. In our previous work [9] a substrate integrated waveguide (SIW) rectenna operating at 24 GHz was presented. The obtained efficiency was 16.2% at 8 dBm which is comparable to reported literature values for low input power levels below 10 mW.

In this paper we demonstrate an ultra low cost, low profile 24 GHz rectenna fabricated on common paper substrate using inkjet printing fabrication technique. We present preliminary simulation results for the rectenna towards the implementation of low cost batteryless backscatter wireless sensor nodes. The rectenna achieves a maximum simulated RF-dc conversion efficiency of 35.25% at 24.125 GHz for an input power of 15 dBm at the antenna terminals.

II. RECTENNA DESIGN

In order to implement the rectenna design, a topology with one dipole antenna and a single diode was considered. The goal of this work was to increase efficiency and reduce complexity and only one diode was used, since diodes increase losses. In order to minimize the cost, a commercial photo paper lossy substrate was used, despite the fact that losses reduce efficiency. The geometry of the rectifier with the connected dipole antenna is depicted in Fig. 1.

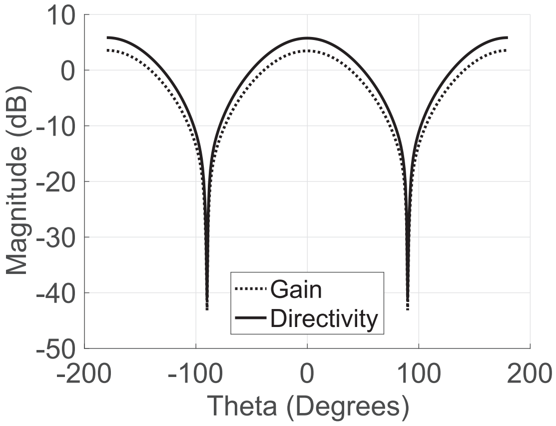

Fig. 2. Rectenna gain and directivity for yz plane (E-plane).

The printed structure of the rectenna circuit was simulated with the momentum simulator of Keysight ADS software. Next, harmonic balance analysis was applied in order to optimize the efficiency of the rectifier circuit. The analysis takes into account the losses of the substrate and the metallic parts, the fringing fields and the non-linear behaviour of the rectifier due to the diode. The antenna was simulated first at 24.125 GHz and after that was connected with the circuit of the rectifier. An optimization procedure was applied during the rectenna design (i.e., trace dimensions and load R_L estimation) in order to achieve impedance matching of the rectifier circuit to the antenna and maximize the RF-dc conversion efficiency. The matching network consists of a parallel line section followed by a shorted parallel line stub. Due to the electrical length of the stub, its layout was bended in order to avoid perturbing the radiation pattern of the dipole antenna by acting as a director/reflector. A second shorted stub is placed after the diode in order to suppress second harmonic signal generation. The single Schottky barrier diode MA4E1317 [10] was used while the paper substrate was modelled with $\varepsilon_r = 2.9$, $tan\delta = 0.045$ and substrate height 210 μm. The conductor thickness was assumed to be 5 μm. During the simulation procedure the goal was the maximization of the RF-dc efficiency:

$$\eta = \frac{V_{\mathrm{L}}^2/R_L}{P_{\mathrm{in}}}, \tag{1}$$

with P_{in}, available power to the rectifier at the antenna terminals and power and V_{L} the dc voltage across the load R_L. The obtained optimum lumped element value for the load R_L for 15 dBm at 24.125 GHz was 280 Ohm. A 1 pF capacitor was placed in parallel to the load in order to both filter out high frequency signals and to be used as an energy tank.

III. SIMULATION RESULTS

In Fig. 2, the gain and directivity of the dipole antenna (E-plane) are shown in dB. The antenna simulated radiation efficiency including the metal losses was 59%. Fig. 3 shows the simulated RF-dc conversion efficiency versus different input power values. The obtained efficiency for P_{in} = 10 dBm is η = 22.6%, while for Pin = 15 dBm and 20 dBm, η = 35.2% and 20.3%, respectively. One can see that for power levels above 15 dBm the diode breakdown voltage is reached and efficiency is reduced. In Fig. 4, the rectenna efficiency versus operation frequency is shown for P_{in} = 15 dBm and R_L = 280 Ohm. It is seen that the rectifier has a broad operating bandwidth. The Fig. 5 shows the rectifier efficiency versus load for different power inputs at 24.125 GHz. For P_{in} = 15 dBm the maximum η = 35.2% occurs when R_L = 208 Ohm, as expected, while for P_{in} = 5 dBm and P_{in} = 10 dBm, maximum η = 10.2% and 22.7%, occurs when $R_L = 520$ Ohm and $R_L = 310$ Ohm, respectively.

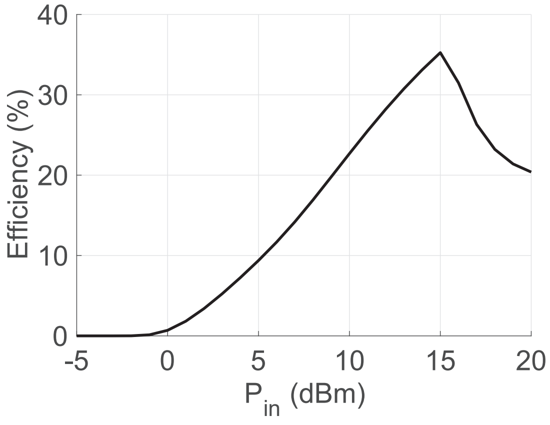

Fig. 3. Optimal Rectanna efficiency versus power input for fixed frequency 24.125 GHz. The load was fixed at 280 Ohm.

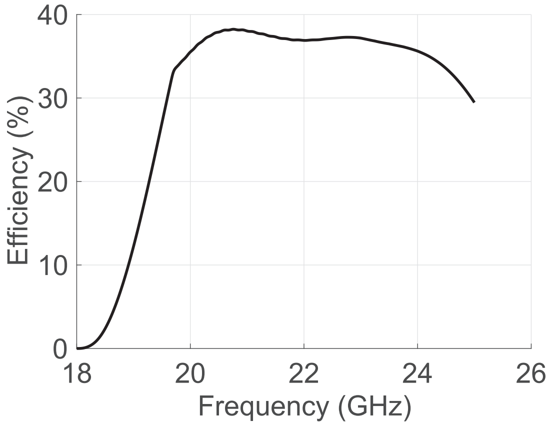

Fig. 4. Optimal Rectenna efficiency versus frequency for fixed power input at 15 dBm and optimal load 280 Ohm.

Finally, the rectifier was fabricated using inkjet-printed technology [11] on a flexible paper substrate (Fig. 6) with inkjet-printed silver nanoparticle (SNP) ink (conductivity $\sigma = 5 \times 10^6$ S/m). Conductive epoxy was used for placing the discrete components of diode and capacitor on the flexible board. The measurements of the rectenna performance are

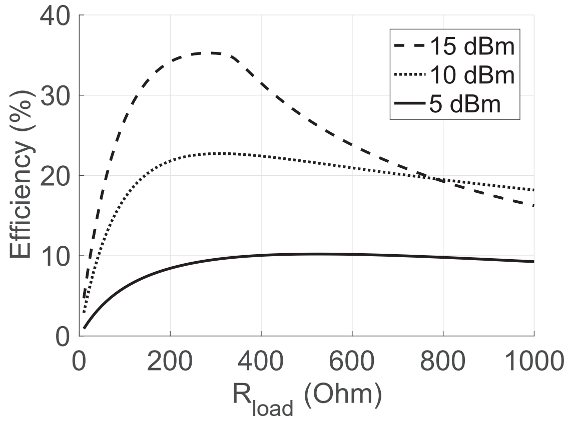

Fig. 5. Optimal Rectenna efficiency versus load for three different power input values.

TABLE I
RECTENNAS PERFORMANCE.

Work	Sim. Max Eff.	Meas. Max Eff.	Freq. (GHz)	Input Power
This work	22.6%	-	24	10 dBm
This work	35.2%	-	24	15 dBm
[4]	38%	24%	24	10 mW/cm^2
[4]	44%	42%	24	20 mW/cm^2
[5]	-	42.9%	24	16.02 dBm
[5]	-	54.2%	24	21.14 dBm
[6]	65%	60%	35	20.79 dBm
[6]	50%	39%	35	20.79 dBm
[7]	-	41%	20	1.8 mW/cm^2
[8]	-	42	18.8	2.2 mW/cm^2
[9]	17%	16.2%	25.7	8 dBm
[9]	8.5%	7.5%	25.7	1 dBm

under way in order to validate the simulation results.

Table I summarizes the performance of several published rectennas operating at frequencies near 24 GHz, in terms of their RF-dc conversion efficiency. One can see that despite the low cost fabrication and substrate material used, the obtained simulated efficiency is comparable with the values obtained in the literature for similar input power levels.

IV. CONCLUSION

A high efficiency, low-cost with lossy photo paper substrate, low-complexity rectenna is presented. The band of operations is in millimeter wave at 24.125 GHz. The circuit was evaluated with only one double Schottky diode and a small capacitor as lumped elements. The rectifier was connected with dipole antenna and was fabricated using silver nanoparticle ink. Future work should be focused on the measurements of the final rectenna design.

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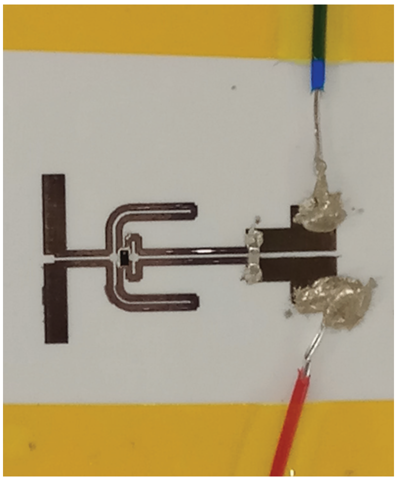

Fig. 6. Fabricated Rectenna on commercial photo paper substrate.

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