Compact and efficient 2.45 GHz circularly polarised shorted ring-slot rectenna

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A compact and efficient rectenna based on a printed shorted annular ring-slot antenna with circular polarisation properties has been designed and evaluated at 2.45 GHz. The rectifier part is localised at the back side and centred inside the radiating element, resulting in a more compact structure in comparison with most conventional devices where rectifying circuit and antenna parts are geometrically clearly separated. In addition, the printed annular ring antenna is mismatched at the 4.9 GHz second and 7.35 GHz third harmonics, thus avoiding the use of an input lowpass filter. The proposed antenna and rectifier circuit have been first simulated and optimised separately using electromagnetic and circuit analyses, and then connected together. A maximum efficiency of 69% and an output DC voltage of 1.1 V have been measured over an optimised 2500 Ω resistive load at a power density of 20 $\mu W/cm^2$. This rectenna is particularly suitable for powering wireless sensors or sensor networks by recycling ambient RF energy because it exhibits a global efficiency of more than 50% for power densities more than 10 $\mu W/cm^2$.

Introduction: Recently, most printed rectenna (rectifying antenna) circuits have been developed to supply wireless low consumption sensors or sensor nodes [1, 2]. The rectenna is an essential device to capture ambient or controlled RF sources and convert this into useful electricity. To optimise the global efficiency and decrease the polarisation losses, antennas with circular polarisation (CP) properties are often preferred. Indeed, both efficiency and output DC voltage are relatively insensitive to the rectenna alignment in the azimuthal plane. Among the circularly polarised planar antennas studied earlier, it has been shown that the printed annular ring-slot antennas have good performances in terms of radiation properties [3]. When associated with a dedicated rectifier circuit, these constituted rectennas are particularly suitable for relatively low power densities as previously demonstrated at 2.45 and 5.8 GHz [4, 5]. However, in these configurations and more generally, antenna and rectifier parts are separated in space resulting in a large rectenna area. We propose a novel rectenna design based on a circularly polarised annular ring-slot antenna and a zero bias serial Schottky diode converter dedicated for low power density applications (less than 20 $\mu W/cm^2$) [6]. In this configuration, the rectifier part is directly localised at the back side of the antenna, thus reducing the dimensions of the structure and the insertion losses of the rectifier. This makes the structure more compact and low cost.

Antenna and rectifier were, respectively, designed with HFSS and Advanced Design System (ADS) commercial softwares. A coupling between Harmonic Balance and Momentum has been performed and is well suitable to accurately optimise rectenna designs [7]. Finally, measured results in term of axial ratio, global efficiency and output DC voltage are presented and discussed.

Antenna design: The antenna depicted in Fig. 1 is printed on ARLON 25N substrate with $\varepsilon_r = 3.38$ and 1.524 mm thickness. It contains a shorted annular ring-slot structure designed at 2.45 GHz by using HFSS software. The geometrical dimensions of the antenna are summarised in Fig. 1. The ring-slot is mainly defined by the radii R_0 and R_1 but, to radiate CP wave, a small shorted section angle (noted θ_1) is localised at an appropriate position on the ring-slot antenna [3]. The folded short-circuited stub ($L_4 + L_5$) is adjusted to maximise the electromagnetic coupling between the ring-slot antenna and the rectifier (P_0) at 2.45 GHz. It is also used for DC path. This tuning-stub section is accurately localised near but outside the radiating element. For dimensions given in Fig. 1, the simulated input impedance of the antenna (P_0) computed at 2.45 GHz is equal to $126 + j6\ \Omega$ and will impose a complex conjugate input impedance of the rectifier for power matching. At the 4.9 and 7.35 GHz second and third harmonics, the input impedances are equal to $197 - j95\ \Omega$ and $75 + j69\ \Omega$, respectively. Then, there is a mismatch between the antenna and the rectifier at these frequencies and the unwanted harmonics generated by the diode cannot be re-radiated by the antenna. The simulated and measured CP gains are equal to 5.25 and 4.7 dB at 2.45 GHz, respectively. The measured axial ratio (AR) at boresight is shown in Fig. 2 and superimposed on the simulated one. The experimental minimum axial ratio (AR) is 0.39 dB with a 3 dB AR bandwidth of 200 MHz. There is a shift of 50 MHz between simulated and experimental AR results owing to the tolerances of the dielectric constant and manufacturing process.

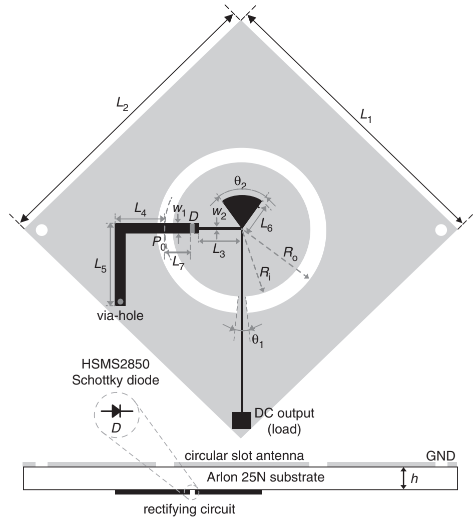

Fig. 1 *Geometry of printed shorted annular ring-slot rectenna*

$L_1 = 95$, $L_2 = 95$, $L_3 = 10.1$, $L_4 = 15.5$, $L_5 = 27.3$, $L_6 = 10.4$, $L_7 = 7.9$, $w_1 = 3.5$, $w_2 = 1$, $R_i = 21.5$, $R_o = 26.5$, $h = 1.524$, $\theta_1 = 5°$, $\theta_2 = 86°$ (dimensions in millimetres)

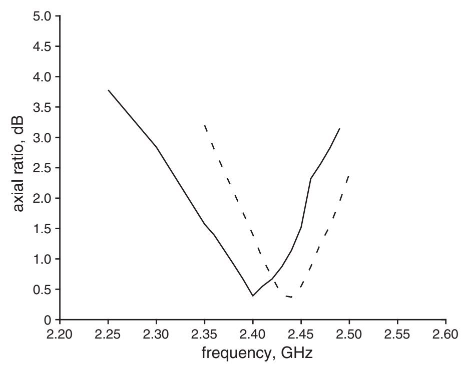

Fig. 2 *Axial ratio of printed shorted annular ring antenna against frequency*

- - - simulated
___ measured

Rectenna design and results: The rectifier is based on a commercial zero bias Schottky diode HSMS2850 ($R_s = 25\ \Omega$, $C_{j0} = 0.18$ pF, $B_v = 3.8$ V and $C_p = 0.08$ pF, $L_p = 2$ nH for the SOT 23 package) [8], and connected in series with a DC filter at the output of the circuit to suppress the 2.45 GHz harmonic over the resistive load. It has been numerically optimised at 2.45 GHz and 100 mW RF input power using ADS software. The distributed part has been simulated with Momentum electromagnetic software coupled with Harmonic Balance for the nonlinear model of the diode.

The Schottky diode, inserted on a 50 Ω microstrip line (length L_7), has a series impedance of $54 - j277\ \Omega$. The optimised microstrip line (length L_3, $Z_0 = 95\ \Omega$) is used to tune the reactance of the diode. The dedicated 50 Ω feeding line (length L_7) associated with the 50 Ω short-circuited stub have been accurately adjusted to match the input of the rectifier ($Z_{rect.} = 111 - j3\ \Omega$) to the antenna input impedance ($Z_{ant.} = 126 + j6\ \Omega$) at point P_0.

The rectifier contains a radial quarter-wavelength open-circuited stub (length L_6, sectoral angle θ_2), which acts as a short-circuit and then blocks the unwanted 2.45 GHz RF component flowing from diode to the resistive load.

In remote power supply applications, the dedicated sensor can be accurately inserted in a discrete location inside the ring slot antenna and connected between the radial stub and the ground plane. For practical considerations during the measurements, the DC voltage is measured across an optimised 2500 Ω resistive load connected outside the annular ring-slot radiating element. Then the load is soldered at the end of a thin printed line accurately localised below the short section of the slot antenna to avoid the RF coupling with the radiating element.

The performance of the complete rectenna was tested in an anechoic chamber. A 30 dB gain power amplifier has been connected between a RF signal generator and a 12 dB linearly polarised horn antenna transmitter localised at a distance of 1.8 m from the rectenna under test to satisfy the far field condition. The overall efficiency is the ratio between the output DC power and the input RF power obtained from the effective aperture of the antenna and the incident power densities on the rectenna.

Both output DC voltage and overall efficiency (η) have been measured as a function of power density (Fig. 3) using the Friss transmission equation for free-space wave propagation in four different rectenna alignments in the azimuthal plane ($\phi = -45^\circ$ 0° 45° and 90°). The rectenna is illuminated by a linearly polarised incident plane wave from 0.54 $\mu W/cm^2$ ($E = 1.43$ V/m) to 19.4 $\mu W/cm^2$ ($E = 8.54$ V/m) at its broadside.

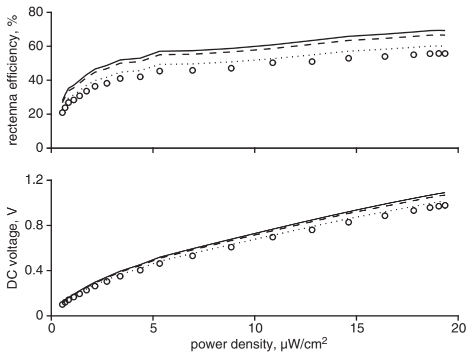

Fig. 3 *Measured rectenna efficiencies and DC voltages against power density for different rotation angles*

______ $\Phi = -45^\circ$
- - - - - - $\Phi = 0^\circ$
ooooooo $\Phi = 45^\circ$
. . . . $\Phi = 90^\circ$

At 2.75 $\mu W/cm^2$ power density ($\simeq$100 mW at the input of the rectifier), the output DC voltage and overall efficiency are respectively 343 mV and 48.7% in the $\phi = -45^\circ$ plane. The resulting output DC power is equal to 47 mW over an optimised 2500 Ω resistive load.

In the power density range, all the curves corresponding to different rotation angles are very close. At 20 $\mu W/cm^2$ input power, the output DC voltage ranges between 980 mV ($\eta = 56\%$) and 1090 mV ($\eta = 69\%$). In terms of output DC power, the difference between the $\phi = -45^\circ$ and $\phi = 45^\circ$ planes has a maximum value of 1 dB. This difference is mainly due to the nonideal axial ratio but these results show the advantages of the circularly polarised rectenna with comparable and stable output DC voltages and overall efficiencies over the four different rotation angles.

Conclusions: A shorted compact and efficient annular ring-slot rectenna has been designed and evaluated at 2.45 GHz. In this structure, the rectifying part has been centred inside at the backside of the circularly polarised antenna. In addition, no input lowpass filter is needed. This is due to the antenna mismatching at the 4.9 and 7.35 GHz second and third harmonics, respectively. The rectifier circuit has been optimised at 2.45 GHz for an input power of 100 μW. The output DC voltage and overall efficiency are respectively higher than 960 mV and 56% at 20 $\mu W/cm^2$ input power and over a 2500 Ω resistive load. This circularly polarised rectenna should have applications in small actuators and low power consumption sensors supply by recycling ambient energy because it exhibits an overall efficiency of more than 50% when power density exceeds 10 $\mu W/cm^2$.

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