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An efficient rectenna based on a dual Schottky diodes converter has been designed at 2.45 GHz. The proposed rectifying circuit is well suitable for wireless sensor applications because no input lowpass filter and no via-hole connections are required, resulting in a more simple structure. A simulation mixing an electromagnetic and circuit analysis has been first used to optimise the rectifier. In addition, the performances of the rectenna has been correctly predicted and characterised using an FDTD formulation extended to lumped circuit elements. The realised rectenna exhibits 83% efficiency over a 1050 Ω resistive load at a power density of 0.31 mW/cm^2.

Introduction: The rectenna is an important component for converting RF or microwave power into DC power. These techniques are of great interest to supply actuators [1] or wireless sensors [2] through free space without wire connections or a battery. A rectenna usually contains a receiving antenna, a combination of one or several Schottky diodes in series [3] or shunt [4], in voltage doubler configurations [5] or in a modified bridge converter [6], an input lowpass filter (LPF), an output DC pass filter and a resistive load. The input (LPF) rejects harmonics created by the diodes and provides matching between the antenna and the rectifier. It can be directly included on the radiating element by using harmonic-rejecting antennas [7].

We propose an efficient rectenna design based on a dual diodes converter. In this configuration, the LPF between the antenna and diodes can be eliminated, reducing the insertion losses of the rectifier. The structure has been optimised and characterised using advanced design system (ADS) commercial software and the 3D-FDTD algorithm extended to lumped element circuits. Finally, simulated results are compared with the measured ones and show good agreement.

Rectenna design: The rectenna shown in Fig. 1 is printed on ARLON 25N substrate with $\varepsilon_r = 3.38$ and 1.524 mm thickness. It contains a linearly polarised rectangular patch antenna designed at 2.45 GHz by using ADS Momentum software. The rectenna contains two HSMS2860 commercial Schottky diodes in a SOT23 package. These diodes have forward and breakdown voltages of 0.3 and 7 V, respectively. The zero bias junction capacitance C_{j0} is 0.18 pF and the series resistance R_s is 5 Ω.
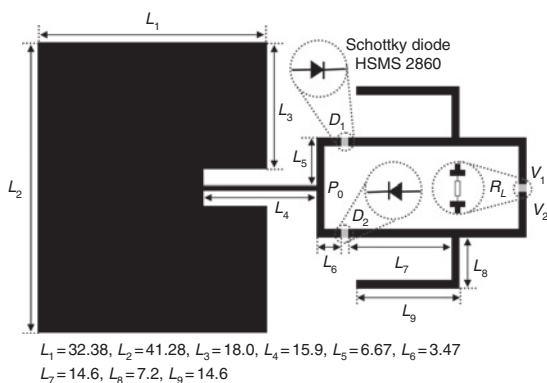

$L_1 = 32.38$, $L_2 = 41.28$, $L_3 = 18.0$, $L_4 = 15.9$, $L_5 = 6.67$, $L_6 = 3.47$
$L_7 = 14.6$, $L_8 = 7.2$, $L_9 = 14.6$

Fig. 1 *Geometry of rectenna (dimensions in millimetres)*

The simulated input impedance of the diode is $95 - j200\,\Omega$ at 2.45 GHz and 10 dBm input RF power. The optimised symmetric lines (length L_7) are used to tune the reactance at the input of the diodes. All the lines have a characteristic impedance (Z_0) of 87 Ω except at the input of the circuit where a 100 Ω microstrip line is used as the feeding line. These lines are chosen to match the input of the rectifier with the patch antenna.

The DC voltage is obtained by measuring the voltage difference between V_1 and V_2 across the resistor load, without reference to the RF ground plane. Therefore, there is no need for any via-holes.

The 2.45 GHz power yields from the antenna is split into two separated equivalent RF components, which propagate in phase on both symmetrical and parallel 87 Ω microstrip lines towards diodes D_1 and D_2. The RF signal is then partially converted into DC current with unwanted higher-order harmonics.

To correctly optimise the efficiency of the rectifier, simulations were carried out with the aid of ADS software. A coupling between Momentum (for the distributed part) and Harmonic Balance (including the nonlinear model of the diode) has been performed. A 'gradient' method was also used to optimise the rectifier by means of a criterion based on the conversion efficiency. Here, the parameters (lengths of the microstrip lines and load) have been computed for an input power of 10 dBm. We have obtained an optimised 1050 Ω resistor load and dimensions, as shown in Fig. 1.

FDTD numerical results: We have computed the current distribution on transmission lines by using the full-wave 3D-FDTD algorithm including linear and nonlinear lumped circuit elements extension. In addition, the total-field/scattered-field formulation has also been included to realise an arbitrary plane-wave illumination on the rectenna [8]. The rectenna is illuminated by a linearly polarised incident plane wave of 20 V/m (0.106 mW/cm^2) at its broadside. Current distributions are given after fast-Fourier transform (FFT) computation. The DC current flows through D_1, D_2 and R_L without reference to the RF ground plane.

Fig. 2 shows the current distribution on the structure at 2.45 GHz. The rectifier contains two folded quarter-wavelength open-circuited stubs that act as short-circuits (a peak of current appears on the main lines). These stubs block the unwanted 2.45 GHz RF component flowing from the diodes to the resistive load.
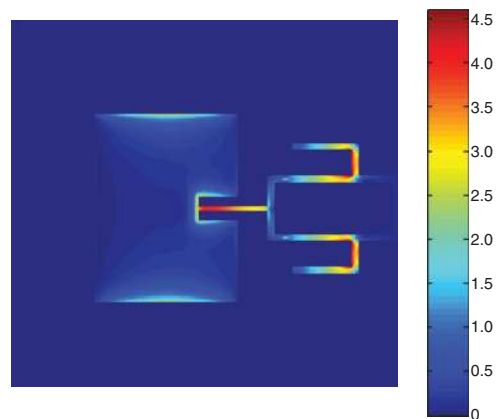

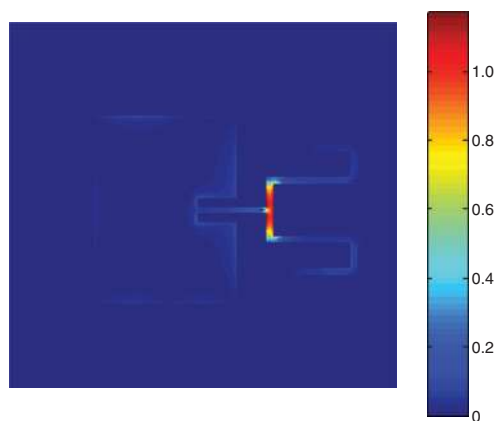**Fig. 2** *Current distribution (A/m) at 2.45 GHz*

Fig. 3 *Current distribution (A/m) at 4.9 GHz*

Fig. 3 shows the current distribution at 4.9 GHz. The diodes have been accurately localised on a null of current to minimise the power losses. In addition, owing to the half-wavelength distance between the diodes at 4.9 GHz, the second harmonic is then distributed by a standing wave with a peak of current at the input of the circuit (P_0), resulting in a short-circuit. The second harmonic generated by the nonlinear diodes has been confined and there are no propagation effects towards the microstrip antenna, where no current exists at 4.9 GHz, and the resistive load. The 7.35 GHz third harmonic is largely reduced (−30 dB

attenuation) and there is a mismatch between the antenna and the rectifier at this frequency. Therefore, the efficiency is not affected.

Rectenna measurements: The linearly polarised patch antenna has been measured in an anechoic chamber. It exhibits a gain of 4.7 dB and a minimum return loss of −20 dB at 2.45 GHz. Results agree well with those obtained by Momentum software. The output DC voltage and overall efficiency have been measured against power density from the Friss transmission equation [1] and considering a distance of 70 cm between the transmitting linearly polarised horn antenna ($G_{trans} =$ 12 dB) and the rectenna under test. On the transmitter side, we have used a 30 dB gain power amplifier at 2.45 GHz connected to a signal generator. The output DC voltage across the resistor load has been measured by a voltmeter.

The FDTD simulated and measured output DC voltages and overall efficiencies are shown in Fig. 4. In the power density range (0–0.31 mW/cm^2), the measured rectenna efficiency is above 80% from 0.22 mW/cm^2 power density ($E = 29$ V/m) and the corresponding output DC voltage is 2.6 V over a 1050 Ω optimised load resistance. FDTD and measured results are in good agreement and clearly show that the output voltage and efficiency increase when the power density increases.
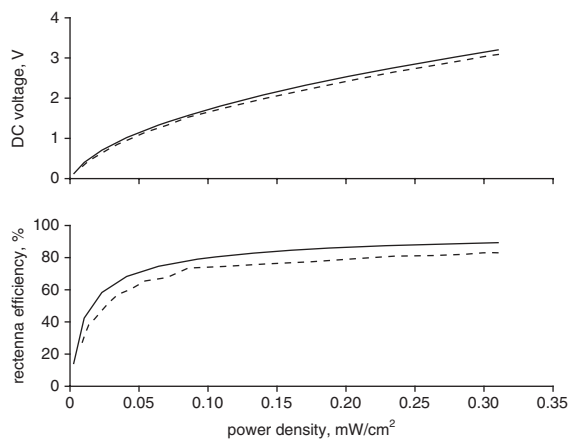

Fig. 4 *Simulated and measured DC voltages and rectenna efficiencies against power density*

_____   FDTD method
- - - - -   measured

Conclusions: We propose an efficient rectenna design, based on a dual-diode circuit topology. Owing to the symmetry of the rectifier and the optimised length of the lines and load, no input lowpass filter is needed, thus reducing the insertion losses and the dimensions of the circuit. In addition, owing to the differential DC measurements, no via-holes are necessary. The rectifying circuit has been optimised at 2.45 GHz for an input power of 10 dBm. The rectenna exhibits a measured efficiency of 83% at 0.31 mW/cm^2 power density and an output DC voltage of 3.1 V. These results are very close to those obtained by full-wave FDTD simulations. This rectenna should have applications for remote power supply and the driving of small actuators and sensors.

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