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Global Analysis of Rectifying Antenna with GaN Schottky Barrier Diode using WCIP Method for Wireless Power Transmission

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Abstract A precise technique based on the wave concept iterative procedure (WCIP) and a fast mode transformation (FMT) is used to analyze a rectifying antenna (Rectenna) circuit. This global analysis is achieved by using surface impedance to model the nonlinear element (GaN Schottky Barrier diode). These systems use the manufacturing processes of integrated circuits. In order to initialize the iterative procedure, an incident wave is defined in spectral domain. The numerical results are compared to those obtained with the measured one. The good agreement between simulated and published data justifies the design procedure.

Keywords: *rectenna, WCIP, GaN Schottky barrier diode, RF, 2D-FFT algorithm*

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1. Introduction

Within the framework of the recovery of energy for wireless sensor networks, the energy-harvesting system using the rectenna has a big interest [1,2,3]. This paper presents a global analysis of (Rectenna) rectifying antenna by using surface impedance to model the nonlinear element (GaN Schottky Barrier diode). The Rectenna behaving like a wireless battery is a necessary device to convert the energy RF in direct current. Usually, a Rectenna consists of a microwave antenna to collect incoming RF power, an input low-pass filter (LPF) to suppress unwanted higher harmonics rejected by the rectifying circuit [4,5,6,7], an output dc pass filter, and a resistive load. In Rectenna design, simulation is an essential step in modeling this type of circuit. In this framework, several analytical methods have been developed [5,9]. Among these methods that already exist, we present in what follows a new iterative method based on the wave concept [9,10,11,12,13]. This method has major advantages over other methods. These advantages are concerning, in special, the execution velocity of the resolution procedure and the arbitrary form of the under studied structure. Besides this iterative technique uses a rapid transformation FMT which ensures a rapid transition between the spectral and spatial domain [4]. We combine the wave concept with the two dimensions Fast Fourier Transformation (2D-FFT) algorithm to change the domain. The use of the 2D-FFT algorithm is required to mesh the circuit plane into 2D small rectangular pixels the 2D-FFT algorithm, a high computational speed can be achieved [4].

2. Theory

A brief overview of the WCIP method [3-8] based on wave concept is presented here. It consists of generating a recursive relationship between a given incident and reflected waves generated from the discontinuity planes (eq.1). The analysis structure shown in Figure 1 is composed of planar microstrip enclosed in the metal box; the interface Ω is divided into cells which form sub-domains corresponding to metal, dielectric and sources.

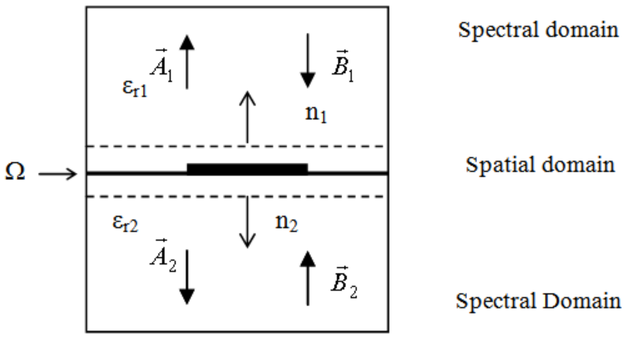

Figure 1. Illustration of waves on both sides of the interface Ω

$$\vec{A}_i^n = \hat{\Gamma}_\Omega.\vec{B}_i^n + \vec{A}_i^0$$
$$\vec{B}_i^n = \hat{\Gamma}_i.\vec{A}_i^{n-1} \quad (1)$$

The wave concept is introduced by writing the tangential electric field E, (on **Ω**) and surface tangential current density J, (on **Ω**) in terms of incident and reflected waves.

$$A_i = \frac{1}{2\sqrt{z_{0i}}}\left(E_i + Z_{0i}.J_i\right)$$
$$B_i = \frac{1}{2\sqrt{z_{0i}}}\left(E_i - Z_{0i}.J_i\right) \quad (2)$$

where J_i is the surface tangential current density which is defined as**:** $\vec{J}_i = \vec{H}_i \Lambda \vec{n}_i$; n_i is a unit vector normal to **Ω**. A_i and B_i are two tangential vectors associated with the discontinuity interface **Ω**. Z_{0i} is the characteristic impedance of region i (Eq. 3):

$$Z_{0i} = \sqrt{\frac{\mu_i}{\varepsilon_i}} \quad (3)$$

ε_i, μ_i are the permittivity and permeability of region I, respectively. E_i and H_i are the tangential electric and magnetic field on **Ω**. The interface **Ω** is characterized by a scattering operation matrix depending on boundary conditions defined for each point of **Ω**. The continuity conditions for fields in each point of **Ω** (spatial domain) are:

$E_1 = E_2 = 0$	on the metal domain.
$E_1 = E_2$ and $J_1 + J_2 = 0$	on the dielectric domain.
$E_1 = E_2 = E_0$	on the source domain.

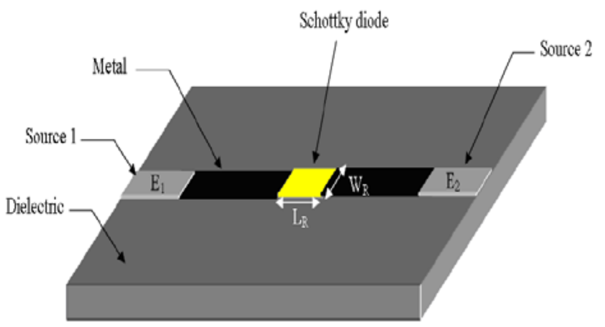

Figure 2. Planar structure including a Schottky diode

In this section we focus on the study of planar microwave structures incorporating Schottky diodes [14] in order to provide specific functions. Figure 2 shows a localized element inserted into a planar circuit.

Z_L is the impedance of equivalent circuit element, the electric field in the area of the element is connected to the voltage V by the equation:

$$V_L = \int_0^{L_R} E(x,y).dx \quad (4)$$

The current density is related to the tangential current density by:

$$I_L = \int_0^{W_R} J(x,y).dy \quad (5)$$

The dimensions of the element are very small spot in front of the working wavelength λ_g, ($L_R \langle\langle \lambda_g$) and $W_R \langle\langle \lambda_g$), then we can assume that E and J are uniform in the area of the element.

Equations (4) and (5) become:

$$V_L = E.L_R$$
$$I_L = J.W_R$$

Thus, we can define the surface impedance Z_S by:

$$Z_S = \frac{E}{J} = \frac{W_R}{L_R}\frac{V_L}{I_L} = \frac{W_R}{L_R}Z_L \quad (6)$$

W_R/L_R is the form factor of the element located and Z_L is the impedance of the equivalent circuit.

To study a circuit containing such an element by the iterative method which is based on the concept of waves, it is necessary to determine the relation between the incidental waves and the waves reflected in its domain, and to add it in the expression of the operator diffraction in the spatial domain.

Hz is the matrix on the area of the element, the boundary conditions in this area are: $E = Z_s J$.

In terms of waves, we can write:

$$\sqrt{Z_{01}}(A_1 + B_1) = Z_s\left(\frac{(A_1 - B_1)}{\sqrt{Z_{01}}} + \frac{(A_2 - B_2)}{\sqrt{Z_{02}}}\right) \quad (7)$$

The operator of this field diffraction is:

$$\begin{bmatrix} B_1 \\ B_2 \end{bmatrix} = \begin{bmatrix} \alpha H_Z & \beta H_Z \\ \chi H_Z & \delta H_Z \end{bmatrix}\begin{bmatrix} A_1 \\ B_1 \end{bmatrix} \quad (8)$$

with:

$$\alpha = \frac{Z_s(-Z_{01} + Z_{02}) - Z_{01}Z_{02}}{Z_s(Z_{01} + Z_{02}) + Z_{01}Z_{02}}, \beta = \frac{2Z_s\sqrt{Z_{01}Z_{02}}}{Z_s(Z_{01} + Z_{02}) + Z_{01}Z_{02}}$$
$$\chi = \frac{2Z_s\sqrt{Z_{01}Z_{02}}}{Z_s(Z_{01} + Z_{02}) + Z_{01}Z_{02}}, \delta = \frac{-Z_s(-Z_{01} + Z_{02}) - Z_{01}Z_{02}}{Z_s(Z_{01} + Z_{02}) + Z_{01}Z_{02}}$$

The diffraction operator of the surface impedance in the diode region becomes:

$$\Gamma_\Omega = \begin{pmatrix} \left(-H_n - \frac{-1+n_1+n_2}{1+n_1+n_2}H_s + \frac{1-N^2}{1+N^2}H_d + \alpha H_s\right) & \left(\frac{2N}{1+N^2}H_d + \frac{2_n}{1+n_1+n_2}H_s + \beta H_s\right) \\ \left(\frac{2N}{1+N^2}H_d + \frac{2_n}{1+n_1+n_2}H_s + \beta H_s\right) & \left(-H_n - \frac{-1+n_1+n_2}{1+n_1+n_2}H_s + \frac{1-N^2}{1+N^2}H_d + \delta H_s\right) \end{pmatrix}$$

The equivalent circuit of the circuit with the Schottky diode is shown in Figure 3.

C_p = 0.05 pF is a parasitic capacitance, L_p = 0.5 nH is a parasitic inductance, and $C_j(V)$ is a variable capacitor:

$$C_j(V) = C_j(0) \Big/ \sqrt{1 - \frac{V}{\varphi}}$$

where $C_j(0)$ = 1pF is the junction capacitance at zero bias potential and is called the integrated (built-in potential). The boundary conditions in the area of the Schottky diode given by the equivalent circuit are:

$$E_1 = \left(j\varpi L_p + R_s + \frac{\dfrac{R_j}{\omega C_j}}{\left(\left(\dfrac{1}{\omega C_j} \right)^2 + R^2 \right)^{1/2}} \right) J_1$$

$$E_2 = \frac{1}{j\omega C_p} J_2$$

$$E_1 = E_2 = Z_s \left(J_1 + J_2 \right)$$

or: $\frac{V}{\varphi} \pi\pi 1 \quad \Rightarrow \sqrt{1 - \frac{V}{\varphi}} \approx \left(1 + \frac{V}{2\varphi} \right).$

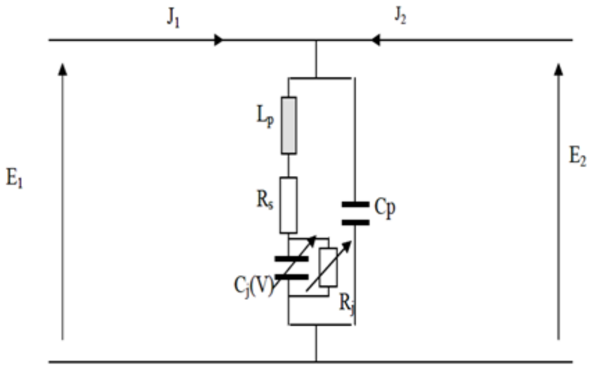

Figure 3. Equivalent circuit of planar circuit with Schottky diode

For this diode, the form factor is 1. The operator for the diffraction field of the diode is:

$$\begin{bmatrix} B_1 \\ B_2 \end{bmatrix} = \begin{bmatrix} {K_2}/{K_1} H_L & {K_3}/{K_1} H_L \\ 0 & \dfrac{1 - jwC_p Z_{02}}{1 - jwC_p Z_{02}} H_L \end{bmatrix} \begin{bmatrix} A_1 \\ A_2 \end{bmatrix}$$

with:

$$K_1 = \frac{\alpha}{\sqrt{Z_{01}}} + Z_{01} + 2\left(\frac{\alpha}{Z_{01}} \right)$$

$$K_2 = \frac{\alpha}{\sqrt{Z_{01}}} - Z_{01} + 2\left(\frac{\alpha}{Z_{01}} \right)$$

$$K_3 = \frac{-1}{j\omega C_p \sqrt{Z_{02}}} \left(\frac{2 j\omega C_p Z_{02}}{1 + j\omega C_p Z_{02}} \right)$$

$$\omega = 2\,\pi\, Freq$$

$$\alpha = j\omega L_p + R_s + \frac{\dfrac{R_j}{\omega C_j}}{\left(\left(\dfrac{1}{\omega C_j} \right)^2 + R^2 \right)^{1/2}}$$

3. Applications

We propose here an analysis of a Rectenna circuit at 2.45 GHz in microstrip technology previously studied by Alexander et al Douyère [15]. It consists of a rectangular patch antenna with linear polarization and a conversion circuit series Schottky diode. The two parts of the Rectenna have been adapted on 50 Ω impedance. In addition, the supply line between the antenna and the converter circuit has a width W1 = 2 mm and a characteristic impedance of 50 Ω. The Schottky diode has been rigorously modeled by an impedance surface and introduced into the calculation of the method.

To reconstruct the process of measuring a complete Rectenna illuminated by an incident plane wave inside an anechoic chamber, the global simulation based on the iterative method was used. The distributions of the electric field and surface current were calculated. They will be presented and used to demonstrate the performance of the Rectenna circuit in terms of performance and compactness. The results are routinely compared with measurements. In this case, the structure is excited by a plane wave at normal incidence with a polarization along (ox).

Figure 4 shows the Rectenna using a Schottky diode.

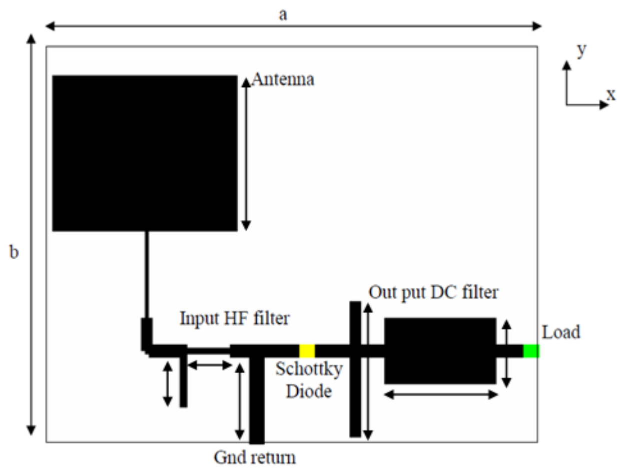

Figure 4. tructure of the single layer containing a Schottky diode Rectenna

Table 1. Dimensions of the Rectenna in mm

a	91
b	99
Lp	35
L1	11.4
L2	8.5
L3	15
L4	29.3
L5	20.3
L6	13.7

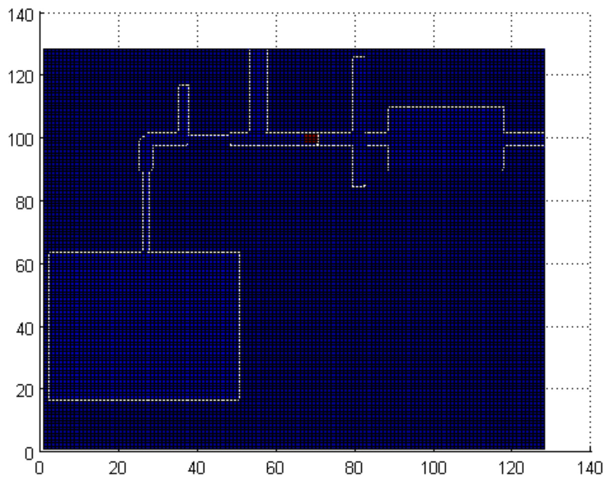

Figure 5. Schematic of Rectenna discretized into pixels

The circuit consists of a square patch antenna with linear polarization and a conversion circuit series. In addition, a matching circuit between the antenna and the converter circuit was designed. The Rectenna is printed on a teflon glass substrate (εr = 3.2, tan δ = 0.003 and h = 0762 mm). The number of iterations required for convergence of results is obtained from 200 iterations. The total structure is synthesized using a mesh of 128 × 128 pixels with basic dimensions of Δx = 0.71 mm and Δy = 0.77 mm. Figure 5 shows the discretization of the circuit plane.

The space contains two main sub-areas, namely the space containing metal, dielectric, and load and frequency domain that contains the source area of the incident plane wave form. We need to determine the diffraction operator in each area based on the boundary conditions for each area. The mesh size of space is done by dividing the interface containing the circuit in rectangular pixels, so we can define a matrix on each area. (Hm: metalworking, Hd: dielectric and field Hs: field of the diode and Hc: domain of the load) that takes the value 1 in the pixels that represent the field and 0 elsewhere.

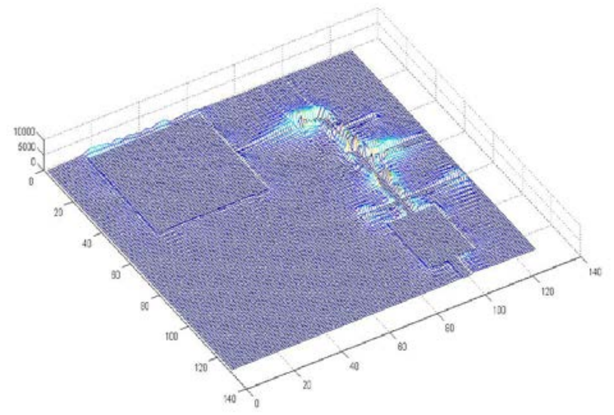

Figure 6. Distribution of the electric field | Ex | V/m in terms of the interface at 2.45 GHz

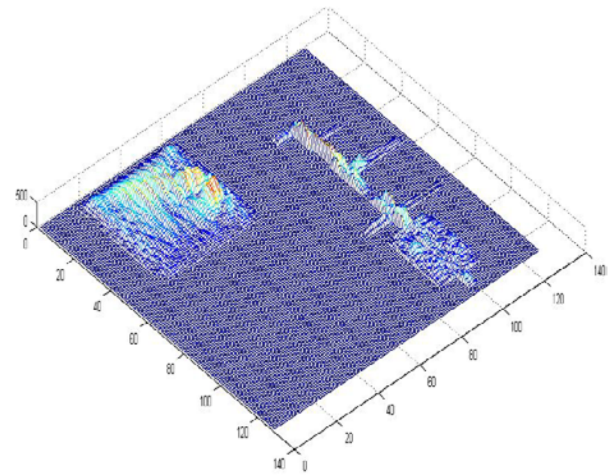

Figure 7. Distribution of the electric current density | J x | in Ampere/m in terms of the interface at 2.45 GHz

The 3D representations of electric fields (Figure 6) and current densities (Figure 7) to 2.45 GHz frequency obtained after a computation time of 1 min 05 s show that the boundary conditions are met at every point of the interface containing the circuit since the sum of current densities is zero on the dielectric and density fields is zero on the metal.

For an electrical device (microwave-RF-low frequency or other) to be usable, it must present a stable condition during its simulation. Thus, by studying the convergence of the admittance seen by the source (Yin) versus number of iterations, we can conclude that the electrical stability is obtained.

The curve in Figure 8 shows that the convergence of the admittance seen by the source (Yin) is reached fairly quickly, in less than 200 iterations.

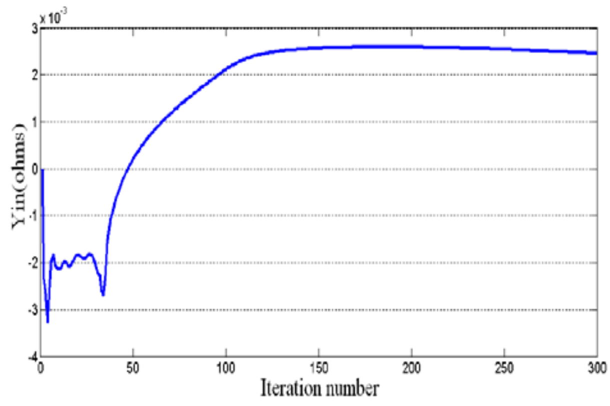

Figure 8. Convergence of source admittance (Yin) versus number of iterations at 2.45 GHz

The analysis concludes by comparing simulation results with measurement results. From the curves shown in Figure 9, the maximum efficiency of the Rectenna is obtained for a power of 15 dBm and a load of 200 Ω. The simulation results obtained with the iterative method are compared with measured results from reference [15].

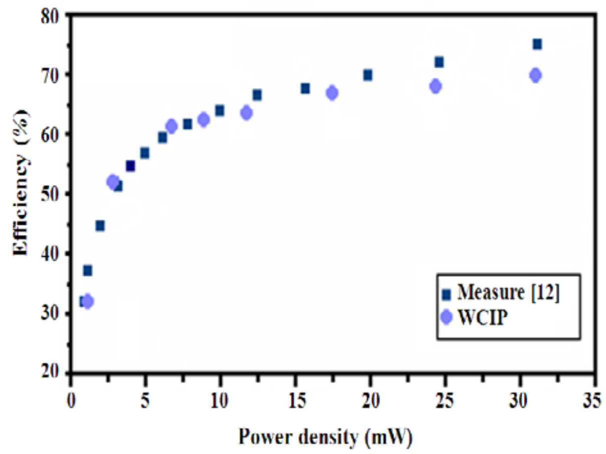

Figure 9. Rectenna efficiency versus power density

The efficiency of the Rectenna raised to power densities ranging from 0 to 35 mW is plotted in Figure 9. We note that there is good agreement between the two gaits. The good consistency between WCIP and results from any action is undeniable.

4. Conclusion

We have used in this paper a method to determine an overall characterization of an energy recovery circuit (Rectenna) incorporating an active non-linear component (Schottky diode). The iterative method adopted could be applied to model the diode by an impedance surface. A

Matlab program was developed for the simulation of the method. The comparison of our results with those available in the literature validates our approach.

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