Voltage, Efficiency Calculation and Measurement of Low Power Rectenna Rectifying Circuit [†]

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1. Introduction

A rectenna (rectifying antenna) is a receiving antenna combined with a rectifying circuit which converts RF or microwave power into useful DC power. It can operate under both large and small signal (low power) conditions.

In some low power applications, a rectenna is required to supply certain output DC current and voltage. For example, an intelligent RFID passive tag requires an Integrated Circuit (IC) to communicate with the interrogator. The IC requires a certain DC current and voltage to be activated. As an illustration, current state of the art low power CMOS IC would require a DC voltage supply of about 1 V and DC current of $\geq 30\ \mu A$ for complex logical operations. Therefore, the issue in the rectenna design is not only how efficient the rectenna is but also what the output DC voltage and current of the rectenna are at a certain RF input power level. Hence, an appropriate model for a diode that operates at low RF power level (≤ 0 dBm) and provides desired DC output current level is crucial for designing the matching circuit to obtain an optimum power transfer.

In this paper, we present a zero-bias Schottky diode and a rectifier circuit models for a low power (≤ 0 dBm) rectenna rectifying circuit. These models rely primarily on data obtained from the diode characteristic curve measurement. The zero-bias Schottky diode model provides diode parameters at the desired output DC current level to be matched with the antenna so that optimum power transfer from antenna to the diode takes place. The rectifier circuit model provides equivalent circuit model for the rectenna rectifying circuit to calculate RF to DC conversion efficiency at the desired output DC current level.

2. A zero-bias Schottky diode rectifier circuit models

Generally in RF design, a diode can be modeled as combination of resistance and capacitance. This is shown in Fig. 1 [1]. R_{pd} is the resistance of the barrier at the rectifying contact and varies with current flowing through it. R_{sd} is the parasitic series resistance of the diode. C_j is junction capacitance arises from

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storage of charge in the boundary layer. Usually, only R_{sd} and C_j are provided in a component databook. R_{pd} is only given at certain operating current. However, by measuring diode characteristic curve, one will be able to obtain R_{pd} for various diode DC current and appropriate matching circuit can be designed.

The model shown in Fig. 1 can be simplified further to that shown in Fig. 2. In terms of the components in Fig. 1, $R_d(\omega)$ and $C_d(\omega)$ in Fig. 2 are expressed as [2],

$$R_d(\omega) = R_{sd} + \frac{R_{pd}}{1+\omega^2 R_{pd}^2 C_j^2} \quad (1) \qquad C_d(\omega) = C_j\left(1+\frac{1}{\omega^2 R_{pd}^2 C_j^2}\right) \quad (2)$$

These are the parameters to be matched for optimum power transfer at the desired DC output current [2].

The rectenna circuit can be simplified into AC and DC equivalent circuits as shown in Figs. 3a and 3b. In the AC circuit, V_s is the receiving antenna. The transformer and the inductor represent the antenna-diode matching circuit. In the DC circuit, the diode could be modeled as a voltage source with R_s source resistance. R_L is a variable load resistor to vary the DC output current.

The desired operating frequency is chosen as a resonant frequency ω. In the rectifier circuit model, $R_d(\omega)$ and $C_d(\omega)$ are calculated by using the value of R_{pd} when the DC current approaches zero in the diode characteristic curve. Similarly, R_s is the slope of the diode characteristic curve (dV/dI) when the DC current approaches zero. To be practical, we can use 1 μA in the diode characteristic curve to obtain all these values. At resonance, the voltage drops across the capacitance $C_d(\omega)$, denotes as V'_{out}, is $V'_{out} = jQV_1$ where voltage magnification factor $Q = (\omega R_d(\omega)C_d(\omega))^{-1}$.

The variable that correlates the AC and DC model are V'_{out} and V_{out}. V_{out} in the DC model shown in Fig. 3b is equal to the amplitude of V'_{out} in the AC model (Fig. 3a). Let P_{in} be the power received by the antenna. V_1 can be expressed in terms of P_{in} as $V_1 = (2\, R_d(\omega)P_{in})^{1/2}$.

The RF to DC conversion efficiency η which is defined as the ratio of the power dissipated on R_L and P_{in} for a rectenna circuit can be written as,

$$\eta = \frac{V_{out}^2 R_L}{(R_L + R_s)^2 P_{in}}. \qquad (3)$$

Utilizing relations (1), (2) and (3), one could calculate η and the required received power at the antenna to achieve the required V_L and I_{out} at a certain resonant frequency without having to develop the prototype of the rectenna circuit.

3. Results

As an example, we design a single diode rectenna rectifying circuit using HSMS-2850 Schottky diode. From HP Technical Data Sheet, R_{sd} for HSMS-2850 is 20 Ω. C_j is 0.16 pF. From the diode characteristic curve, R_{pd} and R_s when the diode DC current is 1 μA are 7.2 kΩ and 5 kΩ, respectively. The measured diode characteristic curve is displayed in Fig. 4. For 1.47 GHz, by using Eqs. (1) and (2), $R_d(\omega) \approx 82\ \Omega$ and $C_d(\omega) \approx 0.16$ pF. A prototype was built and optimized for $I_{out} = 30$ μA by following procedure described in Sec. 2. The return loss after matching to 50 Ω is excellent ($S_{11} < -20$ dB) when $I_{out} = 30$ μA. The rectifying circuit is connected to a signal generator (50 Ω input impedance) which is set to -10 dBm. The output load resistance of the rectifying circuit R_L is varied to obtain the desired I_{out}. Figure 5 illustrates the RF to DC conversion efficiency (η) for various I_{out} at a fixed RF input power (-10 dBm). The solid line represents estimated η by utilizing Eq.(3). The black dots represent measured η. The measured and calculated results are comparable and show similar behavior. The measured efficiency is lower because there are some RF power that is converted to higher order harmonics. A careful measurement of the diode characteristic curve would also enhance the agreement between the estimated and measured η. V_L can be obtained by multiplying I_{out} with R_L. The models have been applied to rectifying circuit design using HSMS-8101 Schottky diode, and the results are in good agreement.

4. Summary

A diode model and rectifier circuit model, which rely on the diode characteristic curve, for designing low power rectenna rectifying circuit is presented. The diode model allows one to design a matching circuit between the diode and an antenna for optimum power transfer to occur at the desired DC output current. The rectifier circuit model calculates RF to DC conversion efficiency. It can be used to determine whether the rectenna circuit can achieve the desired DC output voltage and current for a given RF input power. These two models are a very useful tools in calculating and predicting the performance of a rectenna at low RF input power without having to develop the rectenna prototypes.

5. References

1. H. C. Torrey and C. A. Whitmer, "Crystal Rectifiers," MIT Radiation Lab. Series, no. 15, New York : McGraw Hill, 1948.
2. J. Joe, M. Y. W. Chia, A. K. Marath, and C. H. Ang, "Zero Bias Schottky Diode Model for Low Power, Moderate Current Rectenna," DETS'97 Proc., pp. 141-145, Nov. 1997.

6. Figures

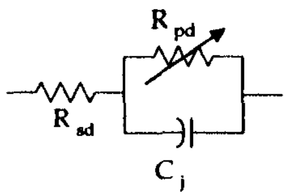


Fig. 1. Diode equivalent Circuit.

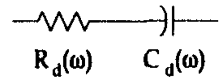
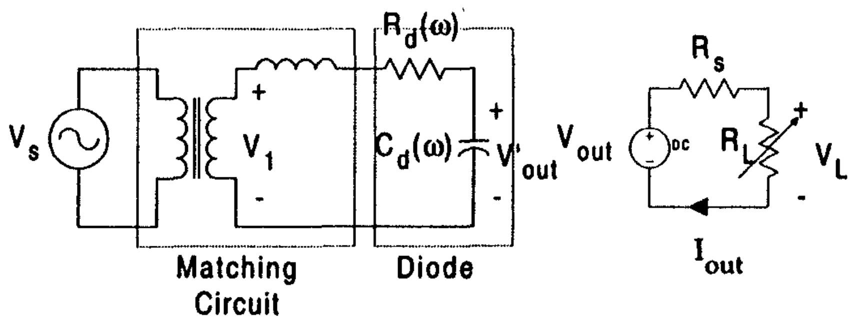


Fig. 2. Zero-bias Schottky diode model



(a)

(b)

Fig. 3. Rectifier circuit model (a) AC model (b) DC model

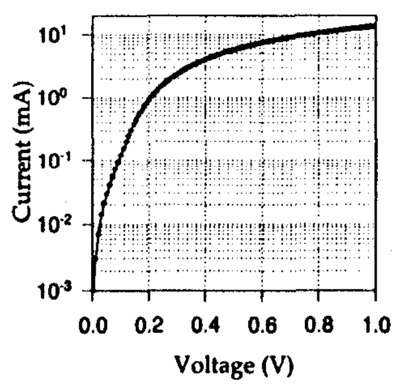


Fig. 4. Measured diode characteristic curve

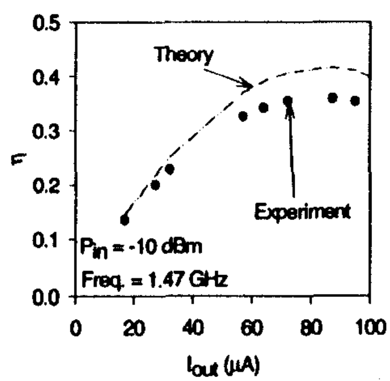


Fig. 5. η vs. I_{out}