the cost of increasing the degree of ill-posedness. Furthermore, also the case of near field data can be accommodated through again modifying the data equation given by (11) accordingly.

REFERENCES

1. D. Colton and P. Monk, A novel method for solving the inverse scattering problem for time-harmonic acoustic waves in the resonance region, SIAM 3, J Appl Math 45 (1985), 1039–1053.
2. D. Colton and P. Monk, A novel method for solving the inverse scattering problem for time-harmonic acoustic waves in the resonance region II, SIAM 3, J Appl Math 46 (1986), 506–523.
3. D. Colton and P. Monk, The numerical solution of the three-dimensional inverse scattering problem for time-harmonic acoustic waves, SIAM 3, J Sci Stat Comput 8 (1987), 278–291.
4. R.L. Ochs, The limited aperture problem of inverse acoustic scattering: Dirichlet boundary condition SIAP, 47 (1987), 1320–1341.
5. A. Kirsch, R. Kress, P. Monk, and A. Zinn, Two methods for solving the inverse acoustic scattering problem, Inverse Problems 4 (1988), 749–770.
6. W.C. Chew and Y.M. Wang, Reconstruction of two-dimensional permittivity distribution using the distorted Born iterative method, IEEE Trans Med Imaging 9 (1990), 218–225.
7. R.F. Remis and P.M. van den Berg, On the equivalence of the Newton-Kantorovich and distorted Born methods, Inverse Problems 16 (2000), L1–L4.
8. R. Kress and P. Serranho, A hybrid method for sound-hard obstacle reconstruction, J Comput Appl Math 24 (2007), 418–427.
9. R. Kress and P. Serranho, A hybrid method for two-dimensional crack reconstruction, Inverse Problems 21 (2005), 773–784.
10. D. Colton and R. Kress, Inverse Acoustic and electromagnetic scattering theory, 2nd ed., Springer, Berlin, 1998.
11. D. Colton and R. Kress, Integral equation methods in scattering theory, Krieger Pub Co., 1991.

AN ENHANCED MICROWAVE RECTIFYING CIRCUIT USING HSMS-282

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ABSTRACT: *A novel single diode rectifying circuit at 2.45 GHz is presented. An inductor is series-connected with an HSMS-282 Schottky diode to enhance the rectification performance. The imaginary part of the complex impedance of the diode is taken into consideration. Simulations and measurements show that the dynamic range of the load is widened with good radio frequency to direct current conversion efficiency (RF-to-DC Eff.). A conversion efficiency over 70% is demonstrated in this novel design.* © 2009 Wiley Periodicals, Inc. Microwave Opt Technol Lett 51: 1151–1153, 2009; Published online in Wiley InterScience (www.interscience.wiley.com). DOI 10.1002/mop.24237

Key words: *microwave; rectifier; Schottky diode; rectenna*

1. INTRODUCTION

Various kinds of rectifiers are available in microwave wireless power transmission applications [1–4]. Not only Schottky diodes but also GaAs FET [5] and HEMET [6] are applied to rectifiers. Moreover, dual-band and dual-polarization rectennas appeared as well [7, 8]. Reference [9] presented the model of a Schottky diode and its proper matching circuits. Rectifying circuit suffers from varying RF-to-DC Eff. with different DC loads and RF input power level [10]. In this letter, we took the imaginary part of diode (HSMS-282) complex impedance into account, and designed an enhanced rectifying circuit.

2. RECTIFIER DESIGN AND ANALYSIS

2.1. Diode Impedance and Series Inductor

In our design, the large signal model of HSMS-282 Schottky diode is used [9]. Its basic parameters are the series resistance $R_S = 6\ \Omega$, the zero-bias junction capacitance $C_{J0} = 0.7$ pF, the forward bias turn on voltage $V_{BI} = 0.65$ V, and the reverse break-down voltage $V_{BR} = 15$ V. The complex impedance of the diode is shown in Figure 1. It is unlike the Schottky diode MA40150-119 [4] of which the imaginary part of diode impedance approaches zero with large DC load resistance. The higher the RF input power is, the less the junction capacitance is, and the higher the imaginary part of diode impedance is. However, the diode impedance approaches a constant independent on frequency, while the DC load resistance is high.

The imaginary part of the diode is

$$\mathrm{Im}[Z_D] = \frac{-j\pi}{\omega C_j\left(\dfrac{\pi-\theta_{on}}{\cos\theta_{on}} + \sin\theta_{on}\right)} \tag{1}$$

where $\tan\theta_{on} - \theta_{on} = \pi R_s/R_L\left(1 + \dfrac{V_{BI}}{V_0}\right)$, $C_j = C_{j0}\sqrt{\dfrac{V_{BI}}{V_{BI}+V_0}}$, and V_0 is the diode self-bias DC voltage.

Assuming that the input RF power is large enough to provide self-bias DC voltage, and the turn-on angle is small, that is, $\theta_{on} \to 0$, with the first-order approximation, we obtain

$$\mathrm{Im}[Z_D] \approx \frac{1}{j\omega C_j} \tag{2}$$

A series inductor may easily cancel the reactance of the diode and lead to a simpler impedance matching circuit. The required series inductance is determined by

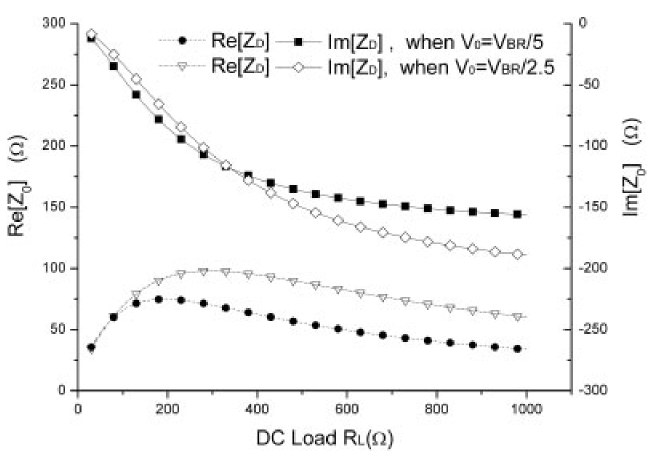

Figure 1 Diode impedance of HSMS-282

$$\omega_0^2 = \frac{1}{LC_{\mathrm{j}}} \tag{3}$$

where ω_0 is the operational frequency.

2.2. Rectifier Design

An inductor is series connected to a Schottky diode HSMS-282 in Figure 2. The 8 nH inductance is obtained from (1.7) with operating frequency at 2.45 GHz. The applied RF power is $P_{\mathrm{RF}} = 20$ dBm. The scheme and layout are shown in Figures 2(a) and 2(b), respectively.

The rectifier is realized on a substrate with $\varepsilon_{\mathrm{r}} = 2.65$ and thickness of 1 mm. A low pass filter is applied before the diode to block harmonics produced by the diode. The Schottky diode is followed by a segment of microstrip line terminated with a capacitor C_2 and a load R. Microstrip lines before and after the Schottky diode are applied to adjust the real part of the diode impedance match. The optimum lengths of those 50 Ω microstrip lines are 25.0 and 16.8 mm, respectively.

The RF-to-DC Eff. is defined as

$$\eta = \frac{(V_{\mathrm{DC}})^2}{R_{\mathrm{L}}} \times \frac{1}{P_{\mathrm{RF}}} \times 100\% \tag{4}$$

where V_{DC} is the output DC voltage, R_{L} is the load, and P_{RF} is the input RF power.

The conversion efficiency dependent on series inductance is shown in Figure 3. The simulation is performed with the harmonic balance method in Agilent ADS. The inductance varies from 0 nH (without series inductor) to 12 nH. The best performance is achieved when the series inductance is 8 nH. The result agrees with the diode impedance analysis as well.

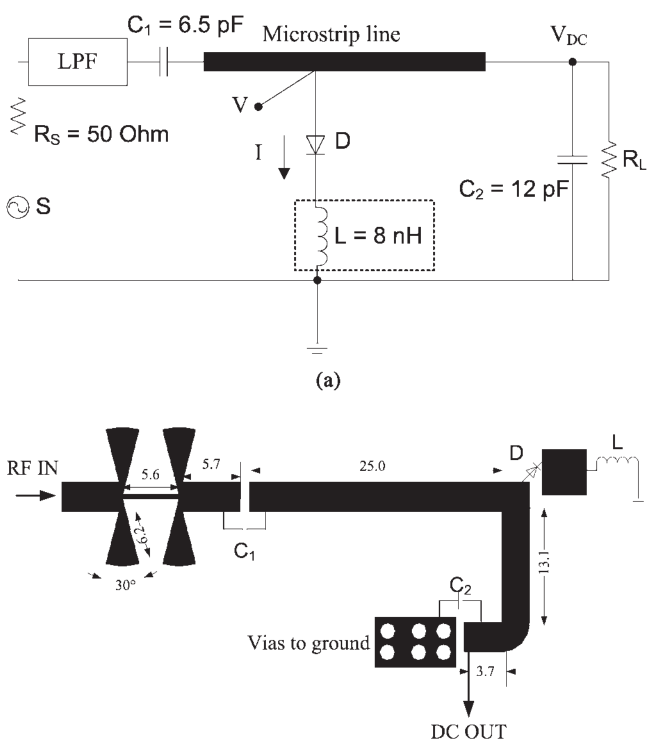

Figure 2 (a) Proposed single diode rectifying circuit (b) Layout of the proposed rectifier

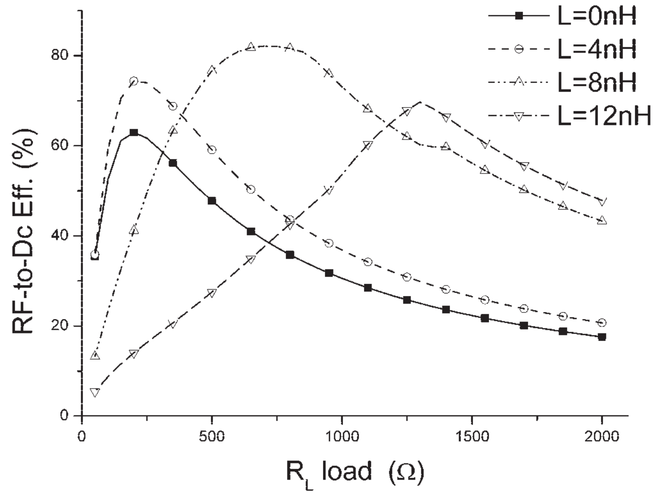

Figure 3 Efficiency with various inductance

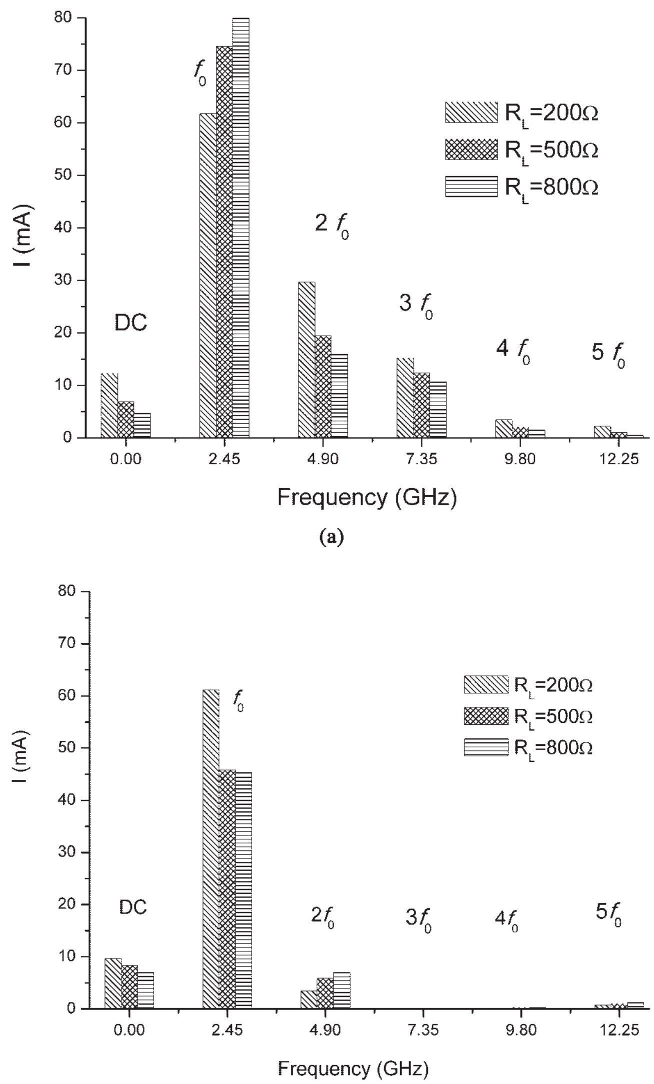

Figure 4 (a) Spectrum of the diode current $L = 0$ nH (b) Spectrum of the diode current $L = 8$ nH

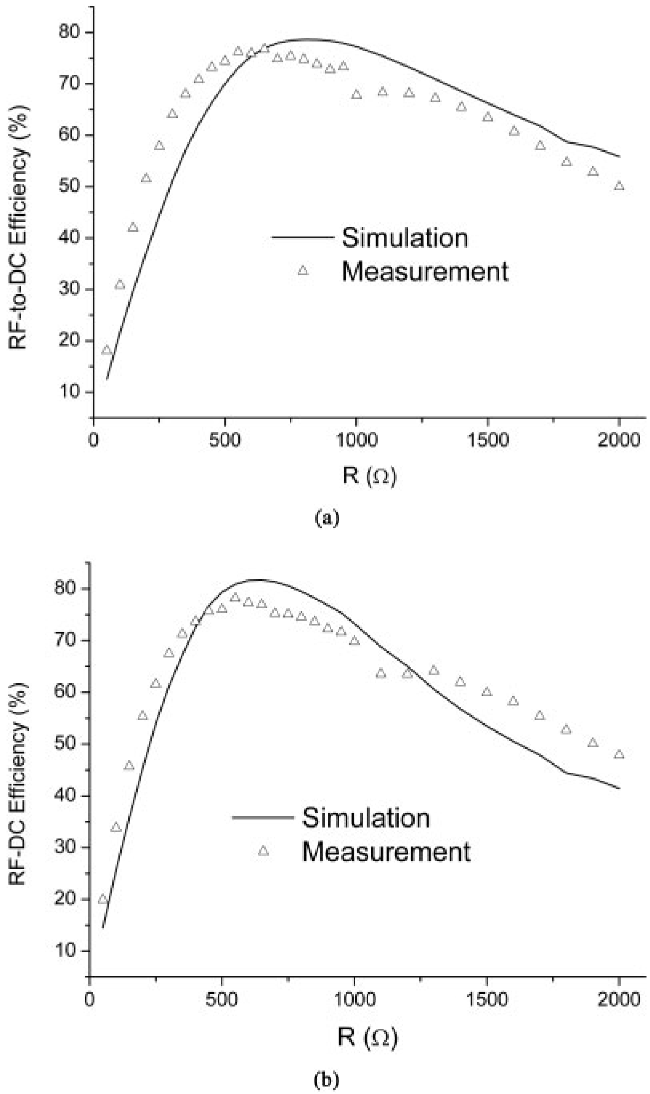

Figure 5 (a) Simulated and measured RF-to-DC conversion efficiency 17 dBm (b) Simulated and measured RF-to-DC conversion efficiency 20 dBm

An appropriate series inductor enhances the performance of the rectifying circuit. Not only the RF-to-DC Eff. but also the dynamic range of the DC load is improved.

2.3. Spectrum Consideration

The spectrum of the rectifying circuit with and without the series inductor is compared. When the input RF power is $P_{\mathrm{RF}} =$ 20 dBm, Figure 4 gives the spectrums of the diode currents with DC loads from 100 to 800 Ω. It shows that the harmonics, especially the second harmonics, are suppressed when the series inductor is $L = 8$ nH in the rectifier. There is a threshold R_{TH} for the load R. When $R > R_{\mathrm{TH}}$, the DC components with 8 nH inductor is greater.

4. EXPERIMENTAL RESULTS

An Agilent E8267C microwave vector signal generator, a dual-channel microwave power meter, a 20 dB bi-directional coupler, and a DC voltage meter are used in experiments. Figure 5 shows the simulated and measured RF-to-DC Eff. with 8 nH inductor and with input RF power at 17 and 20 dBm, respectively. The measured efficiencies are the average of two measurements, which agree well to the simulations from ADS. If the reflected RF power is taken into consideration, the conversion efficiency will increase about 3 to 5%.

From the comparison between different input RF powers in Figures 5(a) and 5(b), the optimum DC load decreases to achieve the best RF-to-DC Eff. when RF power increases. Both input power 17 and 20 dBm have high RF-to-DC Eff. and wide dynamic range of DC load and this indicates that DC load and RF-to-DC Eff. do not vary much sharply with input RF power in this inductor conjugate matched rectification circuit.

5 CONCLUSIONS

In this letter, a rectifier using a single diode with a series inductor is proposed. Spectrum analysis of harmonic frequencies is taking into consideration. Both simulations and experimental results verify the theory and analysis. The dynamic range of DC load is widened, and the RF-to-DC Eff. is improved. The rectifier using a diode with a series inductor could enhance the impedance matching and improves the rectification performance, while the design procedure remains mostly unchanged.

REFERENCES

1. T. Yamamoto, K. Fujimori, M. Sanagi, and S. Nogi, The design of mw-class RF-DC conversion circuit using the full-wave rectification, Proc 37th Eur Microwave Conf (2007), 905–908.
2. B. Strassner and K. Chang, Highly efficient C-band circularly polarized rectifying antenna array for wireless, IEEE Trans Antenna Propag 51 (2003), 1347–1356.
3. Y. Tikhov, II-J. Song, and Y.H. Min, Rectenna design for passive RFID transponders, Proc 10th Eur Conf Wireless Technol (2007), 237–240.
4. O.M. James, F. Lu, and K. Chang, Design and experiments of a high-conversion-efficiency 5.8-GHz rectenna, IEEE Trans Microwave Theory Tech 54 (1998), 2053–2060.
5. Y.H. Suh and K. Chang, A novel low-cost high-conversion-efficiency microwave power detector using GaAs FET, Microwave Opt Technol Lett 44 (2005), 29–31.
6. J.Q. Lü, M.S. Shur, R. Weikle, and M.I. Dyakonov, Detection of microwave radiation by electronic fluid in high electron mobility transistors, Electron Lett 32 (1996), 2148–2149.
7. Y.H. Suh and K. Chang, A high-efficiency dual-frequency rectenna for 2.45- and 5.8-GHz wireless power transmission, IEEE Trans Microwave Theory Tech 50 (2002), 1784–1789.
8. D.G. Youn, K.H. Kim, Y.C. Rhee, S.T. Kim, and C.C. Shin, experimental development of 2.45GHz rectenna using FSS and dual-polarization. Eur Microwave Conf (2000), 1–4.
9. J.O. McSpadden, T. Yoo, and K. Chang, Theoretical and experimental investigation of a rectenna element for microwave power transmission, IEEE Trans Microwave Theory Tech 40 (1992), 2350–2366.
10. J.A. Hagerty, F.B. Helmbrecht, W.H. McCalpin, R. Zane, and Z.B. Popovic. Recycling ambient microwave energy with broad-band rctenna arrays, IEEE Trans Microwave Theory Tech 52 (2004), 1014–1024.