A C-Band Microwave Rectifier Based on Harmonic Termination and with Input Filter Removed

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***Abstract*—This paper presents a C-band rectifier employing a third harmonic termination which is realized by a $\lambda_g/12$ short-ended microstrip transmission line. The proposed harmonic termination balances the capacitive impedance of the diode at the fundamental frequency and blocks harmonic current of the diode. The input low-pass filter or matching circuit is removed and the bandwidth of rectifier is enhanced. Theoretical analysis and experiments are carried out. The results show that the proposed topology can realize high efficiency with a wide input frequency range. The fabricated rectifier has a compact dimension of 14mm by 22mm. A maximum RF-DC conversion efficiency of 75.6% at 13 dBm input power is observed. The measured efficiency remains above 70% with the operating frequency form 5.2 GHz to 6 GHz.**

Keywords—Broadband, Schottky diode, rectifier, harmonic termination, source-pull, high efficiency

I. INTRODUCTION

In a rectifier, filters are used to reject the harmonics which produced by diode during rectifying, which consist of a low pass filter and DC-pass filter [1]. However, the input filter or matching circuit limits the bandwidth of rectifier.

Currently several broadband and multi-band rectifier are designed by wideband matching network. For instance, a broad-band rectifier is based on maximizing the quality factor of matching circuits is presented in [3]. In [4], a broadband energy harvesting system is realized by high impedance antenna. Simplified real frequency technology is proposed to optimize the input matching architecture in [5].

Harmonic terminations is used to shape the current and voltage waveforms across the diode to minimize the overlap and improve the efficiency. In [6], a compact Class-F converter is realized by anti-symmetric configuration of two shunt-diode. However, we can get high efficiency with narrow bandwidth by combining the harmonic termination with input matching.

As the input low-pass filter puts a limitation of bandwidth of rectifier, and conversion efficiency can be improved by eliminating harmonic power, we propose a novel rectifier which has no input low-pass filter. The proposed rectifier employs a $\lambda_g/12$ short-ended transmission line as open circuit to third harmonic and high reflection to second harmonic. Meanwhile, the $\lambda_g/12$ short-ended transmission line cancels the imaginary part of diode capacitive impedance because it presents inductive reactance at fundamental frequency. The resonance effect is generated and the harmonic components of proposed rectifier are sufficient low that the input low-pass filter is not needed. We employ a lumped DC- pass filter which chokes the RF signal before the DC load.

II. PRINCIPLE AND DESIGN METHOD

A. Principle

A conventional microwave rectifying schematic is shown in Fig. 1, in which a low-pass filter and a DC-pass filter are applied to recycle the harmonics produced during rectification. The input low-pass filter will acts as matching circuits as well, and it rejects the generated harmonics during rectification. However, it will bring insertion loss and put a limitation to the band width of rectifier.

For the 2nd and 3rd harmonics, the conventional rectifier needs a high performance DC-pass filter as well.

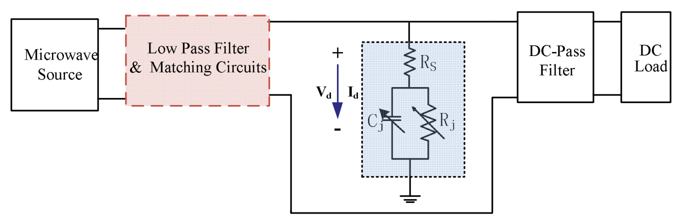

Fig. 1. The conventional microwave with a low-pass filter and a high performance DC-pass filter

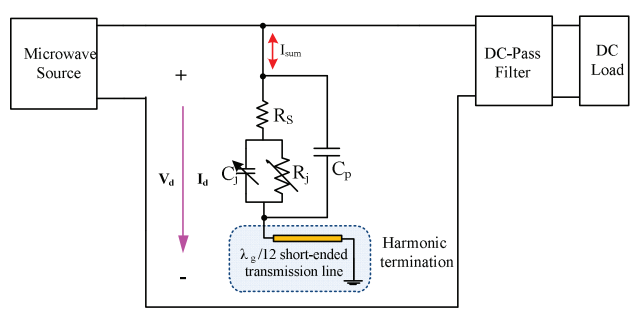

Fig. 2. Proposed rectifier has a third harmonic termination but no filter or matching stub

As the input low-pass filter put a limitation to the bandwidth of rectifier, we propose novel topology which removes the input matching circuit or low pass filter. The block diagram of proposed rectifier is shown in Fig. 2, is that a $\lambda_g/12$ short-ended

978-1-5090-4585-3/17/$31.00 ©2017 IEEE

transmission line is inserted at the diode's cathode and ground plane.

The $\lambda_g/12$ short-end has the following functions:

i) Presents high impedance at the third harmonic and relatively high impedance at the second harmonic.

ii) Provides a DC path for the DC output of rectifier.

iii) Cancelling the diode capacitive impedance. In the view of impedance matching, the $\lambda_g/12$ short-end transmission line presents $0.58jZ_{SE}$ at fundament frequency, which compensates diode capacitive reactance.

B. Theoretical Analysis

An ideal perfect harmonic termination which presents high impedance at 2nd and 3rd harmonics at same time is hard to realize in practice. The $\lambda_g/12$ short-end transmission line which presents an open circuit at $3\omega_0$ is easy to fabricate. The $\lambda_g/12$ short-ended transmission line presents inductive 0.5 jZ_{SE} at the fundamental frequency ω_0, as shown in (1) where Z_{SE} is the characteristic impedance of the transmission line [7].

$$Z_{\lambda g/12} = jXL = jZ_{SE}\tan\left(\frac{\pi}{6}\frac{\omega}{\omega_0}\right) = \begin{cases} 0, & \omega = 0 \\ 0.58\,jZ_{SE}, & \omega = \omega_0 \\ 1.73\,jZ_{SE}, & \omega = 2\omega_0 \\ \infty, & \omega = 3\omega_0 \end{cases} \quad (1)$$

The short-ended transmission line presents a zero impedance at DC, which provides a path for DC output. If the diode impedance matching needs an inductive reactance of 50 Ω at ω_0, which means that $0.58jZ_{SE}$ = 50 Ω, the $\lambda_g/12$ turns out to be 150 Ω at second harmonic $2\omega_0$.

C. Rectifier design-Simulation

Fig. 3 shows the schematic of propose rectifier. The capacitor C_1 blocks the DC from the rectifier to the microwave source, and the inductor L and capacitor C_2 form a DC-passed filter. The HSMS-2860 Schottky diode, capacitor C_1=9.1 pF, C_2=30 pF, L=10 nH and R_L=900 Ω are used.

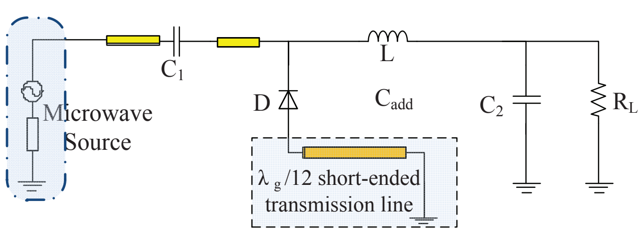

Fig. 3. Schematic of the proposed microwave rectifier, the $\lambda_g/12$ short-ended is in dash rectangle.

The fundamental input impedance of rectifier such as the one shown in Fig. 3, is a shunt R_e in parallel with a capacitor C_e. The R_e and C_e depend on the input power, output voltage, diode turn on angle Θ_{on}, dynamic resistance of diode and reverse bias voltage on diode. The input impedance of proposed rectifier with one shunt HSMS-2860 diode was simulated using harmonic balance for given 900 Ω DC load and 10 dBm input power. The equivalent R_e and C_e were extracted for the LSSP simulation results.

The equivalent circuit is shown in Fig. 4. The inductor L_e has compensated the imaginary part of diode impedance. We can calculate the characteristic impedance of $\lambda_g/12$ short-ended transmission line, and then determine the width of $\lambda_g/12$ line at given substructure by (2).

$$jXL_e = 0.58\,jZ_{SE} \quad (2)$$

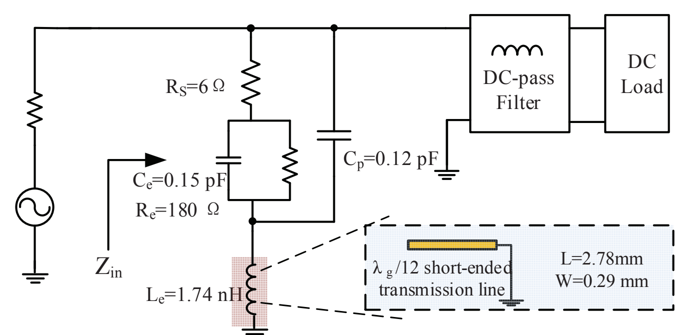

Fig. 4. Equivalent circuit of proposed rectifier, the L_e has the same impedance as the $\lambda_g/12$ short-ended transmission line.

After simulation, in Fig. 4, the L_e has compensated the imaginary part of diode impedance and it has a value of 1.74 nH. Thus, the characteristic impedance of $\lambda_g/12$ short-ended transmission line is 108 Ω at 5.8 GHz. For RO-4350B with thickness of 0.76 mm and dielectric constant of 3.70, the width of $\lambda_g/12$ is 0.3 mm and the length of $\lambda_g/12$ is 2.78 mm.

By replacing the L_{add} with $\lambda_g/12$ short-ended transmission line, we present the impedance and $|S_{11}|$ return loss of equivalent rectifier circuit in Fig.5.

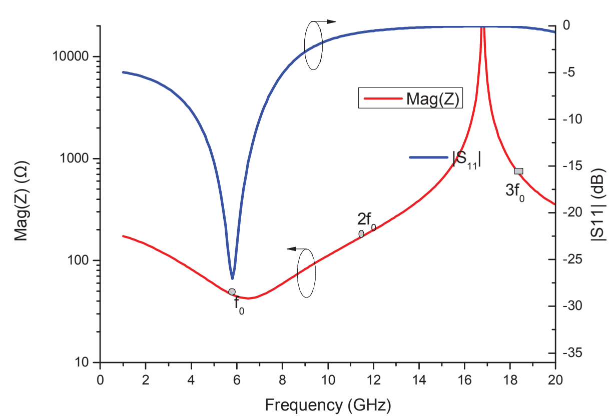

Fig. 5. The return loss $|S_{11}|$ and input impedance of equivalent rectifier circuit

The schematic of proposed rectifier has been designed and optimized by source-pull technology to achieve a high performance. The case of 13 dBm input power with the source-pull contours is shown in Fig. 6.

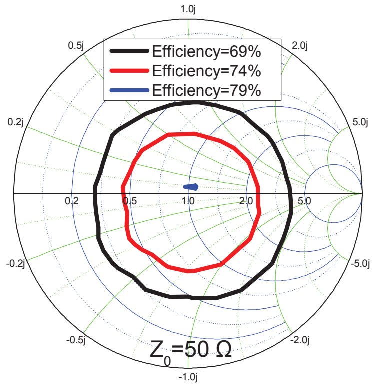

Fig. 6. Source-pull contours with input power = 13 dBm and DC load = 500 Ω. The imaginary part of diode impedance has been compensated by $\lambda_g/12$ short-ended transmission line

As shown in Fig. 6, a peak efficiency of 79.4% occurs with Z_p= (54+j*3) Ω. With the optimal input impedance, there is no need for extra matching circuits at input port.

III. Experimental and Simulation Results

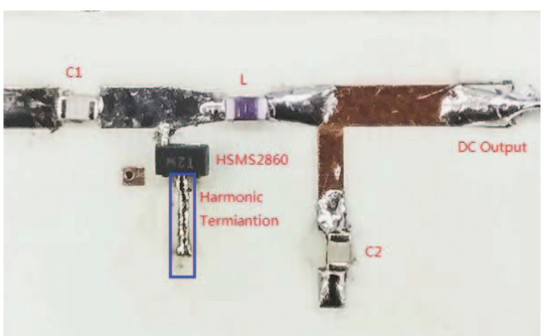

Fig. 7. Photograph of fabricated microwave rectifier which has a dimension of 14mm × 22 mm

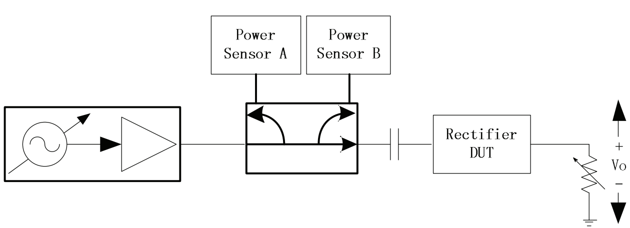

Fig. 8. Block diagram of RF-DC efficiency and reflected harmonics levels measurement system.

The prototype, Fig. 7, has been fabricated in accordance with the schematic shown in Fig. 3. The finished rectifier has a very compact dimension of 14mm × 22 mm. The measurement setup was as follows, Fig. 8: a direction coupler was connected between the signal generator and the rectifier. The reflected power is measured by power sensor B. By varying the input power and frequency, the DC voltage was measured across the load; the efficiency was calculated by (3). The P_{IN} is the available power from the microwave source, V_0 is the output DC voltage, and R_L is the DC load.

$$\eta_{RF-DC} = \frac{P_{DC}}{P_{IN}} \times 100\% = \frac{V_0^2}{R_L} \times \frac{1}{P_{IN}} \times 100\% \qquad (3)$$

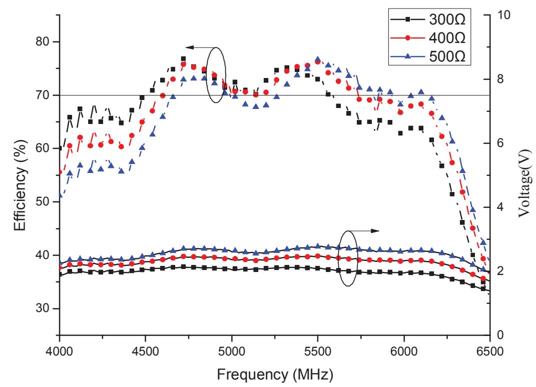

Fig. 9. Measured conversion efficiency and output voltage with respect to frequency for 13 dBm input power

At first, the rectifier has been measured with 300 Ω, 400 Ω and 500 Ω at 13 dBm input power, and the conversion efficiency and output DC voltage is depicted in Fig. 9. With regard to 500 Ω, a peak efficiency of 75.6% at 5.4 GHz is observed, and greater than 70% efficiency can be obtained from 5.2 GHz to 6 GHz.

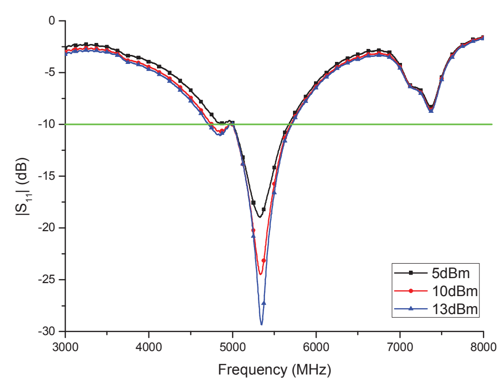

Fig. 10. . $|S_{11}|$ of the rectifier at 5dBm, 10 dBm and 13 dBm input power

Secondly, the rectifier has been measured at P_{IN} = 5, 10, and 13 dBm, respectively, the measured return losses are shown in Fig. 10.The vertical network analyzer (Agilent N5230A) and 500 Ω DC load were used. With the input power increasing, the reflection becomes low. The results demonstrate that the rectifier has more than 1GHz bandwidth at each input power.

IV. CONCLUSIONS

This paper has presented a novel high efficiency, broadband rectifier with principle of harmonic termination and elimination of input filter. Table 1 shows performance comparison among the proposed rectifier and some prior rectifier based on Schottky diode.

As the input low-pass filters or matching circuit in conventional microwave rectifiers has been removed, and the $\lambda_g/12$ harmonic termination leads to a compact dimension, high efficiency and low harmonic. The proposed rectifier shows a wide operating frequency bandwidth and high conversion efficiency.

TABLE I. **COMPARISON WITH SOME PRIOR RECTIFIER WITH DIODE**

reference		[8]	[9]	[10]	**This work**
dimension		N.A	35×26mm	N.A	**14×22mm**
frequency bandwidth of efficiency over 70%		0	0	0	**5.2- 6 GHz (14.2 %)**
rectifier Elements		HSMS286	HSMS286	MA4E2054	**HSMS2860**
number of diode		1	1	1	**1**
The maximum efficiency	efficiency	68.1%	51.5%	65.3%	**75.6%**
	input power	19 dBm	10 dBm	19 dBm	**13 dBm**
	frequency	5.8 GHz	5.8 GHz	5.8 GHz	**5.4 GHz**
	DC Load	200 Ω	N.A	600 Ω	**400Ω**

REFERENCES

[1] [1] T. W. Yoo and K. Chang, “Theoretical and experimental development of 10 and 35 GHz rectennas,” *IEEE Trans. Microw. Theory Tech.*, vol. 40, no. 6, pp. 1259–1266, Jun. 1992.

[2] [2] J. O. McSpadden, L. Fan, and K. Chang, “Design and experiments of a high-conversion-efficiency 5.8-GHz rectenna,” *IEEE Trans. Microw. Theory Tech.*, vol. 46, no. 12, pp. 2053–2060, Dec. 1998.

[3] [3] H. Sakaki and K. Nishikawa, “Broadband rectifier design based on quality factor of input matching circuit,” in *2014 Asia-Pacific Microwave Conference*, 2014, pp. 1205–1207.

[4] [4] M. Arrawatia, M. S. Baghini, and G. Kumar, “Broadband RF energy harvesting system covering CDMA, GSM900, GSM1800, 3G bands with inherent impedance matching,” in *2016 IEEE MTT-S International Microwave Symposium (IMS)*, 2016, pp. 1–3.

[5] [5] D. Wang, X. A. Nghiem, and R. Negra, “Design of a 57 % bandwidth microwave rectifier for powering application,” in *2014 IEEE Wireless Power Transfer Conference*, 2014, pp. 68–71.

[6] [6] A. Noda and H. Shinoda, “Compact class-F RF-DC converter with antisymmetric dual-diode configuration,” in *Microwave Symposium Digest (MTT), 2012 IEEE MTT-S International*, 2012, pp. 1–3.

[7] [7] D. M. Pozar, *Microwave engineering*. John Wiley & Sons, 2009.

[8] [8] B. Zhang, W. Jiang, C. Yu, and C. Liu, “A C-band microwave rectifier without capacitors for microwave power transmission,” *Int. J. Microw. Wirel. Technol.*, vol. 7, no. 6, pp. 623–628, 2015.

[9] [9] D. Wang and R. Negra, “Design of a dual-band rectifier for wireless power transmission,” in *2013 IEEE Wireless Power Transfer (WPT)*, 2013, pp. 127–130.

[10] [10] S. Imai, S. Tamaru, K. Fujimori, M. Sanagi, and S. Nogi, “Efficiency and harmonics generation in microwave to DC conversion circuits of half-wave and full-wave rectifier types,” in *2011 IEEE MTT-S International Microwave Workshop Series on Innovative Wireless Power Transmission: Technologies, Systems, and Applications*, 2011, pp. 15–18.