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Towards Millimeter-Wave High-Efficiency Rectification for Wireless Energy Harvesting

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Abstract — This paper introduces a simple dual diode rectifier circuit in microstrip technology operating at K-band towards millimeter-wave applications. The designed rectifier circuit has a special architecture that enables the separation of the DC component of the rectified wave from the data-related IF channel. Diode characteristics are discussed for efficiency enhancement which is involved in accurate system simulations. Optimization procedure is carried out in order to maximize the RF-to-DC conversion efficiency. A measured efficiency of 40% for 35 mW input power is achieved for the designed circuit, showing an improvement in efficiency in comparison with previous works. The circuit presents potential applications in the design of integrated microwave and millimeter-wave systems for wireless power transmission and energy harvesting.

Index Terms — Wireless power transmission, rectenna, rectifier circuit, Schottky diode, RF-to-DC conversion efficiency.

I. INTRODUCTION

With the emerging of low power integrated electronics and wireless systems, numerous researchers have been looking into the feasibility of powering mobile devices through the harvesting of ambient electromagnetic energy. It can be anticipated that RF power harvester that generates a sufficient amount of DC power to drive the operation of a wireless device could be instrumental in the development of future wireless systems with limited use of batteries. Therefore, wireless power transmission (WPT) has become a refreshed and refocused technology for wireless applications such as RF identification (RFID) and wireless sensor networks [1]. A rectenna, made up of a receive antenna and a rectifier circuit, is one of the critical components of the WPT system that wirelessly receives the microwave power and converts it into DC. Thus, it is essential to realize high-efficiency rectennas or rectifier circuits. Generally, the rectifying circuit determines the overall efficiency of the system. So far, commonly used wireless frequencies in the design of rectennas have been studied and experimentally tested, which are lower than 10

GHz. At low-frequency, antenna structure may be limited by its size although the absolute power is largely available at low wireless frequencies. In the literature, various structures of rectifier circuit have been studied from two aspects, namely operating frequency and RF-to-DC conversion efficiency [2]-[4]. A rectenna with 85% and 82% RF-to-DC conversion efficiency operating at 2.45 and 5.8 GHz, respectively, was studied in [2]. Another structure of rectenna operating at 10 GHz and 35 GHz with 60% and 39% RF-to-DC conversion efficiency respectively was reported in [4]-[5]. Recently, a study has been performed at 24 GHz with 54% efficiency driven by 130 mW input power [6].

Generally, a rectifier consists of an input filter which is band-pass or low-pass based on the operating frequency to suppress undesired higher harmonics rejected by the rectifying component, a matching circuit to ensure the impedance matching between the antenna and the rectifier component, a rectifier component that can be a diode or a transistor, an output filter which is normally a low-pass filter suppresses harmonics created by the non-linear characteristics of the rectifier component and improves the system performance and finally a resistive load [7]. The microwave rectifier may have different configurations depending on the configurations of the diodes used for rectification process such as single serial

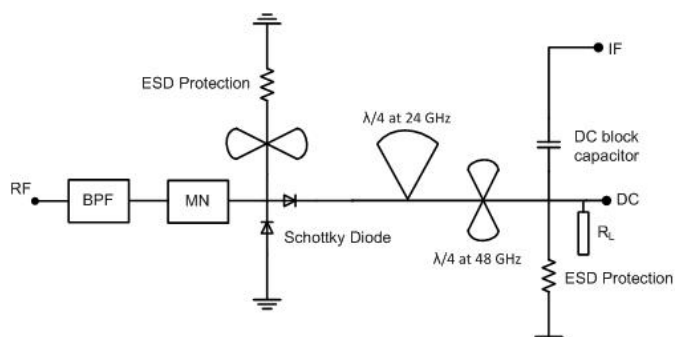


Fig. 1. Schematic configuration of the rectifier circuit.

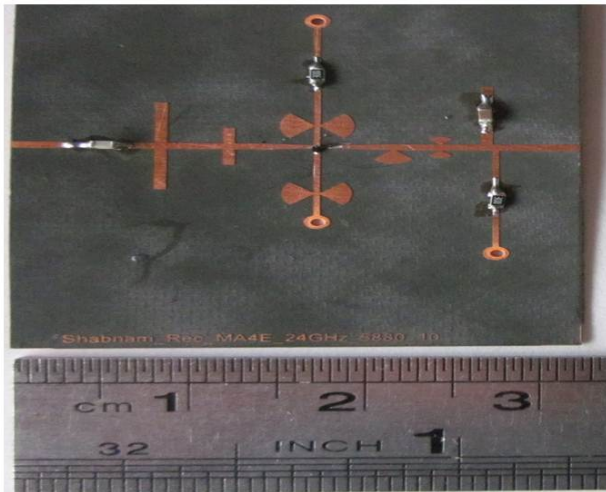
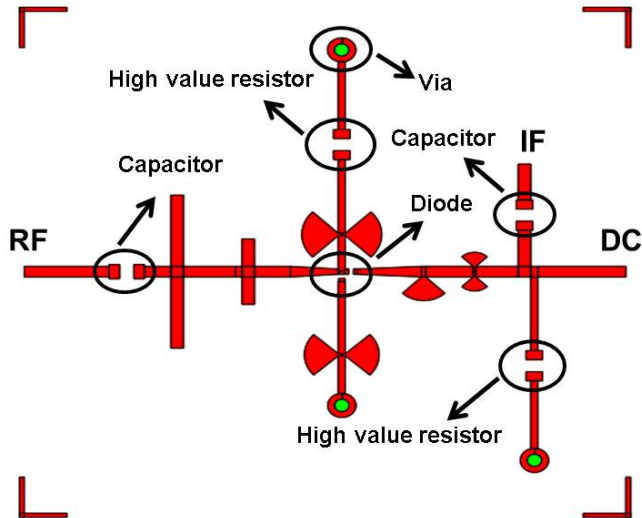


Fig. 2. Layout and fabricated prototype of the designed rectifier.

[8]-[9], shunt topology [6], [9] and voltage doubler [7], [12]-[14].

In this paper, a structure of a diode-based rectifier operating over 24 GHz ISM band in microstrip technology is proposed. The rectifier circuit consists of two diodes in a voltage doubler configuration which produces at least twice higher dc output voltage than the single-diode rectifier, while the size of the circuit is unchanged. This scheme towards up microwave and millimeter-wave frequency operations is used to lower the required input power while at the same time enhances the conversion efficiency.

II. STRUCTURE OF RECTIFICATION CIRCUIT AND ITS PRINCIPLE OF OPERATION

A block diagram of the entire system is shown in Fig. 1. The proposed structure of rectifier circuit consists of a

TABLE I
RF-to-DC CONVERSION EFFICIENCY.

Diode	Maximum Conversion Efficiency	RF Input Power (mW)
HSMS 2862 (Avago)	45%	40
DMK 2790 (Skyworks)	42%	9
MA4E1317 (MACOM)	68%	20

bandpass filter (BPF) and matching circuits at the input followed by a rectifying component (here Schottky diode) and DC pass filter. This topology presents a special mechanism that allows the separation of the DC part of the rectified wave from the IF component. This is done by using a DC block capacitor just after the harmonic rejection filter. The collected DC part at the output of this rectifier provides the required power for the system while the IF part consisting the complete I and Q components of the received RF signal is directed to the data processing units of the receiver. This scheme provides a simple rectifier topology that can be employed in self-powered transceiver architecture.

A. Design of BPF and Matching Circuit

As it is shown in Fig. 1 and Fig. 2, a BPF made of open circuit and series stubs, is located at the input of the circuit. This filter passes the 24 GHz operating frequency and reflects the higher order harmonics produced by nonlinear rectifying elements. A proper matching circuit is needed to ensure good impedance matching between the antenna and the rectifying circuit for maximum power transfer. Simple impedance matching with high efficiency is the most important goal in the design of the matching circuit. Two methods of impedance matching that include L-type matching and π -type matching can be used to realize high RF-to-DC conversion efficiency. Of course, the choice of appropriate diodes is critical for achieving high efficiency conversion efficiency.

B. Selection of Diode

In a high-efficient rectifier circuit, the diode is the core component because it is the main source of loss and its performance is critical for the overall performance of the circuit. From the analysis of [4], the power conversion efficiency of a rectifier is mainly determined by three parameters of diode including series resistance (R_s), zero-bias junction capacitance (C_{j0}) and breakdown voltage (V_{br}). For rectification purpose, the desired diode should have low series resistance, low junction capacitance and high breakdown voltage. Also, it is necessary to select a diode with the capability of a high speed switching to follow a high frequency input signal and have a low cut-off voltage to operate at low RF input power.

The evaluation of diode performances is carried out using Advanced Design System (ADS) 2009 from Agilent Technologies Inc. The equivalent model of the diode is constructed with the diode parameters obtained from the respective datasheet of the candidate diode and the real circuit model of the diode including packaging and parasitic elements obtained by small signal measurement [5]. HB and LSSP simulators are chosen to carry out simulations for the non-linear circuit. Three Schottky diodes from Skyworks, Avago and MACOM are simulated and their performances are compared and summarized in Table I. According to the simulation results, MA4E1317 from MACOM with series resistance $R_s = 4\Omega$, zero-bias junction capacitance $C_{j0} = 0.02$ pF, forward bias turn-on voltage $V_{bi} = 0.7$ V, and breakdown voltage $V_B = 7$ V, shows superior performance and it is chosen as a rectifying component in the designed circuit. As shown in Fig. 1 and Fig. 2, two lossy paths using high value resistance, in this design 200k Ω , are designed in order to protect the diodes from Electrostatic Discharge (ESD) and prevent them from being burnt.

C. Design of output filter

To avoid unwanted power dissipation, a structure of low-pass filter (LPF) is employed at the output of the circuit that is used to remove the fundamental frequency and harmonics generated by the non-linear characteristic of the diode. This filter is made up of a quarter-wave radial stub for removing the signal at the operating frequency (24 GHz) and one quarter-wave butterfly stub which rejects the signal at the first harmonic frequency (48 GHz) from being dissipated. A DC-block capacitor is employed in order to separate DC component of the rectified wave from IF part.

III. TEST STRUCTURE

The proposed topology of the rectifier is designed at 24 GHz on a 10-mil-thick high frequency Rogers 5880 ($\epsilon_r = 2.2$, $\tan\delta = 0.0004$ and copper thickness 17 μm). The layout and the fabricated circuit are shown in Fig. 2. Simulations have been done on both schematic and layout levels. Layout level simulations were done with the electromagnetic (EM) simulator Momentum in ADS. It should be mentioned that the whole RF circuit, including all passive components, via holes, component's pads and terminations are simulated individually and as a whole as well. This is important for evaluating the coupling effects among different components at up-microwave and millimeter-wave frequencies. Subsequently, they are brought back to the schematic in order to run co-simulation process. The co-simulation feature is used to make sure that all designed components show desired performances at 24 GHz. According to the simulation results, the circuit is optimized at 35 mW RF input power with 610 Ω resistive load. Fig. 3 and Fig. 4 show the simulated and measured results of achieved output DC power and RF-to-DC

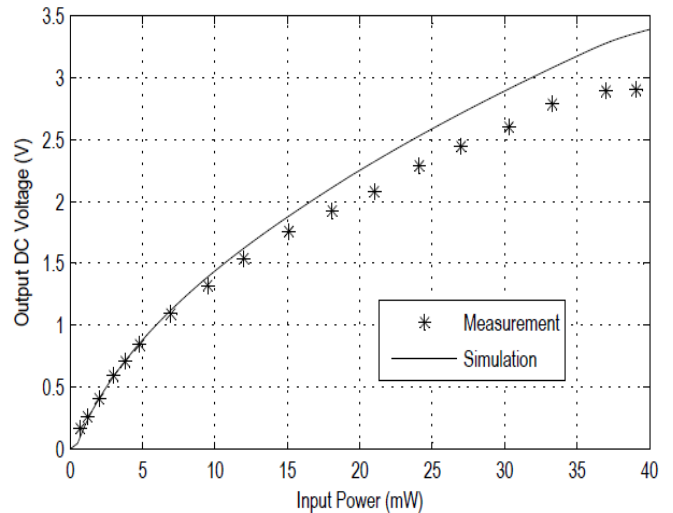


Fig. 3. Output DC voltage versus RF input power.

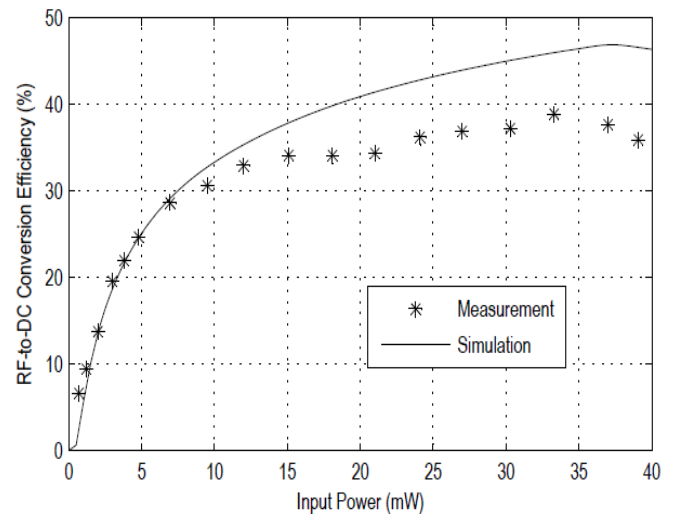


Fig. 4. RF-to-DC conversion efficiency versus RF input power.

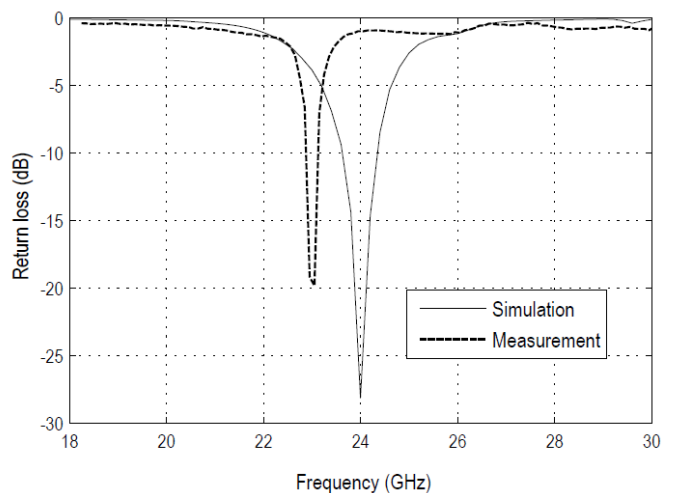


Fig. 5. The isolation at input port of the circuit.

conversion efficiency versus the input power. The measured efficiency is reported at 23 GHz since the fabricated prototype is matched at 23 GHz, Fig. 5, and it shows better performance at this frequency. The 4% frequency shift, 1 GHz, between simulation and fabricated prototype is acceptable at 24 GHz. It is necessary to mention that at mm-wave frequencies there is some difference between simulation and measurement results of efficiency. This deviation is considered because of the effect of the non-linear junction capacitance of the rectifying diode which becomes dominant at microwave and up microwave frequencies [4]. The conversion efficiency increases gradually when the input power is less than 35 mW then the efficiency drops down rapidly because the diode voltage exceeds the break down voltage. The RF-to-DC conversion efficiency of the rectifier is defined as follows:

$$\eta = \frac{P_{DC}}{P_{in}} \quad (1)$$

$$P_{DC} = \frac{V_D^2}{R_L} \quad (2)$$

where P_{in} is the incident RF power and V_D is the DC voltage on the load, respectively.

VII. CONCLUSION

A simple structure of dual-diode rectifier is introduced. The RF-to-DC conversion efficiency of three different Schottky diodes is examined. According to the simulation results, the diode with more RF-to-DC conversion efficiency and the ability of supporting K-band is chosen as the rectifying component in the designed circuit. The proposed structure is studied by the full-wave simulations using Advanced Design System software and also experiments. The obtained results show that the proposed topology provided 40% RF-to-DC conversion efficiency for 35 mW input power experimentally. The obtained RF-to-DC conversion efficiency is a significant enhancement in the design of a high efficiency rectifier at high frequencies towards millimeter-wave applications in compare with the previous works.

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