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High-efficiency 2.45 and 5.8 GHz dual-band rectifier design with modulated input signals and a wide input power range

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ABSTRACT

This paper presents a new rectifier design for radio frequency (RF) energy harvesting by adopting a particular circuit topology to achieve two objectives at the same time. First, work with modulated input signal sources instead of only continuous waveform (CW) signals. Second, operate with a wide input power range using the Wilkinson power divider (WPD) and two different rectifier diodes (HSMS2852 and SMS7630) instead of using active components. According to the comparison with dual-band rectifiers presented in the literature, the designed rectifier is a high-efficiency rectifier for wide RF power input ranges. A peak of 67.041% and 49.089% was reached for 2.45 and 5.8 GHz, respectively, for CW as the input signal. An efficiency of 72.325% and 45.935% is obtained with a 16 QAM modulated input signal for the operating frequencies, respectively, 69.979% and 54.579% for 8PSK. The results obtained demonstrate that energy recovery systems can use modulated signals. Therefore, the use of a modulated signal over a CW signal may have additional benefits.

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1. INTRODUCTION

A significant amount of radio frequency (RF) energy is released into space due to the trillions of radio transmitters, including RF devices and base stations that have popped up all over the world due to the fast growth of wireless communication technology. These transmitters represent a reliable source for energy collection. Future green communications will be possible and look promising if mobile and low-power devices can be charged using this wireless power transfer (WPT) technology.

Numerous WPT methods have been presented with differences in operation and scope [1]. As an example, we have a magnetic resonance (MR) approach [2] that needs the resonance of two coils at the same frequency. It has a rather modest range. While the range of electromagnetic induction, the second approach, will be somewhat constrained. There is a third approach, called microwave power transmission (MPT), which is characterized by the use of a single-tone GHz-order RF signal [3]–[5]. Rectifiers are a crucial part of MPT because they transform RF power into direct current (DC) power. Numerous rectifiers with different configurations have appeared in publications [6]–[8]. The development of single-band [9]–[11], multiband [12]–[15], and broadband [16], [17] rectifiers has been made in response to the increasingly demanding energy requirements of wireless devices.

In reality, however, power density can change significantly between different sites and settings. Therefore, for the majority of mobile devices, the received RF strength is often variable and unexpected. Unfortunately, because of the restrictions on diodes and circuitry topologies, the traditional rectifier could only reach high conversion efficiency for a limited input power range. Numerous efforts have been made to increase the rectifier's input power range in order to address these issues. However, these rectifiers often require a number of supplementary circuit branches and rectifiers, which necessitates the use of more circuit components (diodes, resistors, and capacitors) and microstrip lines, increasing the size, cost, loss, and complexity of the rectifier [18], [19].

For a wide range of input powers, certain rectifier designs that use active RF switches have been described [10], [11], [20]–[22]. According to the incident power level, the configurable rectifying circuit in [10], [20] may automatically select the most suitable rectifier architecture by employing an embedded single-pole double-throw switch (SPDT) or 4-throw RF switch (SP4T). There will be more switch loss and bias network loss introduced as a result of the active switch used, which will increase complexity, loss, and integration challenges. Various rectifiers with field-effect transistor (FET) or metal oxide semiconductor field effect transistor (MOSFET) switches have been suggested to increase the input power range of rectifiers [11], [21], [22]. The overall conversion efficiency is decreased by the usage of FET and MOSFET, which can still use a lot of power. In addition, these active switches may encounter linearity and thermal issues [11], [21], [22], particularly at high operating frequencies (above 3 GHz).

Our first objective in the design process was to create a rectifier with large input power densities without using active components. Secondly, since MPT mostly employs the same hardware as microwave data transmission, it has been introduced in [23] as a wireless communication and power transmission method by using modulated signals. The goal of this system is to use a single device to send and receive both energy and information. The impact of the modulated signal on MPT must be assessed in order to implement this approach. Therefore, modulation for quadrature phase-shift keying (QPSK), 8-ary phase-shift keying (8 PSK), 8-ary quadrature-amplitude modulation (8 QAM), and 16-ary quadrature-amplitude modulation (16 QAM) is examined in this article. Through the use of a rectifier circuit and its conversion efficiency (RF/DC), the impact of modulated signals on MPT is assessed. Analysis and comparison of the rectifier efficiency using modulated signal sources to continuous wave (CW) signal sources.

This paper proposes a new rectifier design for MPT by adopting a new harvesting topology. This rectifier has the ability to provide both capabilities at the same time, i.e., working with modulated input signal sources instead of only CW signals and operating with high input power densities by using the Wilkinson power divider (WPD) power divider and two separate rectifier diodes instead of using active components. The WPD divides the design into two branches; the first branch will be a rectifier with HSMS2852 diodes to harvest relatively high input power, and the second branch linked to SMS7630 for lower power levels. The structure of this paper is as follows. First, a design phase for the suggested rectifier is described, followed by an analysis of its properties. Secondly, the efficiency of the conversion from RF to DC for modulated and CW signals is compared. Finally, a conclusion is made.

2. RECTIFIER DESIGN

The rectifying circuit is printed on the Rodgers RT/Duroid 5880 substrate. It is made to handle a broad range of input power. A WPD, two impedance matching networks, two voltage doubler circuits with two distinct diodes, and a load are all components of the proposed rectifying circuit. The chosen diodes are HSMS2852 and SMS7630

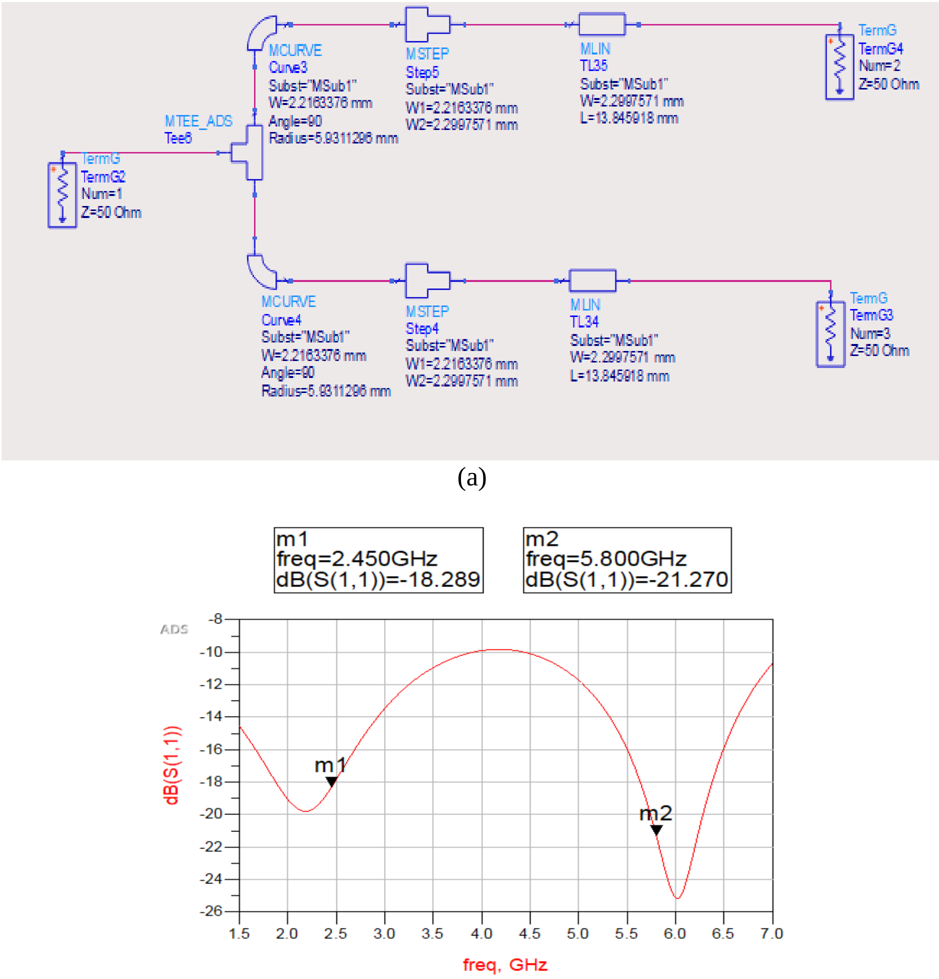
2.1. Wilkinson power divider WPD

To achieve our goal of making the rectifier work for a large input power, we opted to use a double band WPD to partition the input power into two signals, and therefore the power is distributed to the two branches, each working for a specified input power range. The first design parameters for WPD are generated using MATLAB [24], and these parameters will next be optimized using the advanced design system (ADS) software to get the best results. Figures 1(a) and 1(b) show, respectively, the WPD design circuit and its resulting S11 parameter using the ADS.

2.2. Impedance matching circuit

As depicted in Figure 2, a standard rectifier circuit is designed with an impedance matching circuit (IMC) and an RF to DC conversion circuit. Typically, this circuit consists of diodes, a DC filter using a capacitor, and a resistive load that simulates the powered system's usage. Taking into account the power levels, frequency, and load resistance values employed, and due to the non-linearity of diodes, IMCs are employed. These IMCs will work as an input filter, and together with the output filter, they will not only shield the antenna from the reversed current but also reduce high-order harmonics. There are works that have mainly used matching networks based on lumped components [25], [26]. Lumped component circuits exhibit more noise when the frequency exceeds 1 GHz. Hence, more significant loss will occur. That is why it is more used in circuits that operate in 2.45 GHz and 5.8 GHz [27], [28]. The matching unit in our design is based on microstrip lines. Concerning our approach, we used two impedance matching circuits (IMC1 and IMC2) for two input power ranges as depicted in Figure 3(a)-(b). IMC1 is made to handle relatively high input power (>0 dBm) because it is the one connected directly to the HSMS2852 diodes, while IMC2, which is linked to the SMS7630 diodes, is designed for the lowest power.

The initial design parameters are obtained by employing MATLAB and using the equations from [29]. The ADS optimization tools were then used to improve these parameters for a more efficient resulting rectifier. The following is a quick summary of the design principles for these matching networks: i) at low input power, the rectification of diodes SMS7630 is dominated. The effect of IMC2 becomes significant to get a good match between the low input power and the rectification circuit to pass RF power through the SMS7630 diodes; and ii) as the input power increases, the majority of RF power is transformed into DC power, and IMC1 fulfils its function by sending RF power to the HSMS2852 rectifier.



(a)

(b)

Figure 1. WPD (a) ADS design and (b) resulting S11 parameter using ADS

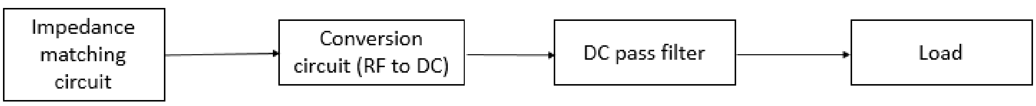


Figure 2. Basic functional representation of the rectifier stage

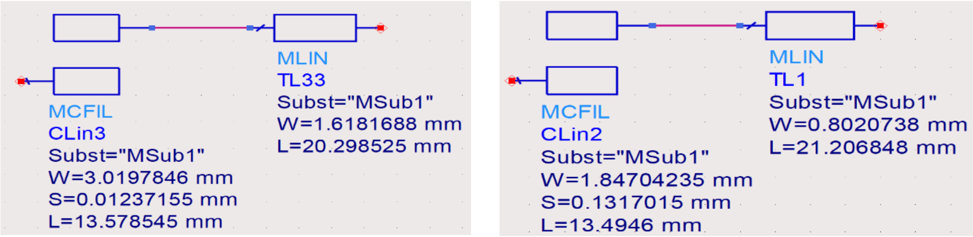


Figure 3. ADS design (a) IMC 1 and (b) IMC2

2.3. Rectifier resulting circuit

Due to the enhanced energy management capabilities of the voltage doubler topology, high conversion efficiency, and frequent use in double band circuits, we selected to employ it for the conversion circuit in our design [30], [31]. The choice of the most suitable and efficient diode is a significant step since diodes are a key component for rectifying RF energy in general. Schottky diodes are most frequently employed in rectifier circuits [32]–[35] because of their quick switching capabilities, which enable them to detect very low input signals [36]. For our design and to achieve the desired objective of large input power capability, we used two distinct diodes. The SMS7630 diode was selected for the low input rectifier since it has the best qualities for low forward power [36]. For the rectifier part, which operates at a relatively high input power, the HSMS2852 diode was used. At the end of this section, we arrived at a satisfactory rectifier design with respect to the starting criteria. All of our rectifier units are described below. The circuit will next be designed through simulation using ADS software. The suggested rectifier circuit illustration in ADS is shown in Figure 4.

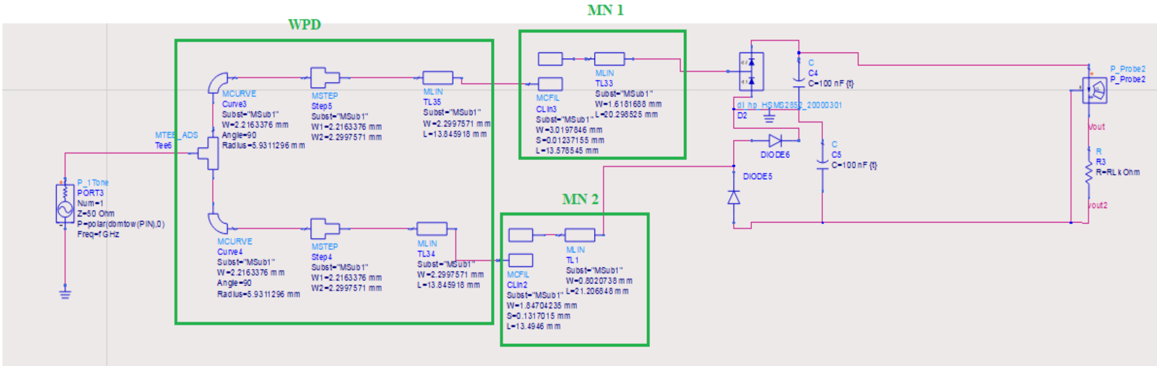


Figure 4. The final design of the wide input power dual-band rectifier through ADS simulations

3. RESULTS AND DISCUSSION

In this section, the properties of the rectifier simulation outcomes are shown. Agilent ADS 2019 is a commercially available software used for simulations. First, the parameter s11, then the efficiency of the rectifier with a CW and modulated signals as input power. All these results will be compared with each other and with other previous work.

3.1. Suggested design results

At an input power of -10 dbm, the s11 parameter of the resulted rectifier is shown in Figure 5 where the chosen load value is 5 kΩ. It is known that a good resonance corresponds to a return loss value less than -8 dB. As shown in Figure 5 the obtained return loss for 2.45 GHz is -20.082 dB and for 5.8 GHz is -10.287 dB. Efficiency is one of the critical performance metrics employed to evaluate a rectifier's effectiveness. The definition of rectifier conversion efficiency is

$$\text{Conversion Efficiency}\ \% = \frac{\text{Output DC Power}}{\mathit{REctifier\ Input\ RF\ Power}} * 100.$$

A load is connected to the rectifier's output. It is understood that the load value will alter the effectiveness of the RF/DC conversion. This may be described by thinking of the rectifier as a power source that is viewed from the load. The calculated output DC power is:

$$\text{Output DC Power} = \frac{{V_{DC}}^2}{RL}$$

where V_{DC} is the DC voltage value obtained at load resistance RL.

Figure 6 portrays the RF-to-DC efficiency (%) and the rectifier's output DC power (Pout) as a function of the input power (PIN). From the presented graphs, we can infer that the suggested RF-to-DC circuit achieves a maximum performance of 67.041% and 49.089% when a CW signal is applied, the input power is equal to 7 and 8 dBm, and for the desired frequencies, respectively.

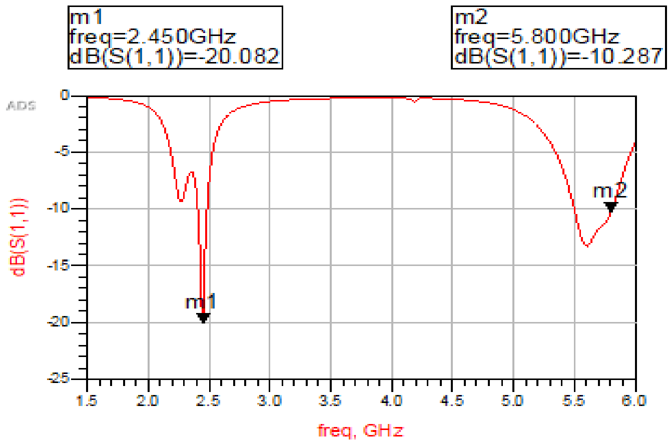


Figure 5. S11 of the resulting rectifier

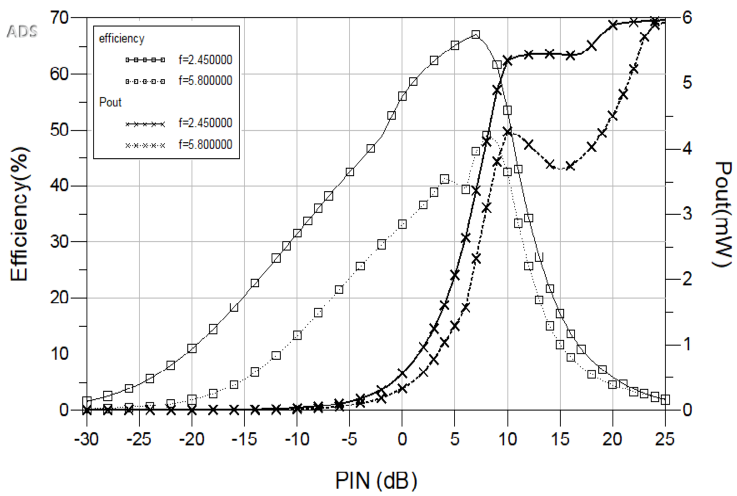


Figure 6. Rectifier’s input output characteristic

3.2. Modulation signal condition

This part evaluates the rectifier's output after inserting a modulated signal. The simulation setup is represented by Figure 7. A differential power probe is used to measure the total DC power produced since the rectifier circuit contains two branches. The load resistance value is 5 KΩ. Modulated signals are provided at the beginning of the circuit as depicted in Figure 7. For the simulation, the modulation types are QPSK, 8 PSK, 8 QAM, and 16 QAM. The same simulator, ADS, is used to generate modulated signals. Table 1 lists the modulation filter parameters used in simulations.

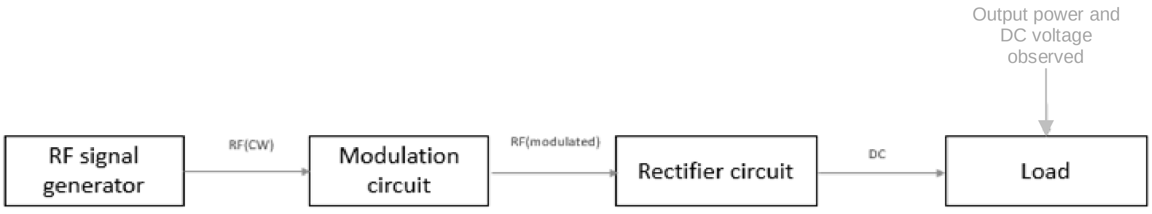
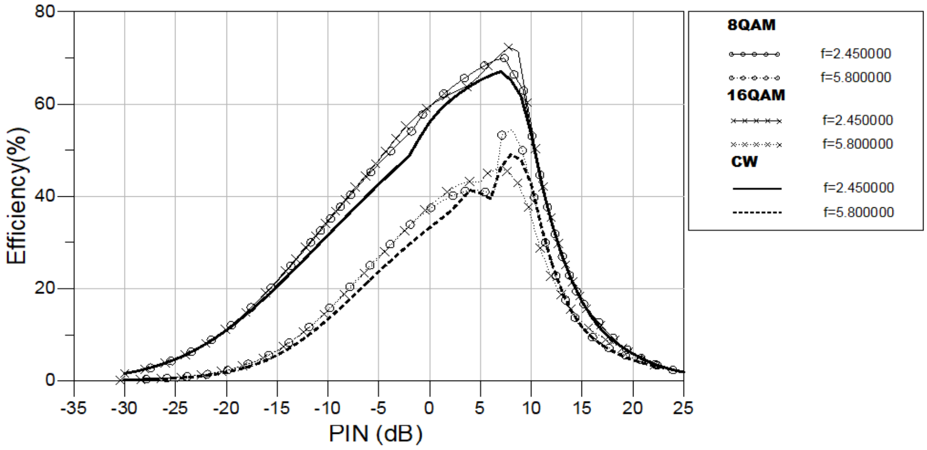


Figure 7. Simulation block diagram

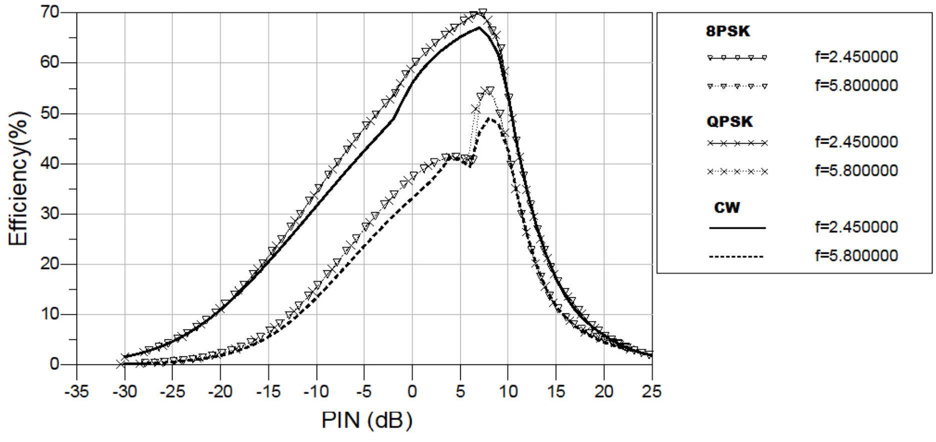
Table 1. Modulation filter parameters

Filter Type	Roll off Factor	Symbol rate
Root Raised Cosine	0.5	40 MHz

As shown in the Figure 8, we have evaluated the efficiency of the rectifier according to the input power of the rectifier by comparing it to that of continuous wave RF (CW). The RF/DC conversion efficiency of CW was 67.041% and 49.089% for 2.45 and 8.5 GHz, respectively. In Figure 8(a), the maximum RF/DC conversion efficiency difference to CW for 8QAM and 16QAM was within +2.9% and +5.49% for 2.45 and 5.8 GHz, respectively. In Figure 8(b), for the 8PSK and QPSK modulation types, the maximum conversion efficiency with respect to the CW signal was +5.2% and +4.1% for the operating frequencies, respectively.



(a)



(b)

Figure 8. Efficiency as a function of rectifier input power (PIN) (a) 8 QAM, 16 QAM and CW and (b) 8PSK, QPSK and CW

3.3. Comparison with other works

Table 2 shows the proposed rectifier's performance compared with existing dual-band rectifiers that have been reported and with our rectifier using the modulated signals as input signals. The dual-band rectenna described [37] has conversion efficiencies greater than 80% at received power levels of 35.6 mW (15.5 dBm) and 39.26 mW (16 dBm), and these powers are not normal levels captured in the air of RF energy due to the standard that defines the powers of emission of RF waves and the attenuation that these waves can undergo. Unlike the reported rectifiers, our rectifier exhibits exceptional efficiency values at the frequencies needed at relatively wide and low RF power levels.

Table 2. A comparison with dual-band rectifiers

Ref	Bands [GHz]	Maximum efficiency (%) at 2.45 GHZ		Maximum efficiency (%) at 5.8 GHZ	Input power for maximum efficiency [dBm]
[37]	2.45/ 5.8	84.4		82.7	≈15.5 for 2.45 GHz ≈16 for 5.8 GHz
[38]	2.45/ 5.85	57.1		39.2	0 for 2.45GHz 1 for 5.8 GHz
[39]	0.915/ 2.45	38		*	0
This work	2.45/5.8	CW	67.041	49.089	7 for 2.45 GHz 8for 5.8 GHz
		8QAM	69.979	53.281	5
		16QAM	72.325	45.935	8 for 2.45 GHz 7 for 5.8 GHz
		QPSK	69.942	54.496	≈6 for 2.45 GHz ≈7 for 5.8 GHz
		8PSK	69.979	54.579	≈7 for 2.45 GHz ≈8for 5.8 GHz

* Not Applicable

4. CONCLUSION

Through the use of a novel harvesting topology, this research suggested a new rectifier architecture for MPT. The Wilkinson WPD power divider and two types of rectifier diodes, rather than active components, allow this rectifier to operate with a wide input power range of -20 to 17 dB for the 2.45 GHz frequency and -11 to 15 dB for 5.8 GHz (for efficiencies >10%). According to the dual-band rectifiers designed in the literature, the proposed rectifier with CW input signal is a high-efficiency rectifier for large RF power input ranges, with a peak of 67.041%, 49.089% achieved for 2.45 and 5.8 GHz respectively. As can be seen from the Table 2, the modulated signals for the majority of modulation types achieved higher efficiency under the assumed condition of full input RF power. These results indicate that modulated signals can be used for MPT under the specified circumstances. Thus, using a modulated signal instead of a CW signal for MPT can provide additional benefits.

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