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A 2.4 GHz Rectifier Insensitive to the Angle of Incidence of Incoming Waves

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Abstract

In this paper a high efficiency, low-cost and low-complexity RF-DC converter was designed at 2.4 GHz that maintains increased efficiency range for a wide range of incident angles. The circuit of converter is based on a Wilkinson power combiner with two single-diode rectifiers. The proof of concept prototype uses a single-diode rectifier instead of the isolation resistor for recycling the wasted power when the input signals do not have the same phase. The modified Wilkinson power combiner was fabricated and measured using commercially available components. The measured rectifier RF-to-DC efficiency was 19.7% for in-phase input signals with power −20 dBm. Measurement results also showed that when the relative phase of input signals varied from 90 to 360 degrees, a variation in efficiency between 15% and 20.7% was observed.

1 Introduction

Radio frequency (RF) energy harvesting is a promising technique to maintain power availability in the conditions where e.g. light sources are not available [1]. It is widespread due to the large number of indoor and outdoor RF emitters. Mobile base stations, handheld radios, WiFi routers and television/radio broadcast stations are some of them. The goal is to collect unused ambient RF energy and supply with power small electrical devices and sensors [2], [3]. The ability to harvest RF energy, from ambient or dedicated sources, enables wireless charging of low-power devices. Various attempts have been made towards this direction. The basic approach is the utilization of an antenna and a rectification system, i.e., a RF to direct current (DC) rectifier, in combination, forming a rectenna.

The main aim of this proposed work is to design a RF energy harvesting rectenna based on a Wilkinson combiner [4] for frequencies in industrial, scientific and medical (ISM) band. In this work, 2.4 GHz was selected as center frequency due to the fact that some radio frequency identification (RFID) devices could operate in this frequency. Passive RFID sensor nodes/tags are limited to short range communication from a few centimeters to a few meters. They do not require a local power source thus they are powered by the RF energy generated by the "reader" which is also used

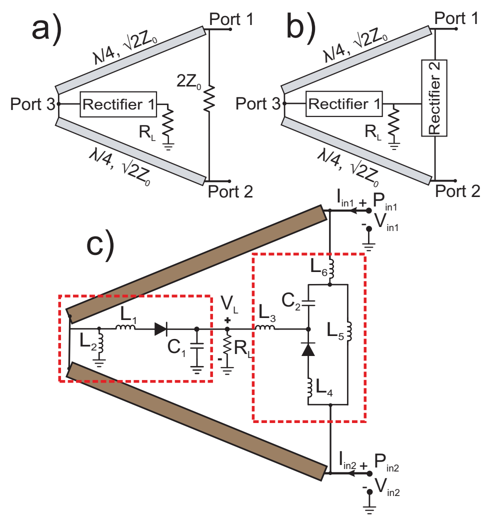

Figure 1. The Wilkinson rectifier designs. a: In "single" design only one rectifier is used to collect combined RF power. b: In "double" design, a second rectifier is used to replace the isolation resistor and acts as power-recycling circuit. c: Schematic of "double" design.

for the communication link. This work could be useful for power supply the tag thus our novel circuit is insensitive to the angles of the incoming reader waves. A Wilkinson circuit combines two incoming RF signals coming from two patch antennas and through a single-diode rectifier, it converts the RF power to DC power. The novelty is based on a second single-diode rectifier placed instead of the isolation resistor. With this single power-recycling technique, the power lost in the resistor can be collected when the incoming waves are not in-phase.

Noticeable research efforts have been made in harvesting using Wilkinson cominers. In [5] the researchers present results of an RF energy harvester at 2.4 GHz. A Wilkinson's circuit is used to combine the RF signals from two patch antennas and supply a modified Greinacher rectifier. In [6] an RF-DC rectifier is also used to replace the isolation resistor of the Wilkinson power combiner to recycle the power that would originally be dissipated in the isolation resistor. However, only one rectifier circuit is used and the application is to improve the efficiency of power amplifiers (PAs) configured as dual-phase pulse modulated polar transmit-

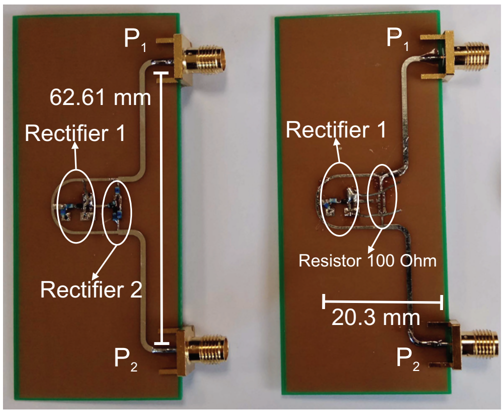

Figure 2. The fabricated Wilkinson rectifier circuits. Low cost FR-4 substrate was used for the fabrication.

ters (PMPTs). In our work we present a circuit which acts both as RF combiner through the two Wilkinson inputs, and as DC combiner through the two rectifiers. In addition, our topology is scalable to large antenna-array configurations with multiple combiner circuits.

A very important performance parameter in a rectenna is the rectifiers RF-to-DC efficiency, i.e., the ratio of the DC power output to the RF power input. Many researchers are working on the design of high-efficiency rectennas and most prior art designs operate optimally at high input power, namely greater than 0 dBm. Efforts have also been made towards high-efficiency rectennas for low power input around -20 dBm [7]. In this work, two input -20 dBm continuous signals with different phases were tested using two signal generators.

2 Wilkinson Power Combiner

The idea of Wilkinson combiner/divider is based on two quarter-wave transformers (arms) in order to match the split Ports $1,2$ to the common Port 3. The impedance of each arm is $1.41 \times Z_0$ as depicted in Fig. 1, (a, b). The Z_0 is defined as the characteristic impedance of the overall system and in our case is 50 Ohm. The circuit is particularly simple and can easily be fabricated using lumped components on a printed circuit board. In this work will be studied the two-way split, single-stage Wilkinson combiner. Due to the fact that in three-port network, ports could not be simultaneously matched, there is one resistor with value $2 \times Z_0$ between the Ports 1 and 2. The resistor isolates Port 1 from Port 2 and vice versa at the selected operation frequency. When there is only one signal at Port 1 or 2, only the half power is delivered to Port 3 and the other half of the power is dissipated in the resistor. On the other hand when there are two signals with the same phase at the inputs, it delivers the sum of the power at the two inputs. The Wilkinson combiner was connected with two singe-diode rectifier circuits for RF energy harvesting. One rectifier circuit was placed at Port 3 in order to collect the combination of power when the input signals are in-phase (Fig. 1, a). This design is referred as “single” in the following text. When the input signals do not have the same phase, a significant amount of power is dissipated in the isolation resistor and for this reason the 100 Ohm resistor was replaced by a second rectifier as showed in Fig. 1 (b). To summarise, the novel design is able to convert the waste power to DC power whenever the system is not balanced and it is called “double” in the following text.

3 RF-DC Converter Design

In order to increase RF-to-DC efficiency and decrease complexity, only one diode was used in each rectifier circuit, since double diode circuits increase losses [8]. The schematic of the “double” RF-DC converter is depicted in Fig. 1 (c) and each rectifier has a matching network consisting of inductors as it is shown in dash rectangles. The rectifier outputs were joined together, adding the currents from each diode and finally, feeding the load R_L. The low-cost Schottky single-diode SMS7630-040LF from Skyworks Solutions was selected due to its low capacitance 0.3 pF and low forward voltage. In order to decrease the total cost of the design, the FR-4 lossy substrate was used with parameters $\varepsilon_r = 4.58$, $\tan\delta = 0.022$, copper thickness 35 μm and substrate height 0.6 mm.

For simulations, Keysight Technologies’ ADS software was employed. The “single” and “double” converters were initially electromagnetically simulated with the method of moments and next, harmonic-balance (HB) analysis was applied. The HB analysis takes simultaneously into account the losses of the substrate, the conductive lines, the components and the non-linear behaviour of the rectifiers due to the diodes. Multi-objective optimization procedure was applied during the simulation with degrees of freedom, the lumped elements C_i, L_i and load R_L. The goal for optimization procedure was the maximization of RF-to-DC efficiency for both Wilkinson converters. The efficiency is defined as:

$$\eta = \frac{P_{out}}{P_{in}} = \frac{V_L^2/R_L}{P_{in,1} + P_{in,2}}, \tag{1}$$

with $P_{in,1,2}$ the input RF power at the ports of converter, P_{out} the output power at load and V_L the DC voltage across the load, R_L. The “double” converter was simulated first for $P_{in,1} = P_{in,2} = -20$ dBm at 2.4 GHz. After that the “single” circuit was simulated by replacing the second rectifier circuit with a 100 Ohm resistor. Each Wilkinson RF-DC converter will be connected to two patch antennas with 50 Ohm input impedance in future work.

The obtained optimum component values for the “double” design were found at L_1 = 5.1 nH, L_2 = 2.2 nH, L_3 = 21 nH, L_4 = 5.6 nH, $L_{5,6}$ = 1.8 nH, $C_{1,2}$ = 100 pF and R_L = 1559 KOhm, respectively. For the “single” circuit, the L,C values were the same but the optimum load was found at 1762 Ohm. For validation purposes, the RF-to-DC converters were fabricated as is depicted in Fig. 2. The two

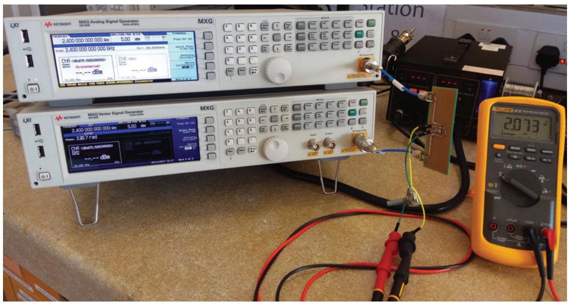

Figure 3. Measurement setup with two signal generators.

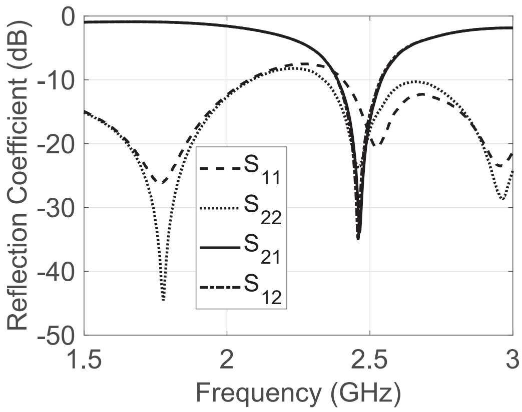

Figure 4. S parameters of "double" Wilkinson board

printed circuit boards (PCBs) look similar but the left design contains an extra rectifier circuit in order to capture the dissipated energy for different phases at the input. The design on the right was fabricated for comparison purposes with the design on the left.

4 Measurement Results

The "double" Wilkinson PCB was measured with a vector network analyser (VNA) at frequencies 1.5 GHz to 3.5 GHz. The input signals were the carrier wave (CW) tones of VNA with $P_{in,1} = P_{in,2} = -20$ dBm and the exported S parameters are depicted in Fig. 4. The measured reflection coefficients Γ_{11} and Γ_{22} are under -10 dB for 2.4 GHz. Next, the RF-to-DC efficiency was measured for the two boards. Each board was connected with two signal generators simultaneously as depicted in Fig. 3 setup. The generator outputs were connected with board inputs through two "same-length" RF cables. The total power P_{in}, is considered as the sum of $P_{in,1}$ and $P_{in,2}$ and $P_{in,1}$ was fixed to be the same as $P_{in,2}$. The first generator was used for phase change from 0 to 360 degrees thus at the second generator, the phase of the incoming signal was fixed at 0 degrees.

Fig. 5 shows the RF-to-DC efficiency versus load for $P_{in,1} = P_{in,2}$=-20 dBm at 2.4 GHz when the two inputs have zero phase difference. The maximum η occurs when R_L = 1.6 kOhm and R_L = 1.7 kOhm for "double" and "single" design, respectively as was expected from the simulation results. In Fig. 6 is depicted the measured efficiency versus power input when the inputs are in-phase. The maximum efficiency in "double" design was achieved for $P_{\text{in, 1,2}}$ = 5 dBm. The maximum η for "single" was 21.41% and for "double" 15.27%, respectively. Finally, Fig. 7 depicts the most significant results. The designs were simulated and tested for input signals with phase difference. The figure depicts the efficiency achieved for phase different from 0 to 360 degrees. Good agreement between simulation and measurements is observed for "single" design. When the inputs signals are not in-phase is observed a approximately constant efficiency for "double" design between 15% and 20.2%. On the other hand for the "single" design, the efficiency goes to 0 when the phase different is 180 degrees and it is repeated periodically every 360 degrees. Finally, for phase difference 0 degrees, the measured efficiency was 24.6% and 19.7% for "single" and "double" design, respectively.

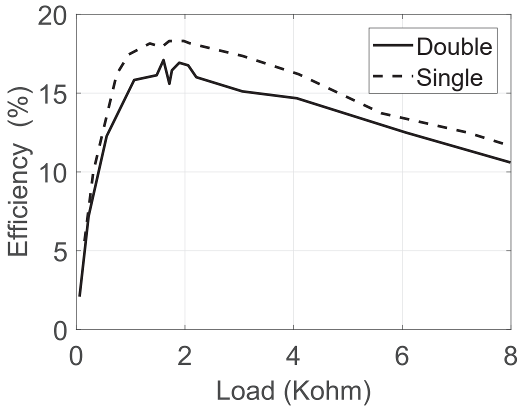

Figure 5. Measured RF-to-DC efficiency versus load at in-phase for fixed frequency 2.4 GHz. The $P_{in,i}$ was fixed at -20 dBm.

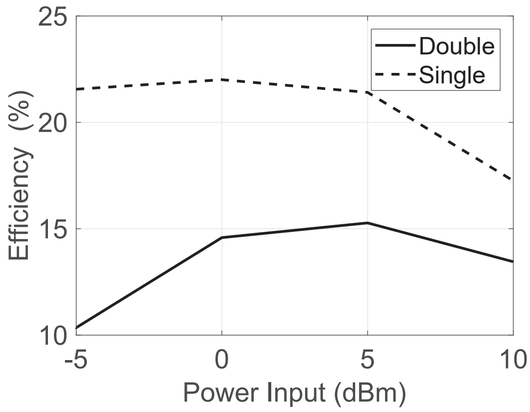

Figure 6. Measurement efficiency vs $P_{in,i}$ for in-phase case at 2.4 GHz.

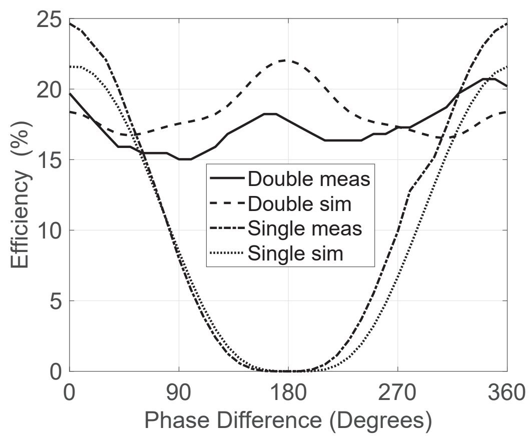

Figure 7. Efficiency versus phase difference for $P_{in,i}$= -20 dBm at 2.4 GHz. The measured load was fixed at 1588 Ohm and 1759 Ohm for "double" and "single" design, respectively.

5 Conclusion

In this work, we present a novel high efficiency for low power input rectifier as a future rectenna design for RF energy harvesting. The circuit combines a Wilkinson combiner with two single rectifier circuits in order to collect the energy from two inputs when the phase difference between them is not zero. This enables maintaining high efficiency for a wide range of incidence angles. The circuit was fabricated on FR-4 substrate and measurements were agreed with simulation, demonstrating high efficiency rectification.

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