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Polarization-Insensitive 2.45 GHz Rectenna Using Hybrid Coupler for Wi-Fi Energy Harvesting Application

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Abstract

A polarization-insensitive dual-polarized rectenna with a hybrid coupler strategy for energy harvesting applications is proposed in this letter. With a dual-polarized antenna, the incident wave can be received and divided into the horizontally and vertically polarized components, which are equally redistributed by a hybrid coupler. The power equally delivered to the two rectifiers is independent of the incident wave's polarization. By the equal power routing similarly, two rectifiers are designed and analyzed. In simulation, the maximum efficiency of 58.15% has been measured with a 600 Ω load at 2.45 GHz.

***Keywords**: Dual-polarized; energy harvesting; rectenna; stacked antenna.*

Tóm tắt

Bài báo này đề xuất một rectenna phân cực kép không phụ thuộc vào góc phân cực của sóng tới với bộ chia công suất hybrid coupler, ứng dụng cho các mạch thu hoạch năng lượng. Với một ăng-ten phân cực kép, sóng tới sẽ được phân tách thành thành phần phân cực theo chiều ngang và chiều dọc, sau đó được phân phối đều lại bởi bộ chia công suất hybrid coupler. Năng lượng được phân chia đều cho hai bộ chỉnh lưu mắc song song. Hai bộ chỉnh lưu được thiết kế và phân tích để hiệu suất chuyển đổi là tối ưu nhất. Trên mô phỏng, hiệu suất chuyển đổi tối đa của toàn mạch đạt 58.15% đối với tải 600 Ω tại tần số sóng 2.45 GHz.

1. Introduction

Nowadays, along with the technology development, wave telecommunication is becoming a trend in digital technology. Harvesting energy from this wave source is an optimistic idea for low-power devices. Some reported works [1]-[6] focus on this method. By using rectenna (rectifying antenna), antenna elements are used for converting telecommunication wave into alternating current, then rectifier element converts alternating current to direct current. Wi-Fi waves are widely used almost everywhere, thus we can harvest energy from 2.45 GHz Wi-Fi waves. In reality, the polarization direction of the incident wave is unknown, which can cause polarization mismatch loss in the received power and conversion efficiency. Hence, a solution to the polarization mismatch problem is needed using a dual-polarized antenna [1], the incident wave can be received and decomposed into the horizontally and vertically polarized components. Several works have been focused on this problem as in [1] and [7]-[10], a dual-polarized antenna is proposed to collect more power and rectified by 2 parallel rectifiers. However, the received energy at two rectifier circuits is not equal leading to unequal input impedance of rectifiers. Therefore, the conversion efficiency is reduced. A hybrid coupler circuit is proposed to equally divide the power between the two rectifier circuits. The works at [11]-[14] used hybrid coupler to divide the power of the circuit showing potential solution to increase conversion efficiency and independent of the incident waves.

In this paper, a rectenna based on a dual-polarized antenna, a hybrid coupler and two rectifiers is proposed. In this way, the efficiency of the rectenna is independent of the incident wave's polarization and is improved. The antenna size is 62.4 mm x 62.4 mm x 17.4 mm and the size of the hybrid couplers along with the rectifiers is 80 mm x 80mmm, which is relatively small when placed next to IoT devices.

2. Analysis

2.1. Dual-polarized antenna design

Dual-polarized antennas possess two polarization modes that are perpendicular to each other. The two polarization modes can be excited using two ports of the same antenna.

As shown above, a dual-polarized antenna with two ports aim to receive and decompose the incident wave into the horizontally and vertically polarized components. The proposal antenna working at 2.45 GHz is a stacked antenna consisting of a square patch radiator and a parasitic patch. The radiation patch uses a 0.8 mm RO4003C substrate with a dielectric constant of 3.55 and loss tangent of 0.0027, and has two feeds perpendicular to each other. While the parasitic patch uses a 1.6 mm FR4 substrate with a dielectric constant of 4.3 and loss tangent of 0.02. Radiating patch is a 36

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mm square. Opposite parasitic patch is a 32.3 mm square with distance H of 15mm. The design of the two patches is shown in Figure 1.

The stacked antenna was fabricated and measured. By using two perpendicular feeds, the antenna creates a dual polarization. Besides, parasitic patch improves gain and bandwidth for the antenna without affecting its polarization. To stabilize the position of the two patches, four plastic screws are used to avoid affecting the radiation of antenna.

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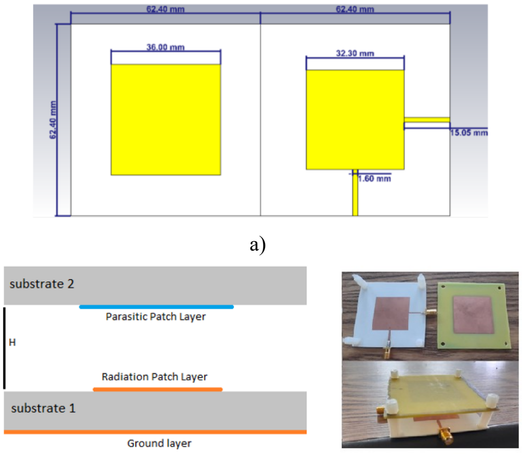


Figure 1: Design of the receiving antenna: a) Antenna dimensions, b) Side view of the proposed antenna, c) Antenna prototype.

S-parameters of the proposed dual-polarized antenna were simulated and measured, as shown in Figure 2. The impedance bandwidths (return loss >10 dB) are from 2.37 to 2.47 GHz, the return loss at 2.45 GHz is greater than 16 dB. The measured gains of both ports at 2.45 GHz better than 5 dBi.

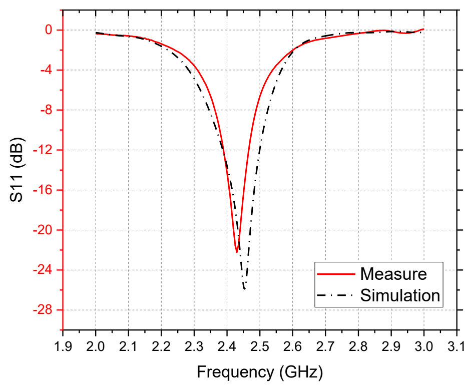


Figure 2: Simulated and measured S11 of the dual-polarized antenna.

In addition, as can be seen from Figure 3, at frequency of 2.45 GHz, the isolation between two ports is around 30 dB.

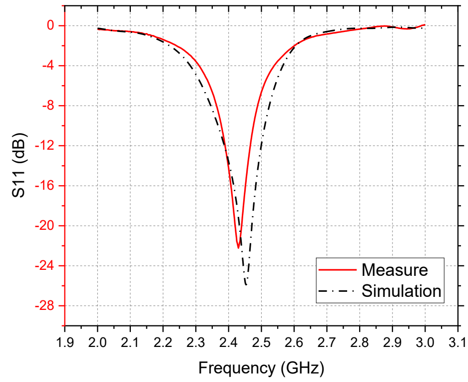


Figure 3: Simulated and measured S12 of the dual-polarized antenna.

2.2. Rectifier with hybrid

2.2.1. *Power divider hybrid coupler*

The used dual-polarized antenna has two ports, therefore, absorbed electromagnetic wave energy can also be emitted through those two ports, which are called V-port (Vertical) and H-port (Horizontal).

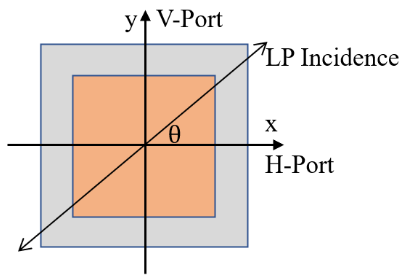


Figure 4: Illustration of the incident wave's polarization.

As shown in Figure 4, the antenna is illuminated by an arbitrarily linearly polarized (LP) wave with a polarization direction angle of θ. When $\theta = 0°$, the amplitude of the complex voltage excited at the H-port is assumed to be V_{max}. For arbitrary θ, the amplitudes of the complex voltages excited at the H- and V-ports, V_{HP} and V_{VP}, can be expressed as

$$V_{HP} = V_{\max} \cos\theta \quad (1)$$

$$V_{VP} = V_{\max} \sin\theta \quad (2)$$

As seen from the equations, the energy going through two ports are not equal and depend on the value of polarization direction angle of θ. If we directly put the voltage of these two ports to two separated rectifier circuits, the voltage difference can cause rectifier circuit with lower output voltage to turn into a load of the other rectifier, which brings about not only energy loss, but also lower the efficiency. Besides, the phases of the output ac voltage are perpendicular to each other, therefore sharing one rectifier is impossible. Power divider circuit is needed to equally divide power for two separated rectifier circuits. Therefore, we use the hybrid coupler Figure 5.

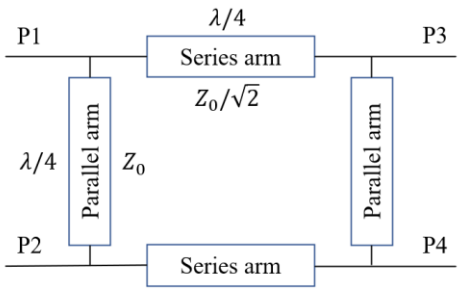


Figure 5: Schematic diagram of a hybrid coupler.

Connect H-port to input port P1, V-port to input port P2. The phase difference of two input voltages at P1 and P2 is 90 and the length of transmission lines are equally $\lambda/4$, which lead to the 90 degrees phase difference of two output voltages at P3 and P4. Output voltage at output ports P3 and P4 is calculated by (3)(4) through the S-parameters.

$$V_{P3} = V_{P1}.S_{13} + V_{P2}.S_{23} = V_{HP}.S_{13} + V_{VP}.S_{23} \quad (3)$$

$$V_{P4} = V_{P1}.S_{14} + V_{P2}.S_{24} = V_{HP}.S_{14} + V_{VP}.S_{24} \quad (4)$$

C is the power dividing ratio.

$$|S_{14}|^2 = |S_{23}|^2 = C \quad (5)$$

$$|S_{13}|^2 = |S_{24}|^2 = 1 - C \quad (6)$$

With C = 0.5, in order to make the voltage at P3 equal P4, the impedance of parallel arms and series arms are calculated by (7)(8).

$$Z_{series} = Z_0\sqrt{1-C} = \frac{Z_0}{\sqrt{2}} \quad (7)$$

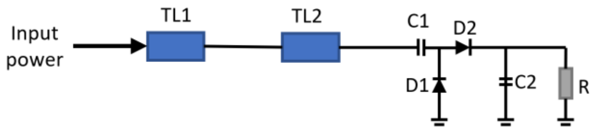
$$Z_{parallel} = Z_0\sqrt{\frac{1-C}{C}} = Z_0 \quad (8)$$

From that two output P3 and P4 will have the same power and will be independent of the incident wave's polarization angle θ. Then two rectifiers in parallel rectify two equal parts of RF power. Therefore, the RF-to-DC power conversion efficiency of the rectenna can maintain the stability without getting affected by polarization direction.

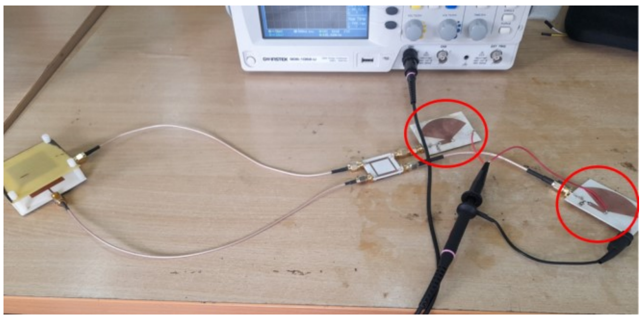
2.2.2. *Rectifier Design*

A rectifier based on hybrid coupler is designed and simulated by using the software ADS (Advanced Design System), printed on a 0.8 mm RO4003C substrate, which operates at 2.45 GHz. To design this rectifier, an AC-DC conversion is designed first.

The voltage doubling structure [2][8-11] is applied to the rectifier circuit consisting of capacitors C1, diode D1 and D2, with the aim to convert AC to DC voltage. The rectifier circuit uses a 0.8 mm RO4003C substrate. In addition, the circuit operates at high frequency, the SMS7630 diode is chosen for its high efficiency. To filter the high frequency harmonics, the filter, which has a capacitor C2 for frequency of 2.45 GHz, is used. The radial stub operates as capacitor C2. An impedance matching circuit includes two components, which are used to connect the rectifier circuit with the hybrid coupler. In which, TL2 has the effect of bringing the impedance matching to the required resonant frequency.



a)



b)

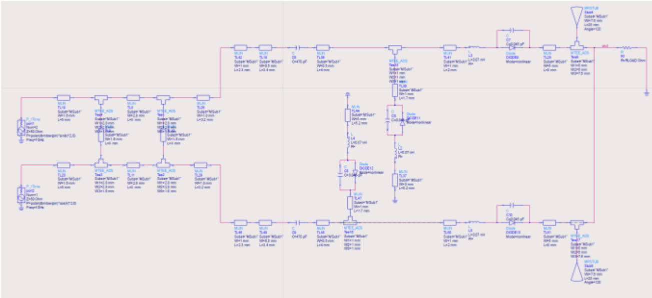
Figure 6: a) Rectifier circuit structure, b) Rectifier prototype

2.2.3. *Combine rectifier circuit with hybrid coupler*

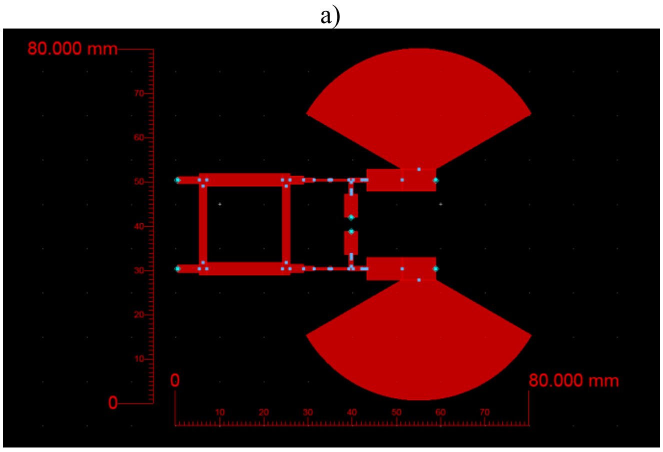
Using ADS software to combine rectifier circuit with hybrid coupler, optimize the size of the whole circuit in accordance with 2.45GHz frequency. In hybrid coupler power divider circuit, the length of each arm is $\lambda/4$. As above calculation, Z_{series} = $Z_0/2$ with Z_0 = 50 Ω, the series arms will have the size of 2.8x17.2 mm. $Z_{parallel}$ = Z_0, parallel arms have the size of 1.6x17.2 mm. The total size of the whole circuit is 80x80 mm. The design is shown in Figure 7.

As shown in Figure 8, the circuit operates at 2.45 GHz frequency, acquiring 21% and 48% efficiency from -10 and 0 dBm input power, respectively. The maximum efficiency of 58.15% has been measured with a 600 Ω load at 2.45 GHz.

Simulated with 600 Ω resistor and 0 dBm input power, the efficiency is slightly affected by wave's polarization direction angle, between 43.5% and 48% which is described in Figure 9.



a)



b)

Figure 7: Schematic and layout of the proposed power divider circuit and rectifier

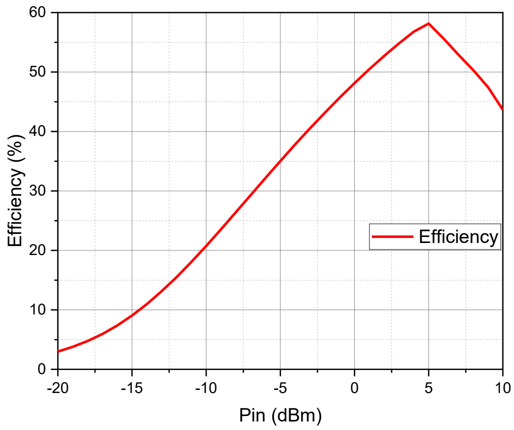


Figure 8: Simulated conversion RF-DC efficiency with input power

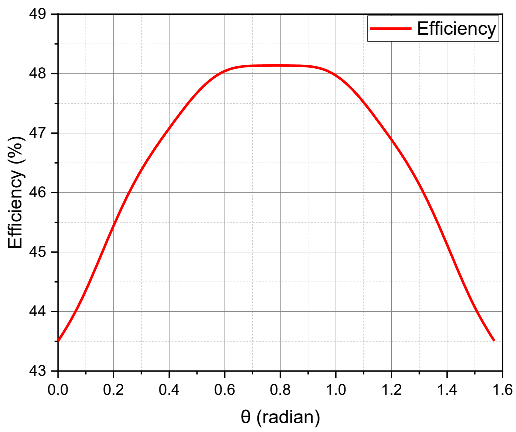


Figure 9: Simulated conversion efficiency with a polarization direction angle of θ at 0dBm input power

2.3. Results and Discussion

Based on Advanced Design System simulation software, the rectifier was operating at frequency of 2.45GHz, reaching the efficiency of 23% and 45% with input power of -10 dBm and 0 dBm respectively. The maximum efficiency of 58.15% has been measured with a 600 Ω load at 2.45 GHz.

Table 1: Performance comparison

Ref	Frequency	Conversion RF-DC efficiency	Size (mm)
[4]	2.45 GHz	34%	55 x 55
[5]	2.45 GHz	35%	75 x 75
[6]	2.45 GHz	38%	135 x 138
Proposal	2.45 GHz	43.5% - 48%	80 x 80

Simulated conversion efficiency RF-DC of the proposed rectenna at input power 0 dBm is compared with previously simulation reported rectennas in Table I. Our design has better efficiency and does not depend on polarization. Moreover, antenna has a straightforward structure and makes it easy to manufacture.

Measured results of the dual-polarized rectenna shown in Figure 10. The mismatch between measurement and simulation results comes from the error due to the fabrication process and the non-linear behavior of diodes when they are soldered into the circuit under high temperature. The measured efficiency is lower than simulation efficiency.

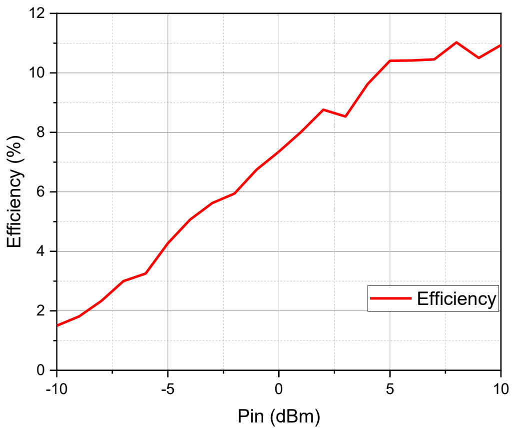


Figure 10: Measured result of conversion efficiency with input power

3. Conclusion

The radio frequency power received by the antenna can be equally distributed for the rectifiers to achieve constant efficiency by using hybrid coupler. Measurement illustrates that rectenna is insensitive to the incident wave's polarization direction angle. System efficiency on simulation is 43% greater at 0 dBm in-put power. We propose antenna and rectifier structure for energy harvesting application.

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