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Research Article

An S-Band Compact Meander-Line Dual-Polarized Rectenna Array Design and Application Demonstration

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This paper presents a compact, dual-polarized rectenna array operating at 2.45 GHz and demonstrates its use in a microwave wireless power transmission (MWPT) system. The MWPT system comprises a compact voltage-controlled oscillator (VCO), a power amplifier (PA), and the dual-polarized rectenna array. The VCO and PA together form a transmitter that delivers an output power of 1 W at 2.45 GHz. The transmitter's DC power port features a universal type-C interface, which facilitates its use in daily life. We designed a meander-line dipole rectenna that eliminates the matching network between the antenna and diode. The meander-line structure improves the rectenna's impedance and reduces its size. The measured maximum efficiency of the rectenna is 62.5% at −2 dBm. DC power combining is applied to the rectenna array to achieve dual polarization and voltage boosting simultaneously. The proposed rectenna array is integrated into a commercial digital thermometer. The digital thermometer was powered by the proposed MWPT system, demonstrating its bright prospects for MWPT applications.

1. Introduction

Wireless power transmission (WPT) technology has been attracting significant interest for its application in various fields, such as iPhones, smartwatches, and smart homes [1–3]. The WPT technologies include microwave wireless power transmission (MWPT), inductive power transmission, and magnetically coupled inductive power transmission [4–6]. MWPT technology refers to the conversion of electrical energy into microwaves, which are then radiated to the receiver via the transmitting antenna. The receiver uses a rectenna to receive and rectify the microwave power into DC for use in electronic devices [7, 8].

MWPT technology offers a significant advantage in enabling WPT over longer distances. In 2022, Xiaomi Corporation launched Mi Air Charge Technology, which has garnered considerable attention. This technology uses a phased array to transmit radio frequency (RF) waves for charging mobile phones, smart wearables, and home appliances in a living room. However, the cost of this technology is relatively high due to its requirement of a phased array and high-power RF sources. Recently, various types of rectennas have been reported to promote the application of WPT in different fields, such as rectenna arrays, high-efficiency rectennas, dipole rectennas, dual-band rectennas, and reconfigurable rectennas [9–17]. Generally, ambient RF radiation is random, with multiple paths and polarizations, which limit the uniform rectennas' ability to harvest ambient RF energy.

With the increasing development of wireless sensor networks in various fields such as intelligent transportation, environmental monitoring, and healthcare, as well as the rise of the Internet of Things, low-power sensors have been widely used [18–20]. Due to the disadvantages of battery power supply, there has been growing research on using rectifying antennas to power electronic devices for IoT applications. Generally, the ambient RF radiation is random with multipath and multipolarization. A

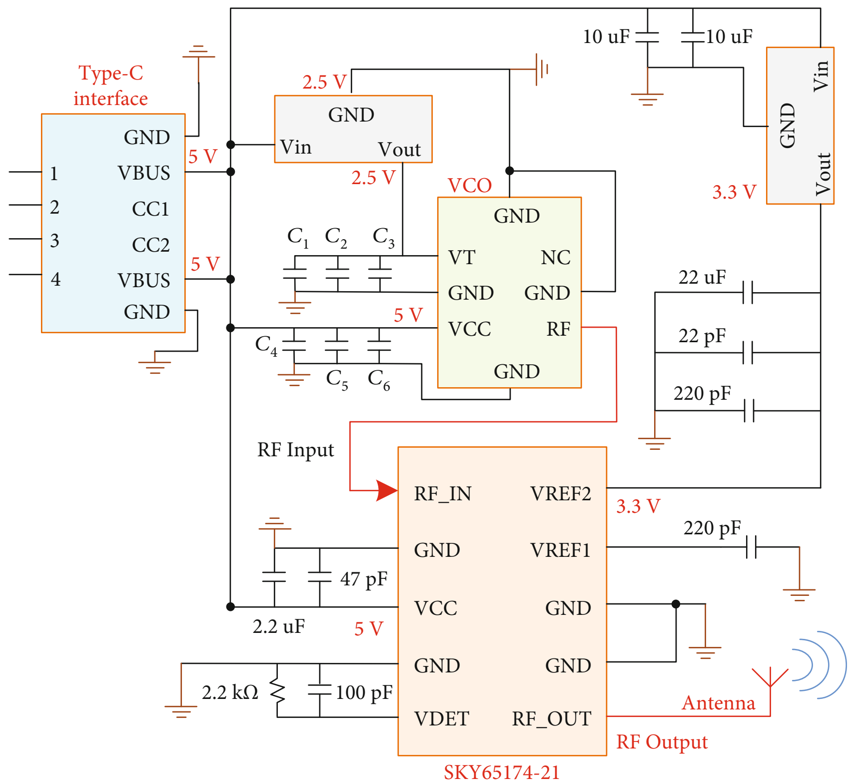

FIGURE 1: Schematic diagram of the VCO-PA circuit.

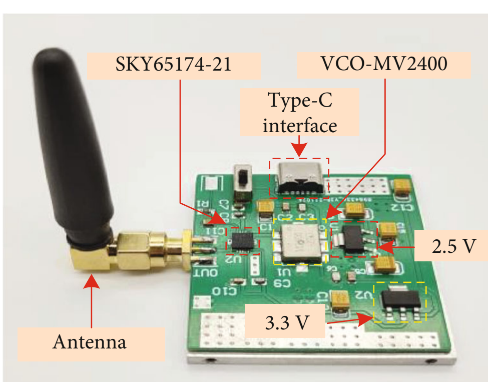

FIGURE 2: Transmitter with a VCO-PA circuit.

single-band circularly polarized rectenna at 2.45 GHz with a hexagonal microstrip radiator and voltage double rectifier was proposed for smart city applications. The rectifier achieved a maximum conversion efficiency of 65.1% and an output voltage of 1.65 V at 0 dBm suitable for powering low-power sensing devices [18]. An ultrasensitive energy harvester using antenna-and-rectifier codesign is presented with a highly efficient cross-coupled rectifier directly connected to a square loop antenna. The product of radiation and matching efficiencies is proposed as the optimization metric, and the harvester can operate at a maximum distance of 20 m and be used in remote sensing and IoT applications [19].

In order to overcome the challenge of battery recharging and replacement in IoTs and meet a variety of low-power electronic devices, we proposed a dual-polarized rectenna

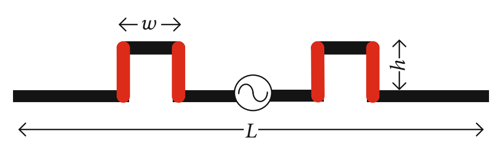

FIGURE 3: Two meander line antenna.

array to harvest RF energy in a multipath and multipolarized environment. Our contributions are as follows:

(1) The transmitter is small in size and low in cost, which allows for widespread distribution within a room. The benefit of our design is that a low-power electronic device powered by the proposed rectenna array can easily find a power supply

(2) Proposing a compact rectenna using meander-line structures with circular loops to eliminate the impedance-matching network. The circular loops present more flexibility to utilize the rectenna effective area

(3) Building rectenna array through directly connecting all rectennas in series at each adjacent end with DC power combining. Not only dual polarizations but also voltage boosting is realized simultaneously. We can freely change the number of rectennas according to an electronic device's available space. We demonstrated a commercial digital thermometer powered by the rectenna array, that can harvest ambient RF energy

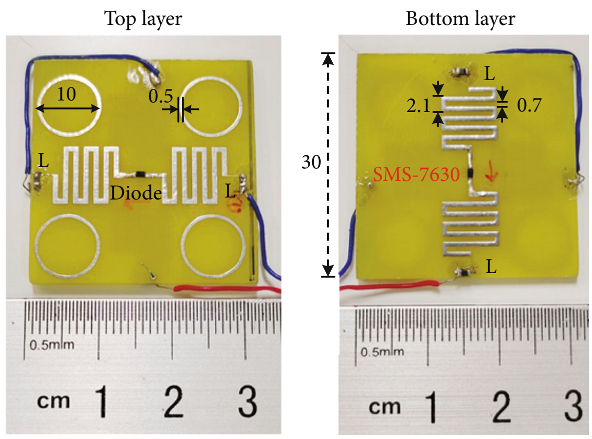

FIGURE 4: Photograph of the rectenna with the top layer and bottom layer.

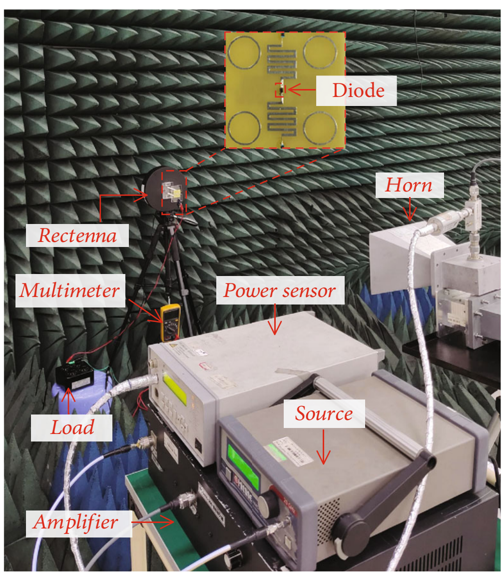

FIGURE 5: Fabricated rectenna and measurement in an anechoic chamber.

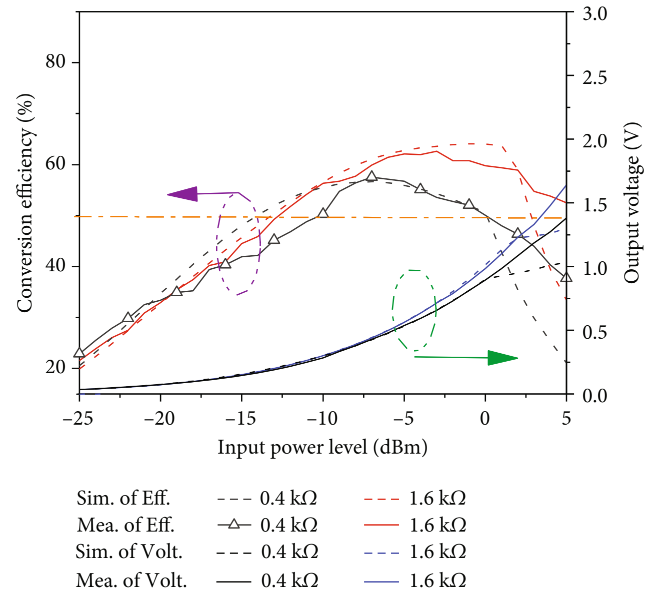

FIGURE 6: Measured and simulated RF-to-DC conversion efficiencies of the unit rectenna.

2. VCO-PA Circuit Design and Measurement

As shown in Figure 1, a VCO circuit (MVE2400) with a band of 2300~2500 MHz (@5 dBm) and a power amplifier (SKY65174-21) are designed together. The power supply ports of the VCO and PA are powered by type C (5 V). The bias ports VT (2.5 V) and VREF (3.3 V) of the VCO and PA use voltage regulator chips AMS1117-2 V5 and AMS1117-3 V3, respectively. The output port of the VCO-PA transmitter is connected to a monopole antenna with a gain of 3 dB. The physical picture of the VCO-PA is shown in Figure 2. Its size is only 45 mm × 45 mm × 1 mm. The bottom surface is a heat-dissipation aluminum plate with a thickness of 3 mm. The measured transmit power of the proposed VCO-PA at 2.45 GHz is 30 dBm. The type-C port of the VCO-PA transmitter can connect with a 5 V charger of general electronic equipment, making it more convenient for application.

3. Rectenna

One meander dipole rectenna is used as an energy harvester to convert the collected RF energy from the VCO-PA transmitter into DC energy. Figure 3 shows a two-meander line antenna with length L, height h, and width b. The two red meander lines are treated as a twin line with a short-circuited termination.

The characteristic impedance of twin lines (red lines in Figure 3) can be expressed in the following form:

$$Z_0 = \frac{\eta}{\pi} \log \frac{2w}{b}, \tag{1}$$

where η is the wave impedance in free space.

The ADS software is used to simulate the impedance of the diode SMS-7630. Its impedance is 60-j270 Ω at 2.45 GHz (-2 dBm@1.6 kΩ). A meander dipole rectenna is shown in Figure 4. The unit rectenna dimension is about 30 mm by 30 mm. The substrate is FR4 ($\varepsilon_r = 4.4$, $\tan\delta = 0.02$) with a thickness of 1 mm. The Schottky diode (SMS-7630) is placed in the middle of the rectenna. The meander line structure is applied on two diploe antennas on the top and bottom layers with different polarization, respectively. The optimal impedance of the rectenna is $50 + j280\,\Omega$ at 2.45 GHz.

The proposed rectenna was measured in an anechoic, as depicted in Figure 5. The signal was amplified using a power amplifier (WSPA, Wattsine) and transmitted using a standard horn antenna with a gain (G_t). A directional coupler was placed between the power amplifier (PA) and the horn antenna. A power sensor (AV-2433) was connected to the coupler to measure the transmitted power (P_t). The received power P_r by the rectenna in mW was calculated by the Friis equation.

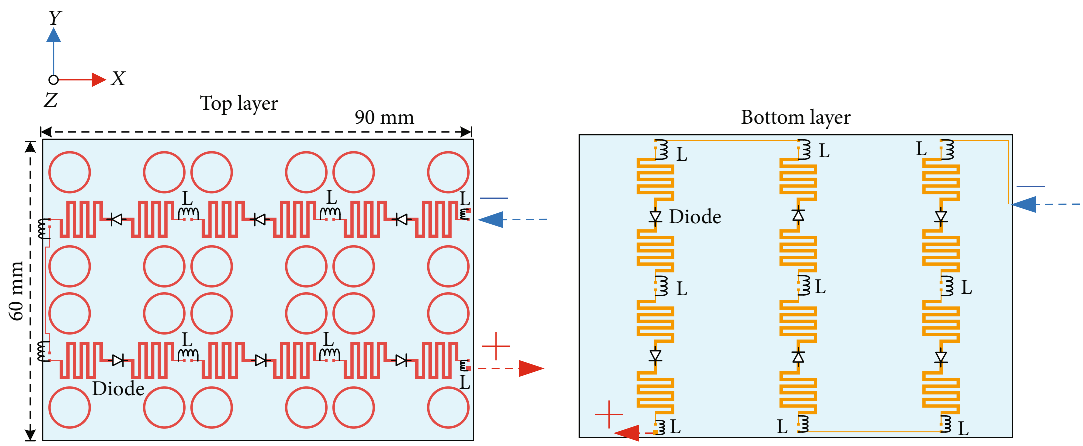

FIGURE 7: Schematic diagram of rectenna array design.

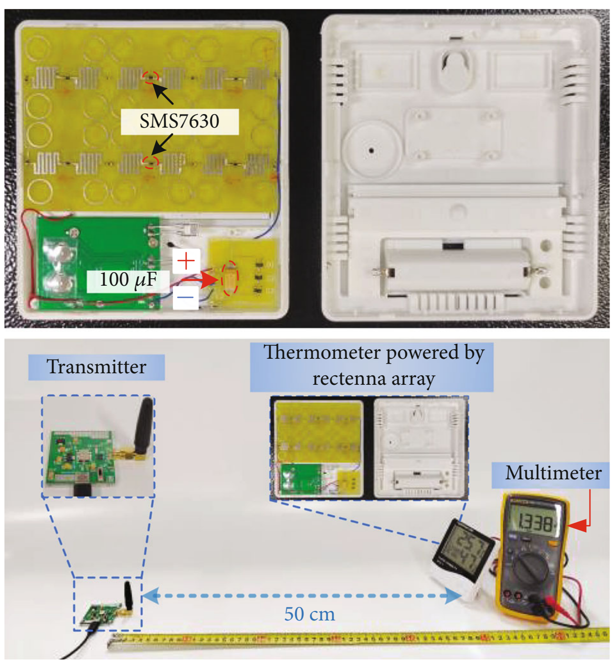

FIGURE 8: Indoor measurements system of the digital thermometer powered by a VCO-PA.

$$P_r = \frac{P_t G_t G_r \lambda^2}{(4\pi D)^2}, \quad (2)$$

where G_r is the gain of the rectenna. D is the distance from the horn to the rectenna ($D = 1.2$ m). The microwave-to-DC conversion efficiency is

$$\eta = \frac{V_{DC}^2}{P_r \times R_{Load}} \times 100, \quad (3)$$

where V_{DC} is the output voltage of the load R_{load}.

A comparison between the simulated and measured RF-DC conversion efficiencies of the rectenna at various input power levels is shown in Figure 6. The simulation and measurement results remain relatively consistent. A high conversion efficiency (>50%) can be achieved with the input power range from -12 to 4 dBm. When the load is 1.6 kΩ, the maximum efficiency measured at -2 dBm incident power is 62.3% with an output voltage of 0.72 V. As the power continues to increase, the voltage keeps rising. However, the conversion efficiency starts to decline due to the limitation of the diode's broken-down voltage.

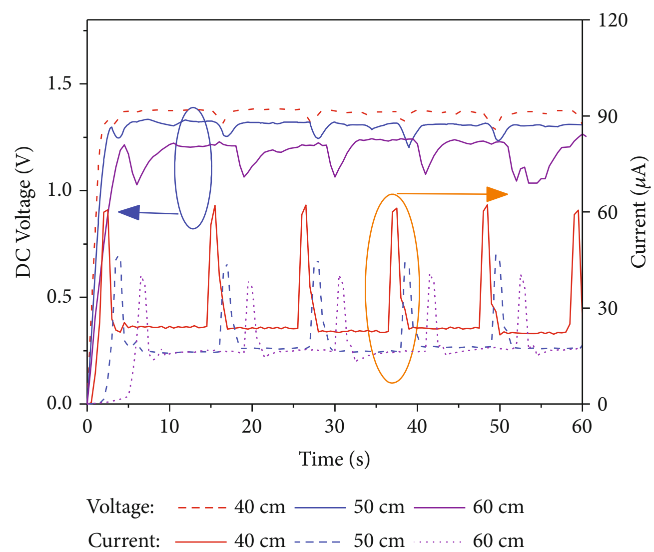

FIGURE 9: Measured output DC voltages and currents of the rectenna array at various distances from the VCO-PA.

4. Rectenna Array

Usually, the RF energy in the environment is a multipolarized environment. A multipolar rectenna array is an effective method to harvest more ambient RF energy. To harvest RF energy in multipolarizations in the complex environment, we propose a dual-polarized rectenna array, as shown in Figure 7. The meander line structures are applied to a rectenna array on the top and bottom layers with different polarizations, respectively. An x-polarized rectenna is placed in the top layer of the substrate to mainly receive microwave energy in the x-polarization direction. A y-polarized

Table 1: Performance comparison with reported designs.

References	Frequency (GHz)	Dimensions (mm)	Polarization	Matching network	Efficiency
[6]	1.80	$45 \times 45 \times 0.8$	Single	Yes	61%@0 dBm
[10]	2.15	$120 \times 60 \times 1.0$	Single	Yes	55%@3 dBm
[12]	2.45	$30 \times 30 \times 1.0$	Single	No	74%@18 dBm
[17]	2.45	$60 \times 60 \times 5$	Single	Yes	83%@21 dBm
[21]	2.3-2.6	$80 \times 80 \times 1.6$	Circular	Yes	65%@0 dBm
This work	2.45	$60 \times 90 \times 1$	Dual	No	62%@-2 dBm

antenna is placed in the bottom layer of the substrate to mainly receive microwave energy in the y-polarization direction. Therefore, the entire antenna array can achieve dual-polarization characteristics in the x and y directions at 2.45 GHz. The size of the rectenna array is 60 mm × 90 mm × 1 mm. The rectenna array is connected in series and in parallel to realize a DC power combination. ANSYS HFSS simulation software is used to simulate the isolation between the rectennas. The x-polarization and y-polarization are realized on the top and bottom layers of the substrate, respectively. The rectenna array uses a DC power combining approach to connect all the rectennas in series at adjacent ends by ultrathin copper traces and inductances (470 nH). The ultrathin line has a width of 0.1 mm and a thickness of 0.017 mm.

A photograph of rectenna measurement with a VCO-PA in an indoor environment is shown in Figure 8. The voltage and current measurements of the rectenna array with a digital thermometer load at various distances from the VCO-PA are shown in Figure 9. The x-axis represents the time in seconds. A 100 μF capacitor is used to save the harvested energy from the VCO-PA transmitter at 50 cm. The voltage of the rectenna array reached 1.3 V within 9 s, and the digital thermometer then started to work stably. As the distance to the router decreased, the voltage increased because of the increased energy that could be harvested by the array.

The performance comparison between the proposed rectenna array and the reported rectennas is depicted in Table 1. Through the comparison, it can be discovered that the polarization of those rectenna arrays is single. Our proposed rectenna array has a multipolarization and omnidirectional RF energy harvesting. The size of a single rectenna is compact. This advantage broadens its application on other electronic devices to implement omnidirectional and multi-polarized RF energy.

5. Conclusion

This manuscript proposed a compact and cost-effective microwave power transmission (MWPT) system. A dual-polarization rectenna array is designed to eliminate the matching network. A compact VCO-PA transmitter measuring 45 mm × 45 mm × 1 mm is designed, and its measured transmit power at 2.45 GHz is 30 dBm. Additionally, a meander-line dipole rectenna that eliminates the need for a matching network between the antenna and the dipole is proposed, and its maximum efficiency is measured to be 62.3% at −2 dBm. To evaluate the performance of the proposed rectenna array in an indoor RF environment, it is integrated into a digital thermometer. The proposed MWPT system was able to successfully power the digital thermometer using the rectenna array, demonstrating its potential for use in smart home applications in the future.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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