Polarization Reconfigurable Patch Antenna for Wireless Power Transfer Related Applications

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Abstract: A polarized reconfigurable patch antenna is proposed in this paper. The proposed antenna is a dual cross-polarized patch antenna with a programmable power divider. The programmable power divider consists of two branch line couplers (BLC) and a digital phase shifter. By adjusting the phase of the phase shifter, the power ratio of the power divider can be changed, and thus the feed power to the antenna input port can be changed to reconfigure the antenna polarization. The phase-controlled power divider and the cross dual-polarized antenna are designed, fabricated and tested, and then they are combined to realize the polarized reconfigurable antenna. By moving the phase of the phase shifter, the antenna polarization is reconfigured into vertical polarization (VP), horizontal polarization (HP), and circular polarization (CP). The test is conducted at the frequency of 915 MHz, which is widely used for simultaneous wireless information and power transfer (SWIPT) in radio-frequency identification (RFID) applications. The results demonstrate that when the antenna is configured as CP, the axial ratio of the antenna is less than 3 dB, and when the antenna is configured as HP or VP, the axial ratio of the antenna exceeds 20 dB. Finally, experiments are conducted to verify the influence of antenna polarization changes on wireless power transmitting. As expected, the reconfigured antenna polarization can help improve the power transmitting efficiency.

Keywords: power transfer; branch line coupler; polarization reconfigurable; dual cross polarization antenna

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1 Introduction

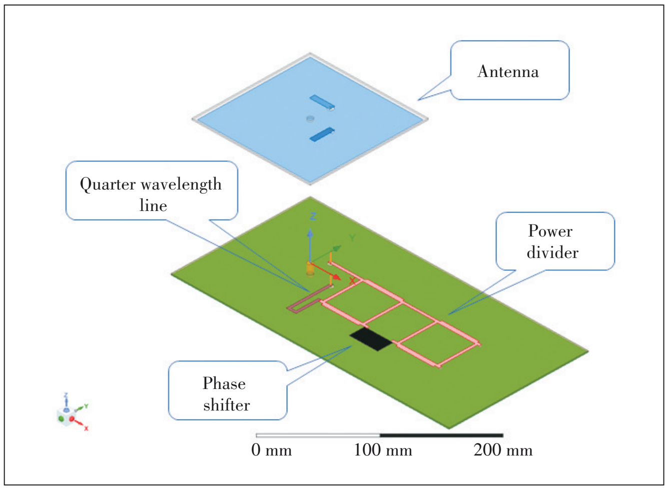
Nowadays, the wireless power transfer (WPT) technology is widely used to charge electronic devices and activate passive wireless sensors[1]. The microwave power can be transmitted over long distances under suitable conditions, but it needs the support of high-efficiency antennas with high levels of performance ensured by antenna matching. The matching mentioned here includes not only the matching between the antenna and the feeding circuit, but also the polarization matching between the transmitting antenna and the receiving antenna. Otherwise, in the case of the crossed polarization between the transmitting antenna and the receiving antenna, power will be lost. In order to minimize the adverse effects of cross polarization, antennas are usually designed for circular polarization (CP)[2]. However, during the wireless power transmission, there is a 3 dB power loss between CP and linear polarization. In order to reduce power loss caused by polarization mismatching for better energy transmission, the antenna polarization reconfiguration technology can be used. There has been a lot of work and research on reconfiguring the antenna polarizations. Re-routing the surface current in the radiating element can reconfigure the antenna polarization[3 – 5], but it is easy to generate nonlinear components of the injected signal and cause additional power loss. The reconfigurable feeding network controlled by PIN diodes can also change the antenna polarization from linear to circular[6]. The radio frequency (RF) switch can be used to select antennas with different polarizations to achieve different antenna polarizations[7 – 9]. The 1: 1 power divider with or without an additional quarter-wave phase line can drive the linear polarization or CP of the antenna, and the diode can be switched on and off to select the feeding circuit that leads to different polarizations[10]. Diodes can also choose different quasi-cross-shaped coupling slots to activate different polarizations[8]. Metasurface applications with feed port changes are another way to reconfigure antenna polarization[11 – 12]. In addition to PIN diodes, varactor diodes are selected as a switch to feed different feed networks to achieve different antenna polarizations[13], and there is also a single-pole double-throw switch that selects feed networks to reconfigure the antenna polarization[14].

This paper proposes a new type of polarization reconfigurable antenna. Different from previous works that reconfigure the limited number of antenna polarizations, this antenna can be programmed for linear polarization at any angle or for CP. With the programmable antenna polarization, the wireless power can be transferred more efficiently. It also provides the possibility to transfer the wireless power and wireless information with different antenna polarizations to get better isolation between wireless power and wireless information. Section 2 will introduce the design of the proposed antenna, including the power divider design and antenna design, as well as the overall structure of the antenna. In Section 3, the prototype of the antenna is fabricated, the actual performance of the antenna is tested and demonstrated, and the antenna is used to simulate on-site wireless power transfer. Finally, Section 4 concludes the paper.

2 Design Principle of Antenna

2.1 Antenna Structure

The proposed reconfigurable antenna is shown in Fig. 1. The antenna has two substrates, both of which are FR4 (flame retardant 4) materials with dielectric constant ε_r=4.4, loss tangent tanδ=0.02 and a thickness of 1.6 mm. The radiating element is located on the top substrate and consists of a square patch element and two open stubs. The square patch element is printed on the top substrate. Two stubs are printed on the other side of the top substrate. The capacitors are formed between the two stubs and the square patch, and the RF signal is coupled to the patch element through the capacitor and radiates to the space. The feeding network is located on the bottom substrate and consists of a programmable power divider and quarter-wavelength phase lines. The feeding network and the patch antenna are connected by two copper pillars. One of the copper pillars connects a power divider output and a stub, and the other copper pillar connects the other stub and the other end of the quarter-wavelength phase line. The programmable power divider consists of two branch line couplers (BLCs) and a digital phase shifter. The digital phase shifter is located between the two BCLs and is used to adjust the power ratio between the two outputs of the power divider.



▲Figure 1. Physical configuration of the proposed antenna

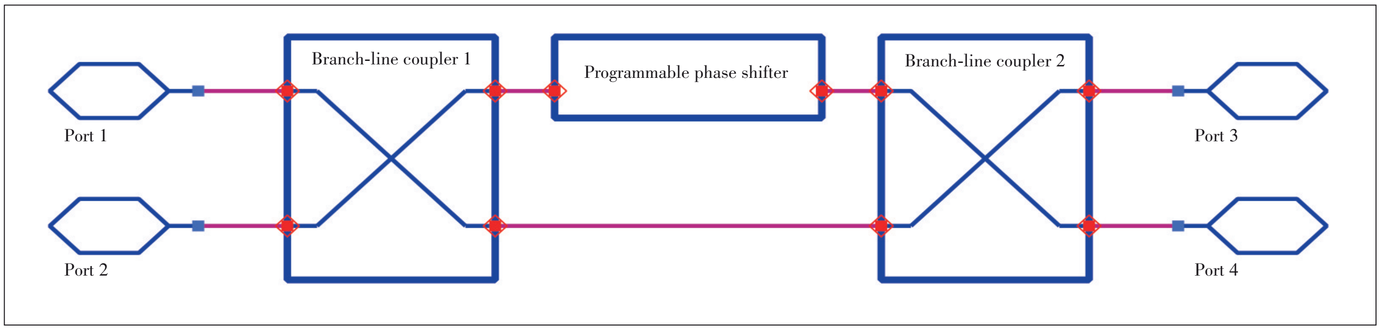
2.2 Design of Power Divider

The schematic diagram of the programmable power divider is shown in Fig. 2. The power is injected into Port 1. Port 2 is terminated by a matching load. The re-allocated power is output from Ports 3 and 4. When the phase of the phase shifter changes, the RF signal power ratio between Ports 3 and 4 of the power splitter will change accordingly.

The scattering matrix of the proposed power divider can be written as follows [15], where φ is the phase of the phase shifter.

$$[S]=je^{\frac{j\varphi}{2}}\begin{bmatrix} 0 & 0 & \sin\left(\frac{\varphi}{2}\right) & -\cos\left(\frac{\varphi}{2}\right) \\ 0 & 0 & -\cos\left(\frac{\varphi}{2}\right) & \sin\left(\frac{\varphi}{2}\right) \\ \sin\left(\frac{\varphi}{2}\right) & -\cos\left(\frac{\varphi}{2}\right) & 0 & 0 \\ -\cos\left(\frac{\varphi}{2}\right) & \sin\left(\frac{\varphi}{2}\right) & 0 & 0 \end{bmatrix}. \quad (1)$$

Therefore, the output power ratio of Ports 3 and 4 can be described as follows.



▲Figure 2. Schematic of power divider

$$b_3 = je^{\frac{j\varphi}{2}} \sin\left(\frac{\varphi}{2}\right), \tag{2}$$

$$b_4 = -je^{\frac{j\varphi}{2}} \cos\left(\frac{\varphi}{2}\right), \tag{3}$$

$$\text{PowerRatio} = \left(\tan\left(\frac{\varphi}{2}\right)\right)^2 . \tag{4}$$

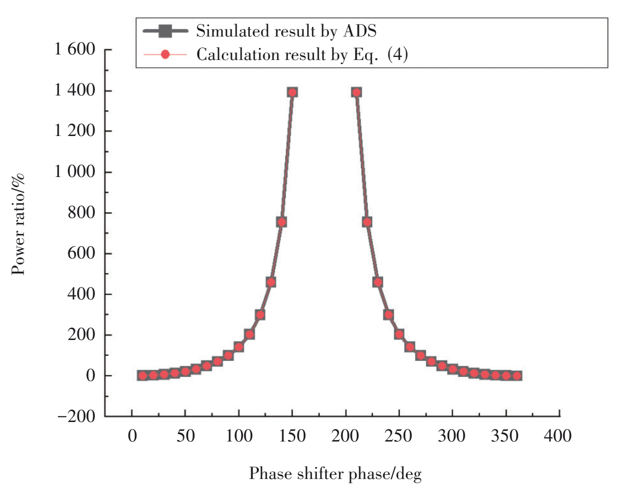
It can be seen from Eq. (4) that the output power ratio is continuous and a function of the phase shifter phase correlation. In order to verify the correctness of Eq. (4), a simulation was carried out in the commercial software Advanced Design System (ADS), and the comparison between simulation and calculation results is shown in Fig. 3. As we can see, these two curves are exactly the same.

There are typical values for this power divider. When the phase of the phase shifter is set to 90 degrees, $\varphi = 90^{\circ}$, the power ratio is 1, and the power of Port 3 and that of Port 4 are the same. When the phase of the phase shifter is set to 0 degrees, $\varphi = 0^{\circ}$, the power ratio is 0 and all the radio frequency power is allocated to Port 4 at this time. When the phase of the phase shifter is set to 180 degrees, $\varphi = 180^{\circ}$, the power ratio is infinite and all the radio frequency power is allocated to Port 3 at this time.

Branch line couplers are designed on the 1.6 mm FR4 board, and the center frequencies are both 915 MHz, as shown in Fig. 4.

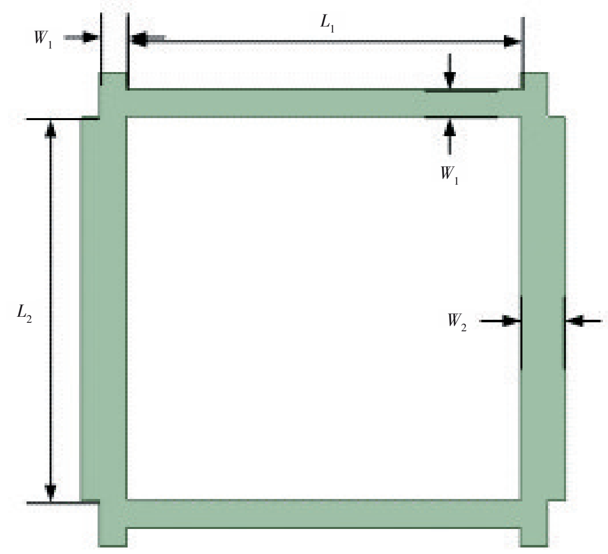
2.3 Antenna Geometry

As described in Section 2.1, the patch is on the bottom of the top substrate and the two open stubs are on the top of the top substrate. The top substrate is supported by a conducting post at the center. The open stubs are connected to the two outputs of the power divider by copper pillars and excite the patch capacitively. The antenna geometry is shown in Fig. 5.



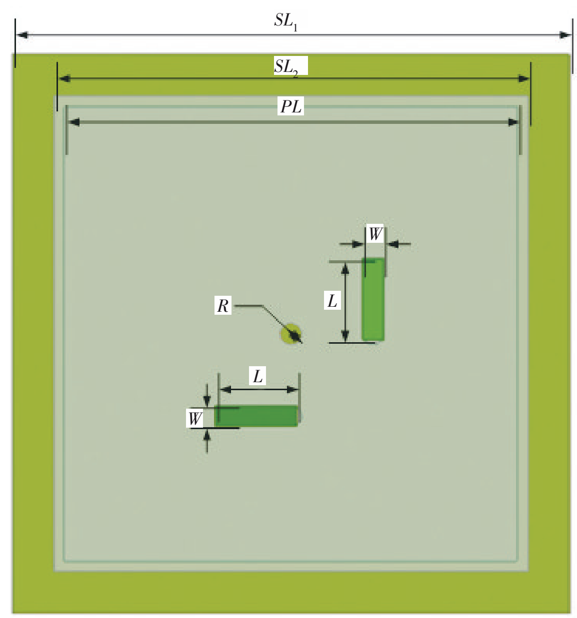
ADS: Advanced Design System

▲Figure 3. Equation verification: power ratio versus phase



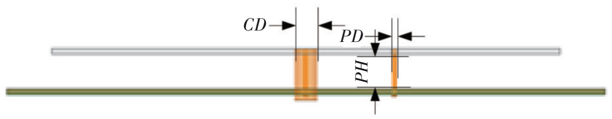
W_1 and L_1 are the width and length of the 50 ohm microstrip line, respectively. W_2 and L_2 are the width and length of the 35 ohm microstrip line. The detailed numerical values are W_1=3 mm, W_2=5 mm, L_1=43 mm, and L_2=43 mm.

▲Figure 4. Branch line coupler structure



PL is the patch length, W is the stub width, L is the stub length, R is the cutout radius on the top substrate, SL_1 is the width of the bottom substrate, and SL_2 is the width of the top substrate. The detailed numerical values are SL_1=160 mm, SL_2=136 mm, PL=130 mm, L=23. 2 mm, W=6 mm, and R=3 mm.

(a) Top view



CD is the diameter of the center pole, PD is the probe diameter, and PH is the probe height, with CD=3 mm, PD=1. 3 mm, and PH=9. 4 mm.

(b) Side view

▲Figure 5. Cross polarization antenna structure

This antenna is a dual cross polarized antenna with good import impedance match, high isolation and exactly the same feeding structure[16] which is required by this wireless power transmitting antenna.

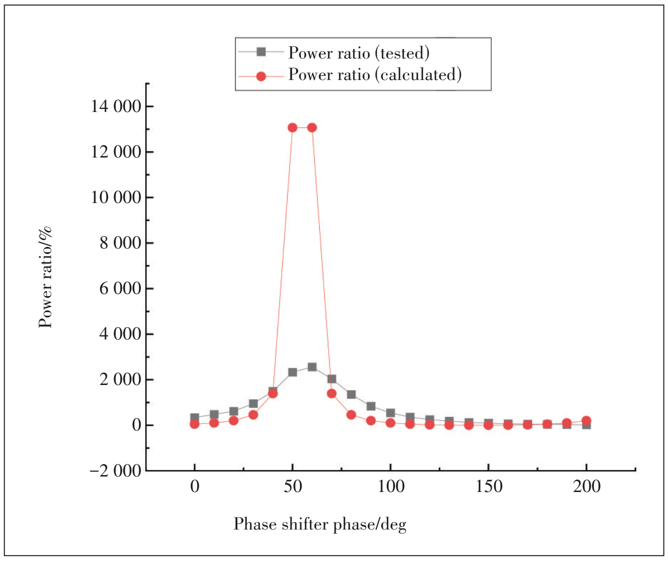
The input probes (copper pillars) excite two orthogonal modes, TM10 and TM01. These two modes have the same resonant frequency which is decided by the patch size. High isolation between the two probes can be achieved by adjusting the probe inductance and stub capacitance. At the frequency decided by the patch size, the TM10 electric field is theoretically zero along the center line of the patch where the feed probe for the TM01 mode is located, and the TM01 electric field is zero along the center line of the patch where the feed probe for the TM10 mode is located. Therefore, high isolation between probes is achieved at the desired frequency.

3 Test Results and Discussion

For the purpose of test and tuning for each part of the proposed antenna, the prototypes of the radiation element, BLC and digital phase shifter are fabricated separately. A quarter wavelength phase cable is used as a 90° phase line and connected to Port 3 of the power divider.

3.1 Test of Power Divider

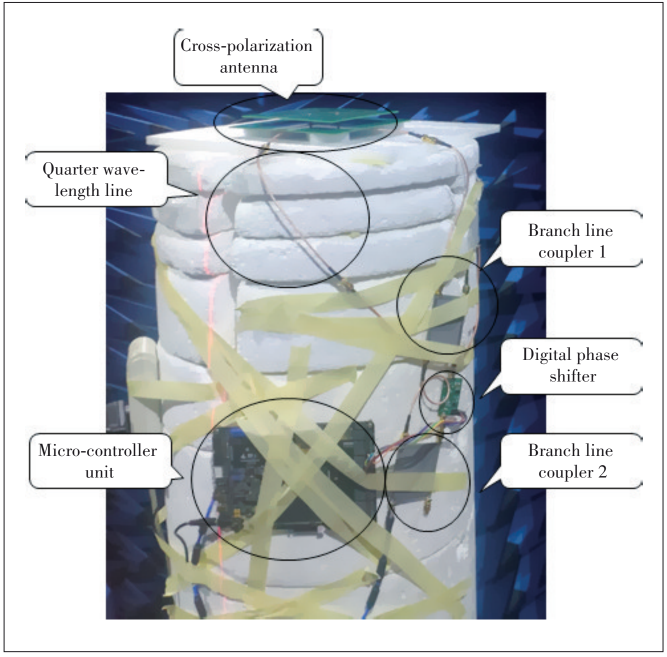
The power ratio versus the phase of the power divider was measured and the comparison of the measured and calculated results by Eq. (4) is shown in Fig. 6. As the recorded phase values are the absolute phase shifter phases but not the phase differences which are defined as φ between two BLCs, the red curve in Fig. 3 is the calculation result after calibration. When the phase shifter phase is set to an absolute value of 150°, the power ratio is 1, which means that the phase difference between the two paths connecting the two BLCs is 90°. When the phase shifter phase is set to 60°, the power at Port 4 is the maximum. When the phase shifter phase is set to 200°, the power at Port 3 is the maximum. Therefore, when the absolute value of the phase shifter is set to 60°, the phase difference is 0; when the absolute value of the phase is set to 200°, the phase difference is 180°.



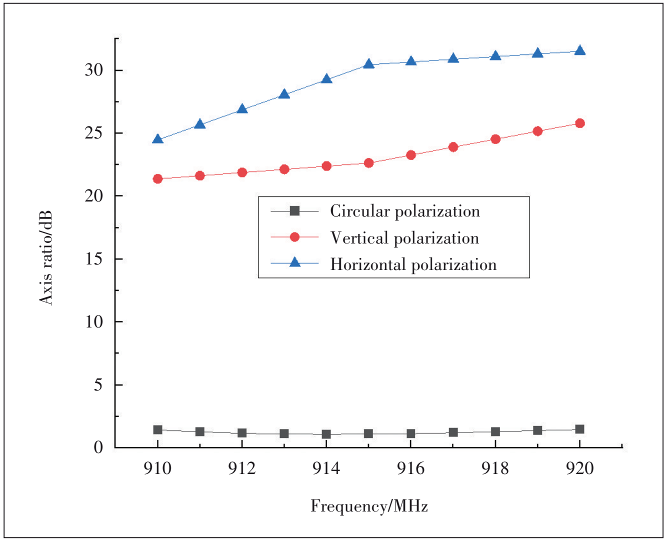
▲Figure 6. Power divider: power ratio versus phase

3.2 Test of Antenna

The antenna test was carried out inside a chamber as shown in Fig. 7, and the test frequency is 915 MHz. Typically, when the phase shifter phase was set to 60°, 150° and 200°, the gain and axial ratio of the antenna were tested. The axis ratio (AR) result is shown in Fig. 8. When the phase is 150°, the antenna polarization is configured as CP and the AR is about 1 dB.



▲Figure 7. Antenna test setup inside the chamber

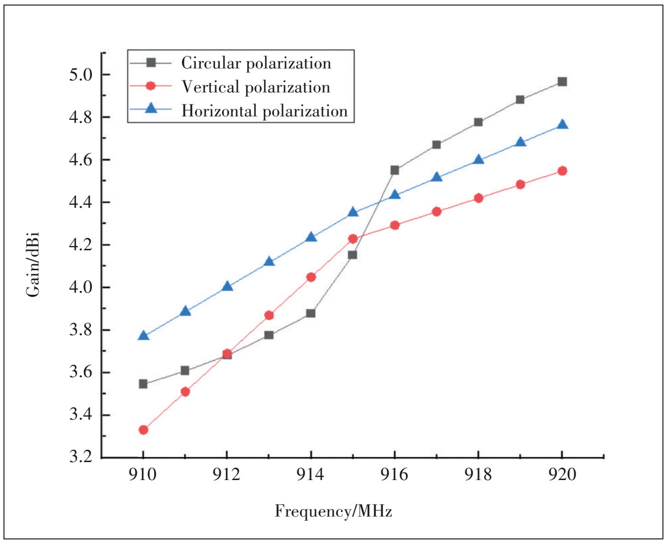


▲Figure 8. Tested Axis Ratio (AR) results of the proposed antenna

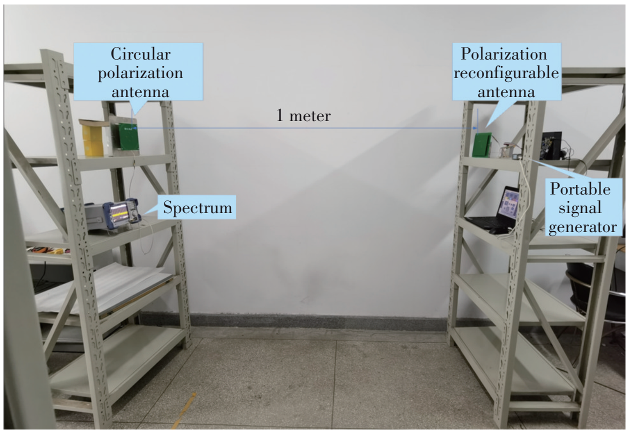
When the phase shifter phase is set to 60° and 230°, the antenna is configured as horizontal polarization (HP) and vertical polarization (VP), and the AR is higher than 20 dB. The results show the reconfigurable antenna polarization controlled by the phase shifter, which is in line with the design expectations. The gain result of the antenna is shown in Fig. 9. The gain of the antenna does not change much when the polarization of the antenna changes. It demonstrates the stable gain performance with the phase shifter phase changing.

3.3 Test of Wireless Power Transfer Field

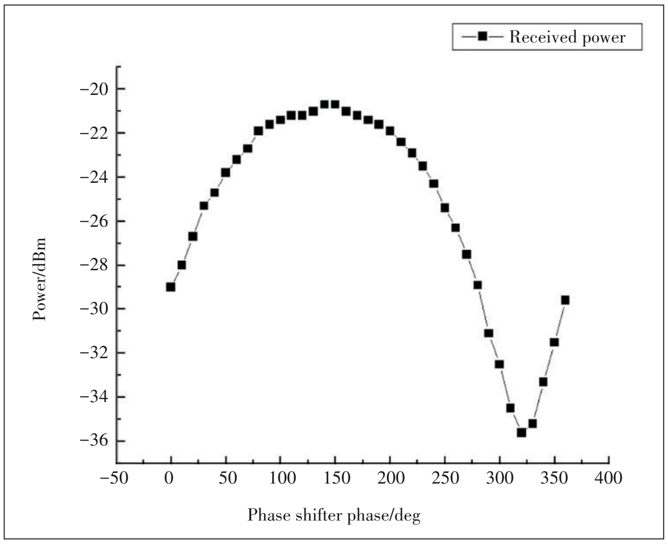
To verify the effect of antenna polarization during wireless power transfer, a simple simulation test was performed. As shown in Fig. 10, the power transmitter is on the left shelf and consists of a polarization reconfigurable antenna and a signal generator for transmitting wireless signals. The receiving end is on the right shelf and includes a circularly polarized antenna and a spectrum analyzer to measure the received wireless signal. The distance between the transmitter and receiver is 1 m, and they are at the same height. The signal generator generates a 915 MHz wireless signal, which is transmitted to the receiving end through a phase-controlled polarization reconfigurable antenna. The circularly polarized antenna at the receiving end receives the wireless signal, and the spectrum analyzer measures the amplitude of the received wireless signal. With the same frequency and amplitude of the transmitted signal, the phase shifter phase of the transmitting antenna is changed and the amplitude change of the received signal is recorded. The test results are shown in Fig. 11. As expected, when the phase shifter phase is set to 150°, the transmit antenna polarization is configured as circular which is the same as the receive antenna polarization. Meanwhile, the received power is the maximum.



▲Figure 9. Tested gain results of the proposed antenna



▲Figure 10. Wireless power transfer field test setup



▲Figure 11. Antenna polarization during wireless power transfer

4 Conclusions

This paper proposes a method to further improve wireless power transfer by reconfiguring the antenna polarization, which is controlled by a programmable phase shifter. Experiments show that different antenna polarizations can be configured through programmable phase shifters without changing the antenna gain performance. The wireless power transmission simulation experiment demonstrates that tuning the transmitting antenna polarization to match the receiving antenna polarization can improve the efficiency of wireless power transmission. This makes it possible for the automated antenna polarization adaption during wireless power transfer.

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