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Microwave Wireless Power Transfer System Based on a Frequency Reconfigurable Microstrip Patch Antenna Array

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Abstract: The microwave wireless power transfer (MWPT) technology has found a variety of applications in consumer electronics, medical implants and sensor networks. Here, instead of a magnetic resonant coupling wireless power transfer (MRCWPT) system, a novel MWPT system based on a frequency reconfigurable (covering the S-band and C-band) microstrip patch antenna array is proposed for the first time. By switching the bias voltage-dependent capacitance value of the varactor diode between the larger main microstrip patch and the smaller side microstrip patch, the working frequency band of the MWPT system can be switched between the S-band and the C-band. Specifically, the operated frequencies of the antenna array vary continuously within a wide range from 3.41 to 3.96 GHz and 5.7 to 6.3 GHz. For the adjustable range of frequencies, the return loss of the antenna array is less than -15 dB at the resonant frequency. The gain of the frequency reconfigurable antenna array is above 6 dBi at different working frequencies. Simulation results verified by experimental results have shown that power transfer efficiency (PTE) of the MWPT system stays above 20% at different frequencies. Also, when the antenna array works at the resonant frequency of 3.64 GHz, the PTE of the MWPT system is 25%, 20.5%, and 10.3% at the distances of 20 mm, 40 mm, and 80 mm, respectively. The MWPT system can be used to power the receiver at different frequencies, which has great application prospects and market demand opportunities.

Keywords: microwave wireless power transfer; antenna array; power transfer efficiency; frequency reconfigurable



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1. Introduction

The power supply technology used for various electronics is important, and the conventional power supply technology is provided by using cables, which can be hazardous, inconvenient, or impossible [1,2]. The transformation of charging technology from using traditional cables to wireless power transfer (WPT) is suitable for the booming development of portable devices, consumer electronics, robots, and other fields [3–5]. The WPT technology has attracted great attention due to its promising application potential in the field of charging [6,7]. One of the interesting and highly requested directions for wireless energy transfer is sensor applications [8,9]. There are many types of WPT technologies including magnetic resonant coupling, microwaves, inductive coupling, radio waves, lasers, and so forth [10,11]. Out of these, the microwave wireless power transfer (MWPT) technology can transfer energy over relatively long distances with miniaturized antennas, which has great market demand [12].

At present, the MWPT technology has been applied in various fields, such as electric vehicles and mobile phones powered by electromagnetic waves and the MWPT systems inside buildings [13,14]. The microstrip patch antenna array has advantages of a simple process, small volume, light weight, low profile, and easy integration, which is why it is widely used in the field of WPT. A series of theoretical and experimental results about MWPT systems with the microstrip patch antenna arrays were conducted [15]. Also,

many various methods have been employed to increase the power transfer efficiency (PTE), performances, and robustness of the MWPT systems by designing transmitting arrays [16–19]. A MWPT system operating at the frequency of 5.8 GHz by using an 8×8 transmitting antenna array and a 4×4 receiving antenna array was presented, and the PTE of the system was 33.4% at the distance of 40 cm [20]. Additionally, in order to improve the efficiency of the system, an optimized MWPT system using an 8×8 transmitting patch antenna array and a 8×8 receiving patch antenna array at the frequency of 5.8 GHz and the distance of 100 cm. The measured results show that the PTE of this MWPT system is 46.9% [21]. However, for the above mentioned WPT systems, receivers only catch the energy at a single frequency, regardless of their demands. This may cause malfunctions and failures, and the PTE of the system may therefore be reduced.

In order to resolve this issue, many methods have been adopted in the magnetic resonant coupling wireless power transfer (MRCWPT) system [22–25]. Frequency reconfigurable MRCWPT systems were developed in previous works [22,23] by adding adaptively switching resonant capacitances. In the reference [24], a new approach based on reconfigurable magnetic resonant structures is proposed to achieve high energy efficiency and low volt-amp ratings. This basic principle is to create more than one efficiency-load curve. By combining a variable coupling technique, a frequency reconfigurable MRCWPT system has been proposed by varying the distance between the transmitter and the receiver [25]. In addition, a shape-reconfigurable modularized MRCWPT system in [26] achieves shape reconfigurability by using different structures and positional combinations of resonant modules. The reconfigurability in the reconfigurable MRCWPT system in [27] is achieved by adaptively switching between different sizes of drive loops and load loops. Here, instead of a MRCWPT system, a novel MWPT system based on a frequency reconfigurable (covering the S-band and C-band) microstrip patch antenna array is proposed for the first time to power the receiver at the different frequencies. This paper is organized as follows. The frequency reconfigurable microstrip patch antenna array is described in Section 2. In Section 3, the simulation and the measurement of the proposed frequency reconfigurable MWPT system are presented. The experimental results are compared with the simulation results. Finally, Section 4 draws conclusions.

2. Frequency Reconfigurable Microstrip Patch Antenna Array

2.1. The Configuration and Design of the Patch Antenna Array

A conventional antenna array only works at one frequency. This is because when the conventional antenna is used as the transmitter for wireless power transfer (WPT), the conventional antenna used as the receiver only receives the energy from the transmitter at the same working frequency. Also, when the working frequency of the receiver changes, the power transfer efficiency of the system will reduce. In addition to the conventional antenna only being able to power the receiver at one working frequency, it cannot power the receiver for different frequencies, regardless of energy demands. This may cause malfunctions and failures, and the PTE of the system may decrease as a result. The frequency reconfigurable antenna continuously adjusts the working frequency within a certain frequency range. The WPT system based on a frequency reconfigurable antenna can power the receivers at different frequencies. It was shown that the PTE of the WPT system remains stable at different frequencies. Also, the PTE of the system does not clearly decrease as the resonant frequency of the receiver changes. Therefore, the frequency reconfigurable array more important than the conventional antenna array for wireless power transfer.

The operating mechanism of the array is that the array radiates the electromagnetic wave if four patches are excited. Under the excitation of the main mode, the direction of the electric field changes along the length of the half-wavelength patch. The antenna array radiates energy mainly through the gap between the open edge of the patch and the floor, and the electromagnetic wave radiated over the narrow seam can be equivalent to the magnetic flux. According to the array antenna theory, the radiation field at the center of two arrays is the largest, as the direction of patch normal, while the radiation field

deviating from the corresponding direction with the normal direction becomes smaller. The electric field of the two radiated edges can be decomposed into the vertical and horizontal components relative to the ground plane. The length of the radiation patch is set as a half wavelength. According to the transmission line theory of half wavelengths, the vertical components of the two radiation edge crevice decomposition cancel each other out in the far field and generate no radiation, while the horizontal component has the same direction and produces the strongest radiation, meaning that the radiation field is the strongest in the direction perpendicular to the antenna surface.

The frequency reconfigurable antenna array is fed by a coaxial feed. The feed network of the antenna array uses the power divider. The power divider is designed to provide the same excitation power. For a frequency tuning operation, varactor diodes are used. The varactor diode is placed between the larger main patch and the smaller side patch, which has the variable bias voltage provided by the adjustable DC power source. By changing the capacitance of those varactors, the resonance frequency of the patch antenna array can be tuned.

The antenna dimensions can be derived from the working frequency of the microstrip patch antenna. The variable symbol W represents the width of the patch, which can be derived as follows [28]:

$$W = \frac{c}{2f} \left(\frac{\epsilon_r + 1}{2} \right)^{-\frac{1}{2}} \quad (1)$$

where the variable symbol c is the speed of light, and the variable symbol ϵ_r is the relative dielectric constant of the dielectric material. The dielectric material is epoxy resin, while the variable symbol f is the working frequency of the patch antenna. The thickness of dielectric material is h . The metal layer is copper and the effective dielectric constant ϵ_e can be derived as follows [29]:

$$\epsilon_e = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2} \left(1 + 12 \frac{h}{W} \right)^{-\frac{1}{2}} \quad (2)$$

The length of the radiation gap is ΔL and the length of the patch is L [30].

$$\Delta L = 0.412h \frac{(\epsilon_e + 0.3)(W/h + 0.264)}{(\epsilon_e - 0.258)(W/h + 0.8)} \quad (3)$$

$$L = \frac{c}{2f\sqrt{\epsilon_e}} - 2\Delta L \quad (4)$$

The simulation model of the frequency reconfigurable microstrip patch antenna array is shown in Figure 1. The patch antenna array mainly consists of 4 main patches, 16 side patches and the feed network. By placing the varactor diode (SMV1281) inside the larger main patch and the smaller side patch, the antenna can perform as a frequency reconfigurable antenna array. The SMV1281 varactor diode has an adequate range of capacitance values from 0.69 pF to 13.3 pF, and it has low series resistance. Adding 4 varactors on the side of the patch is used to changing the working frequency of the frequency reconfigurable antenna array. The feed network is used to feed the antenna array and the lumped port is used in the simulation software HFSS (High Frequency Structure Simulator) to excite the patch antenna array.

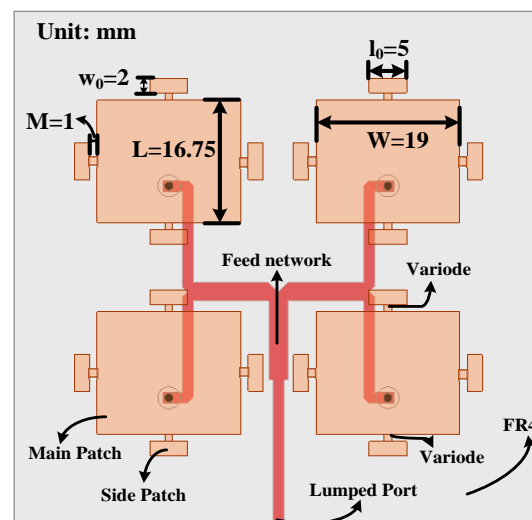


Figure 1. The general geometry of the patch antenna array (four smaller patches are all connected to the larger main patch).

The frequency reconfigurable antenna array has two working states. There are four smaller patches around the larger main patch, as shown in Figure 1. When four smaller patches are all connected to the larger main patch by using four varactors, the frequency reconfigurable patch antenna array works at frequencies from 3.41 GHz to 3.96 GHz. The details of simulation in this case are shown in Figure 2a. The varactor diode model in HFSS is replaced by the lumped RLC boundary. The return losses at different frequencies for the general reconfigurable antenna array are illustrated in Figure 2b. The working frequency belongs to S-band. In this case, the return losses are less than -15 dB when the capacitance values are changed. Then, the working frequency of the patch antenna array are adjusted. When just one smaller patch is connected to the larger main patch, the frequency reconfigurable patch antenna array can work at frequencies from 5.7 GHz to 6.3 GHz. The details of simulation in this case are shown in Figure 3a. The varactor diode model in HFSS is also replaced by the lumped RLC boundary. The return losses at different frequencies in this case are illustrated in Figure 3b. The working frequency belongs to C-band, and the return losses are also less than -15 dB at different working frequencies.

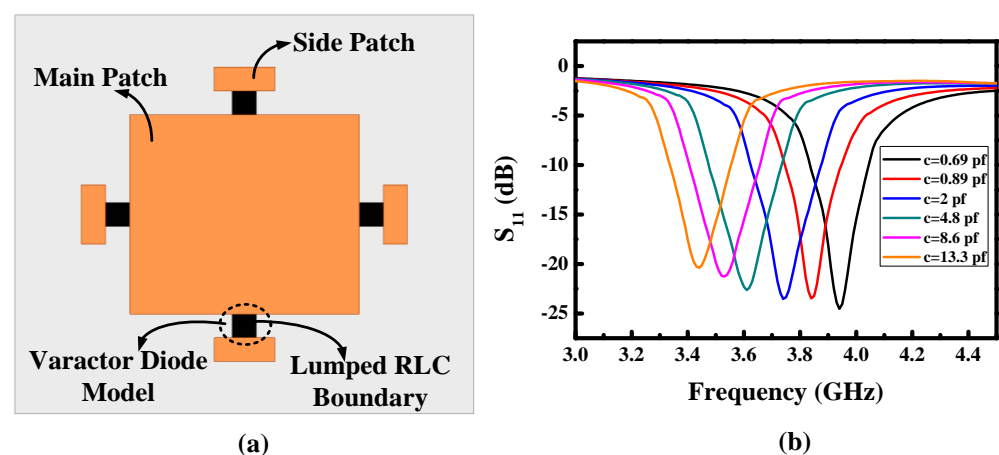


Figure 2. (a) Details of the simulation model (four smaller patches are all connected to the larger main patch). (b) The return losses at different frequencies for the reconfigurable antenna array.

The patch antenna array is designed on a double-sided substrate using the planar technology, while the feed network is designed on a single-sided substrate. In assembling the microstrip patch antenna array, the non-copper side of the feed network is placed in

direct contact with the ground of the patch antenna array, as shown in Figure 4a. This leads to a low profile and compact structure. The dimensions of the frequency reconfigurable patch antenna array in Figures 1 and 4a are listed in Table 1. The fabricated patch antenna array is shown in Figure 4b,c for measurement. The SMA (SubMiniature Version A) connector is fed to the feed-line through the substrate material and the ground plane. The reconfigurable antenna array and the SMA connector are designed on the FR4 substrates, which have a dielectric constant of 4.4 and a loss tangent of 0.02.

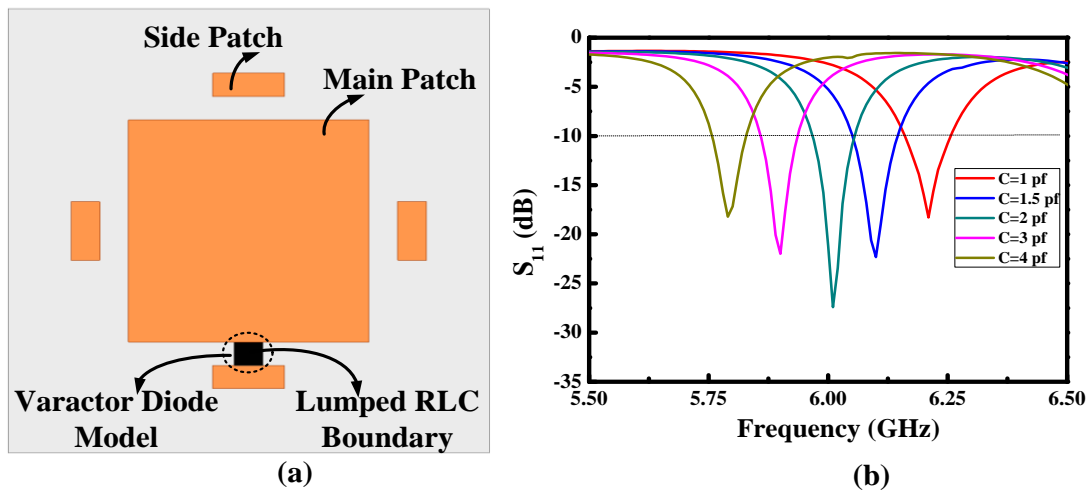


Figure 3. (a). Details of the simulation model (one smaller patch is connected to the larger main patch). (b). The return losses at different frequencies.

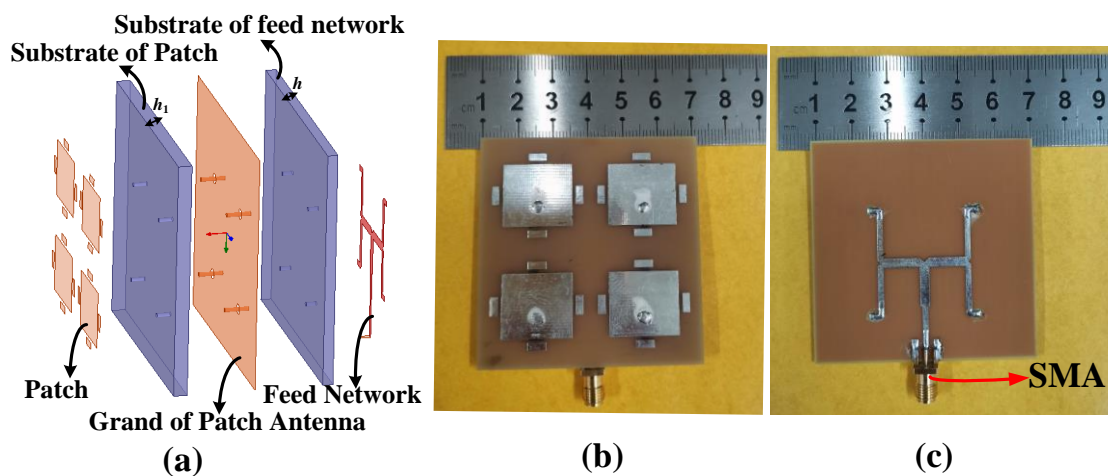


Figure 4. (a). Assembly schematic of antenna. (b) Top and (c) bottom views of the fabricated antenna.

Table 1. Dimensions of the antenna array.

Parameters	Values
W	19.0 mm
L	16.8 mm
w_0	2.0 mm
l_0	5.0 mm
M	1.0 mm
h	0.8 mm
h_1	1.6 mm

2.2. Simulation and Measurement Results

Simulation results are obtained in the simulation software HFSS, and the return losses are measured by the vector network analyzer (Agilent Technologies N5230A, which is manufactured by Agilent in Palo Alto, USA.) to verify the accuracy of the frequency reconfigurable antenna array. When four smaller side patches are all connected to the larger main patch, the simulated and measured return losses at different frequencies for the reconfigurable antenna array are illustrated in Figure 5a. The resonant frequency of the antenna array changes significantly from 3.41 GHz to 3.96 GHz by varying the DC bias voltage from 0 to 20 V. The working frequency from 3.41 GHz to 3.96 GHz belongs to the S-band (2–4 GHz). The simulated and measured return losses at different frequencies that are obtained when just one smaller side patch is connected to the larger main patch are illustrated in Figure 5b. The working frequency changes significantly from 5.7 GHz to 6.3 GHz by varying the DC bias voltage from 3 to 11 V. The working frequency in this case belongs to the C-band (4–8 GHz). The frequency which belongs to the S-band and the C-band have been widely used in the fields of radar, satellite communication and so on. Now other widely used forms of technology such as Bluetooth, ZIGBEE, wireless routing, wireless mouse device and a wide range of electronic products also use this frequency, which belongs to the S-band and C-band. The resonant frequency of the antenna array shifts toward higher values with an increase in DC bias voltages and a decrease in capacitance values of the varactor diodes. For the adjustable range of frequencies, the return loss of the antenna array is less than -15 dB at the resonant frequency. There is a slight difference between simulation results and measurement results because of the fabrication tolerance and small measurement errors. Also, the ohmic loss of the varactor diodes cannot be precisely modeled in the simulation software HFSS. Also, there are a number of modulations that are needed because lots of varactor diodes are welded between the larger main patches and the smaller side patches, and lots of wires are used. The frequency reconfigurable antenna array is affected by interference caused by using lots of wires.

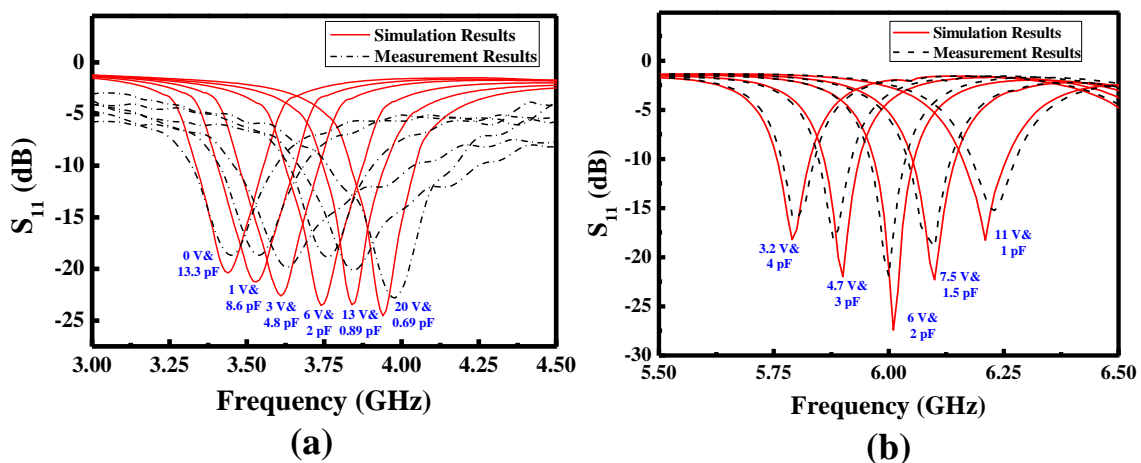


Figure 5. (a). Simulated and measured return losses for the antenna (four smaller side patches are all connected to the larger main patch). (b). Simulated and measured return losses (one smaller side patch is connected to the larger main patch).

The antenna pattern refers to the pattern in which the relative field intensity of radiation field changes with the direction at a certain distance from the antenna. The antenna pattern is an important pattern to measure the antenna performance. The antenna pattern is a diagram used to show the directivity of the antenna. The parameters of the antenna can be observed from the antenna pattern. The frequency reconfigurable antenna is continuously adjusted at the working frequency within a certain frequency range. A good frequency reconfigurable antenna should have a relatively stable antenna pattern. We show the antenna pattern of the frequency reconfigurable antenna array at different

frequencies. This pattern indicates that the frequency reconfigurable antenna array works normally at different working frequencies. As a result, the antenna is very important for the wireless power transfer system. The radiation gain patterns of the antenna array in the xz plane and yz plane at different frequencies are shown in Figure 6. The xz plane means that Phi is 0 deg, and the yz plane means phi is 90 deg. Radiation gain patterns maintain similar shapes at different states. In summary, with 16 varactors, this array can operate with the maximum gain varying from 7.87 to 7 dBi when the operating frequency is tuned from 3.96 to 6.21 GHz.

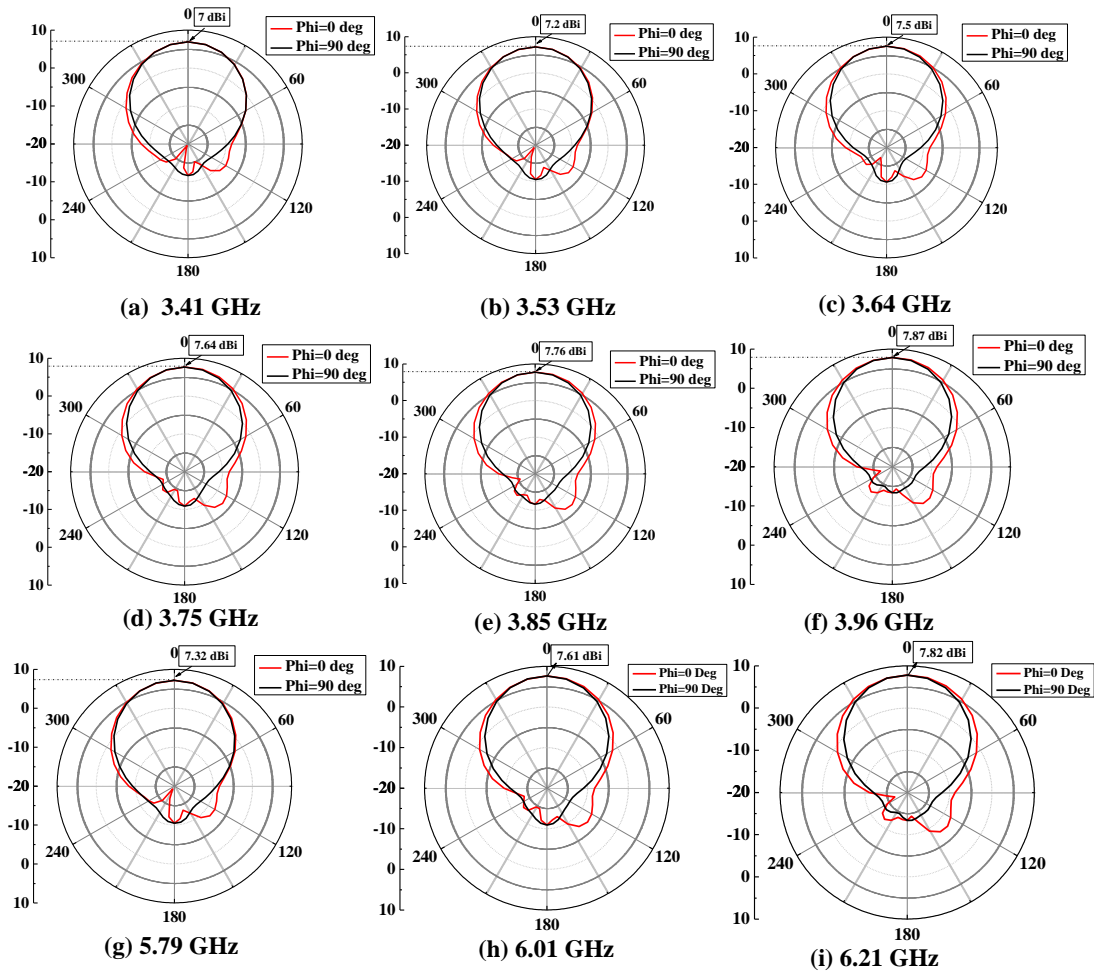


Figure 6. Radiation gain patterns of the antenna array in the xz plane and yz plane at different frequencies.

The gain of the single patch antenna and the gain of the patch antenna array without any smaller side patches are simulated. The gains of the single patch antenna and the patch antenna array are shown in Figure 7. The gain of the single patch antenna is 4.4 dBi. Also, the gain of the single patch antenna array is 7.8 dBi. Therefore, the gain is improved by using the array. As a result, we updated the gains of the frequency reconfigurable antenna array.

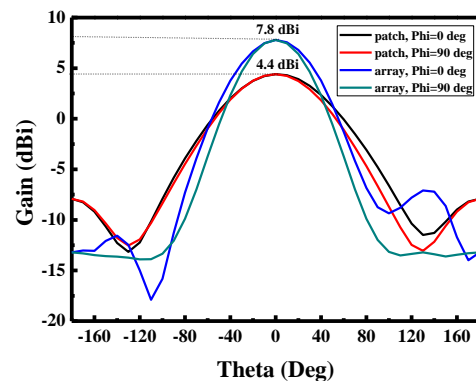


Figure 7. The gains of the single patch antenna and the patch antenna array.

The gains of the antenna array at different frequencies between the S-band are shown in Figure 8a. Also, the simulated and measured gains are illustrated in Figure 8b when one smaller side patch is connected to the larger main patch. Simulated results have shown that the gain is above 7 dBi. Measurement results have shown that the gain of the antenna array is above 6 dBi at different frequencies. There was an error rate of about 6% between the simulation results and the measurement results. Measured gains were slightly lower than the simulated gains due to measurement errors and the fabrication tolerance. In short, the gains of the antenna array are relatively stable within the range of the frequency. The gains of the frequency reconfigurable antenna array are slightly lower than the gains of the patch antenna array without any smaller side patches. Also, these gains are reduced as the capacitance of the varactor increases due to increases in internal resistance. In short, the radiation patterns and the gains of the antenna array are relatively stable within the range of the frequency.

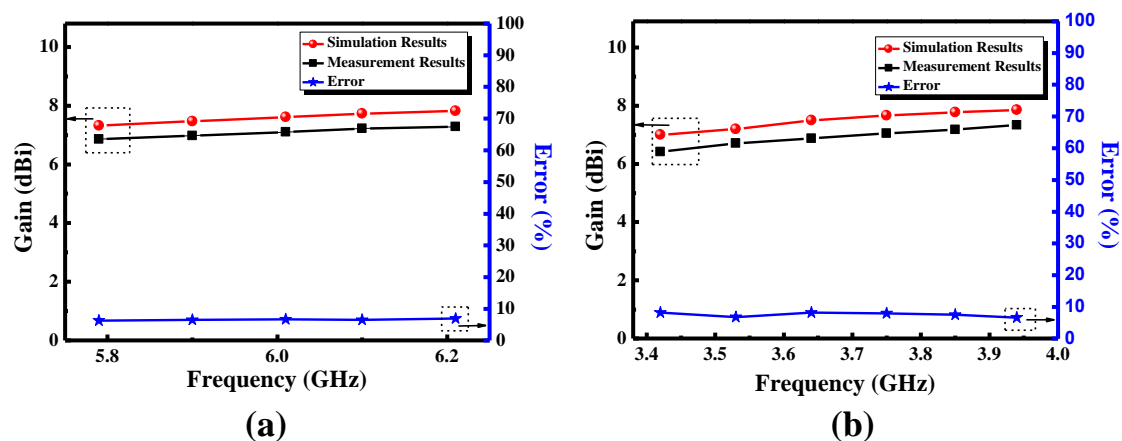


Figure 8. (a). Simulated and measured gains of the antenna (four smaller side patches are all connected to the larger main patch). (b). Simulated and measured gains (one smaller side patch is connected to the larger main patch).

3. The Microwave Wireless Power Transfer System

The simulation model of the MWPT system can be built by using the simulation software HFSS. The model of the proposed MWPT system is shown in Figure 9a. The frequency reconfigurable antenna array is used as the transmitter of the MWPT system to transmit energy. The antenna is also used as the receiver of the MWPT system to receive energy. The capacitance value of the varactor diode changes with different voltage, which has been shown in Figure 9a. This suggests that the frequency reconfigurable antenna array can work at the continuous switchable resonant frequency within a certain range. The energy is transmitted from the transmitter to the receiver through the electromagnetic

field at the different working state, as shown in Figure 9a. The variable symbol d is the distance between the transmitter and the receiver.

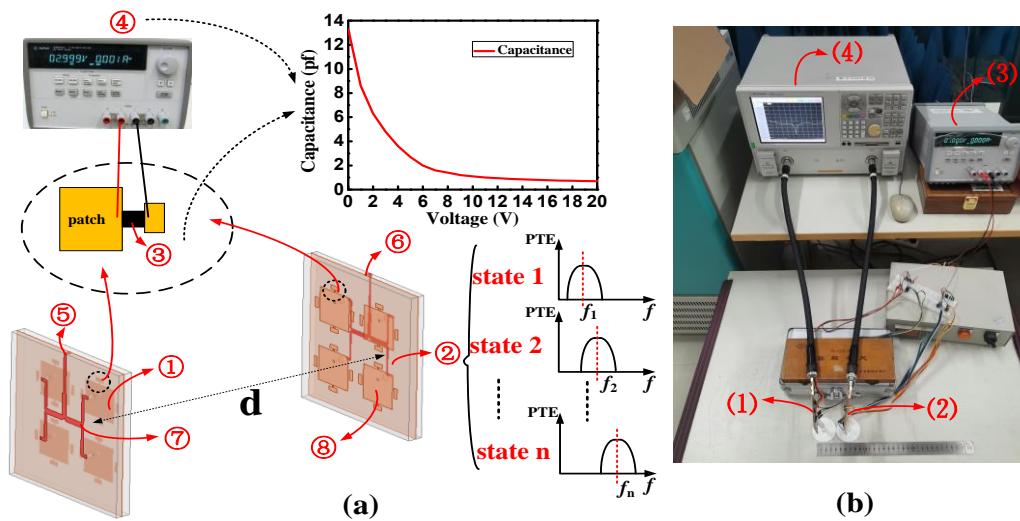


Figure 9. (a). The model of the microwave wireless power transfer (MWPT) system (①: transmitter, ②: receiver, ③: varactor diode, ④: DC voltage source, ⑤: lumped port 1, ⑥: lumped port 2, ⑦: feed network, ⑧: patch). (b). The experimental platform for the MWPT system ((1): transmitter, (2): receiver, (3): DC voltage source, (4): vector network analyzer).

The experimental platform for the MWPT system is illustrated in Figure 9b. The transmitter and the receiver are connected to port 1 and port 2 of the vector network analyzer (Agilent Technologies N5230A, which is manufactured by Agilent in Palo Alto, USA.), respectively. The adjustable DC voltage source (KEYSIGHT E3633A, which is manufactured by KEYSIGHT in Shenzhen, China.) is used to provide the variable DC bias voltage for the varactor diode. The transmitter is fixed in a certain position, and the receiver is placed in a coaxial position of the transmitter. PTE of the frequency reconfigurable MWPT system is calculated by the equation in [21], which is:

$$PTE = 10^{|S_{21}|/10} \times 100\%. \quad (5)$$

The S_{21} of the MWPT system is measured by the vector network analyzer. Simulation and measurement results of PTE of the MWPT system at different frequencies between S-band and C-band are illustrated in Figure 10a,b, respectively. The measured results have shown that the PTE of the MWPT system stays at around 20% at different frequencies. The measured results agree with the simulated results, but there is an error rate of about 10% between the simulation results and the measurement results. Also, the measured results are lower than the simulated results due to the fabricated tolerance and measurement errors. The MWPT system based on the frequency reconfigurable antenna array can be used to power the receiver at different frequencies, and the PTE of the system does not decrease as the resonant frequency of the receiver changes.

Simulation and measurement results of power transfer efficiency of the system at the different distance are shown in Figure 11. Obviously, the PTE of the MWPT system decreases as the distance value increases. After repeated testing, the relative error between the simulation and experimental results is distributed at around 10%. The measurement results are relatively lower than the simulation results because of the practical fabrication tolerance. When the antenna array works at the resonant frequency of 3.64 GHz, the PTE of the MWPT system is 25%, 20.5% and 10.3% at distances of 20 mm, 40 mm and 80 mm, respectively.

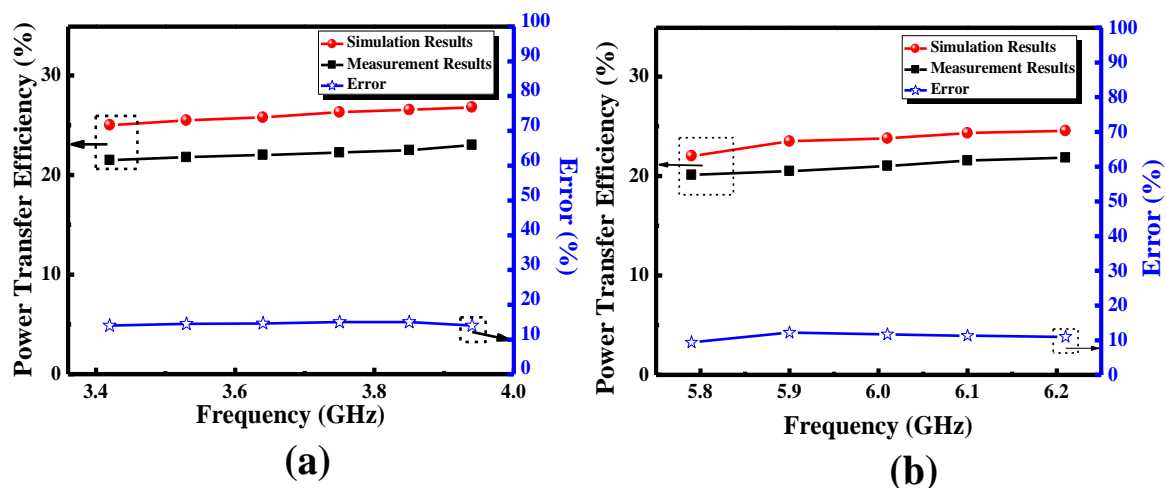


Figure 10. (a) The power transfer efficiency (PTE) of the MWPT system at different frequencies (four smaller side patches are all connected to the larger main patch). (b) The power transfer efficiency (PTE) of the MWPT system at different frequencies (one smaller side patch is connected to the larger main patch).

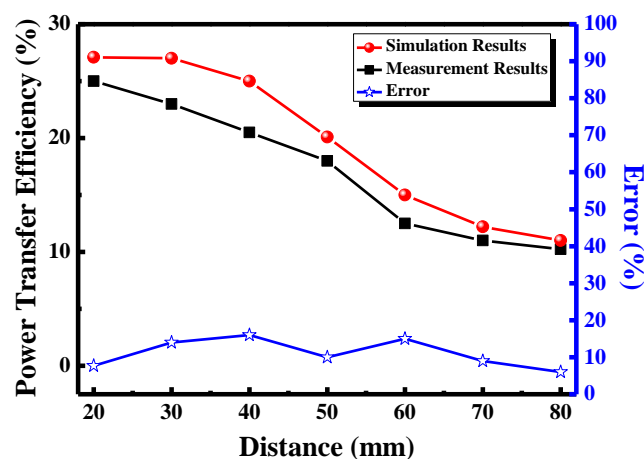


Figure 11. The measurement results of the four-coil MWPT system.

As we know, the energy is transmitted from the transmitter to the receiver, while the antenna is operated as the transmitter to transmit energy, as well as being operated as the receiver to receive energy. The research based on the transmitter and the receiver is very important. In this paper, we proposed the idea that the frequency reconfigurable microstrip patch antenna array can be used for a microwave wireless power transfer system. This would allow the energy to be transmitted to the receiver at different frequencies. Also, when the energy is transmitted to the load from the receiver in the wireless power transfer system, there should be a rectifier circuit which converts alternating current to direct current. In this paper, we only verify the efficiency of the power transmitted to the receiver from the transmitter. Notably, the rectifier circuit is not involved in power transfer from the transmitter to the receiver. As a result, the rectifier circuit is not in our present work. The systematic efficiency involving the rectifier circuit will be focused on in future design research.

4. Conclusions

In this paper, a MWPT system based on the frequency reconfigurable antenna array was proposed. The frequency reconfigurable antenna array works at different frequencies covering a wide range from 3.41 to 3.96 GHz and 5.5 to 6.3 GHz, and the working frequency band could be switched between the S-band and the C-band. The frequency reconfigurable

antenna array can work with good performance at different resonant frequencies. The return loss of the frequency reconfigurable antenna array is less than -15 dB at the different frequencies. Radiation patterns of the antenna array at different frequencies are relative stable. Also, the gains of the antenna array are above 6 dBi at different working frequencies. In addition, PTE of the MWPT system based on the frequency reconfigurable antenna remains above 20% at different frequencies. Also, PTE of the MWPT system at the frequency of 3.64 GHz is 25%, 20.5% and 10.3% at the distances of 20 mm, 40 mm and 80 mm, respectively. The MWPT system based on a frequency reconfigurable antenna array can be used to power the receiver at different frequencies, and PTE of the system does not decrease in a clear way as the resonant frequency of the receiver changes, which enables this system to greatly meet the demands of users.

Author Contributions: H.W. proposed the main idea. H.L. checked and discussed the results and the whole manuscript. L.D., J.D., D.Z. and S.H. contributed to the discussion of this study. All authors have read and agreed to the published version of the manuscript.

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