Research, Design and Fabrication of 2.45 GHz Microstrip Patch Antenna Arrays for Close-Range Wireless Power Transmission Systems

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***Abstract*—Antennas play a very important role in wireless power transmission (WPT) systems using microwave since they affect the system transmission efficiency. General requirements for an antenna used for WPT systems are high directivity and narrow beamwidth. This paper presents the design, simulation and fabrication of microstrip patch antenna arrays for close-range WPT systems. Various antenna prototypes such as single patch, 2×2, 2×4, 4×8 and 8×8 microstrip patch antenna arrays working at 2.45 GHz are proposed. The 2×4 microstrip patch antenna array is fabricated and measured using Anritsu 37364D Vector Network Analyzer and NSI 2000 Nearfield System. Measurement results show that the fabricated antenna obtains a directivity of 14.7 dBi and a 3 dB beamwidth of 23.2 degree. The experiment with the WPT system is carried out. This paper also presents structure of a WPT system and the role each building block in the system.**

***Index Terms*—Wireless Power Transmission, Rectenna, Microstrip Patch, Antenna Array, Microwave Engineering**

I. Introduction

Nowadays, the WPT systems are popularly used for variety of purposes not only in military but also in typical life. The demand of offering high efficiency of power transmission process leads to the problem for finding new methods to implement those systems. One of the innovative ideas solving the problem is using microwave engineering. Indeed, the WPT systems using microwave (WPT) have proved that they are the future of power transmission. This paper is going to present and analyze the components of the WPT systems including the transmitter and receiver. The main part focuses on the design, simulation and fabrication of microstrip antenna arrays used for the WPT systems to satisfy the requirements of offering high transmission efficiency and long distance between the transmitter and the receiver.

II. Architecture of WPT Systems

Fig. 1 shows the block diagram of a WPT system. This system can be divided into two parts: the transmitter and the receiver. The former includes the microwave power generator and microwave amplifiers. The latter is more complex with bandpass filter (BPF) and microwave rectifier. More detail descriptions and the roles of components are depicted in the following sections. The role of a antenna in the WPT system and the characteristics of a preferable antenna are specified.

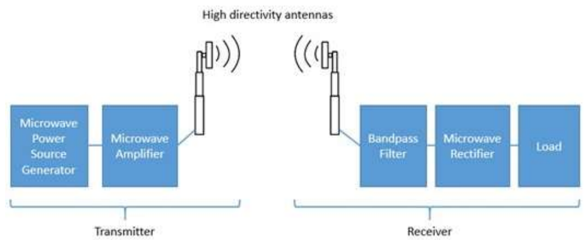

Fig. 1. Block diagram of the WPT system using microwave.

A. The Transmitter

As mentioned before, the main part of the transmitter used for the WPT systems are microwave power generator, microwave amplifier and transmitting antenna. This section will present the two first components.

1) Microwave Power Generator: The microwave power generator generates microwave power and the output power is controlled by electronic control circuits [1]. The microwave transmission systems prefer to work at 2.45 GHz or 5.8 GHz for ISM band. Besides, the frequency 8.5 GHz, 10 GHz, 35 GHz is also used for these systems. However, the most preferable frequency is 2.45 GHz since it achieves the highest transmission efficiency of over 90% [1].

2) Amplifier: It can be seen that amplifier is one of the most basic and prevalent circuit in modern RF and microwave system. Thanks to the rapid innovations of semiconductor technology, most RF and microwave amplifiers today are using transistor devices such as Si BJTs, GaAs or SiGe HBTs, Si MOSFETs, GaAs MESFETs, GaAs or GaN HEMTs [2]. For the WPT systems, power amplifier circuits are used to amplify the power generated from the source. The higher power transmitted, the longer transmission range can be achieved.

B. The Receiver

The receiver seems to be more complex with the appearance of filter, microwave rectifier and receiving antenna.

1) Microwave Filter: The main purpose of using microwave filter for this system is focusing the power at center frequency of 2.45 GHz. Thus, a bandpass filter with high frequency selectivity, narrow bandwidth and low attenuation characteristic is designed.

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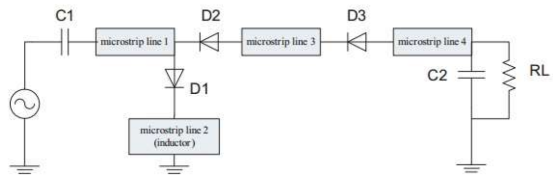


Fig. 2. A rectifying circuit.

2) Microwave Rectifier: A microwave rectifier is a RF power receiver converting the received power into DC power. Rectenna is a component that combines a receiving antenna and a microwave rectifier circuit. Microwave rectifier circuits use diodes and impedance matching networks to produce a DC voltage. The efficiency of the rectification circuit depends strongly on the impedance matching. This value is typically medium and the highest RF-DC conversion efficiency is 60% at 5.8 GHz and approximately 50% at 2.45 GHz. Fig. 2 shows one of the structures of rectifier circuits and the formulas for estimating the rectification efficiency are as follow [3] [4]:

$$\eta_0 = \frac{\text{DC Output Power}}{\text{Incident RF Power}}$$

$$\eta_C = \frac{\text{DC Output Power}}{\text{Incident RF Power - Reflected RF Power}} = \frac{V_0^2}{R_L P_R}$$

Where η_0 is the overall efficiency, η_C is the rectifier conversion efficiency, P_R is the received RF power of the rectifier circuit and V_0 is the DC output voltage across the load resistor, R_L.

C. Transmitting and Receiving Antennas

Previous sections have presented components for generating, amplifying, filtering and converting RF power of WPT system. However, to transmit and receive power, we need antennas and they play very important role for the whole process. Generated power after being amplified in the transmitter will be overspread into free space to receiver. The receiving antenna will receive power and deliver to the receiver. An antenna can be combined with a rectifier to form a rectenna. A good antenna with high gain and high directivity can raise the power transmission efficiency and the possible transmission range. The preferable antenna for the WPT system must satisfy the following conditions: high gain, high directivity and narrow beamwidth. In addition, the size of the antenna is also considered. In current WPT systems, different types of antennas are being used such as the slotted waveguide antenna, microstrip patch antenna, parabolic dish antenna and Yagi/Quasi-Yagi antenna. In this paper, a microtrip patch antenna array is designed. The advantages of this type of antenna are high gain, high directivity, and low cost. The research, design and fabrication of microstrip patch antenna array for the WPT system at 2.45 GHz is presented in following sections.

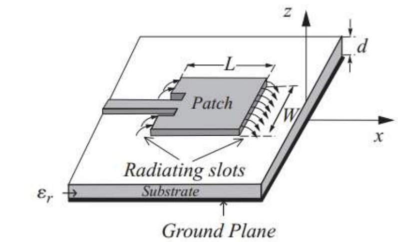


Fig. 3. Single microstrip patch antenna.

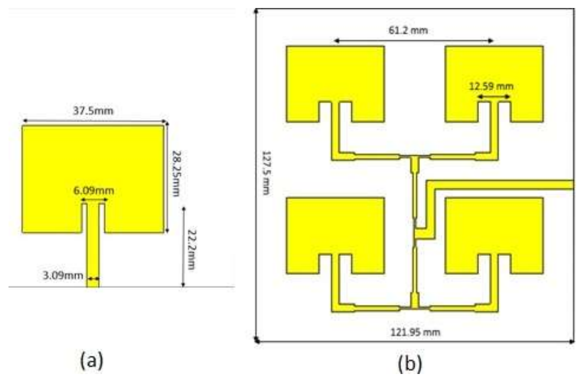


Fig. 4. Proposed design for (a) single microstrip patch and (b) 2×2 microstrip patch antenna array.

III. Design of Microstrip Patch Antenna Arrays for WPT Systems

A microstrip antenna, also known as patch antenna, consists of a metal patch on a substrate with a ground plane on the other side as shown in Fig. 3. The shapes of the patches are different such as: rectangular, square, circular and circular ring. Feed line configurations contain aperture coupled, microstrip line feed and coaxial feed. Ref. [5] gives the formulas for calculating the width and the length of a uniform patch antenna.

A. Antenna Design

Several prototypes of microstrip patch antenna arrays are designed on FR-4 (lossy) substrate with a relative dielectric constant of 4.3, thickness of 1.6 mm and metal thickness of 0.035 mm. The widths of 50 Ω, 70.71 Ω and 100 Ω transmission lines are 3.09 mm, 1.64 mm and 0.72 mm, respectively. The design of antennas includes single patch antenna, 2×2, 2×4, 4×8 and 8×8 patch antenna arrays. The dimensions of antenna prototypes are demonstrated in Fig. 4, Fig. 5, Fig. 6, respectively. Simulation results are presented in the next section.

B. Simulation Results

All parameters of the antennas are optimized by CST Studio Suite. The simulated S_{11} of different antenna prototypes are

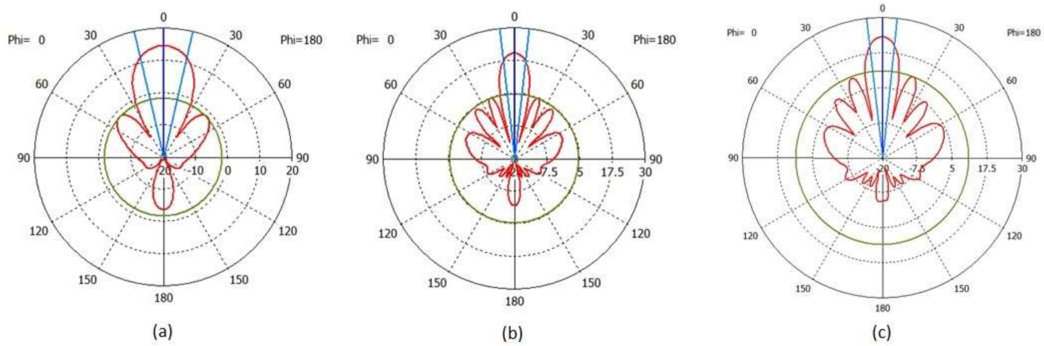


Fig. 8. Simulated radiation pattern of (a) 2×4 patch antenna array (b) 4×8 patch antenna array (c) 8×8 patch antenna array.

TABLE I
SIMULATION RESULTS FOR DIFFERENT ANTENNA PROTOTYPES

Parameters	Single Patch	2×2 Array	2×4 Array	4×8 Array	8×8 Array
Dimensions (mm)	75×58	122×128	240×150	490×290	490×585
S_{11}@2.45 GHz (dB)	-20.2	-24.2	-31.5	-36.6	-21.6
Directivity (dBi)	7	10.8	14.5	20.3	23.2
Gain (dBi)	4.4	7.8	10.8	15.8	17.1
Bandwidth S_{11} < -10 dB (MHz)	57.9	76.5	60.4	102.1	162.6
3 dB Beamwidth (degree)	78.5	52.8	26.5	13	12.6
Sidelobe Level (dB)	-13.1	-21.9	-16.1	-15.5	-12.3

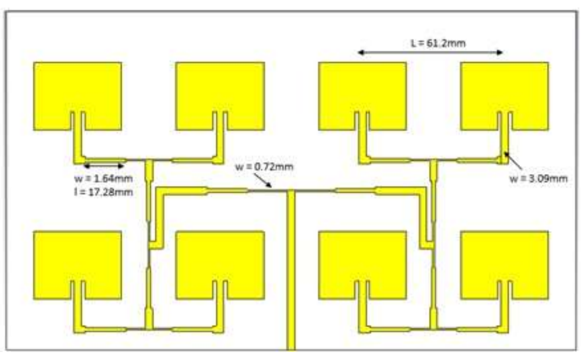


Fig. 5. Proposed design for 2×4 microstrip patch antenna array.

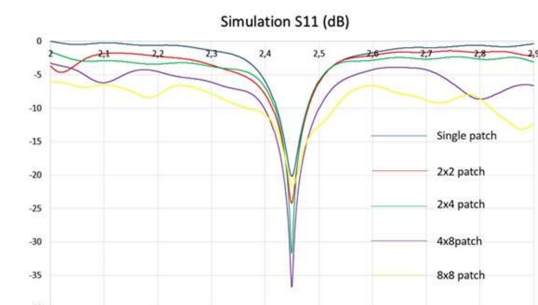


Fig. 7. Simulated input return loss of different antenna prototypes.

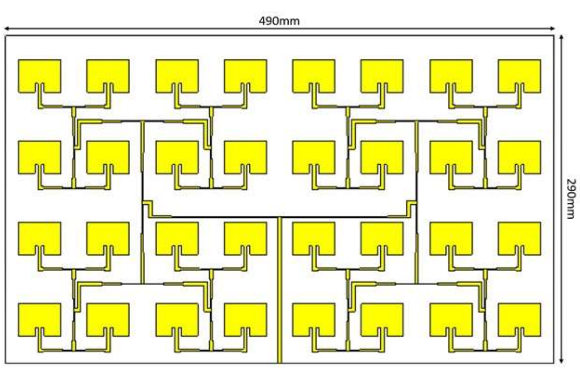


Fig. 6. Proposed design for 4×8 microstrip patch antenna array.

plotted in Fig. 7 which shows that the 4×8 microstrip antenna array gives lowest return loss value (less than -35 dB) while for single patch, this value is lower than -20 dB, but this is still a good result. Fig. 8 shows the simulation results for far field directivity of 2×4, 4×8 and 8×8 patch antenna. Simulation results of different antenna prototypes are summarized in table I.

IV. Measurement Results

To verify the performance of proposed antennas, two 2×4 patch antenna arrays are fabricated as shown in Fig. 9. The measurement results in term of of input return loss and directivity are shown in Fig. 11 and Fig. 12 respectively. The input return loss is measured using a Anritsu 37364D Vector Network Analyzer while the radiation pattern and directivity

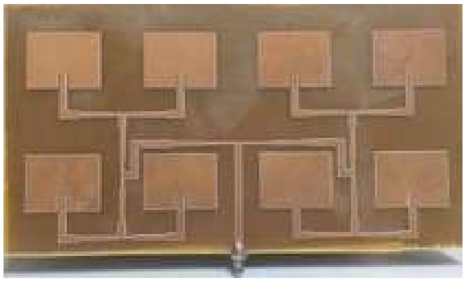


Fig. 9. The fabricated 2×4 patch antenna array.

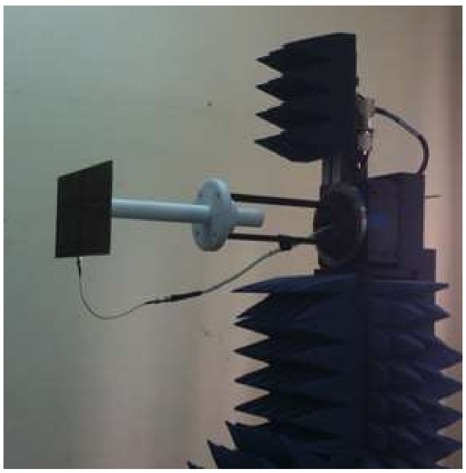


Fig. 10. The fabricated antenna measured by Nearfield System NSI 2000.

are measured by a Nearfield System NSI 2000 as shown in Fig. 10, which is a powerful tool for measuring radiation patterns. Measurement results show that S_{11} reaches -29.5 dB at the center frequency of 2.45 GHz. It can be seen that the measured S_{11} is smaller than the simulated one. As a result, the bandwidth is extended to 200 MHz compared to 60 MHz bandwidth in simulation. The measurement results also give the directivity value of the two antennas is approximately 14.7 dBi at 2.45 GHz. The comparisons between simulation and measurement of antennas are indicated in table II. The fabricated transmitting and receiving antennas are integrated with the close-range WPT system as shown in Fig. 13. The transmitter includes a 2 W power amplifier and a transmitting antenna while the receiver encompasses receiving antenna and a rectifier circuit loaded by a LED. Due to small transmitting power, the longest transmission distance is only approximately 70 cm. If higher transmitting power are applied, the transmission distance will be increased.

TABLE II
COMPARISON BETWEEN SIMULATION AND MEASUREMENT RESULTS FOR 2×4 PATCH ANTENNA ARRAY

Parameters	Simulation	Measurement
S_{11}@2.45 GHz (dB)	-31.5	-29.5
Directivity (dBi)	14.5	14.7
Gain (dBi)	10.8	10.8
Bandwidth $S_{11} < $ -10 dB (MHz)	60.4	200
3 dB Beamwidth (degree)	26.5	23.9
Sidelobe Level (dB)	-16.1	-16.3

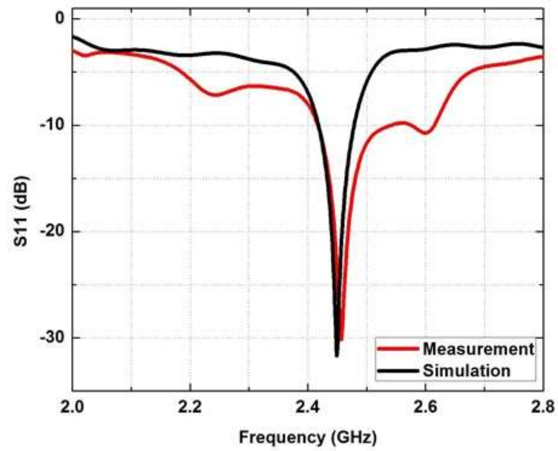
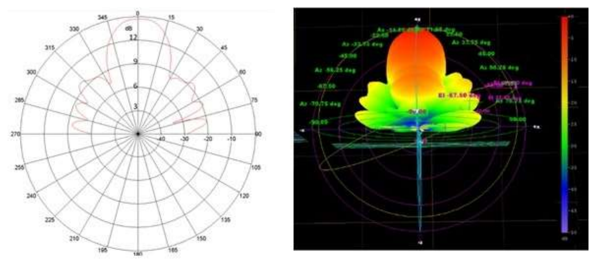


Fig. 11. Comparison between the measured and simulated input return loss of the 2×4 patch antenna array.



(a) (b)

Fig. 12. Measurement results for radiation pattern in (a) 2D dimension and (b) 3D dimension.

V. CONCLUSION

In this paper, we have presented the design, simulation and fabrication of transmitting and receiving antennas used for the close-range WPT system. Single patch, 2×2, 2×4, 4×8 and 8×8 microstrip patch antenna arrays are proposed offering high directivity and narrow beamwidth. The input return loss varies from -35 dB to -20 dB at the center frequency of 2.45 GHz. The directivity of the 4×8 antenna array is 20.3 dBi while the 3 dB beamwidth is 13 degree. Two 2×4 microstrip patch antenna arrays are fabricated on FR4 substrate. Measurement results show that these antenna arrays obtain the directivity of 14.7 dBi and the narrow beamwidth of 23 degree. They are also measured with the WPT system giving good results at close distance.

Fig. 13. Measurement setup for the WPT system.

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