A Focused Microwave Power Transmission Scheme Based on Phase Adjustable Microwave Source

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Abstract. In this paper, an electric field focus scheme based on phase adjustable microwave source is used to improve the power transmission efficiency. A microwave power transmission system is consisted of the microwave source, a transmitting antenna and a receiving antenna. Measurement results proved that when compared with the same phases condition, the output DC power of the receiving antenna is increased from 23.5W to 31.5W and the relative increment of power is 34% under the focal phase condition. In addition, the system-level MW-DC power transmission efficiency is increased by 2.7%.

1. Introduction
The power transmission for most electronic devices are mainly based on wired equipment. However, for some long-distance applications, the wires method will cost a lot. To overcome this shortcoming, some wireless power supplication ways are explored, such as coupled magnetic resonance (CMR) [1], inductive coupled power transfer (ICPT) [2] and laser wireless power transfer technology [3]. But CMR and ICPT methods are both limited by energy transmission distance, the longer the distance is, the less the energy harvested, and it decreases exponentially with distance. The laser power transmission method can realize long-distance power transmission, but it is seriously influenced by the surrounding environment. It is different from the above mentioned power transmission methods, the microwave power transmission technology is more suitable for long-distance energy transmission and the strong penetrating ability determines that it is almost unaffected by the non-metal surrounding environment.

A microwave power transmission (MPT) scheme is proposed by C. Brown in 1969, which plane to collect the solar energy at geosynchronous Earth orbit (GEO) and then transmitted it to the Earth in the formation of microwave. Usually, an MPT system is consisted of microwave source, transmitting antenna, receiving antenna and rectifier circuit. The diagram of MPT system is depicted as figure.1.

![Figure 1: Diagram of MPT system.](image)

To improve the power transmission efficiency of the MPT system as much as possible, there are many previous works. As for the transmitting terminal, various kinds of transmitting antennas are
designed and fabricated. In reference [4], a transmitting antenna is designed based on electromagnetic band gap structure (EBGs) to obtain a better performance in the MPT system than the traditional one, the measurement results proven that the power transmission efficiency of the power transmission system can increase by 5 ~ 12% and the half power beam width (HPBW) is narrower than antenna without EBGs. Besides, Kyoung-joo Lee presents a stacked micro-strip patch antenna array with four elements as transmitting antenna in the MPT system. The gain of the proposed antenna is obviously higher than that of the antenna without stacked parasitic patch [5].

In the MPT system, receiving antenna and rectifier circuit are working together as the receiving terminal. To harvest more energy, there are some meaningful investigations. In reference [6], a reconfigurable rectenna is designed and investigated. By controlling the states of switch p-i-n group, the rectenna can easily realize the pattern modes change and capture the incoming wave at eight directions. In order to make a rectenna can operate under different frequency, a depletion-mode field-effect transistor (FET) is used to make sure that the matching stub can be adaptively selected, so that it can operate at two working frequencies when the FET works ON and OFF states. The final measurement results demonstrate that the rectenna has same level power conversion efficiency under different working frequency when input power is 6.5dBm [7]. In recent years, researchers find that the microwave metamaterial can be used as a receiving terminal because some metamaterials can efficiently and fast absorb microwave power and only a little reflected waves. So, that ability make it has a potential application in the MPT system. Because of the rectennas have limitations on the operation bandwidth, the incoming wave incident angle and the polarization types, the mate-material is regard as a substitute of rectenna. In reference [8], to overcome the shortcomings of rectenna, the author designs a series of metamaterial with polarization-independent or wide incident angle or wide operation frequency band for microwave power transfer. All measurement results demonstrate that these designs have a good performance when they are acted as a receiving terminal.

2. Theoretical Analysis and System Design

A. Theoretical analysis

All above works indeed help the MPT system to have a better ability to transmit microwave power. However, all these transmitting terminals and receiving terminals have complex topology which results in a higher cost to fabricate these designs. In fact, another method is also used to improve the efficiency of power transmission without the need for advanced hardware, and that is microwave electric field focus technology. As shown in Fig. 2, when the positions of the transmitting array antenna and the receiving antenna are fixed, it can be found that the distances (\(R_i\)) between each unit of the transmitting array antenna and the receiving terminal (focal position) are different. Different distances lead to different phases at position (0, 0, \(R_i\)), assuming that the coordinate axis is at the center of the transmitting array antenna and the input signals (amplitude and phase) are the same for all units. Thus, it is possible to calculate what the phase of the wave from the ith unit is at the terminal antenna position, and the phase with respect to the array center (0, 0, 0) can be expressed by formula (1).

\[
\varphi_i = \frac{2\pi}{\lambda} \left( \sqrt{(x_i - 0)^2 + (y_i - 0)^2 + (0 - R)^2} - R \right)
\]

(1)

Where \(\lambda\) is the working wave length, and \(x_i, y_i\) are the x-axis, y-axis of the ith unit respectively. Therefore, most of the unit waves will be transmitted to the receiving terminal at different positions, and according to the principle of vector addition, the difference phases always result in the electric filed strength impossible to reach the maximum value. Hence, in order to make all waves arrive at the receiving terminal at the same time, the phase compensation is necessary and the value can be obtained from formula (1), so that the same phase waves will make electric filed reach the maximum based on the principle of vector addition. This phenomenon of obvious electric filed enhancement is also called electric filed focus.
Figur.e.2. Diagram of the transmitting array antenna and receiving terminal.

In past decades, there are some meaningful works to realize electric filed focus. In reference [9], a focused antenna array is designed based on an inhomogeneous medium and easily product an electric filed focus point in the space. However, the focal position is seriously dependent on the thickness of the medium, once the thickness of the inhomogeneous medium is not correct, there will be obtained a bad result. Moreover, in order to have a stronger electric filed, X. Yi uses the coaxial cables with different lengths to obtain different phases, then realize electric filed enhance. A microwave power transmission experiment demonstrated that the transmission efficiency is significantly increased by using the focal phases [10]. whatever the thickness of medium or the length of coaxial cable, once the parameters and the focus position are decided, the parameters of the medium and the coaxial cables need to be recalculated if another focus position is to be obtained.

In this paper, to overcome the shortcomings of medium and coaxial cables focusing scheme, a phase adjustable microwave source is used to control the input phases of all units of the transmitting array antenna. Generally, the phase adjustable microwave source can not only generate different phases, but also control the amplitudes. In this microwave power transmission scheme, the amplitudes of all units are constants and only the phases are changed.

The phase adjustable microwave source is consisted of an original signal generator, the amplifiers, the phase shifters and a phase/amplitude controlling unit. The topology of microwave source is presented in figure 3. In this MWPT system, a 64-channels (i=64) phase adjustable microwave source is used to generate focal phase, the phases of each channel can be tuned 5.6 degrees with each step. In addition, the amplitude of each channel can be adjusted from 0.1W to 10W, thus the maximum output power can reach 640W, it can meet most of the experimental needs in the laboratory.

Figure.3. Topology of the microwave source.
B. Transmitting antenna

In this system, a transmitting antenna is consisted of 64 micro-strip array antennas, the array antennas are fabricated on F4B substrate with the thickness of 1.0mm, the $\epsilon$ and $\tan\delta$ of the substrate material are 2.65 and 0.002, respectively. Every array antenna contains $4 \times 4$ units and all units are connected to the SMA connector via a power divider network. Moreover, the distance between two adjacent units is 300 mm, all array antennas are connected with the microwave source channel by coaxial cables and can independently get the signal from the source. The structure of the micro-strip array antenna is shown in figure 4 and the parameters are depicted in Table 1.

![Figure 4. The structure of micro-strip array antenna.](image)

| Parameter | Value 1 | Value 2 | Value 3 | Value 4 |
|-----------|---------|---------|---------|---------|
| $d$       | 17.1 mm | 2.0 mm  | 5.0 mm  | 22.0 mm |
| $d$       | 14.8 mm | 15.7 mm | 11.0 mm | 22.4 mm |
| $d$       | 11.0 mm | 12.0 mm | 13.0 mm | 14.0 mm |
| $l_1$     | 22.0 mm |
| $l_2$     | 22.0 mm |
| $l_3$     | 22.0 mm |
| $l_4$     | 22.0 mm |
| $w_1$     | 1.0 mm  |
| $w_2$     | 2.8 mm  |
| $w_3$     | 1.1 mm  |
| $w_4$     | 1.2 mm  |
| $w_5$     | 2.5 mm  |
| $w_6$     | 2.5 mm  |
| $w_7$     | 1.6 mm  |
| $w_8$     | 1.5 mm  |
| $w_9$     | 2.5 mm  |

C. Receiving antenna

To capture microwave power efficiently, a rectenna is designed and fabricated based on a single Schottky diode (HSMS2860), the measurement results is shown in figure 5.

![Figure 5. The curves of power conversion efficiency and output DC voltage.](image)
From the above measurement results, it is easily found that the peak value of power conversion can reach 65.3% when the input power is 22 dBm, and the output DC voltage is 3.52V (@ load resistance is 120Ω). However, cause single Schottky diode can not withstand higher power (>25dBm), in order to improve the power tolerance of the power receiving unit, the 121 Schottky diodes are integrated to construct a power receiving unit in this design scheme. Eventually, the establishment of the receiving terminal is based on 16 such power receiving units. The fabricated front and back views of the unit is presented in figure 6(a) and 6(b), respectively.

3. Experimental Varification
To test the microwave transmission efficiency in unfocused and focused conditions, the MPT system with a transmitting antenna, a receiving antenna and the phase adjustable microwave source is constructed, which is shown in figure 7.

Finally, the transmitting antenna with the area of 1300×1300 mm² and the receiving antenna with the dimension of 2000×2000 mm². In this power transmission system, the receiving antenna is fixed in the near-filed of the transmitting terminal with the distance of 30000 mm. To guarantee the electric filed focused at the receiving terminal, the phases of each micro-strip array antenna are obtained from formula (1). However, as is mentioned previously, the phase shifter is 6-bits phase shifter, which results in the phase adjusting just 5.6 degrees or multiple of 5.6 degrees each time. So, the output
phases of microwave source can’t meet with the theory phases. Nevertheless, a set of calculated phases based on the 6-bits phase shifter are used to replace the theory phase. The theory phases and calculated phases are presented in Table 2.

|                | 255.6/257.6 | 193.1/190.4 | 151.3/151.2 | 130.5/128.8 | 130.5/128.8 | 151.3/151.2 | 193.1/190.4 | 255.6/257.6 |
|----------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|
| Phase 1        | 255.6/257.6 | 193.1/190.4 | 151.3/151.2 | 130.5/128.8 | 130.5/128.8 | 151.3/151.2 | 193.1/190.4 | 255.6/257.6 |
| Phase 2        | 193.1/190.4 | 130.5/128.8 | 88.7/89.6   | 67.9/67.2   | 67.9/67.2   | 88.7/89.6   | 130.5/128.8 | 193.1/190.4 |
| Phase 3        | 151.3/151.2 | 88.7/89.6   | 47/44.8     | 26.1/28     | 26.1/28     | 47/44.8     | 88.7/89.6   | 151.3/151.2 |
| Phase 4        | 130.5/128.8 | 67.9/67.2   | 26.1/28     | 5.2/5.6     | 5.2/5.6     | 26.1/28     | 67.9/67.2   | 130.5/128.8 |
| Phase 5        | 130.5/128.8 | 67.9/67.2   | 26.1/28     | 5.2/5.6     | 5.2/5.6     | 26.1/28     | 67.9/67.2   | 130.5/128.8 |
| Phase 6        | 151.3/151.2 | 88.7/89.6   | 47/44.8     | 26.1/28     | 26.1/28     | 47/44.8     | 88.7/89.6   | 151.3/151.2 |
| Phase 7        | 193.1/190.4 | 130.5/128.8 | 88.7/89.6   | 67.9/67.2   | 67.9/67.2   | 88.7/89.6   | 130.5/128.8 | 193.1/190.4 |
| Phase 8        | 255.6/257.6 | 193.1/190.4 | 151.3/151.2 | 130.5/128.8 | 130.5/128.8 | 151.3/151.2 | 193.1/190.4 | 255.6/257.6 |

In the microwave power transmission experiment, the output microwave power amplitude of each channel is the same and the total output power is 300W. The output DC voltage and DC power of the 16 receiving units are measured under two conditions, one in which all output phases of the microwave source are identical and the other in which the focal phase is used. The output DC voltage/power of receiving units are depicted in the table3 (a) and (b), respectively.

|                | 3.8V/0.1W | 9.9V/0.8W | 11.3V/1.1W | 7.5V/0.5W | 6.5V/0.4W | 11.4V/1.1W | 13.2V/1.4W | 8.7V/0.6W | 13.3V/1.5W | 21.1V/3.7W | 18.2V/2.7W | 14.1V/1.7W | 23.1V/4.4W | 19.9V/3.3W | 15.9V/2.1W | 8.6V/0.6W | 17.9V/2.6W | 18.0V/2.7W | 11.3V/1.1W |
|----------------|-----------|-----------|------------|-----------|-----------|-----------|------------|-----------|------------|-----------|------------|-----------|------------|-----------|------------|-----------|-----------|-----------|------------|-----------|
| DC voltage     | 3.8V/0.1W | 9.9V/0.8W | 11.3V/1.1W | 7.5V/0.5W | 6.5V/0.4W | 11.4V/1.1W | 13.2V/1.4W | 8.7V/0.6W | 13.3V/1.5W | 21.1V/3.7W | 18.2V/2.7W | 14.1V/1.7W | 23.1V/4.4W | 19.9V/3.3W | 15.9V/2.1W | 8.6V/0.6W | 17.9V/2.6W | 18.0V/2.7W | 11.3V/1.1W |
| power          | 3.8V/0.1W | 9.9V/0.8W | 11.3V/1.1W | 7.5V/0.5W | 6.5V/0.4W | 11.4V/1.1W | 13.2V/1.4W | 8.7V/0.6W | 13.3V/1.5W | 21.1V/3.7W | 18.2V/2.7W | 14.1V/1.7W | 23.1V/4.4W | 19.9V/3.3W | 15.9V/2.1W | 8.6V/0.6W | 17.9V/2.6W | 18.0V/2.7W | 11.3V/1.1W |

From Table III, it is easy to find that compared with the same phases condition, the values of output DC voltage and power increased significantly in the focal phase condition. In addition, the maximum voltage increment of a single receiving unit can reach 3.7V and the maximum power increment of receiving unit is 1.3W. Total output power in two conditions are 23.5W and 31.5W, respectively.

4. Conclusion

In this paper, a focused microwave power transmission scheme based on phase array source is proposed. Unlike traditional methods, a phase array source is used to obtain focal phases to rise up the MW-DC power transmission efficiency in this power transmission system. System level measurement results demonstrate that the total output DC power of receiving units is increased by 8.5W and relative increment of power is 34% when same phases change to focal phases. Finally, the system level MW-DC power transmission efficiency has increased from 7.8% to 10.5%.

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