# A high-efficiency near-field focused transmitting antenna based on the equal power divisions

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# A high-efficiency near-field focused transmitting antenna based on the equal power divisions

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## ABSTRACT

For microwave power transmission (MPT), the transmitting (Tx) array with a tapered amplitude distribution can achieve a maximum beam collection efficiency, but it needs a feeding network with an arbitrary power division ratio; thus, it is complicated and costly in practical applications. This work explores realizing high transmission efficiency by a Tx array with the equal-ratio steps amplitude distribution (ERSAD). By using the ERSAD, the amplitude value of the central units of the Tx array is uniform, and the amplitude feeding of the edge units only needs equal power divisions. Thus, the amplitude feeding is greatly simplified. Besides, a compensated phase distribution is used to focus the radiating beam on the receiving aperture. To validate the proposed design, a Tx antenna consisting of 8 × 8 units with a total aperture size of 1 × 1 $m^2$ is designed. The operating frequency and the focused distance are 5.8 GHz and 10 m, respectively. A 64-way microwave power source is used to adjust the amplitude and the phase of the Tx array, and an MPT experiment is conducted. The measurement shows that, compared with the 10 dB Gaussian amplitude array, the proposed array nearly has the same transmission efficiency against different receiving apertures.



## I. INTRODUCTION

Microwave power transmission (MPT) is a wireless energy transmission technology with microwaves, which has great application potential in solar power satellites (SPSs),[1,2] energy supplies of near-space aerocraft, unmanned aerial vehicles,[3,4] etc.[5,6] An MPT system usually consists of a microwave source, a transmitting (Tx) antenna, a receiving (Rx) antenna, and a rectifying circuit. The Tx antenna is responsible for radiating the microwave power to the Rx antenna through free space.

To ensure an MPT system works efficiently, it is vital to maintain high beam collection efficiency (BCE). BCE is defined as the ratio of the power received on the Rx antenna to the total transmitted power. Much research has shown that the Tx array with tapered amplitude distribution can realize maximum BCE.[7–10] Gaussian amplitude distribution (GAD) is one of the best taper designs.[10] Table I lists a few SPS projects. It is shown that all of these projects are designed with 10 dB Gaussian amplitude distribution.[11–14]

Unfortunately, the amplitude of Gaussian distribution is continuous from the center to the edge; thus, large numbers of different kinds of amplifiers or attenuators are needed, which make actual large MPT systems costly and complicated. To relieve tapered amplitude feeding problems, isosceles trapezoidal distribution (ITD) edge tapering was studied in Refs. 15 and 16. Besides, syntheses of sub-arrayed antennas were studied to simplify the feeding network and decrease the cost.[17] Stepped amplitude distribution for MPT was also demonstrated recently.[18] However, the aforementioned methods[15–18] still need unequal amplitude feeding.

Until now, Tx antennas of most MPT systems are designed with equal amplitude and in-phase to realize the maximum gain in far-field, but actual MPT systems are commonly worked at the near-field.[19–21] A Tx antenna has a deteriorative main lobe and increased side-lobes in the near-field, and the transmission efficiency is greatly limited. Near-field focused technologies are proposed to solve the problem.[22–24] By compensating the phase difference, the microwave power radiating from the Tx antenna can be focused on the Rx

**TABLE I.** A few SPS projects.

| Project | Sun-tower[11] | ISC[12] | ALPHA[13] | OMEGA[14] |
|---|---|---|---|---|
| Frequency (GHz) | 5.8 | 5.8 | 2.45 | 5.8 |
| Type of the tx antenna | Array | Array | Array | Array |
| Amplitude distribution | 10 dB Gaussian | 10 dB Gaussian | 10 dB Gaussian | 10 dB Gaussian |

antenna; hence, the transmission efficiency will be improved. However, the transmission efficiency of the equal amplitude and focused array is still lower than that of the tapered amplitude array.

Based on our previous work,[6] this paper explores a high-efficiency near-field focused Tx antenna with equal power divisions. The focused beam is realized by compensating the aperture field phase difference of the Tx antenna. Moreover, an equal-ratio steps amplitude distribution (ERSAD) is used to derive the suppressed side-lobes. A Tx antenna of $1 \times 1$ m$^2$ is fabricated, and an MPT experiment is conducted to validate the design. The amplitude design is introduced in Sec. II. The design of the Tx antenna is given in Sec. III. The experiment process is explained in Sec. IV. Finally, some conclusions are drawn in Sec. V.

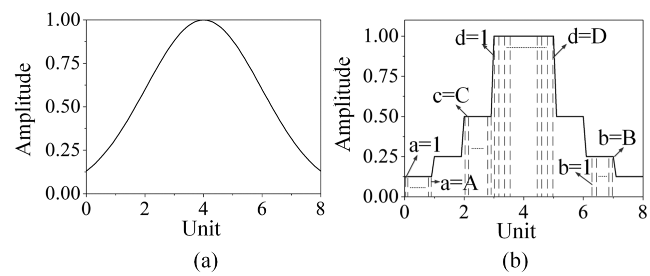


**FIG. 2.** Diagram of (a) the 10 dB Gaussian amplitude distribution (GAD) and (b) the equal-ratio steps amplitude distribution (ERSAD).

## II. AMPLITUDE DESIGN WITH EQUAL POWER DIVISIONS

Figure 1 shows an MPT system, where both the Tx and Rx antennas are square arrays with lengths of side $L$, and they are separated by a distance $R$. The Gaussian distribution can be expressed by[9]

$$f(x_n, y_n) = \exp\left[\frac{-\ln(10)\cdot T_t}{20}\cdot\frac{x_n^2+y_n^2}{\left(\frac{L}{2}\right)^2}\right], \quad (1)$$

where $T_t$ is the aperture field amplitude taper in dB and ($x_n$, $y_n$) represents the sub-array position of the Tx antenna. By using (1), the aperture field amplitude distribution of the Tx array can be calculated. Figure 2(a) shows a normalized 10 dB Gaussian amplitude distribution (where $T_t = 10$, $y_n = 0$, $L = 6$, and $x_n$ is from 0 to 8).

However, the Gaussian amplitude distribution (GAD) is hard to implement for actual large MPT systems. Based on the ITD[15,16]

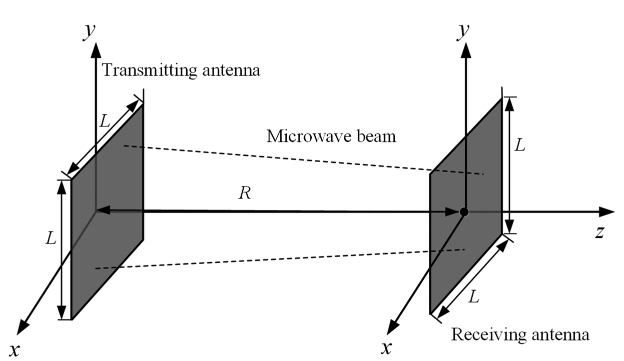


**FIG. 1.** Illustration of an MPT system.

and the stepped amplitude distribution,[18] an equal-ratio steps amplitude distribution (ERSAD) is proposed in this paper to simplify the amplitude scheme of the Tx antenna further. Figure 2(b) shows a normalized ERSAD, and the number of steps is 4. Suppose the units of the array are uniformly-spaced, and therefore, the array factor (AF) of the ERSAD is

$$AF = 2\times\sum_{a=1}^{A}0.125e^{j\varphi a} + 2\times\sum_{b=1}^{B}0.25e^{j\varphi b} + 2\times\sum_{c=1}^{C}0.5e^{j\varphi c} + \sum_{d=1}^{D}e^{j\varphi d}, \quad (2)$$

where A, B, C, and D are the number of units with a normalized amplitude value of 0.125, 0.25, 0.5, and 1, respectively. $\varphi_a$, $\varphi_b$, $\varphi_c$, and $\varphi_d$ are the phases of corresponding units. The amplitude and the phase of the left side and the right side units of the array are the same because of symmetry.

Design of the proposed amplitude distribution includes three steps. Initially, use the ITD to uniform the amplitudes of most central units. It is known from Ref. 15 that only 18.54% of units need to be tapered while maintaining high BCE. Furthermore, utilize the stepped amplitude distribution to design the amplitudes of edge units. It is learned from Ref. 18 that the BCE increases with the increase in the number of steps. Finally, normalize the amplitude distribution scheme, and combine the amplitude value of edge units with 0.5, 0.25, and 0.125. Although the above-mentioned designs are for 1-D arrays and the number of units are limited, which can also fit for large 2-D arrays.[15,16]

To investigate the validity of the proposed method, full-wave simulation was carried out on the high-frequency structure simulator electromagnetic software. The working frequency is 5.8 GHz, and a simple square microstrip antenna is used as the unit. The whole Tx array includes $50 \times 50$ units, and the size of a unit is $0.6 \times 0.6\lambda^2$. Figures 3(a) and 3(b) show the normalized amplitude distribution

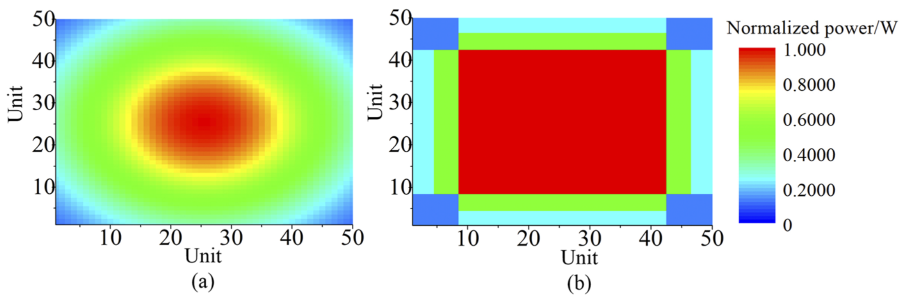


**FIG. 3.** Normalized amplitude distribution of (a) the 10 dB Gaussian amplitude distribution (GAD) and (b) the equal-ratio steps amplitude distribution (ERSAD) of the Tx array.

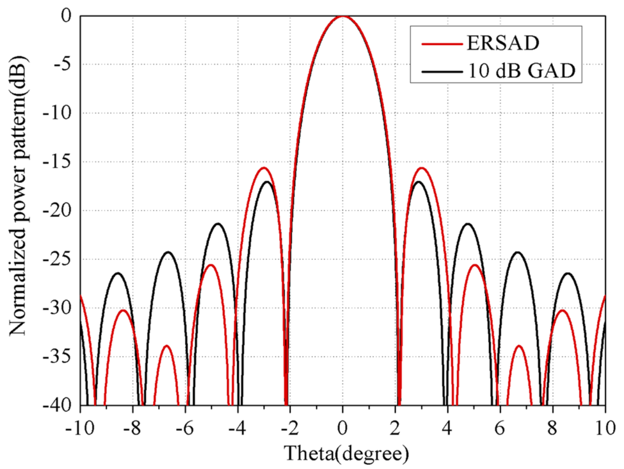


**FIG. 4.** Normalized power pattern of the 10 dB Gaussian amplitude distribution (GAD) and the equal-ratio steps amplitude distribution (ERSAD) of the Tx array.

of the 10 dB GAD and the ERSAD of the Tx array, respectively. As for the ERSAD, the 1156 central units feed with uniform amplitude, and the percentage is 46.24%. Figure 4 shows the normalized power pattern of the 2 Tx arrays. It is shown that compared with the 10 dB GAD, the ERSAD has the same main lobe width. Although the first side-lobe level of the ERSAD is higher than that of the 10 dB GAD, the difference is marginal, and both are lower than −15 dB.

## III. TRANSMITTING ANTENNA DESIGN

A planar microstrip Tx antenna of 1 × 1 $m^2$ is designed and fabricated on a 1 mm thick polytetrafluoroethylene substrate ($\varepsilon_r$ = 2.65 and tan $\delta$ = 0.001). The array consists of 8 × 8 units, and the size of a unit is 125 × 125 $mm^2$. The operating frequency is 5.8 GHz, and the focused distance is 10 m.

Figure 5 illustrates a unit of the Tx antenna, which consists of 4 × 4 radiating elements. Each circular patch is loaded with a metal ring, which can be equivalent to a parallel capacitance and a series inductance. The quality factor of the equivalent circuit is decreased, and the bandwidth of the microstrip array is improved.[25] The input reflection coefficient $|S_{11}|$ of the unit is measured with a vector network analyzer (Agilent N5230A), and the measured bandwidth of $|S_{11}| < -10$ dB is 8.2% from 5.67 GHz to 6.15 GHz. The

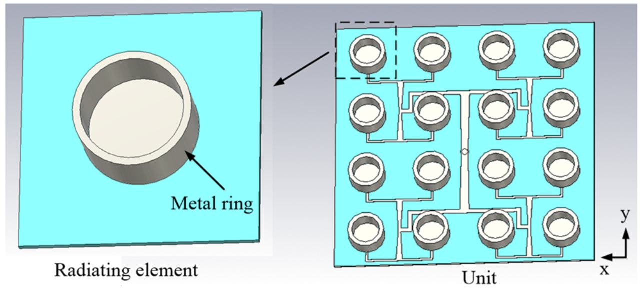


**FIG. 5.** Unit of the transmitting array.

structure and more parameters of the unit are given in Ref. 6. The measured gain of the unit is 17.47 dBi, and the radiating efficiency is 82.1%.

Normalized ERSAD of the Tx array is given in Fig. 6(a). It is observed that the amplitude value of the inner units of the Tx antenna is 1 and that the edge units are 0.5, 0.25, and 0.125. Hence, normal 1:2, 1:4, and 1:8 equal power dividers can be used to derive the amplitude distribution scheme. Besides, near-field focused technologies are used to focus the microwave beam on the receiving antenna, and the compensated phase distribution is given in Fig. 6(b).[23] It can be observed that the closer it is to the center, the lower its value is.

## IV. EXPERIMENT

To demonstrate the feasibility and effectiveness of the above-mentioned designs, an MPT experiment is conducted, and the transmission efficiency is measured. To show the results clearly, not only the equal-ratio steps amplitude and focused array (ERSAFA) but also the Gaussian amplitude and focused array (GAFA) are measured. Amplitude distribution of the GAFA is a 10 dB Gaussian distribution, which is counted by (1). The MPT experiment system is shown in Fig. 7, where a 64-way microwave power source, a Tx antenna, and a Rx antenna are included.

The microwave power source is made by Shenzhen Hongxiyou Technology Co., Ltd., China, with the model number SPA-5800-64-10. The microwave power source uses a GaN power device and has 64 output ports. Each port can control the amplitude and phase freely. The maximum power output for one port is 40 dBm, and the minimum adjustment is 0.25 dB. The phase range is 0 –360°, and the

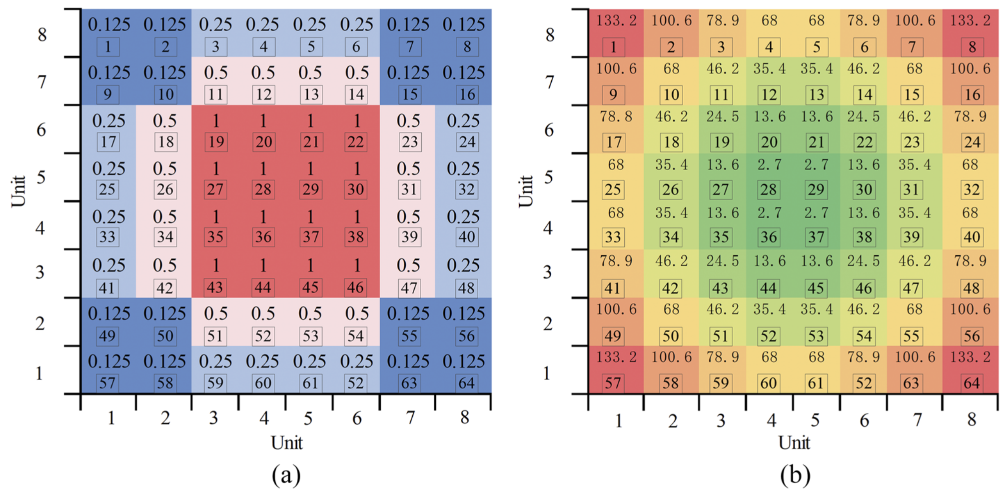


**FIG. 6.** (a) Amplitude (linear value) and (b) phase (°) distribution of the transmitting array.

minimum adjustment is 5.6°. Both the Tx and Rx antennas are 1 × 1 m$^2$, and the distance between them is 10 m.[6] The microwave power received by each unit of the Rx antenna is measured by an AV 2433 microwave power meter.

Using the same method,[6] the H plane power density distributions of the ERSAFA and the GAFA were measured. It is observed from Fig. 8 that the measurements agree with the simulations. The GAFA and the ERSAFA nearly have the same main lobe. Besides, the two measured results are somewhat asymmetrical because the output power from different microwave source ports inevitably has errors.

Then, the received power distributions of the 2 Tx arrays were measured. The transmitted power of the two arrays was both 50 W. Table II shows the total received power and the transmission efficiency vs different Rx aperture sizes. The transmission efficiency $\mu$ is defined as

$$\mu = \frac{P_r}{P_t} \tag{3}$$

where $P_t$ is the total microwave power outputted by the microwave power source and $P_r$ is the total received microwave power outputted by the Rx antenna. It can be clearly concluded from Table II that the GAFA and the ERSAFA have received nearly the same microwave power with different receiving apertures sizes. The measured transmission efficiency difference of the GAFA and the ERSAFA is only 0.68%, 1.63%, and 1.08% when the receiving aperture size is 0.5 × 0.5 m$^2$, 0.75 × 0.75 m$^2$, and 1 × 1 m$^2$, respectively. Besides, it is shown that the measured values are lower than the simulated results because the simulation did not consider the radiating loss of the Tx and Rx antennas. If the loss is considered, the

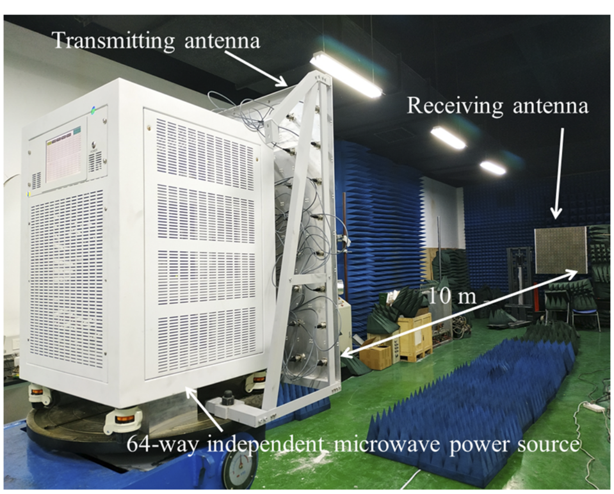


**FIG. 7.** MPT experiment system.

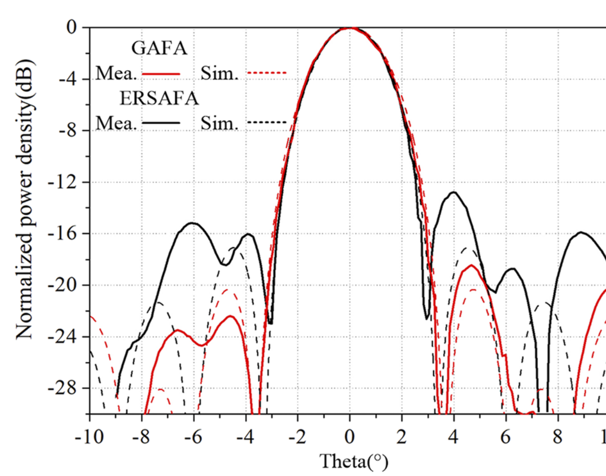


**FIG. 8.** Normalized simulated and measured power density distributions of the Gaussian amplitude and focused array (GAFA) and the equal-ratio steps amplitude and focused array (ERSAFA).

**TABLE II.** The received microwave power and the transmission efficiency against different receiving aperture sizes.

| Receiving aperture size ($m^2$) | | 0.5 × 0.5 | 0.75 × 0.75 | 1.0 × 1.0 |
|---|---|---|---|---|
| Simulated-$P_r$ (W) and $\mu$ (%) | GAFA | 26.89/53.79 | 39.72/79.44 | 44.12/88.24 |
| | ERSAFA | 26.25/52.5 | 39.15/78.3 | 43.95/87.9 |
| Measured-$P_r$ (W) and $\mu$ (%) | GAFA | 16.88/33.76 | 25.45/50.9 | 28.44/56.88 |
| | ERSAFA | 16.54/33.08 | 24.635/49.27 | 27.9/55.8 |

simulated transmission efficiency of the GAFA and the ERSAFA would be 59.89% and 59.65% when the receiving aperture size is 1 × 1 $m^2$, which is close to the measured results. Furthermore, transmission efficiency of the equal amplitude and in-phase array and the equal amplitude and focused array is also measured to validate the proposed design further. The measurement shows that the transmission efficiency is 38.5% and 49.1% when the receiving aperture size is 1 × 1 $m^2$. Hence, compared with the equal amplitude and in-phase array and the equal amplitude and focused array, both the GAFA and the ERSAFA realize high transmission efficiency.

## V. CONCLUSION

A high-efficiency near-field focused Tx antenna based on equal power divisions has been introduced. An MPT experiment was conducted to validate the theoretical designs. According to the measured results, compared with the 10 dB Gaussian amplitude arrays, the proposed array nearly has the same transmission efficiency with different receiving aperture sizes. It is known that equal power dividers are much easier to realize than unequal power dividers. Hence, the proposed design can not only realize high transmission efficiency but also simplify the amplitude feeding and save the cost, which are useful for engineering.


## ACKNOWLEDGMENTS

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## DATA AVAILABILITY

The data that support the findings of this study are available within the article.

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