Methods for Testing the Performance of Long-distance Wireless Power Transmission Systems

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RESEARCH

Methods for Testing the Performance of Long-distance Wireless Power Transmission Systems

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Abstract

Long-distance wireless power transmission can reduce the dependence of unmanned systems on energy storage systems, which is especially advantageous for unmanned aerial vehicles. This approach is key for building an integrated and uninterrupted air-to-ground power supply network. This paper introduces the technical characteristics of long-distance wireless power transmission systems, reports the development of such systems at home and abroad, and proposes technical indices and methods for performance evaluation of these systems. A test was conducted using a testing device, and the key parameters of the system performance were obtained. This work provides a solid foundation for the performance evaluation studies of long-distance wireless power transmission systems.

Keywords: Wireless power transmission; long-distance; laser; microwave; testing method

Introduction

Wireless power transmission technology refers to a brand-new mode of power supply, whereby power can be transmitted without cables. Using lasers and microwaves as vectors, long-distance wireless power transmission technology can be applied to terrestrial power distribution systems, space energy utilization, unmanned networking, and unmanned clusters. Wireless transfer of power between subsystems and "unlimited" power supply for weapons equipment can be achieved in principle. This paper mainly analyzes the technical characteristics of laser wireless power transmission and microwave wireless power transmission systems, and proposes two types of methods for testing the performance of such wireless power transmission systems. A performance test that uses a testing device is also described. Some key parameters, such as power and efficiency, are obtained. This research provides the basis for the subsequent development of relevant work.

Related work

The long-distance wireless power transmission technology mainly considers laser wireless power transmission and microwave wireless power transmission systems. The principle of laser wireless power transmission is the transmitting end converts the electrical energy into a laser beam using a photoelectric device, and the receiving end converts the laser beam energy back into electrical energy. Its merits are long transmission distance, strong directivity, small transceiver antenna aperture, concentrated energy. Its shortcomings are high energy consumption, sensitivity to clouds and obstacles, low transmission efficiency. Laser wireless power transmission is commonly used for unmanned aerial vehicles, microsatellites, space probes, wireless sensor networks. Microwave wireless power transmission's transmitter uses a vacuum device to convert the electrical energy to microwaves, and the receiver uses a rectifier to convert the microwaves to direct current. Its merits are large transmission power, small transmission loss in the atmosphere, one-to-many transmission. Its shortcomings are large scattering loss, jamming communication equipment, low efficiency, large antenna aperture. Microwave wireless power transmission is commonly used for distributed satellite platforms, solar power stations, deep space exploration.

Laser Wireless Power Transmission

In the laser-based wireless power transmission process, the electrical energy in a power grid or energy storage unit is converted by a laser power source and is provided to a laser. The laser converts the electrical energy into a laser beam, which is captured by a photovoltaic array. The laser output is converted into electrical energy at the receiving end after free-space transmission [1]. The laser-based wireless power transmission technology is advantageous owing to its high energy density, strong energy convergence, strong directivity, long transmission distances, and small transmission/reception aperture (only 10 % of that of a typical microwave wireless power transmission system). After long-distance transmission, the laser beam is still concentrated and suitable for powering long-distance mobile devices [2]. Therefore, laser-based energy transmission can be used for ground electric energy distribution, spatial scientific research, spatial energy utilization, and concealed spatial communications. It provides energy for mobile electric equipment such as mobile base stations, unmanned aerial vehicles (UAVs), airships, robots, deep-space probes, and module spacecraft.

In 2004, inspired by concentration cells, Howell [3] designed a receiver for laser-based power transmission signals. On the front surface of a GaAs photovoltaic cell (diameter, 4 mm), a lens (diameter, 3.7 cm) was used for collecting light. In the experiment, the laser wavelength was 830 nm and the power was 0.52 W. The optimized photoelectric conversion efficiency of the laser-receiving system was above 56 %. In 2010, the US Naval Laboratory [4] simulated the effects of different laser power densities on the characteristics of InGaP/GaAs/Ge triple-junction solar cells, which were irradiated by three laser systems (wavelengths at 555 nm, 860 nm, and 1510 nm). The objective was to optimize the laser wavelength and power density through calculations. In 2013, He [5] reported a laser power transmission ground system for studying the energy transmission efficiency. Using this system, the effects of the laser wavelength and different photovoltaic device materials on the energy transmission efficiency were quantified. In 2014, Qiao and co-workers [6] studied the effects of the laser wavelength and laser power density on the energy conversion efficiency of GaAs photovoltaic cells. In their experiment, lasers with the wavelengths of 532 nm, 671 nm, 808 nm, and 980 nm irradiated GaAs batteries at 2 m, and the photoelectric conversion efficiency of the irradiated GaAs batteries exhibited a single-peak characteristic as a function of the laser power density.

Microwave Wireless Power Transmission

In the microwave-based wireless power transmission (MWPT) process, the city power system completes the conversion of high-voltage direct current (DC) through a power supply. Alternating current (AC) is converted into microwaves by a vacuum device, and the resulting waves are emitted using a transmitting antenna. Using a rectifying device, the receiving antenna receives and converts the microwave energy into DC power output [7]. The output power range is 10-100 kW; the transmission distance range is 1-20 km. The microwave-based wireless power transmission technology is advantageous owing to its high transmission power, strong environmental adaptability, flexible focusing and scattering, high conversion and transmission efficiency, low atmospheric loss, and strong penetration. This technology can be used for high-precision controlled beam pointing. With high security, it is suitable for powering long-distance unmanned equipment and for information exchange in complex environments. It can also be used for ground power distribution, space energy utilization, and microsensor-based energy communications, providing fast and convenient energy requirements for mobile electrical equipment such as microsensors, drones, and distributed satellites [8].

In 1984, Brown applied the plane technology to designing a rectifier antenna for microwave wireless power transmission systems [9], in which the receiving antenna was a planar dipole and the rectifier diode was directly connected to two metal strip lines (the so-called CPS transmission line). Later, Chang and co-workers applied a CPS-feeding dual rhombic loop to the receiving antenna. This loop had high gain, broadband, and circular polarization characteristics. In 2014, Yang and coworkers [10] published a review on the two types of rectifier antenna elements and arrays. AC-band MWPT system was designed for meeting the requirements of high beam capture efficiency to the distribution of the transmitting antenna aperture. Japanese Mitsubishi researchers converted 10 kW of electricity into microwaves and used wireless power transmission to successfully power light-emitting diodes (LEDs) on the receiving device, from a distance of 500 m. From 2008 to 2011, technical research has been performed in the US about the ground microwave wireless power transmission tests at a distance of 100 km, an airship energy supply test for a height of 20 km, a space solar power station platform ground test for 100 kW, and a microwave driven lunar rover ground test for 20 kW [11].

Methods

Methods for Testing the Laser Wireless Power Transmission Systems

Testing Index

Technical indexing can be divided into transmitter, space transmission, and receiver indices, according to the system composition, and it can also be divided into size, power, and efficiency indexing, according to the index type. The technical indexing system is shown in Fig. 1. In practical applications, a laser-based wireless power transmission system needs to focus on the miniaturization and weight reduction of the receiving end. The transmitting aperture, the size of the receiving photovoltaic cell array, and the transmission distance are typically used as size indicators, and then the power at each node of the transmitting/receiving system is measured. The transmission efficiency of the system can be obtained from calculations.

Figure 1 Indexing system of the laser-based technology

Testing Methods

The experiment adopted a fiber-coupled semiconductor laser with adjustable power. The laser wavelength was 808 nm. The laser was connected to a collimated beam expansion system through an optical fiber; then, the laser beam was irradiated on a 43×43 cm^2 photovoltaic cell array, and the power was supplied to the load after passing through a photoelectric converter and a rectifier regulator. During the test, an infrared viewer was used for observing the laser beam and the light spot on the photocells array. A digital multimeter measured the DC power supply at the input end of the semiconductor laser. An optical power meter measured the optical power of the laser output through the fiber. The output current and output voltage were measured using an electronic load. The test process was conducted as follows. First, the laser power supply was started and the temperature of the semiconductor laser was stabilized at 25 °C using a cool-water machine. Next, the system input AC power was adjusted, and the light spot in the center of the probe was determined using an infrared viewer, allowing to point the optical power meter to the fiber. The output power of the laser was measured for different input power values, and the current and voltage at the output end of the rectifier regulator were measured for obtaining DC output power. The test procedure is shown in Fig. 2.

Figure 2 Flowchart of the laser-based wireless power transmission system evaluation experiment

Methods for Testing the Microwave Wireless Power Transmission Systems

Testing Index

The microwave technical indexing system can be divided into transmitter, space transmission, and receiver types, according to the system composition. It can further be divided into size, power, and efficiency indexing, according to the index type. The technical indexing system is shown in Fig. 3.

Figure 3 Indexing system of the microwave-based technology

Testing Methods

A vacuum device (klystron) converted the alternating current into microwaves. The microwaves were efficiently transmitted after being focused by a Cassegrain transmitting antenna (aperture, 1.6 m). The receiving end used a 2×2 m^2 antenna, to connect a rectifier device (cyclotron-wave rectifier), and converted the microwave power into the DC output power [12]. During the test, a digital multimeter was used for measuring the power input to the microwave power generator, and an electronic load was used for determining the output current and output voltage of the rectifier circuit.

The test process was conducted as follows. First, the system input power was adjusted and recorded. Next, the output current and voltage were measured for different input power values. From the obtained power data, the power conversion efficiency of the system for different input power values was calculated. The workflow of the test procedure is shown in Fig. 4.

Figure 4 Flowchart of the microwave-based wireless power transmission system evaluation experiment

Results and Discussion

Testing Examples and Analysis of Laser Wireless Power Transmission Systems

According to the test conditions in Table 1, both the laser performance and the system performance were tested.

Table 1 Test conditions

	Parameter	Value
1	Transmission Distance	50 m
2	Cell Array Size	430×430 mm^2
3	Beam Aperture	44 mm
4	Wavelength	808 nm

Performance Tests of Lasers

The output characteristics and conversion efficiency of the laser, for different input powers, are shown in Table 2. According to the data in the table, the relationship between the output power of the semiconductor laser and the power supply was obtained, and the conversion efficiency waveform was obtained.

Table 2 Test results of the laser-based wireless power transmission system

	Parameter	Measured Values				
		Group 1	Group 2	Group 3	Group 4	Group 5
1	System Input AC power (W)	139.2	239.4	341.3	453.2	579.5
2	DC Power of Laser (W)	73.5	152.1	235.8	323.46	414.95
3	Laser Power (W)	23.17	66.01	107.7	148.7	185.3
4	Electro-optical Conversion Efficiency of Laser	31.52 %	43.40 %	45.67 %	45.97 %	44.66 %
5	AC-optical Power Conversion Efficiency	16.6 %	27.6 %	31.6 %	32.8 %	32.0 %

Figure 5 Input-output relationship for the semiconductor laser-based system

Fig. 5 shows the output power versus the power supply, for the semiconductor laser. The lasers optical power increases linearly with increasing the DC power supply, and the electro-optical conversion efficiency reaches 46%. The internal loss, series resistance, and threshold current of the semiconductor laser reduce its photoelectric conversion efficiency. Among these, the internal loss is mainly caused by the free carrier loss in the confinement layer and in the quantum well; the resistance of the laser p-type waveguide layer and the free carrier loss in the highly doped p-type confinement layer lead to the high series resistance and high overall loss for this laser [13].

Figure 6 Semiconductor laser conversion efficiency

As is shown in Fig. 6, the electro-optical conversion efficiency of the semiconductor laser increases linearly with increasing the power supply, then slowly increases to a peak value, and finally gradually decreases. Assuming that the laser output optical power is P, the laser DC supply power is P_1, the AC to optical power conversion efficiency is η_1, and the rectifier circuit AC-DC conversion efficiency is η_2, it follows that the electro-optical conversion efficiency of the laser is $\eta_{electro-optical} = P/P_1$, and the AC-optical power conversion efficiency is $\eta_1 = \eta_{lectro-optical} \quad \eta_2$. As the power supply increased from 73.5 W to 323 W, the electro-optical conversion efficiency of the laser increased from 31.5% to 46%. Subsequently, as the power supply increased to 415 W, the conversion efficiency slowly decreased to 44.6%. The efficiency of the AC-optical power conversion was reduced by 10 %, and the waveform was consistent with the trend of the electro-optical conversion efficiency. The energy loss in semiconductor lasers can occur via five routes: 1) Joule heating, 2) carrier leakage, 3) subthreshold spontaneous emission, 4) voltage loss, and 5) photon scattering and carrier absorption loss [14]. As the power supply of the laser increases, the carriers are injected into the active region, and the non-radiative recombination loss and photon scattering loss also increase. The structural parameters of the laser make these mutually restrictive. When an optimal working point is reached, the balance is broken; past the optimal working point, the efficiency starts to decrease slowly [15]. The AC-optical power conversion efficiency exhibits similar trends. The addition of a rectifier module induces a power loss, lowering the efficiency by 10% compared with the DC electro-optical conversion efficiency. The test results provide a good foundation for optimization studies of high-efficiency laser line arrays and laser-based wireless energy transmission systems.

Performance Test of the Entire System

The laser beam and the spot on the cell panel were observed using an infrared viewer, and the spot falling on the center of the probe was calibrated, as shown in Fig. 7.

Figure 7 Laser emission beam and receiving end

The measured data in the experiment are shown in Fig. 8. The transmission distance of the laser wireless power transmission system was 50 m, the laser beam aperture was 4.4 cm, the size of the photovoltaic cell array was 43 × 43 cm^2, the system input AC power was 579.2 W, the laser DC power supply was 414.2 W, and the load could stably receive the DC power of 45.86 W; the conversion efficiency of the entire system (AC input to DC output) reached 7.9 %.

By performing the experiment at different input power levels, the power response characteristics of the laser and the energy conversion efficiency trends were obtained.

Figure 8 Diagram of the laser-based wireless power transmission system

The analysis of these trends revealed that under the irradiation using the 808-nm laser, the output power increased linearly with the input power, and then the increasing trend became weaker; the energy conversion efficiency firstly increased up to the optimal point and then decreased.

Testing Examples and Analysis of Microwave Wireless Power Transmission Systems

According to the test conditions in Table 3, a test site was arranged for testing the performance of the microwave wireless power transmission system. The physical device is shown in Fig. 9 and Fig. 10.

Table 3 Microwave test conditions

	Parameter	Measured Values
1	Transmission Distance	70 m
2	Working Band	10 GHz
3	Antenna Aperture	1.6 m
3	Size of Rectenna	2×2 m^2

Figure 9 X band microwave transmission system

Figure 10 Rectifier antenna of the receiving end

Table 4 to control sequence lists the output characteristics and conversion efficiency of the system, for different input power values. According to the data in the table, the relationship between the DC output power and the input power was obtained, and the oscillogram plots of the microwave power conversion were generated.

Table 4 Test data

	Parameter	Measured Values					
		Group 1	Group 2	Group 3	Group 4	Group 5	Group 6
1	Input Power (W)	1500	2008	3060	4100	4520	4580
2	DC Output Power (W)	122.2	167.6	273.5	381.0	456.6	440.5
3	Transmission Efficiency	8.15 %	8.35 %	8.94 %	9.29 %	10.10 %	9.62 %

Figure 11 Input-output power conversion results

As shown in Fig. 11, the DC output power of the rectenna increased with increasing the system input power. After the input power reached 4500 W, the output power started to decrease. The conversion efficiency waveform trend was similar, reaching a maximal efficiency of 10.4 % at 4500 W, and then decreasing as the input power further increased. The optimal working power of the power transmission system was determined as 4500 W.

The systems efficiency first increased linearly and then decreased. This occurred because the power amplifier in the microwave power generator responded nonlinearly for strong signals, and its nonlinearity increased with increasing the input power, probably yielding nonlinear indices such as gain compression, intermodulation distortion, and harmonic distortion. In addition, the power consumed by the power amplifier accounts for half or more of the energy consumed by the system, and the dissipated power increases the temperature of the power tube and the cavity. The increasing temperature affects the performance of the power amplifiers gain, gain flatness, and linearity; thus, affecting the systems transmission efficiency [16].

The partial data measured in the experiment are shown in Fig. 12.

Figure 12 Diagram of the microwave-based power transmission system

The transmission frequency of the high-power microwave transmission system was 10 GHz, the transmission distance was 100 m, the transmitting antenna aperture area was 2 m^2, the receiving antenna area was 4 m^2, and the input power was 4500 W. The stable DC power output of the system was 468 W, and the system efficiency reached 10.4 %.

Conclusions

(1) According to long-distance wireless power transmission systems and their constituent units (including the transmitting antenna, space transmission, and the receiving end), performance evaluation indicators including size, power, and efficiency are proposed. Methods for testing the systems and components performance are constructed. An evaluation system for completely testing long-distance wireless power transmission systems was put forward.

(2) Using a testing device, the laser-based and microwave-based systems were tested using the proposed testing methods. The optical power of the laser-based wireless power transmission system reached 185 W, and the conversion efficiency of the system reached 7.9% for the transmission distance of 50 m. The power of the microwave-based wireless power transmission system was 4500 W, and the electric-electric conversion efficiency reached 10.4 % for the transmission distance of 70 m. The key parameters of the components and systems were obtained from these testing experiments, proving the feasibility of the proposed testing methods. The results provide a solid framework for the performance evaluation of long-distance wireless power transmission systems.

Competing interests
The authors declare that they have no competing interests.

Author's contributions
This paper is completed with the cooperation of seven authors. WX proposed the research direction. LC and WC proposed the research methods. LP carried out the experimental verification. XW analyzed the data and wrote this manuscript. ZY carried out the translation work. WF proofread the paper.

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Abbreviations
None

Availability of data and materials
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Ethics approval and consent to participate
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Consent for publication
We agree to the publication of the paper.

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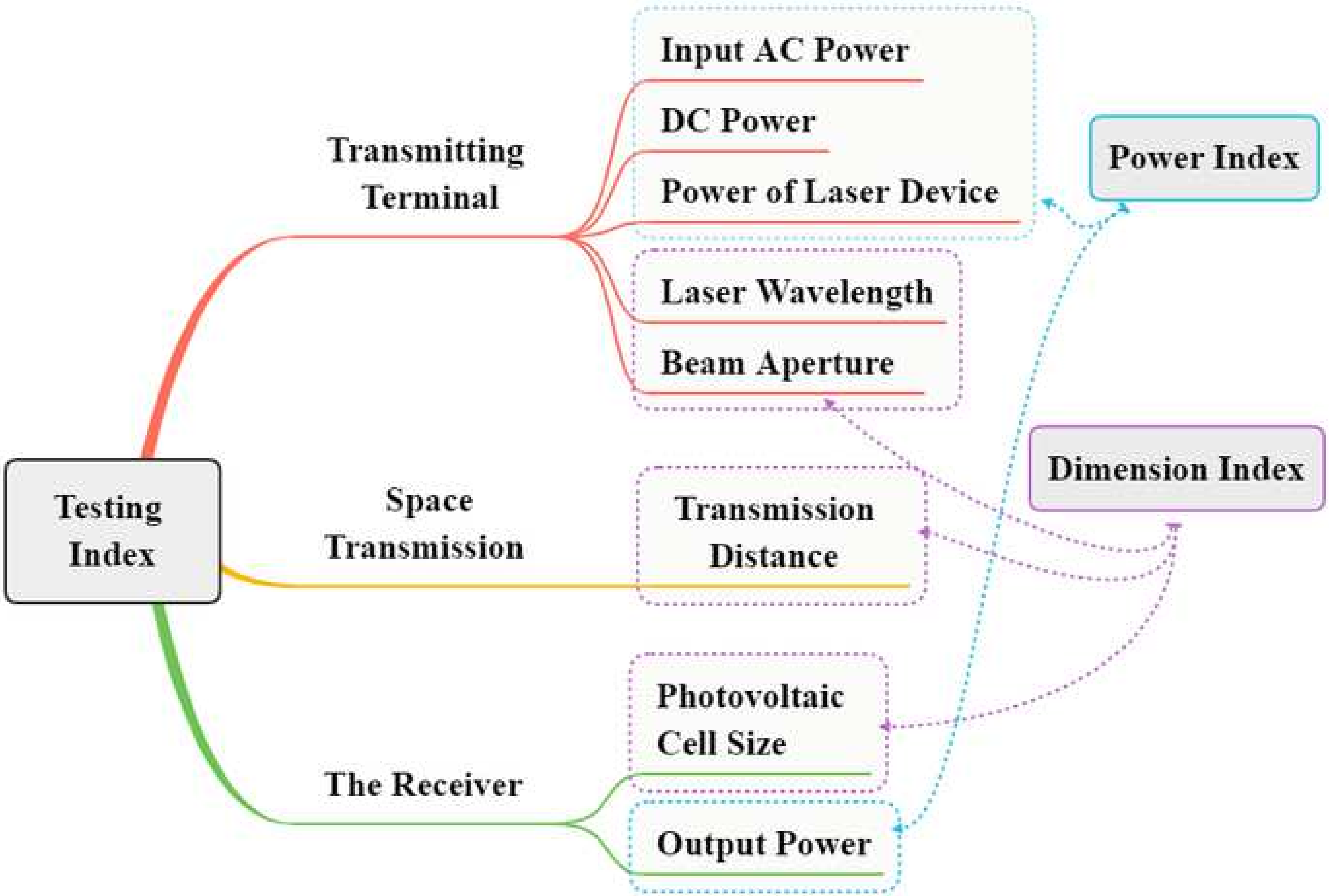
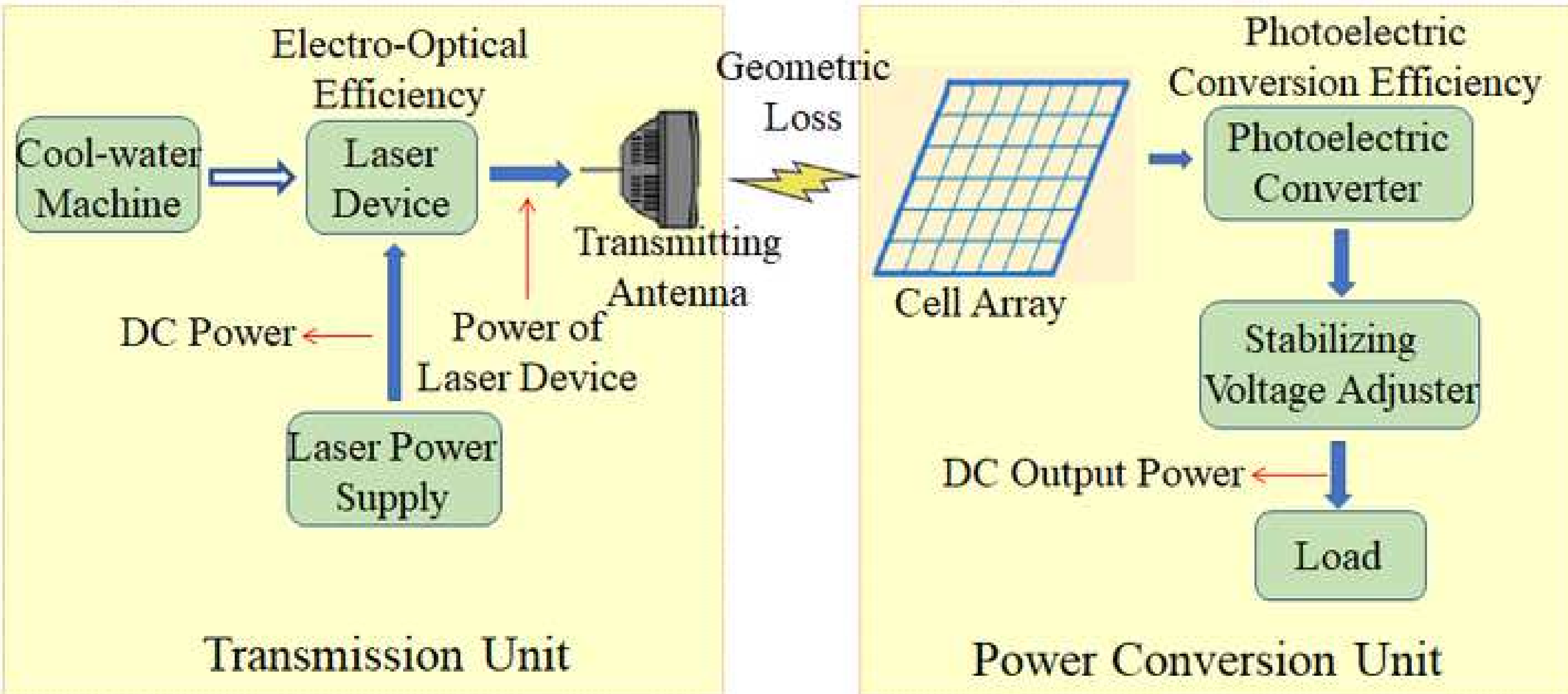
Figure

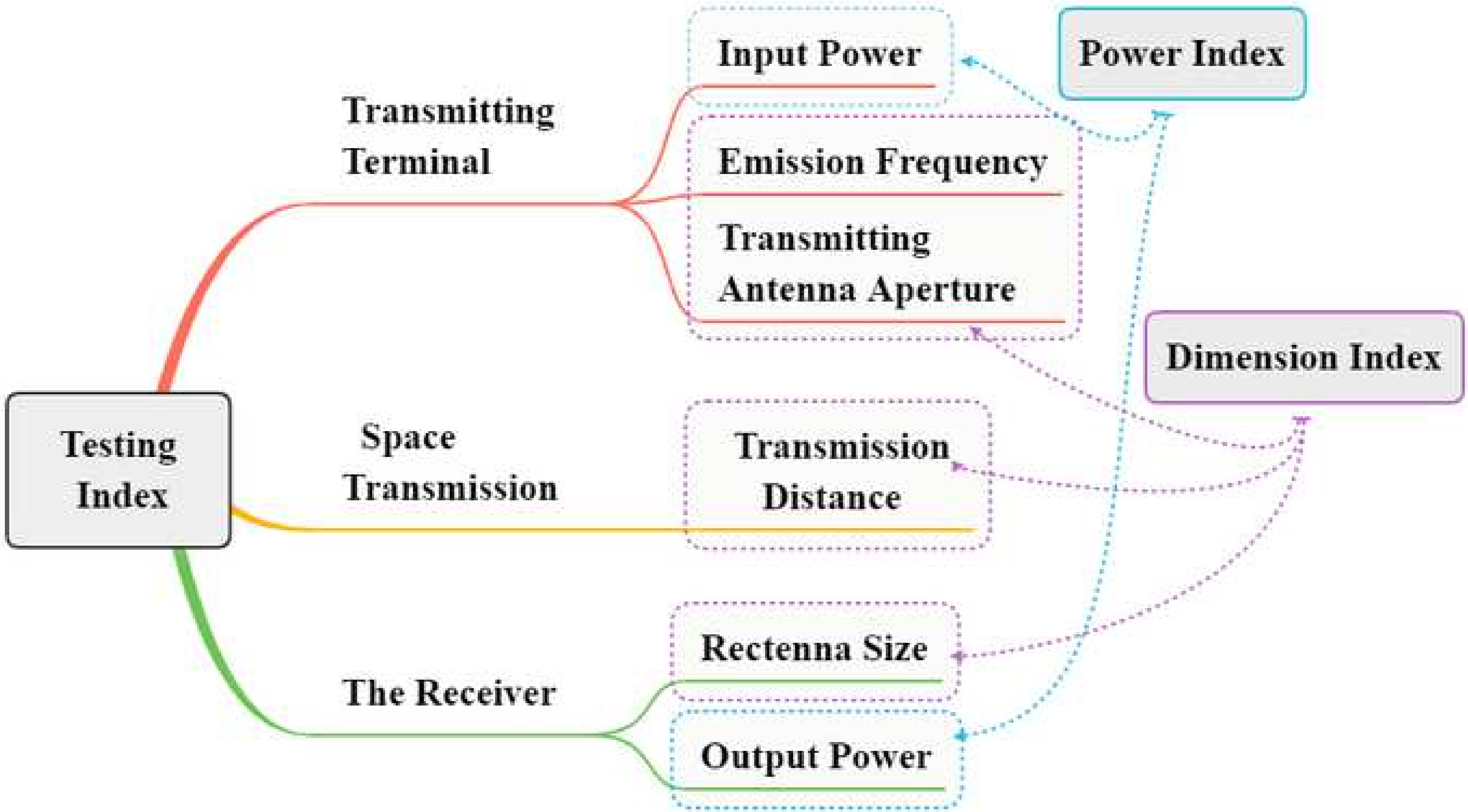


Testing Index
Transmitting Terminal
Input AC Power
DC Power
Power of Laser Device
Laser Wavelength
Beam Aperture
Power Index
Dimension Index
Space Transmission
Transmission Distance
The Receiver
Photovoltaic Cell Size
Output Power

Figure

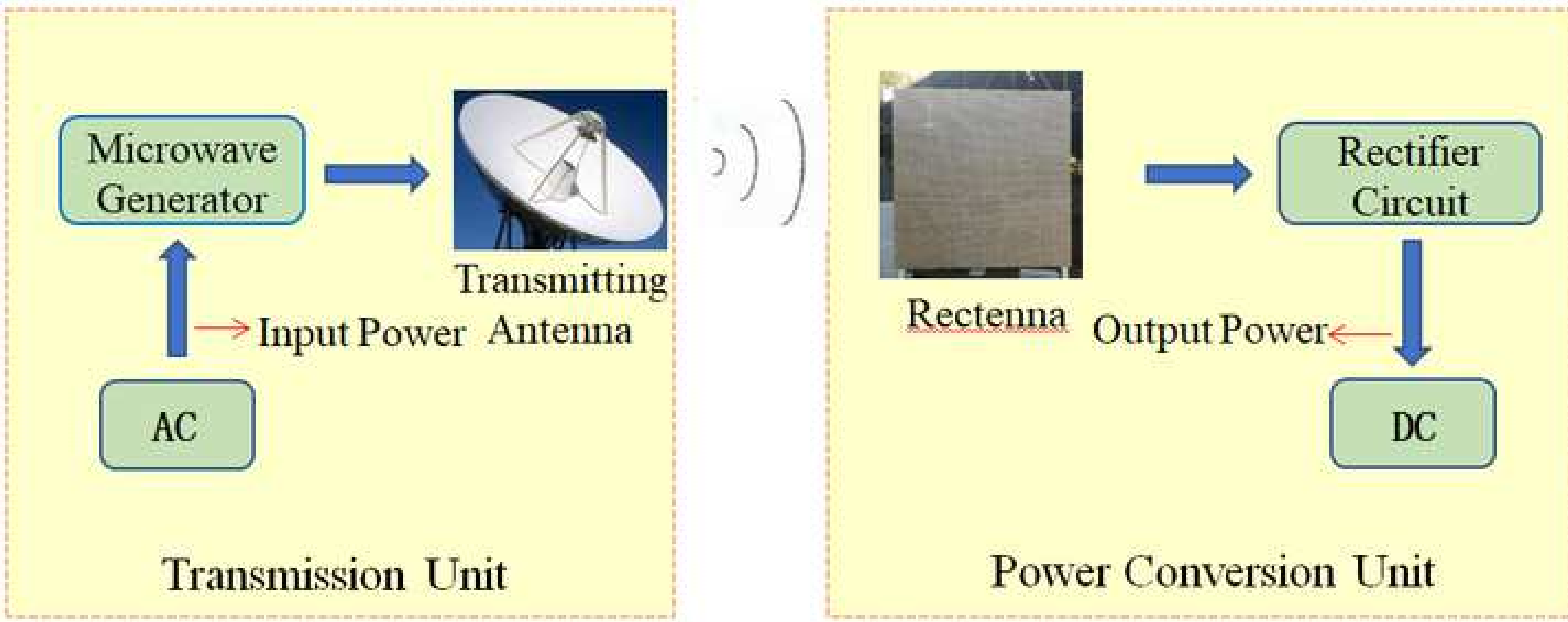

Electro-Optical Efficiency
Cool-water Machine
Laser Device
DC Power
Power of Laser Device
Laser Power Supply
Transmitting Antenna
Geometric Loss
Cell Array
Photoelectric Conversion Efficiency
Photoelectric Converter
Stabilizing Voltage Adjuster
DC Output Power
Load
Transmission Unit
Power Conversion Unit

Figure

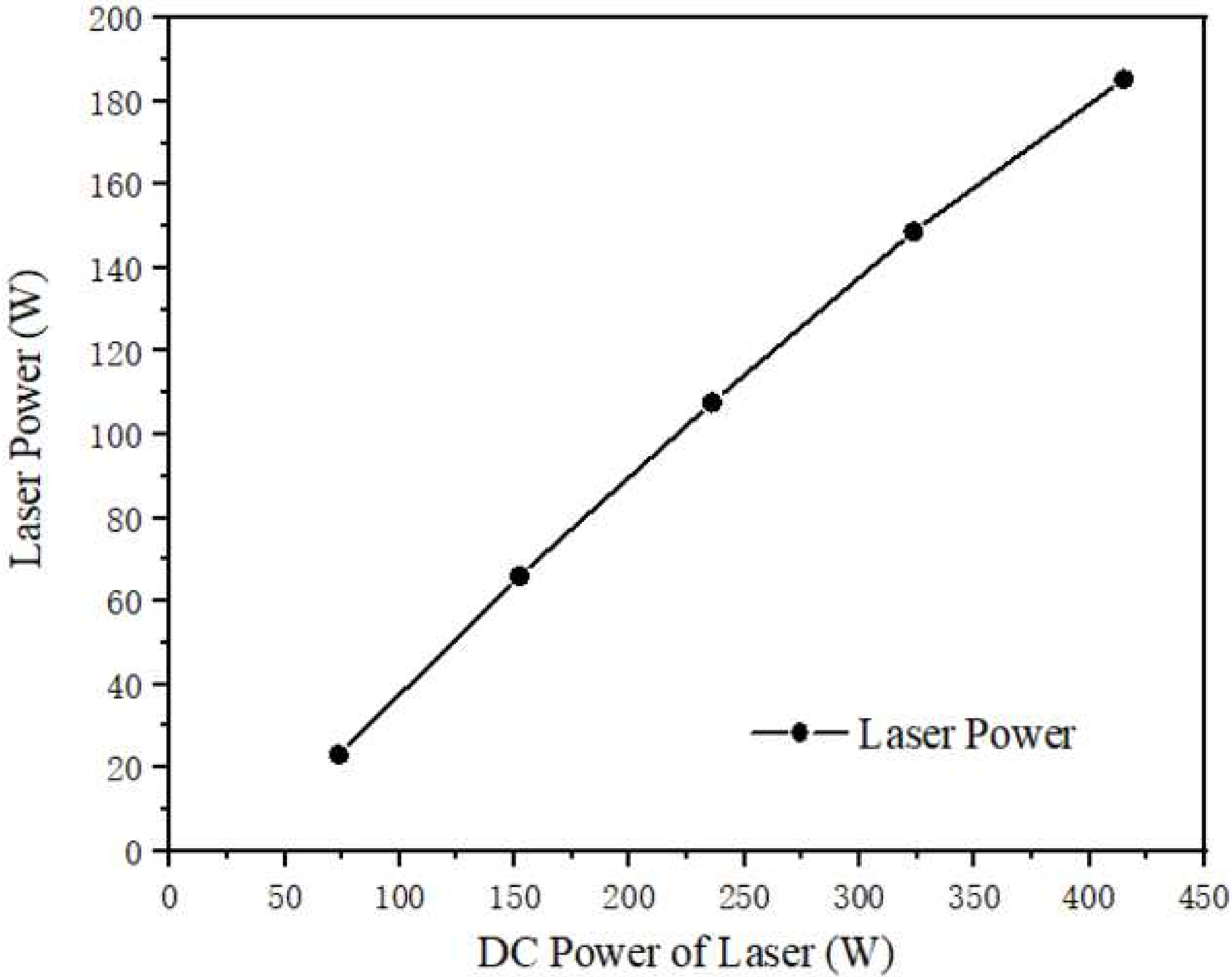


Testing Index
Transmitting Terminal
Space Transmission
The Receiver
Input Power
Emission Frequency
Transmitting Antenna Aperture
Transmission Distance
Rectenna Size
Output Power
Power Index
Dimension Index

Figure

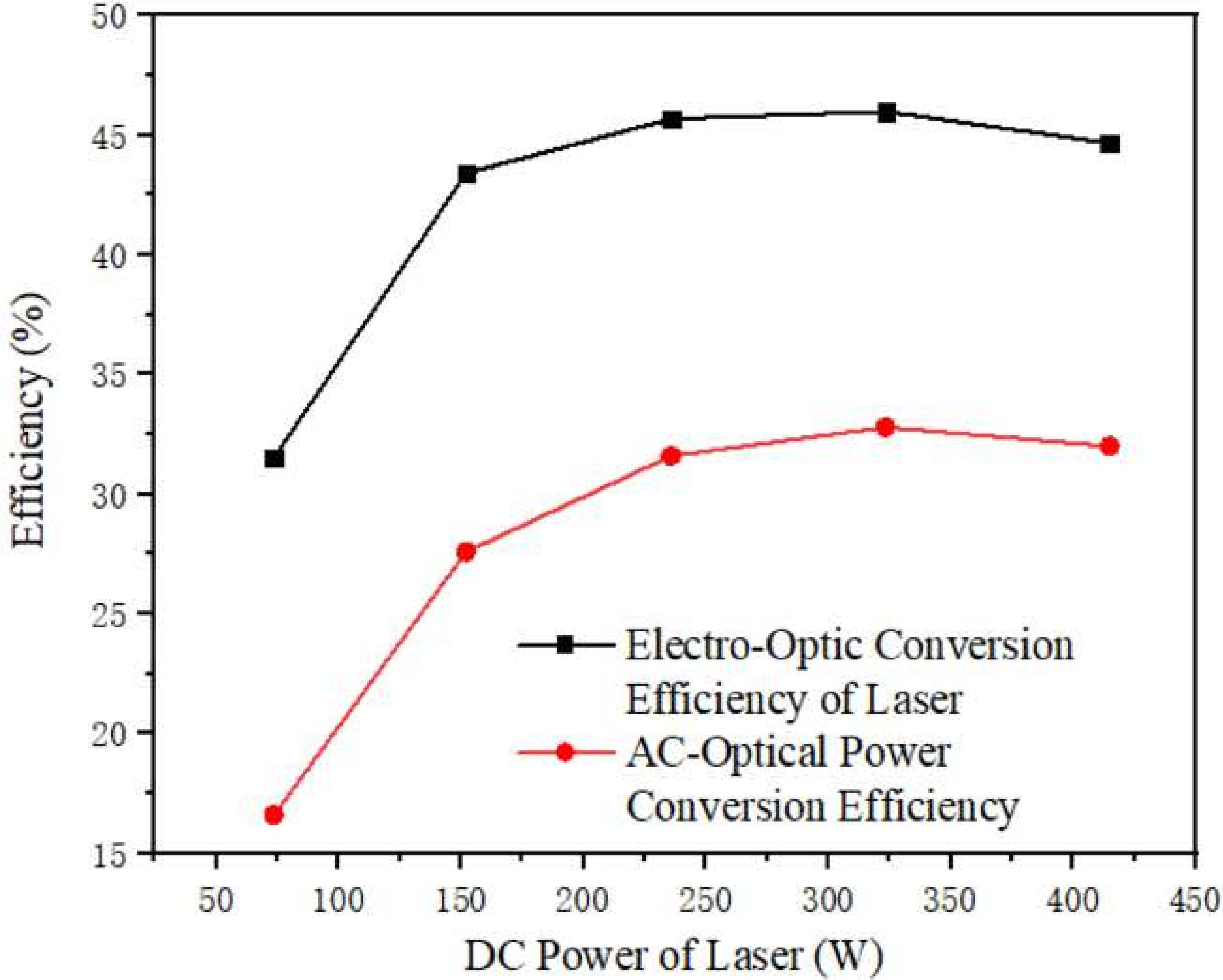

Microwave Generator
Transmitting Antenna
Input Power
AC
Transmission Unit
Rectenna
Rectifier Circuit
Output Power
DC
Power Conversion Unit

Figure



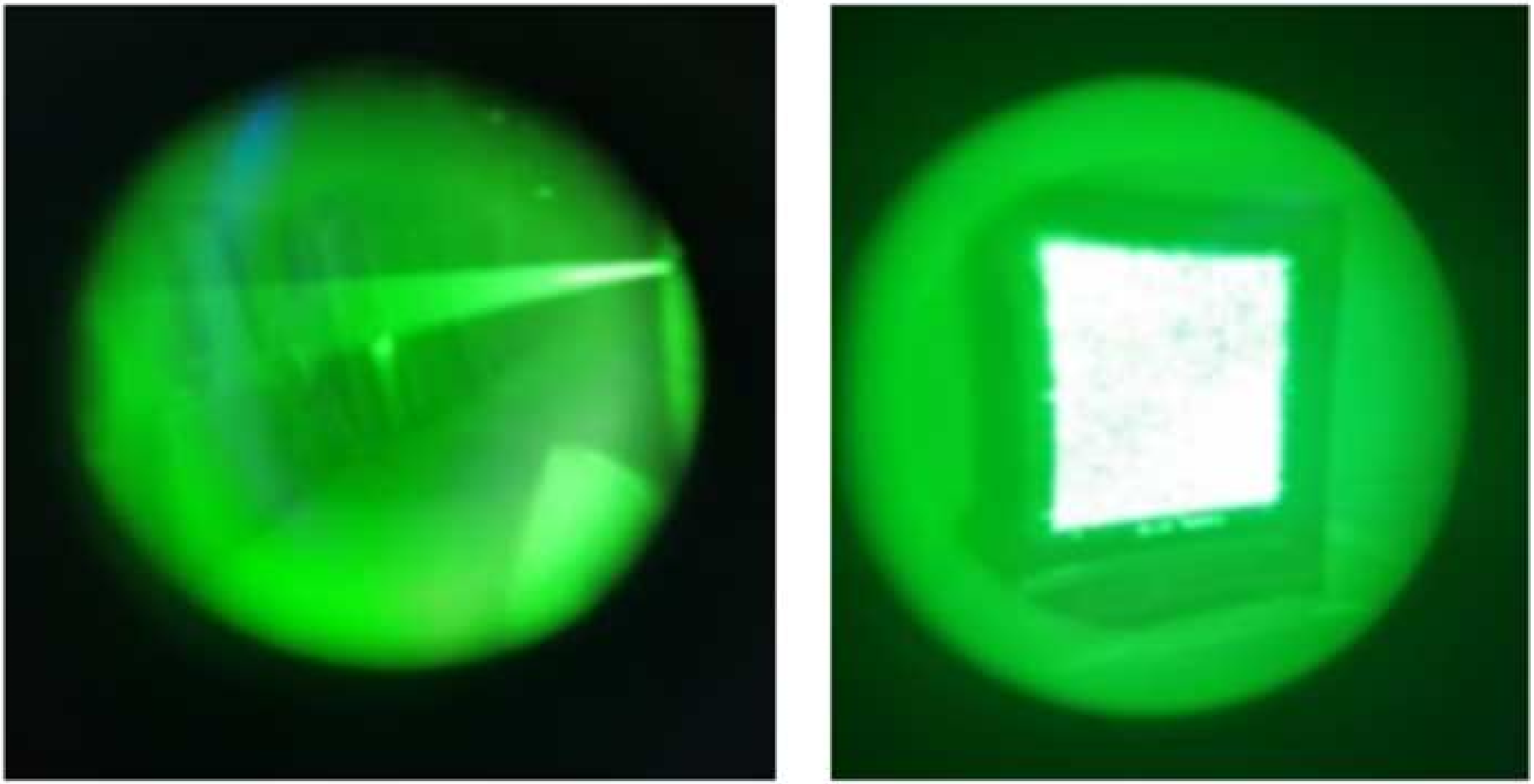
Laser Power (W)
DC Power of Laser (W)
Laser Power
0
20
40
60
80
100
120
140
160
180
200
0
50
100
150
200
250
300
350
400
450

Figure



Efficiency (%)
50
45
40
35
30
25
20
15
50
100
150
200
250
300
350
400
450
DC Power of Laser (W)
Electro-Optic Conversion Efficiency of Laser
AC-Optical Power Conversion Efficiency

Figure



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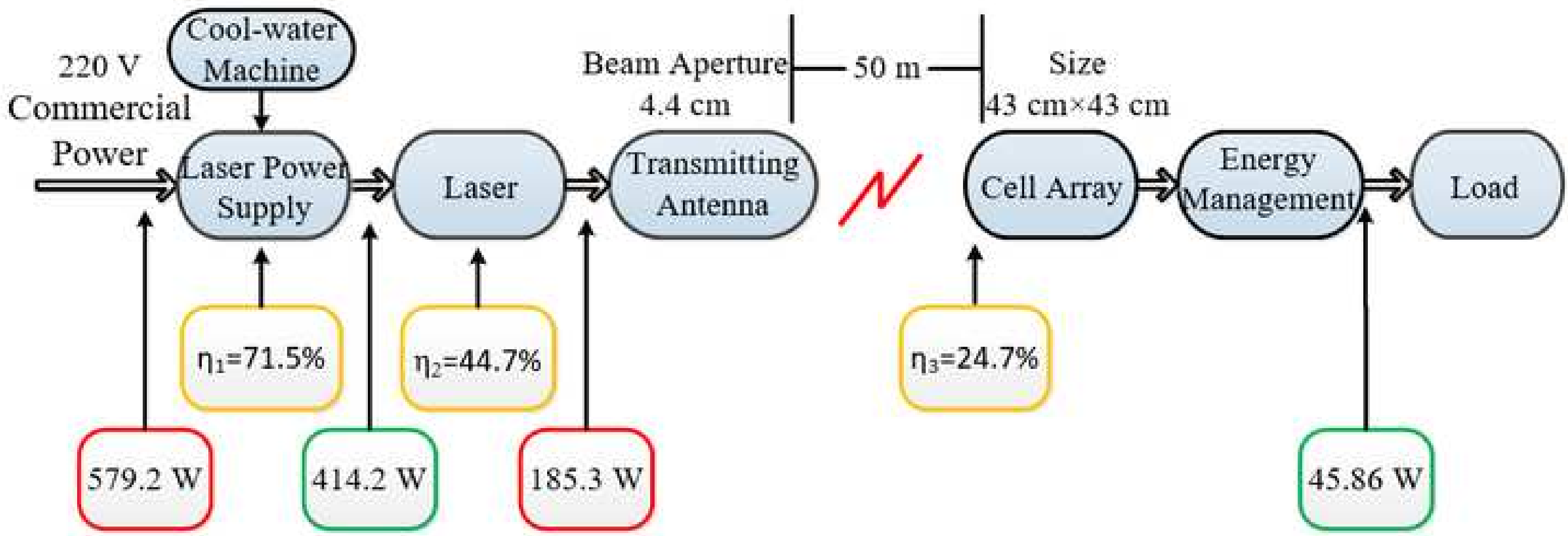
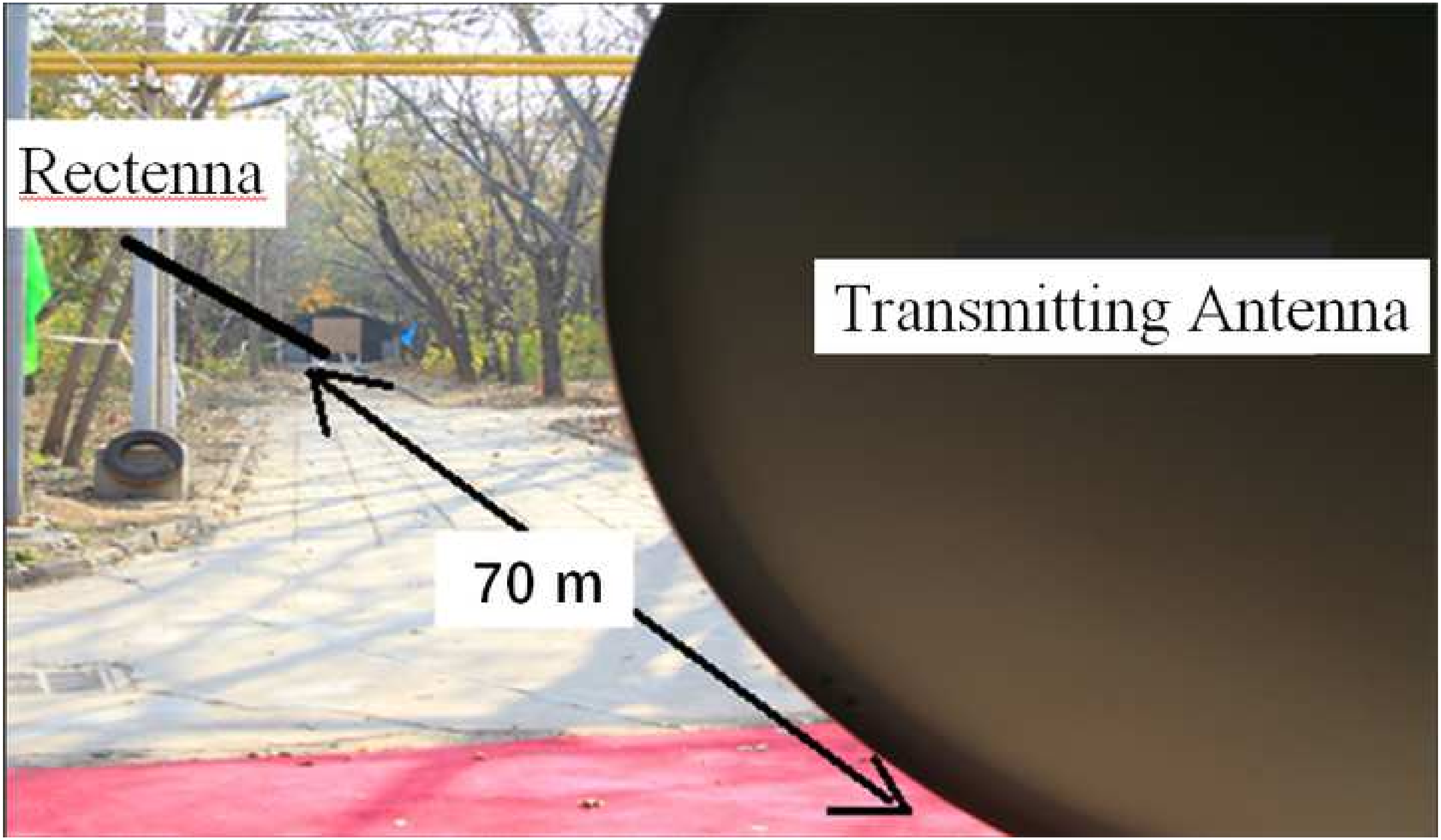


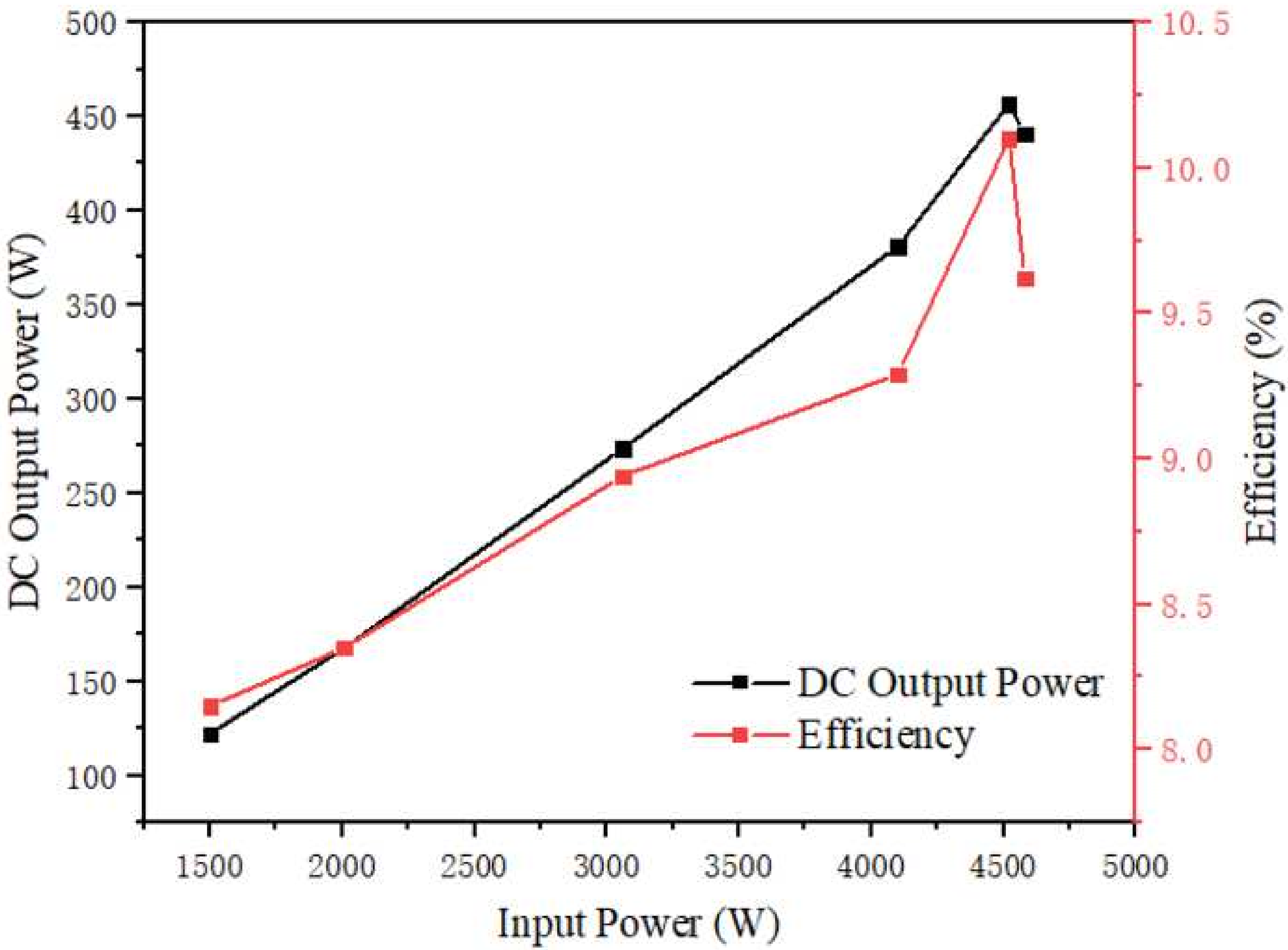
Cool-water Machine
220 V Commercial Power
Laser Power Supply
Laser
Beam Aperture 4.4 cm
Transmitting Antenna
50 m
Size 43 cm×43 cm
Cell Array
Energy Management
Load
η1=71.5%
η2=44.7%
η3=24.7%
579.2 W
414.2 W
185.3 W
45.86 W

Figure



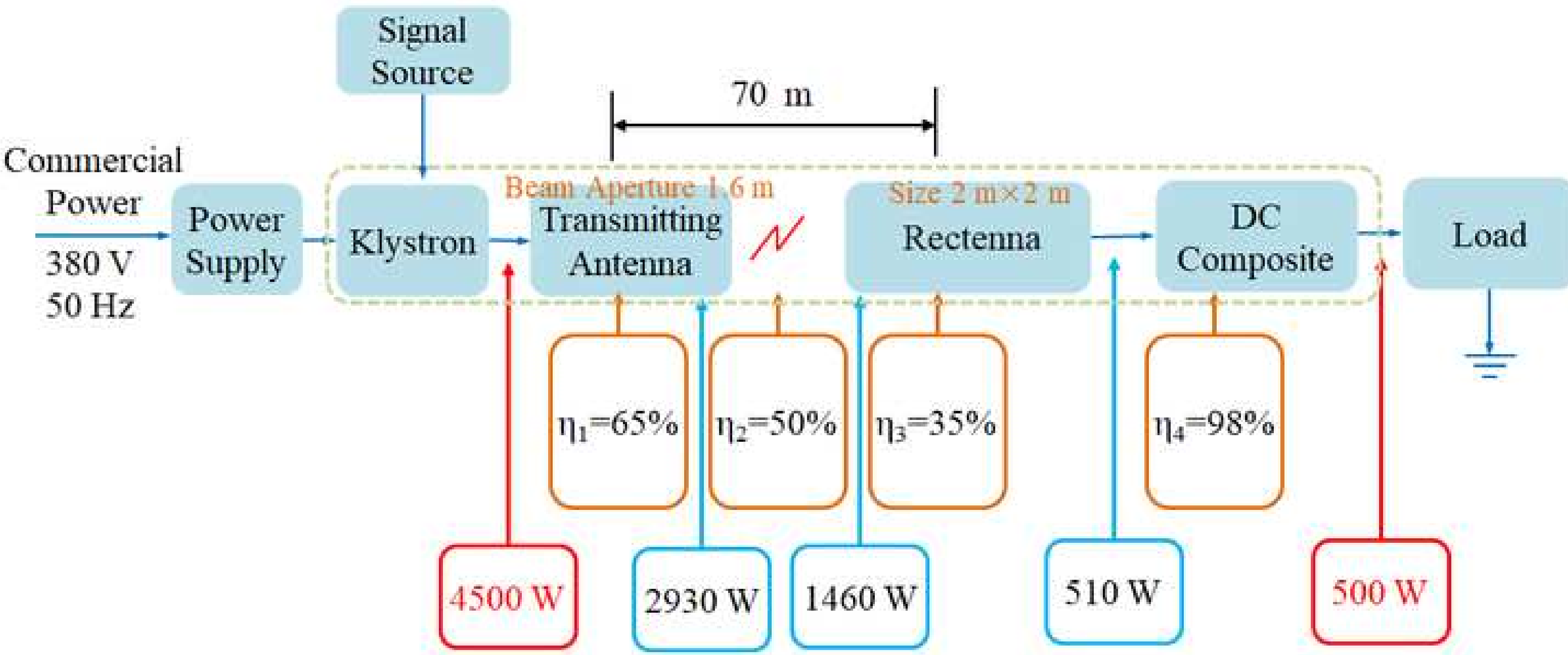
Figure

Figure



500
450
400
350
300
250
200
150
100
DC Output Power (W)
10. 5
10. 0
9. 5
9. 0
8. 5
8. 0
Efficiency (%)
1500
2000
2500
3000
3500
4000
4500
5000
Input Power (W)
DC Output Power
Efficiency

Figure



Signal Source
70 m
Commercial Power
380 V
50 Hz
Power Supply
Klystron
Beam Aperture 1.6 m
Transmitting Antenna
Size 2 m×2 m
Rectenna
DC Composite
Load
η1=65%
η2=50%
η3=35%
η4=98%
4500 W
2930 W
1460 W
510 W
500 W

Figures

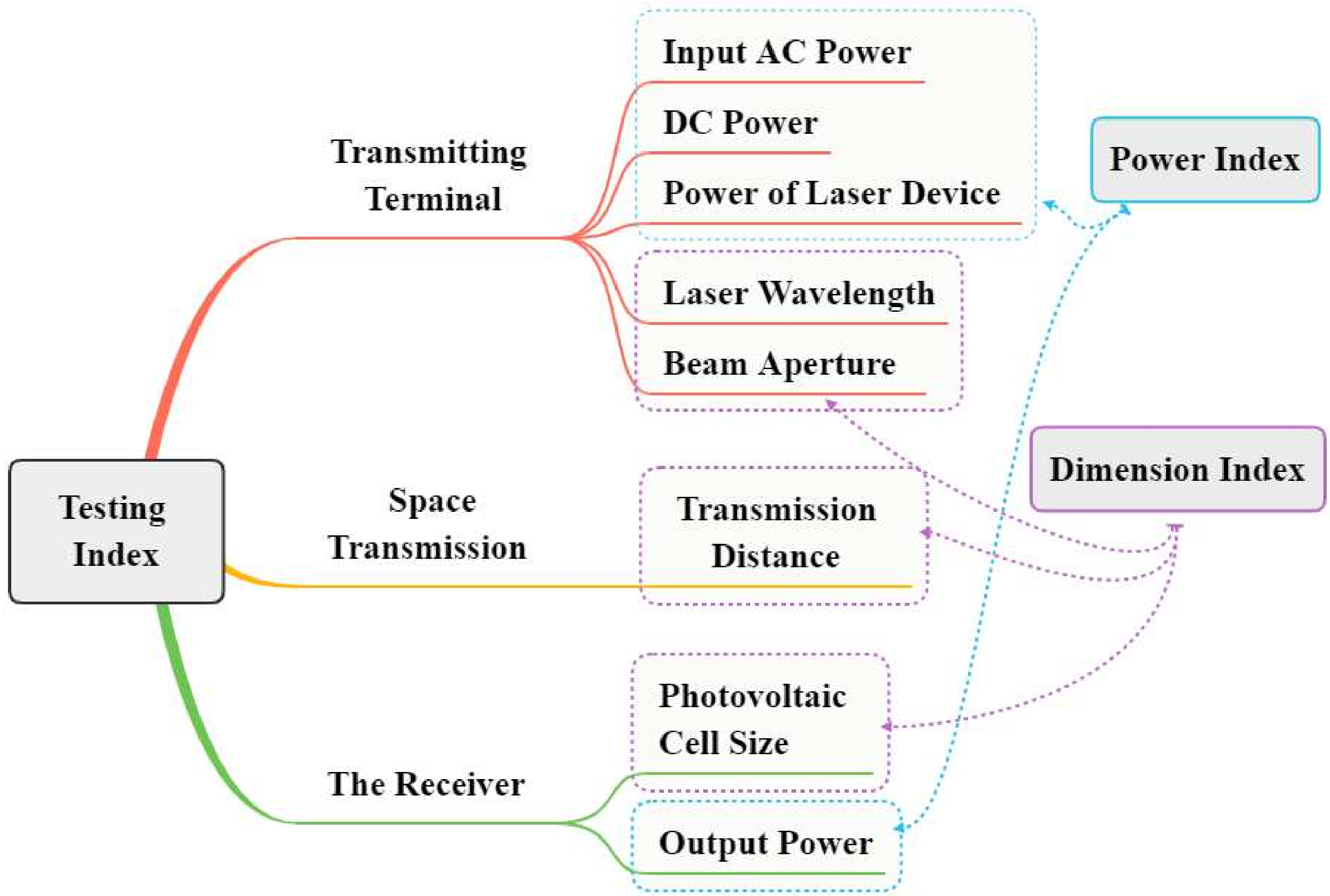


Figure 1

Indexing system of the laser-based technology

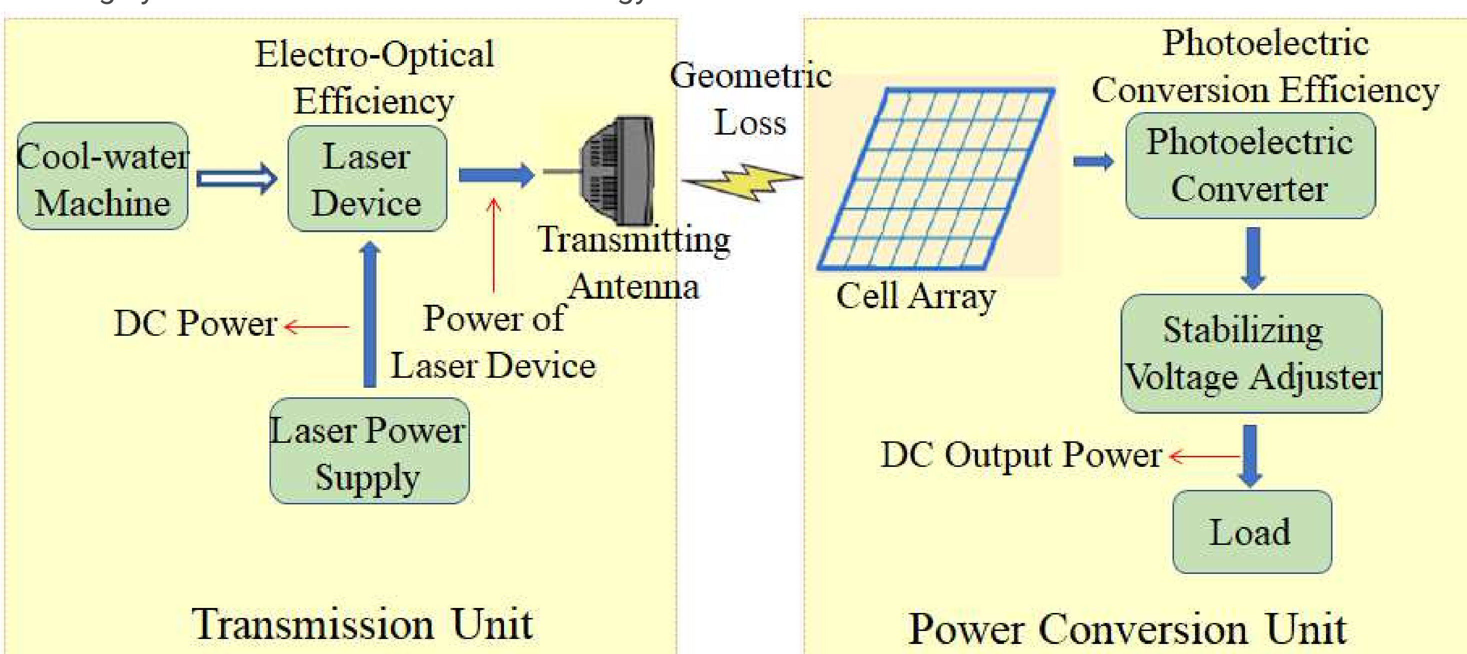


Figure 2

Flowchart of the laser-based wireless power transmission system evaluation experiment

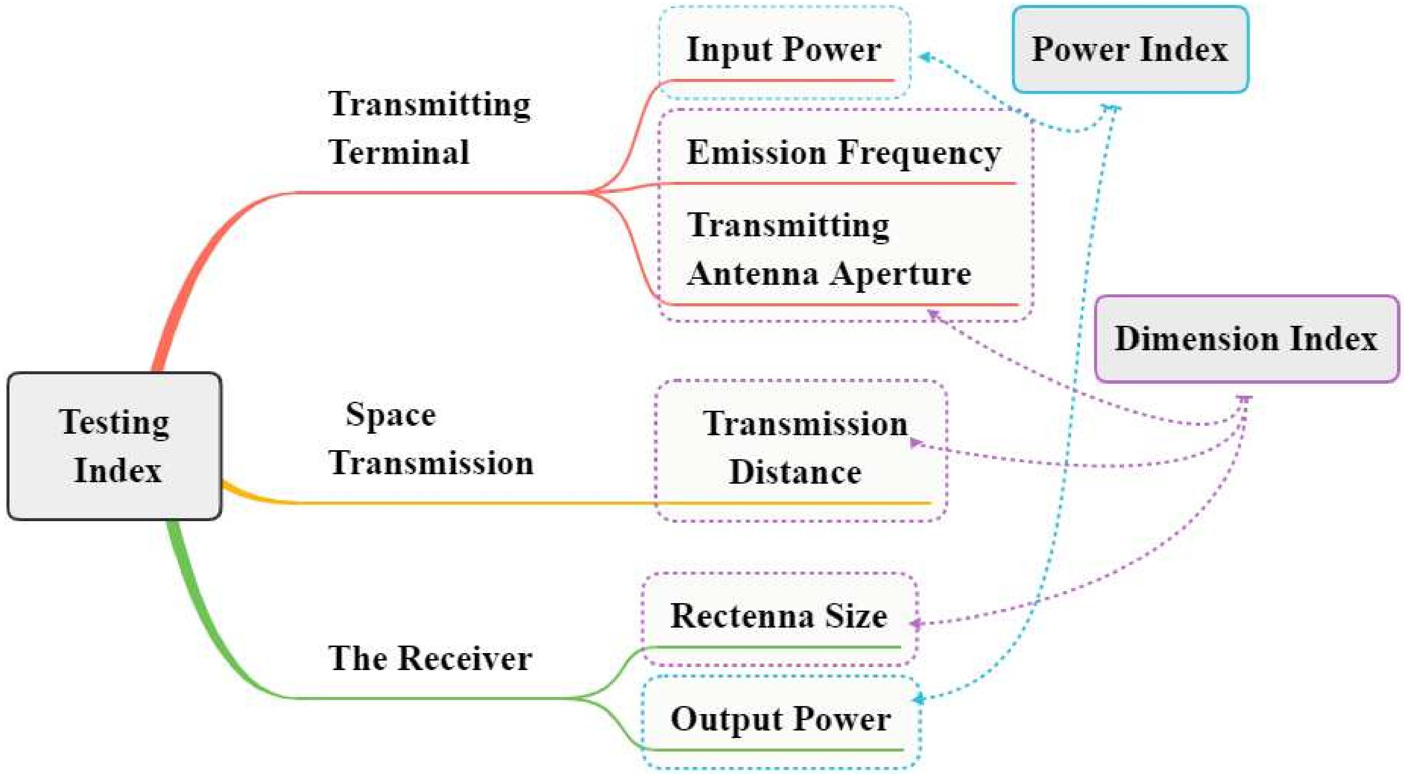


Figure 3

Indexing system of the microwave-based technology

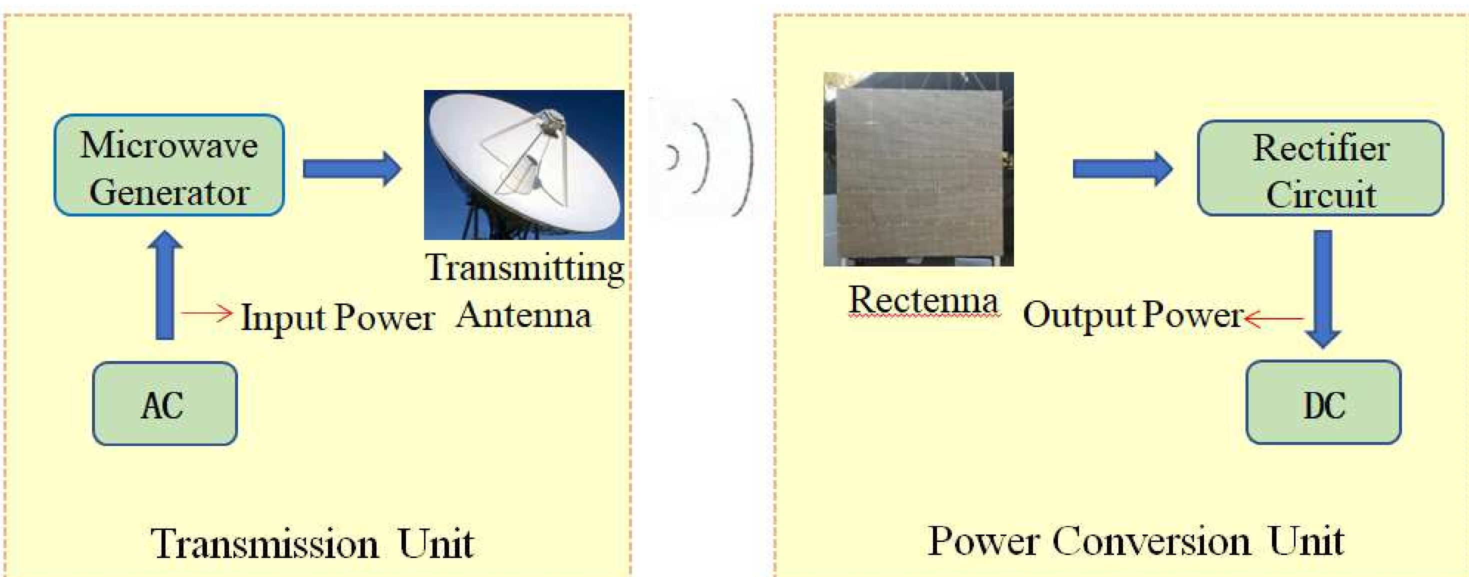


Figure 4

Flowchart of the microwave-based wireless power transmission system evaluation experiment

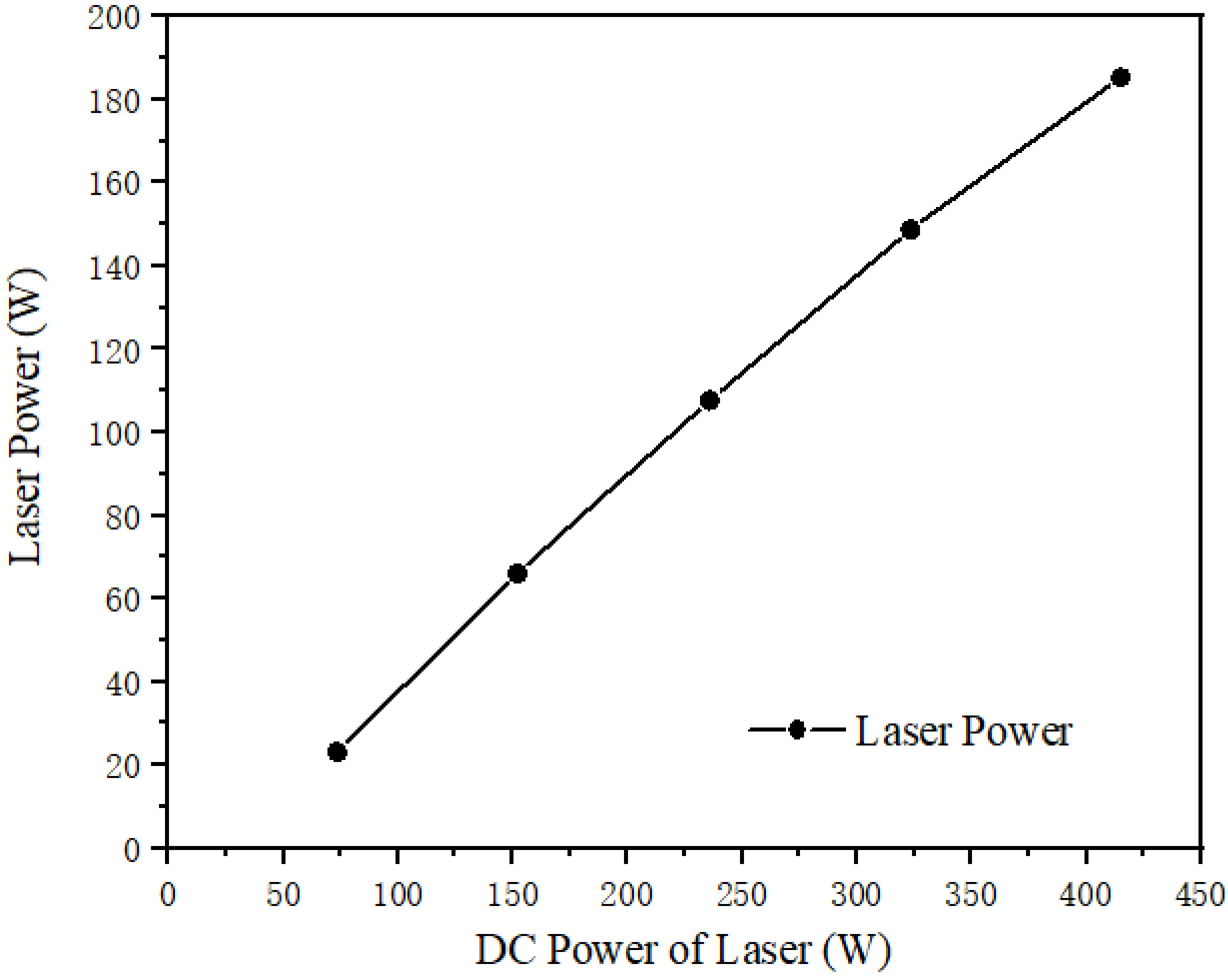


Figure 5

Input-output relationship for the semiconductor laser-based system

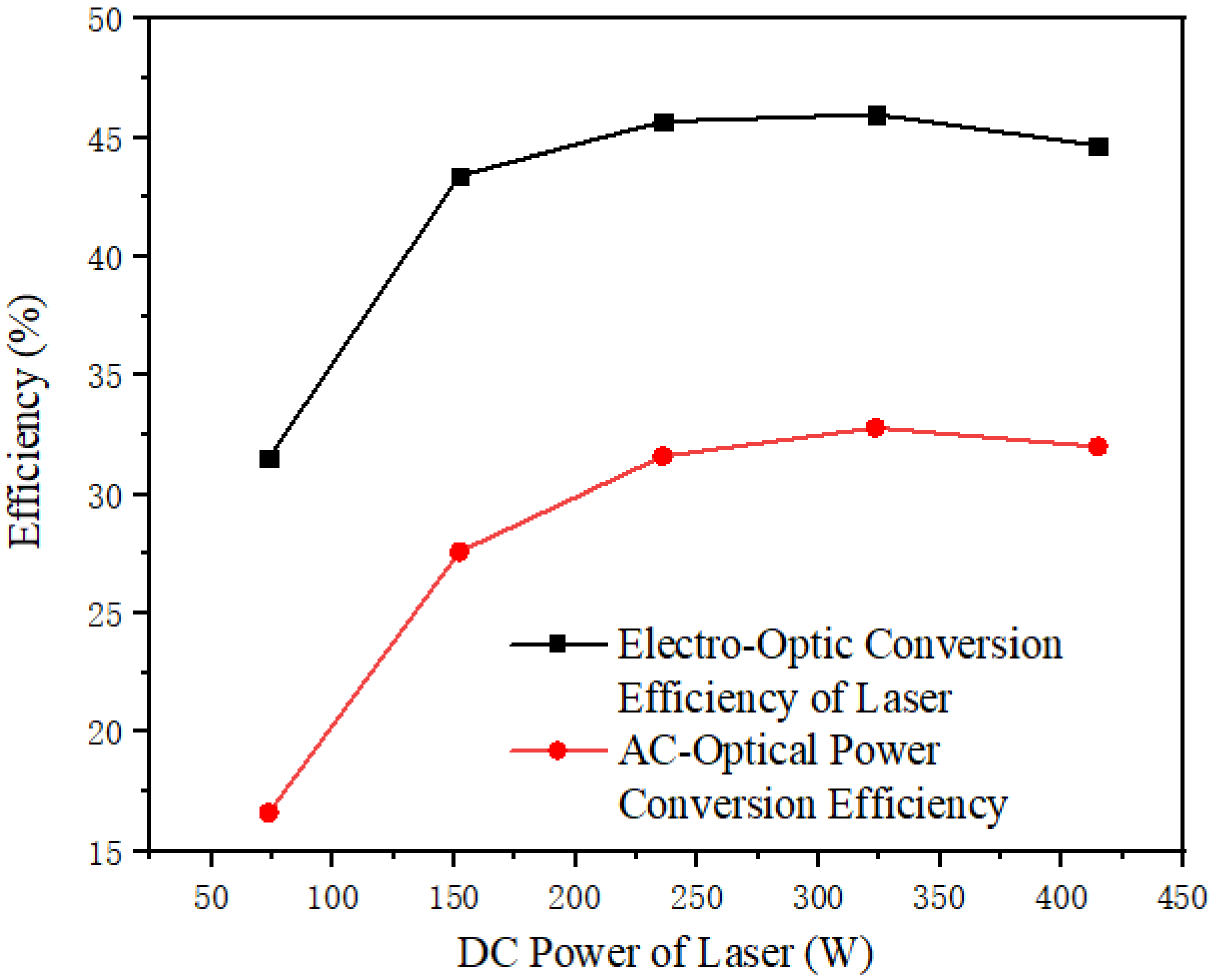


Figure 6

Semiconductor laser conversion efficiency

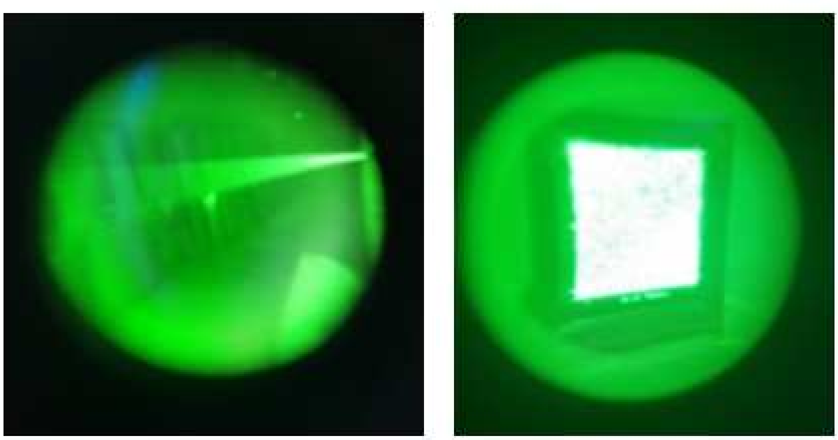


Figure 7

Laser emission beam and receiving end

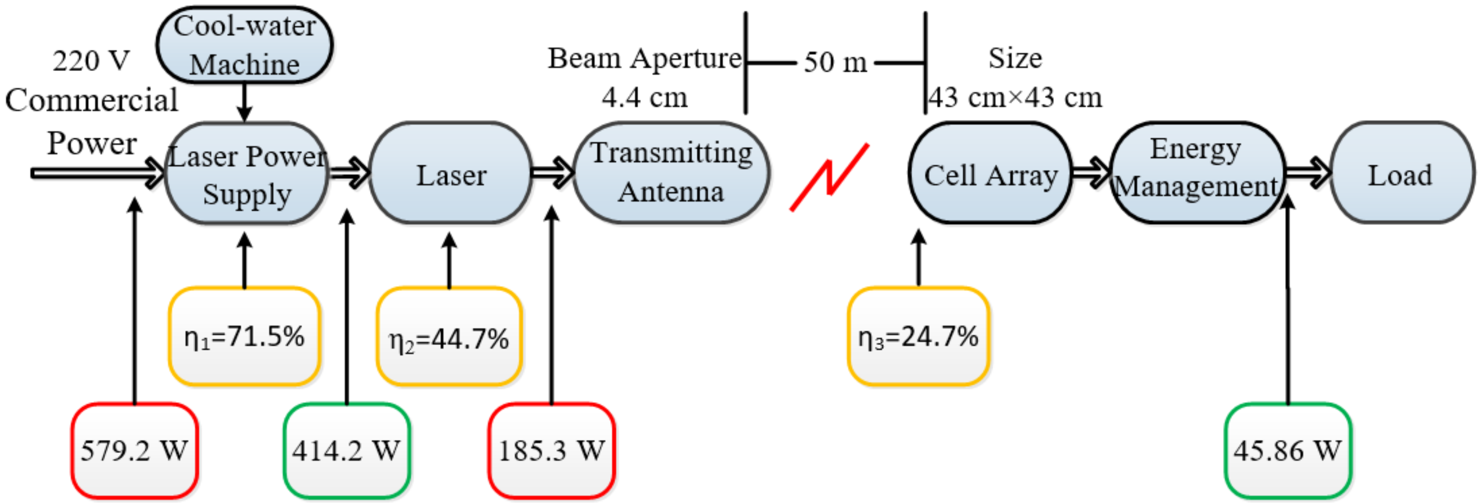


Figure 8

Diagram of the laser-based wireless power transmission system

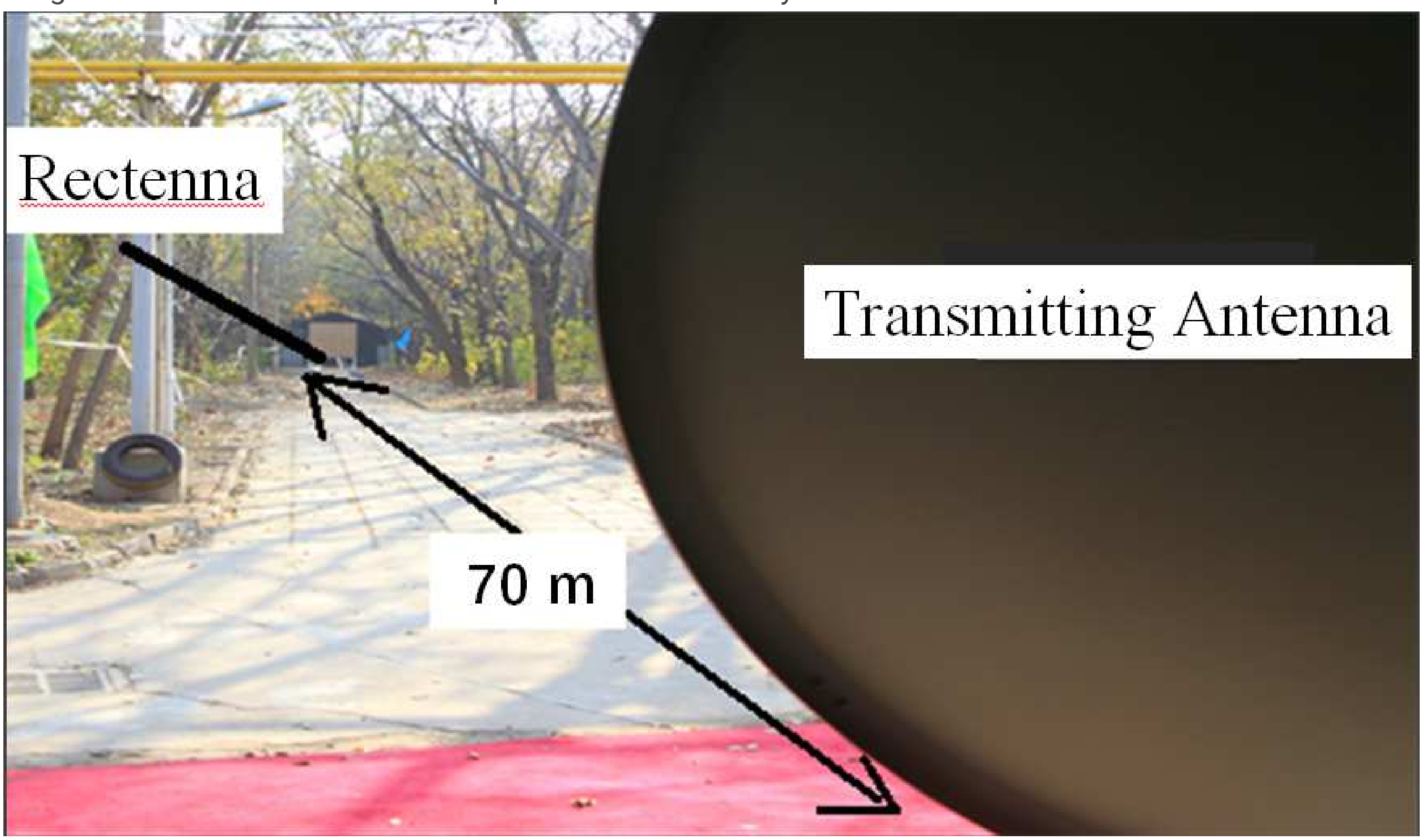


Figure 9

X band microwave transmission system

Figure 10

Rectifier antenna of the receiving end

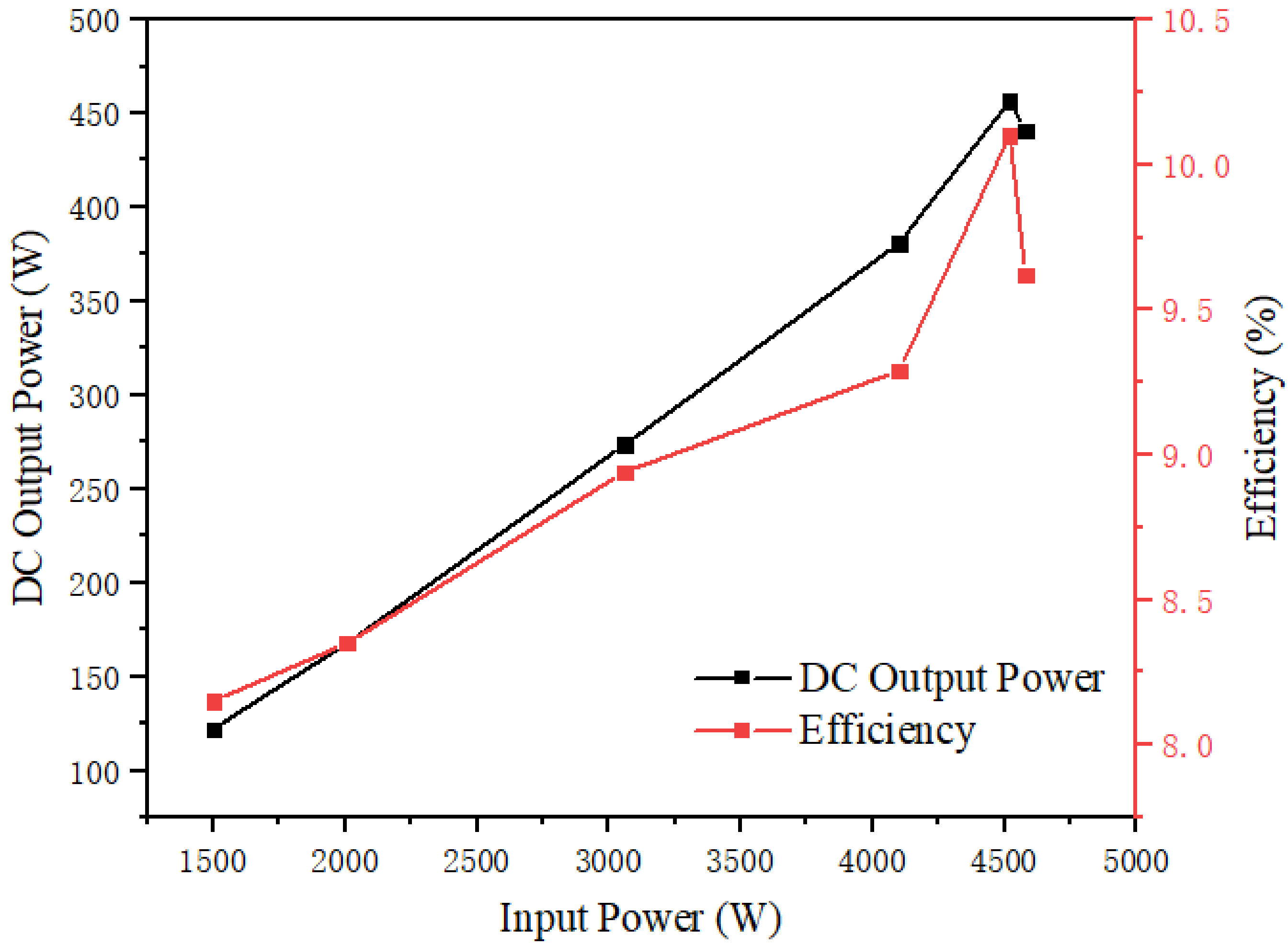


Figure 11

Input-output power conversion results

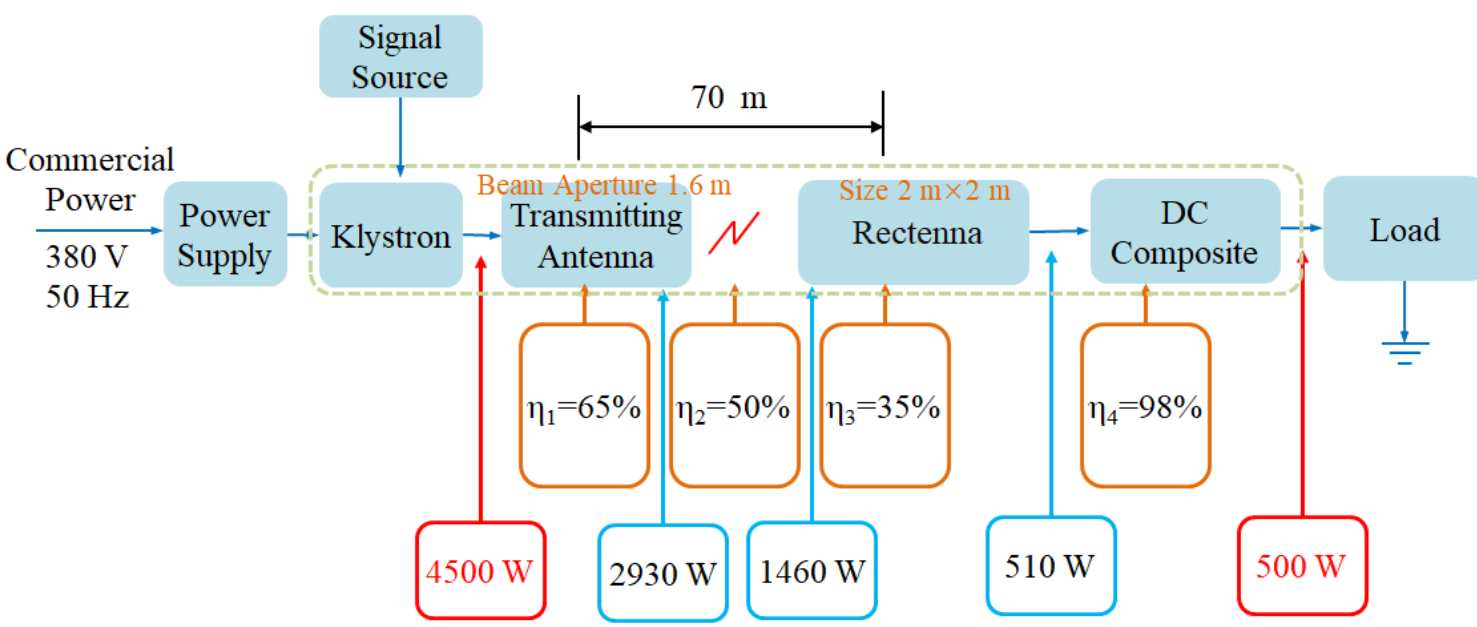


Figure 12

Diagram of the microwave-based power transmission system