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Analysis and Experiment of the Laser Wireless Energy Transmission Efficiency Based on the Receiver of Powersphere

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ABSTRACT Long-distance wireless energy transmission is realized by photoelectric conversion through lasers and photovoltaic cells. However, existing devices have low transmission power and low transmission efficiency. Exploring the main factors that limit the transmission efficiency during transmission is necessary to improve the transmission power and efficiency, and theoretically analyze these factors that affect transmission efficiency, such as beam quality, divergence angle, wavelength and so on. This will provide research directions for subsequent work. A multiwavelength laser wireless energy transmission experimental platform was built by using powersphere, laser with three different wavelengths and other devices. This platform was used for transmission efficiency verification experiment. The total electro-optical-electric conversion efficiency values obtained by the 532, 1030, and 808 nm lasers are 0.01%, 0.08%, and 0.11%, respectively. The corresponding laser-to-electric conversion efficiency values are 1.37%, 1.60%, and 0.73%, respectively. Experimental results show that the electro-optic conversion efficiency of the laser and the photoelectric conversion efficiency of the photovoltaic receiver is the main reasons for the low conversion efficiency of the system. In addition, factors such as the expansion ratio of the beam expander, laser collimation, laser uniformity at the photovoltaic receiver end, and circuit structure, affect the conversion efficiency of the system.

INDEX TERMS Laser, conversion efficiency, wireless energy transmission, photovoltaic.

I. INTRODUCTION

The traditional wired electrical transmission is prone to producing electric sparks due to exposed wires during use, which is unsuitable for flammable and explosive applications. The location of electricity is fixed and is difficult to move, and the mobile use equipment needs to drag long wires to work [1], [2]. These conditions are the limitations reflected in traditional cable transmission. Thus, exploring wireless charging technology and introducing it into people's lives are of great research importance [3]–[8].

Wireless energy transmission technology first started in Long Island Laboratory, New York, USA [9]. This technology can transmit electromagnetic waves through a vacuum or air medium to achieve electrical energy transmission. At present, the commonly used methods of wireless energy transmission are electromagnetic induction, magnetic resonance coupling, microwave, and laser [10]–[16]. Among the four methods, the electromagnetic induction technology and magnetic resonance coupling technology belong to near-field technology. The transmission distance varies from mm to m. This technology can only perform short-distance energy transmission and is not suitable for long-distance use. Microwave and laser belong to remote technology. However, the divergence angle of the microwave is large, the transmitting and receiving devices are very large, and the implementation device is complicated. In high-power applications of several kilowatts, the transmission efficiency is less than 10% [17]–[21]. Wireless energy transmission via laser is a technology that uses the photoelectric conversion of laser

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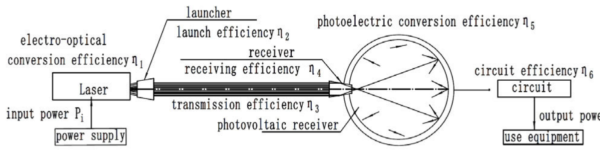


FIGURE 1. Process of wireless energy transmission.

and photovoltaic cells to achieve long-distance and wireless power transmission [22]–[28]. Transmission distance can reach several kilometers. The device used is compact and suitable for mobile applications. When the power is up to several kilowatts of power, the transmission efficiency is higher than that of microwaves (up to approximately 20%). Thus, the long-distance energy transmission via laser is considered to be a promising transmission technology. The aforementioned technology has the characteristics of long transmission distance, high transmission efficiency, and small receiving device. This technology has a unique application value and important application prospect for mobile devices far from the mainland in aviation, aerospace, and navigation and has attracted great attention from researchers in the related fields.

To obtain high conversion efficiency in future engineering applications, the article analyzes several key factors affecting wireless energy transmission via laser, including: The parameters related to electro-optic conversion efficiency, such as laser power, beam quality, divergence angle, spot area, modulation current, and threshold current; the parameters related to launch efficiency, such as the spherical aberration, diffraction, dispersion, and absorption of the beam expander and the alignment deviation of the laser and the beam expander; the parameters related to transmission efficiency, such as extinction coefficient, transmission distance, and light diffusion factor of the medium. The structure of the photovoltaic receiver related to receiving efficiency focuses on the advantages and disadvantages of the powersphere structure, and the factors affect its efficiency, such as injected power, direct radiation area, and power density; the parameters related to photoelectric conversion efficiency, such as material band gap, laser frequency and wavelength, power density, temperature, and other parameters; the global MPPT method relating to circuit efficiency; and the circuit structure of static and dynamic circuits.

To further verify the influence of the parameters on the transmission efficiency, a powersphere was used as the receiver, and the wireless energy transmission via laser experiments with different parameters is carried out. This type of experiment has not been reported. The powersphere receiver can improve the uniformity of light on the photovoltaic receiving surface, thereby reducing the largest loss in wireless energy transmission, that is, the circuit loss caused by the inconsistency of current and voltage, and fundamentally solve the problem of low output power. It is of great significance to improve the transmission efficiency.

II. THEORETICAL ANALYSIS OF THE KEY PARAMETERS

Many factors, such as power supply, laser, transmitting device, receiving device [17], [29], [30], photovoltaic receiver, circuit structure, and use equipment, are involved during wireless energy transmission via laser. In Figure 1, the power supply provides power to the laser, and the laser generates laser. The power consumed by the laser is the input power P_i. The output laser is collimated by the launcher and then transmitted over a long distance to the receiver. The laser is received by the receiver and converted into electricity by the photovoltaic receiver. The generated electricity is outputted by the series and parallel circuits and generates the output power P_o. The ratio between output power Po and input power Pi is the total transmission efficiency of the wireless energy transmission via laser, as shown in Formula (1).

$$\eta_{EE} = \frac{P_o}{P_i}. \tag{1}$$

The factors affecting the efficiency of wireless energy transmission via laser are shown in Figure 1. Electro-optical conversion efficiency η_1 refers to the ratio of the laser power by the laser to the electrical power consumed by the laser. Launch efficiency η_2 refers to the ratio of the laser power before and after the laser is collimated by the launch device. Transmission efficiency η_3 refers to the ratio of the laser power before and after the long-distance transmission of the laser. Receiving efficiency η_4 refers to the ratio of the laser power collected by the receiver and used for photoelectric conversion to the laser power at the receiving end. Photoelectric conversion efficiency η_5 refers to the ratio of the laser power to the electric power before and after the photoelectric conversion of the laser. Circuit efficiency η_6 refers to the ratio of the electric power generated by photovoltaic cells before and after passing through the circuit. Therefore, the total transmission efficiency of the wireless energy transmission via laser is equal to the product of the efficiency of each step, as shown in Formula (2).

$$\eta_{EE} = \frac{P_o}{p_i} = \eta_1\eta_2\eta_3\eta_4\eta_5\eta_6. \tag{2}$$

A. ELECTRO-OPTICAL CONVERSION EFFICIENCY

The laser is the electro-optical conversion device, and it is also the light source in wireless energy transmission via laser. Laser consumes electrical energy to produce light energy that can be used for transmission. The performance, parameters, and efficiency of the laser directly affect the overall efficiency of the entire energy transmission.

With regard to the target at a distance of R meters from the laser, the radiance L(W/sr*m^2) of the laser must satisfy Formula (3) to obtain the irradiation of E(W/m^2) [22]:

$$ER^2 = \eta LS, \tag{3}$$

where S is the total area of the laser spot, and η is the transmission efficiency between the laser output end and the target, which is also equal to $\eta_2^*\eta_3^*\eta_4$.

The relationship between radiance L and the power of the laser (P), the beam quality of the laser, the divergence angle of the laser (Ω), and the wavelength of wavelength (λ) is shown in Formula (4) [22]:

$$L = \frac{P}{\lambda^2 M_x^2 M_y^2} = \frac{P}{S\Omega}, \tag{4}$$

where $M_X^2 M_y^2$ is the beam quality factor for the [x, y] axis.

Substituting Formula (4) into Formula (3) yields Formula (5):

$$E = \frac{\eta LS}{R^2} = \frac{\eta PS}{R^2 \lambda^2 M_x^2 M_y^2} = \frac{\eta P}{R^2 \Omega}. \tag{5}$$

Formula (5) demonstrates that the longer the transmission distance (R), the smaller the irradiation (E) of the target; the higher the power of the laser (p), the greater the irradiation (E) of the target; the better the beam quality, that is, the smaller the value of $M_X^2 M_y^2$, the greater the irradiation (E) of the target; the higher the transmission efficiency (η), the greater the irradiation (E) of the target; the smaller the divergence angle (Ω), the greater the irradiation (E) of the target; the larger the spot area, the greater the irradiation (E) of the target; the beam expansion of the laser increases the spot area and reduces the divergence angle; thus, the irradiation (E) is increased. The above formula fully shows that the parameter performance of the laser affects the conversion efficiency of the system.

In wireless energy transmission via laser, the more the same electric energy is converted into light energy, the higher the conversion efficiency of the laser. The more energy that can be transmitted, and the more energy that can be received after long-distance transmission, the more optical energy can be used for photoelectric conversion. Considering that the device that affects the electro-optical conversion efficiency is only a laser, selecting a laser with a high conversion rate can improve the electro-optical conversion efficiency of the transmission. At present, the lasers with relatively high efficiency mainly include semiconductor and solid-state lasers, and their highest efficiency reaches 60% and 40%, respectively. The selection of lasers needs to consider the volume, weight, and cost factors based on the needs of system integration.

Semiconductor lasers regulate the power of the laser by adjusting the current. The relationship between input current and output power is shown in Formula (6) [31]:

$$p_0 = \eta_d (i - I_{th}), \tag{6}$$

where i is the current of the laser, η_d is the differential slope efficiency of the laser, and I_{th} is the threshold current of the laser.

Formula (6) shows that when the input current is higher than the threshold current, the output power of the laser increases with the increase in the input current.

The input voltage V in a semiconductor laser does not greatly change; thus, the electro-optic conversion efficiency η_1 of the laser can be expressed as follows:

$$\eta_1 = \frac{P_{out}}{P_{in}} = \frac{\eta_d}{V}(1 - \frac{I_{th}}{i}), \tag{7}$$

where P_{out} is the input power of the laser, and P_{in} is the output power of the laser.

Formula (7) shows that the electro-optical conversion efficiency increases with the increase in the input current. When the current is low, the growth rate is relatively large. The growth rate gradually decreases with the current increase. Therefore, for semiconductor lasers, the higher the input current, the lower the threshold current, and the higher the electro-optical conversion efficiency.

B. LAUNCH EFFICIENCY

The laser with Gaussian distribution presents a strong light intensity distribution at the center part and weak at the edge part. This type of laser does not uniformly radiate into space compared with spherical waves, but it is restricted to spread within a certain small launch angle. Unlike spherical waves that uniformly radiate into space, the laser with Gaussian distribution is limited to spread within a certain small launch angle. This laser has excellent directivity, and the energy is concentrated at the center of the beam. In long-distance transmission, the smaller the divergence angle is, the longer the propagation distance, and the smaller the energy loss during propagation. Therefore, reducing the divergence angle of the laser is necessary to increase the transmission distance and minimize the energy loss of laser transmission. The common method used to improve launch efficiency is to collimate and expand the laser through the beam expander, increase the size of the output spot, and reduce the divergence angle. However, the spot size after transmission should not be extremely small. This condition can easily cause the photovoltaic cells on the concentrated part of the laser to burn out, or some photovoltaic cells cannot obtain light and cause voltage difference.

Many factors affect the transmission efficiency of the expanded beam, which can be divided into two categories: The first one is the inherent loss of the beam expander system, such as loss caused by spherical aberration, diffraction, dispersion, absorption, and Fresnel. This loss is reduced by optimizing the design.

The other one is alignment loss, which is caused by the deviation between the optical axis of the laser and the optical axis of the beam expander. The most effective way to reduce this loss is to adjust the positional relationship between the laser and the beam expander to ensure that the laser can achieve optimal output.

For a beam expander with a beam expansion rate of M, the relationship between the waist before and after beam expansion and the divergence angle before and after beam expansion is shown in Formula (8):

$$\mathrm{M} = \frac{\omega_2}{\omega_1} = \frac{\theta_1}{\theta_2} \tag{8}$$

where ω_1, ω_2 are the waist before and after beam expansion, and θ_1, θ_2 are the divergence angles before and after beam expansion.

For laser, its light intensity is expressed as:

$$\mathrm{I}(z,\mathrm{r}) = \mathrm{I}_0 exp^{\left(-\frac{2\mathrm{r}}{\omega^2(\mathrm{z})}\right)} \tag{9}$$

where I(z,r) is the light intensity at z in the propagation direction, I_0 is the initial light intensity, r denotes the curvature radius of the wave front.

Substituting Formula (8) into Formula (9), the intensity of laser after beam expansion is:

$$\mathrm{I}(\mathrm{z},\mathrm{r}) = \mathrm{I}_0 \left(exp^{\left(-\frac{2\mathrm{r}}{\omega_1^2(\mathrm{z})}\right)} \right)^{\frac{1}{\mathrm{M}}} \tag{10}$$

Since the beam expansion rate is greater than 1, it can be seen from Formula (10) that the larger the beam expansion rate, the larger the output spot area, and the smaller the divergence angle, the greater the loss.Specifically, the launch efficiency will decrease with the increase in the beam expansion rate.

C. TRANSMISSION EFFICIENCY

The energy of laser attenuates during long-distance transmission. Many random factors cause laser attenuation. However, the main reason depends on the absorption and scattering of light by the transmission medium. Absorption refers to the process in which light encounters absorbing particles during transmission and converts light energy into other forms of energy. Scattering indicates that light collides with other particles and deviates from the transmission direction during transmission, thereby reducing the light energy in the transmission direction. The media commonly used in wireless energy transmission via laser are air and water. Particles, such as dust, smoke, minerals, and other medium molecules, are found in the air. Accordingly, during the laser transmission in the air, part of the energy is absorbed by the particles or medium, and part of the energy is scattered away from the direction of energy transmission. Water contains various minerals, thereby causing its unevenness. Although the laser divergence angle is the same, the energy attenuation of the laser transmission in water is more serious than that in the air. The attenuation coefficient of laser in impure water varies with the composition of water. The absorption rate of water in lasers of different wavelengths varies. The larger the wavelength or the smaller the wavelength does not indicate greater water absorption rate. However, an optimal wavelength is found. When the wavelength is greater or less than this wavelength, the absorption rate of water decreases. The 532 nm green laser has lower absorption rate and better penetration ability in water compared with the 1064 nm Nd:YAG laser and 10.6 μm CO_2 laser. Thus, this laser is suitable to be used as an underwater energy transmission carrier.

After the laser has been transmitted over a long distance, the irradiation on the target surface is [32]:

$$E = \frac{3.44Pexp(-\varepsilon L)}{\pi L^2(\sigma^2_{diffraction} + \sigma^2_{turbulence} + \sigma^2_{jitter} + \sigma^2_{bloom})}, \tag{11}$$

where P is the power of the laser; L is the distance of the target; ε is the transmission medium extinction coefficient of the beam due to absorption or scattering; and $\sigma_{diffraction}$, $\sigma_{turbulence}$, σ_{jitter}, and $\sigma_{blooming}$ are the beam spreading factors for diffraction, turbulence, beam jitter, and thermal blooming, respectively.

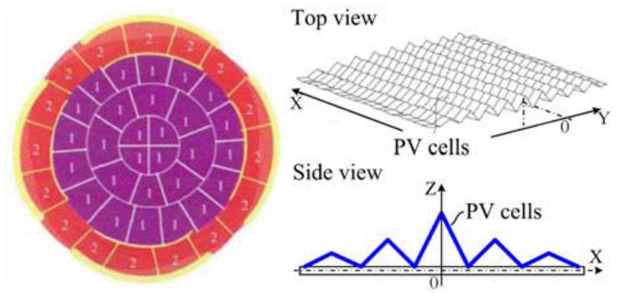
Formula (11) demonstrates that the irradiation on the target surface is related to the power of the laser, the extinction coefficient of the medium, the transmission distance, and the beam spreading factors for diffraction, turbulence, beam jitter, and thermal blooming. The greater the power of the laser, the greater the irradiation; the longer the distance, the smaller the irradiation; The irradiation on the target surface has an exponential relationship with the extinction coefficient, and it has an inverse relationship with the square of the beam spreading factors. Specifically, if the beam spreading factors slightly increase, then irradiation on the target surface will greatly drop.

D. RECEIVING EFFICIENCY

Although the divergence angle of the laser outputted from the transmitting device is small, the spot size at the receiving device is larger after long-distance transmission. The spot diameter is larger than the input diameter of the receiving device. The low energy area can be easily ignored and does not enter the receiving device, thereby causing energy loss. Therefore, considering the size of the receiving device's end face is necessary. This factor mainly involves the divergence angle of the transmitting device and the transmission distance of the laser when designing the receiving device. If the diameter of the receiving end is smaller than the spot diameter, then the transmitted energy is incompletely collected, and loss occurs. If the diameter of the receiving end is extremely large, then the receiving device becomes heavy, thereby affecting installation and use and increasing the difficulty of manufacturing.

The structure of photovoltaic receiver is an important factor affecting the receiving efficiency. In actual use, photovoltaic panels are commonly utilized receivers. The illuminance received at each position of the photovoltaic panel is different due to the Gaussian distribution of the laser; thus, the current of each photovoltaic cell is not equal. This situation makes the photovoltaic cell with low current become a load and consume the generated power, thereby severely reducing the receiving efficiency of the system. With regard to a photovoltaic receiver with a flat panel structure, only the absorbed laser by the photovoltaic cell is converted into electricity, and the rest is lost by reflection from the surface of the photovoltaic cell.

The following three methods are commonly used to improve the conversion efficiency: The first one is to



(a) Radial orientation array (b) Sawtooth configured array

FIGURE 2. Structure of the photovoltaic receiver.

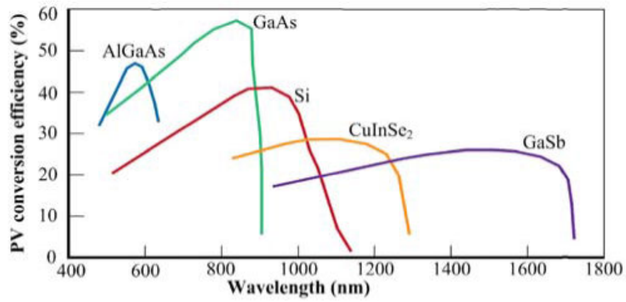


FIGURE 3. Relationship between wavelength and photovoltaic materials.

customize the photovoltaic cells according to the distribution of the laser, as shown in Figure 2(a) [23]. This method will make the output power of each photovoltaic cell equal. However, problems such as high cost and complex combination, exist. The other method is to arrange the photovoltaic cells at different angles according to the distribution of light intensity, as shown in Figure 2(b) [33]. Many lasers cannot be received by the photovoltaic cell due to substantial light reflection, which reduces the transmission efficiency.

The third is a spherical closed photovoltaic receiver, as shown in Figure 1. This structure injects the laser into the sphere and then through multiple reflections in the ball to achieve the uniform of the light, thereby improving the receiving efficiency. In addition, the reflected laser is transmitted to other photovoltaic cells of the photovoltaic receiver, and the laser can be reused to improve the receiving efficiency. Three methods affect the transmission efficiency of this structure: The first one is to inject enough laser energy to ensure that the laser can be continuously reflected in the cavity; the second method is to increase the area of direct radiation of the laser and ensure that each photovoltaic cell can receive direct radiation of the laser; the third method is to increase the density of photovoltaic cells, that is, to reduce the size of photovoltaic cells.

E. PHOTOELECTRIC CONVERSION EFFICIENCY

A photovoltaic receiver is a device that converts light energy into electrical energy. The quality of the receiver directly affects the power output and conversion efficiency of wireless energy transmission via laser. A photovoltaic cell is the basis for manufacturing photovoltaic receiver and is the key and core component for converting laser into DC power. When the laser irradiates the photovoltaic cell, the electric energy can be generated only when the energy of the incident photon is equal to or greater than the material band gap of the photovoltaic cell. The energy of the incident photon is directly proportional to its frequency. Therefore, the photovoltaic cell can produce the highest photoelectric conversion efficiency only when the frequency of the photon matches the energy band gap of the photovoltaic cell. The reciprocal of the frequency of the laser is the wavelength. Therefore, the photovoltaic cell can obtain the maximum power output only when the laser wavelength matches the energy band gap of the photovoltaic cell. The energy band gap and response frequency of the different photovoltaic cells are different. Therefore, the photoelectric current generated by the photovoltaic cell per unit area varies for monochromatic light of different wavelengths although the irradiance is the same.

The relationship between the short-circuit current of the photovoltaic cell and the wavelength is called the spectral response. This response characterizes the photoelectric conversion ability of the photovoltaic cell to light of different wavelengths. Figure 3 shows the relationship between the material of the photovoltaic cell and the laser wavelength tested by Krupke *et al.* in 2003 [34]. The test results show that the 950 nm laser wavelength for commonly used monocrystalline and polycrystalline silicon materials has high conversion efficiency. However, the propagation attenuation of 950 nm wavelength laser in the atmosphere is serious. The corresponding laser wavelength of the photovoltaic cells made of gallium arsenide materials is 808 nm and has a conversion efficiency of more than 50%. Aluminum gallium arsenide, which has a slightly low conversion efficiency, can achieve a conversion efficiency close to 50%, and its corresponding laser wavelength is 532 nm. In addition to the wavelength factor, considering the effect of temperature on the photoelectric conversion efficiency is also necessary, especially when using high-power lasers.

Table 1 lists the best matching wavelengths of different photovoltaic cells and their conversion efficiency [35]. In Table 1, the power density of the incident laser is also one of the factors that affect the photoelectric conversion, in addition to the wavelength. The conversion efficiency increases with the increase in the power density. In addition, the temperature also affects the photoelectric conversion efficiency of photovoltaic cells. The photoelectric efficiency will decrease with the increase in temperature.

The laser photoelectric conversion efficiency can also be estimated from the efficiency under the solar spectrum by using Formula (12) [32]:

$$\eta_5 = \eta_{solar} \frac{P_{solar}}{J_{sc}} (QE) \frac{\lambda}{1240nm} \times \left[1 + \frac{25mV}{V_{OC}} ln \left(QE \frac{\lambda}{1240nm} \frac{\phi}{J_{sc}} \right) \right], \tag{12}$$

TABLE 1. Electro-optical conversion efficiency.

Material	GaAs		Si		InGaAs/InP	InGaP	CIS
Laser Wavelenth (nm)	810		950		> 1000		
Efficiency (%)	53.4	60	27.7	28	40.6	40	19.7
Power intensity (KW/m2)	430	110	10	110	2,37	2.6	10

where η_5 is the photoelectric conversion efficiency of the laser, η_{solar} is the photoelectric conversion efficiency of the solar, P_{solar} is the intensity of the solar, J_{sc} is the short-circuit current density under solar, and V_{oc} is the open-circuit voltage under solar. φ is the intensity of the laser, and QE is the internal quantum efficiency of the wavelength of the laser.

Formula (12) shows that the photoelectric conversion efficiency is related not only to the wavelength of the laser but also to its intensity. The photoelectric conversion efficiency is somehow improved with the intensity of the laser. Formula (12) became invalid only when the intensity of laser is up to a certain limit where the series resistance has become an important factor of efficiency.

F. CIRCUIT EFFICIENCY

The commonly used lithium battery charging voltage is 3.3 V, the charging voltage of lead storage battery is 15 V, and the charging power of standard USB charging interface is 5–10 W. The output voltage of a monolithic photovoltaic cell is approximately 0.5–1V. Accordingly, a monolithic battery cannot meet the power requirements of the load, and a photovoltaic array composed of multiple photovoltaic cells is required to meet the conventional power demand.

The connection methods of photovoltaic cell array mainly include series, parallel, and series–parallel (SP). The advantages of series connection are its simple structure and high output voltage. The disadvantages are that the photocurrent of each photovoltaic cell is different when they are irradiated by uneven light, and the current of the series array is limited to the photovoltaic cell with the smallest photocurrent. The battery with small current consumes other battery energy as a load, resulting in energy loss and ''heat spot effect''. In addition to the simple structure of parallel connection, the photogenerated current is less affected by light unevenness. However, the open circuit voltage of photovoltaic cells has a logarithmic relationship with light intensity, and the output voltage is low, affecting the output power of the photovoltaic array.

At present, the three ways to improve circuit efficiency are as follows: The first one is the global MPPT, that is, the global detection of the maximum power point to obtain the maximum power output; the second one is to change the combination form of the array. The structure of the circuit must be structured according to the light intensity distribution to obtain higher circuit efficiency. The structure can be divided into two types: static and dynamic. The circuit of static structure is fixed, and the commonly used ones are: SP, total cross-tied (TCT), and bridge-linked configurations [36]. In [37], [38], the experimental results show that the efficiency of TCT is higher than that of SP. The biggest advantage of the dynamic structure circuit is that the photovoltaic cells in the circuit can be arbitrarily combined according to the current and voltage; finally, several branches of the same current are obtained. Reference [39] reported that the efficiency of dynamic circuits is 10% higher than that of static circuits. However, the disadvantages of dynamic circuits are complex structure and high cost.

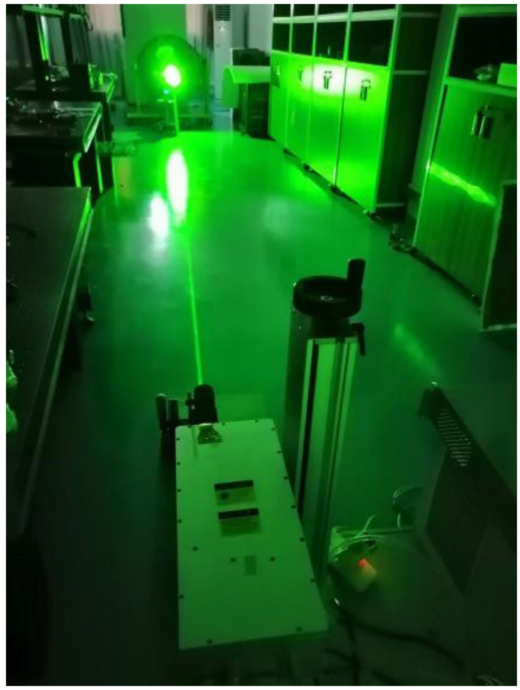


FIGURE 4. Experimental platform.

Therefore, finding the most suitable circuit structure is the best way to improve the circuit efficiency.

III. EXPERIMENTAL RESEARCH ON TRANSMISSION EFFICIENCY

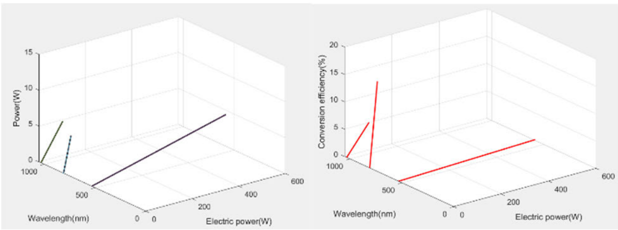
In accordance with the composition shown in Figure 1, single crystal silicon photovoltaic cells, Fresnel lens, beam expander, lifting platform, and 532, 808, and 1030 nm lasers are used to build a laser wireless energy transmission experimental platform with multiple wavelengths. This platform is used to study the transmission efficiency, as shown in Figure 4. In the experiment, the diameters of the 532, 808, and 1030 nm laser spots are 3, 8, and 5 mm, respectively.

A. ELECTRO-OPTICAL CONVERSION

The output power of the three lasers is the same to ensure the comparability of the experiment. The electric power consumed, laser power output, and electro-optical conversion efficiency are shown in Table 2. An electric power metering

(a) Electric power test. (b) Laser power test. (c) Laser power test after beam expansion.

FIGURE 5. Measurement process.



(a) Electrical power, optical power, and wavelength. (b) Electrical power, electro-optical efficiency, and wavelength.

FIGURE 6. Diagram of the relationship between parameters.

socket was used to measure the electric power. The electric power used can be displayed in real time as long as the laser power plug is inserted into the metering socket. A thermopile laser power meter with a wavelength range of 0.19–11 μm was used to measure the laser power. The use of the same laser power meter can reduce the error between different power meters. The measurement process is shown in Figure 5. As shown in the experimental data, the electric power consumed by the frequency doubled laser is 577.5 W when the laser power is approximately 5 W, which is six times that of fiber lasers and 18 times that of semiconductor lasers. The power consumption of the fiber laser is 94.2 W, which is three times that of the semiconductor laser. The power of the semiconductor laser is 32.32 W, and the power consumption is the smallest. The electro-optical conversion efficiency rates of the three lasers are 0.85%, 5.30%, and 15.47%, respectively. The relationship between the parameters is shown in Figure 6. In terms of the principle of laser generation, the 1030 nm laser is produced by 808 nm laser pumping. The 532 nm laser is pumped by the 808 nm laser to generate 1064 nm laser through frequency doubling. The 532 nm laser is obtained by the frequency-doubled 1064 nm laser, and the 1064 nm laser is produced by 808 nm laser pumping. Accordingly, 532 nm>1030 nm>808 nm when the same laser power is generated, which is consistent with the experimental results. Therefore, the semiconductor laser is the most suitable laser for wireless energy transmission in terms of electro-optic conversion efficiency.

B. LAUNCH EFFICIENCY

The loss of laser launch mainly refers to the energy lost by the laser through the beam expander. A 3× beam expander was used for the 532 and 1030 nm lasers, and an 8× beam expander was used for the 808 nm laser due to the large divergence angle. This process was performed in accordance with the parameters, such as laser divergence angle, transmission distance, and incident diameter of the photovoltaic receiver in the experiment. The laser power and divergence angle after beam expansion are shown in Table 3.

As shown in the experimental data, the divergence angle of the laser has a relatively large influence on the laser emission efficiency. If the divergence angle is extremely large, then the edge of the laser diverges out of the transmission optical path after being collimated, thereby causing launch loss. In Table 2, the highest launch efficiency is obtained by the 532 nm laser with 93.50%, followed by the 1030 nm laser with a launch efficiency of 91.00%, and the lowest is the 808 nm semiconductor laser with a launch efficiency of only 86.00%. From the perspective of launch efficiency alone, semiconductor lasers are less suitable for wireless energy transmission via laser than the two other lasers. However, considering the total efficiency of the two stages of electro-optical conversion efficiency and launch efficiency, the 808 nm laser remains the best choice. Therefore, reducing the divergence angle of the laser while maintaining its high electrical-optical conversion efficiency is an important direction for studying wireless energy transmission via laser.

C. TOTAL TRANSMISSION AND RECEIVING EFFICIENCY

Many factors affect the efficiency of laser transmission. Air was used as the transmission medium in the experiment. Under the same conditions, particles, such as dust, smoke, minerals, and other medium molecules in the air, are basically the same. Accordingly, three different wavelength laser contrast experiments were conducted. In the experiment, the spot sizes of the 532 and 1030 nm lasers after the transmission distance of 8700 mm are 90 and 40 mm, respectively. The light spot is larger than the circular detectable range of the power meter with a diameter of 28 mm. The power values measured

TABLE 2. Electro-optical conversion efficiency.

Wavelength (nm)	Electric power (W)	Laser power (W)	Conversion efficiency (%)
532	577.50	4.92	0.85%
1030	94.20	5.00	5.30%
808	32.32	5.00	15.47%

TABLE 3. Laser launch efficiency.

Wavelength (nm)	Expansion rate	Divergence angle after expansion (mrad)	Laser power before expansion (W)	Laser power after expansion (W)	Launch efficiency (%)
532	3	3.45	4.92	4.60	93.50%
1030	3	1.43	5.00	4.55	91.00%
808	8	126.32	5.00	4.30	86.00%

(a) 532 nm laser. (b) 1030 nm laser.

FIGURE 7. Measurement of transmission efficiency and receiving efficiency.

by the power meter is 1.1 and 2 W, as shown in Table 4. The measurement result cannot reflect the laser power after long-distance transmission because all the spot energy cannot be measured. Accordingly, the transmission efficiency cannot be separately measured. A 200 mm × 200 mm square Finier lens was used for focusing to accurately measure the energy lost during transmission, as shown in Figure 7. This lens was also used as the receiver in the device to receive the maximum energy transmitted. The measurable laser power after focusing is shown in Table 3. The total transmission and receiving efficiency values of the 532 and 1030 nm lasers are relatively close, which are 86.96% and 85.71%, respectively, and they consume approximately 15% of energy.

The divergence angle of the 808 nm laser is extremely large. The power meter cannot basically measure the laser power when the transmission distance exceeds 1000 mm. The laser power after focusing is only 0.5 W. This condition is because the spot size is larger than the Finier lens size. A transmission distance of 500 mm was used in the experiment for a better comparison with the two other lasers. The laser power that the power meter can measure before focusing is 0.2 W. Meanwhile, the laser power that the power meter can measure after focusing is 2.3 W. The transmission and receiving efficiency rate is 53.49%. The experimental data show that the divergence angle of the laser, especially the divergence angle after the laser beam expands, has a great influence on long-distance laser transmission. The laser with extremely large divergence angle cannot be used in wireless energy transmission via laser. If the divergence angle is extremely small, then the spot transmitted over a long distance is small. Other measures may be required to increase the spot size to ensure that the laser can irradiate all photovoltaic cells.

In order to better compare the conversion efficiency of the three wavelengths at the same distance, the data of 532nm and 1030nm at the distance of 500mm are measured, as shown in Table 4. In the experiment, the output power of the 532nm and 1030 lasers were 4W and 5W respectively. In Table 4, although the output power of 532nm under 8700mm and 500mm is different, the efficiency of beam expansion is basically the same, 92% and 92.75% respectively, so it has little effect on the experimental comparison. Since the spot diameter of 532nm and 1030nm at 500mm is smaller than

TABLE 4. Transmission and receiving efficiency.

Wavelength (nm)	Transmission distance (mm)	Power after beam expansion (W)	Power before focusing (W)	Power after focusing (W)	Transmission and receiving efficiency (%)
532	8700	4.60	1.10	4.00	86.96%
1030	8700	4.55	2.00	3.90	85.71%
808	500	4.30	0.20	2.30	53.49%
532	500	3.71	3.61	3.25	87.60%
1030	500	4.45	4.39	3.89	87.42%

(a) Inside of the power sphere. (b) Outside of the powersphere.

FIGURE 8. Photovoltaic receiver.

the detection surface diameter of the power meter, the laser power at 500mm can be measured without focusing. However, the spot diameter at 8700 is larger than the diameter of the detection surface, so the measured value without focusing will be smaller than the actual value. It can be seen from the data in Table 4 that the power after focusing is less than before focusing, indicating that the focusing lens has also caused the loss of transmission energy, and the loss rate is about 10%. As the transmission distance decreases, the transmission and reception efficiency increases, but the increase is not significant. At the same distance, the efficiency of 532nm and 1030nm is almost the same, but both are much higher than that of 808nm.

D. PHOTOELECTRIC CONVERSION EFFICIENCY

In the experiment, more than 7000 20 mm×20 mm monocrystalline silicon cells were spliced into a closed hollow spherical photovoltaic receiver with a diameter of 1000 mm, as shown in Figure 8. The light-receiving surface of the photovoltaic cell faces the inside of the sphere and is used for photoelectric conversion of the input laser light, as shown in Figure 8(a). A hole with a diameter of 100 mm was opened on the end of the sphere for the incidence of laser light, as shown in Figure 8(b).

The circuit structure causes losses. The power of each branch before the final parallel connection is measured in the experiment. The power obtained by adding the power of each branch is taken as the total power after photoelectric conversion. In the experiment, the 1030 nm laser obtains the largest electric power of 86.68 mW, followed by the green laser with 81.64 mW of electric power; the photoelectric conversion

TABLE 5. Photoelectric conversion efficiency.

Wavelength (nm)	Power before focusing (W)	Output electric power (mW)	Conversion efficiency (%)
532	4.00	81.64	2.04%
1030	3.90	86.68	2.22%
808	4.30	39.79	0.93%

efficiency between them reaches 2.22% and 2.04%, respectively. The difference in conversion efficiency between the two wavelength lasers is mainly that the silicon cell's spectral response to the 532 nm laser is lower than that of the 1030 nm laser.

In the experiment, the 808 nm laser achieves 0.01 W because it is seriously attenuated when it is transmitted to the 1000 mm and is only 0.5 W after focusing. Accordingly, the output end of the 808 nm laser is placed at the entrance of the photovoltaic receiver, that is, the transmission distance is 0 mm. The experimental data are shown in Table 5. The input laser power is 4.3 W, the obtained electric power is 39.79 mW, and the conversion efficiency is 0.93%, which is lower than the two other lasers. This condition is mainly because the divergence angle of the laser is extremely large. After the laser is transmitted to 1000 mm, the laser power in many positions is lower than the threshold of the photovoltaic cell, and the photovoltaic cell at this position cannot output photogenerated current. Therefore, a certain laser power must be guaranteed during the photoelectric conversion to obtain high photoelectric conversion efficiency. The use of monocrystalline silicon photovoltaic cells with low photoelectric conversion efficiency to form the receiving device affects the overall efficiency of the equipment.

E. CIRCUIT EFFICIENCY

In the experiment, the photovoltaic receiver uses a three-stage circuit structure. The first stage uses 10 photovoltaic cells in series to increase the output voltage. The maximum output voltage is 5 V. In the second stage, 10 groups of first-stage branches are connected in parallel to ensure that the current of the parallel branches can be added to increase the output current. The third-stage circuit connects all eight groups of secondary branches in parallel to form an output, as shown in Figure 9. Some secondary circuits in the actual circuit have not reached 10 groups in parallel because the photovoltaic cells are less than 8000, and only nine parallel circuits are found.

In the experiment, the output voltage and current of eight groups of the second-stage branches were measured, as shown in Table 6. The total power values of the 532, 1030, and 808 nm second-stage branches through calculation are 81.64, 86.68, and 39.79 mW, respectively. The voltage, current, and power comparison charts of each wavelength are shown in Figure 10 in accordance with the voltage, current,

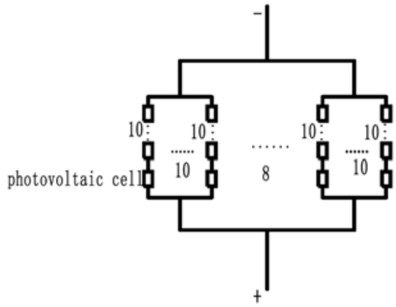


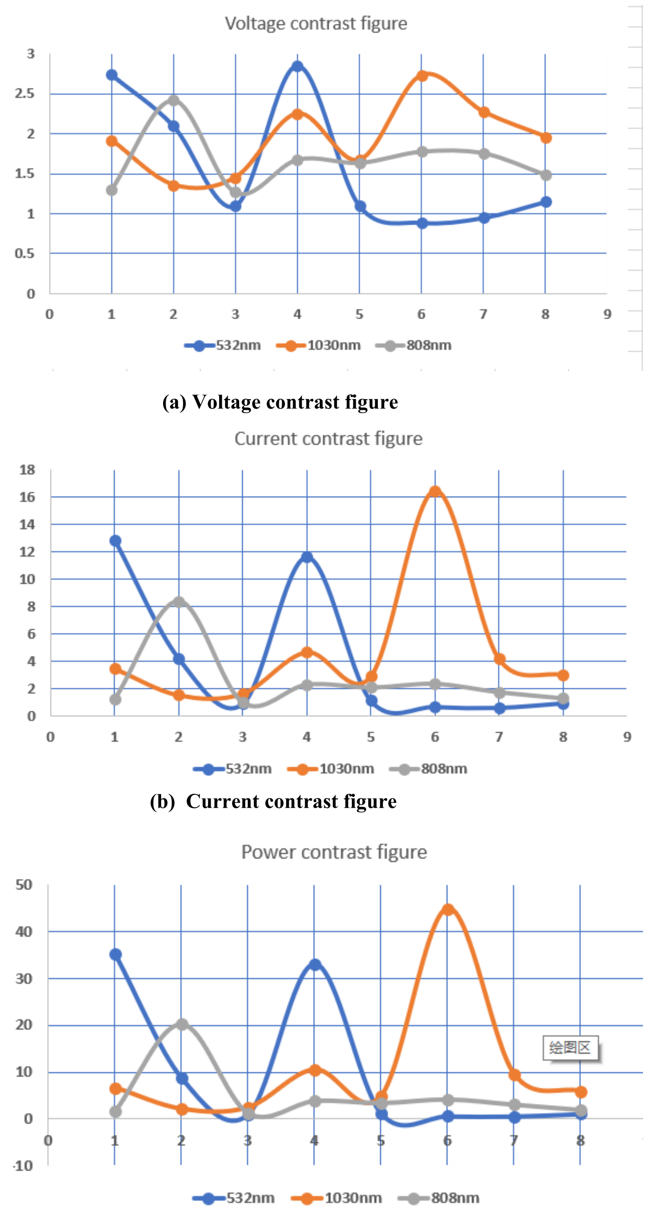
FIGURE 9. Circuit structure diagram.

TABLE 6. Current, voltage, and power of the secondary branch.

Area	532 nm	1030 nm	808 nm	532 nm	1030 nm	808 nm	532 nm	1030 nm	808 nm
	Voltage (V)			Current (mA)			Power (mW)		
1	2.74	1.92	1.30	12.87	3.45	1.27	35.264	6.624	1.651
2	2.10	1.36	2.42	4.20	1.52	8.38	8.820	2.067	20.280
3	1.10	1.45	1.27	0.89	1.64	1.00	0.979	2.378	1.270
4	2.85	2.25	1.68	11.62	4.66	2.30	33.117	10.485	3.864
5	1.10	1.67	1.64	1.12	2.90	2.09	1.232	4.843	3.428
6	0.89	2.73	1.78	0.66	16.45	2.36	0.587	44.909	4.201
7	0.95	2.27	1.76	0.60	4.19	1.75	0.570	9.511	3.080
8	1.15	1.96	1.49	0.93	2.99	1.31	1.070	5.860	1.952

and power data in Table 6. Two maximums and five minimums are found in the voltage, current, and power graphs under 532 nm laser irradiation, and only one value is found in the middle position. Under 1030 nm laser irradiation, the current and power have a maximum value, and the voltage has two maximum values. In comparison with 532 nm laser irradiation, the gap between other values and the maximum value becomes smaller. A maximum value is found under 808 nm laser irradiation; however, the gap between the maximum value and the other values is reduced. Figure 8 shows that the 808 nm laser relatively uniformly irradiates all the cells of the photovoltaic receiver. The 1030 nm laser has two irradiation areas with high light intensity, and the other areas are relatively uniform. The 532 nm laser has two areas with high light intensity, and the light intensity of the other areas rapidly drops.

Table 6 illustrates that the total power of the second-stage branch of 532, 1030, and 808 nm can be calculated. This value and the measured power value of the third-stage branch are listed in Table 7. The experimental data show that all the second-stage circuits are higher than the third-stage circuits. This condition is mainly because different photovoltaic cells receive different light intensities, causing the branch with low voltage to become a load and consume energy. The output power values of the second-stage and third-stage circuits of the 1030 nm laser are 81.64 and 78.75 mW, respectively, which are greater than the two other laser wavelengths. However, the circuit conversion efficiency of the 1030 nm laser is slightly lower than that of the 808 nm laser, which is 90.85%.



(a) Voltage contrast figure

(b) Current contrast figure

(c) Power contrast figure

FIGURE 10. **Comparison of voltage, current, and power.**

This condition is because of the lower optical uniformity of the 1030 nm laser than that of the 808 nm laser. The 532 nm second-stage circuit is 81.64 mW, the third-stage circuit after paralleling obtains 64.41 mW, and the conversion efficiency is 82.56%. This value is lower than the two wavelength lasers. The power outputs of the second-stage and third-stage circuits of the 808 nm laser are 39.79 and 36.11 mW, respectively, and the circuit conversion efficiency is up to 90.91%. If the position of the laser is close to the spherical position, then the output power increases. Improving the uniformity of laser is an effective way to enhance the conversion efficiency of the circuit.

The conversion efficiency of each stage of wireless energy transmission via laser is shown in Table 8. The corresponding graphical representation is shown in Figure 11. The 808 nm laser power irradiated to the photovoltaic cell after the long-distance transmission cannot be measured. The ratio of electrical power to launch power is used as the 808 nm laser's photoelectric conversion efficiency. Therefore, 53.49% of the 808nm laser's transmission efficiency value in Table 8 is not substituted into the calculation of the total efficiency and laser-electric total efficiency and does not affect the calculation of the total efficiency value.

TABLE 7. **Circuit conversion efficiency.**

Wavelength (nm)	Output power of the second-stage circuit (mW)	Output power of the third-stage circuit (mW)	Circuit conversion efficiency (%)
532	81.64	64.41	82.56%
1030	86.68	78.75	90.85%
808	39.79	36.11	90.91%

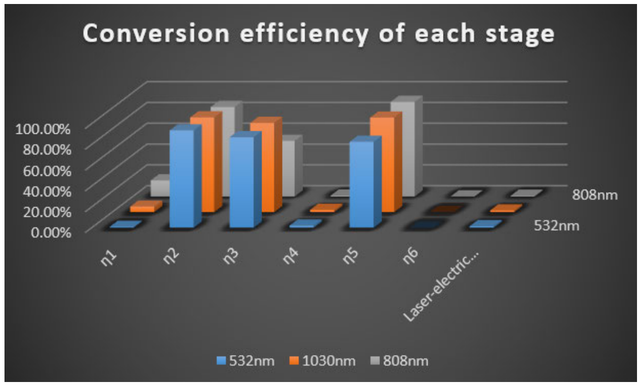


FIGURE 11. **Efficiency of each stage.**

Table 8 illustrates that the total efficiency of electrical–optical–electrical conversion of the 532 nm laser is the lowest, which is only 0.01%. This condition is because the electro-optical conversion efficiency of the 532 nm laser is only 0.85%, which is 1–2 orders of magnitude lower than fiber and semiconductor lasers. The total efficiency of the 1030 laser is 0.08%. The total efficiency of electrical–optical–electrical conversion of the 1030 laser ranks second, which is 0.08%. This condition is because the low electro-optical efficiency of the 1030 laser affects the total efficiency of wireless energy transmission via laser. Therefore, the laser generated by multiple pumps during laser energy transmission should not be used as a light source. Among the three types of lasers, the total conversion efficiency of the 808 nm laser is the highest, which is 0.11%. This condition is mainly because this laser has the highest electro-optic efficiency. However, the total efficiency is not improved due to the large divergence angle and large transmission loss of this laser when its electro-optical efficiency is considerably greater than the two other lasers. In terms of transmission loss, the laser-electric conversion efficiency is the lowest, which

TABLE 8. Conversion efficiency of each stage.

Wavelength (nm)	Electro-optical efficiency (%)	Launch efficiency (%)	Transmission and receiving efficiency (%)	Photoelectric efficiency (%)	Circuit efficiency (%)	Total efficiency (%)	Laser-electric total efficiency (%)
532	0.85%	93.50%	86.96%	2.04%	82.56%	0.01%	1.37%
1030	5.30%	91.00%	85.71%	2.22%	90.85%	0.08%	1.60%
808	15.47%	86.00%	53.49%	0.93%	90.91%	0.11%	0.73%

is only 0.73%. The improvement method is to increase the beam expansion ratio to ensure that the divergence angle is significantly reduced, thereby minimizing transmission loss.

The electro-optical conversion efficiency and photoelectric conversion efficiency are two important links that affect the efficiency of laser wireless energy transmission. The photoelectric conversion efficiency of monocrystalline silicon is approximately 17%. Meanwhile, the photoelectric conversion efficiency measured in the experiment is approximately 2%.

The laser power in the experiment is only 5 W, and 7000 photovoltaic cells are irradiated. The acceptable light intensity of a single photovoltaic cell is only 0.07 mW, that is, 1.79 W/m^2. This value is smaller than the standard test value of 1000 W/m^2 for photovoltaic cells. Accordingly, the photovoltaic cell does not reach the saturation state of light intensity, and the conversion efficiency can still be improved. Therefore, increasing the laser power can increase the photoelectric efficiency, thereby increasing the overall conversion efficiency. The use of photovoltaic cells with high photoelectric conversion efficiency inevitably increases the overall conversion efficiency. These conditions need to be proven in future experiments.

IV. CONCLUSION

The influence of key technologies and parameters of wireless energy transmission via laser on the efficiency of electricity transmission is theoretically analyzed. A verification experiment platform is built using photovoltaic cells, Fresnel lenses, beam expanders, and lasers. The key parameters and conversion efficiency of the device are measured. The laser-electricity conversion efficiency rates of the 532, 1030, and 808 nm lasers are 1.37%, 1.60%, and 0.73%, and the corresponding electrical–optical–electrical efficiency values are 0.01%, 0.08%, and 0.11%, respectively. The experimental results show that the electro-optic conversion efficiency and photoelectric conversion efficiency are the main reasons for the low conversion efficiency of the wireless energy transmission via laser. The main solution is to use a nonpumped laser with high electro-optical conversion efficiency as a light source and high-photoelectric conversion efficiency photovoltaic cells to form the receiver. The laser distribution per unit area is improved, thereby enabling the photovoltaic cell to reach its highest conversion efficiency.

In addition to the above-mentioned two factors, the beam expansion ratio of the beam expander affects the launch efficiency. The divergence angle of the laser affects the transmission efficiency of the laser in the transmission medium. The light uniformity at the receiving end affects the circuit efficiency of the device. The collimation of the laser and the uniformity of light at the receiving end are the two contradictory factors and need to be weighed in actual work.

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