Beam collimation scheme of laser wireless power supply system for high potential monitoring node of power transmission and transformation

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Abstract: Laser wireless power supply technology has the advantages of high energy density, good directionality, small transmitting and receiving aperture, convenient and flexible installation and deployment. It is very suitable for power supply for sensors or mobile electrical equipment in complex high potential environment, such as patrol UAV. Because the beam quality of high-power semiconductor laser is far worse than that of other types of lasers, when it is used as the transmitter of beam shaping system, it must be equipped with corresponding beam shaping system to obtain laser beam with uniform spot, appropriate size and small divergence angle, so as to ensure that the photoelectric cell module has high conversion efficiency and meet the needs of long-distance laser transmission. In this paper, a beam collimation scheme based on aspheric lens group is designed, which integrates optical devices with low cost, reduces the energy loss in the process of laser transmission, and obtains laser beam with certain intensity uniformity. The test shows that the collimator can better meet the parameter requirements of the collimation system.

1. Preface
In recent years, with the rapid development of smart grid and power system automation, the application of intelligent electronic devices and sensors for real-time monitoring of medium and high voltage power equipment is becoming increasingly important. In order to accurately monitor a variety of physical quantities of electrical equipment, a large number of various types of sensor nodes will be densely distributed in the area to be measured. Wireless sensor nodes used in transmission line monitoring system are generally composed of four modules, including sensing module, data processing module, wireless communication module and power supply module. Sensors and electronic equipment are generally powered by batteries, but in the complex working environment of medium and high voltage electrical equipment, the energy of sensor nodes is usually supplemented by manually replacing batteries, which greatly limits the operation and use of these devices, and the cost is also very huge. Therefore, in
order to ensure the stable and efficient work of the monitoring device, the problem of power supply for the monitoring sensor needs to be solved\textsuperscript{[1]}. Energy acquisition of sensor equipment can be divided into three categories: battery power supply mode which needs to be replaced regularly, local energy acquisition mode and low-voltage power supply mode. Local energy collection includes solar energy and many kinds of micro source energy collection technologies, such as vibration, temperature difference, wind energy, etc. low voltage power supply includes electromagnetic induction technology, magnetic resonance coupling technology, microwave technology, laser technology, etc.\textsuperscript{[2]} Laser wireless power transmission technology has the advantages of high energy density, good directivity, small transmitting and receiving aperture (only 10% of the microwave radio power transmission system), convenient installation and flexible deployment. It can be used as a separate power supply module, and can also be used as a composite module in the multi-source energy acquisition mode.

In this paper, focusing on the laser wireless power supply beam collimating radiation technology, a beam shaping scheme based on aspheric lens group is proposed to obtain the laser beam with uniform spot, appropriate size and small divergence angle, so as to ensure the high conversion efficiency of photocell module and meet the needs of laser remote transmission.

2. Semiconductor laser in laser energy transfer system

Laser wireless energy transmission technology includes laser emission, laser transmission, laser receiving (optical electric conversion) and many other links, as shown in Fig 1. In order to achieve long-distance and efficient energy transmission, it is necessary to find out the main factors affecting the efficiency of energy transmission and take effective measures to improve the efficiency of energy transmission.

![Fig 1. Laser wireless power supply system architecture](image)

Considering the efficient use of electro-optic energy conversion of laser and the matching of laser wavelength with the best conversion wavelength of photocell, the high-power semiconductor laser with 808nm output wavelength is adopted in this paper. The advantages of this kind of laser are low price, high electro-optic conversion efficiency, high output power, and good matching of laser wavelength with the best conversion wavelength of GaAs, Si based semiconductor photocell.\textsuperscript{[3]} However, due to its large divergence angle and poor uniformity of light intensity, it cannot be directly applied to remote energy transmission.

There is no essential difference between the working principle of semiconductor laser and that of other lasers. The core basis is the excited light radiation. The basic structure of LD includes P-region, N-region and active region, and the common excitation methods can be divided into current injection, electron beam injection and optical pump injection. The basic structure of current excited semiconductor laser is shown in Fig 2.
The light field distribution of LD output beam is generally divided into near field and far field. The near-field distribution refers to the beam intensity distribution in the vicinity of the laser exit surface (the distance from the exit surface is about equal to the beam wavelength); the far-field distribution refers to the beam intensity distribution at the distance from the laser exit surface (far greater than the beam wavelength, \(d \gg \lambda\)). The far-field and near-field beam characteristics of semiconductor lasers are shown in Fig 3.

3. Beam collimation Technology

1. Light wave catheter shaping

The principle of light wave tube is to reflect the light with different incident angles in the tube for different times, divide it into several parts in the tube, and transmit it to the output end. After the light is superimposed and mixed at the output port, uniform laser intensity distribution can be obtained. The different incident angles of light are obtained by focusing the lens.

2. Micro-lens array shaping

Micro-lens array method is based on the input wave-front segmentation of laser beam by micro-lens array. Each segmented wave-front is superimposed on the focal plane of the subsequent optical system to obtain the spot with uniform intensity distribution, that is, the process of differentiation before integration.\[4\]
The advantages of micro-lens array shaping are small volume and good homogenization effect, but the disadvantages are large energy dissipation of laser beam.

3) Multi surface lens group shaping

The multi curved lens group refers to the lens group that cut the free-form lens and assembled to meet the requirements of shaping[6]. The advantages of multi curved lens group shaping are simple structure and ideal energy transmittance, but the disadvantages are high production cost and lens splicing will bring uniformity problems.

The above laser collimation technologies have their own advantages and disadvantages, but for the laser beam needed for power supply, they all have disadvantages that cannot be ignored, that is, large energy dissipation or uneven spot, which will lead to the increase of heating and the decrease of efficiency of the whole system. In order to meet the needs of power supply laser, according to the specific situation of the experimental laser, the laser spot must be homogenized on the basis of reducing the optical components, and the aspheric lens group should be considered for laser shaping.

4. beam collimation technology based on aspheric lens group

Aspherical lens group shaping system is usually composed of two aspherical lenses. Compared with the collimating technology mentioned above, although the laser beam is shaped by geometric optics, it has the following obvious advantages: 1) there are only two pieces of optical devices, so the structure is simple and easy to realize; 2) there are few reflecting surfaces in the laser optical path, which can effectively reduce the loss; 3) in order to ensure the quality of the laser beam Under the premise of lens quality, the uniformity of light spot is high enough to meet the requirements of the system.

Considering the flexibility of the laser wireless energy transmission system, the laser shaping device must be able to be integrated into a smaller device. The output light of ldm-3v-75a-bds semiconductor through optical fiber is shaped by aspheric lens[7]. The shaped laser beam with circular shape, small energy loss, beam divergence angle within 10 mrad and uniformity not less than 60% is obtained.

4.1 structure design of beam shaping system

Through the analysis of the characteristic parameters of the laser beam obtained from the experimental measurement, it can be seen that the laser beam emitted by the fiber coupling is Gaussian beam. The complex amplitude of the Gaussian beam satisfies the Gaussian function distribution.

\[ I(r) = \frac{2}{\pi \omega_0^2} \exp \left( -\frac{2r^2}{\omega_0^2} \right) \]  

(1)

Where \( \omega_0 \) is the frequency of the outgoing laser and \( r \) is the radius of the laser beam. It can be seen that the center energy of the laser beam coupled by the fiber is the largest, and the energy decreases geometrically with the increase of the beam radius, which is very disadvantageous for laser wireless energy transmission. When the beam energy is very high, it may directly lead to overheating of the irradiated optical elements, or even permanent damage. Therefore, the energy of the coupled beam must be homogenized.

Due to the high energy of the laser beam used in the experiment, in order to ensure the safety, we should try to avoid the light spots with too concentrated energy. Because the laser beam shaped by aspheric mirror system is flat topped beam, and its spatial distribution conforms to Fermi Dirac function, the intensity distribution at \( z=\theta \) in cylindrical coordinates is as follows:

\[ I(r) = I_0 \left[ 1 + \exp \left( \beta \left( \frac{r}{R_0} - 1 \right) \right) \right]^{-1} \]  

(2)

Where \( r \) is the radius of the Fermi Dirac beam, \( I_0 \) is the intensity value on the beam axis, \( R_0 \) is the beam radius when the intensity attenuation is half of the maximum, \( \beta \) is the ratio of \( R_0 \) and \( W \), and \( W \) is the decreasing index of the intensity. It can be seen that the intensity of flat topped beam is the
strongest on the central axis, and the weaker the light intensity is, and the degree of attenuation is determined by $\beta$ and $R_0$.

In order to get the intensity distribution of flat topped beam, we normalize the formula and get the expression of $I_0$.

$$I_0 = \frac{1}{2\pi \int_0^\infty \frac{r}{1+\exp \left( \beta \left( \frac{r}{R_0} - 1 \right) \right)} dr}$$  \hspace{1cm} (3)

It can be seen that the light intensity at any point in the flat topped beam is inversely proportional to its distance from the central axis. In order to ensure the safety of the experiment, and considering the size of the shaping system, the Galileo aspheric lens group was selected. Galileo aspheric lens group consists of an aspheric concave lens and an aspheric convex lens, as shown in Figure 4.

**Fig 4.** Galileo aspheric lens set

4.2 numerical calculation of beam shaping system

Because the aspheric lens does not have the concept of focal length, it cannot simulate such a lens directly in ZEMAX, but can only be constructed by numerical fitting.

First of all, it is assumed that the laser emitted by the laser is strictly monochromatic light, the wavelength is $\lambda$, the propagation direction of the beam is parallel to the z-axis, and satisfies the axisymmetric distribution. Two aspherical mirrors are selected as one plane and the other is aspherical. Then the cylindrical coordinates are established along the beam propagation direction, and the coordinates of any point on the two aspheric lenses can be obtained by using the coordinates $(r, z)$ and $(R, Z)$. Deflection curves $z(r)$ and $Z(R)$ are established to describe the shape of aspheric side of two lenses. The relation between $r$ and $R$ is $R=k(r)$, where $z>0$. Neglecting the absorption of the beam energy by the lens group and the scattering of the laser energy by the air, the total energy of the laser beam before passing through the beam shaping system must be equal to the total energy after passing through the beam shaping system according to the law of conservation of energy

$$2\pi \int_0^r f(x)dx = 2\pi \int_0^R g(x)dx$$  \hspace{1cm} (4)

Where $f(x)$ is the intensity distribution function of the beam before passing through the shaping system, and $g(x)$ is the intensity distribution function of the beam after passing through the shaping system. In this experiment, the beam before shaping system is Gaussian beam coupled by fiber. So the expression of $f(x)$ is:

$$f(x) = \frac{2}{\pi \omega_0^2} \exp \left( -\frac{2x^2}{\omega_0^2} \right)$$  \hspace{1cm} (5)

According to the formula, the expression of $g(x)$ is as follows:

$$g(x) = g_0 \left\{ 1 + \exp \left( \beta \left( \frac{x}{R_0} - 1 \right) \right) \right\}^{-1}$$  \hspace{1cm} (6)

Where $g_0$ can be expressed as:
According to geometrical optics, the intensity of the beam will decrease with the increase of the propagation distance, but it cannot be negative. Therefore, the values of $f(x)$ and $g(x)$ are greater than zero and monotonically decreasing, so for any value $R$, there must be a corresponding numerical solution $R$, and when $r > 0$, there must be $R > 0$. When it is brought into the formula, we can get:

$$\frac{dR}{dr} = \frac{2r}{\pi \omega_0^2 g_0 R} \exp\left\{-\frac{2x^2}{\alpha_0^2}\right\} \left[1 + \exp\left\{\beta \left(\frac{x}{R_0} - 1\right)\right\}\right]$$  \hspace{1cm} (8)

Using MATLAB software to solve this equation, we know that the function $R = k(r)$ has no analytical solution, only numerical solution. The surface functions of two aspheric lenses are obtained.

$$z(r) = \int_0^r \left(n^2 - 1\right)^{-1/2} \left\{(n-1)d\right\}^2 dx \hspace{1cm} \text{(9)}$$

$$Z(R) = \int_0^R \left(n^2 - 1\right)^{-1/2} \left\{(n-1)d\right\}^2 dx \hspace{1cm} \text{(10)}$$

Where $n$ is the refractive index of two aspheric lenses, $D$ is the distance between the center points of two aspheric lenses, and $k^{-1}(x)$ is the inverse function of $k(x)$. Then the numerical solutions of $R = k(r)$ and $r = k^{-1}(x)$ are brought into the formula, and the corresponding numerical solutions of the curves $z(r)$ and $z(R)$ can be obtained.

4.3 ZEMAX simulation of beam shaping

In ZEMAX software, even fitting method is usually used to fit aspheric mirror. Even degree fitting equation can be expressed as follows:

$$z = \frac{cr^2}{1 + \sqrt{1 - (1+k)c^2r^2}} + \alpha_4 r^4 + \alpha_6 r^6 + \alpha_8 r^8 + ...$$ \hspace{1cm} (11)

The first term of the formula can be approximately considered as a quadratic term $\alpha_2 r^2$ when the accuracy requirement is not particularly high, and the coefficient of the higher term can only be fitted to order 16. Then the surface function of the two aspheric mirrors can be approximately expressed as:

$$z(r) = \sum_{i=1}^{8} \alpha_{2i} r^{2i} \hspace{1cm} \text{(12)}$$

$$Z(R) = \sum_{i=1}^{8} A_{2i} r^{2i} \hspace{1cm} \text{(13)}$$

The aspheric coefficients of two aspheric lenses can be obtained by least square fitting with MATLAB software, as shown in Table 1 and Table 2.

| asphericity coefficient | $\alpha_2$ | $\alpha_4$ | $\alpha_6$ | $\alpha_8$ | $\alpha_{10}$ | $\alpha_{12}$ | $\alpha_{14}$ | $\alpha_{16}$ |
|------------------------|------------|------------|------------|------------|----------------|----------------|----------------|------------|
|                        | 0.0034     | -3.16×10^5| 8.63×10^5 | -3.58×10^11| 2.01×10^14 | -3.11×10^17 | 5.56×10^21 | -9.88×10^-25 |
Tab 2. Fitting coefficient of plane convex aspheric mirror

| asphericity coefficient | \( A_2 \) | \( A_4 \) | \( A_6 \) | \( A_8 \) | \( A_{10} \) | \( A_{12} \) | \( A_{14} \) | \( A_{16} \) |
|-------------------------|----------|----------|----------|----------|----------|----------|----------|----------|
| \( 7.56 \times 10^{-5} \) | \( 5.24 \times 10^{-7} \) | \( -2.56 \times 10^{-10} \) | \( 1.43 \times 10^{-13} \) | \( -2.99 \times 10^{-17} \) | \( 5.63 \times 10^{-21} \) | \( -4.28 \times 10^{-25} \) | \( 1.96 \times 10^{-29} \) |

The optical path of aspheric mirror shaping system is shown in Figure 5

Fig 5. Optical path of aspheric mirror shaping system

In order to maximize the energy transmission efficiency of the shaping system, it is necessary to optimize the overall performance of the system while ensuring the shape and intensity uniformity of the cross-section spot. First call afocal image in ZMAX sequence mode Space function is used to optimize the wave aberration and light height in the meridian plane and the sagittal plane to ensure that the output light spot is 10 × 10 cm square; then NSDD and nstr functions are called in ZMAX non sequential mode to optimize the uniformity of the light spot and the overall transmission efficiency of the system, so as to ensure that the system has the maximum energy transmission efficiency on the premise that the output light beam meets the requirements.

Fig 6. Light intensity distribution of aspheric mirror group after shaping

After optimization, the specific situation of the exit spot is shown in Figure 6. The shape of the spot is a circle with a diameter of 6 cm, the divergence angle of the beam is 7.4 mrad, the intensity uniformity is 74%, and the overall energy transmission efficiency of the system is 88%. In the far field (about 2 m), the uniformity effect is still good, and the spot size has no change in the range of 1.5 m-4 m. ZMAX simulation results show that the system can achieve the desired shaping goal.

4.4 system implementation and experiment

The processed optical wedge, curved surface mirror and the components of prism group are placed in the given position in the optical path according to Fig. 5. The distance between the light source and the plane concave aspheric mirror and the plane convex aspheric mirror is 1 m and 1.8 m respectively. The observation screen is placed at the far field position 2 m away from the light source. Turn on the laser and fine tune the position of each shaping element repeatedly until the ideal shaping spot is achieved on the screen. At this time, the profile photo of the spot 2 meters away from the transmitter.
In order to ensure the accuracy of the measurement value and the safety of the measurement process, the output power of the laser is adjusted near the minimum value (about 2W), and the light intensity attenuator is placed in the optical path to prevent the detector from saturation; then the silicon photodiode detector (the diameter of the light inlet hole is 2mm) is placed on the two-dimensional adjusting frame, along the horizontal and vertical direction through the center of the light spot. Data are measured every 2 mm on the crosshairs. Finally, the total power and intensity uniformity of the spot are obtained by fitting the measured data.

Finally, the parameters of the shaped beam are as follows: the spot shape is a circle with a radius of 6cm; the divergence angle of the beam is about 8.2mrad; when the laser output power reaches the maximum power of 30W, the laser power on the surface of the light screen is 21.7w, the overall energy transmission efficiency of the system is 72.3%, which is less than the theoretical transmission efficiency of 88%; the intensity uniformity is 66.3%, which is also less than the theoretical uniformity of 82%. Compared with the output power of signal level laser beam which is often MW level or W level in the research at home and abroad, the output power of the current system is increased by one order of magnitude, and the collimating system has completed the scheduled task under this requirement.

After testing, with the collimator, the diameter of laser spot is 2.3cm, 5.7cm and 11.6cm at the distance of 2m, 5M and 10m respectively, which meets the parameter requirements of collimating system.

5. Summary
This paper first introduces the application of high-power semiconductor laser in laser energy transmission system. Because its beam quality is far worse than other types of lasers, when it is used as the transmitting end of beam shaping system, it must be equipped with corresponding beam shaping system to ensure that the photovoltaic cell module has a higher conversion efficiency. Then the research of laser alignment technology at home and abroad is summarized, and several common laser alignment technologies are investigated, and their advantages and disadvantages are compared. Finally, an aspheric lens group shaping method is proposed, which integrates the optical devices with low cost, reduces the energy loss in the process of laser transmission, and obtains the laser beam with certain intensity uniformity. The performance parameters of the shaped beam are measured. According to the parameters, a small and portable optical fiber end collimator is selected as the beam shaping system. The collimator can meet the parameter requirements of collimating system.

Acknowledgments
This work was supported by the Research Project of Institute of State Grid Corporation of China (SGRIXTKJ[2017]NO.840).

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