Research on Mirror Coupling Process in Array Semiconductor Laser

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Abstract: In order to improve the coupling efficiency of the array semiconductor laser and the multimode fiber, this paper establishes an ideal coupling model for the general structure of the array semiconductor laser. Combined with experiments and Zemax simulation, the relationship between the size error of the mirror package and the coupling efficiency is studied. The results show that in the displacement error, the coupling efficiency is most sensitive to the X-axis displacement; in the angle error, the coupling efficiency is more sensitive to the Y-axis rotation angle than the Z-axis rotation angle error; the coupling efficiency curve has obvious peaks and is sensitive to changes, and the tolerance is small, which puts forward higher requirements on the stability of the coupling device.

1. Introduction
Array semiconductor laser is a necessary pump light source for solid-state lasers. It has many advantages such as small size, light weight, high efficiency, long life, and high power. It is widely used in laser ranging, nuclear explosion simulation, lidar transmission, materials processing, micro-processing, modern medical and other key areas. Array semiconductor lasers usually arrange 19-49 groups of single-tube light-emitting units in one direction [1], and each group of light-emitting units is collimated by the fast axis, collimated by the slow axis, reflected by the mirror, and finally coupled into the optical fiber through the focusing lens. In this process, the coupling efficiency is the core factor for evaluating the quality of laser packaging, and it is of great engineering significance to study the influence of coupling efficiency on package size errors.

At present, domestic and foreign scholars have carried out some research work on improving the efficiency of lasers. Treusch et al. proposed a double microstep mirror beam shaping device, which is used in array laser diodes with a coupling efficiency of up to 70%. [2] Zhou Xiaojun et al. proposed a beam shaping system. Through simulation design, the system can further increase the coupling efficiency of a 1500W array semiconductor laser to 93%. [3] Wu Yulong et al. designed a 6000W laser by using physical optical simulation methods, with an efficiency exceeding 87% [4]. These research results mainly focus on how to obtain high-efficiency coupling methods for lasers, and there are not many research results on factors affecting coupling efficiency. Zhang Fan exemplified the influence of the distance between the laser diode, the spherical lens and the optical fiber on the coupling efficiency [5]. Jiang Shenghong studied the influence of the distance between the lenses on the coupling efficiency of lidar single-mode fibers through theoretical calculations [6]. Yu Junhong and He Kai obtained the
results of the effect of fiber alignment error on the coupling efficiency through simulation and experimental analysis. The mirror is an optical element that changes the propagation path of the laser beam in the array semiconductor laser, and it has no shaping effect on the beam. Therefore, there is almost no research on the influence of the position of the mirror on the coupling efficiency. In addition, in actual production, the packaging of each optical element in the array semiconductor laser device relies on manual operation, the production process lacks scientific guidance, the production efficiency is low, and the product consistency is low. Therefore, the research on the mirror coupling technology of the array semiconductor laser has practical application value.

This article first established an ideal coupling model for the general structure of the array semiconductor laser, and then analyzed the influence of the degree of freedom change in each direction during the coupling process of the array semiconductor laser mirror on the coupling efficiency of the model, and built an experimental platform for experimental verification; the simulation and experimental results were compared and analyzed, and the sensitivity of the coupling efficiency to each degree was obtained; the research results guided the selection of the motion platform and the design of the coupling equipment.

2. Coupling model design

Figure 1 shows the general structure of the array semiconductor laser coupling model. As can be seen from the figure, the light beam emitted by the light source is first collimated by the fast-axis collimator lens and the slow-axis collimator lens. The ideal spot after collimation can be regarded as a rectangular light source with a certain light-emitting area. Finally, a focusing coupling lens is used to perform all beams. After spatial recombination, it is coupled into the multimode fiber. In the simulation parameter design, the collimating lens material is S-TIH53, the focus coupling lens glass material is BK7, to match the numerical aperture of the multimode fiber, the fiber core material is N-LLF6, and the cladding material is N-BK7. Two concentric rings are set in the fiber, and the attribute is set to Absorb to eliminate the light reflected from the core and enter the cladding, and improve the calculation accuracy of coupling efficiency.

\[
\eta = \left| \frac{\int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} \psi_1 \psi_2 \, dx \, dy}{\int_{-\infty}^{+\infty} |\psi_1|^2 \, dx \, dy \int_{-\infty}^{+\infty} |\psi_2|^2 \, dx \, dy} \right|
\]

In the formula (1), \( \psi_1 \) and \( \psi_2 \) respectively represent the mode field distribution of the light source and optical fiber on a certain plane. The mode field after combining the light source selected above is shown in Figure 2(a), which is basically rectangular, and the mode field shape of the fiber is circular. In order to obtain high coupling efficiency, the mode field after combining the light source must be the field is shaped into a circle. In this paper, a focusing coupling lens is used to focus and shape the beam.
The spot after the model is focused and coupled is shown in Figure 2(b). The spot is basically circular, which is consistent with the circular mode field of the fiber. Therefore, the coupling efficiency of the system has reached 99.86%.

3. experiment
First, analyze the simulation model, and establish the coordinate system shown in Figure 3, and obtain the influence of the six degrees of freedom error of the mirror on the coupling efficiency. The simulation analysis shows that the error in the Y, Z, and TX directions of the mirror does not affect the coupling efficiency of the mirror. The errors in the other three directions (X, TY, TZ) affect the coupling efficiency of the mirror. The schematic diagram of the errors in the three directions (X, TY, TZ) affecting the coupling efficiency is shown in Figure 4. Figure 4 (a), (b), (c) respectively show the influence of X-axis displacement error, Y-axis angular error, and Z-axis angular error on the coupling efficiency. It can be clearly seen that the changes in the three directions will affect the coupling efficiency coupling of light beam and fiber.

The following is an experimental platform for error analysis in X, TY, and TZ directions. The experimental platform is shown in Figure 5(a), including an array semiconductor laser device, a five-degree-of-freedom high-precision motion platform, a motion control system and an optical power meter. The five-degree-of-freedom motion platforms are X, Y, Z, TY, and TZ directions.
The device used in the experiment is a 20-channel array semiconductor laser model, as shown in Figure 5(b). Figure 1 illustrates the beam collimation and coupling process of the array semiconductor laser. During the beam shaping process, each laser unit emits laser light from the chip and passes through the fast axis collimating lens (FAC) and the slow axis collimating lens (SAC) are collimated, and then reflected by the mirror, the beam enters the focusing lens and couples into the optical fiber.

The experiment is carried out according to the following steps. First, use a special fixture to clamp the mirror lens, and adjust the position of the mirror lens and the base of the array semiconductor laser, then use the coupling algorithm to find the best installation position of the mirror lens, and then adjust the fixture to make the mirror deviate from the optimal coupling position to simulate the presence of errors and test the effects of six degrees of freedom errors on coupling efficiency. Each degree of freedom error is divided into 20 groups (10 groups in the forward direction and 10 groups in the reverse direction), and the obtained experimental data is compared with the simulation data. This experiment is aimed at one of the laser units, because the error caused by a single degree of freedom of the mirror has an aggravating effect with the propagation distance of the beam, so it is not suitable to discuss the positioning error of each mirror together. After the experiment, the experimental data was fitted, and the curve of error and coupling efficiency was obtained, and the curve was compared with the simulation curve to verify the correctness of the experimental data.

4. Results and discussion

4.1. The influence of displacement error on coupling efficiency
The experimental and simulation results of the influence of the displacement error in the X direction on the coupling efficiency of the mirror are shown in Figure 6. The red and black curves represent simulation results and experimental results, respectively. Since only one of the laser units is selected for analysis, the ordinate is the percentage of the actual coupling efficiency to the maximum coupling efficiency in a single optical path. In the Z-axis direction, when the mirror is shifted from the standard position by 1mm, the coupling efficiency will be reduced to about 20%.
4.2. The influence of angle error on coupling efficiency

The experimental and simulation results of the influence of the angle error in the Y and Z directions on the coupling efficiency of the mirror are shown in Figure 7. The red and black curves represent simulation results and experimental results respectively. In addition, error curves in different directions are marked with different symbols. The ordinate is still the actual coupling efficiency as a percentage of the maximum coupling efficiency in a single optical path. It can be seen that the angular error of the mirror has the greatest impact on the coupling efficiency. Whether in the Y-axis direction or the Z-axis direction, when the mirror deviates from the standard position by 0.4°, the coupling efficiency will be reduced by more than 70%. At the same time, the curves of the influence of the angle error in the Y and Z directions on the coupling efficiency of the mirror do not coincide. This is because the working part of the mirror in the array semiconductor laser is the upper part of the mirror, and the actual reflected spot center is not in the lens. The experiment is based on the exact center of the lens as the origin to establish the coordinates for the error experiment, which leads to different curves of the effect of the angle error in the Y and Z directions on the coupling efficiency of the mirror. Therefore, the installer of the reflector must pay attention to it and avoid it to prevent the angle error of the reflector caused by installation error and deformation.

4.3. Comparative analysis of tolerance

In the actual coupling process between the laser and the optical fiber, the coupling errors shown in Figures 6 to 8 cannot be avoided. Scholars at home and abroad have introduced the concept of tolerance when studying the coupling process of lasers and optical fibers to analyze various errors in coupling. The definition of tolerance refers to the maximum range of errors allowed in the device package under a certain additional loss index. Generally, we define the maximum range corresponding to each error when 1dB additional loss is generated as tolerance. At this time The coupling efficiency is 80% of the maximum coupling efficiency. In the same way, we define the maximum range of the alignment error corresponding to the additional loss of 0.1dB (97.7% of the maximum coupling efficiency) as the alignment accuracy. In this article, in the case of a single error, the tolerance of each error in the experimental data and the alignment accuracy of the alignment error are shown in Table 1.

Table 1  Tolerance and alignment accuracy of X, Y, Z axis displacement and rotation angle

| Parameter        | Tolerance interval | Alignment accuracy |
|------------------|--------------------|--------------------|
| X axis displacement | (-0.5 mm, 0.5 mm) | (-0.1 mm, 0.1 mm)  |
Y axis rotation angle \((0.2°, 0.2°)\) \((-0.04°, 0.04°)\)

Z axis rotation angle \((-0.28°, 0.28°)\) \((-0.08°, 0.08°)\)

In order to more intuitively explore the sensitivity of the coupling efficiency to the errors of the mirror in different directions (X, TY, TZ), the error value is taken as the abscissa, and the first derivative of the coupling efficiency is taken as the ordinate, and the relationship curve between them is drawn. The result is shown in Figure 8. Combining the analysis of the coupling error loss in Figures 6-8 and the theoretical analysis results given in Table 1, it can be seen that if the coupling error of the array semiconductor laser and the fiber is divided into displacement error and angle error, the coupling additional loss varies with various types. The increase of the error increases according to the law of function, and the change trend can be approximated to a Gaussian distribution. Among them, in the displacement error, the coupling efficiency is sensitive to the X-axis displacement; in the angle error, the coupling efficiency is more sensitive to the Y-axis rotation angle than the Z-axis rotation angle error sensitivity.

Taking into account the alignment accuracy, through theoretical analysis, to make the additional loss less than 0.1 dB, when each error exists alone, it is required that the X-axis displacement is less than 1mm, the Y-axis rotation angle is less than 0.08°, and the Z-axis rotation angle is less than 0.16°. Therefore, when selecting the mirror coupling platform, the X-direction displacement platform, the Y-axis rotating platform, and the Z-axis rotating platform need to choose high-precision platforms.

5. Conclusion
This paper studies the influence of the mirror positioning error on the coupling efficiency, and mainly draws the following conclusions:

(1) The author designed and optimized the general structure of the array semiconductor laser coupling model, and built an experimental platform, and the design experiment verified the feasibility of the model.

(2) In the mirror coupling package of the array semiconductor laser, the control requirements for the rotation of the mirror Y axis and the Z axis are relatively high, and the control of the Y axis rotation should be stricter; for the X axis The rotation, Y-axis displacement, and Z-axis displacement can have relatively large packaging tolerances.

(3) The coupling efficiency curve has obvious peaks and is sensitive to changes, and the tolerance is small. This puts forward higher requirements for the stability of the coupling device, and at the same time brings great challenges to the subsequent dispensing and curing package.

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