Spherical distribution structure of the semiconductor laser diode stack for pumping*

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Abstract: A semiconductor laser diode stack is used for pumping and 8 semiconductor laser diode arrays of the stack are put on a sphere, and the output of every bar is specially off-axis compressed to realize high coupling efficiency. The output beam of this semiconductor laser diode stack is shaped by a hollow duct to the laser active medium. The efficiency of the hollow light pipe, which is used for semiconductor laser diode stack coupling, is analyzed by geometric optics and ray tracing. Geometric optics analysis diagnoses the reasons for coupling loss and guides the design of the structure. Ray tracing analyzes the relation between the structural parameters and the output characteristics of this pumping system, and guides parameter optimization. Simulation and analysis results show that putting the semiconductor laser diode arrays on a spherical surface can increase coupling efficiency, reduce the optimum duct length and improve the output energy field distribution.

Key words: semiconductor pump; laser diode array; beam shaping; coupling duct
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1. Introduction

The lens duct used for a coupling laser diode pumping light into a working material has already been well analyzed and widely used[1]. Due to some unavoidable drawbacks, a hollow duct made of four high reflection mirrors was put forward to substitute the lens duct. A hollow duct is a good optical device to collect large-emitting-size high-power laser to a small point, for the reasons of that it can avoid problems of wide band AR (anti-reflection) coating, glass absorption, risk of thermal stress damage, which a lens duct cannot avoid, and it can also better meet the divergence requirements of a laser active medium[2]. When a large laser diode stack is used for pumping, to obtain an optimum structure it is advised that big laser diode arrays are divided into several small ones, assembled together and the emission surface of all the small arrays placed on a specific sphere[3−5].

Calculation and ray tracing results have shown that placing laser diode arrays on a sphere can change the energy distribution in the output space, prolong the effective pump distance, reduce the optimum duct length and make the structure more condensed. The simulated result also shows that the pumping system coupling efficiency is 91.2%, and the experimental result is 86.2%-high enough to provide sufficient energy for a multi-pass Nd:glass magnification structure.

The following part of this paper will introduce the spherical laser diode stack pumping structure, analyze the relation between duct parameters and output pumping laser characteristics, all of which are based on calculation and optical ray tracing simulation.

2. Pump structure using spherical laser diode arrays and its efficiency calculation

The multi-pass traveling wave structure we designed could amplify a 1053 nm signal laser from 0.3 to 300 mJ by a 8 mm thickness Nd:glass slice. In order to a maintain a high energy density on the 8×8 mm^2 pump area, a 25.2 kW total power laser diode stack was used. Because the single bar power and the size of geometric structure are limited, the pump source needs 168 bars and the emission area is therefore be very large. This means that the laser diode arrays in the laser diode stack should be well placed, and the beam well shaped in order to maintain a high efficiency. Considering that the energy distribution in the Nd:glass should match the multi-pass amplifier structural requirements, all 168 bars are made into 8 arrays and arrangedas a 2×4 structure. The total emission area is 28×124 mm^2. Emmision surfaces consisting of two laser diode arrays in the horizontal and of each four arrays in the vertical, were put on a sphere, and the center of them are on the coupling duct export center.

Cylindrical lenses are placed in front of every bar to compress the fast axis divergence to maintain a high transmission efficiency[6]. The beam generated by each bar is compressed to be a narrow band. At the same time, off-axis placed cylindrical lenses also change the emission direction of each bar. Compressed laser beams of each array are focused, and the total spot width is the same as the width of the hollow duct exit at a distance of exactly the length of the duct. Meanwhile, compressed narrow light bands of all the bars in an array are uniformly placed at the duct exit to make the output beam of the

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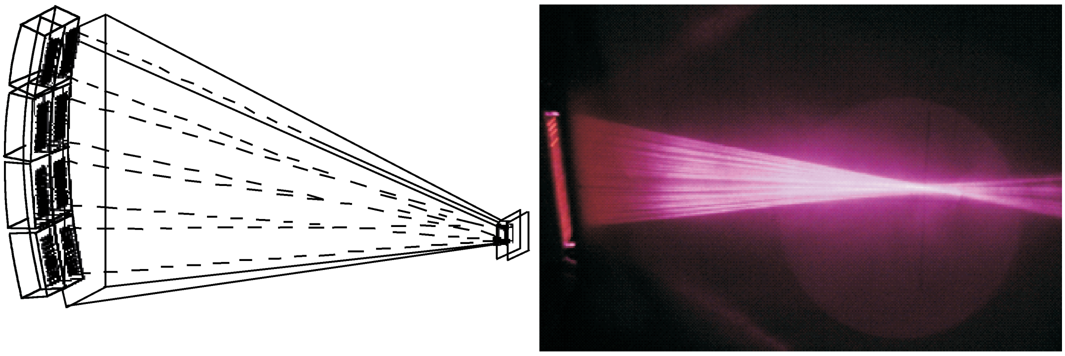
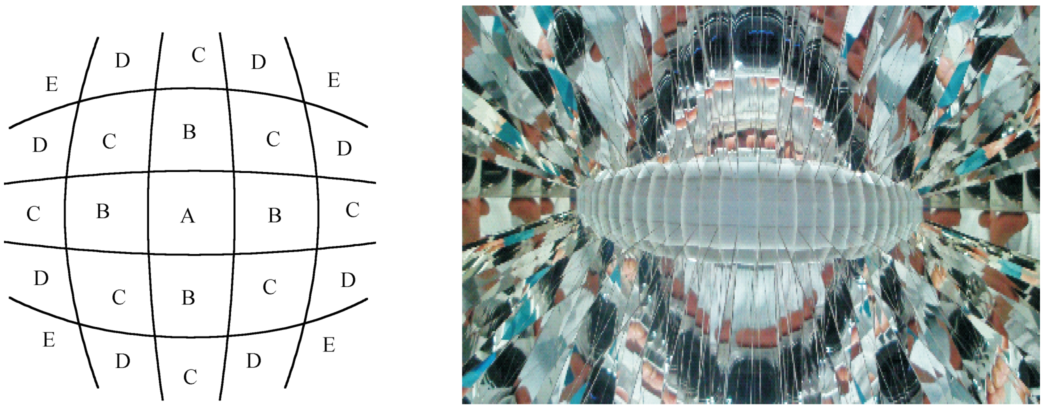


(a) (b)

Fig. 1. (a) ZEMAX model of the laser diode stack pumping structure and (b) photograph of a laser diode array with off-axis compressing effect.



(a) (b)

Fig. 2. (a) Efficiency distribution on the unfolded duct toroid. (b) Photograph of the toroid.

duct uniform.

A ZEMAX module of the pumping laser diode stack and the coupling duct is shown Fig. 1(a). The laser diode stack is on the left, the hollow duct is in the middle and the Nd:glass slice is on the right. The dashed lines in the hollow duct show the compression directions of the outer four laser diode arrays beams. The photograph in Fig. 1(b) is an example of a shaped laser diode array beam, it is the focal effect of the laser diode array. The focus point is set in the hollow duct.

Through consideration of the reflection theory, light in the duct can be unfolded one or more times to become a straight line[3, 4]. According to the same theory, the duct exit and images of it constitute a toroid. The toroid can be seen through observations from the input side of the duct,. It comprises many small rectangles, they are the images of the exit on the side walls. An image of this toroid can be seen in Refs. [4, 5]. Laser beams illuminated on the toroid will be outputted from the duct, otherwise the energy will be reflected back to the entrance of the duct.

For an ideal hollow duct, if the entire laser beam output emitted by the laser diode is on the reflected toroid, all the energy will go out from it. Defining θ_x, θ_y as the angles between the duct side surface and the central axis, the toroid can be calculated by Eq. (1). L is the length of the duct, X is the laser entrance width, Y is the entrance height, x is the exit width and y is the exit height. Every small image size and coordinate of every intersection point can also be calculated from these structural parameters. The energy distribution emitted by the laser diode array can be calculated from Eq. (2), where α_x is divergence angle X in degrees, α_y is divergence angle Y in degrees, β_x and β_y are far field divergence angles in these directions. Therefore, the efficiency of this emission point can be calculated from the overlap between the toroid and the energy distribution.

$$r_x = \frac{xL}{X - x} = \frac{1}{2} x \text{ctg}\theta_x, \quad r_y = \frac{yL}{Y - y} = \frac{1}{2} y \text{ctg}\theta_y, \quad (1)$$

$$I(\theta_x, \theta_y) = I_0 \exp\left\{-2\left[\left(\frac{\beta_x}{\alpha_x}\right)^2 + \left(\frac{\beta_y}{\alpha_y}\right)^2\right]\right\}. \quad (2)$$

The duct reflection walls are made from silver coated glass, and SiO_2 coats the outside of the silver to prevent it from being oxygenized. Experiments show that the reflection efficiency of the walls can be higher than 97% between an angle of 10° and 80°. If a laser beam goes through the duct exit with no reflection, the beam efficiency is 100%. If the beam is reflected once, the energy it contains should multiply with the reflectivity once. When the laser is reflected several times, the decline in transmission efficiency induced by reflection can not be ignored. At any emission point on the stack, the spot on the toroid can cover several quadrangles, and a precise calculation

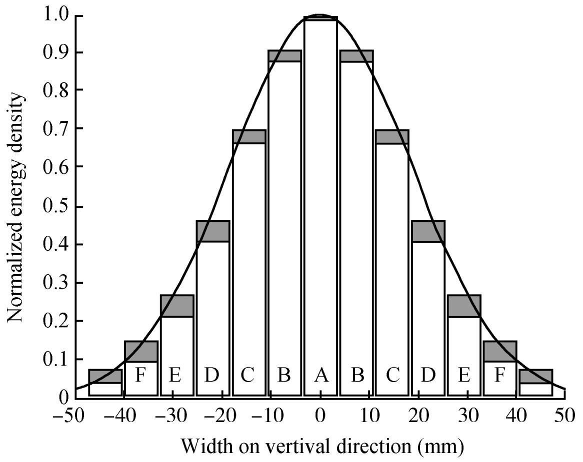


Fig. 3. Reduction of duct efficiency induced by side wall reflection. The X axis shows the middle line of Fig. 2, the origin is the center of the duct exit, and the width and position of FEDCBABCDEF is calculated and drawn.

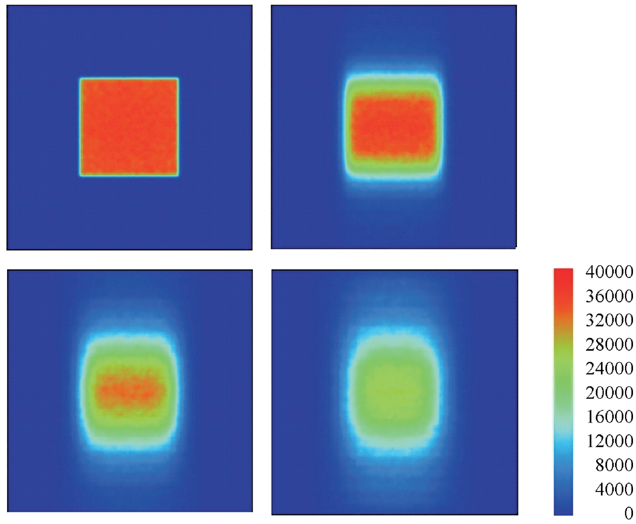


Fig. 4. Simulation results of energy distribution on the used duct.

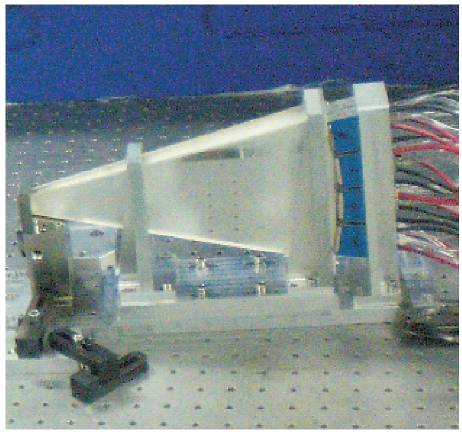


Fig. 5. Laser diode stack, coupling duct and the experimental structure.

of the transmission efficiency requires that every quadrangle should be considered.

Figure 2 shows the efficiency relation between a quadrangle and its position, and a photograph of the toroid of the designed duct is shown. Quadrangle "A" is the exit of the duct, and its efficiency is 100%, because the laser passes through the duct with no reflection; the four quadrangles marked "B" around it, multiply the reflection once, and the quadrangles marked "C" multiply the reflectivity twice; the quadrangles marked "D" three times, and so on. Every conjoined point of these quadrangles can be calculated because the angle between quadrangle "A" and "B" can be calculated by θ_x and θ_y. Through the calculation overlap of every emission point spot on Fig. 2, the efficiency of this emission point can be calculated. Figure 2 also predicts that if the beam width on the duct exit is larger than y, some of the energy will emit on the outside of the central band "…DCBABCD…". The energy on the "…EDCBCDE…" band needs to multiply the reflection once and the energy on the "…FEDCDEF…" band needs to multiply the reflection twice. To avoid this part of reflection loss, cylindrical lenses are off-axis placed to compress every array beam width to be the same as the duct exit.

Based on the aforementioned consideration about reflection loss and energy distribution, a curve for duct efficiency can be drawn and in shown Fig. 3. The Gaussian in Fig. 3 illustrates the output energy distribution of an emission point on the laser diode array. The column marked "…DCBABCD…" presents the middle horizontal line in Fig. 2. If we normalize the Gaussian peak value to be 1, from Eq. (2), average energy density could be

A: 0.992, B: 0.907, C: 0.691, D: 0.441, E: 0.235, F: 0.105.

The loss efficiencies obtained from Fig. 3, from A to F, is 0%, 0.030%, 0.059%, 0.087%, 0.115% and 0.141%. The width of the surface from A to F would be

$$x \cos\left(2n \arctan \frac{X - x}{2L}\right), \quad n = 0, 1, 2, 3, 4, 5.$$

By multiplying the average energy distribution factor with the width of each image and the reflection loss efficiency, and adding all these rectangles up, the duct coupling efficiency can be calculated. The column in Fig. 3 shows the total energy on every image surface and the shadowed part represents the loss. The total loss of coupling efficiency is 6.8%.

Although geometric analysis can precisely solve the problem of laser diode stack transmission efficiency, it takes a long time to classify and calculate all of the emission points on the laser diode stack. Ray tracing can solve this problem both fast and precisely. After setting up the module of every emission point on the laser diode stack and of the duct with ZEMAX, 2000000 rays are traced every time in order to maintain a large sample space. Optical field distribution and duct efficiency can both be calculated from the number of rays hitting certain areas. The characteristics of the duct used for shaping laser diode stack beams are obtained by multiple ray tracings using different duct and stack structural parameters.

The simulation and results of the output are shown in Fig. 4. From the left to the right is 0, 2, 4, 6 mm to the exit of the duct. By comparing the simulation and experimental results, we can find that the module, which is revised sev-

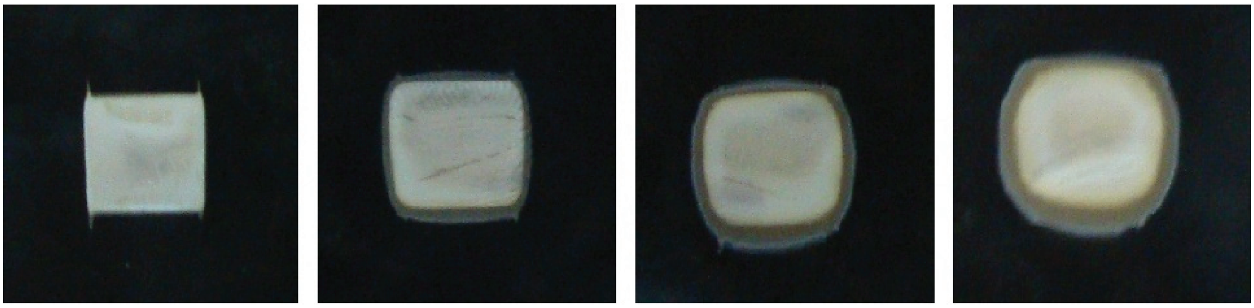


Fig. 6. Photos of exposed photographic paper at different distances.

eral times, matches the pumping structure well. Therefore, though the simulated structure, the energy distribution in the Nd:glass slice can be obtained and this can be used to guide the calculation of energy withdrawal. The simulation results also shown that energy in the Nd:glass will become scattered due to the pumping structure, combined with the absorbability of this kind of Nd:glass (N31). The optimum thickness of the Nd:glass slice can be obtained and it is about 5 mm.

3. Experimental results

Figure 5 shows the toroid of the duct we used and the experimental structure. The experimental results show that when the stack output energy is about 9.25 J, it can reach 7.97 J on the exit of the duct, and the coupling efficiency is 86.2%. The difference between the simulated and experimental results is mainly caused by the incoherence of the collimated bar emission beams and the fact that the reflection rate of the duct is lower than that of the side wall.

From the efficiency theory above, if a big cylindrical lens is used in front of each laser diode array to compress the slow axis beam divergence, the coupling system efficiency could be higher. However, due to several factors we did not choose this structure. The first reason was because the energy distribution on the duct exit crossing surface could not be considered. In the direction of the fast axis, the beams were compressed and many stripe beams were overlapped in order to obtain a flat energy distribution. However, in the direction of the slow axis, the compressed energy distribution curve is similar to a Gaussian shape. Reflection can flatten the energy distribution on a slow axis to meet working material requirements. The second reason is that the efficiency only displays a limited improvement. As analyzed before, the maximum improvement of coupling efficiency is 6.8%. The third reason is that the expansion of the distance from the laser diode stack to duct and increasing the complexity of the total structure is also a defect.

References

[1] Beach R J. Theory and optimization of lens ducts. Appl Opt, 1996, 35(12): 2005

[2] Miller G H, Moses E I, Wuest C R. The national ignition facility. Opt Eng, 2004, 43(12): 2841

[3] Zhao Tianzhuo, Fan Zhongwei, Chen Yannan, et al. Large area laser diode stack pumping structure. Chinese Journal of Lasers, 2008, 36(8): 1951

[4] Eichhorn M. Theory and optimization of hollow ducts. Appl Opt, 2008, 47(11): 1740

[5] Zhao T, Fan Z, Cui J. Research on coupling duct for slab amplifier pumping. Opto-Electron Eng, 2008, 36(11): 69

[6] Niu Gang, Fan Zhongwei, Wang Peifeng, et al. A single fiber coupling technique for high power diode laser arrays. Chinese Journal of Semiconductors, 2007, 28(10): 1607