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ABSTRACT

With continuous increase in output power of fiber lasers, small volume, low weight, high electro-optic efficiency and high brightness diode laser pump source has become the trend of development. Using spatial beam combining and polarization beam combining methods, BWT has developed a compact pump laser achieving 600W level out of a fiber of 0.22 NA and 200 μm core diameter. At 12A, electro-optical efficiency is higher than 49%. Its brightness is higher than that of the commercially available 158W pump from BWT.

Keywords: Polarization beam combination, single emitter diode laser, rigorous coupled wave analysis, fiber coupling

1. INTRODUCTION

Diode lasers have advantages of high efficiency, compact structure, low cost, and high reliability. With the development of industrial applications using fiber laser, demands on high brightness diode lasers are constantly increasing. Fiber coupling is an important measure for flexible transfer of laser beam. When light from free space is coupled into the fiber waveguide, it not only maintains the brightness but also reduces the damage probability of back light to the chip [2]. However, its relatively poor beam quality, including nonuniform beam distribution and low power density[1], limits its direct application on material processing. Increasing the output power and improving the beam quality has always been a focus of research on diode lasers. In July, 2014, Dilas reported a diode laser that outputs 500W from a 200μm core diameter NA 0.22 fiber with a weight of only 455g and a size of 110×75×70mm^3. To reduce its size and weight, the laser employs T-bars of good beam quality and compact mechanical design [3]. Through spatial and polarization combination of light from single emitters, Everbright Photonics Co. Ltd. developed a laser that outputs 700W from a 200μm core diameter NA 0.22 fiber, with a size of 260×240×65mm^3.

In this paper, we discussed a 600W diode pump laser developed by BWT Beijing Ltd. This pump laser has a compact design with a size of 180×150×70mm^3. At 12A, this pump laser reached 650W out of a 200μm core diameter NA 0.22 fiber. With special mechanical and optical designs, a high-power fiber coupled laser with conduction cooling by tap water is realized. This diode laser can be conveniently used as pump source for fiber lasers or directly used in material processing.

2. SIMULATION AND DESIGN

Spatial and polarization beam combination of single emitters are used in the design. As shown in Fig. 1, beams from emitters are stacked up in both directions of fast axis and slow axis. after polarization, and coupled into a fiber with a spherical aberration reducing lens set.

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For design to be optimized, steady state propagation of electromagnetic wave in free space is simulated. With assumption of slowly varying field, ABCD matrix is used to describe the propagation and transformation of beams outputted from diode lasers. The advantage of this method is that the beam quality of combined beams from diode lasers can be directly described with beam parameter product. With basic acceptance condition of fiber coupling and initial beam parameters of diode laser emitters considered, the acceptable set of key optical components that meets certain conditions can be numerically computed. Thus, proper combinations of optical components can be selected precisely to meet certain requirements. For example, to keep the power leaking into the cladding of a N*1 or (N+1)*1 fiber combiner at low level, the divergence of the beam output from a pumping fiber needs to be kept below a certain numerical aperture.

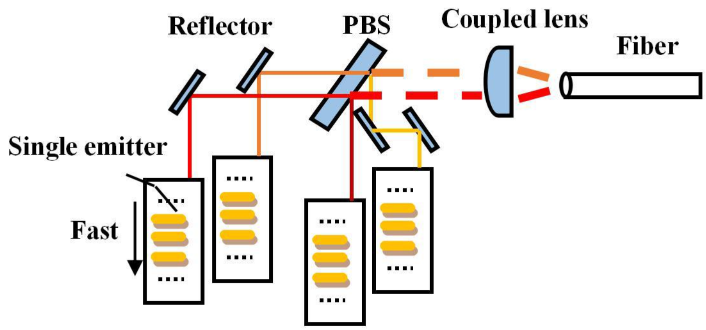


Fig. 1 schematic diagram of combining light from multi-emitters and coupling into fiber

The beam output from the wave-guide cavity of a diode laser can be obtained from steady-state propagation of electromagnetic wave in free space with assumption of slowly varying field. Whereas $A_{m,n}$ is a constant for normalization, $H_m\left(\frac{\sqrt{2}}{\omega(z)}\cdot x\right)$ and $H_n\left(\frac{\sqrt{2}}{\omega(z)}\cdot y\right)$ are m stage Hermite polynomial and n stage Hermite polynomial respectively. $\omega(z)$ is beam radius, $\Phi(x,y,z)$ is total phase shift and ω_0 is beam waist radius.

$$E_{m,n}(x,y,z)=A_{m,n}\cdot E_0\cdot\frac{\omega_0}{\omega(z)}\cdot H_m\left(\frac{\sqrt{2}}{\omega(z)}\cdot x\right)\cdot H_n\left(\frac{\sqrt{2}}{\omega(z)}\cdot y\right)\cdot\exp\left(-1\cdot\frac{x^2+y^2}{\omega^2(z)}\right)\cdot\exp(-1\cdot i\cdot\Phi(x,y,z))$$

$$\begin{cases}\omega(z)=\sqrt{\frac{L\cdot\lambda}{2\cdot\pi}\cdot\left(1+\xi^2\right)}=\frac{\omega_{0s}}{\sqrt{2}}\cdot\sqrt{1+\left(\frac{z}{f}\right)^2}=\omega_0\cdot\sqrt{1+\left(\frac{z}{f}\right)^2}\\ \Phi(x,y,z)=k\cdot\left(f\cdot(1+\xi)+\frac{\xi\cdot\left(x^2+y^2\right)}{1+\xi^2\cdot 2\cdot f}\right)-(m+n+1)\cdot\left(\frac{\pi}{2}-\psi\right)\end{cases}\qquad(1)$$

Propagation and transformation of beams in the beam combination system can be computed with ABCD matrices[4]. Whereas $\frac{1}{R_2}-i\cdot\frac{\lambda}{\pi\cdot\omega_2^2}$ is the inverse of the complex beam parameter at exiting plane, $\frac{1}{R_1}-i\cdot\frac{\lambda}{\pi\cdot\omega_1^2}$ is the inverse of the complex beam parameter at entering plane.

$$\frac{1}{R_2} - i \cdot \frac{\lambda}{\pi \cdot \omega_2^2} = \frac{C + D \cdot \left(\frac{1}{R_1} - i \cdot \frac{\lambda}{\pi \cdot \omega_1^2} \right)}{A + B \cdot \left(\frac{1}{R_1} - i \cdot \frac{\lambda}{\pi \cdot \omega_1^2} \right)} \tag{2}$$

The amount of light that can be coupled into the fiber is ultimately limited by the Beam Parameter Product (BPP) of the fiber. The definition of fiber BPP is given in Equation (3). Whereas BPP_f, ω_f and θ_f are respectively BPP, half beam width and full far-field divergence of the fiber.

$$BPP_f = \frac{1}{2} \cdot \omega_f \cdot \theta_f \tag{3}$$

For a laser beam to be captured by the fiber, its BPP has to be lower than the fiber BPP. On the other hand, at the diode output, the quality of the beam is given by the Beam Parameter Product (BPP) in two orthogonal directions (fast and slow axis) as defined in Equations (4) and (5). Whereas BPP_{fast}, ω_{fast} and θ_{fast} are respectively BPP, half beam width and full far-field divergence of the module in the fast axis. BPP_{slow}, ω_{slow} and θ_{slow} are respectively BPP, half beam width and full far-field divergence of the module in the slow axis.

$$BPP_{\mathbf{fast}} = \frac{1}{2} \cdot \omega_{\mathbf{fast}} \cdot \theta_{\mathbf{fast}} \tag{4}$$

$$BPP_{\mathbf{slow}} = \frac{1}{2} \cdot \omega_{\mathbf{slow}} \cdot \theta_{\mathbf{slow}} \tag{5}$$

Following condition needs to be met to achieve efficient fiber coupling

$$BPP_f > BPP_{fast} + BPP_{slow} \tag{6}$$

Combined Eqn. (6) with core diameter and numerical aperture of the fiber, it can be estimated whether the combined beams can be coupled into the fiber. A loop that repeats the calculation over a range of collimation element parameters can precisely estimate the range of usable parameter of collimation elements. The flow chart is shown in Fig. 2:

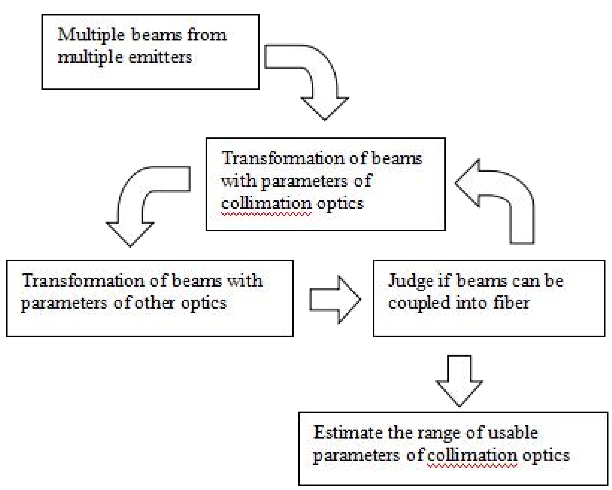
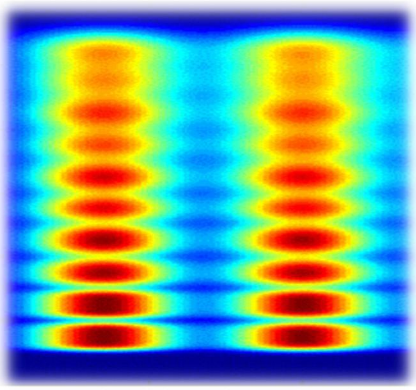


Fig. 2 Flow chart of the calculation

With consideration on electric properties, optical properties and output power of diode laser emitters, emitters with stripe width of 100μm are selected. As shown in Fig. 3, through spatial beam combination, beams from emitters are stacked up in both directions of fast axis and slow axis. After polarization combining, the beams are coupled through coupling lens set into a 200μm core diameter, NA 0.22 fiber. To keep the power leaking into the cladding of the fiber at low level, above theoretical calculation is used to select proper focal lengths of FAC, SAC and coupling lens. The optimized design is illustrated as point A in Fig. 4. The selected parameters ensures a good utilization of core diameter and numerical aperture while keeps a coupling efficiency over 95%.



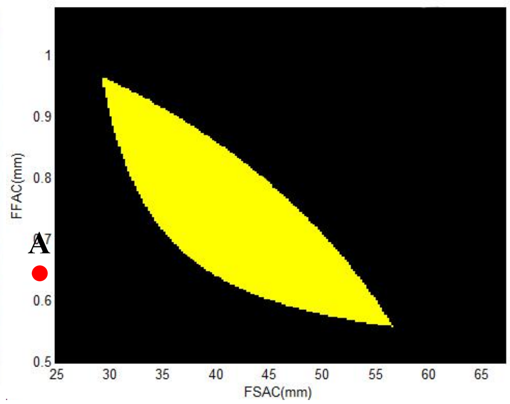


Figure 3(Left). multiple single emitter diode lasers are spatially beam combined in two directions

Figure 4(Right). The yellow area corresponds to the set of focal lengths of SAC (lateral axis) and FAC (vertical axis) that meet the condition of fiber coupling

3. PUMP PERFORMANCE

Photo of the module is shown in Fig. 5, with a size of 180×150×70mm^3. To ensure long-term reliable operation, the chips are placed over water cooling channels to minimize thermal resistance and lower temperature of junctions. Patent pending mechanical and optical designs are employed to reduce the size of the laser module. All optical elements are placed on two sides of one cold plate. This method shortens optical path, makes better use of water cooling channels in the plate, and improves the overall stability. There is always some loss along the optical path. Through increasing the absorption of lost laser power during first pass of light, the amount of scattered background light can be reduced. As the lost laser power is more rapidly converted into heat and taken away by the heat sink, there is less chance for chips and other optical elements to be damaged by heat accumulation and optical interference in the device. Fig. 6 shows the profile of the beams from 4 columns of emitters after spatial and polarization beam combination.

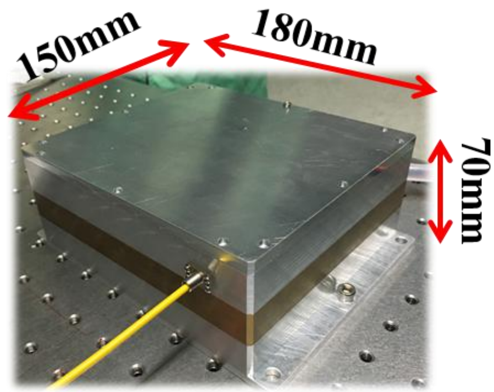


Figure 5. The prototype module

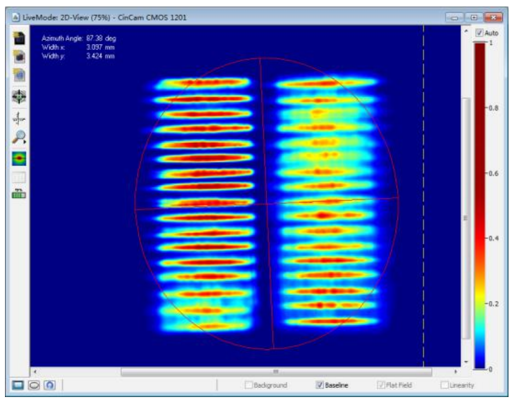


Figure 6. Beam profile of combined beams

A typical LI curve is shown in Fig. 7. From this curve, at an injection current of 12A, power of the combined beams at coupling lens is 712W, and 650W of laser power is coupled into a 200μm core diameter, NA 0.22 fiber. Fig.7 also shows the change of output power and coupling efficiency with current, which is almost constant at all current level. Its electro-optical efficiency is higher than 49%, and a brightness of 13.7MW/cm^2-str is obtained. The spectrum at 12A and cooling water temperature 20°C is shown in Fig. 8. A good control of waste heat keeps the maximum temperature on the top of the device below 35 °C.

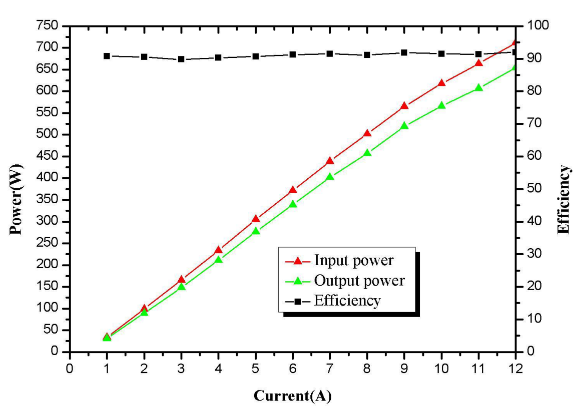


Figure 7. Output power and coupling efficiency

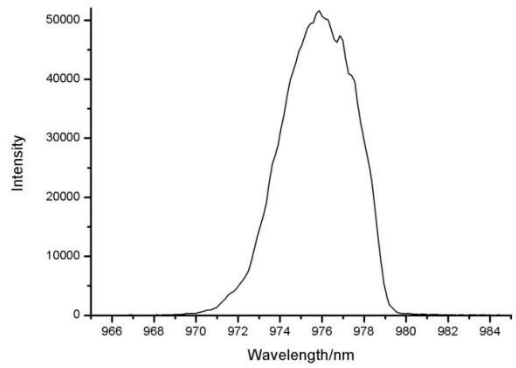


Fig.8 Spectrum

4. SUMMARY

We developed a multiple emitters beam-combining technology that achieves output power at 600W level. Limited by existing pump combiner technology, the market of pump source over 500W grows very slowly. Compared with bars technnology, pumps based on single emitters have less advantage on size, but their long term stability and reliability are proven. Especially while used as pumping sources, multiple emitters spatial beam combination has shown irreplaceable flexibility. In fiber coupling, beams from multiple emitters are usually stacked up in a rectangular arrangement and then polarization combined. However, such an arrangement doesn't fully utilize the acceptable BPP of the fiber. With certain emitter beam quality and BPP allowed by fiber, we have derived a spatial beam combination structure that approaches the BPP limit of the fiber. For a 200 μm core diameter and 0.22 NA fiber, 1.1kW pump power is theoretically possible with 120 single emitters through spatial and polarization beam combination. Applying such diode laser source directly in materials processing may have a bright future.

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