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High Coupling Efficiency of the Fiber-Coupled Module Based on Photonic-Band-Crystal Laser Diodes *

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The coupling efficiency of the beam combination and the fiber-coupled module is limited due to the large vertical divergent angle of conventional semiconductor laser diodes. We present a high coupling efficiency module using photonic-band-crystal (PBC) laser diodes with narrow vertical divergent angles. Three PBC single-emitter laser diodes are combined into a fiber with core diameter of 105 μm and numerical aperture of 0.22. A high coupling efficiency of 94.4% is achieved and the brightness is calculated to be 1.7 MW/(cm^2·sr) with the injection current of 8 A.

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Individual laser diodes have a number of attractive features, such as compact, low-cost, reliable, and wavelength-versatile, but with limited power and brightness. Conventional laser diode laser arrays, used for power scaling, do not allow beams to provide the required brightness. Beam combination approach offers an order of increasing both power and brightness, and can be classified into coherent combination and incoherent combination.[1–3] The incoherent combination is the primary method used in practical applications since it is regardless of phase, spectrum, and frequency. Incoherent combination includes spatial beam combination, polarization beam combination and spectrum combination.[4–6] Compared with a spatial beam shaped with multiple bars or stack, beam combination of multiple single-emitter laser diodes is more flexible and has simpler spatial arrangement of beams. It can provide laser output with better beam quality and can be coupled into a smaller fiber core and numerical aperture (NA) without complex and expensive micro lens array.[7]

In recent years, we have seen rapid development of beam combination and fiber-coupled modules.[8,9] For example, in 2016, Wang *et al.* presented a fiber-coupled module combining 14 single-emitter laser diodes into a fiber with core diameter of 105 μm and NA of 0.22, providing 120 W output power with the brightness of 9.1 MW/(cm^2·sr).[10] Qi *et al.* designed a module with 150 W output power using the same type of fiber based on 16 single-emitter laser diodes at the wavelength of 915 nm. The coupling efficiency of simulation was above 95% and the highest brightness was estimated to be 11 MW/(cm^2·sr).[11] In 2015, direct photonics industries (Germany) developed a continuous wave (CW) 500 W with the beam quality of 5 mm·mrad and the brightness of 41.19 MW/(cm^2·sr) in a fiber core of 100 μm and NA of 0.22 based on beam shaping, wavelength and polarization beam combination.[12,13] BWT Beijing Ltd. developed a module based on 18 single-emitter laser diodes, providing more than 140 W output power from a fiber with core diameter of 105 μm and NA of 0.15 at the wavelength of 915 nm. The coupling efficiency was over 90% within NA of 0.13.[14]

The coupling efficiency of a fiber-coupled module is limited due to the large vertical divergent angle of conventional laser diodes, and PBC laser diodes designed to reduce it have been investigated for many years.[15–17] Under the CW operation, the vertical and lateral divergent angles of 10.5° and 5.7° with full width at half maximum (FWHM) were presented in Ref. [18]. In this Letter, we report the coupling efficiency of PBC laser diode module, which has not been reported before. A comparison with the coupling efficiency of conventional laser diode module is also presented.

We choose three PBC single-emitter laser diodes to couple into a fiber with a core of 105 μm and NA of 0.22. Conventional single-emitter laser diodes are also used for comparison. The central wavelength is 980 nm for both types of diodes. The PBC type has vertical and lateral divergent angles of 12° and 6°

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(FWHM) as shown in Fig. 1(a), respectively, whereas the conventional type has the angles of 25° and 6° (FWHM) correspondingly. Table 1 shows the parameters of the two types of single-emitter laser diodes. The CW L–I–V curve of the PBC single-emitter laser diode is shown in Fig. 1(b).

Table 1. Parameters of PBC and conventional single-emitter laser diodes.

Parameters	PBC laser diode	Conventional laser diode
Fast axis divergence half-angle	6°	12.5°
Beam radius in the fast axis	1.5 μm	0.5 μm
Slow axis divergence half-angle	3°	3°
Beam radius in the slow axis	45 μm	45 μm

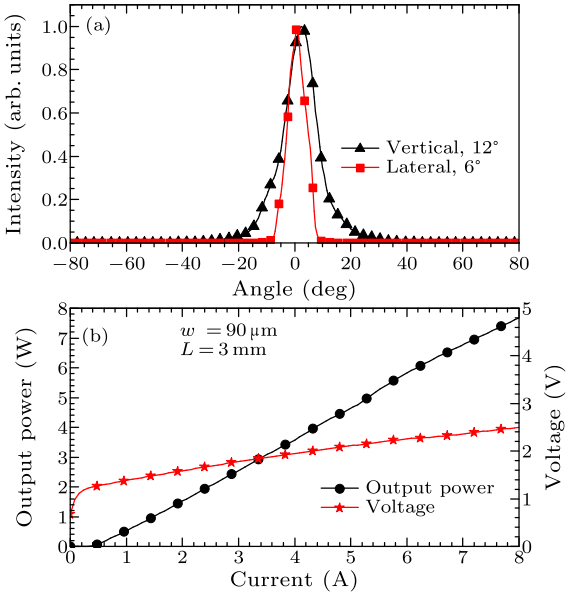

Fig. 1. (a) The vertical (triangle) and lateral (square) far-field divergent angles with an input current of 8 A; (b) CW L–I–V characteristics of PBC laser diode with a ridge width of 90 μm and cavity length of 3 mm.

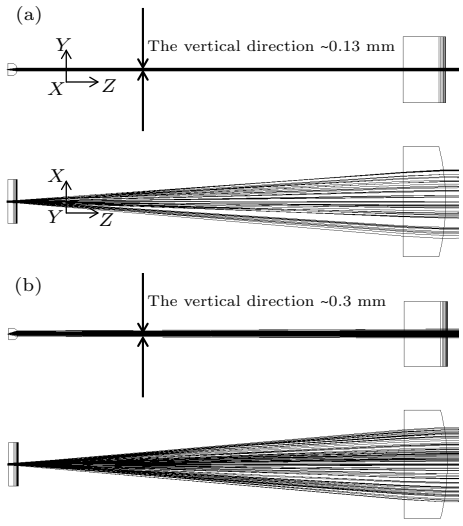

Fig. 2. FAC and SAC collimation diagrams of PBC (a) and conventional (b) single-emitter laser diodes (Y, X, and Z are the vertical (fast) axis, the lateral (slow) axis, and the light axis, respectively).

In the experiment, each beam combination and fiber-coupled module has three single-emitter laser diodes, which are individually collimated by the fast collimators (FACs) and the slow collimators (SACs) separately. Figures 2(a) and 2(b) show the FAC and SAC collimation diagrams of PBC and conventional single-emitter laser diodes, respectively. Since the vertical divergent angle of PBC single-emitter laser diode (12°) is nearly 2 times smaller than that of conventional single-emitter laser diode (25°), we can see that the PBC single-emitter laser diode has much slender beam (~0.13 mm) in the vertical direction, as shown in Figs. 2(a) and 2(b).

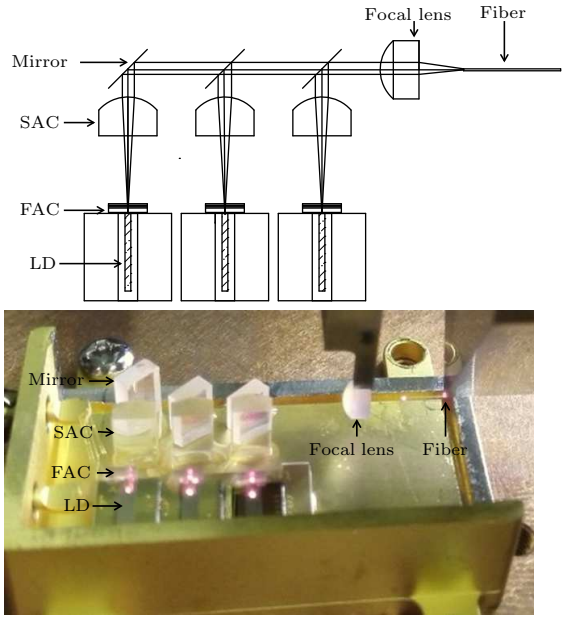

Fig. 3. (a) The light path diagram, and (b) the actual structure of module.

When reflected by the reflectors, three beams are arranged in the fast axis, and then, they are coupled into a fiber using the focal lens. We choose an aspheric cylindrical lens (purchased from LIMO) with the effective focal length (EFL) of 0.3 mm as FAC and that of 5.5 mm as SAC. We use CuW as the sub-mounts to place all the laser diodes since they have almost the same thermal expansion. The step height difference of sub-mounts is 0.5 mm. The performance data of both the PBC and conventional modules are measured at an operation temperature of 20℃. The light path diagram and the actual structure of module are shown in Figs. 3(a) and 3(b), respectively (the two types of modules have the same mechanical structure design).

The laser beam brightness is defined as

$$B = \frac{P}{\pi \frac{D}{4}^2 \pi\theta^2}, \tag{1}$$

where B, P, D and θ represent brightness, output power, core diameter and numerical aperture of the fiber, respectively. With the parameters of fiber and PBC laser diodes, the brightness of PBC laser diode module can be calculated by

$$\begin{aligned} B_{\mathrm{PBC}} &= \frac{8 \times 3 \times 0.944}{\pi^2 \times (\frac{1.05}{2} \times 12.7)^2 \times (\frac{\pi}{180})^2 \times 10^{-4}} \\ &= \frac{22.656 \times 18 \times 18}{\pi^4 \times 6.6675^2} \approx 1.7. \end{aligned} \tag{2}$$

The output power of PBC laser diode module is 22.656 W and the brightness is calculated to be 1.7 MW/(cm^2·sr) with the injection current of 8 A as shown in Eq. (2).

Figures 4(a) and 4(b) display the intensity profiles of PBC laser diode module and conventional laser diode module at the same operating current, respectively. In PBC laser diode module, the highest coupling efficiency achieved is 94.4%, whereas in conventional laser diode module it is only 90%, similar to that reported in Ref. [14]. The 4.4% increase is due to the narrower divergent angle in the vertical direction in PBC laser diodes compared with the conventional laser diodes. All the light propagates in the core of fiber in PBC laser diode module. However, in conventional laser diode module, part of the light propagates in the cladding of fiber, which is why the second larger yellow light circle appears in Fig. 4(b).

Table 2 presents a comparison between the high-power modules based on conventional laser diodes and PBC laser diodes. PBC single-emitter laser diode has a much slender beam (∼0.13 mm), which is nearly one half of the conventional single-emitter laser diode (∼0.3 mm) in the vertical direction (see Fig. 2). When we use the same method to combine beams, the step height difference of sub-mounts of conventional laser diode module is x, and the step height difference of sub-mounts of PBC laser diode module could be $x/2$. Through the above analysis, we can predict that the module which has 14 conventional single-emitter laser diodes can accommodate 28 PBC single-emitter laser diodes, and the module which has 16 conventional single-emitter laser diodes can accommodate 32 PBC single-emitter laser diodes. Hence we can couple nearly twice the PBC single-emitter laser diodes into the same fiber of conventional laser diode module, and obtain nearly twice the output power and brightness as listed in Table 2.

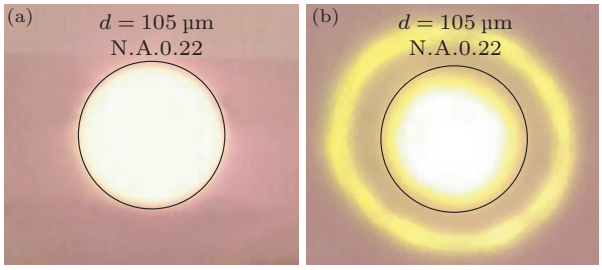

Fig. 4. Intensity profiles of fiber-coupled module of PBC (a) and conventional (b) laser diodes.

Table 2. Comparison of conventional and PBC high-power laser diode module.

Groups	Laser diodes	Number	Method of combination	Fiber (μm)	Output power (W)	Brightness (MW/(cm^2·sr))
Ref. [10]	Conventional	14	Spatial and polarization	105 NA0.22	120	9.1
Ref. [11]	Conventional	16	Spatial and polarization	105 NA0.22	150	11
Prediction 1	PBC	∼ 28	Spatial and polarization	105 NA0.22	∼ 240	∼ 18
Prediction 2	PBC	∼ 32	Spatial and polarization	105 NA0.22	∼ 300	∼ 22

In summary, we have studied the advantage of PBC laser diodes on coupling efficiency in the experiment. We combine three PBC single-emitter laser diodes into a fiber with core diameter of 105 μm and NA of 0.22, the obtained highest coupling efficiency is 94.4% (if the accuracy of lens adjustment is increased further, we will obtain a higher coupling efficiency which is more similar to the simulation results), and the brightness is calculated to be 1.7 MW/(cm^2·sr) with the injection current of 8 A. As a comparison, the highest coupling efficiency of 3 conventional single-emitter laser diodes in combination is only 90%, similar to the result in Ref. [14]. Therefore, using the same fiber and the same number of laser diodes, PBC laser diode module could achieve higher coupling efficiency than conventional laser diode modules. The lower the coupling efficiency is, the more the energy converted into heat is. Hence, the fiber-coupled module based on PBC laser diodes reduces the cost of cooling system, and provides tendentious choice of pump source for fiber lasers applications. In addition, in high power modules, PBC laser diode module can achieve much higher brightness.

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