1.5-W 520 nm continuous-wave output from a 50 μm/0.22NA fiber-coupled laser diode module

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Abstract
In this paper, a high brightness fiber-coupled module with a central wavelength of 520 nm is simulated and designed by ray-tracing software ZEMAX and then is experimentally implemented. Three 1-W continuous-wave green LD single emitters based on TO-9-package are successively collimated, spatially combined, and focused into an optical fiber with a core diameter of 50 μm and a numerical aperture of 0.22. The final output power of 1.53 W is obtained, corresponding to an optical–optical conversion efficiency of 51% and an electro-optical conversion efficiency of 10%. The tolerances between the simulation and the experimental result are analyzed and explained.

Keywords Spatial combination · ZEMAX simulation · Green laser diode · Fiber-coupled module

1 Introduction

Green laser diodes (LDs) play an increasingly important role in biomedical applications, pumping sources, and laser-based displays because of the advantages of compactness, long lifetimes, and good reliability. Especially, high power green diode laser becomes an attractively alternative pump source for Ti:Sapphire lasers because green LDs are low cost and the gain medium does not need to use liquid nitrogen to cool at high pump power, compared with blue LDs pumping (Sawai et al. 2014). However, the research progress of high-power green LD is very slow due to the "green gap" difficulty (Ulrich and Wolfgang 2011). In 2009, Sumitomo, OSRAM, and Nichia successively achieve green output based on GaN substrate (Miyoshi et al. 2009; Queren et al. 2009; Enya et al. 2009; Yoshizumi et al. 2009; Pengfei Zhao pfzhao@semi.ac.cn)

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but all LDs are single-mode with low power, which is not enough for scale applications. In 2013, Nichia successfully manufactured a multimode green LD with a power up to 1 W and a central wavelength of 520 nm based on AlInGaN grown on c-face GaN substrate (Masui et al. 2013). Up to date, the maximum output power of green LDs is merely 1.5 W produced by Nichia (Nakatsu et al. 2020). Naturally, the progress of fiber-coupling green LD is also slow. In 2017, based on the green LDs, Dilas developed a 2 W fiber-coupled green LD module with an optical-fiber core-diameter of 200 μm, and a numerical aperture (NA) of 0.22, corresponding to a brightness of 0.042 MW/(cm² sr)(Simon et al. 2017). It is the first watt-level fiber-coupled green LD product reported.

In our previous work, based on 16 1-W TO-can packaged LDs, a 12 W green output from a 200 μm/0.22NA fiber-coupled module is demonstrated with a brightness of 0.34 MW/(cm² sr) (Zhao et al. 2018). However, the beam quality of such lasers is not good enough for some applications. For example, when the above fiber-coupled modules are used for pumping a laser medium, the beam is focused on a spot with a diameter of around 200 μm, its corresponding Rayleigh length is about 0.5 mm (Sun 2012), which is not suitable for pumping a gain medium with a length of more than 1 mm. In the previous work, we obtained a watt-level continuous-wave (CW) Ti:Sapphire laser oscillator where a 10-mm-long Ti:Sapphire crystal was end-pumped by a 200 μm/ NA 0.22 fiber-coupled green LD module that can deliver a maximum power of 21.68 W (Miao et al. 2020). The experimental results show that the final optical–optical efficiency depends heavily on the beam quality of the pumping source. The Rayleigh length of the pumping laser must match the length of gain medium. Therefore, based on the requirement of end-pumping of Ti:Sapphire with a length of 5 mm, it is necessary to further reduce the core-diameter of coupling fiber, for example, to an optical fiber with a core diameter of 50 μm, and improve its beam quality.

This paper shows a high beam quality fiber-coupled module by combining three 1-W CW TO-can packaged green LDs and coupling them into a 50 μm core-diameter/0.22NA optical-fiber. The implementation process of the module is demonstrated through both the simulation of ZEMAX and the experiment. Total output power is over 1.5 W, which corresponds to a brightness of 0.608 MW/(cm² sr). And compared with the former pumping source (Miao et al. 2020), a 4-folds increase of Rayleigh length, which is about 2 mm, can be obtained. Such a design provides a better mode matching for end-pumping a Ti:Sapphire crystal with a length of 5 mm.

2 Designs and simulations

In this paper, the beam parameter product (BPP) is used to describe the beam quality of LDs, defined as the product of beam waist half-width and divergence half-angle (Qi et al. 2017). For a given optical fiber, the beam quality is half of the product between the core diameter ($d_{core}$) and the numerical aperture (NA) of the fiber ($d_{core} \cdot NA$)/2. According to the coupling conditions between a rectangular beam and a circular fiber, to effectively couple the beam into an optical fiber, the BPPs of the fast axis and the slow axis of the rectangular beam should be less than $\sqrt{2}/2$ times of BPP of the optical fiber, respectively (Yu et al. 2015a, b). Thus, Eqs. (1) and (2) should be satisfied, where $d_{fast}$ and $d_{slow}$ represent the size of the rectangular beam in the fast and slow axes, respectively, and $\theta_{fast}$, $\theta_{slow}$ are the half-divergence angles of the beam.
From Eqs. (1) and (2), it is clear that if the numerical aperture remains the same for optical fiber, a smaller core-diameter of the fiber would directly improve the BPP. For example, if the core diameter can be reduced from 200 to 50 μm while keeping a constant NA, the BPP can be improved by a factor of 4. And this can be achieved based on our following calculations: The specifications of a 1-W green LD manufactured by Nichia are given in Table 1. There is a significant difference between the fast axis divergence half-angle of $\theta_{FA} = 0.4$ rad and the slow axis divergence half-angle of $\theta_{SA} = 0.096$ rad (The degree of angle is converted to radian according to the data shown in Table 1). We need to design a set of mutually orthogonal fast and slow axis collimators (FACs and SACs) to collimate the beams emitted from the LDs. A nearly diffraction-limited aspheric cylindrical lens with a focal length of 3.5 mm is designed as FAC, and a set of positive and negative lens groups with a focal length of 32 mm is designed as SAC. These collimators have been used previously to construct the 12 W green LD module in our group and it worked well (Zhao et al. 2018). The beam sizes of the fast and slow axes after collimation can be obtained from the detector viewer of ZEMAX (Nicola 2010; ZEMAX 2019), which are 2.6 mm and 6.8 mm, respectively. The relationship between radiance and the residual divergence angle and the output beam after collimation is shown in Fig. 1. The residual divergence half-angle of the fast and slow axes after collimation is $\theta_{fast} = 0.78$ mrad and $\theta_{slow} = 1.01$ mrad (1/$e^2$ peak intensity) respectively. Taking $\theta_{fast}$ and $\theta_{slow}$ into Eqs. (1) and (2), $d_{fast} = 9.97$ mm and $d_{slow} = 7.0$ mm can be obtained. Therefore, the maximum quantity of combined beam in the fast and slow axes can be obtained, and they are $N_{FA} = 3$ and $N_{SA} = 1$. Thus, after collimation, three beams can be combined to form a $3 \times 1$ rectangular beam array.

The overall optical configuration of the fiber-coupled module is shown in Fig. 2a. Three LDs are arranged parallelly along the fast axis direction (with an interval of 10 mm), and they are collimated by the FACs and SACs, respectively, and then deflected 90-degrees by three 45-degrees high-reflection (HR) mirrors with the same size (Length: 5 mm; Width: 2 mm; Height: 9 mm). The beams can be tightly stacked and spatially combined along the fast axis by adjusting three HR mirrors. Then, to reduce the volume of the module, the beams are again reflected 90-degrees by a larger HR mirror (Length:

| Table 1 | Optical parameters of green LD single emitter |
|---------|---------------------------------------------|
| Parameter | Typical value |
| Optical output power | 1.0W |
| Center wavelength | 520 ± 5 nm |
| Electro-optic efficiency | 10.13% |
| Fast axis divergence half-angle (Perpendicular direction)$^a$ | 23° |
| Slow axis divergence half-angle (Parallel direction)$^a$ | 5.5° |
| Active area size (Fast axis × slow axis)$^b$ | 1 μm × 15 μm |

$^a$The 1/$e^2$ peak intensity  
$^b$The full width
The beam spot size is 8 mm × 6.8 mm as the beam reaches the coupling lens, as shown in Fig. 2b. Finally, the beams that pass through the coupling lens are focused into the optical fiber. As a thumb of rule, the beam footprint on the facet of the fiber and the beam divergence half-angle must meet the coupling condition, that is:
where $W_{\text{dia}}$ and $\theta_{\text{dia}}$ represent the diagonal length and divergence half-angle of the rectangular beam, respectively. In the simulation, we use a single aspherical focusing lens to focus the rectangular beam. The focal length of the lens can be derived from Eqs. (4) and (5) (Yu et al. 2015a, b), where $f_{\text{FAC}}$ and $f_{\text{SAC}}$ denote the focal length of FAC and SAC respectively, $f_{\text{foc}}$ indicating the focal length of the coupling lens.

Due to the small size of the green LD single emitter, the focal length range satisfying the condition of Eq. (4) is larger than that of Eq. (5). It can be concluded that the divergence angle has more rigorous restrictions on the focal length of the lens compared with the beam size without considering the spherical aberration of the lens. And when Eq. (5) takes the mark of equality, the module has the maximum brightness. Thus, the effective focal length (EFL) of the coupling lens is determined, and a nearly diffraction-limited aspheric lens with the EFL of 25 mm from Thorlabs (AL1225G-A) is selected. In Fig. 2b, the diagonal length of the combined beam is about 10.5 mm. According to Eq. (6), the divergence half-angle of the focused beam could be equal to 0.21.

Figure 3 shows the simulation result of ZEMAX. Figure 3a represents beam divergence angles after focusing, which are about 8.5 degrees in the fast axis and corresponding to 0.15 rad, 8 degrees in the slow axis, and corresponding to 0.14 rad. Figure 3b shows the focused spot, according to the definition of the 4-σ principle (Niu et al. 2015), its size can

\[
W_{\text{dia}} \leq d_{\text{core}}, \theta_{\text{dia}} \leq NA
\]

\[
W_{\text{dia}} = \sqrt{\left(\frac{BPP_{\text{fast}} \cdot f_{\text{foc}}}{\theta_{\text{FA}} \cdot f_{\text{FAC}}}\right)^2 + \left(\frac{BPP_{\text{slow}} \cdot f_{\text{foc}}}{\theta_{\text{SA}} \cdot f_{\text{SAC}}}\right)^2} \leq d_{\text{core}}
\]

\[
\theta_{\text{dia}} = \sqrt{\left(N_{\text{FA}} \cdot \theta_{\text{FA}} \cdot f_{\text{FAC}} \cdot f_{\text{foc}}\right)^2 + \left(N_{\text{SA}} \cdot \theta_{\text{SA}} \cdot f_{\text{SAC}} \cdot f_{\text{foc}}\right)^2} \leq NA
\]

\[
\theta_{\text{dia}} = \frac{W_{\text{dia}}}{2 \cdot f_{\text{foc}}}
\]

Fig. 3  a Simulation result of the beam divergence in the fast and slow axes after focusing; b focusing spot on the fiber facet
be obtained as 28 μm × 40 μm in the fast axis and slow axis, respectively. As we expected, astigmatism in focus is observed because the diode laser beam is an inherent asymmetry between the fast and slow axes. If it is necessary to be eliminated, the beam should be focused separately in the two axes. Here we can find an optimal position that is close to the image plane of the coupling lens by using the global optimization function (ZEMAX 2019) of ZEMAX, where the beam sizes in both fast and slow axes are less than 50 μm as shown in Fig. 3b. Consequently, based on the simulation, the focusing spot can be efficiently coupled into a fiber with a core-diameter of 50 μm and NA of 0.22.

In the simulation, the output power of each LD is set to be 1-W (operating at rated power), so the initial power equals 3 W. The simulated output power after collimation, combination, and fiber-coupling, and corresponding power lost ratio are shown in Fig. 4. The blue line represents the power value after each step, while the pink line represents the power lost ratio to the initial total power. The maximum output power coupled out of fiber can reach 2.65 W with an optical–optical conversion efficiency of 88.3% and a fiber-coupling efficiency of 96%. The maximum power loss occurs in collimation because of the diffraction loss of FACs and SACs.

3 Experimental results and discussion

Figure 5 illustrates the experimental setup with a compact fiber-coupled green LD module that can produce a 1.525 W green laser from a 50 μm/0.22NA fiber based on the design elaborated in Sect. 2. The size of the module is 85 mm × 62 mm × 28 mm.

The spot pattern of the beam after collimation is shown in Fig. 6. Compared with the simulation result, the beam width in the fast axis direction became narrow because a part of the marginal beam is leaked out of the edge of FAC. The leakage of beam and transmission loss of FAC with an AR film of 99.5% lead to about 10% power loss. Besides, the coating loss on the four faces of SAC, each coated with a 99.5% AR film, causes about 2% loss of power. Therefore, the output power of each LD and the sum of the three LDs after collimation are only 0.85 W and 2.5 W, respectively.

As described in Sect. 2, after collimation, the three beams are successively reflected by three small 45-degrees HR mirrors which are evenly spaced along the plane direction, and a large 45-degrees HR mirror to form a beam array. The combined beam is detected by a
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camera-based beam-profiling system (BGS-SP928 produced by Ophir-Spiricon) in front of the coupling lens as shown in Fig. 7. Its size is 7.0 mm × 6.9 mm, and the diagonal width is 9.8 mm. The output power can only reach 2.2 W at this position. When the 45-degrees HR mirrors subsequently reflect a beam with a reflectivity of 99.5%, the light leakage from the edge of the small mirror and reflection loss result in a power loss of 0.3 W.

The divergence half-angle of the beam passing through the coupling lens can be calculated to be \( \theta = 0.20 \) rad. After the optical fiber equipped with SMA connector male is installed on the female connector locating in the module, an optical power meter is placed on the other end of the optical fiber to monitor the output power of the fiber in real-time.

At the cooling temperature of 25 °C, the flow of 6 L/min, continuous-wave operating mode, and typical current (I = 1.5A), the maximum output power of the fiber-coupled module \( P = 1.525 \) W, is ultimately achieved. The root-mean-square (RMS) noise and Standard Deviation of the module are measured of 0.26% and 0.004 W, respectively. The relationship

Fig. 5 Schematic of the green fiber-coupled module

Fig. 6 The beam after collimation
between the power after collimation and the current is described with the red line in Fig. 8. We can obtain that the output power after collimation is 2.5 W under the driving current of 1.5A. And the blue line represents the relationship between the output power after fiber coupling and the driving current. Under the typical current, the output power of the module is 1.53 W, corresponding to a fiber-coupling efficiency of 70%, which can be obtained from the purple line. The optical–optical conversion efficiency and electro-optical conversion efficiency of the coupling module are only 51% and 10%, respectively, and the maximum brightness can reach $0.608 \text{ MW/(cm}^2\text{ sr)}$. It is worth noting that the optical–optical conversion efficiency is much lower than the values in literatures (Zhao et al. 2018; Chin et al. 2017), which is mainly due to the low fiber-coupling efficiency.

The power and loss ratio in each step of the experiment and simulation are illustrated in Fig. 9. There is a significant difference between the results, especially for the fiber-coupling efficiency of only 70% in the experiment, which is far lower than the simulation data of 96%. As shown in Table 2, through comparative analysis of the experimental results and ZEMAX simulation data, we can know the reasons for the differences as follows:

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**Fig. 7** The combined spot after incoherent combination

**Fig. 8** Power-current characteristic curve and coupling efficiency
First, the initial output power of each LD is set to be 1-W in ZEMAX, but in the experiment, the actual output power of the three LD sources we selected is measured as 0.95 W, 0.96 W, 0.96 W, respectively. Second, during the manually assembling and adjusting of the FACs, the position of FACs always deviates from its ideal status so that a part of the beam leaks out from the edge of the FACs, resulting in a power loss of about 0.3 W, while in ZEMAX it is only 0.1 W. Third, to reduce the overall width of the combined beam, the adjacent beams should be closed to each other after the 45-degrees HR mirrors. Thus the beam is partially blocked by the edge of the mirrors in the experiment, which leads to the leakage of the beam. Fourth, surfaces of all optics are coated with an AR coating of 99.9999% in ZEMAX, but in practice, they are about 99.5%. Especially for the end faces of the optical fiber, which are not coated, an additional 8% power loss is added. Finally, the global optimization function of ZEMAX can be used to find the optimal positions of FACs, SACs, HR mirrors, focusing lenses, and fiber. However, due to the limitation of assembly accuracy, it is not easy to find the optimal position in the experiment. Thus, the spot diameter near the focus point may have exceeded 50 μm and cause large losses. To sum up, low efficiency is caused by a variety of reasons. The design parameters of the simulation are not revised according to the experimental measurement, such as the power of LDs, the reflectivity of each optical component, etc. Because the simulation provides the maximum output power that the design can obtain, which will provide the optimization direction for future experiments.

Table 2  The comparison of experimental data and Zemax simulation

| Components            | Experiment | Simulation |
|-----------------------|------------|------------|
|                       | Out power (W) | Loss power (W) | Out power (W) | Loss power (W) |
| LD source             | 2.87       | –          | 3.00         | –              |
| FACs and beam leakage | 2.57       | 0.30       | 2.90         | 0.10           |
| SACs                  | 2.50       | 0.07       | 2.85         | 0.05           |
| HR Mirrors and edge leakage | 2.20     | 0.30       | 2.76         | 0.10           |
| Focusing lenses       | 2.175      | 0.025      | 2.75         | 0.01           |
| Optical-fiber coupling | 1.525      | 0.65       | 2.65         | 0.10           |

Fig. 9  The comparison between the experimental result and the simulation result. a Power and b loss ratio
4 Conclusion

In this paper, by collimating in the fast and slow axes, spatial combination, and focusing, three LDs have been coupled into an optical fiber with 50 μm core-diameter and 0.22NA, a fiber-coupled diode module is presented both by simulation of ZEMAX and experiment. The output power of about 1.53 W at 520 nm and brightness of 0.608 MW/(cm² sr) is obtained in the experiment. The optical–optical conversion efficiency is 51%, and the electro-optical conversion efficiency is 10%. The tolerances between the simulated data and the experimental results are also analyzed. The design presented here can be further combined with polarization multiplexing for coupling more LDs into an optical fiber to double the output power with the same beam quality.

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Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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