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Research Article

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Posted Date: February 9th, 2021

DOI: <https://doi.org/10.21203/rs.3.rs-175061/v1>

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1.5-W 520 nm continuous-wave output from a 50 μ m/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 520nm 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 μ m and a numerical aperture of 0.22. The final output power of 1.53w is obtained, corresponding to an optical-optical conversion efficiency of 51% and an electro-optical conversion efficiency of 10%, and the tolerance between the simulation and the experimental result is analyzed and explained.

Keywords: spatial combination, ZEMAX simulation, green laser diode, fiber-coupled module.

1. Introduction

Laser diodes (LDs) in the range of visible wavelength 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. The output power of the red LD stack can be as high as 56W and the optical-coupled module constructed by incoherent combination has a maximum output power of 100W (Andreas et al. [2013](#)). The blue LD bar has reached 98W, and the fiber-coupled module based on the bar has reached 1KW presented by Laserline and OSRAM in February 2019 (Baumann et al. [2019](#)). And in September 2020, Nuburu launch the latest blue fiber-coupled module (Feve J et al. [2020](#)), AI-1500, which increase the power to 1.5KW under 11 mm·mrad from a 100 μ m /0.22 numerical aperture (NA) fiber, taking a different approach that mounts Osram's GaN single-emitter diodes on a chip in series. For green direct diode laser, it has become an attractively alternative pump source of Ti: sapphire oscillator because of its low cost and without using liquid nitrogen cooling at high power compared to blue LD module. However, the research progress of high-power green LD is very slow due to the "green gap" difficulty. Until 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](#)) but all LDs are single-mode with low power which is not enough for scale applications. In 2013, Nichia successfully manufactures a multimode green LD single emitter with a power up to 1W and a central wavelength of 520nm based on AlInGaIn grown on c-face GaN substrate (Masui et al. [2013](#)). Up to date, the maximum output power of a green LD is merely 1.5-W produced by Nichia (NICHIA [2020](#)). In 2016, based on the green LDs, Dilas proposes a green fiber-coupled module of 2W, with a central wavelength of 520nm, an optical-fiber core diameter of 200 μ m, and a NA of 0.22, corresponding to a brightness of $0.042\text{MW}/(\text{cm}^2 \cdot \text{sr})$ (Dilas [2016](#)). In 2018, a 12 W green output is achieved from a 200 μ m /0.22NA fiber-coupled module based on 16 1-W single emitters, and the corresponding brightness is $0.34\text{MW}/(\text{cm}^2 \cdot \text{sr})$ (Zhao et al. [2018](#)). However, the beam quality of such lasers is not good enough for some applications. For example, when the above laser diode is used for pumping a laser medium, the beam is focused on a spot with a diameter of around 150 μ m, its corresponding Rayleigh length is about 1 mm, which is not suitable for pumping a gain

medium with a length of more than 2 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 power of more than 20 watts(Miao et al. [2020](#)). The experimental results show that the final optical-to-optical efficiency is heavily dependent on the beam quality of the pumping source. Therefore, based on the requirement of end-pumping of Ti: sapphire with a length of 5mm or more, 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.

In this paper, we show 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 / 0.22 NA optical fiber. The implementation process of the module is demonstrated through both the simulation of ZEMAX and the experiment. Total output power is over 1.5W, which corresponds to a brightness of $0.608\text{MW}/(\text{cm}^2 \cdot \text{sr})$. And compared with the former pumping source, a 4-folds increase of Rayleigh length, which is about 4 mm, can be obtained. Such a design provides a better choice for pumping longer Ti: sapphire crystals.

2. Designs and simulations

In this paper, the beam parameter product (BPP) is used to describe the beam quality of LDs, which is 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 of core-diameter (d_{core}) and numerical aperture (NA) of the fiber, that is $(d_{\text{core}} \cdot \text{NA})/2$. According to the coupling conditions between a rectangular spot 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. [2015](#)). Thus, Eq. (1) and Eq. (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 θ_{fast} , θ_{slow} are the half-divergence angles of the beam.

$$d_{fast} \cdot \theta_{fast} \leq \frac{d_{core} \cdot NA}{\sqrt{2}} \quad (1)$$

$$d_{slow} \cdot \theta_{slow} \leq \frac{d_{core} \cdot NA}{\sqrt{2}} \quad (2)$$

It is clear from Eq. (1) and (2) that for an optical fiber if the numerical number NA remains the same, a smaller diameter of the fiber core d_{core} would improve the BPP directly. For example, if the core diameter can be reduced from 150 μ m to 50 μ m while keeping a constant NA , the BPP can be improved by a factor of 3. 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 $\theta_{FA} = 0.4rad$ and the slow axis divergence half-angle of $\theta_{SA} = 0.096rad$ (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 3.5mm 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, which are 2.6mm and 6.8mm respectively. The relationship between radiance and the residual divergence angle, as well as the output beam spot after collimation, is given as shown in Fig.1. The residual divergence angle of the fast and slow axes after collimation is $\theta_{fast} = 0.78mrad$ and $\theta_{slow} = 1.01mrad$ ($1/e^2$ peak intensity) respectively. Taking θ_{fast} and θ_{slow} into Eq. (1) and (2), $d_{fast} = 9.97mm$ and $d_{slow} = 7.0mm$ 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 3×1 rectangular beam array.

Table 1. Optical Parameters of Green LD single emitter

Parameter	Typical value
Optical output power	1.0w
Center wavelength	$520 \pm 5 \text{ nm}$
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 $\times$ slow axis) ^b	$1 \mu\text{m} \times 15 \mu\text{m}$

^aThe $1/e^2$ peak intensity; ^bThe full width

Fig. 1 The relationship between radiance and residual divergence angle and the insert map is output profile after collimation

Fig. 2 (a) Optical configuration of the green fiber-coupled module; (b) Beam spot captured by ZEMAX after combination

The overall optical configuration of the fiber-coupled module is shown in Fig.2(a). 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: 5mm; Width: 2mm; Height:9 mm). By adjusting three HR mirrors, the beams can be tightly stacked and spatially combined along the fast axis direction. Then, to reduce the volume of the module, the beams are again reflected 90 degrees by a larger HR mirror (Length: 10 mm, width: 2mm, height: 8 mm). The beam spot size is 8mm×6.8mm as the beam reaches the coupling lens as shown in Fig.2(b). Finally, the beams 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 must meet the coupling condition, that is:

$$W_{dia} \leq d_{core}, \theta_{dia} \leq NA \quad (3)$$

where W_{dia} and θ_{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. [2015](#)), where f_{FAC} and f_{SAC} denote the focal length of FAC and SAC respectively, f_{foc} indicating the focal length of the coupling lens.

$$w_{dia} = \sqrt{\left(\frac{BPP_{fast} \cdot f_{foc}}{\theta_{FA} \cdot f_{FAC}} \right)^2 + \left(\frac{BPP_{fast} \cdot f_{foc}}{\theta_{FA} \cdot f_{FAC}} \right)^2} \leq d_{core} \quad (4)$$

$$\theta_{dia} = \sqrt{\left(N_{FA} \cdot \frac{\theta_{FA} \cdot f_{FAC}}{f_{foc}} \right)^2 + \left(N_{FA} \cdot \frac{\theta_{FA} \cdot f_{FAC}}{f_{foc}} \right)^2} \leq NA \quad (5)$$

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 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 25mm from Thorlabs (AL1225G-A) is selected. In Fig. 2(b), the diagonal length of the combined beam is about 10.5mm.

According to Eq. (6), the divergence half-angle of the focused beam could be equal to 0.21.

$$\theta_{dia} = \frac{w_{dia}}{2 \cdot f_{foc}} \quad (6)$$

The beam divergences in the fast and slow axis are simulated using ZEMAX, in the simulation, a rectangular detector is placed at the image plane of the coupling lens. The numerical irradiance of the ZEMAX simulation is illustrated in Fig. 3(a) and the image of the focused spot of the rectangular beam obtained by the detector is shown in Fig. 3(b), whose size is $28\mu\text{m} \times 40\mu\text{m}$ in the fast axis and slow axis, respectively. As we expected, astigmatism in the focus is observed because the diode laser beam is the 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 closed to the image plane of the coupling lens by using the global optimization function of ZEMAX, where the beam sizes in both fast and slow axes are less than $50\mu\text{m}$ as shown in Fig.3(b). It can be seen that the beam divergence half-angle in the fast and slow axes after coupling lens are about 8.5-degrees and 8-degrees, corresponding to 0.15 rad and the 0.14 rad. Consequently, based on the simulation, the focusing spot can be efficiently coupled into a fiber with a core diameter of $50\mu\text{m}$ and NA of 0.22.

Fig. 3 (a)Simulation result of the beam divergence in the fast and slow axes after focusing; (b) Focusing spot on the fiber facet

Fig. 4 shows three green LDs are coupled into the fiber, and the maximum output power reaches 2.65w after fiber coupling with the optical-optical conversion efficiency of 88.3% and the fiber coupling efficiency of 96%. The power and the power loss ratio

in each step are illustrated in Fig.4. From which the maximum power loss occurs in the process of collimation because of the Fresnel reflection loss of FACs and SACs with both antireflection (AR) films of 99.5%.

Fig. 4 The output power and loss ratio at maximum power

3. Experimental results and discussion

Fig.5 shows the experimental setup that is a compact fiber-coupled green LD module based on the design elaborated in section 2. The size of the module is 85mm×62mm×28mm. The rays in Fig. 5(a) illustrates the process of three beams being coupled into the optical fiber. Fig. 5(b) illustrates a photograph of the module that can produce 1.53W- green laser from a 50μm /0.22NA fiber.

Fig. 5 Schematic of the fiber-coupled module. (a) top view of the mechanical drawing of the module and (b) photograph of the module

The spot pattern of the beam after collimation is shown in Fig.6. Compared with the simulation result, the beam width in the direction of the fast axis 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 of which is 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 0.85W and 2.5W, respectively.

Fig. 6 The beam after collimation

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

Fig. 7 The combined spot after incoherent combination

The divergence half-angle of the beam passing through the coupling lens can be calculated to be $\theta = 0.20rad$. 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 ($I = 1.5\text{A}$), the maximum output power of the fiber-coupled module, $P = 1.525\text{W}$, is ultimately achieved. The relationship between the power after collimation and the current is described with the red line in Fig.8, from which we can obtain that the output power after collimation is 2.5W 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 1.53W, 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 51% and 10% respectively, and the maximum brightness can reach $0.608\text{MW}/(\text{cm}^2 \cdot \text{sr})$.

Fig. 8 Power-current characteristic curve and coupling efficiency

The power and loss ratio in each step of the module and simulation are illustrated in Fig.9. There is a significant difference between the experimental result and the simulation result, especially for the fiber-coupling efficiency of only 70% in the experiment which is far lower than the simulation data of 96%. This can be explained from the following:

First, the initial output power of each LD is set to 1W in ZEMAX, but in the experiment, the actual output power of three LD is measured as 0.95W、0.96W、0.96W, respectively.

Second, the reflectivity of all mirrors can reach 100% in ZEMAX, but the reflectivity of HR-mirrors in the experiment can only reach 99.5%.

Third, the surface of the focusing lens is coated with an AR coating of 99.9999% in ZEMAX, but in practice, it is only 99.5%. And the end facet of optical fiber is coated with an AR coating of 99.9999% in ZEMAX, but the optical fiber used in the experiment is not coated. The theoretical value of fiber-coupling efficiency can only reach 92%.

In addition, the global optimization function of ZEMAX can be used to find the optimal positions of FACs, SACs, HR mirrors, focusing lens, and fiber. However, due to the limitation of assembly accuracy, it is difficult to find the optimal position in the experiment. Therefore, the spot diameter near the focus point may have exceeded 50 microns because of the existence of assembly error. The CCD detector head cannot be placed near the focusing spot for a compact volume of the module, so the spot diameter cannot be accurately obtained. Later, we replace a fiber with a core diameter of 100 μ m and NA of 0.22, and the output power has been increased to 1.83W, corresponding to a coupling efficiency of 87%, which indirectly verify our conjecture.

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 coupled into an optical-fiber with 50 μ m core diameter and 0.22 NA, a fiber-coupled diode module is presented both stimulatingly and experimentally. The output power of about 1.53W at 520 nm and brightness of $0.608\text{MW}/(\text{cm}^2 \cdot \text{sr})$ is obtained in the experiment. The optical-optical conversion efficiency is 51% and the electro-optical conversion efficiency is 10%. The tolerance 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.

Declarations

Acknowledgements: This work has been sponsored by the National Key Research and Development Program of China (2016YFB0401804). And we thank Professor J. Y. Zhang for his help in the preparation of the paper.

Compliance with Ethical Standards

Conflicts of interest: The authors declare that they have no conflict of interest.

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Figures

Figure 1

The relationship between radiance and residual divergence angle and the insert map is output profile after collimation

Figure 2

(a) Optical configuration of the green fiber-coupled module; (b) Beam spot captured by ZEMAX after combination

Figure 3

(a) Simulation result of the beam divergence in the fast and slow axes after focusing; (b) Focusing spot on the fiber facet

Figure 4

The output power and loss ratio at maximum power

Figure 5

Schematic of the fiber-coupled module. (a) top view of the mechanical drawing of the module and (b) photograph of the module

Figure 6

The beam after collimation

Figure 7

The combined spot after incoherent combination

Figure 8

Power-current characteristic curve and coupling efficiency

Figure 9

The comparison between the experimental result and the simulation result. (a) power and (b) loss ratio