Optical Tuning of VCSEL Side-pumped Nd:YAG Laser Cavity

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Abstract High-power 808 nm vertical-cavity surface-emitting laser (VCSEL) chips have unique characteristics for Nd:YAG laser pumping compared with conventional edge-emitting laser bars, including a chip surface with high reflectivity, near flat top distribution in near field, bigger emitting width and smaller divergence. A novel symmetrical pump cavity with inter-reflective chamber was invented by introducing even-numbered pumping geometry and removing the conventional internal reflector. Several optical tuning measures were taken to improve the uniformity of the pumping distribution, including power and spectrum balancing in the cross section and long axis of the laser rod, a diffuse mechanism in the pump chamber by frosted flow tube, and an optional eccentric pumping geometry. A series of VCSEL pumping experiments were conducted therefore and optical

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tuning measures were evaluated through distribution profiles and efficiencies. A new design philosophy for VCSEL side-pumped Nd:YAG laser cavity was finally developed.

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Key words: high-power 808 nm VCSEL; laser Cavity; Nd:YAG laser; Side-pumping; VCSEL-pumped laser

I. INTRODUCTION

HIGH-POWER 808nm laser diodes, especially for edge-emitting laser (EEL) diode bars, have been widely used for Nd:YAG pumping in CW and QCW (Quasi-CW) mode[1]. Compared with edge-emitting laser diodes, high-power vertical-cavity surface-emitting laser (VCSEL) chips are considered as an alternative pumping source due to better wavelength stability, higher operation temperature, higher reliability, higher repetition rate, longer lifetime and lower manufacture cost[2, 3]. VCSEL has a λ/4 DBR based microcavity thus the wavelength is generally stabilized with a typical shift of around 0.07 nm/K[4] while EEL has a wavelength shift of around 0.28 nm/K[5] at 808nm. Compared with challenging catastrophic optical damage (COD) of EEL[6], there is no optical coating on VCSEL facet and the optical power density is much lower than the EEL, thus there is no COD risk for VCSEL at high temperature, over current inrush or other harsh conditions. The lifetime of VCSEL is expected at least 50 times longer than EEL[3]. The only optical limit from VCSEL is thermal rollover when junction is over heated. The uniform distribution of thousands of mW level emitters on a large VCSEL chip offers a better heat stress during pulsed conditions compared with EEL with Watts level striped emitters so that long lifetime and stability can be expected at high-repetition rates up to several kHz. High-repetition rate VCSEL-pumped laser amplifiers have been successfully used for space debris laser ranging

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at 1 kHz, demonstrating stable operation for years[7]. The fabrication and packaging of VCSEL follow a standard wafer level procedures like LED industry thus the manufacture cost is lower than EEL which involves with cleaving, facet coating and critical packaging procedures[8]. The general structure comparison of EEL and VCSEL is shown in Figure 1.

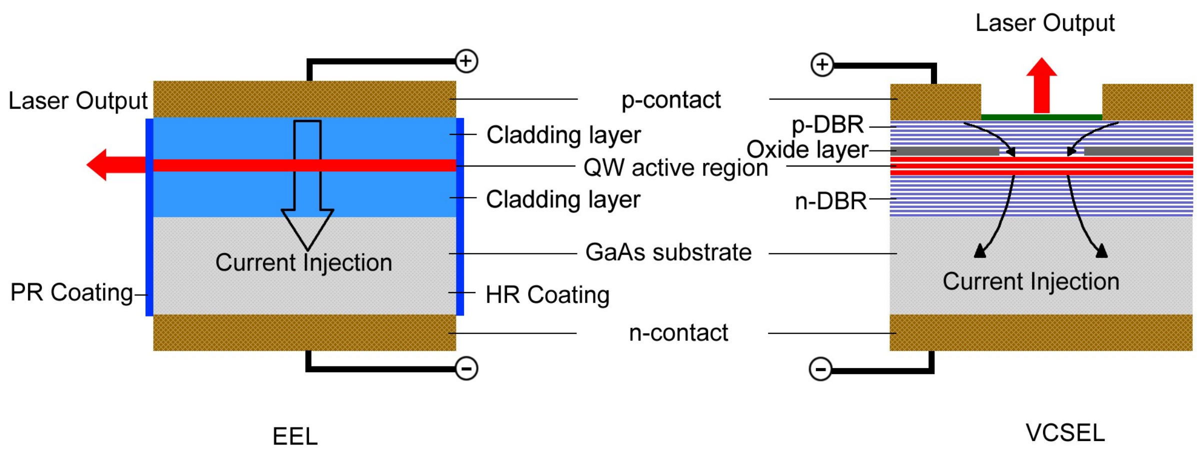

Figure 1. Edge-emitting laser (EEL) and VCSEL structures[9]. Unlike optical coating on the facets of EEL, VCSEL has a COD-free DBR facet grown via epitaxy.

Regarding the laser diode pumps for inertial fusion energy lasers, Lawrence Livermore National Laboratory predicted that the possible future use of surface emitting diodes may offer appreciable future cost reductions and increased reliability[10] in 2011. However, the high-power VCSEL was not ready for volume commercial use during that time due to lower power conversion efficiency (PCE), complicated substrate removal process during chip fabrication and expensive CVD diamond packaging[11]. By authors' efforts recently, high-power single-junction 808 nm VCSEL chips with regular 100 μm thickness substrate and metallized AlN ceramic packaging are now able to offer 100 W CW output power per chip with maximum 44% PCE and 270 W QCW output power with maximum 50% PCE[12]. The fabrication and packaging of these high-power VCSEL chips are mature and production yield is very high. The cost per Watt is now

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becoming lower than EEL laser bars. Higher PCE can be expected with further improvements, and optical power per chip can be doubled or tripled with multi-junction epitaxy in the near future. The high-power VCSEL for solid-state pumping is now ready for commercial use.

Among all the diode-pumped Nd:YAG lasers, side-pumping is the most popular method to get high-power and high-energy output and widely used for industrial, scientific and medical applications[13,14]. A typical side-pumped Nd:YAG laser resonator is shown in the Figure2.

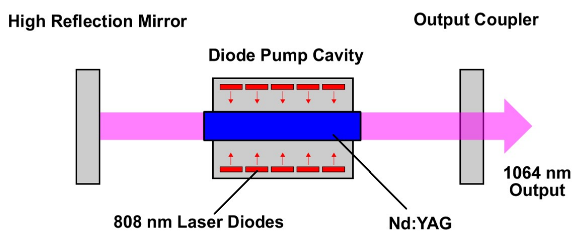

Figure 2. Resonator of a diode side-pumped Nd:YAG laser.

Typical cross section of the side-pumped laser cavity contains laser diode arrays (LDA), a reflector and a laser rod. For water-cooled pump modules, a glass flow tube is usually included between the reflector and laser rod, providing water flow for cooling, as shown in Figure 3. In the textbook of *Solid-State Laser Engineering*, Dr. W. Koechner summarized a basic scheme of a pump chamber with 3 directions of LD arrays, a laser rod and a diffuse reflector[1]. In 2001, S. Fujikawa, K. Furuta, and K. Yasui reported a side-pumped Nd:YAG laser with 6 directions pumping which was combined by two circles of 3-direction pumping units with 60 degrees rotation to avoid reciprocal emitting[15]. In 2009, S.G. Grechin and P.P. Nikolaev mentioned a scheme of a pump module design with 9 directions and a mirror reflector[16]. In 2016, RRCAT of India reported a modular pump head designed with 3-direction pumping discs around Nd:YAG rod and it was observed that the triangular like beam profile by the single disc pumping (120 degrees) was greatly averaged out when two rotated discs pumped together from 6 directions (60 degrees)[17]. The most popular commercial pump modules delivered by Northrop Grumman Cutting Edge Optronics (NG CEO) are typically designed with 3, 5, 7 and 9 pumping directions with internal reflectors. Fluorescence light of a NG CEO RE22 pump module[18] is shown in Figure 4.

In these conventional pumping geometry, odd-numbered LD arrays are adopted to avoid reciprocal damage between the opposite pump diodes because the edge-emitting laser bars usually suffer from strong light injection with catastrophic amplification due to low reflectivity of the emitting facet, such as 10% typically for example[19]. To increase the absorption of the pumping beam and improve the pumping distribution, an internal reflector is usually needed to collect the unabsorbed pumping beam and turn it back for further absorption. This internal reflector is either coated with gold as mirror reflector or made directly from diffuse reflectance material with high reflectivity. This internal reflector is widely used in commercial pump modules by laser manufacturers including NG CEO, Rofin-Coherent, FOBA and many others.

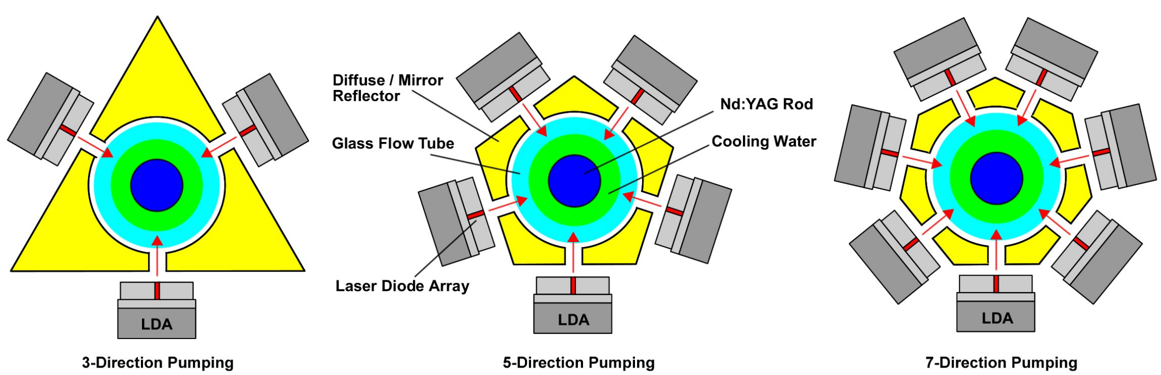

Figure 3. Conventional laser diode pump cavities. Odd-numbered LD arrays are aligned to avoid reciprocal damage and internal reflector is introduced to improve absorption and efficiency.

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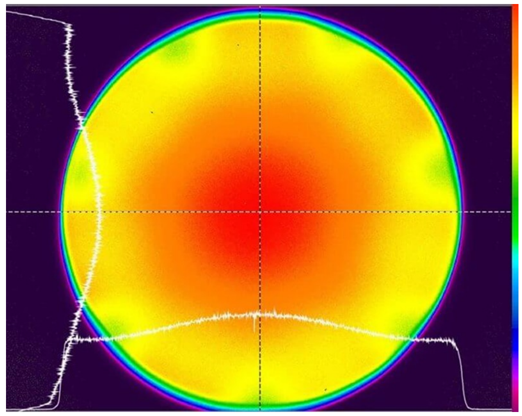

Figure 4. Fluorescence distribution from a NG CEO REA22 pump module[18]. Pumping beam traces from 7 directions can be clearly figured out and beam profile has no circular symmetry.

In the past a few years, a few researchers reported several VCSEL-pumped Nd:YAG laser experiments. In 2012, Princeton Optronics demonstrated a VCSEL side-pumped Nd:YAG laser slab with face-to-face pumping geometry[20]. Two VCSEL stacks collimated by cylindrical lenses were placed at the opposite side facets of the laser slab for pumping. In 2016, W. Chao reported a VCSEL-pumped Nd:YAG rod laser with 7 rows of pumping arrays in a gold coated reflective chamber[21]. In 2022, a VCSEL-pumped rod laser with 652 W CW power and 52.6% optical efficiency was reported by X-P. Li and the laser module was designed with 8mm Nd:YAG rod with pumping in 5 directions[22].

However, the unique characteristics of VCSEL compared with edge-emitting laser diode bars were not fully discovered and significant opportunities remain for the optical tuning of the pumping geometry. In this paper, we will demonstrate a novel pumping geometry and multiple optical tuning mechanisms for VCSEL side-pumped Nd:YAG laser cavity.

II. VCSEL CHARACTERISTICS FOR PUMPING

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The wafer for the 808 nm VCSEL chip is usually prepared with MOCVD system based on n-type GaAs substrate. During epitaxy, the wafer was latticed with n-DBR at the bottom with high reflectivity close to 100% and p-DBR at the emitting facet with reflectivity approximately 99% because the feedback of the emitting facet must be maintained at a very high level to reach the lasing threshold due to the low gain inside of the VCSEL cavity. During the fabrication process of the VCSEL, selective wet oxidation is used to form current and optical confinement, and metallization is introduced for the electrodes both at the bottom and the facet. Gold coating is deposited on the top of the VCSEL chip for current injection and wire bonding purposes. The general structure of the VCSEL is shown in the Figure 5. The overall surface of the bare die has a high reflectivity from top DBR and gold coating in the rest area, as shown in the Figure 6.

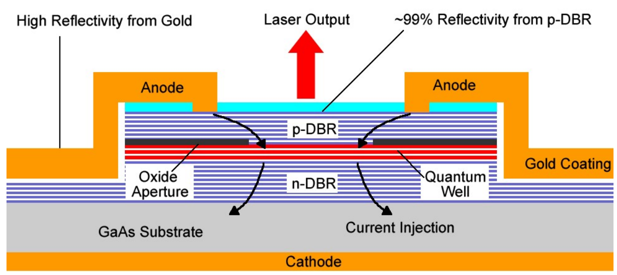

Figure 5. VCSEL resonator principle. The surface of VCSEL chip is highly reflective and external photon injection won't cause any damage in the emitters.

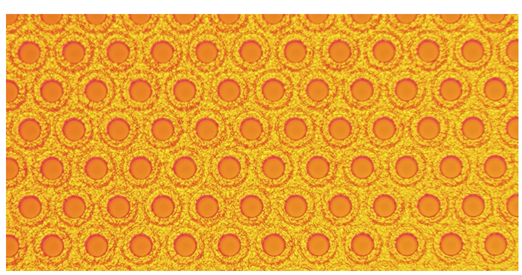

Figure 6. VCSEL emitting facet photo taken by authors from an actual chip.

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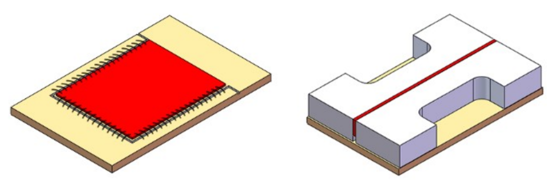
Chip-on-Submount (CoS) packaging is processed after fabrication of the bare die. Metallized AlN submount is the most popular material for die attach and wire bonding. The metallization of the submount contains thick layer of copper at the bottom and gold coating at the surface. The finished VCSEL chip in CoS package is shown in the Figure 7(a). Compared with the typical laser bar packaging, as shown in Figure 7(b), the VCSEL package has a much bigger emitting area rather than a linear emitting line from the laser bar between the clamping electrodes. Apparently the CoS VCSEL package has a very high reflection surface due to the top DBR and gold coating both on the chip and on the submount and this characteristic can be used as reflector in the pumping design rather than the surface of a laser bar assembly.



(a) (b)

Figure 7. (a) VCSEL in CoS package on metallized AlN submount with rectangular emitting area and (b) laser bar assembly with linear emitting line between the clamping electrodes.

Compared with edge-emitting laser bars, another major difference is the divergence and beam profile. The laser bar has a linear emitting line with fast axis divergence up to 35~40 degrees (FWHM) and slow axis divergence up to 7~10 degrees (FWHM) while VCSEL has a uniform 2D emitting area with a uniform divergence of around 15~20 degrees (FWHM) in all axis. Microlensing can be introduced to reduce the divergence of VCSEL if needed[23]. In the near field distance for pumping applications, which is usually a few millimeters to the laser crystal, the beam distribution of VCSEL is close to near flat top though the far field distribution varies due to the different modes from the emitters. If the emitting width of the VCSEL is less

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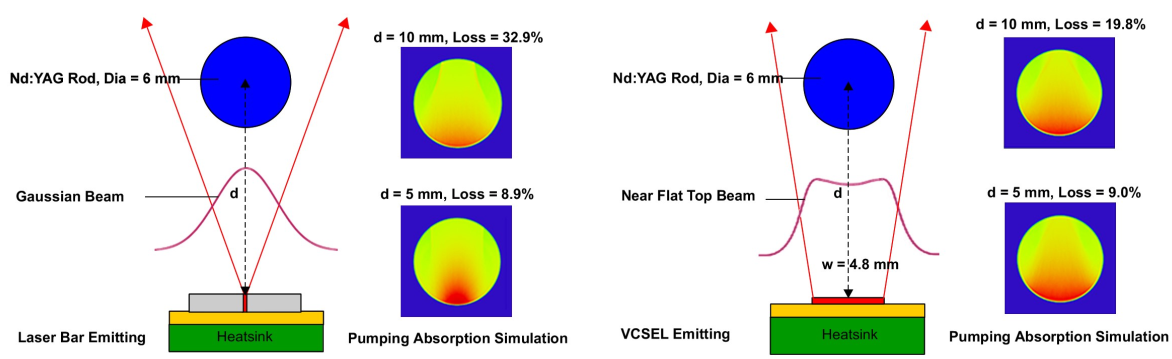
than the laser rod diameter, most of the pump power can be evenly spread in the laser rod surface with very few optical loss. However, due to the bigger divergence and Gaussian distribution in fast axis, the laser bar's pumping is either uneven at very short distance or with a very high loss in longer distance.

The single pass pumping and absorption distribution can be described by optical simulation in Figure 8. In this optical simulation, the distance (d) from the emitting facet to the center of the Nd:YAG is set at 5 mm and 10 mm. The Nd:YAG diameter is 6mm. Considering a variable doping of Nd:YAG from 0.6% to 1.1% and a practical pumping wavelength from 804 nm to 809 nm, we suppose a reasonable absorption coefficient of 4 cm^{-1} in average during the simulation. The emitting width (w) of VCSEL is set at 4.8 mm with a divergence of 18 degrees (FWHM). The divergence of the laser bar is set at 36 degrees (FWHM) in fast axis. In the long axis direction of the laser rod, we suppose uniform distribution and identical pumping power density per centimeter for both laser bar and VCSEL. Different absorption uniformity can be found from the cross section of the Nd:YAG.



(a) (b)

Figure 8. Single pass pumping and absorption simulation at different distances from (a) laser bar and (b) VCSEL.

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The simulation shows clearly that the VCSEL pumping can offer a better uniformity while maintaining a lower loss for the single pass pumping absorption compared with laser bar pumping at short pumping distance.

III. OPTICAL TUNING OF VCSEL PUMP CAVITY

3.1 Optical tuning targets and general measures

Although the application requirements may vary, most of the solid-state laser systems are pursuing two important performances: beam profile and efficiency. For side-pumped Nd:YAG rod lasers, near flat top or Gaussian beam profile is usually expected for amplifiers and oscillators. Optical-to-optical efficiency should be optimized so that laser diode power can be used economically and also the side effects of the wasted heat can be minimized. In a well-designed pump cavity, these two optical tuning targets must be both taken into account.

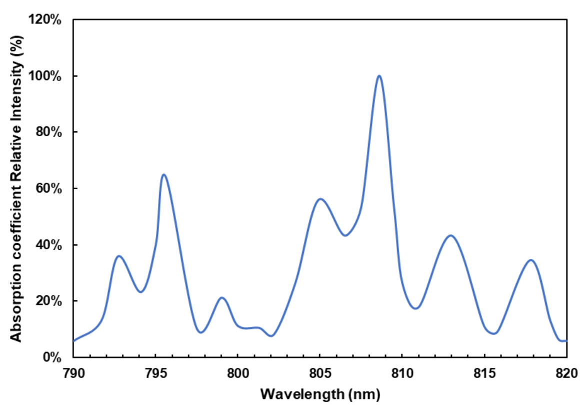

Figure 9. Absorption spectrum of Nd:YAG with peak absorption at 808.5nm. Absorption data was provided by Beijing Opto-Electronics Technology Co., Ltd. and figure was drafted by authors for reference only.

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One important measure is to ensure the whole circle of the pump diodes with same or similar optical power and spectrum characteristics in the cross section plane of the Nd:YAG rod. Due to different absorption level at different wavelength, Nd:YAG pumping is sensitive to the wavelength distribution from the laser diodes. For efficient absorption, laser diode is usually designed at central wavelengths from 804 nm to 809 nm to match the highest peak of the absorptance. However, the wavelength deviation of the laser diode both in the cross section and in the axis direction of the Nd:YAG will cause uniformity problem. The central wavelength must match the Nd:YAG rod diameter and doping level so that a proper path length of the pumping beam can be expected. As absorption coefficient is higher at 808.5 nm, the absorption is very strong near this peak wavelength and the path length of the absorption is very short compared with pumping wavelength far from 808.5 nm, such as 804 nm or 810 nm for example. For bigger diameter or higher doping, pumping wavelength with lower absorptance is required, which is also called wing pump. For smaller diameter or lower doping, pumping at the peak absorptance is preferred.

In the long axis direction of the laser rod, same wavelength from each circle is preferred as well. However, from practical point of view, it is not always economical to pick up exactly the same central wavelength for pumping because the deviation of the central wavelength during laser diode wafer epitaxy is up to ±2.5 nm at modern industrial standards. The tolerance of central wavelength exists not only from wafer to wafer but also from center to edge of the same wafer due to the uniformity limit of the lattice growth in MOCVD. Strict wavelength sorting apparently will increase the cost of the pump diodes. Of course, VBG or other wavelength stabilization methods can be introduced but it will increase the cost as well. In case it is not economically possible to pick up exactly the same wavelength, mixed wavelength between

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different circles is also acceptable, but path length of the absorption must be considered to compensate each other between different circles to ensure the uniformity of the accumulated absorption in the whole laser rod. Please refer to Figure 10.

The intensity distribution of the pump diodes is also important. Just like the central wavelength deviation, the threshold current, slope efficiency and optical power of each laser diodes are also not uniform from wafer to wafer and from center to edge of the same wafer. The laser diode's optical power control is following the same rule like the central wavelength distribution that try to keep the uniformity of each circle and find a proper compensation between different circles.

The central wavelength and optical power of the pump diodes can be controlled by laser diode chip sorting procedures in advance. Nevertheless, from the epitaxy view of point, most of the laser diode chips have similar performance in adjacent area from the same wafer. So using the chips from an adjacent area for each circle is an easy solution.

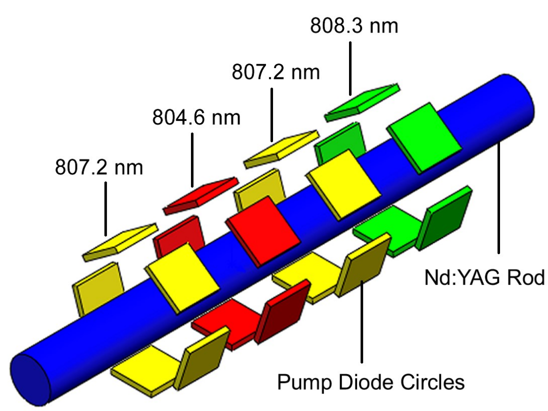

Figure 10. Pump diode alignment around the Nd:YAG rod with uniform wavelength per circle. Each circle is required to be the same wavelength and same optical power.

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The other measure is to ensure the wavelength of the laser diode to be designed against specific conditions for pumping purpose. Besides normal wavelength temperature coefficient of 0.07 nm/K for VCSEL or 0.28 nm/K for laser bar, the laser diode's central wavelength also changes against operation current, pulse width and etc. At a higher temperature, higher current or longer pulse width, the central wavelength has red-shift due to the temperature rise in the junction. For example, a laser diode bar may have a wavelength of 808 nm at CW but 804 nm at QCW (200 μs, 20 Hz typically) conditions at the same 40 A operation current, and a VCSEL chip may have a wavelength of 808 nm under CW but 806.5 nm under QCW (200 μs, 20 Hz typically) conditions at the same 60 A operation current.

3.2 Symmetrical pump cavity with inter-reflective chamber

Since the VCSEL chip in CoS package has a high reflection surface and the facet is not sensitive to external pumping beam injection, the cross section of the pump cavity can be designed to symmetrical geometry instead of odd-numbered pumping directions. The surface of the VCSEL chip can be used as reflector to the unabsorbed pumping beam from the opposite VCSEL. In this inter-reflective chamber, this symmetrical alignment of the VCSEL chips can improve the absorption of the pumping beam. On the other hand, the internal reflector in the conventional pump cavity can be removed if the emitting width of the VCSEL is less than or close to the laser rod diameter. Among all the possible symmetrical pump cavity designs, a typical hexagonal cavity is shown in Figure 11.

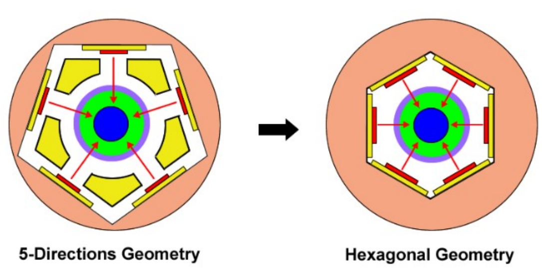

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Figure 11. Pump cavity comparation between odd-numbered and even-numbered directions.

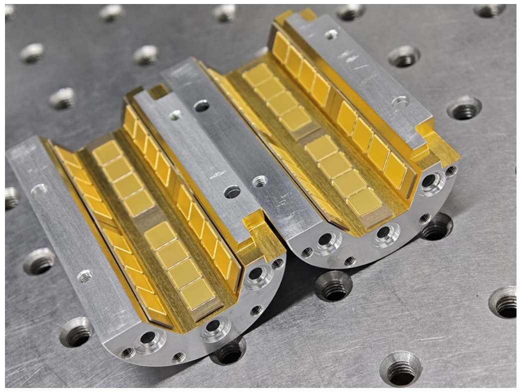
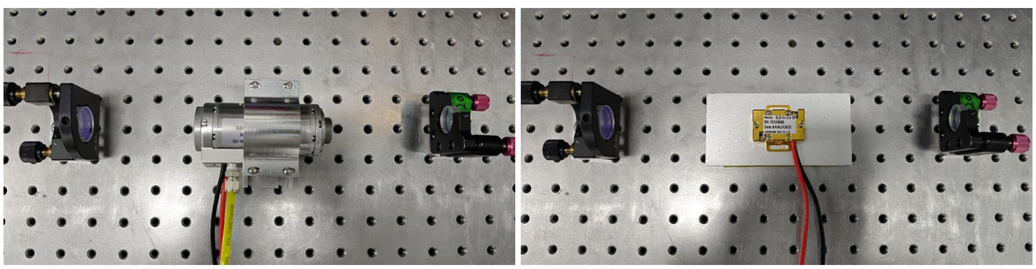


Figure 12. Two VCSEL stacks from a hexagonal pump cavity with 3 rows of VCSEL arrays each. These two stacks will be combined as an inter-reflective pump chamber.



(a) (b)

Figure 13. Pumping experiments with (a) water-cooled pump module and (b) conductively-cooled pump module. The 1064 nm output power/energy is measured in a plano-plano resonator with output coupler with T=20% (R=80%) and cavity length of approximately 250 mm.

Several experiments were conducted with different pumping directions from 3, 4, 5, 6, 8 directions and different Nd:YAG rods with diameter from 4 mm up to 10 mm. The doping level is 0.8%~1% for the Nd:YAG rods. Both conductively-cooled pump modules and water-cooled pump modules were designed. For each pump module, the fluorescence was captured at the end of the Nd:YAG rod with camera and absorption beam profile was analyzed. After fluorescence measurement, output energy at 1064nm was measured in the plano-plano resonator as shown in

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Figure 13 and optical-to-optical efficiency was then calculated. The final results are listed in Figure 14.

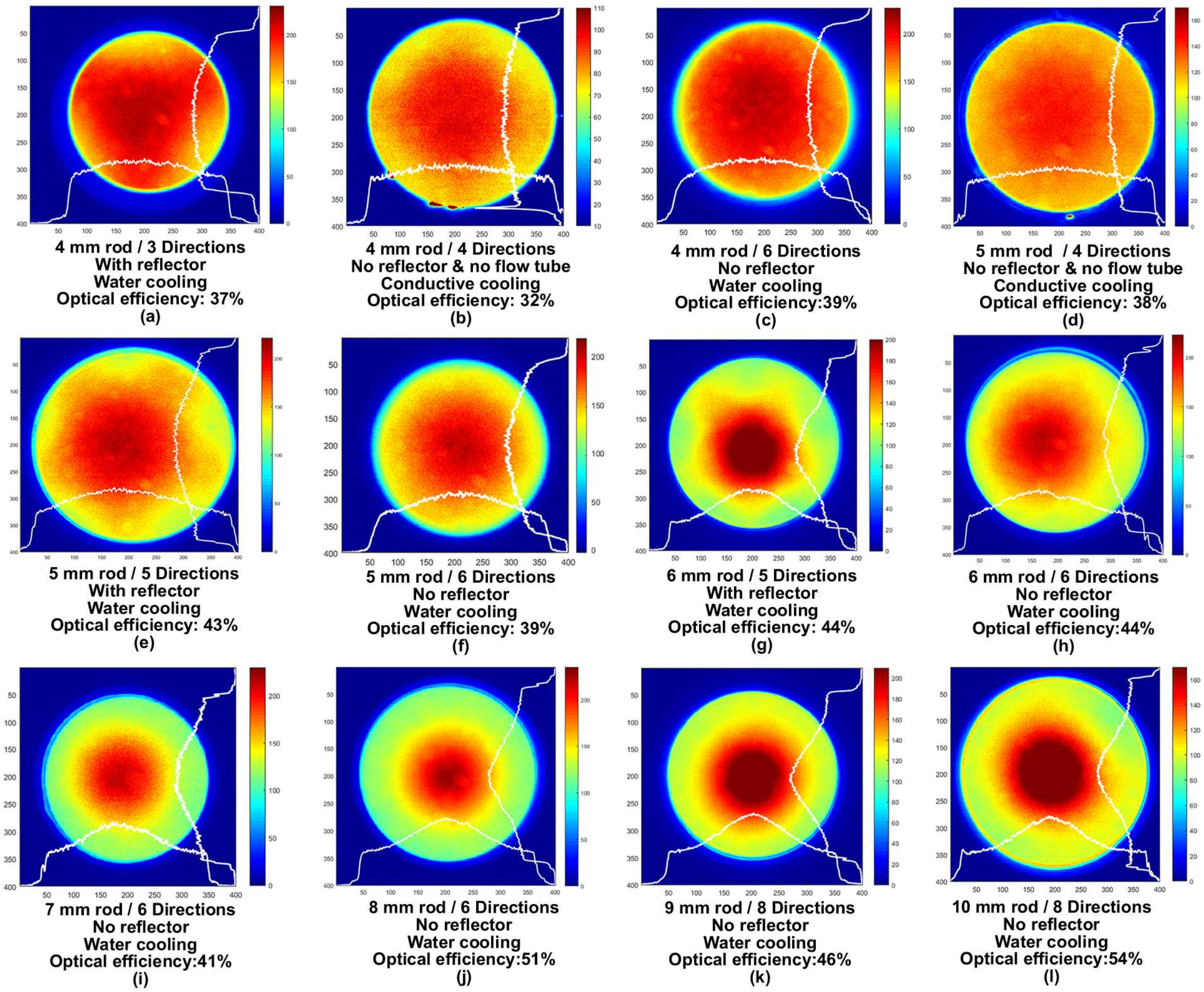

Figure 14. Distribution profiles in various cavity setups. The optical efficiency in the profiles above is defined as optical-to-optical efficiency from 808 nm to 1064 nm. Please notice that (b) and (d) are conductively-cooled pump modules without flow tube while rests are water-cooled pump modules.

It clearly shows that pump modules with even-numbered pumping directions have better circular symmetry compared with odd-numbered pumping directions. Smaller Nd:YAG diameters (e.g., 4 mm or 5 mm) yield a more uniform distribution in even-numbered pump

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modules than larger diameters. We attribute this phenomenon to the fact that the absorption path length is significantly longer than the small Nd:YAG diameter (e.g., 4 mm or 5 mm), allowing the reflected and overlapping pump beams from the inter-reflective chamber to enhance uniformity. In contrast, for larger diameters, the absorption path length becomes shorter than the Nd:YAG rod size, reducing the efficiency of interreflection in improving pump uniformity.

According to the 4 mm and 5 mm Nd:YAG pumping with and without reflector in Figure 14 (a, b, c, d, e, f), due to the interreflection between the VCSEL chips, very similar optical-to-optical efficiency can be maintained even without internal reflector. The removal of the internal reflector will simplify the laser design.

The optical-to-optical efficiency increases along with the Nd:YAG diameter due to better absorption during the first pass. But when pumping directions increased, as inner diameter of the pump cavity will be increased due to the dimension of the pump chips. Then the distance between the VCSEL surface and the Nd:YAG rod center is also increased, thus pumping efficiency will be slightly reduced. Please notice that all the water-cooled and even-numbered pump modules in Figure 14 (c, f, h, i, j, k, l) have a high optical-to-optical efficiency from 39% to 54%, which is comparable with conventional laser bar side-pumped Nd:YAG lasers. Further tuning can be made to reach even higher optical-to-optical efficiency. In this paper, we will focus our topics on the geometry and principles but not challenging cutting-edge parameters.

Please also notice that most of the distribution profiles are not centered, we believe that the main reason is the unbalancing of the central wavelength and optical power intensity from different pumping directions, as discussed in chapter 3.1, and the other possible reason is the uniformity of the doping in the Nd:YAG rod as the deviation of the industrial standard at present is ± 0.1%. We can diagnose these reasons by rotating the laser rod or changing the laser rod

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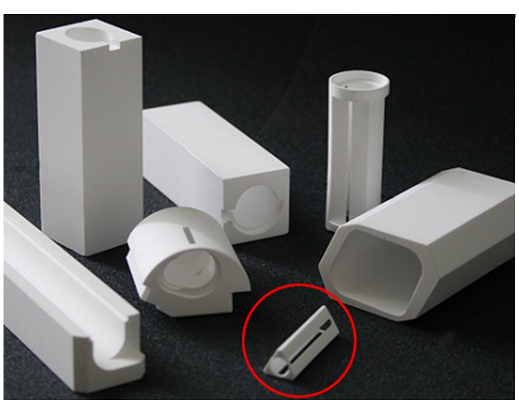
while monitoring the changes of the distribution profiles. If the profiles change along with rotation, then it is the problem of the Nd:YAG rod.

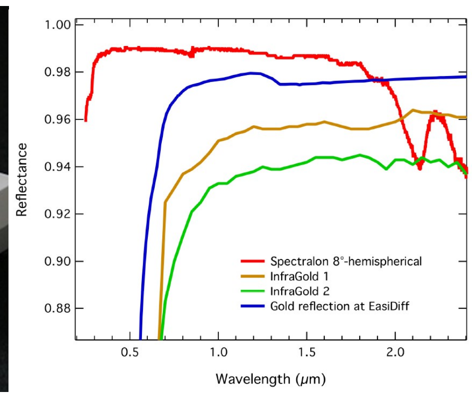
In general, we can conclude that this VCSEL-based even-numbered inter-reflective pump cavity without internal reflector provides a more symmetrical beam profile with a comparable optical-to-optical efficiency relative to conventional pump cavities.

3.3 Pumping beam diffusion

In the pump cavity, diffusion of the pumping beam is usually introduced to improve the uniformity of the absorption. In conventional side-pumped rod lasers, the internal reflector is usually designed with diffuse reflectance material, such as PTFE compound (for example, Fluorilon-99W^{TM} material from Avian Technologies, Spectralon$^{®}$ material from Labsphere), ceramic[24, 25, 26] or other special coatings, as shown in Figure 15. In these pump cavities, the pumping beam transfers through the laser rod and then reaches the diffusive reflector for further reflection and absorption. However, most of the pumping energy is absorbed during the first pass, the effectiveness of the diffusive reflector is limited to the unabsorbed beam only. To improve the uniformity of the absorption, laser crystal with low doping level is usually introduced so that diffusive reflector can be more effective to restructure the pumping beam, but this will be in contrary to the absorption efficiency of the first pass.



(a)



(b)

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Figure 15. (a) Diffusive reflectors made from Spectralon® [27] and (b) material reflectivity[28]. The reflectivity at 808 nm is approximately 99%.

In the symmetrical pump cavity without internal reflector, for example a hexagonal cavity as shown in the Figure 16 below, the glass flow tube which is usually used for the laser rod's water cooling can be processed with frosted surface as a diffuser for the pumping beam. The frosted surface of the glass has two impacts on the pumping beam including diffusive transmission and diffusive reflection. Since the reflected beam will be collected again by the inter-reflective chamber, the efficiency of the absorption will be barely influenced. The diffusive transmission will improve the uniformity of the laser rod absorption during the first pass and further passes of the pumping beam, which is quite different from conventional design.

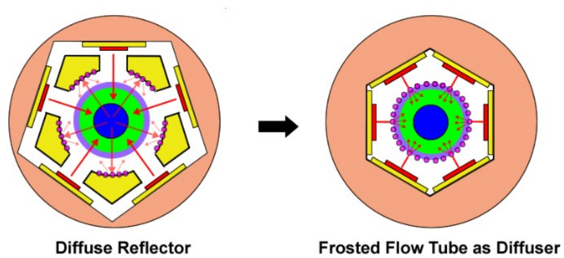

Figure 16. Different diffusion solutions in the pump cavity.

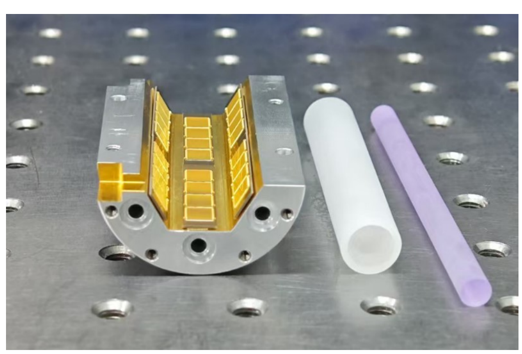

Figure 17. VCSEL pump stack with a frosted flow tube and a Nd:YAG laser rod.

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A comparison experiment was prepared between regular polished and frosted glass tube in a hexagonal pump cavity with two Nd:YAG rods in 5 mm and 6 mm diameter with 1% doping and same VCSEL chips. From the cross section, the distance from VCSEL chip facet to the Nd:YAG rod center is 9.5 mm. The central wavelength of the VCSEL is sorted with ±0.5 nm deviation. Both the polished and frosted glass flow tubes have an outer diameter of 10 mm and an inner diameter of 8 mm. The frosted surface is done by 120 mesh diamond sand. The beam profile images were captured and analyzed, as shown in the Figure 18.

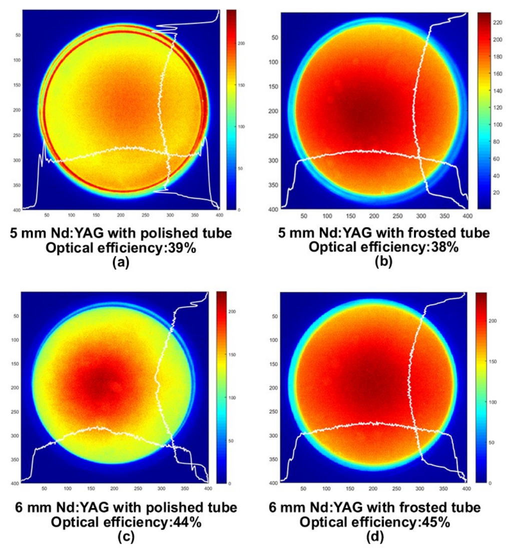

Figure 18. Distribution comparison between polished tube and frosted tube in the pump cavity with 5 mm and 6 mm laser rods.

Apparently, the fluorescence distribution with frosted flow tube was more uniform than the one with polished flow tube because of the diffusion of the pumping beam in the inter-reflective chamber. The brightness from the surface of the Nd:YAG rod was also reduced with frosted flow tube. In the same time, no significant difference was observed in the optical-to-optical efficiency which means this optical tuning measure didn't cause efficiency loss.

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Besides the fluorescence distribution, we processed further test for the pump module with 6 mm Nd:YAG rod in the inter-reflective pump chamber including a frosted flow tube for diffusion. There were totally 48 VCSEL chips in this hexagonal pump chamber with 8 chips from each direction. The total length of the Nd:YAG was 85 mm and pumping length was around 55 mm. The optical power of each VCSEL chip was measured up to 270 W in QCW mode at 200 μs, 20 Hz. The pump module was cooled by water at a temperature of 25 ℃ and flow rate around 3.5 LPM. A high reflection mirror (HR) and an output coupler (OC) with 20% transmission (80% reflection) were well aligned in a plano-plano cavity with a cavity length of around 250 mm. Average output power at 1064 nm was measured with laser power meter and peak power was then calculated. Peak output power of 5867 W at 1064 nm was achieved at a pump power of 12960 W at 808 nm, as shown in Figure 13. The pulse energy was up to 1.17 J at 1064 nm with pulse width of 200 μs. The maximum optical-to-optical efficiency was calculated up to 45%[12]. The fluorescence distribution was described in Figure 12 (d).

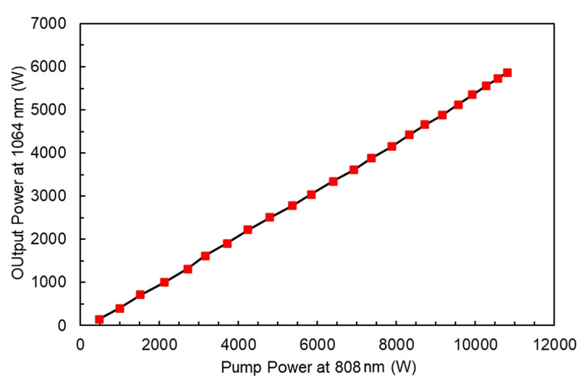

Figure 19. 808 nm pump power vs 1064 nm output power in a hexagonal pump cavity with 6 mm Nd:YAG rod and frosted flow tube[12].

To demonstrate the amplification performance of a VCSEL-pumped laser module, we conducted an experiment within a Master Oscillator Power Amplifier (MOPA) configuration.

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The seed laser was an EO Q-switched VCSEL-pumped Nd:YAG laser with 6 mm diameter and 220 mJ, 10 Hz, 6~8 ns output energy. The amplifier was a VCSEL-pumped Nd:YAG laser module with 8 directions pumping and 8 mm diameter Nd:YAG rod. The seed laser was injected into the center of the amplifier directly in a single pass configuration. The final output energy from the MOPA system was measured with 803 mJ output with 3.65 times of amplification at a pump power of approximately 15900 W, as shown in Figure 20.

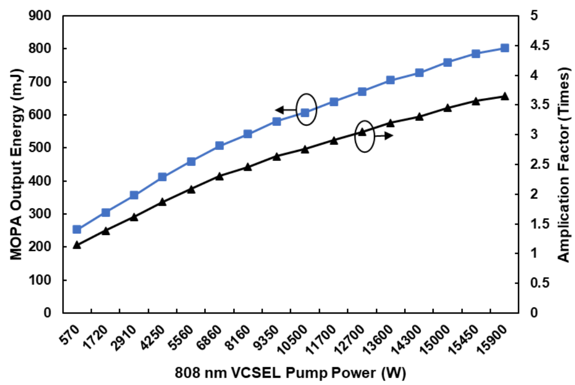

Figure 20. MOPA experiment with 220 mJ seed laser and a VCSEL-pumped amplifier with 8 mm Nd:YAG rod.

In general, the pumping beam diffusion technique through frosted flow tube provides a simple solution to improve the uniformity of the VCSEL-pumped laser modules while maintaining a high optical-to-optical efficiency. This will benefit the further applications with VCSEL-pumped oscillators and amplifiers.

3.4 Centric and eccentric pumping

The pump cavity designs above are all in centric pumping geometry. If the VCSEL chips have uniform optical power and spectrum in each pumping circle, the absorption in the Nd:YAG rod should be centrosymmetric. From Figure 14, we can figure out there are generally two kinds of

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beam profiles: the near flat top and the near Gaussian distribution. Some of the applications, such as seed lasers, may follow Gaussian distribution to get maximum fundamental output in oscillators. However, Gaussian beam has 86.4% of its energy in central core (defined by the $1/e^2$ intensity level), the high peak intensity in the beam center may lead to optics damage, thermal lensing and danger of damage, while the rest of the energy in the wing may be lost because of the threshold behavior existing in many processes for example laser pumping and material processing[29]. Many scientific, industrial and medical applications require flat top spatial energy distribution, high uniformity in the plateau region, and complete absence of hot spots[29, 30]. Especially for high-energy laser amplifiers, near flat top beam profile is always the primary target of the laser system design that many efforts have been made before[31, 32].

For most cases with small Nd:YAG rod diameter or low doping level, VCSEL wavelength can be properly designed to match the absorption distance of the pumping beam so that uniform absorption in the cross section of the laser rod can be expected. However, in most of the Nd:YAG rod pumping, strong concentration in the center is more popular because the limit of the pumping wavelength options (804 nm to 809 nm typically) and Nd:YAG doping options (0.6% to 1.1% typically). In these cases where the concentration is unexpected in the center of the laser rod, measures must be taken to improve the uniformity from a near Gaussian to near flat top. One of the optional measures is the eccentric pumping design, as shown in the Figure 21.

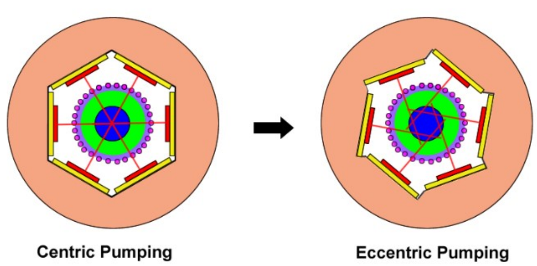

Figure 21. Centric and eccentric pumping schemes.

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From the fluorescence image of 6 mm Nd:YAG with frosted flow tube in Figure 18(d), we can figure out the absorption still comes with a slightly strong center which takes over about 2/5 of the diameter (2.4 mm in diameter accordingly). To reduce the intensity of this center area, we rotate the central axis of each VCSEL chip clockwise for 8 degrees. Considering the 9.5 mm distance from chip facet center to the Nd:YAG rod center, the eccentric distance of the pumping beam is calculated as 9.5 mm × sin(8°) ≈ 1.3 mm, which is close to the edge of current strong center. Pumping experiment was done and fluorescence images were captured and compared, as shown in the Figure 22.

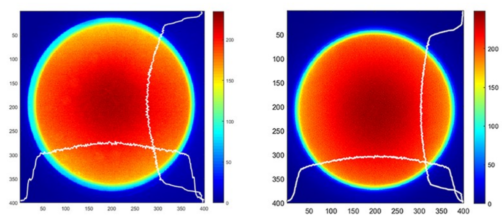

Figure 22. Distribution comparison between centric and eccentric pumping with same 6mm laser rod and frosted tube.

It clearly shows that by introducing the eccentric pumping mechanism, the concentration in the center was reduced and the absorption at the edge of the Nd:YAG rod was enhanced. However, the optical-to-optical efficiency dropped from 45% to 39% due to the distortion of the inter-reflective chamber, which may cause spatial misplacement especially for the first pass of the pumping.

Nevertheless, in some cases where the Nd:YAG rod diameter is much bigger than the path length of the pumping beam, for example, a diameter of more than 8 mm, eccentric

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pumping is a good way to change the beam profile from near Gaussian to near flat top distribution. By using the same pump chamber in Figure 22, we replaced the 6 mm Nd:YAG rod with 8 mm Nd:YAG rod for further eccentric pumping experiment. Fluorescence was captured in Figure 23 (b). Compared with centric pumping from Figure 23 (a) , which is the same as Figure 14(j), eccentric pumping has highly improved the uniformity in the center of the 8 mm Nd:YAG rod, while optical-to-optical efficiency was reduced from 51% to 44%.

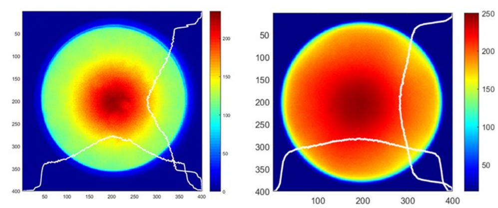

Figure 23. Distribution comparison between centric and eccentric pumping with 8 mm Nd:YAG rod.

In general, the tuning of beam profile through the eccentric pumping provides an optional measure to improve the uniformity of the pumping if necessary.

IV. CONCLUSION

Compared with edge-emitting laser bars, high-power VCSELs are considered as an alternative pumping source due to better wavelength stability, higher operation temperature, higher reliability, higher repetition rate, much longer lifetime and lower manufacture cost. Based on unique optical characteristics of VCSEL chips, a novel symmetrical pump cavity with inter-reflective chamber was invented for VCSEL side-pumped Nd:YAG rod lasers. Even-numbered pumping directions were introduced instead of odd-numbered pumping and conventional internal reflector was removed. Several optical tuning measures were taken to improve the uniformity of

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the pumping distribution, including optical power and spectrum sorting of the diode chips, optical alignment in the cross section and long axis of the laser rod, a diffusion mechanism in the pumping chamber by frosted glass flow tube, and an optional eccentric pumping geometry. A series of VCSEL pumping experiments were conducted therefore and optical tuning measures were evaluated through distribution profiles and optical-to-optical efficiencies. A new ideology of VCSEL side-pumped Nd:YAG laser cavity was then finalized, which may benefit further developments and applications in the future.

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