Compact High-Power-VCSEL-Array Pumped Solid-State Lasers

Robert VAN LEEUWEN, Tong CHEN, Bing XU, Laurence WATKINS, Jean-Francois SEURIN, and Chuni GHOSH
Princeton Optronics, Inc., 1 Electronics Drive, Mercerville, New Jersey, USA
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Vertical-cavity surface-emitting lasers (VCSELs) can be processed in large two-dimensional (2-D) arrays of single emitters to scale up the power for solid-state laser pumping. VCSEL-based kW-level 808 nm pump modules, comprising multiple 2-D arrays, were developed to pump compact Nd:YAG lasers. Various quasi-CW (QCW) VCSEL-pumped pulsed Nd:YAG lasers were investigated, both in end- and side-pumping configurations, demonstrating the viability of VCSEL pumping of compact solid-state lasers.

Key Words: Vertical-cavity surface-emitting laser, High power VCSEL array, 808 nm, Diode-pumped solid-state laser

1. Introduction

Solid-state lasers are used in many applications including materials processing (cutting, drilling, welding, marking), semiconductor fabrication (wafer cutting), industrial printing, laser-based displays, medical and surgical applications, range-finders, instrumentation, and scientific research. Optical pumping of the gain medium is typically performed with lamps (arc or flash lamps) or semiconductor edge-emitting lasers. Lamps are broad-band making them inefficient, and, even though they are low cost, they have a relatively short lifetime. Semiconductor lasers are narrow-band, efficient, small, and have long lifetimes, thus providing compact and efficient pump sources for solid-state lasers.

Recently, high-power VCSEL-based pump sources \(^{6,7}\) have emerged as attractive alternatives to edge-emitting diodes in diode-pumped solid-state (DPSS) lasers. Pumping of solid-state lasers with low power single VCSELs, \(^5,6\) moderate power 2-D VCSEL arrays, \(^6\) and high power VCSEL pump modules comprising multiple 2-D arrays, \(^6,12\) has been demonstrated. The advantages over the existing edge-emitter technology include: circular, low divergence output beams with uniform spatial profile, reduced temperature dependence, \(^12\) increased reliability, especially at high temperatures, \(^13\) no catastrophic optical damage failure, scalability to high power 2-D arrays, and the potential for low-cost manufacturing.

2-D VCSEL arrays comprise thousands of low power high efficiency single emitters. Power levels of these arrays can reach a few hundred Watts, while maintaining high power conversion efficiency. \(^1,2\) Multiple of these 2-D VCSEL arrays can be combined into kW-level VCSEL pump modules \(^10\). These modules exhibit similar properties as their single emitter constituents, including narrow linewidth and high wavelength stability, making VCSEL pump modules very well suited for constructing compact high pulse energy DPSS lasers. E.g. 40 mJ pulse energy was recently demonstrated from a VCSEL end-pumped actively Q-switched Nd:YAG laser. \(^9\)

This paper gives an overview of recent results obtained with VCSEL based kW-level 808 nm pump modules. Various QCW VCSEL-pumped pulsed Nd:YAG lasers were investigated, both in end- and side-pumping configurations, employing active, as well as passive, Q-switching techniques. Visible and ultraviolet (UV) light was produced using harmonic generation in non-linear crystals.

2. VCSEL device structure and fabrication

High power, VCSEL based, pump sources for solid-state laser pumping use 2-D 808 nm VCSEL arrays as basic building blocks. Figure 1 shows a schematic of the cross-section of a small portion of a packaged 808 nm VCSEL array. The epitaxial VCSEL material designed to lase at 808 nm is grown on GaAs substrates using MOCVD. The VCSEL device structure and fabrication has been described in detail elsewhere. \(^2\)

The junction-down, bottom emitting configuration that is used for high power 976 nm VCSEL arrays \(^1\) is not possible for 808 nm arrays because of substantial absorption in the GaAs substrate at that wavelength, while a top-emitting configuration would significantly increase thermal impedance even when the substrate is thinned down. Therefore, for high performance 808 nm VCSEL arrays, the GaAs substrate needs to be completely removed. \(^7\) The growth thus starts with an etch.
stop layer to allow for substrate removal. Following the etch-stop layer is a highly doped n-GaAs layer that is used for the n-contact of the arrays. Then, an AlGaAs n-type high reflectivity distributed Bragg reflector (DBR), the active region, consisting of InAlGaAs strained quantum wells designed for 808 nm emission, and a p-type DBR output mirror, optimized for maximum output coupling, follow. For current and optical confinement a selective oxidation process is used to create an aperture near the active region to improve performance.

3. VCSEL end-pumped solid-state lasers

High power QCW 808 nm VCSEL array pump modules were developed for both end- and side-pumping configurations. Figure 2 shows the layout of the VCSEL arrays in the module designed for end-pumping. The 808 nm VCSEL pump module comprises four closely spaced VCSEL arrays that together form an approximately circular 0.6 cm$^2$ emitting area. Each VCSEL array comprises thousands of small aperture VCSEL elements that emit in circular beams with 150 mrad divergence, and is mounted on a diamond heat-spreader. These diamond submounts are mounted on a Cu heatsink, which is cooled with a thermo-electric cooling (TEC) element. Each VCSEL array is capable of delivering more than 200 W output power of the module is 800 W at 220 A. The voltage drop across each array is 2.7 V, corresponding to 34% power conversion efficiency. The output of this pumping module can easily be focused to a 3 mm diameter spot size with a single lens for end-pumping applications.

QCW end-pumping of an Nd:YAG laser with a high power VCSEL pump module was investigated experimentally. The schematic layout of the VCSEL end-pumped Nd:YAG laser is shown in Fig. 4. The quasi-circular emitting area of the VCSEL pump module was focussed onto a 4 mm diameter 50 mm long Nd:YAG rod using a 12 mm diameter lens with a 10.5 mm focal length. One end of the Nd:YAG crystal was coated with a dual-wavelength dielectric coating that is highly reflective (HR) for the 1064 nm lasing wavelength and highly transmissive (HT) for the 808 nm pumping wavelength, while the other end was AR coated at 1064 nm. The Nd:YAG rod was wrapped in indium foil and placed in a thermo-electrically cooled copper heatsink. A partially reflective flat mirror was used as the output coupler (OC). The cavity length was 68 mm. A Cr:YAG saturable absorber was placed inside the resonator to act as a passive Q-switch. A Brewster plate (BP) was inserted to ensure linear polarization required for efficient second harmonic generation at 532 nm in a non-linear KTP crystal that was placed outside the resonator.

Figure 5 shows the QCW peak power at 1064 nm as a function of peak pump power of the Nd:YAG laser in free running mode without the Q-switch at a low 0.1% duty cycle (250 μs; 4 Hz). The threshold was 150 W and the slope efficiency approximately 45%. Short pulse operation was achieved by passively q-switching the laser by inserting a Cr:YAG saturable absorber with 45% initial transmission into the laser cavity. The best Q-switched pulse energy was obtained with a 72% reflective OC. With 186 mJ pump pulses 18 mJ, 16 ns laser pulses were obtained, which corresponds to 9.7% conversion efficiency.

The Q-switched output of the end-pumped Nd:YAG laser was frequency doubled in a 3 mm long type II phase matching KTP crystal. With a 2 mm diameter input beam the measured 532 nm pulse energy was 10 μJ, which corresponds to 56% second harmonic conversion efficiency. The pulse repetition frequency of the QCW VCSEL end-pumped Nd:YAG laser could be increased to 70 Hz without a significant effect on the 1064 nm pulse energy. At higher repetition rates degradation of the lasing mode due to thermal effects in the gain medium resulted in a decrease of laser pulse energy.

The possibility for scaling the laser output to higher pulse energy by dual end-pumping was investigated as well. The cavity layout was similar as the one in Fig. 4 but a 45 degree turning mirror was added to the cavity right after the AR coated end face of the Nd:YAG rod. The turning mirror was HR.
at 1064 nm and HT at 808 nm. The output of a second VCSEL pump module was directed through the turning mirror onto the AR coated end facet of the YAG crystal with the use of a 3:1 reducing telescope. With 1.5 kW total peak 808 nm pump power 550 W QCW 1064 nm peak power was observed in the free running mode; the slope efficiency was 42%.

4. VCSEL side-pumped solid-state lasers

For scaling to even higher output power side-pumping of solid-state gain media is required. To accommodate side-pumping applications a high power 808 nm VCSEL side-pumping module was designed and fabricated. Figure 6 shows the layout of the VCSEL arrays in a pump module designed for pumping of a 20 mm long Nd:YAG rod. Twelve \(3 \times 3\) mm\(^2\) VCSEL arrays are arranged in a \(6 \times 2\) layout for efficient pumping of the 20 mm long gain medium with a cylindrical pump lens. Each VCSEL array was designed to operate at 100 W peak power output at a 10% duty cycle. These VCSEL arrays were mounted in pairs on a diamond heat spreader. Six pairs were mounted side by side on a 20 mm \(\times\) 20 mm micro-channel cooler. The arrays in each pair were operated in parallel, while the six pairs were operated in series. The VCSEL pump module was connected to a water chiller set to operate at 20 deg. C. Figure 7 shows the 808 nm QCW peak power of the VCSEL pump module as a function of pulse repetition frequency. The peak power dropped slightly from 1.25 kW at 100 Hz to 1.18 kW at 1 kHz. The average 808 nm pump power at 1 kHz, or 12.5% duty cycle, was 150 W, corresponding to 31% power conversion efficiency. The 808 nm output of the pump module has a 2 nm spectral bandwidth resulting in 60% single pass absorption in 2 mm thick 1% doped Nd:YAG.

Since VCSELs are mostly insensitive to incident and back-reflected light dual-side pumping can be implemented to increase pumping power and uniformity. Therefore, two high power VCSEL side-pumping modules were used to construct a dual side-pumped laser head. Figure 8 shows a schematic cross-section view of the VCSEL based gain module. A 20 mm long square or rectangular Brewster cut Nd:YAG rod is clamped between two copper heatsinks, which are water cooled to be able to operate on a high duty cycle (> 10%). The 808 nm output from two VCSEL pump modules (PM) was focused onto the Nd:YAG crystal with a pair of 8 mm diameter high-index half-rod cylindrical lenses.

For a high average power pulsed UV laser application\(^{11}\) a 1.8 \(\times\) 1.5 \(\times\) 20 mm\(^3\) (width \(\times\) thickness \(\times\) length) Nd:YAG rod was installed in the gain module that was inserted into a linear resonator as schematically shown in Fig. 9. The 100 mm long laser cavity was formed by a 1064 nm HR and a 50% reflective OC. Q-switched operation was achieved with an AR coated Cr:YAG crystal with 40% initial transmission. The quarter waveplate (QWP) partially compensates for thermally induced birefringence in the Nd:YAG crystal, and improves the polarization extinction ratio of the laser output. The 1064 nm output of the laser was frequency doubled in type-II phase

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**Fig. 5** QCW peak 1064 nm laser power as a function of peak 808 nm VCSEL pump power at 0.1% duty cycle.

**Fig. 6** Layout of 12 closely spaced VCSEL arrays forming an approximately rectangular 5.8 \(\times\) 20 mm\(^2\) emitting area for side-pumping applications.

**Fig. 7** QCW 808 nm peak (triangles) and average (circles) pump power of the VCSEL side-pumping module as a function of pump pulse repetition rate (125 \(\mu\)s; 240 A).

**Fig. 8** Cross-section view of the VCSEL based dual side-pumped Nd:YAG gain module.
matching process in a 10 mm long KTP crystal placed directly behind the output coupler. The generated 532 nm second harmonic was frequency doubled in a 5 mm long BBO crystal, placed right behind the KTP crystal, to generate 266 nm UV laser pulses.

The VCSEL gain module was operated in QCW mode with 65 mJ pump pulse energy. The pulse repetition frequency was varied while the pulse duration was fixed. Figure 10 shows the average power of the 1064 nm, 532 nm, and 266 nm output of the passively Q-switched VCSEL-side-pumped Nd:YAG laser. The dependence of the Q-switched average output power on pulse repetition rate was approximately linear up to 1.3 kHz. The maximum Q-switched IR output power was 8.3 W, or 6.4 mJ at 1.33 kHz, and was limited by thermal lensing in the Nd:YAG crystal. At 1.33 kHz 4.1 W green power and 0.9 W UV power was obtained, corresponding to 49% and 11% second and fourth harmonic conversion efficiency respectively. The divergence of the Q-switched UV output was 2 mrad, while its pulse length was 10 ns.

For another application the high power 808 nm 2D-VCSEL array technology was applied to develop a compact high-energy pulsed blue laser.\textsuperscript{6,7,10} This laser is based on a side-pumped Nd:YAG laser operating at the weaker 946 nm lasing transition. The VCSEL based laser head contains a 20 mm long square 1% doped Nd:YAG rod of 2.0 mm thickness. The cavity mirrors have dual wavelength 946 nm HR/OC coatings that are HT for 1064 nm to avoid parasitic lasing and amplified spontaneous emission. Short pulse operation was achieved using a low loss, 50 mm long, fused silica acoustic-optic Q-switch. The total cavity length was 125 mm. The laser was externally frequency doubled in a 7 mm long BBO crystal to generate the 473 nm second harmonic in a type I phase matching process. As previously reported\textsuperscript{6} 48% second harmonic generation efficiency was achieved to obtain 10 mJ blue pulse energy at 5 Hz pulse repetition frequency.

Figure 11 shows the free running 946 nm laser pulse energy obtained with 2.4 kW peak pump power at 100 Hz pulse repetition frequency. The 808 nm VCSEL pump pulse energy was varied by adjusting the current pulse duration. The observed slope efficiency with a 75% OC was 12.7%, while the threshold was 140 mJ. With the VCSEL pump modules operating in QCW mode with fixed pulse duration, the repetition rate of the single gain module laser was increased. Figure 12 shows the average 946 nm laser power as a function of pulse repetition frequency for various current pulse durations. To operate at high pulse repetition frequency the OC reflectivity was increased to 85% to lower the lasing threshold and thus increase the optical to optical efficiency. With 100 µs pump pulse duration the maximum average 946 nm was 4.9 W at 340 Hz. With longer pulse durations the laser is more efficient since it operates further above threshold so more laser power is obtained but at lower repetition rates. E.g. with 300 µs pulses the maximum power was 9.1 W at 130 Hz. Independent of pulse duration the average 946 nm laser power reached its maximum at approximately the same incident 808 nm pump power (95 – 100 W), indicating that the laser power was limited by thermal lensing in the Nd:YAG rod.
5. Summary

High power VCSEL-based 808 nm pump modules with kW-level output powers were developed, and various compact Nd:YAG lasers, in both end- and side-pumping configurations, were constructed to demonstrate the viability of VCSEL pumping. A VCSEL end-pumped Nd:YAG laser operating at 1064 nm showed 45% slope efficiency in free running mode at a low duty cycle and, when passively Q-switched, produced 18 mJ IR pulses and 10 mJ green pulses after frequency doubling. A frequency-quadrupled passively Q-switched VCSEL-side-pumped Nd:YAG laser produced 0.9 W UV light with 0.7 mJ pulse energy at 1.33 kHz pulse repetition frequency. A QCW dual VCSEL side-pumped Nd:YAG laser operating on the 946 nm lasing transition with 12.7% slope efficiency and a 140 mJ threshold produced 9.1 W average 946 nm power in free running mode.

In conclusion, because of their 2-D scalability, narrow linewidth, reduced dependence on temperature, high reliability, and potential for low-cost manufacturing, high power VCSEL arrays make excellent pump sources for compact DPSS lasers.

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