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High power VCSEL array pumped Q-switched Nd:YAG lasers

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ABSTRACT

Solid-state lasers pumped by high-power two-dimensional arrays of vertical-cavity surface-emitting lasers (VCSELs) were investigated. Both end-pumping and side-pumping schemes of Nd:YAG lasers with high power kW-class 808 nm VCSEL pump modules were implemented. For one application 10 mJ blue laser pulses were obtained from a frequency-doubled actively Q-switched VCSEL-array dual side-pumped Nd:YAG laser operating at 946 nm. For another application 10 mJ green laser pulses were obtained from a frequency-doubled passively Q-switched VCSEL-array end-pumped Nd:YAG laser operating at 1064 nm. Both QCW and CW pumping schemes were investigated to achieve high average Q-switched power.

Keywords: 808 nm VCSEL array, 946 nm Nd:YAG laser, blue laser, green laser

1. INTRODUCTION

Typically high power diode pumped solid state lasers are pumped by stacks of edge-emitting diode bars[1, 2]. Recent advances in power and brightness of 808 nm vertical-cavity surface-emitting lasers (VCSELs) have made them attractive alternatives for both end and side pumping of solid sate lasers[3, 4, 5, 6]. Compared with edge-emitting bars, VCSELs can be easily arranged in two-dimensional (2D) configurations, which allows for scaling to high powers, as well as uniform illumination of the gain medium. VCSELs have a narrow linewidth (~0.8 nm) and a low dependence on temperature[3] (0.07 nm/deg C), resulting in a high single-pass absorption, which makes it suitable for pumping a thin gain medium. Furthermore, VCSELs offer higher reliability due to a lower power density at the emitter area, and are not sensitive to back reflected light.

In this paper, we demonstrate that high power VCSEL array pump modules can be effectively used for both end pumping and side pumping of solid state lasers. Specifically, we report on a 21 mJ actively Q-switched dual VCSEL side-pumped 946 nm Nd:YAG laser that produces 10 mJ 473 nm blue laser pulses after frequency doubling, as well as on an 18 mJ passively Q-switched VCSEL end-pumped 1064 nm Nd:YAG laser that generates 10 mJ 532 nm green laser pulses.

2. HIGH POWER VCSEL ARRAY PUMP MODULES

Based on end and side pumping configurations, two types VCSEL array pump modules were developed. Fig. 1(a) shows an 808 nm VCSEL array pump module that was designed for side-pumping. Fig. 1(b) shows the uniform distribution of the emitted pump light. This side pump module comprises twelve 3 mm arrays with a total emitting area of 0.87 cm^2. During QCW operation (<1% duty cycle) the peak power of this module is 500 W. The central wavelength is 808 nm with a 1 nm FWHM spectral linewidth, which results in 70% absorption in a 2 mm wide Nd:YAG crystal. Details of the design, assembly, and performance of the pump module were reported previously[5].

Fig. 2 shows the layout and the power performance of the VCSEL pump module that was designed for QCW end pumping of a Nd:YAG laser. The 808 nm VCSEL pump module comprises four closely spaced VCSEL arrays that together form an approximately circular emitting area. The spacing between the light emitting quadrants is about 1 mm, and the total emitting area is 0.48 cm^2. Each VCSEL array comprises thousands of small aperture VCSEL elements that exhibit low-order multi-mode lasing. The numerical aperture of the arrays is 0.15. Each VCSEL array is mounted on diamond heat-spreader that is mounted on a Cu heatsink. The Cu heatsink is cooled with a TEC. Each VCSEL array is designed to deliver 200 W peak power during low duty cycle QCW operation (<1%). The total output peak power of the module is 800 W at 220 A. 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. The top-hat intensity profile ensures a uniform pumping profile in the gain medium.

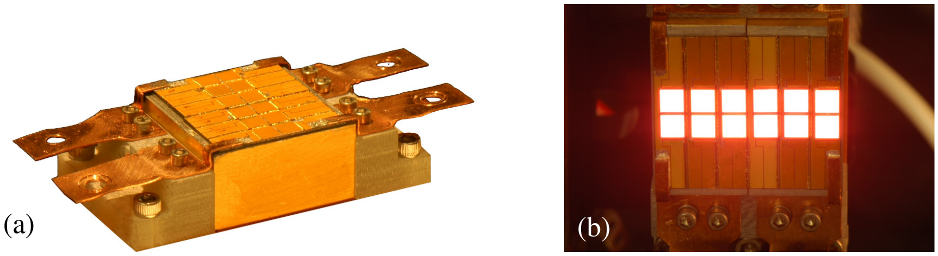

Fig. 1. Pictures of an 808 nm VCSEL array pump module comprising twelve 3 mm VCSEL arrays arranged in a 6 x 2 layout. The picture on the left (a) shows the VCSEL arrays mounted on a 20 mm x 20 mm micro-cooler assembly. The picture on the right (b) shows the uniform distribution of the light emitted from the pump module.

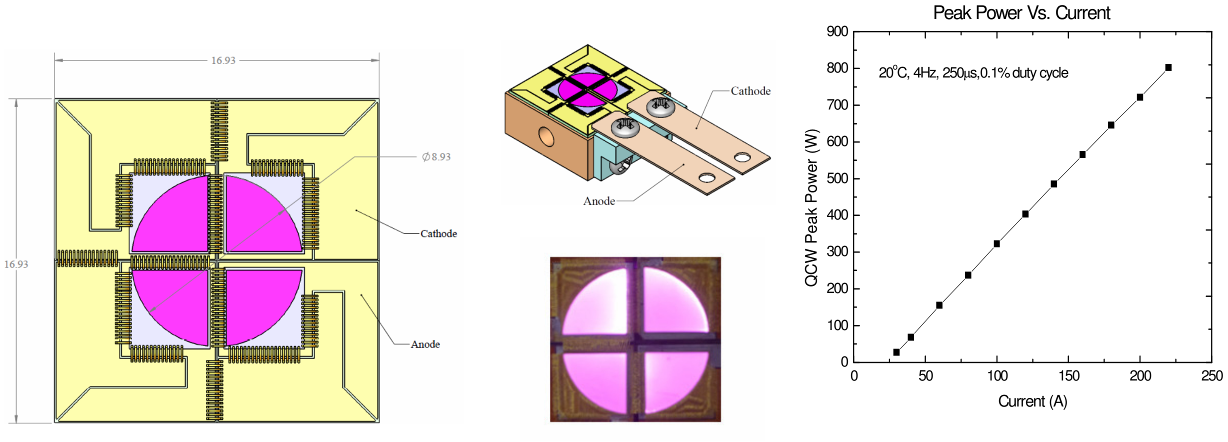

Fig. 2. Layout of the VCSEL arrays in the high power 808 nm VCSEL array pump module (left) with all dimensions in mm. Design drawing of the pump module mounted on a Cu heat-sink with leads (top middle); picture showing the uniform distribution of the light emitted from the pump module (bottom middle); power performance of the high power 808 nm VCSEL array pump module during QCW operation (right).

3. VCSEL ARRAY SIDE-PUMPED BLUE LASER

Four 808 nm VCSEL pump modules like the one shown in Fig.1 were implemented in a dual side-pumped Q-switched Nd:YAG laser operating at the 946 nm lasing wavelength. The output of the laser was externally frequency doubled to obtain high energy blue laser pulses. A schematic layout of the blue laser is shown in Fig. 3. The linear cavity design comprises a curved high reflector (HR) and a flat output coupler (OC) mirror both coated with a dual wavelength coating that suppresses lasing at the stronger 1064 nm transition. Two 2 x 2 x 20 mm^3 1 at. % Nd doped YAG rods were placed inside the laser resonator. The rods were coated with a high damage threshold coating that is AR at 946 nm. Each rod was pumped from two sides by a high power VCSEL pump module. The output of the pump modules was projected onto the YAG crystal by a half-rod lens. The cavity included additional optical elements such as such as a Brewster plate for linear polarized operation, and an acousto-optic Q-switch for short pulse operation. A 7mm long BBO crystal was placed directly behind the OC for blue pulse generation.

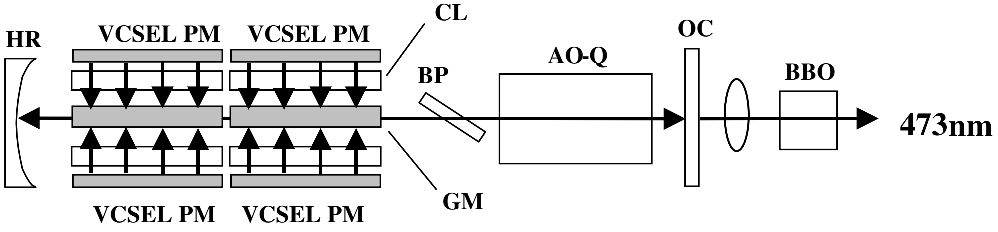

Fig. 3. Schematic layout of the VCSEL pumped blue laser. The Nd:YAG gain medium (GM) is dual side-pumped by multiple VCSEL array pump modules (PM) with the use of cylindrical lenses (CL). The laser cavity is formed by a curved high reflector (HR) and a flat output coupler (OC) and contains a Brewster plate (BP) and an acousto-optic Q-switch (AO-Q). The linear polarized Q-switched 946 nm output is converted to 473 nm UV by second harmonic generation in a non-linear BBO crystal.

The 946 nm Q-switched laser pulse energy is shown as function of pump pulse duration in Fig. 4(a). The IR pulse energy reached 21 mJ with a 250 μs pump pulse duration. The IR output was weakly focused with a 300 mm focal length lens to a 1 mm diameter spot size inside the BBO crystal to efficiently generate high energy blue laser pulses. The results are shown in Fig. 4(b). Due to the good beam quality of the IR output 48% second harmonic conversion efficiency was achieved, resulting in 10 mJ 473 nm blue laser pulses with a 17 ns FWHM pulse width.

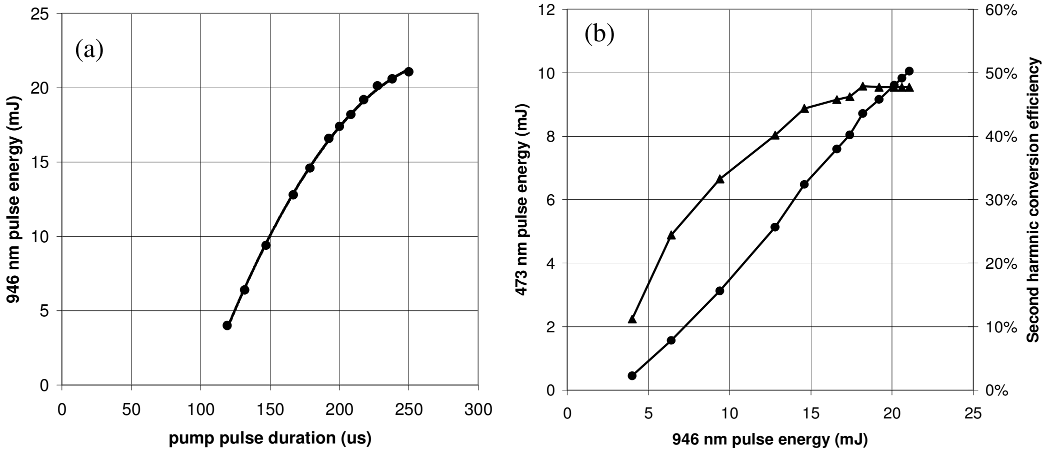

Fig. 4. (a) 946 nm IR pulse energy, with a 250 μs pumping duration the IR energy reached 21 mJ; (b) 473 nm blue pulse energy (solid circles) and second harmonic conversion efficiency (solid triangles). The IR pulses were frequency doubled in BBO with 48% second harmonic conversion efficiency to obtain 10 mJ blue laser pulses.

4. VCSEL ARRAY END-PUMPED LASER

Initially pumping of a Nd:YAG laser with a low power CW VCSEL array was explored to validate the VCSEL end pumping concept. The pumping module comprised a single 3 mm diameter VCSEL array with 2.7 mm x 2.7 mm emitting are that produced 13 W 808 nm pump power. The cavity lay-out is schematically shown in Fig. 5. The laser comprises a 1% Nd:YAG rod that is 4.25 mm in diameter and 50 mm in length. A three-to-one reducing telescope was used to focus the 808 nm VCSEL array output to an 850 um diameter spot size on the end facet of the rod. This surface was coated with a dielectric coating that is highly transmissive for the 808 nm pump wavelength and a highly reflective for the 1064 nm lasing wavelength. The cavity length was 22 cm for a TEM_{00} mode operation. A Brewster plate was added to the cavity to ensure a linearly polarized output. A flat 90% reflectivity end mirror was used as an output coupler. The laser was passively Q-switched by inserting a Cr:YAG saturable absorber with an initial transmission of 90% into the laser cavity.

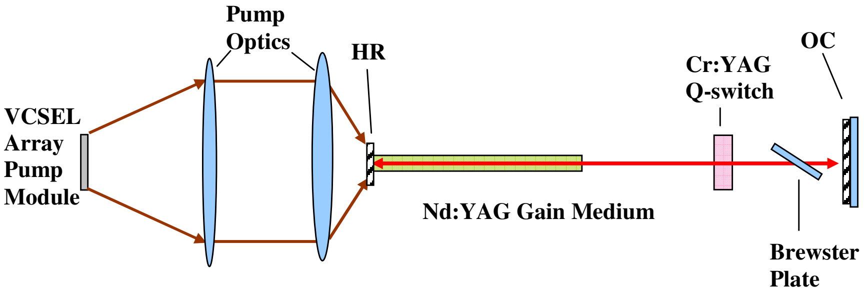

Fig. 5: Schematic layout of the CW-pumped pulsed Nd:YAG laser.

Fig. 6(a) shows the CW output power as well as the average Q-switched power. Fig. 6(b) shows the optical conversion efficiency for CW and Q-switched operation. The threshold for CW lasing was observed at 2.2 W pumping. At 13.2 W pumping 4.05 W CW 1064nm output was obtained. The slope efficiency was 40% and the optical to optical conversion was 30.6% at 13.2 W pumping. After inserting the Cr:YAG for Q-switched operation, the threshold was observed at 6W while at 13.2W pumping 1.86 W Q-switched power was obtained. The slope efficiency was 30% and the optical to optical conversion was 14% at 13.2W pumping. The pulse energy and the pulse train repetition rate were investigated as a function of pump power. Interestingly the Q-switched pulse energy increases with increased pumping. Fig. 7 shows that the pulse energy increased from 140 μJ to 200 μJ while the laser pulse repetition rate increased from 3 kHz to 9.3 kHz, when the 808 nm VCSEL pump power was increased from 7.8 W to 13.2 W.

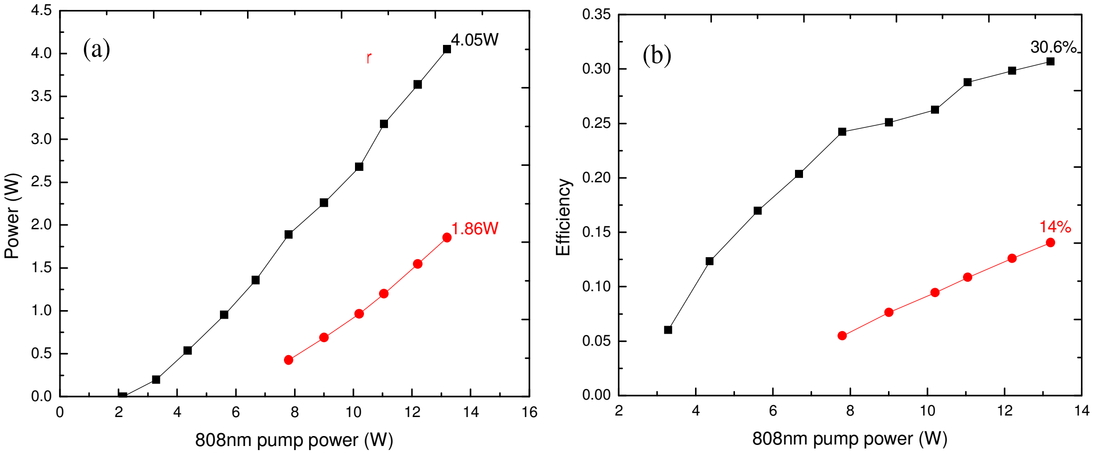

Fig. 6: (a) CW power (solid squares) and average Q-switched power (solid circles) of the VCSEL end-pumped Nd:YAG laser; (b) Optical to optical conversion efficiency during CW (solid squares) and Q-switched (solid circles) operation.

Typically, with edge-emitter pumping, the pulse energy remains constant with increased pump peak, here, with VCSEL pumping, the pulse repetition rate increased while at the same time the 1064 nm pulse energy increased with increasing pump power. This phenomenon was recently observed and reported by Lew Goldberg et al. at U.S. Army NVESD[6]; who contributed it to changes in the angular distribution of the VCSEL emission with increased drive current. As a consequence the pulse energy is adjustable by up 50% in pulse energy simply by changing the pump power.

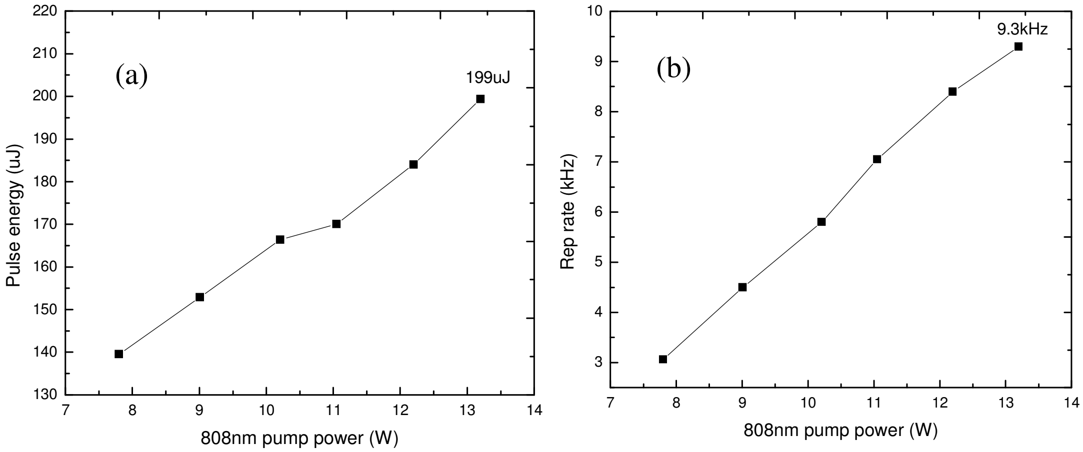

Fig. 7: Q-switched 1064 nm pulse energy (a) and pulse repetition rate (b) of the CW VCSEL pumped passively Q-switched Nd:YAG laser.

In the next set of experiments QCW end-pumping with a high power VCSEL pump module as shown in Fig. 2 was investigated. The schematic layout of the QCW high power VCSEL end-pumped Nd:YAG laser is shown in Fig. 8. The quasi-circular emitting area of the VCSEL pump module is projected onto a 50 mm long 4.2 mm diameter Nd:YAG rod with a 12 mm diameter 10.5 mm focal length focusing lens. A dual wavelength dielectric coating deposited on entrance face is highly reflective for the lasing wavelength and highly transmissive for the pumping wavelength. A flat mirror forms the output coupler. The cavity length was 68 mm. The output of the passively q-switched Nd:YAG laser was focused into a KTP crystal for second harmonic generation of 532 nm.

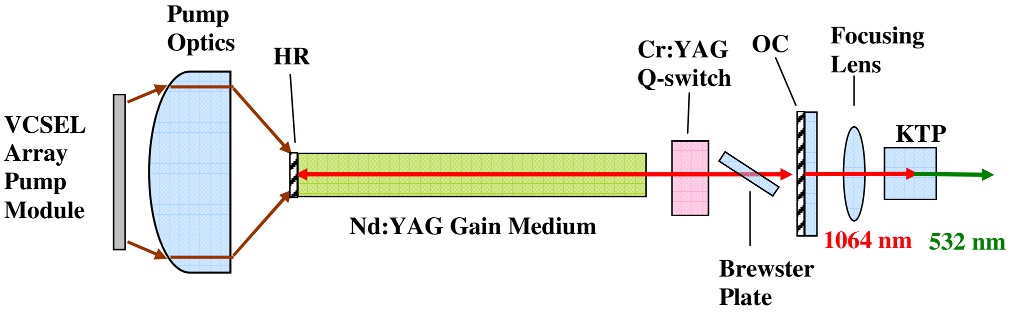

Fig. 8: Schematic layout of the frequency-doubled VCSEL end-pumped passively Q-switched Nd:YAG laser

The graph in Fig. 9(a) shows the QCW peak power at 1064 nm as a function of 808 nm pump power at a low 0.1% duty cycle. Pulses with 63 mJ 1064 nm pulse energy were obtained with 704 W peak power 250 us long pump pulses (176 mJ pump pulse energy). Slope efficiency is 45% and threshold is 150 W. When inserting the Brewster plate the pulse energy drops by 6.8%. Short pulse operation was achieved by passively q-switching the laser by inserting Cr:YAG saturable absorbers with 45% initial transmission into the laser cavity. The best Q-switched pulse energy was obtained with a 72% reflective output coupler. With a 264 us 704 W pump pulse (186 mJ) the observed linearly polarized 1064 nm pulse energy was 18 mJ with a 16 ns pulse width. The optical (pump) to optical (laser) conversion efficiency is 9.7%. The Q-switched output of the end-pumped Nd:YAG laser was reduced with a telescope to a 2 mm diameter spot on a 3 mm long type II phase matching KTP crystal. The green 532 nm pulse energy was 10 mJ, which corresponds to 56% second harmonic conversion efficiency. The repetition rate 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 as shown in Fig. 9(b). In these experiments the laser pulse energy was reduced to 10 mJ by lowering the OC reflectivity to reduce the risk of coating damage on the YAG crystal. At higher repetition rates degradation of the lasing mode due to thermal effects in the gain medium resulted in reduced laser pulse energy.

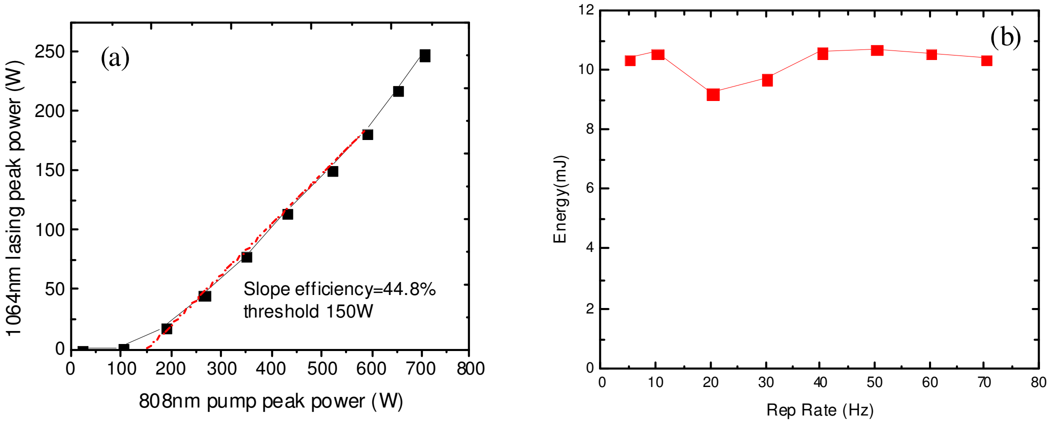

Fig. 9: (a) QCW peak 1064 nm power of the Nd:YAG laser end-pumped by a QCW high power VCSEL pump module operating with a 250 µs pulse duration at a 4 Hz repetition rate; (b) IR laser pulse energy as a function of VCSEL pump pulse repetition rate.

Finally, the possibility for scaling the laser output to higher pulse energy by dual side VCSEL end-pumping was investigated. The schematic layout this configuration is shown in Fig. 10. The first VCSEL pump module is projected on onto the HR coated end facet of Nd:YAG crystal with a 10.5 mm focal length focusing lens. The output of a second VCSEL pump module is projected onto the AR coated end facet of the YAG crystal with the use of a 3:1 reducing telescope. A telescope is implemented to increase the working distance between the YAG crystal and the pump optics. The second end facet of the YAG crystal has an AR coating at 1064 nm that is sufficiently broadband to transmit most of the pump light (>95%) of the second VCSEL module. A flat mirror with a partially reflective coating forms the output coupler.

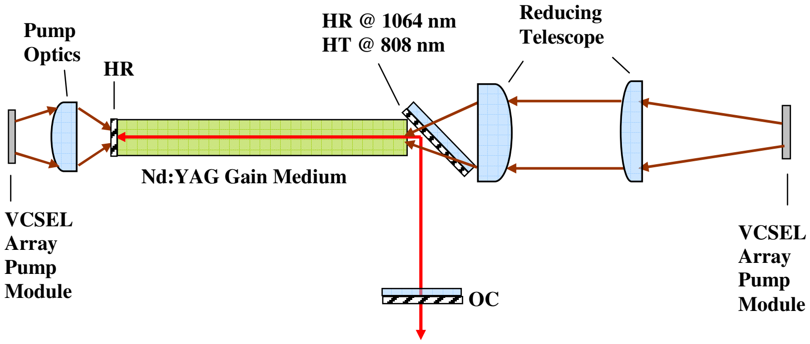

Fig. 10: Schematic layout of the dual VCSEL end-pumped Nd:YAG laser.

The graph in Fig. 11 shows the QCW 1064 nm IR peak power of the Nd:YAG laser in the dual end-pumped configuration with both VCSEL pump modules running. The threshold for QCW lasing is 200 W and the observed slope efficiency is 42%. At the total peak 808 nm pump power of 1.5 kW 550 W QCW IR peak power was achieved. The optical (808 nm) to optical (1064 nm) conversion efficiency was 37%. The pump pulse energy was 370 mJ and the QCW 1064 nm laser pulse energy was 137 mJ.

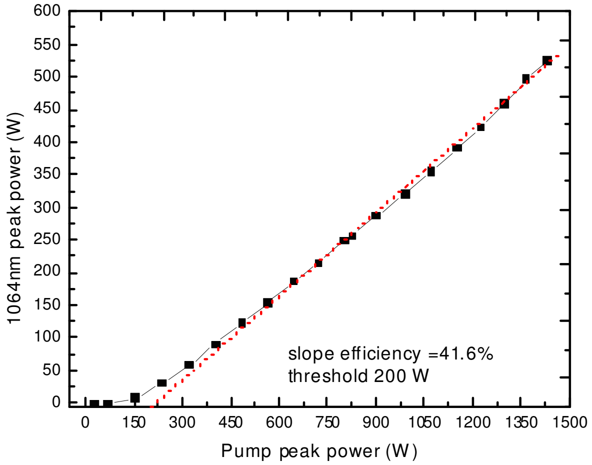

Fig. 11. QCW 1064nm peak power of the Nd:YAG laser in the dual end-pumped configuration with two VCSEL pump modules activated.

5. CONCLUSIONS

Because of their 2D-scalability, uniform beam profile, narrow spectral linewidth, low temperature dependence, and high reliability, VCSEL arrays make excellent pump sources for DPSS laser and are particularly well suited for constructing very compact DPSS lasers. With rectangular shaped VCSEL pump modules for side pumping an actively Q-switched 946 nm Nd:YAG laser was constructed that produced 21 mJ IR laser pulses that were efficiently frequency doubled to generate 10 mJ 473 nm blue laser pulses with a 17 ns pulse width. VCSEL pump modules with circular emitting areas were used to demonstrate a passively Q-switched VCSEL end-pumped Nd:YAG laser producing 18 mJ 1064 nm laser pulses and 10 mJ 532 nm green laser pulses by second harmonic generation.

6. ACKNOWLEDGEMENTS

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