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High power high repetition rate VCSEL array side-pumped blue laser

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ABSTRACT

High power, kW-class, 808 nm pump modules based on the vertical-cavity surface-emitting laser (VCSEL) technology were developed for side-pumping of solid-state lasers. Two 1.2 kW VCSEL pump modules were implemented in a dual side-pumped Q-switched Nd:YAG laser operating at 946 nm. The laser output was frequency doubled in a BBO crystal to produce pulsed blue light. With 125 μs pump pulses at a 300 Hz repetition rate 6.1 W QCW 946 nm laser power was produced. The laser power was limited by thermal lensing in the Nd:YAG rod.

Keywords: vertical-cavity surface-emitting laser, diode-pumped solid-state laser, blue laser, 808 nm, 2-D array, high power, high repetition rate, 946 nm.

1. INTRODUCTION

High-energy pulsed diode-pumped solid-state (DPSS) lasers are typically pumped by quasi-CW (QCW) high-brightness stacks of edge-emitting diode bars.[1-2] Recently, pump modules comprising high power two-dimensional (2-D) vertical-cavity surface-emitting laser (VCSEL) arrays[3-4] have emerged as attractive alternatives to pump DPSS lasers.[5-10] The advantages over the existing edge-emitter technology include simpler pump optics, a reduced wavelength sensitivity to temperature (~0.07 nm/deg), increased reliability, especially at high temperatures, and low-cost manufacturing.

High-power VCSEL arrays comprise thousands of low power (few mW) high efficiency (>40%) single elements that emit in an intrinsically circular, spectrally narrow (~1 nm full width at half maximum), uniform beam of low divergence (~0.15 numerical aperture). Power levels of the VCSEL arrays can reach a few hundred Watts, while maintaining high power conversion efficiency (PCE). Multiple of these 2-D VCSEL arrays can be combined into kW-class VCSEL pump modules. These modules exhibit similar properties as their single element constituents, including narrow linewidth and high wavelength stability, which result in high single pass absorption by the solid state gain medium. Furthermore, since VCSELs are insensitive to incident light, they facilitate dual-side pumping, making VCSEL pump modules well suited for constructing compact high power DPSS lasers.

Various VCSEL pumped 1064 nm Nd:YAG lasers have been reported, both in end- and side-pumping configurations, employing active, as well as passive, Q-switching techniques, demonstrating the viability of VCSEL pumping of compact DPSS lasers.[5-10] Up to 40 mJ and 22 mJ Q-switched IR pulse energy was achieved using active and passive Q-switching respectively.[10] Green and UV light was produced using harmonic generation in non-linear crystals.

For certain applications, such as underwater transmission and detection, blue light with high pulse energy is required. We previously reported a frequency-doubled actively Q-switched VCSEL-array dual side-pumped Nd:YAG laser operating at 946 nm producing >20 mJ Q-switched IR pulses.[5, 7] The laser was externally frequency doubled with 48% second harmonic generation efficiency to obtain 473 nm blue light with 10 mJ pulse energy[5]. The laser contained two gain modules, each comprising one Nd:YAG rod and two VCSEL side-pumping modules operating with 0.6 kW peak power, 250 μs long pump pulses at a 5 Hz repetition rate.

This paper describes our recent efforts to significantly increase the repetition rate of the blue laser. Since we observed previously that the Q-switched 946 nm pulse is comparable to the QCW laser pulse energy,[5,7] our focus was on increasing the average QCW 946 nm laser power, while maintaining the same pulse energy and beam quality. A new generation 808 nm VCSEL arrays was developed with improved performance that allowed the VCSEL pump modules to operate at 1.2 kW peak power, and the cooling of the YAG rod was improved as well. With the improved VCSEL pump modules the number of gain modules in the laser could be reduced to one, leading to strongly reduced re-absorption losses in the quasi three-level gain medium, increased efficiency, and operation at repetition rates up to 300 Hz.

2. VCSEL STRUCTURE AND FABRICATION

The detailed VCSEL device structure and fabrication has been described elsewhere[4], so only on brief summary is given here. The epitaxial VCSEL material designed to lase at 808 nm was grown on GaAs substrates using MOCVD. For current and optical confinement selective oxidation is used to create an aperture near the active region. The growth starts with an etch-stop layer to facilitate 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. A high-aluminum content layer is placed near the first pair of the p-DBR to form the oxide aperture.

For 808 nm VCSEL arrays the GaAs substrate needs to be removed to reduce the thermal impedance. First the epitaxial side of the wafer is fully processed. The wafer is then bonded onto a sacrificial carrier using a special bonding agent. The GaAs substrate is removed using a selective wet-etch. The etch-stop layer is then removed using another selective wet-etch, thus exposing the highly doped n-type GaAs contact layer. At this stage the sample is only 10 µm thick. Patterned n-metal pads are evaporated onto the contact layer. These bonding pads are then plated with Au. The individual arrays are cleaved, with each array still attached to its individual carrier. Each array/carrier assembly is then soldered to a high-conductivity diamond submount. The carrier is removed and the array-on-submount assembly is cleaned. Finally the array is wire-bonded and tested. Fig. 1 shows a schematic of the cross-section of a small portion of a packaged 808 nm VCSEL array.

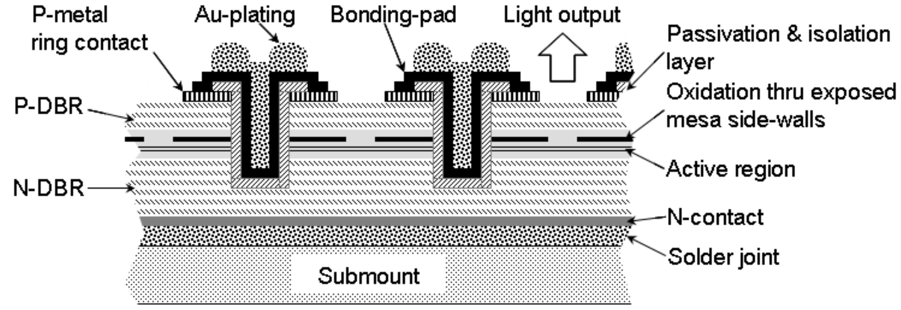

Figure 1: A cross-section schematic of a portion of a packaged 808 nm VCSEL array for which the GaAs substrate has been completely removed during processing to reduce the thermal impedance of the array.

3. HIGH POWER VCSEL ARRAY PUMP MODULES

Two VCSEL 808 nm pump modules designed for side pumping a 2 mm x 2 mm x 20 mm Nd:YAG rod were constructed. Each module comprises twelve 3 mm VCSEL arrays arranged in a 6 x 2 layout to allow for efficient pumping of the 20 mm long gain medium. Each VCSEL array has a 2.7 mm x 2.7 mm emitting area that contains a few thousand elements that emit in a low-order circularly symmetric transverse mode. Each array was designed to operate at 100 W light output at a 10% duty cycle. This is a factor of two higher than the generation of VCSEL arrays used in the blue laser reported previously.[5, 7] These high power VCSEL arrays were mounted in pairs on a diamond heat spreader. Six pairs were mounted side by side on a 20 mm x 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.

The graphs in Fig. 2 show the performance of the high power VCSEL pump module. Fig. 2(a) shows the 808 nm peak power as a function of peak current. The current pulse duration was 200 µs, and the repetition rate was 100 Hz. The threshold of the module was 40 A, and at 240 A the VCSEL pump module produces >1.2 kW peak power. Fig. 2(b) shows the peak power as a function of repetition rate. Here, the pump pulse duration was set at 125 µs, and the peak current was fixed at 240 A. The peak power dropped slightly from 1.25 kW at 100 Hz to 1.18 kW at 1 kHz. The average pump power at 1 kHz, corresponding to a 12.5% duty cycle, was 150 W. The central wavelength of the VCSEL pump module was close to the 808.6 nm absorption line of the Nd:YAG gain medium, while the bandwidth of the pump module was ~2 nm. Over 60% of the pump light was absorbed in the 2 mm wide Nd:YAG rod.

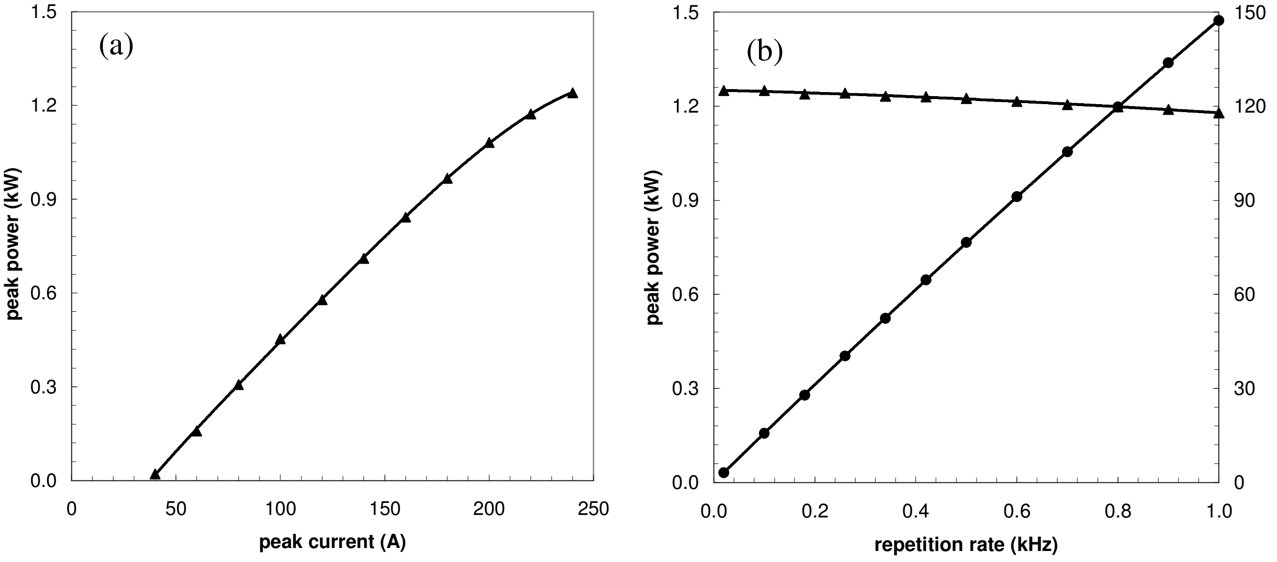

Figure 2: (a) Peak power of the high power 808 nm VCSEL array pump module as a function of peak current; the current pulse duration is 200 µs, and the repetition rate is 100 Hz. (b) Peak power (triangles) and average power (circles) of the pump module as a function of repetition rate; the current pulse duration is 125 µs, and the peak current is 240 A.

4. VCSEL SIDE-PUMPED Nd:YAG LASER

Two high power VCSEL pump module were inserted into a gain module that also contained a 2 mm x 2 mm x 20 mm square Nd:YAG rod placed in a crystal holder and pump optics. The 1% doped Nd:YAG crystal rod was clamped between two copper mounts, with indium foil placed in between the crystal and the mount to ensure good thermal contact. The copper mounts were water cooled by a chiller set to operate at 20 deg C. The Nd:YAG rod was Brewster cut to achieve linearly polarized light that is required for efficient second harmonic generation. The pumping surfaces were AR coated at the 808 nm pumping wavelength.

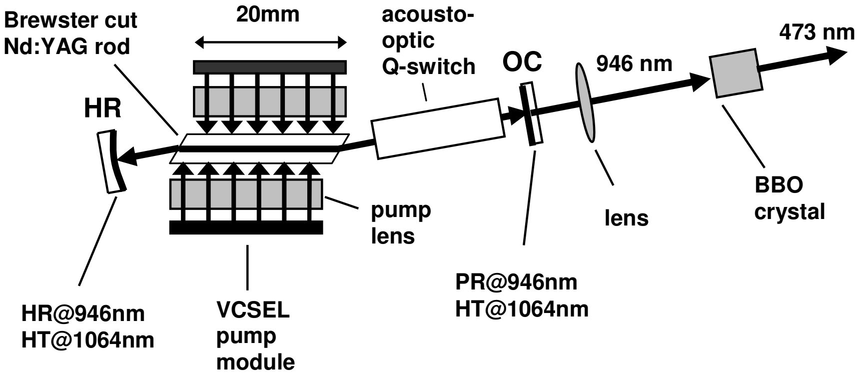

Figure 3: Schematic layout of the actively Q-switched VCSEL side-pumped Nd:YAG laser operating at the 946 nm transition. The laser output is frequency doubled in a non-linear BBO crystal.

The output of the VCSEL pump modules was projected onto the Nd:YAG rod by an 8 mm diameter half-rod lens. Fig. 3 shows the schematic layout of the frequency-doubled actively Q-switched VCSEL side-pumped blue laser. The laser cavity was formed by a curved high reflector and a flat output coupler. The cavity mirrors were coated with a dual wavelength high damage threshold dielectric coating that was highly transmissive at 1064 nm to avoid parasitic lasing at the stronger lasing transition. Short pulse operation was achieved using an acousto-optic Q-switch. The total cavity length was 120 mm. The output of the laser was loosely focused into a 7 mm long BBO crystal to produce blue laser pulses.

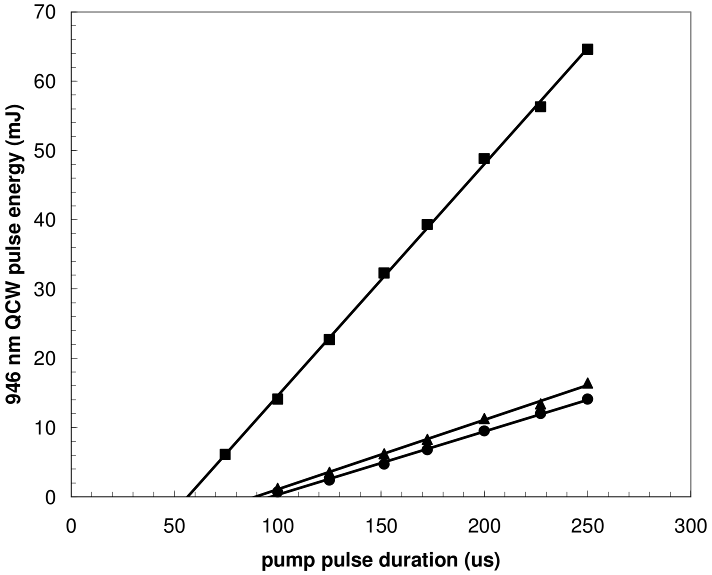

Figure 4: 946 nm QCW pulse energy of the high power VCSEL pumped Nd:YAG laser obtained with dual side pumping (squares), and single-side pumping (circles, and triangles) with 1.2 kW VCSEL pump modules operating at a 100 Hz repetition rate.

Fig. 4 shows the 946 nm quasi-CW (QCW) laser pulse energy for both single side and dual side pumping. The pump current for each module was 240 A, and the repetition rate was 100 Hz. The output coupler reflectivity was 75%. Single side pumping with a 200 µs pump pulse resulted in ~10 mJ IR laser pulse energy, while the laser pulse energy was 49 mJ for dual side pumping. Clearly there is a strong increase in pulse energy when the crystal is pumped from two sides. This is partly due to the high threshold of the laser operating at the quasi three-level 946 nm transition, but also to the more uniform pump profile in the dual side-pumping configuration, and the increased pump light absorption resulting from unabsorbed pump light being back reflected by the other pump module.

Because the thermal population of the lower lasing level leads to significant re-absorption losses at the 946 nm quasi three-level lasing transition, it is more efficient to pump a shorter gain medium with higher peak power pump modules. Fig. 5 compares the results obtained with a single 2.4 kW gain module (containing one 20 mm long YAG rod pumped by two 1.2 kW high power VCSEL pump modules), to the results obtained with two 1.2 kW gain modules (each containing a 20 mm long YAG rod pumped by two 0.6 kW VCSEL pump modules). The 808 nm pump pulse energy was varied by adjusting the pump pulse duration. In both cases the same total incident pump pulse energy was produced with the same pump pulse duration. However, the 946 nm QCW pulse energy obtained with the single gain module laser was much higher than that obtained with the dual gain module laser. With 250 µs current pulses (630 mJ pump pulse energy) the laser pulse energy increased from 27 mJ to 64 mJ. The slope efficiency improved from 7.1% for the laser with two 1.2 kW gain modules to 12.7% for the laser with one 2.4 kW gain module, while the threshold was reduced from 260 mJ to 140 mJ.

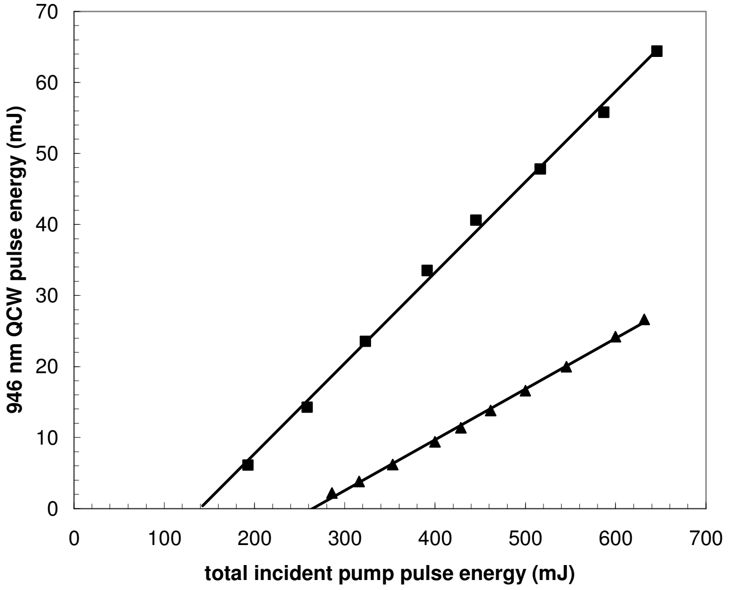

Figure 5: 946 nm QCW pulse energy of a VCSEL pumped Nd:YAG laser that contains one 2.4 kW gain module:(squares), and a VCSEL pumped Nd:YAG laser that contains two 1.2 kW gain modules (triangles) operating at 100 Hz

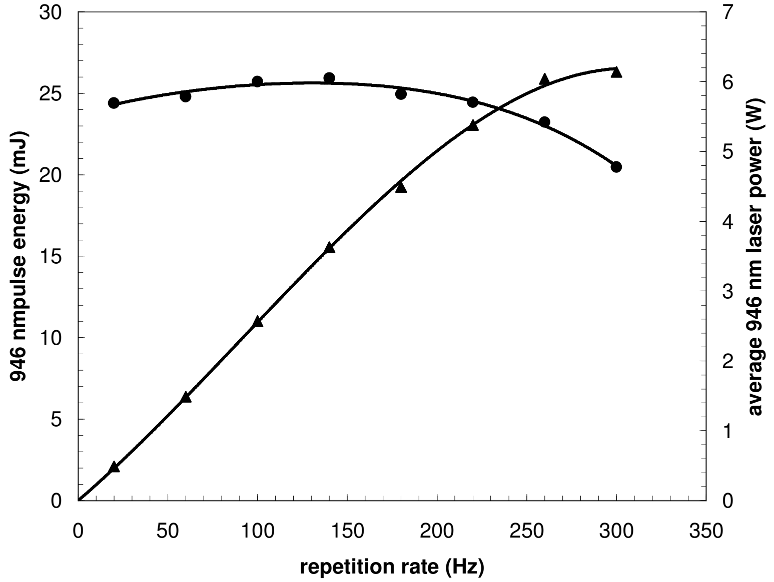

Figure 6: Average 946 nm QCW laser power (triangles) and pulse energy (circles) obtained with 125 µs 2.4 kW pump pulses.

As a result of the increased 808 nm to 946 nm conversion efficiency of the laser pumped by two high power VCSEL pump modules the same QCW laser pulse energy can now be obtained with much shorter pump pulse; e.g. to obtain 20 mJ QCW 946 nm pulse energy the pump pulse duration could be decreased from 225 µs to115 µs.

With the high power VCSEL pump modules operating in QCW mode with 125 µs current pulses the repetition rate of the single gain module laser was increased. Fig. 6 shows the average 946 nm laser power and pulse energy as a function of repetition rate. The maximum average laser power was 6.1 W at 300 Hz, corresponding to 20.4 mJ 946 nm laser pulse energy. The average 808 nm incident pump power is 90 W at roll-over. The laser power was limited by thermal lensing in the Nd:YAG rod.

5. CONCLUSIONS

A new generation 808 nm VCSEL arrays was developed to improve the performance of the frequency-doubled actively Q-switched VCSEL side-pumped 946 nm Nd:YAG laser. Two VCSEL pump modules were constructed that emitted 1.2 kW peak power when operated with 125 µs long current pulses at a 1 kHz repetition rate. With the improved VCSEL pump modules the number of gain modules in the blue laser could be reduced to one, leading to strongly reduced re-absorption losses in the quasi three-level gain medium and an increased laser efficiency. The maximum 946 nm average QCW power was 6.1 W at a 300 Hz repetition rate, corresponding to >20 mJ laser pulse energy. The laser power was limited by thermal lensing in the Nd:YAG rod.

6. ACKNOWLEDGEMENTS

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