# High power 808 nm VCSEL arrays for pumping of compact pulsed high energy Nd:YAG lasers operating at 946 nm and 1064 nm for blue and UV light generation

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## ABSTRACT

High power 808 nm VCSEL arrays were developed to pump compact pulsed Nd:YAG lasers. A QCW side-pumped passively Q-switched Nd:YAG laser operating at 1064 nm produced linearly polarized 4 ns IR pulses with 4.7 mJ pulse energy. These pulses were externally frequency doubled and quadrupled resulting in 2.5 mJ pulse energy at 532 nm and 0.8 mJ at 266 nm respectively. A similar but actively Q-switched dual side-pumped Nd:YAG laser operating at the weaker quasi three-level 946 nm transition produced 12 mJ pulses that were efficiently frequency doubled resulting in 5.6 mJ blue pulses of 17 ns duration.

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

## 1. INTRODUCTION

Vertical-cavity surface-emitting lasers (VCSELs) can be easily arranged in two-dimensional (2D) configurations, which allows for scaling to high powers[1]. Recently high power 808 nm 2D VCSEL arrays were reported[2]. These arrays can be used as pump sources for diode-pumped solid-state (DPSS) lasers such as high-energy Q-switched Nd:YAG lasers for blue and UV applications that include under-water transmission and LIDAR. Typically these types of lasers are pumped by stacks of edge-emitting diode bars often in end-pumped configurations[3,4]. High power VCSEL arrays are particularly well suited for constructing very compact side-pumped DPSS lasers. They can be arranged in a layout that is optimal for uniform illumination of the gain medium; they have a narrow linewidth[1] (typically 0.8 nm) and a low dependence on temperature[1] (0.07 nm/deg C) resulting in a high single-pass absorption that is relatively insensitive to temperature variations. Furthermore since VCSEL arrays are not affected by incident light or back reflections they facilitate dual-side pumping of the gain medium for high pulse energy applications.

The 808 nm VCSEL device structure and fabrication has been described elsewhere[2]. In this paper we report on the results from bench-top experiments with a VCSEL side-pumped frequency-quadrupled passively q-switched Nd:YAG laser operating at the 1064 nm lasing transition producing 0.8 mJ 266 nm UV pulses of 2.7 ns duration. In addition we report on a VCSEL dual side-pumped frequency-doubled actively Q-switched Nd:YAG laser operating at the 946 nm transition producing 5.6 mJ blue 473 nm pulses of 17 ns duration.

## 2. VCSEL ARRAY PUMP MODULES

An 808 nm VCSEL array pump module was designed for side-pumping 2 mm x 2 mm x 20 mm Nd:YAG crystals. A picture of the pump module is shown in Fig. 1(a). The pump module comprises twelve VCSEL arrays that are arranged in a 6 x 2 layout. Each VCSEL array has a 2.7 mm x 2.7 mm emitting area that contains a few thousand small aperture elements that emit in a low-order circularly symmetric mode. At the typical quasi-CW (QCW) array operating current of 40 A over 40 W peak power is emitted from the array within a 0.15 numerical aperture. To construct a pump module VCSEL arrays were mounted in pairs on a diamond sub-mount. Six pairs were mounted side-by-side on a 20 mm x 20

Solid State Lasers XX: Technology and Devices, edited by W. Andrew Clarkson, Norman Hodgson, Ramesh Shori,
Proc. of SPIE Vol. 7912, 79120Z · © 2011 SPIE · CCC code: 0277-786X/11/$18 · doi: 10.1117/12.873952

mm micro-cooler and connected by numerous thin wire-bonds, The arrays in each pair were operated in parallel, while the six pairs were operated in series. The picture in Fig. 1(b) shows the uniform distribution of the light emitted by the VCSEL pump module.

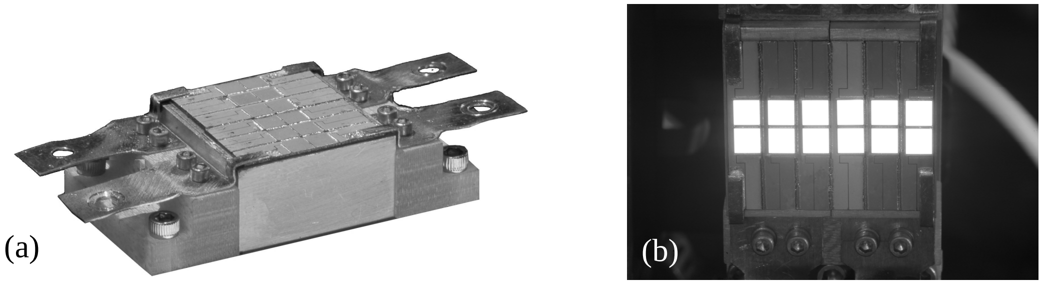

**Fig. 1**. Pictures of an 808 nm VCSEL array pump module comprising twelve 3 mm VCSEL arrays arranged in a 6 x 2 layout. The picture on the left (a) shows the VCSEL arrays mounted on a 20 mm x 20 mm micro-cooler assembly. The picture on the right (b) shows the uniform distribution of the light emitted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

Fig. 2(a) shows the peak power emitted by the pump module under QCW operation with a 300 us pump pulse and a 1% duty cycle. The pump module emits 500 W at the targeted 80 A operating current with an 44% electrical to optical conversion efficiency. Fig. 2(b) shows the optical spectrum of the combined output of the twelve arrays that make up the pump module as measured in the far field with an optical spectrum analyzer. The peak wavelength of the pump module is 808.4 nm while the FWHM of the spectral output is 1.0 nm, which provides a good match to the narrow 808.6 nm absorption line of Nd:YAG. Fig. 2(a) shows that this resulted in a high, close to 70%, single pass absorption of the Nd:YAG crystal at the 80 A operating current. At higher currents the absorbed power drops from the maximum 343 W as the absorption quickly falls when the pump wavelengths exceeds the peak of the 808 nm absorption peak. The asymmetric lineshape in Fig. 2(b) is due to a small variation in the peak wavelengths of the VCSEL arrays in the pump module.

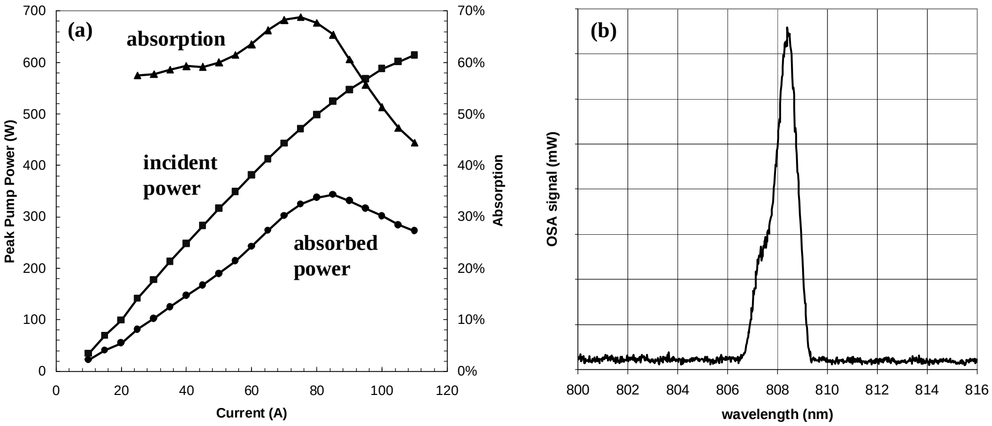

**Fig. 2.** Performance of the 808 nm VCSEL array module designed for pumping a 2 mm x 2 mm x 20 mm Nd:YAG crystal. (a) Peak power incident on the Nd:YAG crystal (solid squares), absorbed peak power (solid circles), and absorption (solid triangles). (b) Optical spectrum of the output of the pump module measured by an optical spectrum analyzer.

## 3. UV LASER

The high power 808 nm 2D-VCSEL array technology was applied to develop a compact high-energy short-pulse UV laser. The schematic layout of the frequency quadrupled VCSEL side-pumped Nd:YAG laser is shown in Fig. 3. The output of a 500 W VCSEL array pump module was projected onto a 2 mm x 2 mm x 20 mm 1% doped Nd:YAG crystal by an 8 mm diameter half-rod cylindrical lens with a 4.8 mm focal length. The laser cavity was formed by a curved mirror with a highly reflective dielectric coating and a flat output coupler mirror with a partially reflective coating at the 1064 nm lasing wavelength. An uncoated thin glass plate was inserted at the Brewster angle to ensure a linearly polarized output needed for efficient harmonic generation. A Cr:YAG saturable absorber was added to the cavity to achieve passive Q-switching. The end surfaces of the Nd:YAG and Cr:YAG crystals were AR coated at 1064 nm. The cavity length was typically about 40 mm. The output of the Q-switched laser was externally frequency quadrupled to 266 nm UV light using non-linear KTP and BBO crystals.

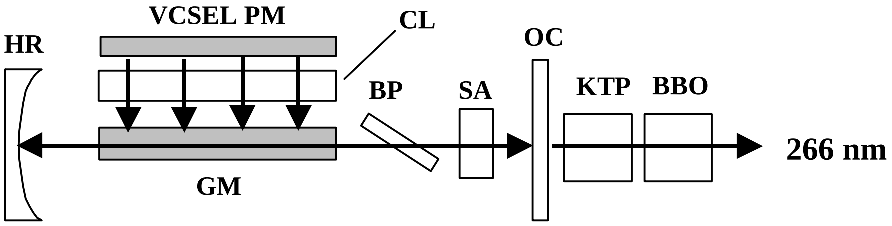

**Fig. 3.** Schematic layout of the UV laser. The Nd:YAG gain medium (GM) is side-pumped by a VCSEL array pump module (PM) with the use of a cylindrical lens (CL). The laser cavity is formed by a curved high reflector (HR) and a flat output coupler (OC) and contains a Brewster plate (BP) and a Cr:YAG saturable absorber (SA). The linear polarized Q-switched 1064 nm output is converted to 266 nm UV by fourth harmonic generation with two non-linear crystals (KTP, BBO).

Initial experiments were carried out without the saturable absorber in the cavity. With an 85% OC and a 320 us low duty cycle pump pulse a 36 mJ QCW 1064 nm pulse was obtained. Fig. 4 shows the linear dependence of the QCW 1064 nm pulse energy on the absorbed 808 nm pump pulse energy.

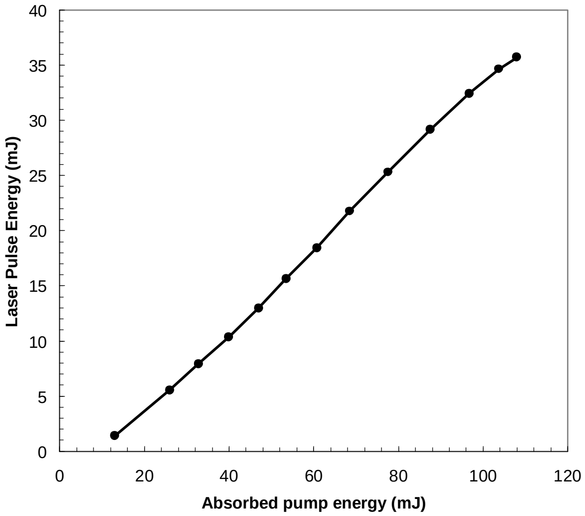

**Fig. 4.** QCW pulse energy of the side-pumped 1064 nm Nd:YAG laser with a 320 us pump pulse

The side-pumped Nd:YAG laser was passively Q-switched by inserting a Cr:YAG saturable absorber into the laser cavity. To maximize the Q-switched IR pulse energy lasing needs to be held off for a time comparable to the 230 us upper state lifetime of the Nd:YAG gain medium to allow for high energy storage in the upper lasing level. This was achieved with a saturable absorber with a low initial transmission. Since the residual losses of the fully saturated Cr:YAG crystal due to excited state absorption are high a low value for the output coupler reflectivity was chosen. Fig. 5(a) shows that a single Q-switched pulse was obtained with a 220 us pump pulse; Q-switching occurred after 210 us. The 1064 nm Q-switched pulse energy was 4.7 mJ. The IR pulse duration was measured with a fast InGaAs photodetector. An oscilloscope trace is shown in Fig. 5(b); the FWHM is 4.0 ns. The far field divergence (half angle at $1/e^2$) of the Q-switched pulse was measured to be 2.0 mrad, indicating that the beam was ~5.9 times diffraction limited.

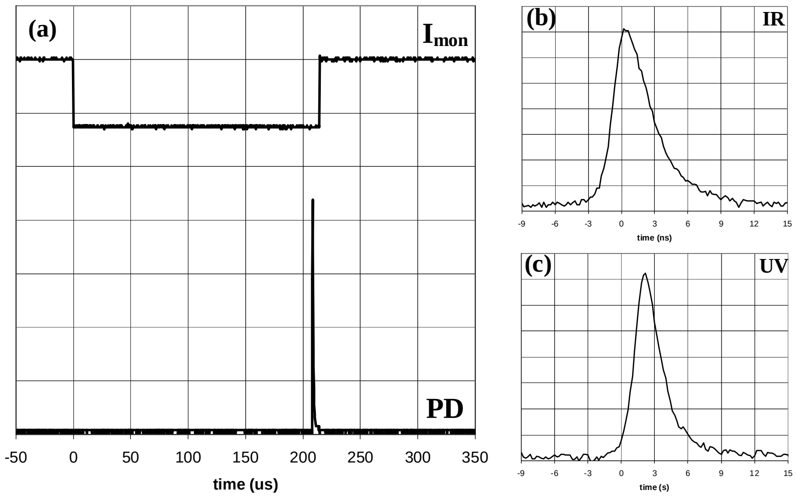

**Fig. 5.** Q-switched output of the passively Q-switched side-pumped Nd:YAG laser. (a) Oscilloscope traces of the current monitor ($I_{mon}$) and the photodiode (PD) show that with a 220 us current pulse a single Q-switched pulse was observed after 210 us. The traces on the right show the temporal shape of the 1064 nm pulse (b) and the frequency quadrupled 266 nm UV pulse (c) measured with a fast photodiode.

The 1064 nm IR output was frequency doubled in a 5 mm long type II phase matching KTP crystal. This resulted in 2.5 mJ pulse energy at 532 nm and thus a 54% IR to green conversion efficiency. The 532 nm output was frequency doubled in a 5 mm long type I phase matching BBO crystal. By weakly focusing the green output into the BBO crystal 0.8 mJ 266 nm UV was achieved with a 32% green to UV conversion efficiency. An oscilloscope trace of the UV output measured by a fast Si detector is shown in Fig. 5(c); the FWHM is 2.7 ns.

## 4. BLUE LASER

For another application the high power 808 nm 2D-VCSEL array technology was applied to develop a compact high-energy short-pulse blue laser. This laser is based on a side-pumped Nd:YAG laser operating at the weaker 946 nm lasing transition. Since this is a quasi three-level laser transition a higher pumping rate is needed to overcome the absorption losses by the thermally populated lower laser level. This was accomplished by dual side pumping. To increase the 946 nm output further multiple Nd:YAG crystals were used and Q-switching was achieved using a lower loss 50 mm long acoustic-optic Q-switch. The laser was externally frequency doubled in a BBO crystal. A schematic layout of the blue laser is shown in Fig. 6. The laser contains multiple laser heads. Each head contains a 2 mm x 2 mm x 20 mm Nd:YAG crystal that is side-pumped from two opposite side by two QCW 500 W 808 nm VCSEL array pump modules using two sets of cylindrical pump optics. The cavity mirrors have dual wavelength dielectric coatings that are highly (HR) or partially reflective (OC) for the 946 nm lasing transition and anti-reflective (R<5%) for the 1064 nm transition to avoid parasitic lasing and amplified spontaneous emission.

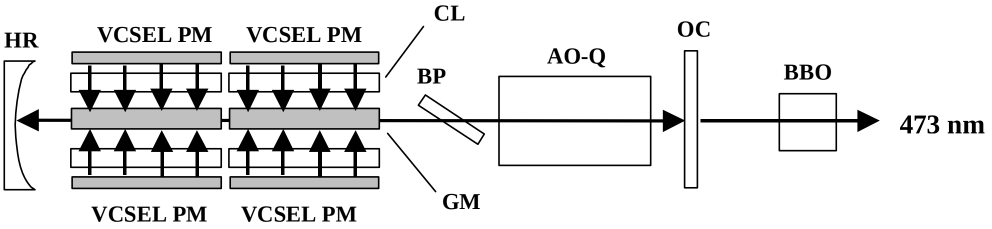

**Fig. 6.** Schematic layout of the blue laser. The Nd:YAG gain medium (GM) is dual side-pumped by multiple VCSEL array pump modules (PM) with the use of cylindrical lenses (CL). The laser cavity is formed by a curved high reflector (HR) and a flat output coupler (OC) and contains a Brewster plate (BP) 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.

Fig. 7(a) shows the QCW 946 nm output of the laser with one, two, and three laser heads operated at a low duty cycle. The acousto-optic Q-switch was present in the cavity but set to the low-loss state. The output coupler reflectivity was 85% for the cavity containing one or two laser heads but lowered to 69% for the cavity with three laser heads. The pump power was kept constant while the pump pulse duration was varied. The pulse energy depends linearly on the pump pulse duration with a slope that approximately doubles or triples when two or three laser heads are used instead of one, demonstrating the scalability of the modular approach. Fig. 7(b) shows the optical spectrum of the QCW 946 nm Nd:YAG laser. No parasitic lasing at the stronger 1064 nm transition was observed.

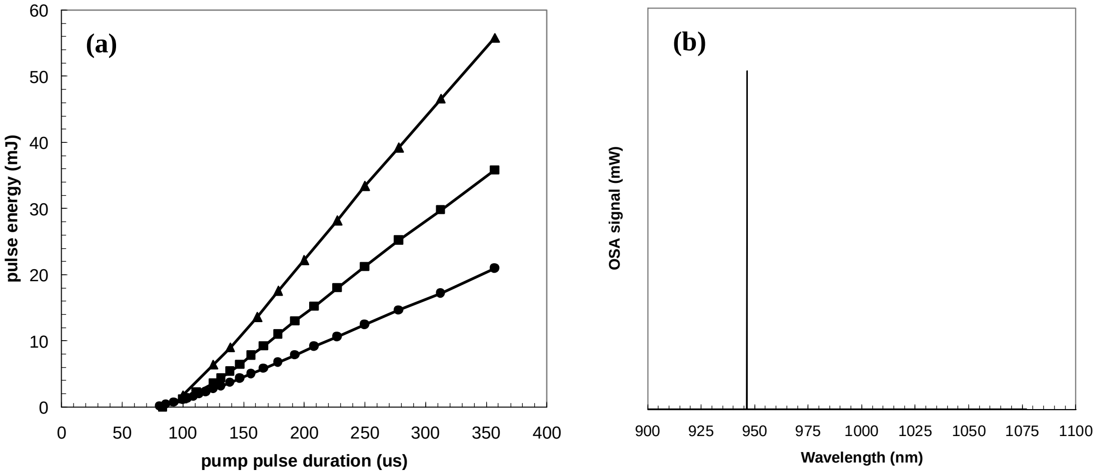

**Fig. 7.** (a) QCW pulse 946 nm pulse energy as a function of pump pulse duration for a laser containing one (solid circles), two (solid squares), or three (solid triangles) laser heads. (b) Optical spectrum of the QCW 946 nm Nd:YAG laser; no lasing at 1064 nm was observed.

Fig. 8 shows the Q-switched 946 nm output of an actively Q-switched dual VCSEL side-pumped Nd:YAG laser with two laser heads. The acousto-optic Q-switch is in the high loss state during the entire length of the pump pulse. The threshold for lasing is reached with an 85 us pump pulse. After that the Q-switched IR output initially increases linearly with increasing pump pulse duration but the slope starts to decline as the upper laser level depopulation losses increase due to fluorescence. With a 220 us pump pulse 12 mJ of Q-switched 946 nm in a 23 ns pulse was achieved. Increasing the pulse length further resulted in pre-lasing at 946 nm and thus to lower pulse energy in a short pulse. This issue is being addressed by increasing the diffraction efficiency of the acousto-optic Q-switch, which is currently at 30%.

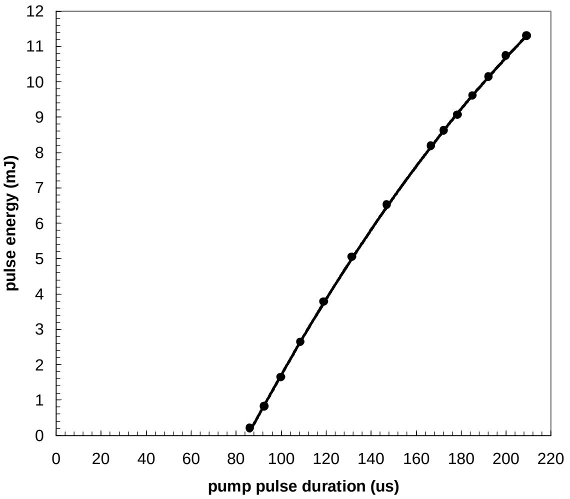

**Fig. 8.** Q-switched 946 nm output of an actively Q-switched dual VCSEL side-pumped Nd:YAG laser with two laser heads.

The Q-switched 946 nm output was efficiently externally frequency doubled in a 7 mm long BBO crystal without the use of a lens. Fig. 9(a) shows the blue pulse energy as a function of the IR pulse energy, which was varied by varying the pump pulse duration. With a 230 us pump pulse a blue 473 nm pulse with 5.6 mJ energy was obtained; this corresponds to a 44% IR to blue conversion efficiency. Fig. 9(b) shows the temporal output of the blue pulse measured with a fast Si photo-detector. The FWHM of the high energy blue pulses is 17 ns.

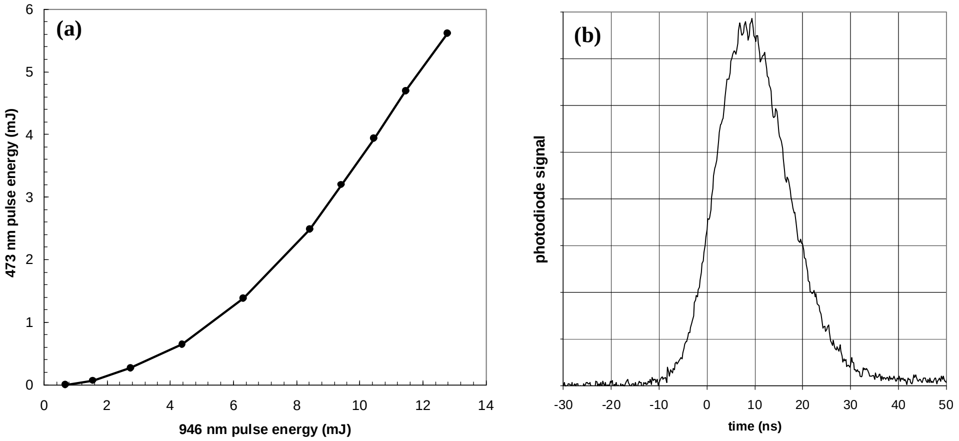

**Fig. 9**. (a) Blue 473 nm pulse energy as a function of IR pulse energy. (b) Temporal shape of a 5.6 mJ blue pulse with a 17 ns FWHM.

## 5. CONCLUSIONS

It was demonstrated that 808 nm VCSEL arrays make excellent pump sources for DPSS lasers. They are particularly well suited for constructing very compact side-pumped DPSS lasers. High energy UV and blue pulses were obtained from a VCSEL side-pumped frequency-quadrupled passively q-switched 1064 nm Nd:YAG laser and a VCSEL dual side-pumped frequency-doubled actively Q-switched 946 nm Nd:YAG laser respectively. These lasers produced 0.8 mJ 2.7 ns UV pulses and 5.6 mJ 17 ns blue pulses.

## 6. ACKNOWLEDGEMENTS

Financial support for this research from NAWCAD LKE and DARPA MTO is gratefully acknowledged.

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