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# 0.9W compact UV pulsed lasers using high-power VCSEL array side-pumping

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## ABSTRACT

A compact UV pulsed laser pumped by high-power two-dimensional arrays of vertical-cavity surface-emitting lasers (VCSELs) was presented. A passively Q-switched 1064-nm Nd:YAG laser was side-pumped by kW-class 808-nm VCSEL pump modules and the output pulses were frequency quadrupled to 266-nm, 10-ns, 0.68-mJ UV pulsed output was obtained at 1.33k-Hz repetition rate. The average UV power is > 0.9-W. This VCSEL pumped high power UV laser source provides a reliable, low-cost and low-profile solution for military and commercial applications including remote sensing, laser processing and spectroscopy.

**Keywords:** 808 nm, VCSEL array, Nd:YAG laser, Q-switched, UV laser, side-pumping

## 1. INTRODUCTION

UV laser sources with output wavelength below 300-nm have wide range of applications including laser micromachining, semiconductor wafer inspections, remote sensing, and spectroscopy. UV laser pulses are typically obtained through frequency up-conversions of Q-switched or mode-locked solid-state lasers in near infrared (NIR) wavelengths<sup>1</sup>. The pursuit of high pulse energy (mJ level) and high pulse repetition rate (>1k Hz) UV laser brings unique challenges to the laser pump sources. Traditionally, high repetition rate solid state lasers are pumped by stacks of edge emitting diode laser bars operating in quasi-continuous-wave (QCW) modes<sup>2</sup>. Sophisticated optics and precise alignment are needed to collimate and focus the edge emitting pump light onto the solid state gain medium. Moreover, due to the large thermal drift of diode output wavelength, accurate control over diode temperature is required to ensure high pump efficiency, which becomes difficult at high pump power.

Recently, two dimensional arrays of vertical-cavity surface-emitting lasers (VCSELs) have been developed for laser pump applications<sup>3-6</sup>. The array consists of a large number of VCSEL elements, each emitting a few mW of optical power. Multiple VCSEL arrays can be combined in a compact form to generate kW-level power. The high output power, flexible configuration, high reliability (high temperature durable and insensitive to back reflection), as well as excellent spectral properties (narrow output wavelength and low wavelength thermal drift) make the VCSEL array an attractive pump source for solid state laser.

A number of VCSEL pumped solid state lasers were demonstrated in the last few years<sup>5-10</sup>. For example, single pulse energy as high as 40-mJ was reported with an actively Q-switched end-pumped Nd:YAG laser at 1064-nm<sup>9</sup>. Meanwhile, pulse repetition rates as high as 240-Hz and 9.3k-Hz were reported for passively Q-switched 1064-nm Nd:YAG lasers with mJ-level and  $\mu$ J-level pulse energy respectively<sup>7,8</sup>. More recently, 300-Hz 20-mJ QCW laser operation was achieved with a 946-nm Nd:YAG laser<sup>10</sup>. In this paper, we demonstrated significant enhancement in both repetition rate and total output power for mJ-level VCSEL pumped Nd:YAG laser and UV laser. With a compact Nd:YAG laser cavity and two high power VCSEL array side-pumping modules, 10.9-W 1064-nm QCW output power was achieved at 1.9k-Hz. Moreover, 8.24-W 1064-nm Q-switched output power was obtained at 1.33k-Hz and consequently converted to 4.05-W green power and 0.9-W UV power respectively. These bench-top results illustrate the feasibility of the VCSEL array side-pumping configuration for high pulse energy, high repetition rate solid state laser applications.

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## 2. VCSEL ARRAY SIDE PUMPING

The side pumping module used in this experiment consists of 12 2.7×2.7-mm VCSEL arrays electronics connected in serial, and compactly positioned on a micro-channel cooler as shown in Figure 1. Each of the VCSEL array is comprised of thousands of single 808nm VCSEL emitters connected in parallel, and is capable of emitting 50-W of peak power with uniform light intensity. Detailed description of the VCSEL structure can be found elsewhere<sup>3-6</sup>. The threshold driving current of the module is 20-A. At driving current of 110-A and QCW pulse duration of 100- $\mu$ s, the module provides > 550-W peak power at repetition rate up to 1k-Hz. With lower driving current of 70-A, the module is able to operate at 2k-Hz repetition rate with >250-W peak output power, as shown in the right of Figure 1.

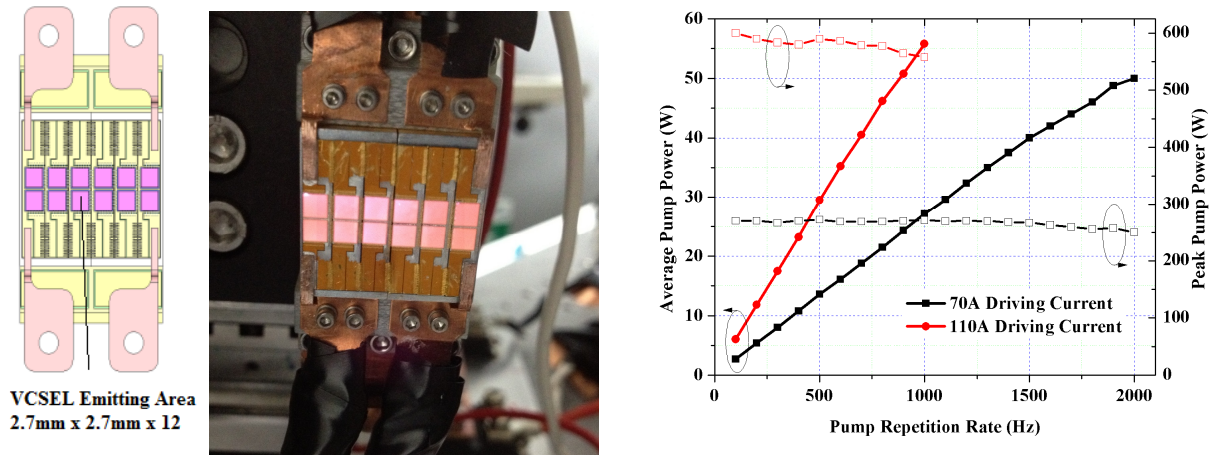


Figure 1 (Color online). Left: layout and picture of the 6×2 VCSEL arrays side-pumping module; Right: Average and peak output power of a single pump module under 100 $\mu$ s pump pulse duration and different repetition rates with 70A and 110A driving currents.

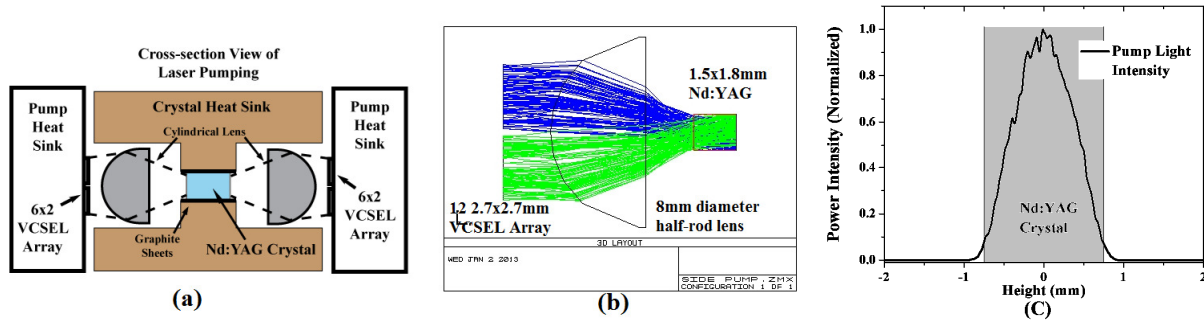


Figure 2 (Color online). Left: Cross-section design of the side-pumped laser head fixture; Middle: Zemax simulation of the 808nm pump light from VCSEL array to Nd:YAG crystal; Right: Pump light distribution on the pump surface of Nd:YAG crystal simulated by Zemax.

The VCSEL side-pumping compatible laser head design was shown in Figure 2a. A 20-mm length × 1.8-mm width × 1.5-mm height 1% w.t. doped Nd:YAG crystal was installed in the laser head fixture. In order to provide linearly polarized laser operation and increase damage threshold, the two un-coated end surfaces of the laser crystal were Brewster-cut at 61°. The two side-pumping surfaces of the crystal were AR coated at both 808nm and 1064nm. One of the side surfaces was also angle polished at 3° to prevent possible parasitic lasing at 1064nm in the transverse direction. Two pieces of graphite sheets were inserted between the copper heat sinks and the top and bottom surfaces of the crystal respectively. The copper heat sinks were cooled by an external liquid chiller (not shown). By adjusting the tensions of four tension-lock screws between top and bottom heat sinks, uniform and moderate pressure was applied to the crystal to ensure good thermal contact between crystal and heat sinks.

808-nm pump light from a pair of 6×2 VCSEL pump modules were focused onto the Nd:YAG crystal using a pair of cylindrical lenses. The emitting area of the pump module is 20-mm × 5.8-mm. The N.A. is ~ 0.15. The cylindrical lenses are 8-mm diameter half-rods with refractive index of 1.82 and anti-reflective coating at 808-nm. The positions of the VCSEL pump modules and the cylindrical lenses can be adjusted individually to maximize the pump absorption. Figure 2b and 2c shows the ray-tracing simulation results of the pump light propagation using Zemax software. With optimal optical alignment, >98% of the pump light is projected onto the Nd:YAG pump surface with a Gaussian-like profile of light intensity, which results in good overlapping between pump light and laser beam.

### 3. HIGH REPETITION RATE QCW AND Q-SWITCHED LASER

The basic laser cavity as shown in Figure 3 consists of the laser head fixture, a 1064-nm highly reflective end mirror and a 1064-nm 50% transmission output coupler. Q-switched operation is forced by the insertion of a 1064-nm AR coated Cr:YAG crystal with 40% initial transmission. The insertion of a quarter waveplate (QWO) compensates the thermally induced polarization rotation in the YAG crystals and ensures the linear polarization output of the laser cavity.

Directly out of the laser cavity, a 1064-nm + 532-nm AR coated KTP crystal was placed at 45° transverse tilting angle to allow efficient type-II second harmonic generation. The size of the KTP is 10-mm×5-mm×5-mm. The 532-nm output was further frequency doubled by a 5-mm×5-mm×5-mm AR-coated BBO crystal placed also at 45° angle after the KTP. The 266nm fourth harmonic output was separated from IR and green output using a silica prism (Not shown). The total length of bench-top setup is less than 6 inches, as is shown in Figure 3.

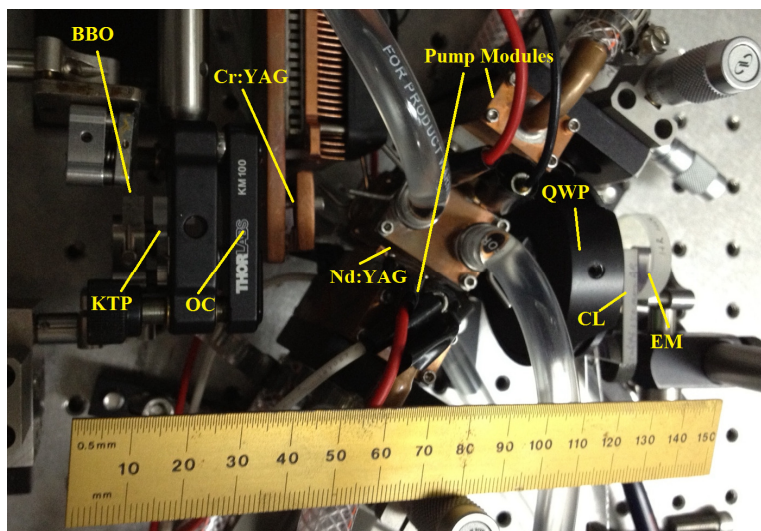
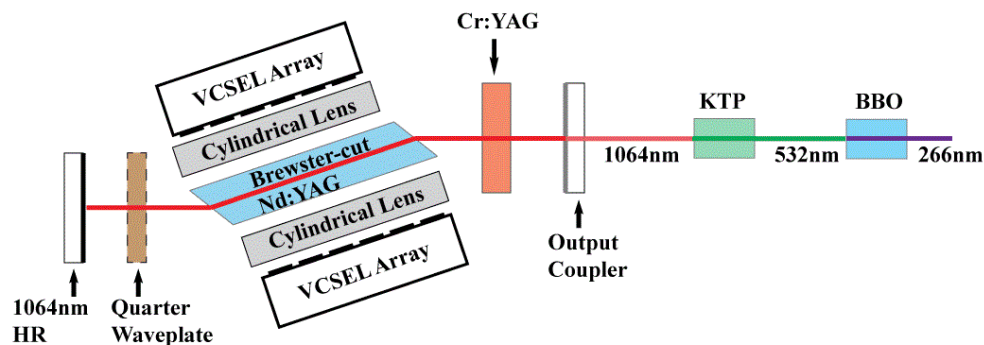


Figure 3 (Color online). Top: schematic layout of UV laser including the VCSEL side-pumped Q-switched Nd:YAG laser cavity and frequency quadrupling; Bottom: Picture of the bench-top UV laser setup. OC: Output Coupler; QWP: Quarter Waveplate; CL: Cylindrical Lens; EM: End Mirror.

As described in the previous section, two VCSEL pump modules were employed in the bench-top setup to side-pump the Nd:YAG crystal. At maximum driving current of 120-A + 120-A, more than 1200-W of peak power can be obtained from the dual pump modules to facilitate high pulse energy and overall laser efficiency. While for high repetition rate operations, lower driving current is preferred to avoid thermal lensing induced laser beam quality deterioration and possible crystal surface damages from Q-switched pulses. Figure 4 compares the QCW output power and pulse energy with different driving currents at pump pulse duration of 100- $\mu$ s. At driving current of 110-A + 105-A, maximum QCW power of 11.8-W was obtained for maximum repetition rate of 1.1k-Hz before thermal rollover. The pulse energy dropped by 31% from 15.6-mJ at 100-Hz to 10.7-mJ at 1.1-kHz, accompanied by serious thermally induced deterioration in laser beam quality. At a lower driving current of 70-A + 70-A, we were able to push the repetition rate up to 1.9-kHz and obtained 10.9-W output power. The pulse energy dropped by merely 11% from 6.4-mJ at 100-Hz to 5.7-mJ at 1.9-kHz.

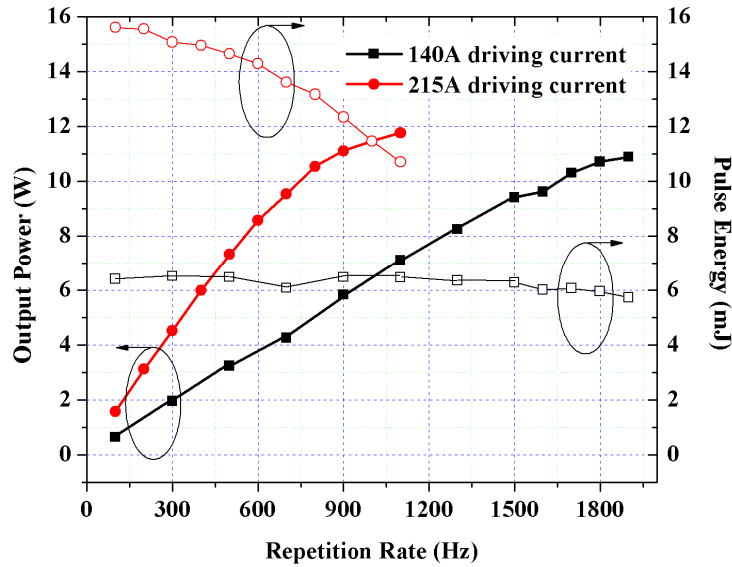


Figure 4 (Color online). Schematic layout of UV laser including the VCSEL side-pumped Q-switched Nd:YAG laser cavity and frequency quadrupling.

#### 4. FREQUENCY QUADRUPLING

With the insertion of Cr:YAG crystal, Q-switched operation was investigated with 140-A driving current, 125 $\mu$ s pump pulse duration and different repetition rates. The results are summarized in Figure 5. Linear dependence of Q-switched average output power vs. pulse repetition rates were observed up to 1.3-kHz. Power roll-over was observed in 1.3k-1.5k-Hz, which is attributed to thermal lensing effect. The maximum Q-switched IR output power is 8.34-W, with single pulse energy of 6.4-mJ at 1.3-kHz. The optical to optical efficiency is estimated as 9.8%, and the electrical to optical efficiency as 2.5%. The QCW to Q-switching efficiency is estimated as 73% at 1.3-kHz. This is attributed to the relatively higher ASE loss and worse pump to laser beam overlapping of Q-switched operation compared with the QCW case.

Frequency up-conversion results to 532-nm Green and 266-nm UV light were also illuminated in Figure 5. At maximum pulse repetition rate of 1.33k-Hz, maximum green power of 4.05-W and UV power of 903-mW were obtained after tuning the laser polarization and aligning the nonlinear crystal. The green and UV pulse energy are 3.05-mJ and 0.68-mJ respectively. The IR to Green and to UV conversion efficiencies are 48.5% and 10.8%.

Pulse duration measurements were performed with a Silicon photodiode (Thorlabs DET10A, 200-1100nm, 1-ns rising time) and an 200MHz digitized oscilloscope. 19-ns, 12-ns and 10-ns pulse durations were obtained for the IR, green and UV pulses respectively, as shown in figure 6. The pulse duration can be further shortened by increasing the intra-cavity

energy and shortening the cavity length. The UV peak power is ~68-kW and the power density is ~90-MW/cm<sup>2</sup> with ~1-mm estimated beam diameter right after the nonlinear crystal. The UV beam divergence is measured as < 2-mrad.

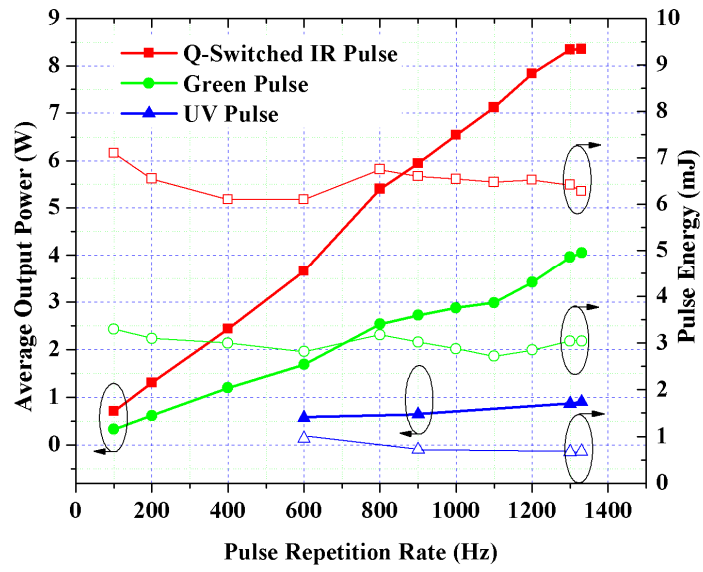


Figure 5 (Color online). Schematic layout of UV laser including the VCSEL side-pumped Q-switched Nd:YAG laser cavity and frequency quadrupling.

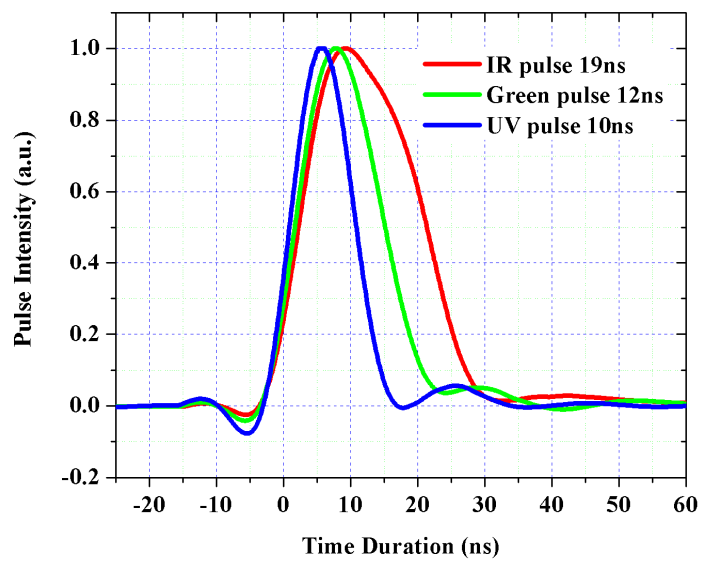


Figure 6 (Color online). Schematic layout of UV laser including the VCSEL side-pumped Q-switched Nd:YAG laser cavity and frequency quadrupling.

## 5. CONCLUSION

We reported a compact UV pulse laser with 1.33k-Hz repetition rate and 0.9-W average power. A 1064-nm passively Q-switched Nd:YAG laser was side-pumped by two 808-nm high power VCSEL array pump modules operating at 70-A driving current and 250-W peak power. With optimized VCSEL driving current and careful laser cavity design, we were able to operate the laser at 1.9k-Hz for QCW mode and 1.3k-Hz for Q-switched mode before thermal rollover. Maximum IR output power of 10.9W and 8.34W were achieved for the QCW and Q-switched mode respectively. With frequency quadrupling efficiency of 10.8%, 10ns 0.68mJ 266nm UV pulse was obtained at repetition rate of 1.33k-Hz. As new generations of 808-nm VCSEL arrays with higher brightness and higher efficiency being developed<sup>10</sup>, further enhancements on the laser pulse energy, repetition rate and efficiency can be expected.

## 6. ACKNOWLEDGEMENTS

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