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1 W frequency-doubled VCSEL-pumped blue laser with high pulse energy

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ABSTRACT

We report on a Q-switched VCSEL side-pumped 946 nm Nd:YAG laser that produces high average power blue light with high pulse energy after frequency doubling in BBO. The gain medium was water cooled and symmetrically pumped by three 1 kW 808 nm VCSEL pump modules. More than 1 W blue output was achieved at 210 Hz with 4.9 mJ pulse energy and at 340 Hz with 3.2 mJ pulse energy, with 42% and 36% second harmonic conversion efficiency respectively. Higher pulse energy was obtained at lower repetition frequencies, up to 9.3 mJ at 70 Hz with 52% conversion efficiency.

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

1. INTRODUCTION

High average power pulsed blue lasers with high pulse energy are needed for certain applications such as long-range underwater detection and imaging. High power pulsed blue lasers are typically achieved by frequency doubling the output of Q-switched 946 nm Nd:YAG lasers that are continuously end-pumped by high power diode laser stacks. High average blue power (> 1 W) has been reported from such lasers but only with low pulse energy (< 1 mJ) when operating at very high repetition rates of tens of kHz.[1-2] High blue pulse energy (9 mJ) has been demonstrated using quasi-CW (QCW) end-pumping when operating at very low pulse repetition frequencies of a few Hz, restricting the average power to tens of mW.[3]

We previously reported 10 mJ 473 nm blue laser pulses at 5 Hz from a frequency-doubled Q-switched 946 nm Nd:YAG laser that was dual side-pumped by QCW 808 nm vertical-cavity surface-emitting laser (VCSEL) pump modules.[4-5] The laser contained several gain modules, each comprising one Nd:YAG rod clamped between two Cu heatsinks and two VCSEL side-pumping modules operating at 0.6 kW peak power. Owing to the excellent mode quality of the Q-switched IR laser output for low thermal loads of the gain medium, a high (48%) second harmonic conversion efficiency was achieved with a BBO frequency doubling crystal.

Recently, 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.[6] With the improved VCSEL pump modules the number of dual side-pumped gain modules in the laser could be reduced to one, leading to strongly reduced re-absorption losses in the quasi three-level gain medium, higher efficiency, and increased pulse repetition frequency. The blue laser output however was limited by strongly asymmetric thermal lensing in the dual side-cooled laser rod, which led to poor mode quality of the Q-switched 946 nm output that resulted in poor second harmonic conversion efficiency.

In this paper we report on our recent efforts to significantly increase the average power of the blue laser. To improve cooling of the quasi three-level gain medium a cylindrical Nd:YAG rod was placed into a flow tube using chilled water as a coolant. To minimize asymmetric thermal lensing the cylindrical rod was symmetrically pumped by three 808 nm VCSEL side-pumping modules each operating in QCW mode with 1 kW peak power. Various laser cavity configurations were investigated. More than 1 W blue output was achieved at 210 Hz with 4.9 mJ pulse energy and at 340 Hz with 3.2 mJ pulse energy with 42% and 36% second harmonic conversion efficiency respectively.

2. VCSEL SIDE-PUMPED LASER GAIN MODULE

High power 808 nm pump modules comprising two-dimensional (2-D) VCSEL arrays make excellent sources for pumping of solid state lasers.[7] The advantages over the existing edge-emitter technology include simpler pump optics, reduced wavelength sensitivity to temperature, increased reliability, high temperature operation, and potential for low-cost manufacturing. High-power VCSEL arrays comprise thousands of low power high efficiency single VCSEL elements that emit in an intrinsically circular, spectrally narrow, low divergence beam. Power levels of the VCSEL arrays reach a few hundred Watts, while multiple of these 2-D VCSEL arrays can be combined to construct kW level VCSEL pump modules. The VCSEL device structure and fabrication has been described in detail elsewhere.[8]

Figure 1(a) shows an 808 nm VCSEL pump module designed for side pumping an Nd:YAG laser. The module comprises twelve 3 mm VCSEL arrays arranged in a 6 x 2 layout for efficient pumping of a 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 peak power. 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 operating at 20 deg C.

The threshold of the VCSEL pump module was 40 A, and at 240 A the VCSEL pump module produces 1.2 kW peak power. 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 resulting in > 60% single pass absorption of the pump light in a 2 mm thick 1% doped Nd:YAG crystal. Recently, these type of VCSEL pump modules were used to construct a frequency-quadrupled side-pumped Nd:YAG laser that produced 0.9 W of UV power at 266 nm.[9]

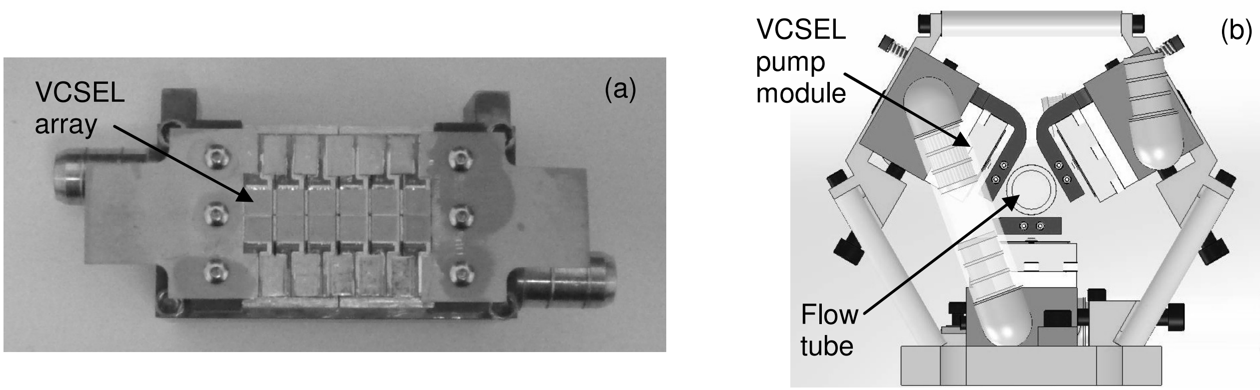

Figure 1: (a) Photograph of a VCSEL pump module comprising twelve 3 mm VCSEL arrays in a 6 x 2 layout, and (b) end-view of the flow tube in a hexagonal structure holding 3 VCSEL pump modules.

A water cooled VCSEL side-pumped laser gain module was constructed by mounting by 3 high power VCSEL pump modules at 120 degree angles with respect to each other in a rigid hexagonal structure containing a flow tube for the gain medium as shown in Fig. 1(b). A circular 2 mm or 3 mm diameter 30 mm long YAG rod with a 20 mm long Nd doped gain section was mounted in the 188 mm long flow tube. Two 5 mm long undoped endcaps were used for mounting purposes and reduction of thermal stress at the crystal surfaces. The outer surface of the rod was neither coated nor polished to avoid parasitic lasing at 1064 nm and amplified spontaneous emission. The gain medium was symmetrically side-pumped by three VCSEL pump modules operating at 200 A, corresponding to 3 kW total incident pump power. The output of the each VCSEL pump module was focused on to the Nd:YAG rod by a 8 mm diameter half rod cylindrical lens.

Thermal lensing in the gain module was investigated by sending the output of a single transverse mode helium-neon gas laser through the flow tube containing a 3 mm diameter Nd:YAG rod and measuring the change in beam size as a function of VCSEL power. A Gaussian beam analysis was used to derive the focal power of the thermal lens as a function of average VCSEL pump power; the results are shown in Fig. 2. The HeNe beam remained approximately circular up to 300 W incident pump power.

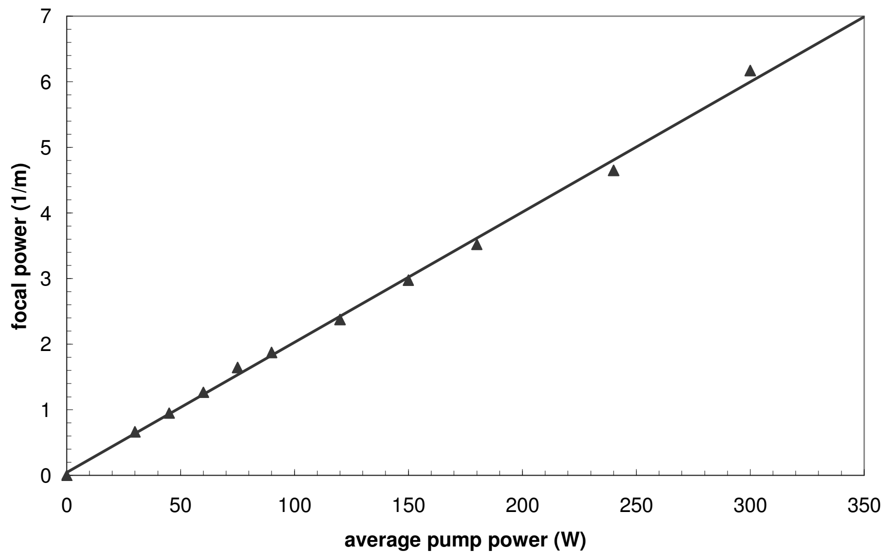

Figure 2: Focal power of the thermal lens of a 3 mm diameter Nd:YAG rod in the water cooled laser gain module under non-lasing conditions derived from measurements with a HeNe laser. The straight line shows a linear fit to the data.

3. Q-SWITCHED BLUE LASER

The laser gain module was placed in a laser cavity designed for single transverse mode output by taking into account the strength of the thermal lens. The schematic layout of the frequency-doubled actively Q-switched VCSEL side-pumped blue laser is shown in Fig. 3. The cavity is formed by a highly reflective (HR) coating on the YAG rod and a partially reflective (PR) output coupler (OC) with 75% reflectivity. The cavity mirrors were coated with dual wavelength, high damage threshold, dielectric coatings that were highly transmissive (HT) at 1064 nm to avoid parasitic lasing at the stronger lasing transition. Two HR folding mirrors were added to the laser cavity to completely suppress parasitic lasing during Q-switched operation. Short pulse operation was achieved using a low-loss Brewster-cut acousto-optic Q-switch (AOQ). A quarter wave plate (QWP) was inserted into the cavity to reduce depolarization losses due to thermally induced birefringence.

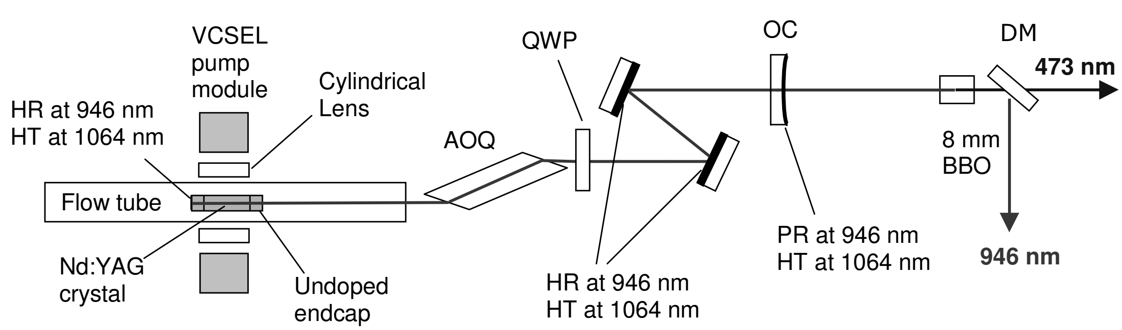

Figure 3: Schematic layout of the actively Q-switched VCSEL side-pumped Nd:YAG laser operating at the 946 nm transition. The 946 nm laser output is externally frequency doubled in a non-linear BBO crystal to 473 nm.

The Q-switched 946 nm output of the laser cavity was frequency doubled to 473 nm in an 8 mm long BBO crystal. A dichroic mirror (DM) was used to remove the residual fundamental IR from the blue second harmonic output. To ensure a short blue pulse width (< 35 ns) the optical path length of the laser cavity was kept below 300 mm. Since the strength of the thermal lens depends on the average VCSEL pump power, a cavity mode diameter that is large enough in the gain medium to suppress higher order transverse modes can be achieved with the right combination of OC curvature and average pump power. This then results in a single transverse mode output with good beam quality, which is required for efficient second harmonic generation in the BBO crystal due to its narrow angular acceptance bandwidth.

For example, when operating the VCSEL pump modules with 200 A, 200 us current pulses and using a reversed concave OC with 0.5 m radius of curvature (roc) acting as a convex mirror, single transverse mode Q-switched operation was achieved at 170 Hz pulse repetition frequency (PRF), corresponding to 102 W average VCSEL power. A BBO crystal was placed at the waist position of concave-convex laser cavity, which was located outside the cavity 150 mm from the OC. The beam diameter of the generated blue light was measured at 0.3 m and 1.8 m from the waist location; the beam divergence was 0.84 mrad. The measurements were consistent with a 360 um single mode beam waist diameter; see Fig. 4(a). IR pulses with 10.5 mJ energy were obtained that were frequency doubled in BBO with 47% second harmonic conversion efficiency to 4.9 mJ blue pulses. An oscilloscope trace of the blue laser output measured with a fast Si photodetector is shown in Fig. 4(b); the full width at half maximum of the blue pulse is 27 ns.

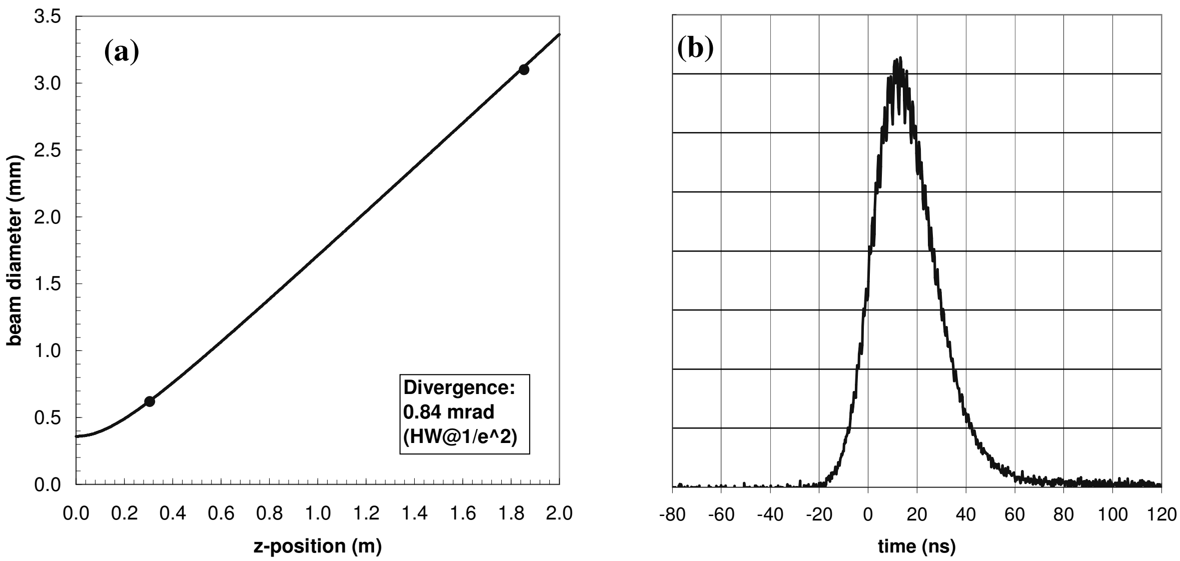

Figure 4: Measurements of the divergence (a) and the temporal pulse shape (b) of the blue output of the frequency doubled VCSEL pumped blue laser operating at 170 Hz PRF. The solid line in (a) shows the expected beam diameter for a 360 um single mode beam.

The pulse repetition frequency of the laser could be varied over a significant range by simultaneously adjusting the pump pulse duration to keep the average VCSEL pump power, and thus the focal length of the thermal lens, constant. This is illustrated in Fig. 5; it shows results for a 3 mm Nd:YAG rod in a near hemispherical cavity configuration with a flat OC and a BBO crystal placed directly behind it. In this configuration the repetition frequency of the blue laser was increased from 200 Hz to 300 Hz while the pump pulse duration was optimized to maximize the blue power. Fig. 5(a) shows that the pump pulse duration decreased from 238 us at 200 Hz to 162 us at 300 Hz PRF, with the average VCSEL pump power varying only slightly from 162 W to 166 W.

Fig. 5(b) shows the blue pulse energy and average blue power obtained with this configuration. The blue pulse energy varied from 4.9 mJ at 200 Hz to 2.3 mJ at 300 Hz. The blue pulse energy is higher at lower PRF because the IR pulse energy, which depends on how much energy is stored in the gain medium before the laser is Q-switched, increases as the pump pulse duration increases toward lower PRF. Lowering the PRF below 200 Hz in this configuration optimized for high pump power did not result in higher blue pulse energy because the Q-switched IR laser pulse energy at longer pump pulse durations is limited by increased amplified spontaneous emission (ASE). The maximum average blue power was 1.02 W at 210 Hz.

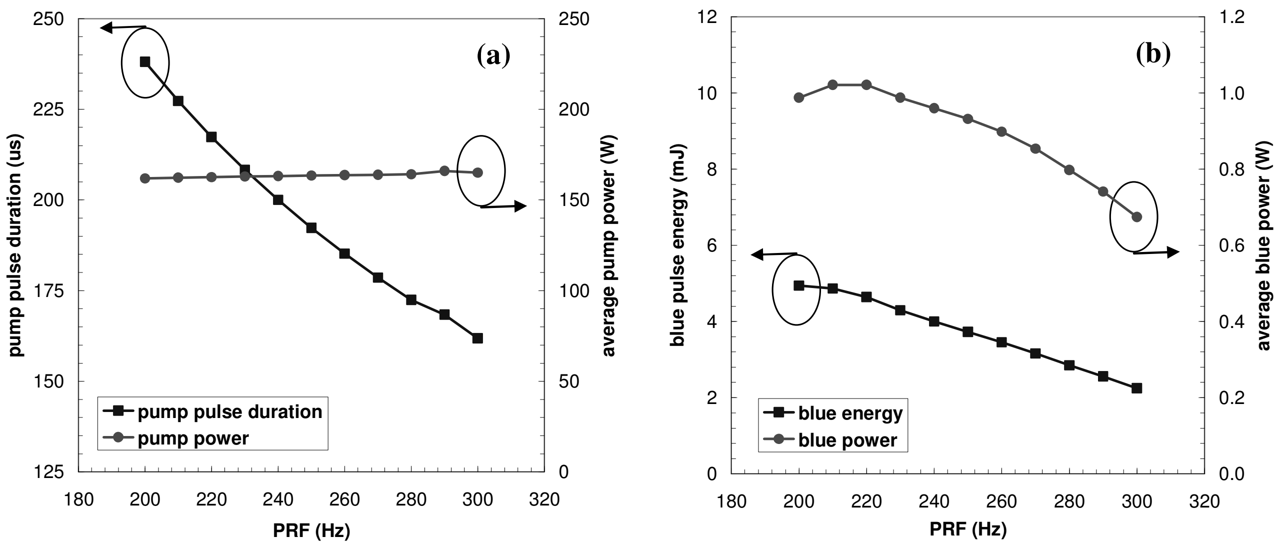

Figure 5: (a) Optimized pump pulse duration and corresponding VCSEL power of the blue laser in a near hemi-spherical configuration with a flat OC. (b) Pulse energy and average power of the blue laser operating at 4.8% duty cycle.

Higher blue laser pulse energies could be achieved however with a different cavity configuration designed for lower average pump power. Using a 1.0 m radius of curvature OC, with again a 238 us pump pulse, 9.3 mJ blue pulse energy was obtained at 70 Hz PRF with 74 W pumping. Pulse energies are higher at lower PRF because, for the same pump pulse energy, the average pump power is lower and the laser is more efficient since temperature dependent losses, such as thermally induced depolarization and reabsorption, are lower. Higher Q-switched pulse energy also leads to higher SHG conversion efficiency, in this case 52%. The maximum blue power for this configuration was 0.73 W at 90 Hz.

The blue pulse energy and power in Fig. 5(b) diminishes with increasing PRF because the laser is operating closer to threshold. The threshold can be lowered by using a smaller diameter Nd:YAG rod and tighter focusing of the output of the VCSEL pump modules. With a 2 mm diameter Nd:YAG rod, using shorter focal length pump optics, and the laser operating again in a near hemi-spherical configuration with a flat OC, 3.4 mJ blue pulse energy was generated at 340 Hz with 36% conversion efficiency, resulting in 1.08 W average blue power. The total incident VCSEL power was significantly lower (~108 W) compared to the 3 mm diameter rod in the same configuration because tighter focusing induced a stronger thermal lens, increasing the 808 nm to 473 nm optical conversion efficiency from 0.6% to 1.0%. Tighter focusing also resulted in stronger ASE and a lower onset for parasitic lasing, which, combined with increased probability for crystal damage due to the reduced 946 nm beam size at the Nd:YAG rod, restricted operation to pulse repetition frequencies of 340 Hz and above.

An overview of all the data collected from the four different cavity configurations is given in Fig. 6. It shows the 473 nm pulse energy, the 946 nm pulse energy, and the second harmonic generation (SHG) efficiency of the frequency-doubled VCSEL side-pumped actively Q-switched Nd:YAG laser as a function of pulse repetition frequency. Using 4 different configurations a frequency range from 70 Hz to 460 Hz was spanned. The highest blue pulse energy of 9.3 mJ was obtained at 70 Hz with a 3 mm Nd:YAG rod and a 1.0 m roc OC, while the highest blue power was reached at 340 Hz with a 2 mm diameter Nd:YAG and a flat OC.

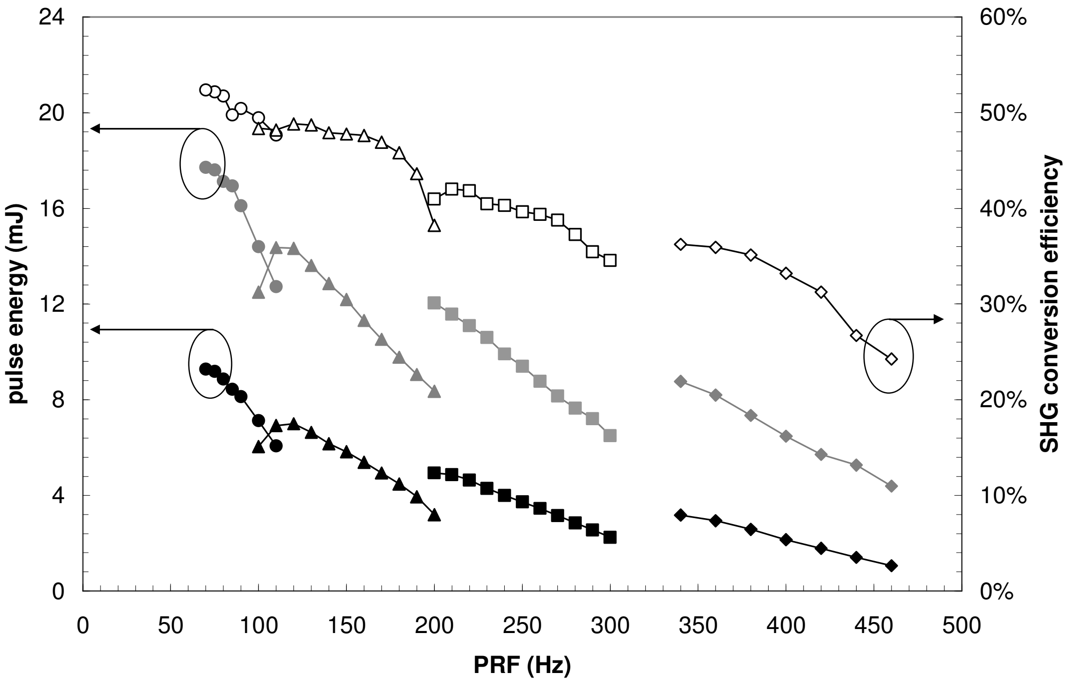

Figure 6: Blue pulse energy (solid black), IR pulse energy (solid gray), and doubling efficiency (open black) of three laser cavity configurations with a 3 mm diameter Nd:YAG rod and a 1.0 m roc OC (circles), a 0.5 m roc OC (triangles), and a flat OC (squares), and one laser cavity configuration with a 2 mm diameter Nd:YAG rod and a flat OC (diamonds).

4. CONCLUSIONS

We reported on a high power frequency-doubled VCSEL side-pumped actively Q-switched Nd:YAG blue laser with high pulse energy. Temperature dependent losses of the quasi three-level gain medium were effectively minimized by placing a cylindrical Nd:YAG rod in a flow tube using chilled water as a coolant. To avoid asymmetric thermal lensing, the cylindrical rod was symmetrically pumped by three 808 nm VCSEL side-pumping modules each operating in QCW mode with 1 kW peak power. Various laser cavity configurations were investigated. More than 1 W blue output was achieved at 210 Hz with 4.9 mJ pulse energy and at 340 Hz with 3.2 mJ pulse energy with 42% and 36% second harmonic conversion efficiency respectively. Higher pulse energy was obtained at lower repetition frequencies, up to 9.3 mJ at 70 Hz with 52% conversion efficiency.

5. ACKNOWLEDGEMENTS

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