High Power Pulsed Intra-Cavity Frequency Doubled Vertical Extended Cavity Blue Laser Arrays

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ABSTRACT

Electrically pumped vertical cavity surface emitting lasers (VCSELs) can produce hundreds of mW's of 976 nm CW output in a TEM00 mode when operated with an external cavity configuration. During pulsed operation (<50ns) a significant increase in the peak power is observed, compared to CW operation. High peak powers makes these lasers very well suited for intra-cavity frequency doubling with a non-linear crystal. We are developing surface emitting lasers in 2D array format and high power pulsed blue laser arrays in a small size. We present results of CW and pulsed operation of such lasers.

Keywords: blue lasers, pulsed lasers, vertical extended cavity surface emitting lasers, second harmonic generation, laser arrays.

1. INTRODUCTION

Vertical extended cavity surface emitting lasers (VECSELs) are well suited for intra-cavity frequency doubling to blue lasing wavelengths[1]. Large device diameter emitters in combination with external cavities can produce high single transverse mode power with good beam quality[2]. With sufficiently high intra-cavity power in the external cavity intra-cavity frequency doubling can be very efficient and produce high power second harmonic output[3]. Direct frequency doubling of single mode edge emitter diode lasers can be very efficient as well when coupled into a periodically poled lithium niobate (PPLN) waveguide crystal.[4,5] But unlike edge emitting diode lasers surface emitting diode lasers can easily be arranged in a two-dimensional configuration, which allows for scaling to high output powers.[6,7] Furthermore, VECSELs can be operated at very high current during short pulse operation leading to a high intra-cavity peak power density, which is beneficial for second harmonic generation. Here we report on intra-cavity frequency doubled CW and short pulse single emitter VECSELs, as well as CW and quasi-CW large VECSEL arrays.

2. EXPERIMENTAL SETUP

The intra-cavity frequency doubled VECSEL is schematically shown in Figure 1. The active region of the VECSEL is composed of several stacks of multiple quantum wells. The quantum wells are grown on a partially reflective n-type distributed Bragg reflector (DBR), and a low doping GaAs substrate. By adding a high reflectivity p-type DBR mirror to the epitaxial structure an internal optical cavity is formed. The p-type top DBR is bonded to a heat spreader, which itself is bonded to a heat sink. The current in the electrically pumped active region is confined by an aperture that is realized by either selective oxidation or proton implantation. The light output is taken from the substrate side of the device (bottom emitting). To avoid optical losses the substrate is thinned down to approximately 100 μm to reduce absorption of the fundamental wavelength that is near the GaAs bandgap, and is coated with an anti-reflective (AR) dielectric coating. By mounting the device junction down larger apertures can be used that are necessary to achieve high power single transverse mode operation. In the experiments reported on here apertures up to 160 μm diameter were used. The reflectivity of the n-type bottom DBR is reduced compared to a standard

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VCSEL so that the device will not lase on its own. Instead an external cavity provides the necessary feedback to enable lasing. The intra-cavity power in the external cavity is higher than would be obtained from a standard VCSEL. In addition the use of an external cavity provides a way of controlling the transverse modes of the VCSEL to force it to lase in a TEM_{00} mode that is desired for efficient second harmonic generation. In its simplest form a single glass mirror with a partially reflective dielectric coating forms the external cavity. Under CW and quasi CW (QCW) operation thermal lensing in the device helps stabilize the cavity so that a flat mirror output coupler (OC) can be used. For short pulse operation a curved mirror OC may be used or a positive focal length lens may be added to the external cavity to ensure stable mode operation. For intra-cavity frequency doubling the lensed cavity approach as shown in Fig.1 is preferred since it allows for a smaller beam diameter inside the non-linear crystal.

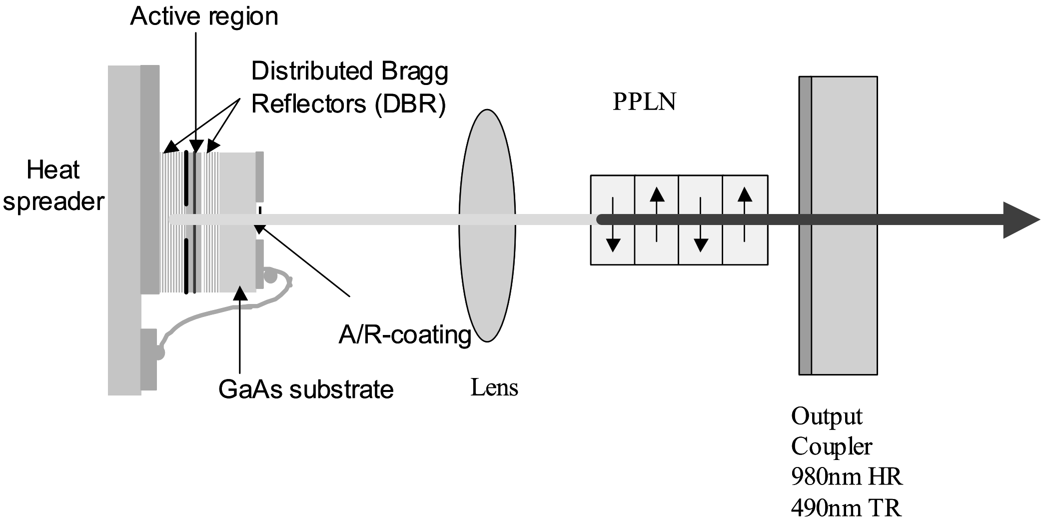

Figure 1: Schematic layout of the intra-cavity frequency doubled VECSEL

Here we use a 10 mm long periodically poled lithium niobate as a second harmonic generating crystal. The periodic poling maintains phase matching between the fundamental 980 nm and the second harmonic 490 nm wavelength and provides a long conversion region. It is important to maintain a uniform temperature over the entire crystal. For that reason, the crystal is mounted in an oven, which tunes the crystal phase matching to the VCSEL wavelength. The PPLN crystal has a broadband dual wavelength dielectric AR coating for the fundamental IR wavelength and the second harmonic blue wavelength on both facets and is placed in between the AR coated lens and the output coupler. To enhance the intra-cavity power the output coupler dielectric coating is highly reflective at the fundamental wavelength and partially transmissive at the second harmonic wavelength.

3. SINGLE DEVICE CW RESULTS

To efficiently produce intra-cavity frequency doubled light from a VECSEL it is important to achieve a high power single transverse mode TEM_{00} output with good spatial and spectral properties from a VECSEL operating at the fundamental wavelength. Figure 2 shows the CW results we obtained with a 160 µm device. By placing a flat mirror output coupler very close (~0.2 mm) to the device a strongly divergent, highly multi-transverse mode output is produced that exhibits greater than 1 W power at thermal rollover. By extending the external cavity length the mode diameter of the external cavity is increased giving rise to disproportional high losses to higher order transverse modes. When the external cavity mode diameter at the DBR becomes comparable to the aperture of the device only the lowest order TEM_{00} mode oscillates.

With a 7 mm long external cavity we observe 365 mW single transverse mode power at 1.15 A, see Fig. 2(a). Increasing the current further leads to a decrease in single mode power due to an increasing mode mismatch between the internal and external cavity as a result of strong thermal lensing. The single transverse mode output is typically not single wavelength but can be made single wavelength by extending the cavity somewhat further. This comes at the expense of single mode power, when operating on a single wavelength the power is reduced by ~20%. The Adventest Q8384 optical spectrum analyzer traces in Fig. 2(b) show wavelength spectra of the single transverse mode output at 1.0 A for a 7 mm (top) and an 8 mm long external cavity (bottom). The longitudinal mode spacing in the top trace corresponds to the free spectral range of the external cavity.

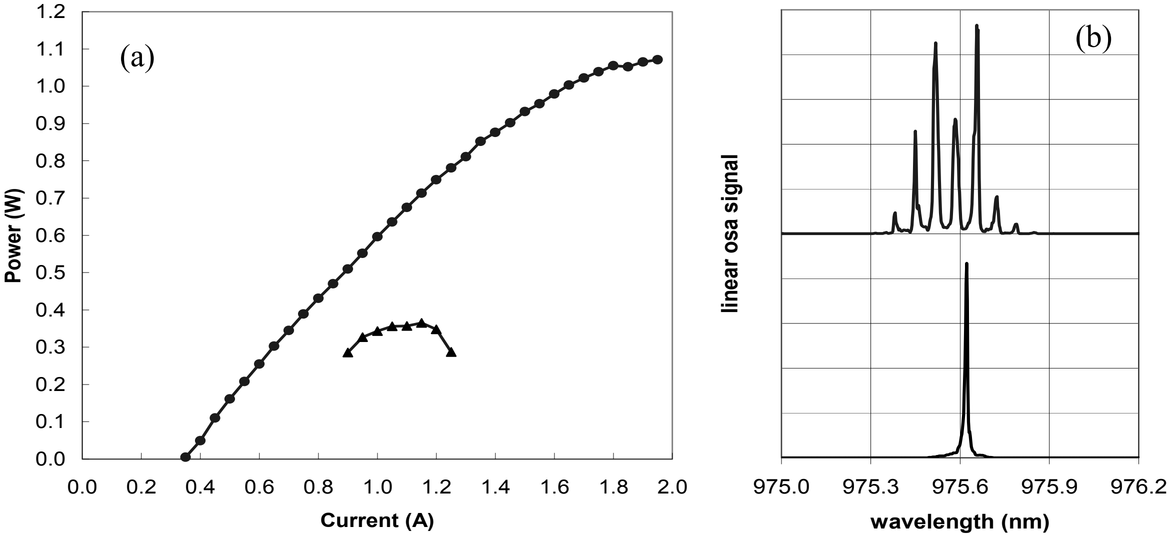

Figure 2: Observed power (a) from a 160 µm aperture VECSEL under multi-transverse mode (solid circles) and single transverse mode (solid triangles) operation, and single transverse mode lasing spectra (b) under multi-longitudinal mode (top trace) and single longitudinal mode operation (bottom trace).

The single mode output is typically linearly polarized and exhibits good mode quality. Fig. 3 shows the near field beam profiles at 1.0 A, as measured by a DataRay BeamMap slit scanning beam profiler. The beam quality factor M^2 was determined in a multi-plane measurement to be less than 1.2. We measured an 80 µm $1/e^2$ beam diameter at the waist, which is located at the flat OC, and observed a 10 mrad divergence.

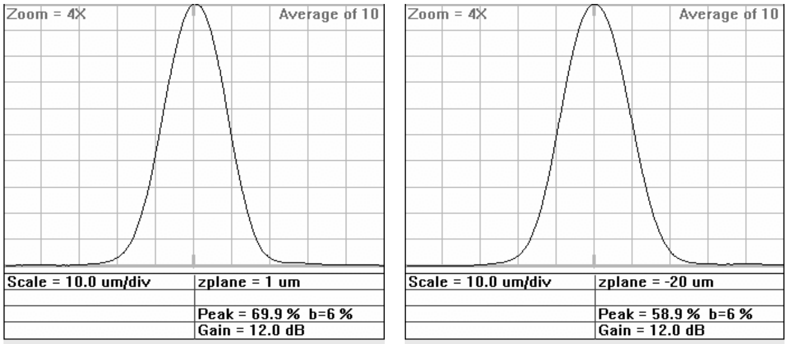

Figure 3: Near field beam profile of the IR output of a 160 mm VECSEL in (a) the x-direction and (b) the y-direction.

When the output of the single wavelength VECSEL was focused externally to a 33 μm diameter spot size inside a 10 mm long temperature optimized PPLN crystal we found a 1.5%/W conversion efficiency of the fundamental into its second harmonic. We found the same conversion efficiency with the single mode fiber output of a DFB laser, which confirms the good beam characteristics of the VECSEL. The external cavity for the intra-cavity frequency doubled VECSEL as shown in Fig. 1, was designed to achieve a small beam diameter inside the PPLN to optimize conversion efficiency. In this experiment we used a 10 mm focal length lens in a 50 mm long external cavity. The lens was placed so that cavity mode diameter at the device is comparable to its aperture, which is necessary to achieve single mode operation, while at the same time the cavity mode diameter near the OC, where the crystal was placed, approached the optimum beam diameter for second harmonic generation.

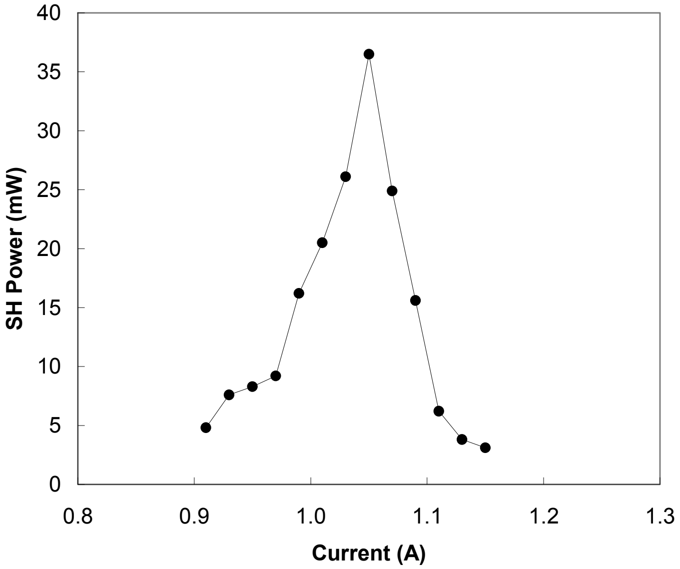

Figure 4. Second harmonic power output of a 160 μm VECSEL with a 10 mm long intra-cavity PPLN crystal

Figure 4 shows that in this configuration we obtained 36 mW of second harmonic power at 1.05 A with the PPLN temperature tuned to 138.6 deg C. The power output is limited because only 70% of the blue light is transmitted by the OC and only blue light generated in one direction traveled toward and reached the OC. In addition we found a trade-off between the fundamental power of the lensed cavity and the beam diameter near the OC. The beam diameter at the position of the PPLN crystal can be adjusted by varying the positions of the lens and the output coupler. When the cavity is adjusted for minimum beam diameter the fundamental power is strongly reduced leading to lower intra-cavity power density and thus poor second harmonic conversion efficiency. With the use of higher quality optics in a redesigned external cavity we expect to be able to significantly improve the blue light output.

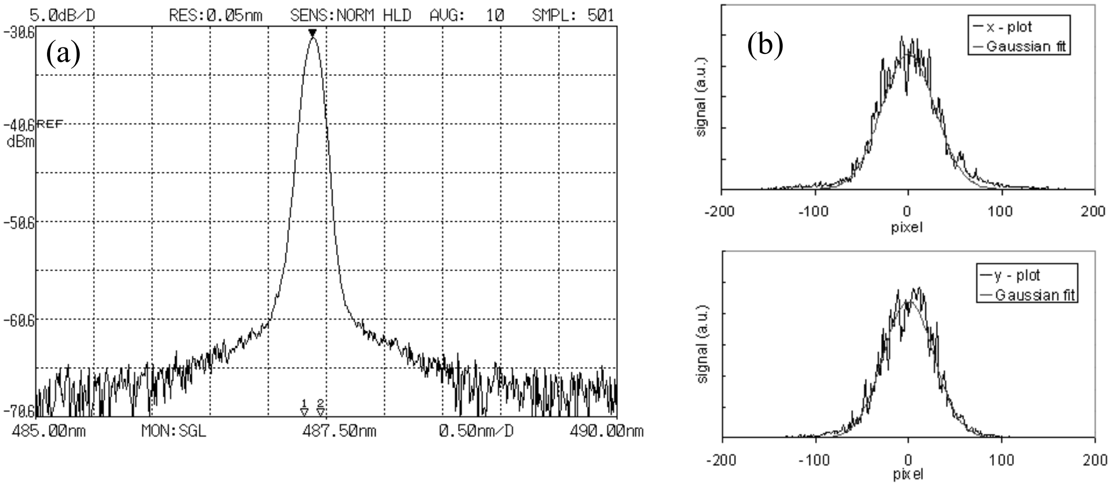

Figure 5: Observed spectral (a) and spatial (b) properties of the second harmonic output of a 160 μm VECSEL

Figure 5(a) shows the narrow (0.1 nm) spectral output at 487.4 nm of the intra-cavity frequency doubled VECSEL as recorded by an ANDO AQ6315B optical spectrum analyzer. The resolution of the OSA is not sufficient to resolve the longitudinal mode spacing of the external cavity. Figure 5(b) shows the far field beam profile in two orthogonal directions of the blue CW laser beam projected onto a white screen and captured by a CCD camera. The fluctuation in the signal is speckle noise in the image and not actual beam intensity variations. The intensity profile fits the Gaussian beam shape well.

4. SINGLE DEVICE PULSED RESULTS

In CW mode operation the heat generated in a VCSEL forms a thermal lens that affects the mode properties in the internal and external cavities. Under short ns pulse conditions the thermal effects are quite different and this results in a much weaker thermal lens. Good mode matching between the internal and external cavity can be maintained at much higher current compared to CW operation and therefore high single transverse mode peak power can be obtained. This is illustrated in Figure 6; it shows the peak power of a 100 μm VECSEL pulsed with a 15 ns current driver operated at a 1 kHz repetition rate. The external cavity was formed by a concave glass mirror with a 14 mm radius of curvature and a 90% reflective dielectric coating for the fundamental wavelength. The OC is positioned 8 mm from the GaAs substrate of the 100 μm surface emitting device. In the absence of a significant thermal lens the TEM_{00} mode diameter at the DBR mirror is expected to be 92 μm. This is large enough to prevent higher order transverse modes from lasing. The maximum single transverse mode peak power is greater than 4 W and higher power can be achieved by reducing the OC reflectivity for optimum coupling. For CW operation the same OC could be used but the cavity length had to be adjusted to obtain single transverse mode operation under increased thermal lensing conditions. The maximum single transverse mode CW power was 200 mW; the pulsed single transverse mode peak power is therefore approximately twenty times higher.

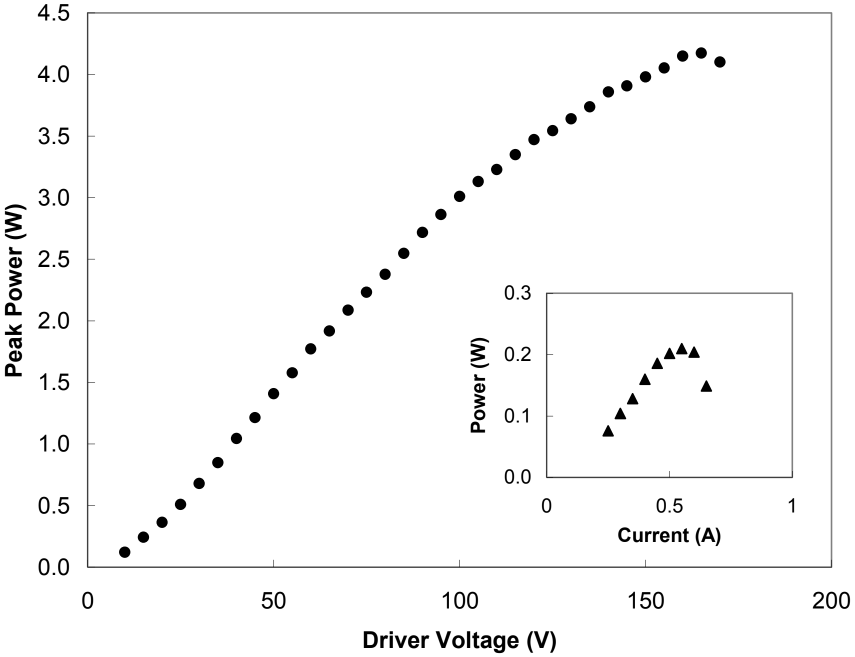

Figure 6: 980 nm peak power of a 100 μm VECSEL when pulsed with 15 ns current pulses at a 1 kHz repetition rate. The inset shows the light output under CW operation.

The pulsed output is in a TEM_{00} mode and the VECSEL can be operated in a fixed configuration over a large range of output powers, indicating a weak thermal lens. To generate short pulse blue light with the VECSEL the external cavity was adjusted by adding a lens and replacing the curved OC by a flat HR mirror. The 10 mm long PPLN crystal was inserted and positioned between the lens and the OC. When pulsed with the 15 ns driver operating at a 2 kHz repetition rate we observed 5 μW average second harmonic power in a single transverse mode; this is shown in Fig. 7. When driven with 15 ns current pulses the pulse duration of the output at the fundamental wavelength is typically 20 ns, while the second harmonic pulsed are shortened to ~10 ns (Fig. 8). The highest peak power at 488 nm is 250 mW. This is lower than expected given the high intra-cavity power density at the non-linear crystal, and the good beam quality of the fundamental. The low second harmonic conversion is likely due to the spectral properties of VECSEL output when operated under short pulse conditions. Here, unlike in the CW case, we were not able to simply adjust the cavity length to produce a single lasing wavelength. In fact we observe a set of wavelengths equally spaced by the longitudinal mode spacing of the external cavity that spans as much as 2 nm, depending on the driver current. This spread is much greater than the acceptance bandwidth of the PPLN crystal. Although we have observed significant wavelength chirp of the fundamental during longer pulse (μs) operation, here we suspect that multiple longitudinal modes are lasing simultaneously since we are operating so far above lasing threshold. In addition, we observed that under multi-wavelength operating conditions the single mode output is no longer linearly polarized. In future experiments we plan to add a Brewster plate to the external cavity as well as a wavelength selective element to ensure a single wavelength singe transverse mode linearly polarized output.

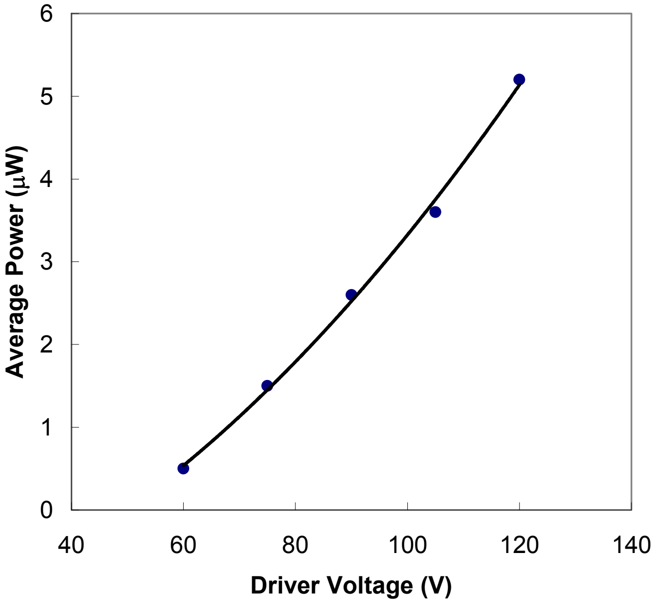

Figure 7: Average second harmonic power output of a intra-cavity frequency doubled 100 μm VECSEL operated with a 2 kHz 15 ns pulse current driver

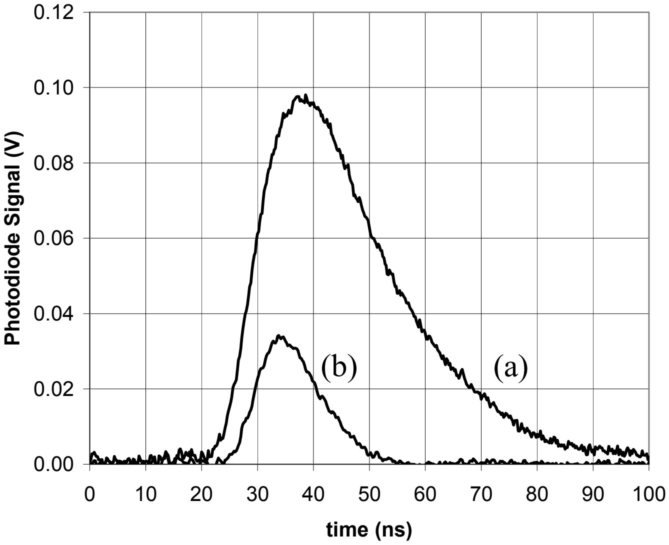

Figure 8: Temporal output of the fundamental (a) and second harmonic (b) output of a 100 mm intra-cavity frequency doubled VCSEL when pulsed with a 15 ns current driver operated at a 1 kHz repetition rate.

5. CW AND QCW ARRAY RESULTS

Surface emitting lasers can easily be arranged in a two-dimensional layout. We developed VECSEL arrays of 70 µm diameters devices in a hexagonal configuration with a 200 µm spacing and tested them under CW and quasi-CW operating conditions. Typical arrays are 5 mm in diameter and contain ~450 devices, depending on the exact layout. The arrays are mounted on a water-cooled micro-cooler assembly. The external cavity is comprised of an output coupler that is located approximately 2 mm from the array. This placement results in single transverse mode operation of each individual device in CW and µs pulse quasi-CW operating conditions used in the experiment described here. Fig. 9 shows that we achieved 42 W total CW power at 120 A current (thermal rollover) for a 475 device array for an average power of 88 mW per device. The power distribution was uniform, with a 1σ spread of less than 10%. We found a 14.5 mrad far-field divergence for the array and a 44 µm beam waist diameter at the OC for each individual device, indicating a near unity beam quality factor M^2. We used an external micro lens array with the same pitch as the device array to reduce the divergence of the array output to 5.5 mrad and were able to couple 70% of the power into a 100 um 0.22 NA multi-mode fiber.

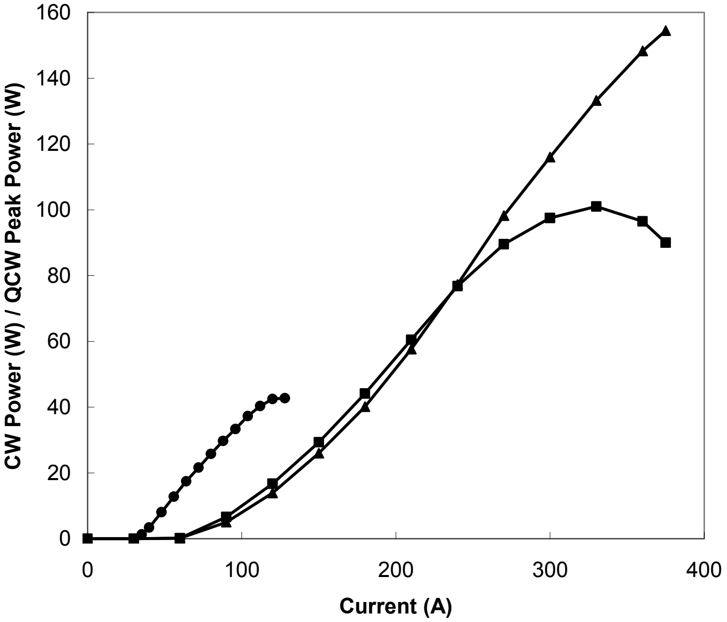

Figure 9: CW power output of a 5 mm diameter array (solid circles), QCW peak power of a 6 mm diameter array operating at 200 Hz / 200 µs (solid squares) and 500 Hz / 65 µs (solid triangles).

A similar but slightly larger (5.8 mm diameter) array was tested under QCW conditions with a 3% to 4% duty cycle. Like in the CW case each of the devices emitted in a single transverse mode. We observed that shortening the pulse duration of the current driver resulted in significantly higher peak power. Fig. 9 shows that 100 W peak power was achieved when operating with a 200 µs pulse duration at a 200 Hz repetition rate (squares), and 155 W peak power with 65 µs pulse duration at 500 Hz (triangles). We anticipate that for short pulse operation at high repetition rate (>1 kHz) significantly higher array power can be reached and experiments are underway to confirm this. Currently we are developing arrays of larger devices and will pursue a lensed-cavity approach to enhance intra-cavity frequency doubling conversion efficiency. For this purpose a micro lens array with the same pitch as the device array will placed inside the external cavity. We expect that with the resulting high intra-cavity power densities shorter non-linear optical bulk crystals may be used to achieve efficient doubling to blue wavelengths.

6. CONCLUSIONS

We demonstrated 250 mW peak power in the blue from a single 100 μm diameter device in a 10 ns pulse. We developed large 2D-arrays and reported 42 W of CW power and 155 W of QCW peak power from devices all operating in a single transverse mode at the fundamental wavelength. We investigated the parameters and necessary conditions to achieve high power pulsed intra-cavity frequency doubled vertical extended cavity surface emitting blue lasers arrays.

7. ACKNOWLEDGEMENTS

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