Stable Narrow-line VECSEL Operation for Sodium Guide Star Generation

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Abstract

In the development of laser guide star (LGS) technology, Vertical External Cavity Surface Emitting Lasers (VECSELs) are attractive because of their simplicity and compactness. VECSELs operating at 1178 nm may readily be frequency doubled to the sodium D_2 resonance at 589 nm. The output power of VECSELs can be scaled to multiple tens of watts by expanding the spot size, or "lateral scaling". It can also be scaled by using multiple VECSEL devices in one cavity, or "longitudinal scaling". In the case of longitudinal scaling, at least one VECSEL device must be at a fold of the cavity. This typically causes problems in longitudinal mode stability. In this paper, we present the results of successful experiments to demonstrate a technique to deliver stable single-frequency operation of a multi-VECSEL cavity at 1178 nm. The new technology paves the way for sodium guide star lasers delivering tens of watts that are more compact and substantially cheaper per watt than any existing technology.

Keywords: adaptive optics, laser guide stars

1. Introduction

AO implemented on ground-based telescopes is a crucial asset in understanding resident space objects (RSOs); it represents an important element of ground-based space situational awareness (SSA). AO enables both high-resolution imaging, of great value in determining RSO configuration and behavior, as well as high-contrast imaging which is essential to detect and characterize faint objects in the vicinity of much brighter ones.

Imaging through the Earth's atmosphere always results in distortion of the image. AO restores good image quality, but requires a beacon of light on the far side of the turbulent aberration to be sensed. Ideally, the beacon is the object whose image is to be compensated, or some feature on that object. However, that is not always possible because the object is too faint, or, in the case of daylight imaging, the background sky is too bright. In these cases, AO systems can continue to operate through use of a laser guide star (LGS) propagated from the telescope in the direction of the object. For objects with large apparent angular velocity such as satellites in low Earth orbit (LEO), the fast telescope track rate leads to a high atmospheric Greenwood frequency. In turn this demands a high-speed AO system with short integration time on the wavefront sensor (WFS), and a correspondingly bright LGS. There is therefore a need for cost effective guide star lasers that are also ideally compact and robust.

VECSELs, also known as Optically-Pumped Semiconductor Lasers (OPSLs), are attractive as candidates for sodium guide star lasers because of their simplicity [1]. At the critical wavelength of 589 nm to generate sodium resonance beacons, guide star lasers built from VECSEL devices promise to deliver suitable power with high efficiency in a compact package and at a price point substantially lower than current commercial lasers. While it is challenging to design a VECSEL that will lase directly at this wavelength, it is relatively straightforward to do so at 1178 nm. The resonance wavelength may then be made by routine frequency doubling in a non-linear crystal. In this paper we report stable single-frequency operation of a laser incorporating two VECSEL devices. The laser exploited the novel technique of mode twisting to assure stability and narrow line width, and delivered >10 W at 1178 nm.

When deployed as a beacon, the built-in narrow width of the twisted-mode cavity will target single velocity classes in the mesospheric sodium population. This will enable effective repumping of the D_2 hyperfine structure with a fraction of the 589 nm power blue-shifted by 1.77 GHz to the D_{2b} resonance [2]. Doing so improves the fraction of sodium atoms available for stimulation, which in turn improves the overall efficiency of the LGS, in terms of return flux per watt of projected power, by about 30%.

2. Laser Design

The output power of VECSELs can be scaled to multiple tens of watts and beyond by scaling in spot size, or "lateral scaling" [3]. It can also be scaled by using multiple VECSEL devices in one cavity, or "longitudinal scaling" [4]. In the case of longitudinal scaling, at least one VECSEL device must be at a fold of the cavity. This can cause problems in longitudinal mode stability. In this paper, we present a technique to alleviate it.

Unlike a VECSEL device placed at the end of a standing-wave cavity, those placed at folds carry a standing wave pattern formed by four beams; forward propagating incident and reflected, as well as backward propagating incident and reflected. The resulting standing wave pattern changes its magnitude depending on the phase difference between the forward- and backward-propagating beams as depicted in Fig. 1, varying the effectiveness of the optical gain provided by the quantum wells. Different longitudinal modes have different phases in the middle of the cavity, hence the gain, driving the longitudinal modes of such VECSEL unstable. In order to overcome this limitation, we have implemented a "twisted-mode" configuration [5] in a VECSEL cavity, forcing the standing wave pattern to be the same for all phase differences. The new standing wave pattern is shown in Fig. 2, and this remains the same regardless of the phase relationship between the forward and backward waves. It therefore holds for all longitudinal modes. As another benefit of placing a VECSEL device at a fold, the round-trip gain is higher as the beam bounces at the VECSEL device twice.

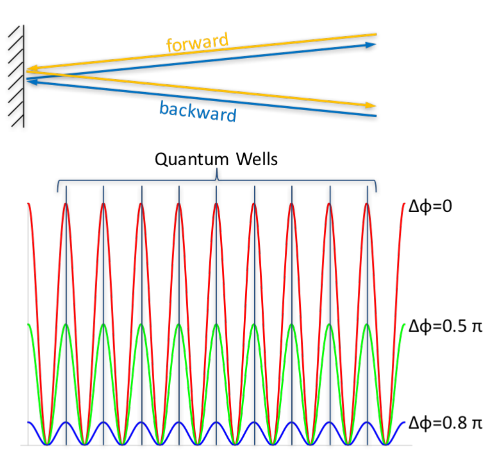

Figure 1. Standing wave pattern at the fold, with different phase relationship in forward and backward beams.

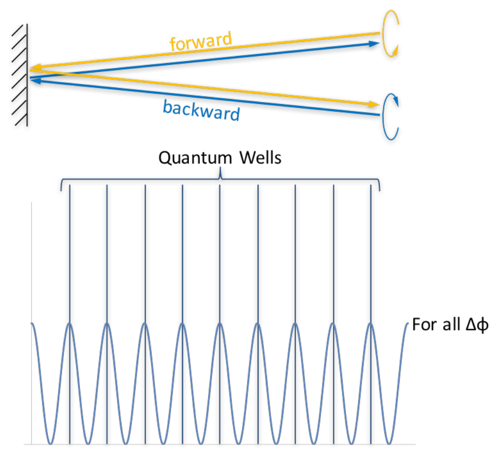

Figure 2. Standing wave pattern at the fold, with twisted mode configuration.

The concept of a twisted-mode cavity is shown in Figure 3. A polarizing element such as a birefringent filter (BRF) enforces linear polarization in most of the cavity. However, a pair of quarter-wave plates (QWP), sandwiching the VECSEL devices, enforces counter-rotating circular polarization for the forward- and backward-traveling waves at the VECSELs themselves. In this configuration, simple Jones matrix analysis shows that the eigenpolarization is circular polarization at the VECSEL devices, in the opposite direction for the two counter-propagating waves. In this way, the coherence between the two waves is removed; they cannot interfere with each other, and the antinode of the standing wave is pinned to the VECSEL quantum wells. The outcome is that stable single-frequency operation is enforced.

Three experiments were carried out. In the first and second, the laser cavity incorporated a single VECSEL, which was an AR-coated GaInNAs-based device with the gain peak near 1180 nm, suitable for operation at 1178 nm. The layout was as shown in Figure 3. The cavity is in Z-fold, with the VECSEL at one of the folds. One end mirror is flat, and can be replaced with another VECSEL device for longitudinal scaling. The other fold mirror and the other end mirror are curved so that the cavity mode has approximately 180 μm radius at the VECSEL and flat end mirror. Both the folding mirror and two end mirrors are highly reflecting at 1178 nm. We inserted an uncoated quartz birefringent filter and etalon, and an uncoated silica plate as an adjustable Brewster's window acting as a variable output coupler. The final experiment added a second VECSEL to validate the concept of longitudinal scaling. This replaced the flat HR mirror at the left-hand end of the cavity in Figure 3.

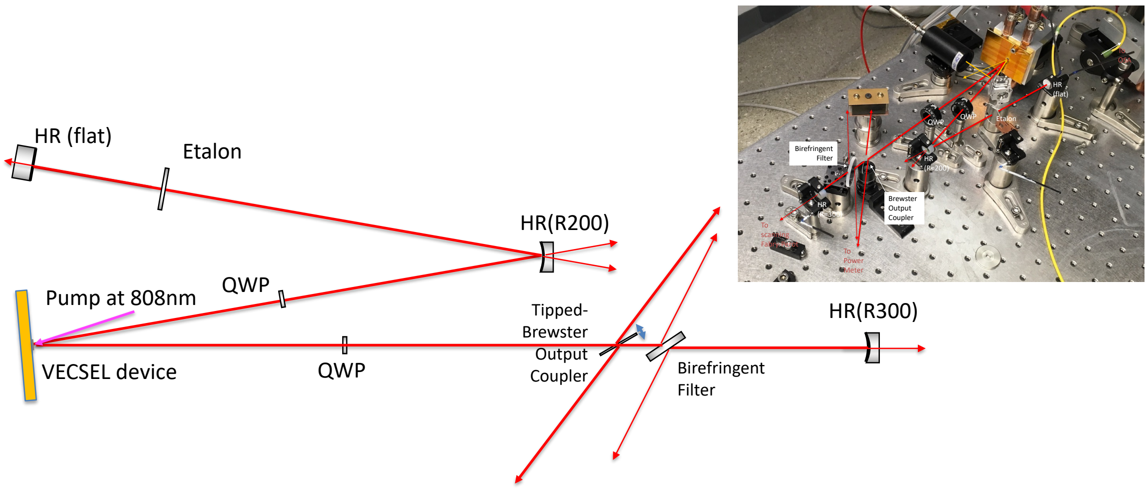

Figure 3. Schematic of the folded VECSEL cavity with mode twisting and a photograph inset of the experimental arrangement.

3. Results

The first experiment, with a single VECSEL, used two pump lasers at 808 nm directed at the device with power up to 45 W. The pump arrangement is shown in Figure 4. All wavelength and polarization selection elements were initially removed from the cavity. Output power as a function of pump power was measured both with the laser free running, and after insertion of the birefringent filter (BRF) to tune the laser to the correct wavelength of 1178 nm. At this point, although tuned, the laser is not single-frequency. The results are shown in Figure 5. The best output coupling for the VECSEL device, delivering the highest output power, was observed to be approximately 3%. However, the output coupler mirror for these initial tests was approximately 1% transmission. With the BRF in place, the output coupling was slightly increased by reflection off the filter itself, which led to higher threshold and also a higher slope efficiency. This effect is evident in that the tuned power output improves at a faster rate than the free running power. Total tuned output power peaked at just above 12 W.

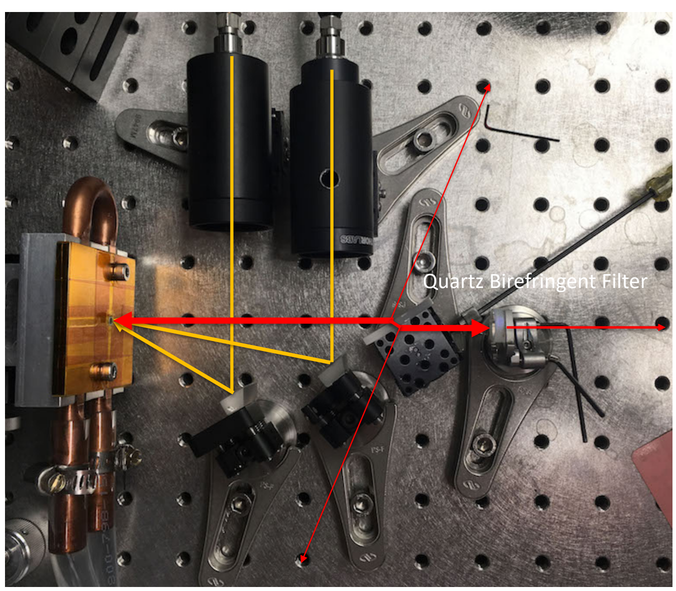

Figure 4. Experimental setup of the 808 nm pumping for the single-device VECSEL experiment.

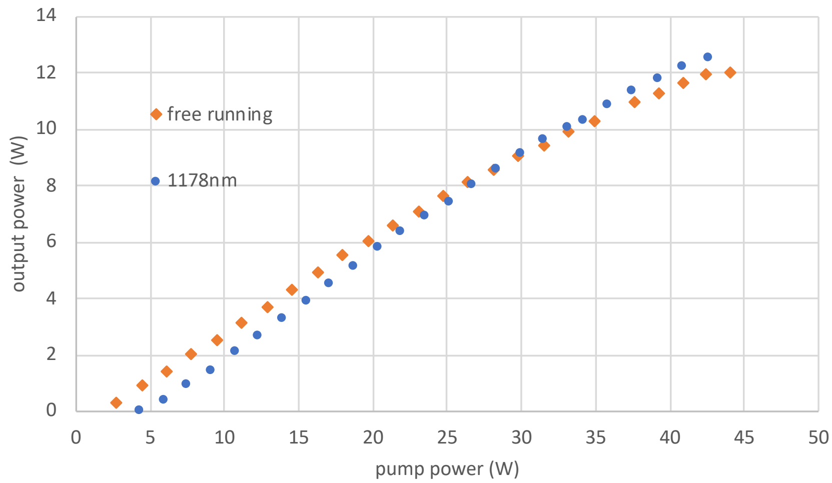

Figure 5. Output power of a single-device VECSEL at 1178 nm.

With the cavity as shown in Figure 3, the laser was expected to run at single frequency in the twisted mode configuration. The mode size of the cavity is approximately the same as the experiment in the previous task, 180 μm, at both the VECSEL device at the fold and the flat end mirror. In order to stabilize the spectrum, it was necessary to insert a 0.5-mm thick uncoated fused silica etalon in the cavity. Two quarter-wave plates (QWP) are inserted in the cavity so that they sandwich the VECSEL device. These introduce the mode twist.

In this single-chip laser, a total output power from both faces of the Brewster window of 7.4 W was observed. The effect of mode twisting is seen by comparing the results of three different configurations:

1. No QWPs in the cavity.
2. QWPs are in the cavity, but the orientation is not properly set.
3. QWPs are in place, and orientation is set correctly.

In configuration 3, the eigenpolarization at the VECSEL is circular, and counter-rotating for forward and backward waves, thus realizing the mode-twisted configuration.

Figure 6 shows the observation of the longitudinal mode structure on a scanning Fabry-Perot interferometer. With no QWPs, the structure is frankly a mess. With the incorrectly oriented QWPs, the structure is not improved, but power output is greatly reduced. Finally, with the mode twisting functioning correctly, single-frequency operation is achieved.

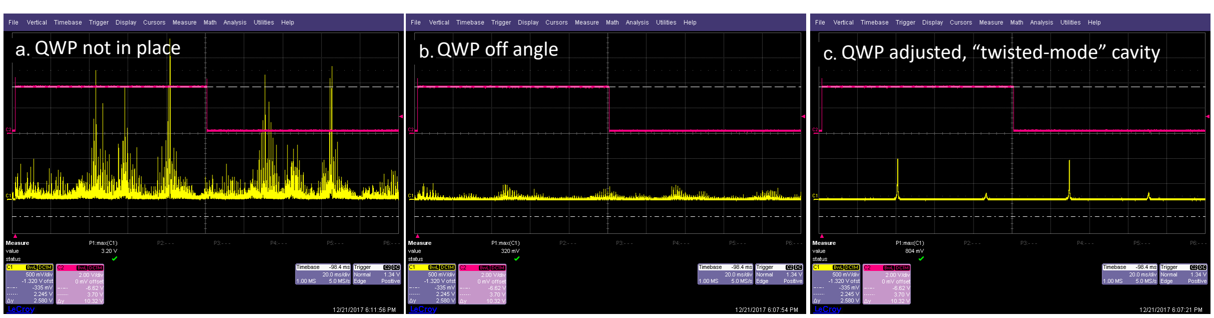

Figure 6. Longitudinal mode configuration observed in the conventional (left) and twisted mode (right) cavities. The central figure shows the mode structure with the essential QWP inserted, but incorrectly oriented.

It should be noted that this stable narrow-line operation was easily achieved with no special considerations for the laser’s operating environment. The work was carried out in a standard optics laboratory with no temperature control applied beyond the lab's normal HVAC, and no baffling used to control air currents. Yet the laser operated continuously at a stable power level and was not observed to mode hop during runs that exceeded 15 minutes.

Finally, in the third experiment, the flat end mirror (Figure 3) was replaced with the second VECSEL device to form a multi-device VECSEL cavity, as pictured in the left side of Figure 7. The primary output coupling remained the tilted Brewster's window, with a small additional contribution from the BRF. With this cavity, a total output power of 10.12 W in single-frequency was observed, as shown in the right side of Figure 7. The power meters in the picture are measuring the single-ended reflection from the BRF (left) and the variable output coupler. The same amount was also reflected in the opposite direction. The total extracted power from the cavity is twice the sum of these two: (4.41 + 0.65) x 2 = 10.12 W is extracted from the cavity from these four ports.

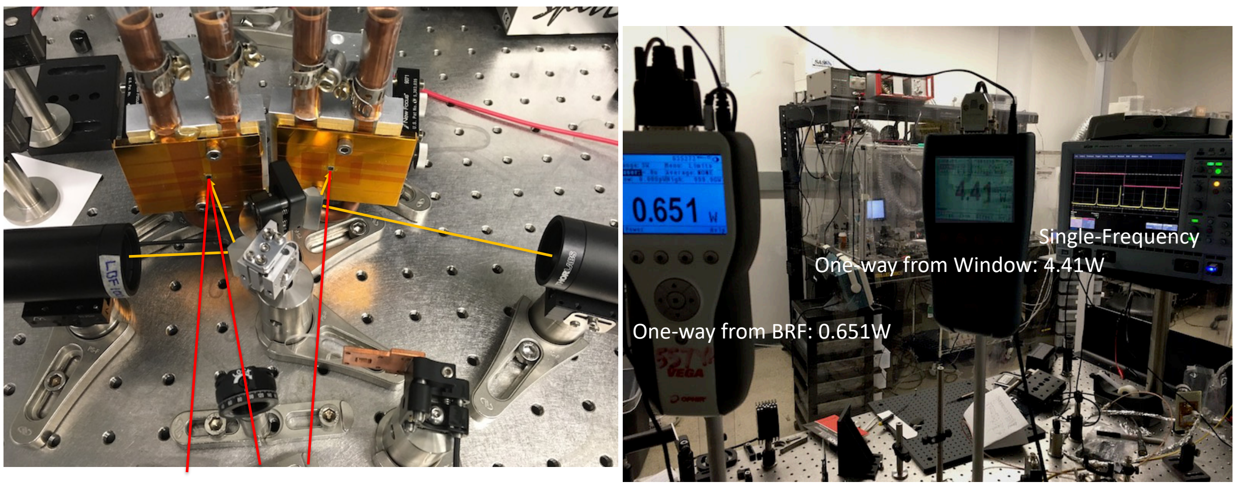

Figure 7. Multi-device VECSEL cavity setup and operation at 10.12 W output power in single frequency.

4. Discussion and Future Work

To summarize the experimental results, we have:

- Demonstrated >10 W output at 1178 nm from single-device VECSELs.
- Demonstrated the twisted-mode folded VECSEL cavity to operate in highly stable single-frequency with a clear and distinct effect of mode-twisting on narrow-linewidth operation.
- Demonstrated single-frequency output from a two-device VECSEL cavity of 10.12 W at 1178 nm.

While this prototype laser relied on the variable output coupler, with additional outputs off the BRF, the next phase will use a conventional OC with transmission of 3% which was found to be optimal during these tests. In that way, and by adjusting the BRF to precisely Brewster's angle, all the power will be extracted from the cavity in a single beam.

Further work will expand the number of VECSEL devices in the laser from two to four in the arrangement of Figure 8. All devices will be placed at folds so that the laser signal will be double-passing all four devices. At the same time, the beam size will be enlarged to take advantage also of lateral power scaling which we expect to deliver another factor of two in power. We expect in this way to achieve 30 W output at 1178 nm. We anticipate the optimum output coupling for the cavity to be 5-6%, which will be determined experimentally. An appropriate output coupler will be procured and installed to optimize the single-ended output power.

The next stage will see a demonstration of operation at 589 nm via second-harmonic generation (SHG). We will implement SHG in an external resonant cavity as shown in Figure 8. While adding modestly to the footprint of the optics compared to intracavity doubling, the approach decouples the generation of the fundamental and harmonic modes, removing any interactions between the doubling elements and the mode twisting which we anticipate will lead to more robust operation.

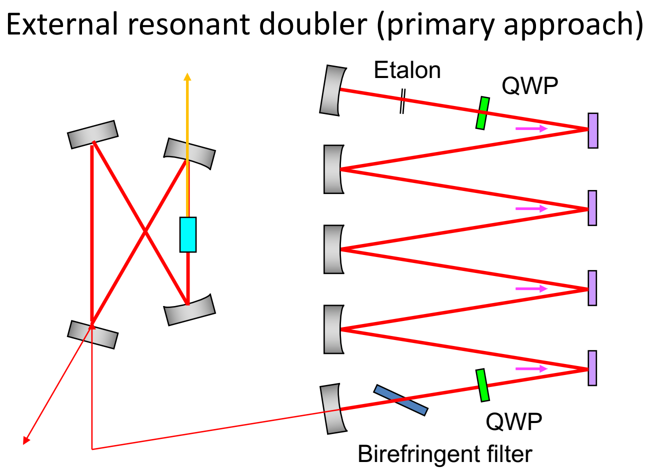

Figure 8. Schematic of the four-device VECSEL laser with external frequency doubling provided by the doubly resonant external cavity on the left.

5. Acknowledgement

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6. References

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