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# High-power single-frequency intracavity doubled VECSEL at 589 nm for sodium guidestar

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## ABSTRACT

Over the last 30 years, Sodium Guidestar Lasers (SGLs) have proved to be an important element of adaptive-optics (AO) image correction techniques for astronomical observatories. In recent years, the astronomy community has employed Raman shifted fiber lasers to meet the need. However, emerging applications would greatly benefit by a reduction in the cost per Watt of on-sky power and the Size Weight and Power (SWAP) required by the laser. Small (meter-class) observatories seek to incorporate AO systems to meet space situational awareness and free space laser communication applications. Simultaneously, large (10 meter class) observatories require larger numbers of lasers on-sky to implement multi-conjugate AO systems. Further, techniques such as re-pumping and frequency-chirping are being developed to increase returns from the sky for a given laser power. The next generation of SGLs (Sodium Guidestar Lasers) must be suited for such modes of operation while reducing cost and SWAP. Optically pumped semiconductor lasers (OPSLs), also referred to as Vertical External Cavity Surface Emitting Lasers (VECSELs), represent a technology pathway to realizing SGLs with high performance, compact size, high reliability, and low acquisition and maintenance costs. In pursuit of the next generation of SGL, we demonstrate 8W of single-frequency power at 589 nm based on in intracavity frequency doubling of 1178 nm fundamental wavelength VECSEL. Our work investigates the key challenges of the laser design; especially frequency selection, tuning, and locking the laser to sodium resonance, laser power, and gain-mirror lifetime.

**Keywords:** VECSEL, OPSL, Sodium Guidestar Laser, Single Frequency

## 1. INTRODUCTION

Sodium guidestars, created by a skyward directed laser whose wavelength is resonant with the  $3^2P_{3/2}-3^2S_{1/2}$  transition in sodium atoms entrained in the mesosphere are used in conjunction with adaptive optics to counter the effects of atmospheric aberrations by ground-based observatories [1]. These closed loop systems provide exquisite astronomical seeing and have applications in astronomy, space surveillance, and optical communications. In comparison to natural guidestars, sodium-guidestars provide near all-sky coverage for high-resolution astronomy. Today most observatories with large aperture telescopes operating in the infrared and visible spectral region utilize SGLs and some employ or plan to employ constellations of SGLs [2-5].

Sodium Guidestar Lasers (SGL) using a variety of laser gain materials such as dye, solid-state crystal, and fiber technologies have been developed and demonstrated on sky. The sodium resonance wavelength of 589 nm does not coincide with transitions in solid-state laser crystals or gas laser transitions. Consequently, SGLs have traditionally relied on nonlinear optics, multiple lasers and complex control strategies to reach the desired wavelength. Reference [6] provides an excellent review of the historical development of SGL's and their deployment.

Despite the inherent advantages of SGLs, technical challenges, high costs, operational complexity, large sizes and environmental constraints associated has complicated and slowed SGLs integration into routine use. High acquisition and operational costs render the technology available to only well-endowed observatories. Applications that require compact low-cost systems do not derive benefit. Consequently, there is a need for continued technology development. Semiconductor SGL's represent potentially low- cost, compact devices that can meet the demanding requirements of for SGLs.

## 2. LASER PERFORMANCE REQUIREMENTS

Table 1 provides nominal performance requirements for a continuous wave (CW) SGSL for astronomy applications. For narrow linewidth CW systems the desired laser power is approximately 20 W. The majority of the output (~18 W) should be resonant with the sodium D<sub>2a</sub> transition. Space situational awareness applications will require higher launch powers because of the higher tracking velocities required. There is a significant enhancement of return signal if light resonant with the sodium D<sub>2b</sub> transition (shifted by 1.71 GHz relative to D<sub>2a</sub>) is broadcast simultaneously and overlaps the beam of the first wavelength. The second wavelength overcomes trapping of atoms in the lower of two hyperfine levels of the ground state by ‘repumping’ them to the higher hyperfine level for D<sub>2a</sub> resonant pumping. Thus a secondary wavelength is included in Table 1 with ~10-15% of the D<sub>2a</sub> power – the power estimated to provide for significant enhancement [7], [8].

Holzlohner et al found that a linewidth of a few MHz is preferable for a 15 W SGSL [7]. The laser must be continuously tunable over the width of the D<sub>2a</sub> transition (~1 GHz) to allow it to be locked to the transition. Additionally, it is desirable to have the ability to tune off the sodium resonance in order to obtain an estimate of the ‘Rayleigh background’ during operations. The laser output must have good beam quality to enable small spot sizes and well-defined polarization to maximize the return.

Table 1. Desired performance parameters for a SGSL.

Characteristic	Values and Rationale
<b>Primary <math>\lambda</math> and Power</b>	~18 W locked to Na(D <sub>2a</sub> ) ~589 nm <i>D<sub>2a</sub> is the strongest D<sub>2</sub> absorption</i>
<b>Secondary <math>\lambda</math> and Power</b>	~2 W locked to Na(D <sub>2b</sub> ) ~589 nm <i>D<sub>2a</sub> to D<sub>2b</sub> Frequency Separation = 1.7 GHz</i>
<b>Linewidth</b>	A few MHz <i>For each Wavelength [8]</i>
<b>Fine Tuning</b>	~1 GHz, continuous <i>Scan sodium transition to enable line locking</i>
<b>Gross Tuning</b>	~5 GHz, does not need to be continuous <i>Allow capture of Rayleigh backscatter</i>
<b>Beam Quality</b>	$M^2 < 1.3$ <i>Near Diffraction Limited</i>
<b>Polarization</b>	Well defined polarization, contrast ratio >20 <i>Circular polarization is broadcast</i>
<b>Waveform</b>	CW or high-duty-cycle modulated CW

## 3. INTRACAVITY DOUBLED RESULTS

Intracavity doubling is an attractive approach for meeting sodium guidestar laser requirements because of its low SWaP and low-complexity. One approach is depicted in Figure 1. Here the semiconductor chip is pumped by 808nm fiber coupled diodes and provides optical gain at 178nm. The BiRefringent Filter (BRF) provides coarse tuning, and the etalon provides fine mode selection. The Piezoelectric Transducer (PZT) mounted to the End Mirror (EM) provides fine tuning of the cavity length to stabilize the laser wavelength to sodium resonance. The Fold Mirror (FM) is HR coated at the fundamental 1178nm and AR coated at the second harmonic 589nm. The EM is typically HR/AR coated at 1178/589 similar to the FM, but may be HR/HR coated at 1178/589 so that all 589nm light is coupled out of one direction in the cavity. The LBO crystal is AR/AR at 1178/589 and provides doubling of the fundamental wavelength. Output coupling occurs in the form of the frequency doubled light exiting through the fold mirror.

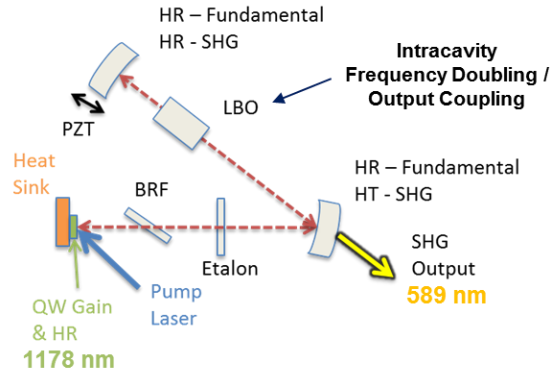


Figure 1: V-cavity design for intracavity doubling

The attraction of intracavity doubling is that the IR laser itself behaves as a resonant cavity in which IR intensities become high enough to achieve efficient Second Harmonic Generation (SHG). Further, because all output coupled power is at the second harmonic, the “conversion efficiency” may approach 100%. This is in contrast to other approaches in which there is a fundamental wavelength laser with output coupling in the IR and a second stage that doubles the IR to the visible with some efficiency.

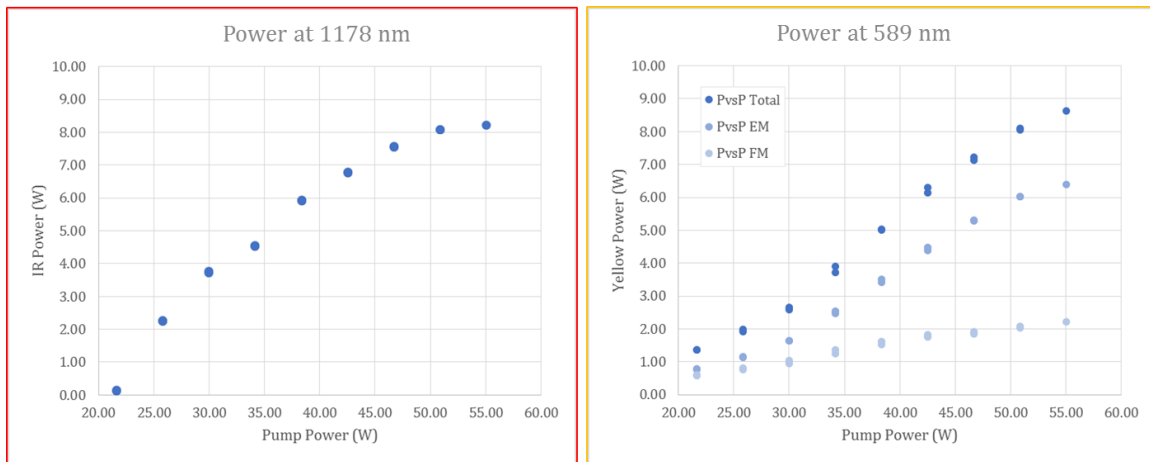


Figure 2: (Left) IR output power coupled through a fixed output coupler EM. (Right) Visible output power coupled through the EM and FM by intracavity SHG. This illustrates the high extraction efficiency that can be achieved with intracavity doubling.

Figure 2 presents graphs of laser output power as a function of incident diode pump power illustrating the efficiency of the intracavity doubled approach. In the left graph we plot the infrared output power of the laser with no LBO crystal in the cavity and a fixed output coupler (near optimal output coupling). The IR laser produces 8W of output power. Introducing the LBO crystal to the cavity and replacing the output coupler with a mirror of high reflectivity at the IR wavelength yields 8.5W of power near 589nm. The slight improvement of laser power and efficiency of the intracavity doubled laser is because the nonlinear output coupling value is slightly better optimized for the cavity losses than the fixed output coupling value. Note that in this configuration, output beams from both the EM and FM contribute to the total laser output coupling at 589nm.

The beam quality that we achieved with this configuration is also good, exhibiting a TEM<sub>00</sub> mode with an M<sup>2</sup> value that has been measured at 1.2. Figure 3 shows an example of a beam quality measurement performed with a Spiricon M2-200.

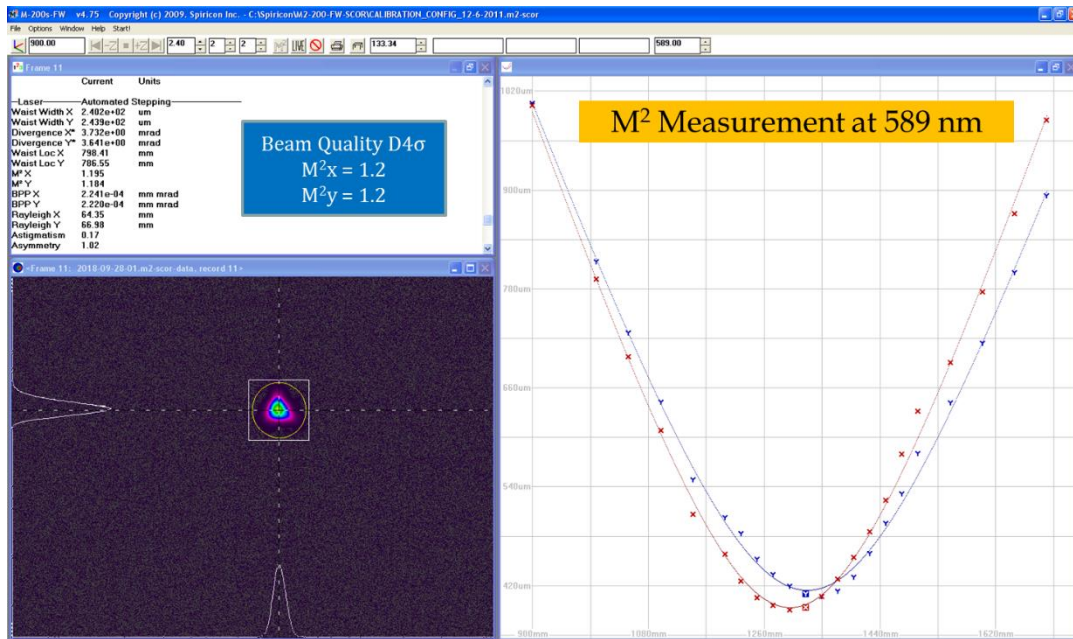


Figure 3: Good Beam Quality at 589 nm

Using this intracavity frequency doubling approach, narrowband single frequency operation was obtained. Typical performance is shown in Figure 4. In the left pane of the figure, we plot the IR output power as a function of incident diode pump power. A maximum of 12W single frequency, IR output power is obtained. When the LBO crystal was introduced into the laser cavity, 8W of single frequency operation output power at 589 nm was achieved. This apparent doubling efficiency of ~60% is in contrast with multi-frequency performance shown previously where effective doubling efficiency approached 100%. This reduction in efficiency results from a combination of factors.

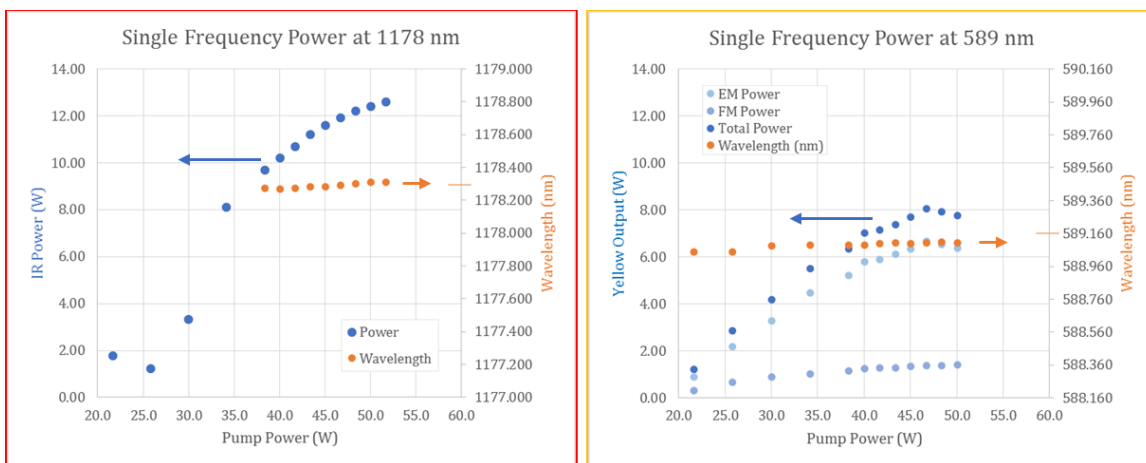


Figure 4: (Left) Single frequency power in the IR. (Right) single frequency intracavity doubled output power.

When operating in the IR the output coupling is fixed and the laser longitudinal mode with the lowest threshold (highest gain and lowest loss) lases first. As the gain of a CW laser is limited to threshold, other modes with slightly lower gain-to-loss ratio are effectively suppressed. Because the lasing mode “steals” gain from other modes, single frequency operation tends to be a stable equilibrium. Thus despite the large 10s of nanometers tuning range of the gain mirrors single frequency operation can be maintained with remarkably little mode discrimination as long as mechanical vibration and electrical noise are sufficiently low.

In contrast, when operating in the yellow by intracavity doubling, the effective output coupling varies with the intracavity power of the laser and is nonlinear. Maintaining single frequency with reasonable output power is a delicate balance. In this situation, the dominant laser mode steals gain from other modes, but also incurs more intracavity loss due to nonlinear output coupling. This may force the laser to an equilibrium laser frequency that has the lowest gain-to-loss ratio (including both output coupling loss and parasitic losses) but that may not be optimally output coupled. The consequence is that to maintain single-frequency operation on the correct laser mode requires limiting the nonlinear output coupling to below the power-optimized output coupling and/or increasing the mode discrimination (for example by adding additional elements), both of which reduce realizable 589nm output power to below that which can be extracted at 1178nm.

With careful optimization, 8W of single frequency output powers at 589nm has been achieved. This power is presently composed of two beams with approximately 6W and 2W. In principle this power can be coupled out of the cavity in a single beam, but we have encountered stability issues when attempting to do so.

Maintaining laser frequency at sodium resonance can be done in multiple ways. One approach is to use a high-resolution wavelength meter to measure the laser wavelength. This has the advantage of providing both fine and broad measurement of the laser wavelength, but wavemeters with sufficient resolution for this purpose can constitute a substantial cost of a guidestar system. Another approach is to use sodium resonance itself as a reference. This is a proven method of laser stabilization and has the advantage of low component costs, but requires the laser reach resonance without any direct wavelength feedback before an error signal and lock can be established. A block diagram for our implementation of this approach is depicted in Figure 5.

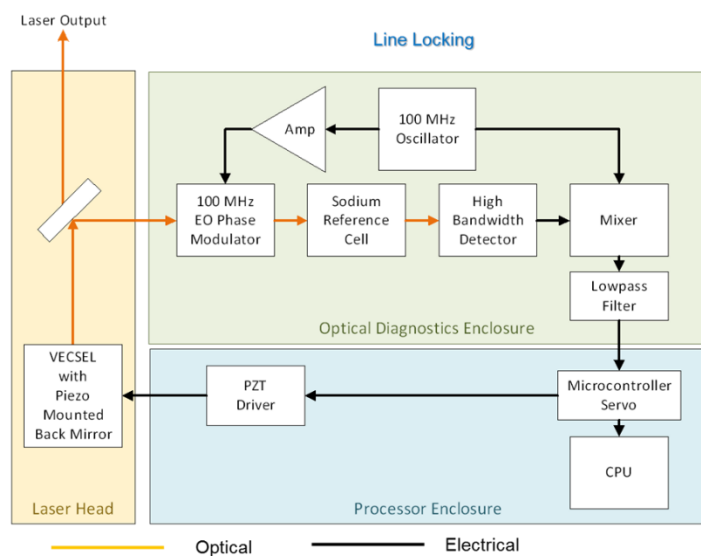


Figure 5: Block diagram for locking to sodium line

Figure 6 shows the modeled and measured error signal generated by sweeping the laser frequency across sodium resonance. The modeled error signal captures the entire D2a/D2b range, while the measured error signal is limited to a subset of the range near the D2a lock point.

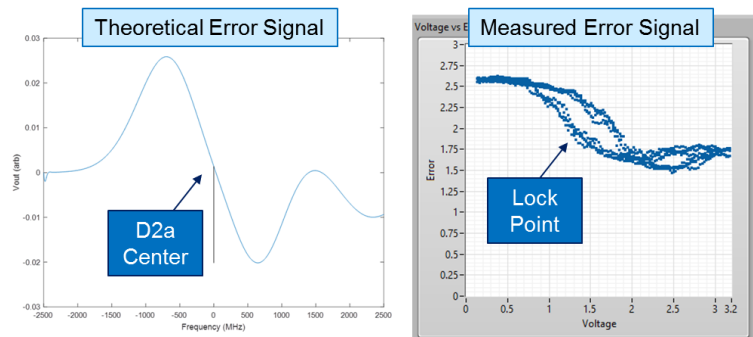


Figure 6: (Left) Modeled error signal for tuning across entire D2a/D2b range and (Right) measured error signal over D2a lock range. Although there is some hysteresis in the signal (likely from the piezo) a clear slope and lockable error signal is established.

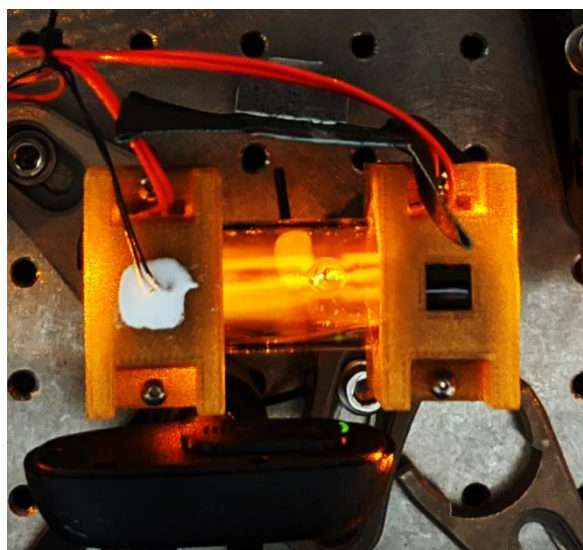


Figure 7: Glow in sodium cell caused by excitation from semiconductor guidestar laser during frequency locking experiments

Using the intracavity doubled approach we have shown 8W of single frequency power near 589nm with suitably narrow linewidth (<50 MHz) and good beam quality ( $M^2 \sim 1.2$ ) required for sodium guidestar applications.

#### 4. IR CAVITY RESULTS

Removing the design constraints imposed by intracavity doubling greatly simplifies the laser design. IR cavities are amenable to scaling single-frequency power through mode volume scaling, by use of multiple gain mirrors or hybrid approaches.

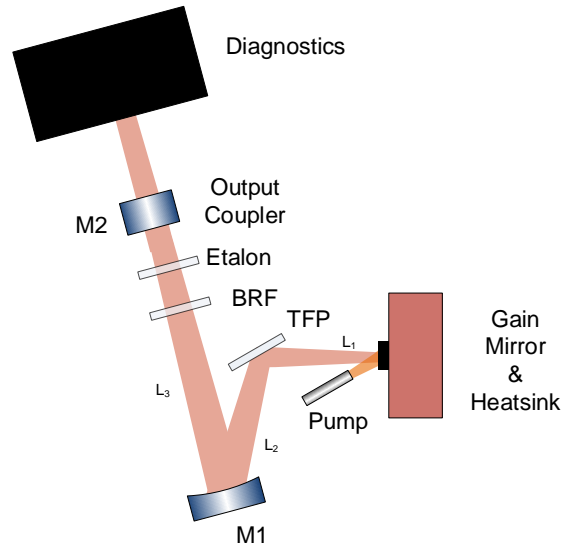


Figure 8: VECSEL designed for output at 1178nm

In intracavity doubled approaches (described in the previous section), it is necessary to have a tightly focused beam within the NonLinear Optical (NLO) crystal to achieve efficient harmonic generation. This constraint limits the extent to which power can be scaled by increasing mode size because to achieve both small-mode within the NLO crystal and large-mode size on the gain mirror can be challenging without compromising other aspects of the cavity design such as mode selection or stability. By contrast, in IR cavities, mode size scaling on the gain mirror may be achieved readily because tightly focused beams are not needed within the resonator to achieve efficient harmonic generation. Besides improved power, it is expected that large mode sizes may also serve to extend gain mirror lifetime because of the improved thermal management.

The obvious drawback to IR VECSEL cavity designs is that to achieve sodium resonance requires coupling the laser to a resonant frequency doubling cavity which may increase cost and/or complexity in comparison to intracavity doubled designs. Ultimately, it is likely that power scaling in the IR and resonant extra-cavity doubling may be necessary to reach the high end of power requirements for guidestar laser applications.

Here we investigate results achieved in a cavity that is designed for 1178nm output, depicted in Figure 8. This design uses a larger mode size than previous intracavity doubled designs.

## 4.1 Large Volume Diamond

In an effort to further improve thermal management we tested a new gain mirror with a Large Volume Diamond (LVD) heat spreader (1.8 mm thick by 5 mm diameter) and compared it to a standard gain mirror with Small Volume Diamond (SVD) heat spreader (300um thick by 3 x 3 mm square) to see if improvements in efficiency or lifetime would be realized with the LVD.

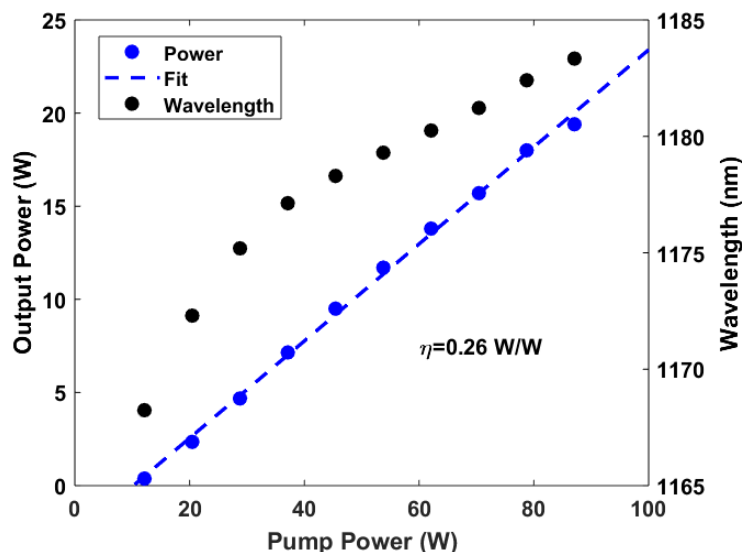


Figure 9: Output power of a large mode volume laser cavity design as a function of the incident pump laser power. The cavity configuration utilized a fundamental mode diameter on the gain mirror of 0.520 mm. The fold mirror was a 250mm ROC high reflector mirror. The end mirror (M2) was 2.5% transmissive at 1178nm. Optical component spacings were L1=57mm, L2=25mm, L3=105mm. The gain mirror temperature was 30C.

Figure 9 shows performance for highly multi-mode (both longitudinal and transverse) operation with no BRF or etalon in the cavity. With a pump spot diameter of roughly 800 $\mu$ m, output power reached nearly 20W with no indication of power rollover. Output power was limited by the amount of cooling power available in the gain mirror heatsink. A slope efficiency of 0.26W/W was achieved. The slope efficiency is computed using the incident pump power. The peak of the output spectrum clearly red-shifts as expected with higher pump currents and the resulting increased gain mirror temperatures. To date, this gain mirror operated for ~360 hours with no sign of degradation.

## 4.2 Small Volume Diamond

In switching to the SVD chip, similar power, threshold, and slope were obtained as with the LVD chip. This is shown in Figure 10 where we plot output power as a function of incident pump power.

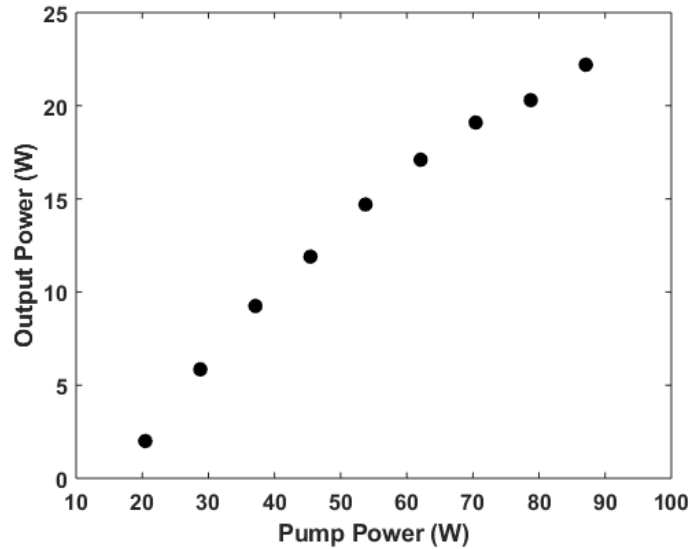


Figure 10: Multi-mode output power of Small Volume Diamond gain mirror as a function of incident pump power. The end mirror (M2) was 2.5% transmissive at 1178nm. The optical component spacings were L1=57mm, L2=25mm, L3=41mm. The fold mirror was a 1000mm ROC high reflector mirror.

After introducing a BRF (no etalon) to the cavity and tuning the cavity to obtain both a TEM<sub>00</sub> single transverse and single longitudinal mode, the output power was reduced to 15W near 1178.3nm. Performance is shown in Figure 11.

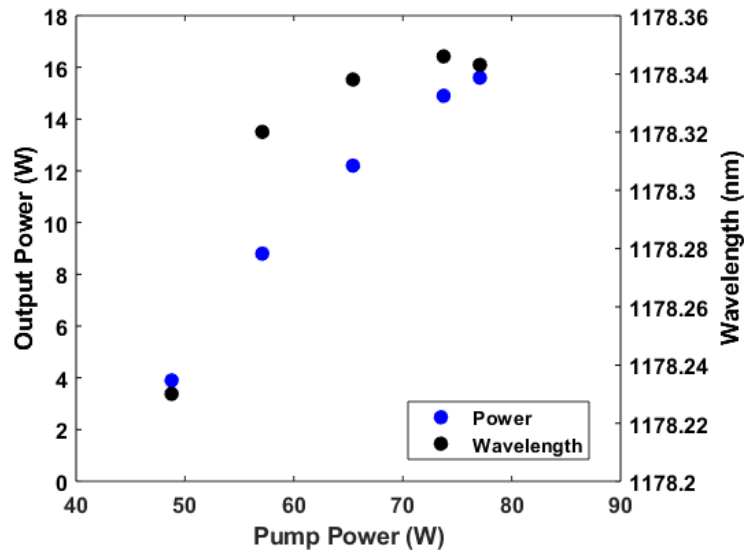


Figure 11 Small volume diamond with predominantly single-frequency operation (occasional mode hops or multi-frequency). The optical component spacings were L1=57mm, L2=25mm, L3=41mm. The fold mirror was a 1000mm ROC high reflector mirror. The end mirror (M2) was 2.5% transmissive at 1178nm. The gain mirror heat sink temperature was 10 C.

A scanning Fabry-Perot trace shows a single longitudinal mode and a resolution-limited linewidth measurement of <10MHz in Figure 12.

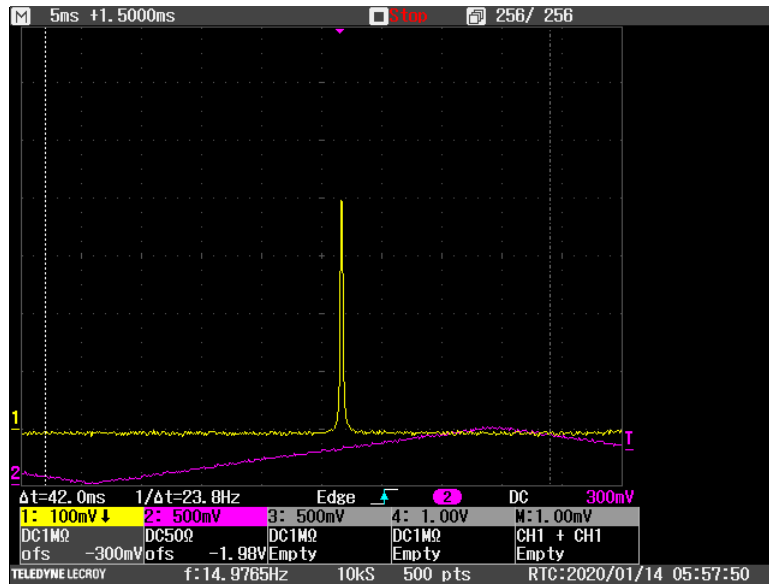


Figure 12: Scanning Fabry-Perot trace shows a single longitudinal mode. Estimated linewidth is <10MHz, limited by the resolution of the Scanning Fabry Perot.

In switching from the LVD to the SVD chip for comparison we had to revert our cooling setup to a lower power system for reasons of mechanical compatibility. In doing this, we found that reductions in laser efficiency negatively impacted cooling performance. For example, after introducing an etalon to the cavity we found our thermal management system was not able to maintain temperature at higher pump powers. In order to compensate for this we reduced the pump spot size on the chip to reduce the threshold enough that reasonable output powers could be obtained before reaching the limit of our cooling system.

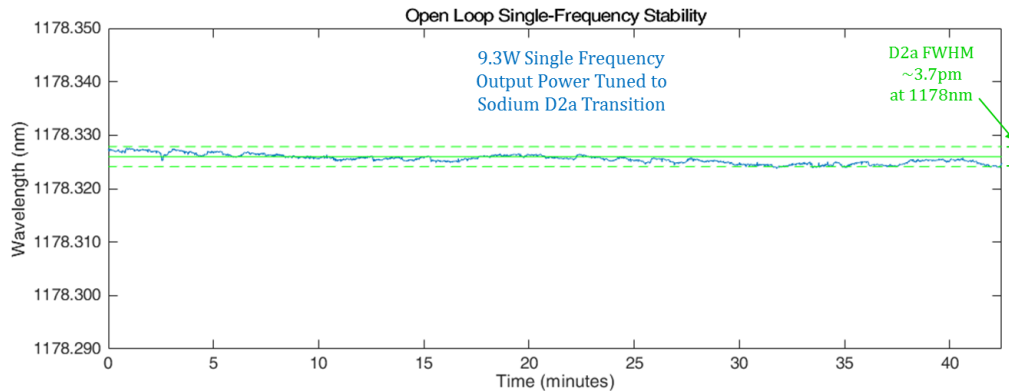


Figure 13: With etalon in cavity, laser maintains stable single-frequency operation for tens of minutes with wavelength variation on the order of the sodium linewidth even when operating without any active feedback or stabilization. Note that our spectrum analyzer has an offset of +7pm.

After introducing an etalon into the cavity, the duration of single-frequency operation and wavelength stability was greatly improved, though output power was reduced to 9W in part from losses from the etalon, but also because of the thermal

management issues described above. The trace in Figure 13 shows >40mins of single-frequency mode-hop-free operation in our breadboard system operating in a laboratory environment *without* any closed-loop stabilization. Even without active stabilization, the laser frequency due to mechanical vibration and thermal drift induced changes in the laser frequency remained on the order of the width of the sodium resonance when translated to the IR. Note that our spectrum analyzer used for this measurement reads 7pm higher than the theoretical vacuum wavelength of 1178.319nm. This offset has been confirmed by comparing the measurement to another wavemeter and also by sodium cell resonance observed in intracavity doubled experiments.

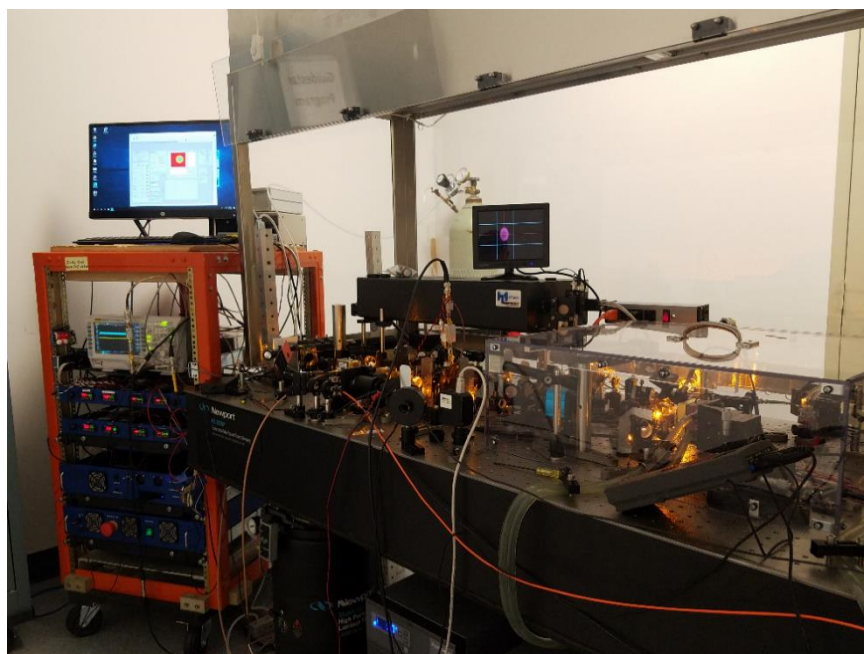


Figure 14 Picture of the SGL laser laboratory at Arete in Longmont Colorado.

## 5. CONCLUSIONS

We have presented progress on two approaches for semiconductor SGL. Using intracavity doubling we have shown power (~8W), linewidth (~10 MHz at 1178nm), and beam quality ( $M^2 \sim 1.2$ ) near 589nm that address SGL applications. Achieving fine tuning to the precise wavelength without compromising power is a remaining challenge with this approach, although we have demonstrated fine-tuning and locking to sodium resonance with reduced output power.

Using the IR cavity designed for 1178nm output we have shown 15W of single-frequency output power which is higher than that achieved with designs intended for intracavity doubling operated with fixed IR output couplers. Prolonged stable single-frequency operation, tuned to the sodium transition been demonstrated at 9.3W, and linewidth has been measured at less than 10 MHz. Power scaling, mode selection and fine-tuning is greatly simplified compared to the intracavity doubled approach. This design has not yet been tested with resonant doubling.

## ACKNOWLEDGEMENTS

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