Robust tunable diode laser implementing volume holographic grating for Rb atom cooling.

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ABSTRACT

We present a robust external cavity diode laser, developed for atom trap experiments, demonstrating a high level of stability. The novel design includes a zerodur tube surrounding the laser cavity for maximal thermal and mechanical cavity stability, a volume holographic grating (VHG) with narrow frequency bandwidth to provide optical feedback, and a micromachined silicon flexure to hold the VHG and allow for laser frequency sweeping. Using a silicon flexure allowed for temperature control of the VHG as well as a reduction of the overall size of the laser system. The results demonstrate a frequency sweeping range of 12 GHz enabled by PZT actuators, a mode-hop-free range of 6 GHz with a non-AR-coated diode, a frequency tuning range of 33 GHz by changing diode current and applied PZT voltage, and a linewidth of <1 MHz. The laser frequency drift was measured to be <1.5 MHz/min, superior to that of many off-the-shelf external cavity diode lasers.

I. INTRODUCTION

Laser diodes have been well documented for their applicability in the fields of laser cooling and atom trapping, and are now widely used in optical and atomic physics [1-5]. Although these devices are compact, simple, and relatively inexpensive, off-the-shelf laser diodes do have some undesirable properties, mostly as a result of their short semiconductor cavity. In particular, their frequency is very sensitive to changes in temperature and injection current; they also have large linewidths of ~100 MHz and poor tunability. It is well known that these shortcomings can be resolved by operating the laser in a longer external cavity which provides frequency-selective optical feedback, with the diode itself acting as the gain medium [1,2]. Such a device is called an external cavity diode laser (ECDL). A particularly simple implementation of this concept uses feedback from a diffraction grating mounted in Littrow configuration shown in Fig. 1[6,7]. Here the first order diffracted beam is used to provide optical feedback. The typical size of this type of laser is quite large (120mm x 90mm x 90mm).

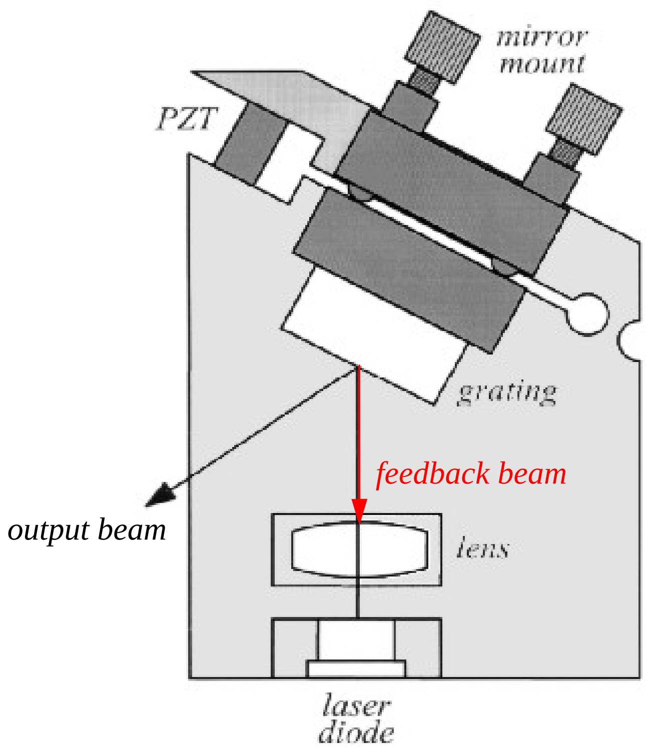


Fig. 1: Schematic layout of a Littrow configured ECDL

Unfortunately, many off-the-shelf ECDLs, such as those sold by New Focus and Toptica, typically have large frequency drift caused by external vibrations and thermal fluctuations within the cavity. It was therefore necessary to design a robust laser with a highly stable cavity, in which the diode, lens, and diffraction grating were each absolutely fixed with respect to each other. In this paper we describe a novel method for constructing a compact ECDL implementing a micromachined silicon flexure and a VHG. The laser cavity itself is entirely encased in a zerodur tube, producing minimal thermal fluctuations within the cavity since zerodur has a near zero (0.01 x 10^{-6} m/K) thermal expansion coefficient and low thermal conductivity. In general, this VHG laser is small, inexpensive, and easy to build compared to other laser designs. The VHG provides a narrow linewidth, along with full degrees of tunability via PZT voltage, diode current, and diode temperature. Additionally, the VHG laser offers the potential to further fine-tune the laser frequency by thermal control of the VHG itself via the silicon flexure.

II. EXTERNAL CAVITY DIODE LASER SYSTEM DESIGN

The essential requirements for a stable ECLD design are that the laser diode, the diffraction grating, and a collimating lens all be fixed rigidly with respect to each other. This assures minimal thermal drift in the lasing frequency, and protects against external vibrations. It is also necessary to allow the lens and/or diffraction grating sufficient degrees of freedom and precise adjustability in order to find optical feedback by steering the feedback beam into the 2 μm diode aperture. In general it is desirable to create a cavity as small as possible to maximize the free spectral range, and thus the mode-hop free range. The free spectral range, defined as the separation between frequencies which can resonate within a laser cavity, is given by the equation:

$$FSR = v_{q+1} - v_q = \frac{c}{2nd}, \qquad (1)$$

where *c* is the speed of light *n* is the index of refraction, and *d* is the length of the laser cavity. Thus, smaller the values of *d created* larger the free spectral ranges [1].

1. Generation 1 VHG Laser design

A first-generation VHG laser was designed and constructed by Rick Chuang in 2006 [8]. The laser successfully implemented a VHG, held by a micromachined silicon flexure (Fig. 2) to provide optical feedback. The silicon flexure was made by bulk micromachining of a 500 μm thick single-crystal silicon wafer. The cavity sat on an invar bed, with thermal expansion coefficient of ~1 μm/K, to prevent thermal drift. The system design, shown in Fig. 3, has an overall size of 28.76mm x 20.65mm x 12mm. Thermo-electric-controllers (TEC) were placed on the diode copper plate and the VHG copper plate to allow for thermal control of each of these components, and an AR-coated diode was used as the light source to minimize mode hops. It was demonstrated that a 17 GHz tuning range could be obtained by varying the VHG temperature [8].

Unfortunately, the cavity was extremely unstable, and it was difficult to keep feedback for an extended period of time. Drifts were also present in the laser frequency, and the mode-hop-free range of the laser was only 4 GHz. The silicon flexure was also deemed to be too stiff, not allowing sufficient PZT sweeping range to see a full rubidium spectrum.

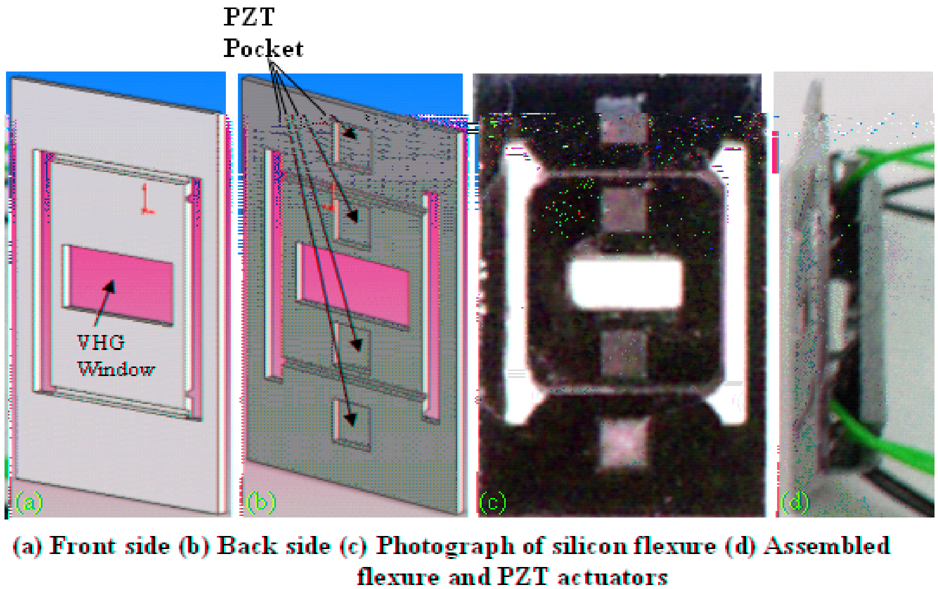


Fig. 2: Silicon flexure with PZT actuators.

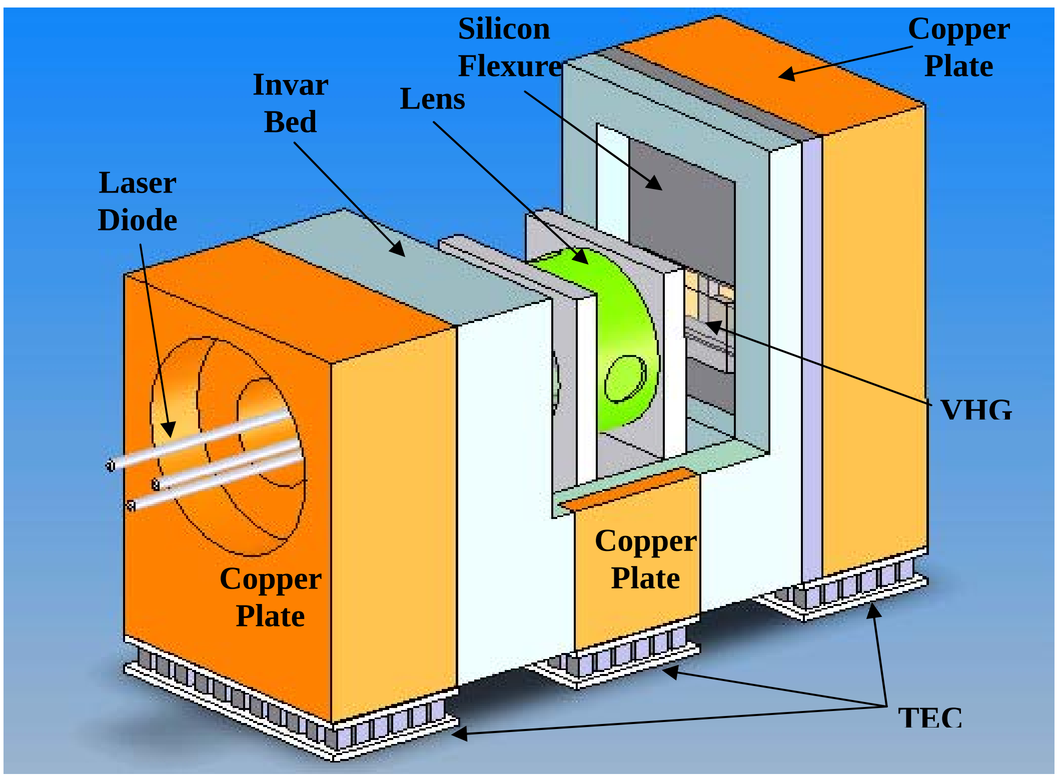


Fig. 3: Schematic drawing of the generation 1 VHG laser system design.

2. Generation 2 VHG Laser design

After the partial success of the first-generation VHG laser, it was necessary to design a second-generation model with a higher level of cavity stability, and with a more flexible silicon flexure to allow for a broader PZT sweeping range. The full second-generation design is shown in Fig. 4. This generation 2 laser has overall dimensions of 18.5mm x 17mm x 17mm. Each component will be examined in more detail in the following discussion.

Zerodur Tubes

One of the main goals in the generation 2 VHG laser design was to created a very stable and robust laser cavity. Thus two circular zerodur pieces were designed to encompass the entire cavity to protect it against thermal fluctuations and external vibrations. Zerodur is a ceramic with low thermal conductivity and a near zero thermal expansion coefficient of 0.01 x 10^{-6} m/K [9]. The design includes two zeordur tubes, one enclosing the lens and VHG, and the other enclosing the diode, to allow for optical feedback to be found by moving the lens and VHG with respect to the diode. After feedback is found, the goal is to optically contact the two zerodur pieces, making them essentially one piece. Thus, the diode, lens, and VHG will ultimately be fixed with respect to the zerodur, and therefore essentially fixed with respect to each other, creating a super-stable laser cavity.

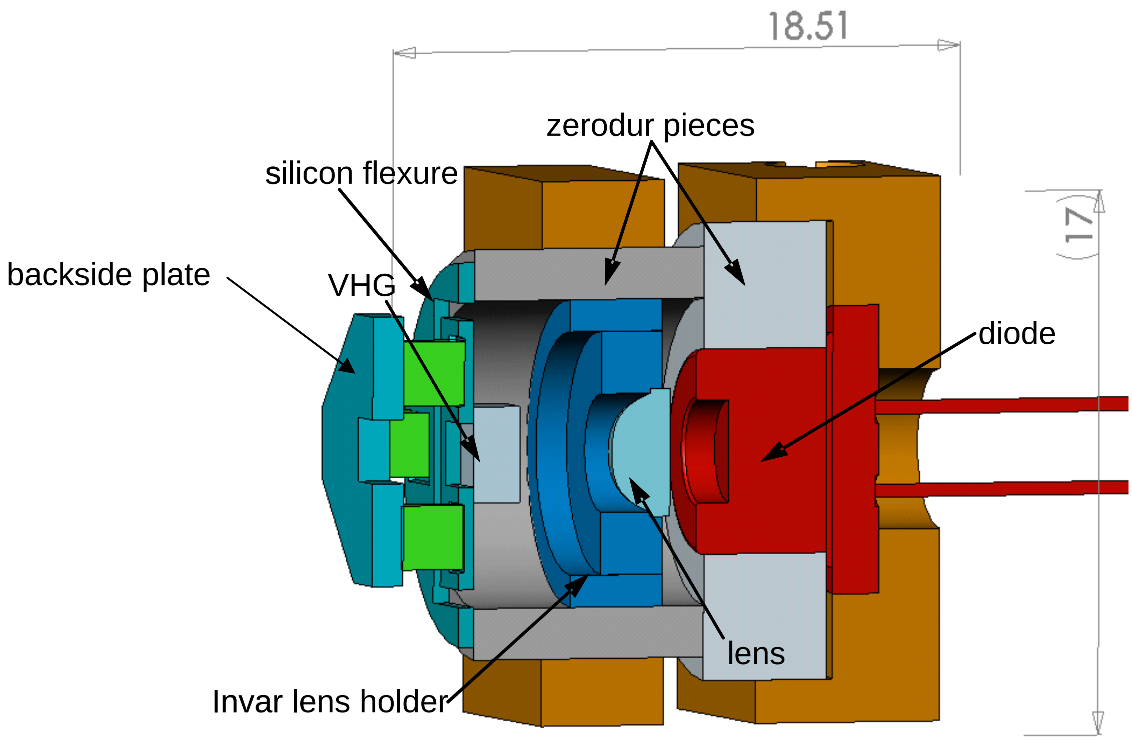


Fig.4: Schematic drawing of the generation 2 VHG laser system design. Dimensions in mm.

Copper Pieces

The main purpose of using copper to surround the two zerodur tubes is its good thermal conductivity. The right copper piece comes in direct contact with the laser diode, making it is easy and quick to control the diode temperature via a TEC placed on the copper piece. The reason to add the second copper piece is to regulate the temperature between the laser diode and VHG. Because the temperature of diode and VHG might be different when the laser system is operating, there will be a thermal gradient between the front and back of the laser cavity. Although zerodur's low conductivity will make it easier to establish this thermal gradient, the addition of the copper piece will further aide in maintaining the gradient. A third copper piece was designed, but never implemented, to thermally control the VHG.

Laser Diode

A 785 nm laser diode (HL7851G, Thorlabs) was used in the laser system. The measured center wavelength of this diode at room temperature (25ºC) was 781 nm. The diode was rated for 50 mW power output at 150 mA current. To save costs, the diode was not AR-Coated, and therefore a less than ideal mode-hop-free range is expected for the entire laser system, since the front diode surface itself forms a cavity within the diode. Thus multiple cavities with competing modes will be formed within the laser, decreasing the mode-hop-free range.

Collimation Lens and Lens Holder

A collimating lens (GELTECH 350390-B molded glass aspheric lens) has been used to collimate the emitted laser beam from laser diode. The numerical aperture is 0.67 mm and the effective focal length is 2.75 mm. The AR-coating for laser wavelength ranges from 600 nm to 1050 nm. The lens holder is designed to hold the collimation lens and permit it to be translated in the cavity's axial direction, providing for optimal collumiation of the laser beam. The lens holder consists of two invar sleeves. The outer sleeve is designed to be glued to the zerodur tube, and the inner sleeve is designed to rigidly hold the lens, thus allowing the inner sleeve and lens to slide axially with respect to the outer sleeve. This provides the lens a sufficient range of motion so that good columniation can be achieved. The lens holder is made of invar, with a low thermal expansion coefficient of 1.2 x 10^{-6} m/K, to minimize thermal drift in the lens position.

Silicon Flexure

The design of the silicon flexure, shown in Fig. 5a, is similar to that of the first generation VHG laser (Fig. 2). It was micromachined of a 500 μm thick single-crystal silicon wafer, with dimensions of 12.7mm x 12.7mm. However, instead of making two 300 μm deep flexure cuts on both the front and back side of the silicon flexure, two 350 μm cuts on the front side and four 350 μm cuts on the back side were made to allow for a larger PZT sweep range of the VHG. Also, the PZT pockets were placed in a rectangular patter, instead of a linear patter, providing a more compact flexure design with less surface area. Since the silicon flexure directly contacts the VHG, it allows for VHG temperature control. The flexure, along with the backside plate, also allow the PZTs to be preloaded.

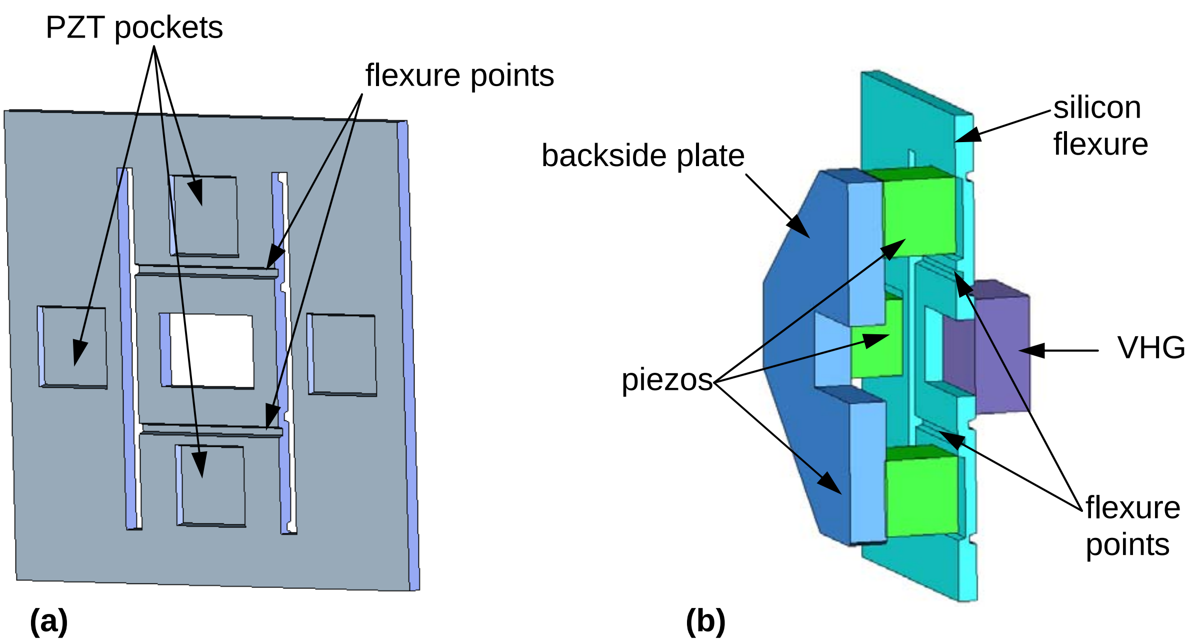


Fig. 5: (a) Generation 2 silicon flexure design, and (b) VHG-flexure system with dimensions in mm.

The backside plate is made with a 1 mm thick silicon plate to which four PZT actuators are mounted. One side of each PZT actuator is attached to the silicon flexure pocket and the other side is attached to the backside plate. When a voltage is applied to the PZT actuators, the

PZT will expand on the silicon flexure side instead of expanding into the backside plate, since the stiffness of the silicon flexure is much smaller than the 1mm thick silicon plate.

Volume Holographic Grating (VHG)

In our laser system design, we choose the reflection VHG (PLR-780.25-10-6.5-3-1.5, Part No. 114-80009-067, ONDAX Inc.) as the external “mirror” for optical feedback. The VHG and sililcon flexure setup (Fig. 5b) will ideally give the laser system high stability, since the grating position will better defined than in a typical Littrow or Littman-Metcalf configuration. Laser frequency tuning can be achieved either by changing the VHG position, and thus the external cavity length, via PZTs, or by changing the VHG temperature, resulting in a change of grating period and refractive index. The dimensions of the VHG are 3.5mm x 3mm x 1.5 mm and the zero-order diffraction angle is 180 deg. The reflectivity is 10% at room temperature and its frequency bandwidth (FWHM) is 0.2 nm. The coefficient of thermal expansion is 6.66 x $^{10\text{-}6}$/K, with an operation temperature range from -200ºC to 200ºC.

Piezo Bulk Actuator (PZT)

Four piezoelectric stack actuators (PL022.20 PI ceramic Inc.) are attached to the backside of the silicon flexure in order to tune and sweep the laser output wavelength. Four PZTs were used rather than two to allow for offset of PZT thermal drift. The PZT overall dimensions are 2mm x 2mm x 2mm and the displacement at 100 Volts is 2.2 μm. The blocking force is 250 N, the electrical capacitance is 25 nF, and the resonant frequency is greater than 300 kHz. The maximum operating voltage is from -20 Volts to 120 Volts, dielectric loss is 0.02 and the maximum operating temperature is 150ºC. The recommended preload for dynamic operation is 15 ~ 30 MPa.

Temperature control system

One Peltier thermoelectric cooler (TEC*)* (SP5446, Marlow Industries Inc.) was attached underneath the copper piece contacting the diode in order to provide diode temperature servo control. Additionally, a precision thermistor (YSI44008) (30 KΩ at 25ºC) was inserted into the copper piece for the temperature servo loop of the laser diode. Finally, a solid state thermal meter (AD590) was attached to the diode copper piece in order to monitor the diode temperature. The thermal meter, also connected to the laser controller, is used to readout the real time temperature of the laser diode.

III. LASER SYSTEM ASSMEMBLY

After each part was made, the laser diode was first inserted and glued to its corresponding zerodur tube, with the two copper pieces glued around their zerodur counterparts. Similarly, the outer sleeve of the lens holder was glued to the lens-VHG zerdodur tube, so that when the two zerodur pieces were placed together, the distance from the laser diode to the sleeve was approximately that of the lens's focal length. The lens was then glued to the inner lens holder sleeve and placed within the outer invar sleeve, but not glued. In each case UV-glue (NORLAND Optical Adhesive type 68) was used to fasten each component. The TEC was epoxied to an aluminum block (3" x 1.5" x 1") that served as a heat sink, and the copper piece containing the diode was firmly clamped atop the TEC (shown in Fig. 9b), with a thin layer of thermal paste between them. The thermal meter was glued to the top of the copper piece, and the thermistor was covered in thermal paste and placed in a small hole drilled within the copper. Each component of the temperature control system was wired to a JILA laser temperature controller (AD014-03) via a 5-pin connector. After temperature control of the diode was obtained, the diode was powered with a precision current source (Lightwave LDX-3525), via a 3-pin connector.

1. Collimation Procedure

To collimate the emitted diode light, the copper piece containing the lens and lens holder was placed on a stable x-y-z translation stand, level with the laser diode. By positioning the lens along the emitted beam path and moving the lens along the cavity axis with the translation stage, one can clearly see the collimating effects of the lens on the beam profile. The goal is to have the lens positioned at an optimal collimation distance while the two zerodur pieces are just touching. This can be achieved by placing the two zerodur pieces in contact with each other and gently adjusting the position of the lens, via the open side of the zerodur tube, by sliding the inner invar sleeve with respect to the outer sleeve. Since the lens focal length is so small, and since it is difficult to precisely control the position of the inner sleeve, this process can be quite tedious. Once the lens is positioned such that good beam collimation is achieved with the zerodur faces touching, the inner invar sleeve is rigidly fixed to the outer sleeve with UV-glue.

2. VHG-Flexure Assembly

Four PZT actuators, each with two voltage-controlling wires attached, were glued into each of the four pockets on the silicon flexure. The PZTs were preloaded using an aluminum block exerting ~20 MPa on each PZT. The backside plate was attached to the opposite side of the PZT actuators. Then the VHG was glued onto the front side of the silicon flexure, as seen in Fig. 5b. This entire assembly was then glued to the end of the zerodur tube containing the lens, with the silicon flexure contacting the zerodur tube. It is important that the VHG be precisely positioned before glueing: it must be centered on the collimated beam so as not to clip the beam profile, and its surface must be made as parallel as possible to the lens and diode faces. While it is clearly not possible to make the diode, lens, and VHG perfectly parallel, the feedback process will be easiest and the beam profile will be optimal if all three components lie parallel to each other and perpendicular to the cavity center axis.

3. Finding Optical Feedback

Locating optical feedback proved to be possibly the most challenging task in the laser assembly. The diode aperture, which the zero-order grating diffracted beam must be steered into in order to obtain optical feedback, spans only 2 μm. Thus it is required to have the zerodur piece containing the lens and the VHG mounted to an x-y-z translation stand. Beam steering is accomplished by moving the entire zerodur piece with the lens and VHG along the x-y plane. This causes diode emitted light to hit the lens at a different point and be deflected off at a different angle (see Fig. 6). Typically, a pinhole is placed within the cavity to help guide the beam steering, but in the case of the VHG Generation 2 laser, the cavity is entirely enclosed in zerodur, so this technique of locating feedback cannot be used.

It was therefore necessary to develop a method of finding feedback using an external pinhole. Optical feedback can only be accomplished when the surface of the VHG is perpendicular to the propagation of the collimated beam. Only then does the beam “retrace its step” back into the diode aperture. By placing a mirror and external pinhole outside of the laser cavity, as shown in

Fig. 7, it is possible to guide the beam steering process to find optical feedback. The mirror serves to reflect the principle output beam back through the pinhole and into the VHG grating. The grating sees this reflected external beam in the same way that it sees the beam emitted directly from the diode. Thus a zero-order grating diffracted beam will be present outside the cavity. When this diffracted beam is made to line up with the principle beam, then the VHG is perpendicular to the beam propagation, since the zero-order VHG diffraction angle is 180 deg. The diffracted beam can be made to line up with the principle beam by moving the zerodur tube with the lens and VHG in the x-y plane. Each time such an adjustment has been made, the external mirror must also be realigned so as to reflect the principle beam strait back through the pinhole. Clearly, the farther away the mirror is placed from the laser, and the farther away you look at the diffracted beam, the more accurate this process becomes.

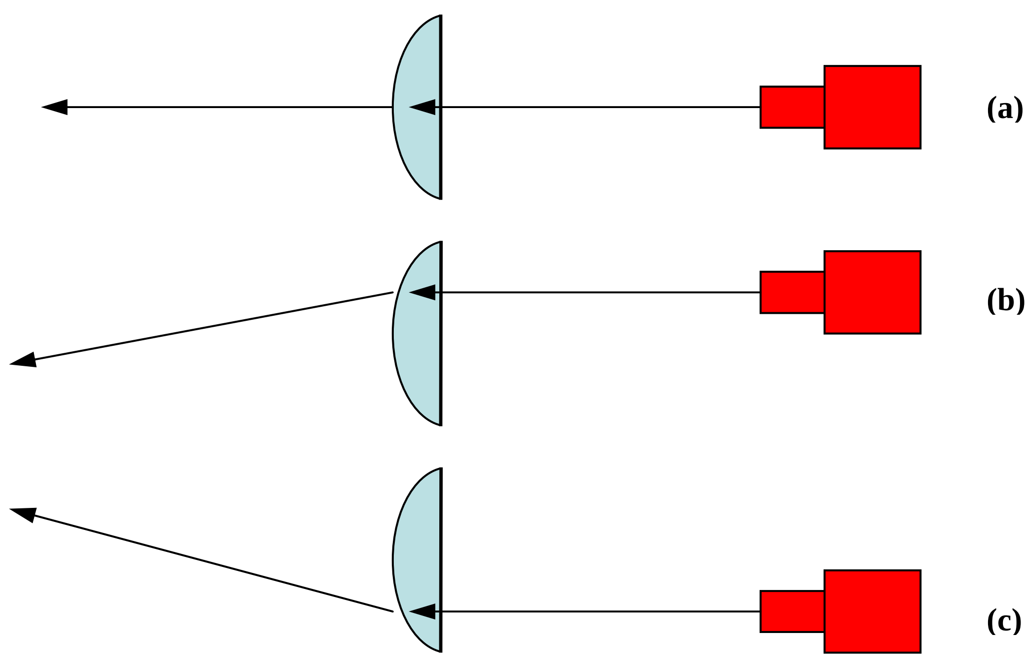


Fig. 6: Steering beam by adjusting lens position relative to diode in x-y plane: (a) lens centered on beam, causing no deflection; (b) lens centered below emitted beam, causing downward deflection; (c) lens centered above emitted beam, causing upward deflection.

After the two beams have been made to line up as close as the eye can tell, a photo-detector should be set up to take current vs. power measurements. If the diode input current is made to sweep out a small range near the threshold current, the threshold current becomes easy to spot on to be flat to within λ/20 (~25 nm), and must be completely clean, for any small spec of dust or oily film will prevent optical contacting [10].

In order to optically contact the two zerodur tubes in this laser setup, it was first necessary to guarantee that the two zerodur pieces were completely parallel to each other when they touched. This was accomplished via a gimbal mount constructed to hold lens-VHG half of the laser (see fig 9a). The gimbal mount (3” x 3” x 1”) consisted of an outer square box encompassing an outer ring, which in turn encompassed an inner ring designed to hold the copper piece around the lens-VHG zerodur tube. The box was attached to the outer ring via two rods and low friction bearing pivots designed to give the ring free rotation about the vertical axis. The outer ring was similarly attached to the inner ring, allowing it free rotation about the horizontal axis. Thus when the two laser halves were brought together the lens-VHG half would be free to rotate such that two zerodur pieces become parallel.

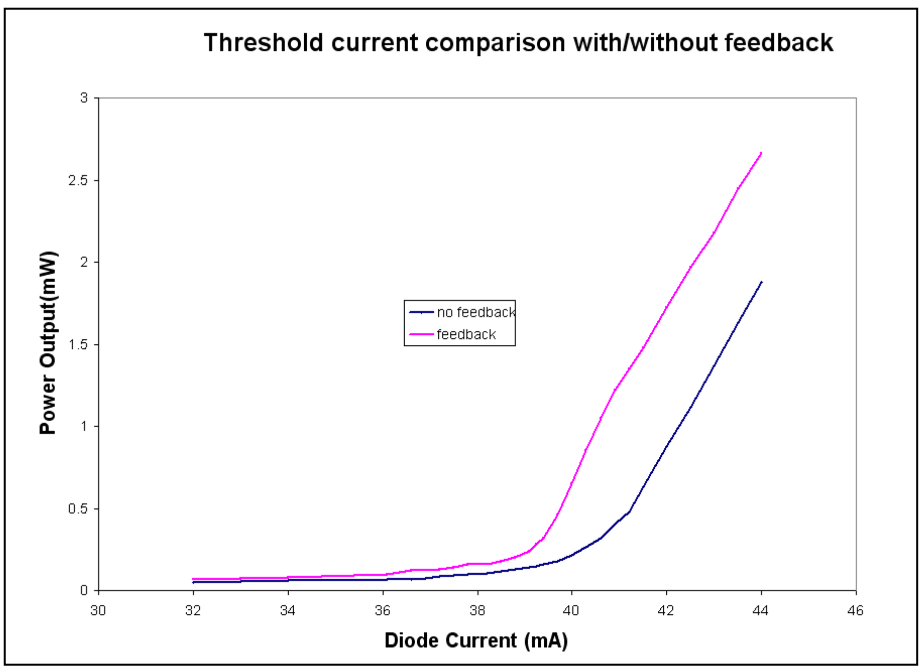


Fig.8: Comparison of laser output power as a function of injection current with and without external cavity optical feedback.

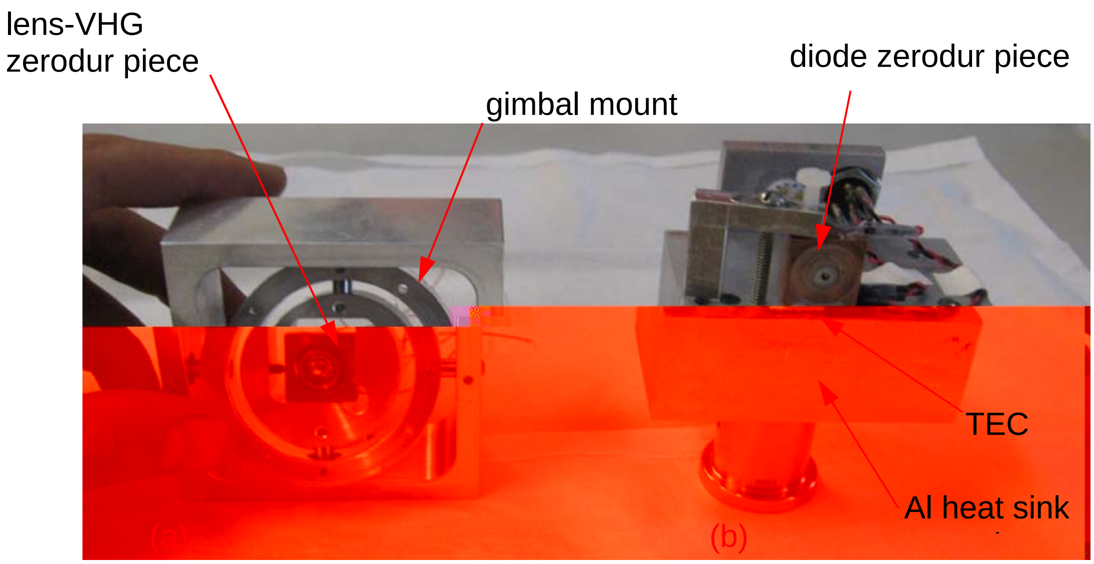


Fig. 9: Picture showing gimbal mount and two halves of generation 2 VHG laser: (a) lens-VHG piece attached to gimbal mount, and (b) diode piece sitting on TEC and clamped to aluminum heat sink.

The gimbal mount was then mounted to the x-y-z translation stand, the zerodur faces were cleaned with dichloromethane and methanol, and optical feedback was again found. However, immediate optical contacting did not occur between the zerodur pieces even after many repeated cleanings. This could be due to imperfect cleanliness or flatness of the zerodur. Also, when optical contacting was earlier accomplished between two zerodur disks in a clean room set up, a significant amount of force perpendicular to the contacted surfaces was required before the pieces would optically contact. However, in the laser setup only small forces could be applied perpendicular to the zerodur faces through the gimbal mount. Eventually, the zerodur tubes were glued together while holding optical feedback in hopes that the zerodur pieces would eventually optically contact. The assembled laser is shown in Fig. 10. The laser cavity has currently remained in stable lasing mode for over 6 weeks.

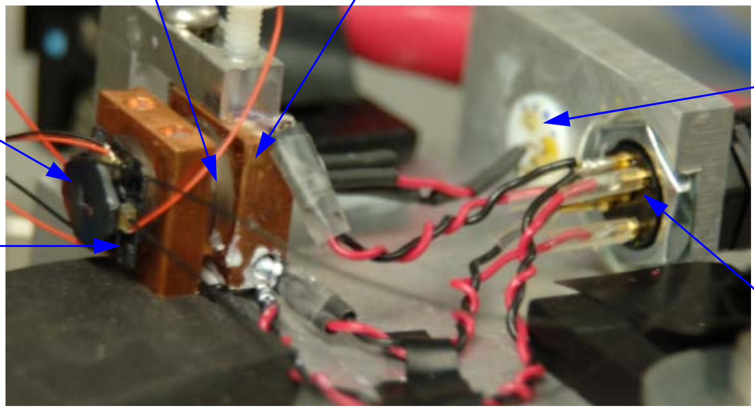


Fig. 10: Fully assembled generation 2 VHG laser, with current and temperature control ports shown.

IV. LASER CHARACTERIZATION

The measured output power of the generation 2 VHG laser was 60 mW at 155 mA, sufficient for many atom cooling experiments. To further determine whether the generation 2 VHG laser can indeed be used for rubidium atom trapping, it is necessary to characterize the laser's tunability, stability, and linewidth. It is also useful to compare these laser characteristics with the leading off the shelf tunable ECDL used in atom cooling experiments.

1. Tunability

It was demonstrated that by adjusting the diode temperature, diode current, and applied PZT voltage, the generation 2 VHG laser could easily be tuned see rubidium fluorescence (780.24 nm) within a rubidium cell. Current adjustment had an effect on laser wavelength of ~0.002 nm/mA, and PZT voltage affected the wavelength by ~2 x 10^{-4} nm/V. The optimal diode temperature was 17-18 °C, with the laser wavelength affected by diode temperature by ~0.2 nm/°C. By sweeping the PZT volage with a function generator (Tektronix CFG280) hooked to a high voltage amplifier (JILA CE049-2), the laser frequency could be made to sweep out multiple rubidium D2 transitions, Doppler-broadened by the random kinetic motion of the rubidium atoms. The silicon flexure proved to allow only two of the four PZTs to sweep the lasing frequency up to 12 GHz when the PZT voltage is swept from -20V to 120V. A mode-hop-free range of ~6 GHz was typical in the laser, with an overall free tuning range of 33 GHz (780.2163 nm to 780.2817nm).

Additionally, the laser was set up, as shown in Fig. 11, using saturated absorption spectroscopy [11, 12] to see Doppler-free rubidium hyperfine transitions. Here a pump beam is used to excite rubidium atoms into higher hyperfine energy states. The laser beam is spit into two separate beams, each passing through the rubidium cell, but with only one crossing the pump beam. Since one beam passes atoms with a different atomic energy state distribution than those crossed by the other beam, the beams will have different frequencies of light absorbed, corresponding to different hyperfine energy levels [11]. When the two beams are subtracted by a subtracting photo detector, a clear Doppler-free hyperfine spectrum can be seen on an oscilloscope (Fig. 12). During the Dopper-free experiment, the laser diode temperature was set at 17.2°C and the diode current was 129 mA. The voltage applied to the PZT actuators was swept between 30 V and 90 V.

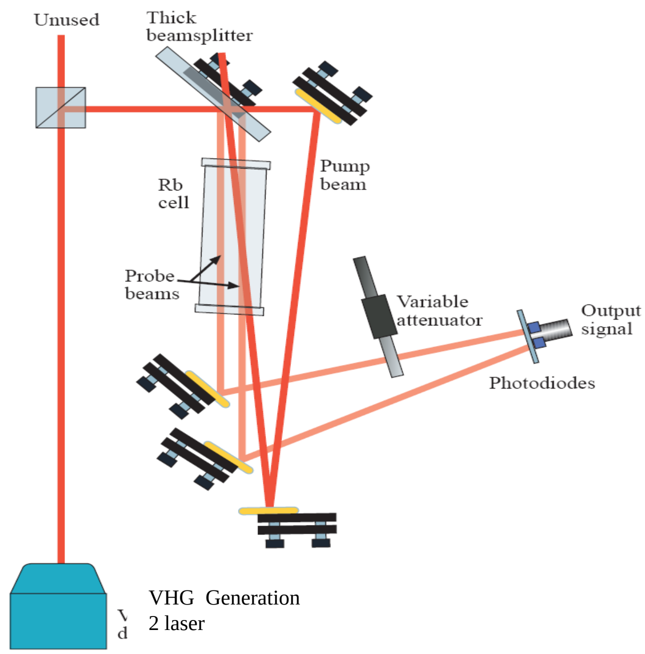


Fig. 11: Optical setup for Doppler-free saturated absorption spectroscopy of rubidium [11]

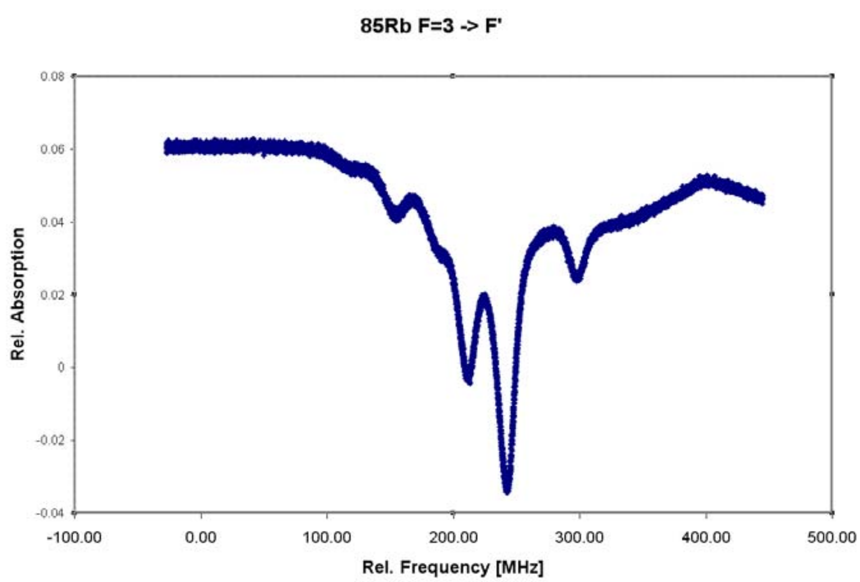


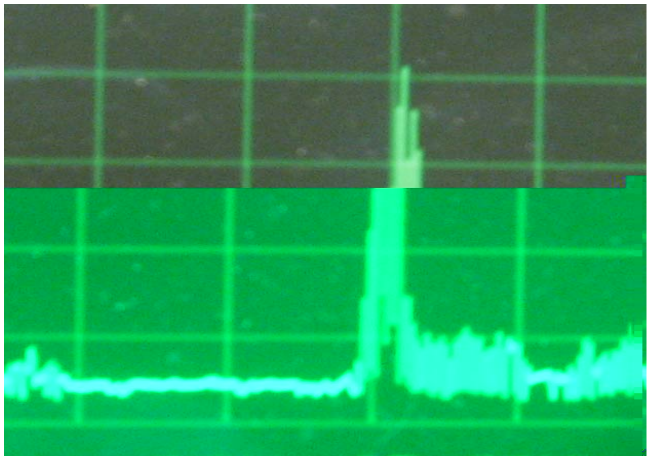
Fig. 12: Doppler-free hyperfine spectral lines of ^{85}Rb F=3

2. Stability

The generation 2 VHG laser demonstrated a high level of stability, indicating the diode, lens, and VHG are mechanically stable. When the laser was completely exposed, it was apparently sensitive to air currents. This could be due to the fact that air currents cause temperature changes in the diode or the VHG, which was not temperature controlled at this point. It could also be due to PZT thermal drift caused by imperfect PZT offset in the silicon flexure. When the laser was covered with a simple cardboard box, the air current induced drift was minimized, and the laser output frequency was highly constant. With the laser enclosed in the cardboard box, it would take over 1 hr for the laser frequency to drift half-way off a hyperfine absorption peak. This corresponds to an average drift rate of <1.5 MHz/min. Furthermore, using a servo peak locking system (Sidelock Servo CE022-06 and 50 kHz Peak Lock AD006-14), the VHG laser was able to be locked to a hyperfine transition for over 7 hrs.

3. Linewidth

Due to the non-ideal nature of the laser cavity and the non-zero bandwidth of the VHG, the laser will output more than one frequency of light at a given time, with the optical spectrum taking a Lorentzian shape. The linewidth is defined as the FWHM of the laser's optical spectrum [13]. The method used for linewidth measurement was to beat the VHG laser against a New Focus Vorex 6000 laser (Model 6013). Both lasers were tuned to rubidium hyperfine transitions, about 1.5 GHz apart, and the beat frequency was analyzed with a homemade 3 GHz fast photo detector, and a spectrum analyzer (8562B, Hewlett Packard). The FWHM of the beat frequency was measured to be <1 MHz (see Fig. 13). The spectrum constantly shifted, due to the high frequency drift of the New Focus laser. An attempt was made to Servo lock both lasers, but this led to a drastically increased beat frequency linewidth, due to imperfections within the servo system. The linewidth of the New Focus laser was rated to <0.3 MHz. From Fig. 13, a conservative upper limit of 1 MHz can clearly be placed on the VHG laser, making it completely suitable for laser cooling experiments.



Frequency (2.5 MHz/div)

Fig. 13: New Focus and VHG laser beat frequency spectrum as seen on spectrum analyzer screen.

4. Comparison

Table 1 gives a comparison between the generation 2 VHG laser and two other leading commercial ECDLs tested in Anderson Labs. The VHG laser clearly fairs quite well, especially considering that it's stability could further be improved with complete packaging and its mode-hop-free range improved by using an AR-coated diode. It has the highest level of mechanical stability, proving to be little affected by large external vibrationgs while other ECDLs show large shifts and oscillations in their lasing frequency due to table vibrations. Also, the VHG laser has the least amount of thermal drift. Its mode hop free range is superior to other lasers employing non-AR-coated diodes, and could be further improved with an AR-coated diode.

Laser Type:	VHG Generation 2	New Focus Vortex 6000	Toptica DL 100
Drift:	<1.5 MHz/min	~20 MHz/min	<1.5 MHz/min
Mode-hop-free range:	6 GHz (non-AR-Coated diode)	>15 GHz (AR-Coated diode)	~3 GHz (non-AR-Coated diode)
Free tuning range:	33 GHz	75 GHz	15 GHz
Linewidth	<1 MHz	<0.3 GHz	<1MHz

Table 1: Comparison of generation 2 VHG laser with other leading commercial ECDLs.

V. CONCLUSION

We have successfully designed and tested a highly stable and compact ECDL for use in atom cooling experiments. This generation 2 VHG laser implements a novel silicon flexure design and a VHG. The cavity is fixed with respect to an encompassing zerodur tube to protect against thermal fluctuations and external vibrations. The laser has demonstrated a level of stability (<1.5 MHz/min drift) as good or better than leading commercial ECDL producers. By adjusting the diode temperature, diode current, and applied PZT voltage, the laser can be easily tuned to rubidium fluoresce. The silicon flexure allows the PZT to sweep the lasing frequency 12 GHz when only two of the four PZTs are swept with voltages from -20V to 150V. From our test results, the laser can be tune over a frequency range of 33 GHz (780.2163 nm to 780.2817nm), with a mode-hop-free range 6 GHz.

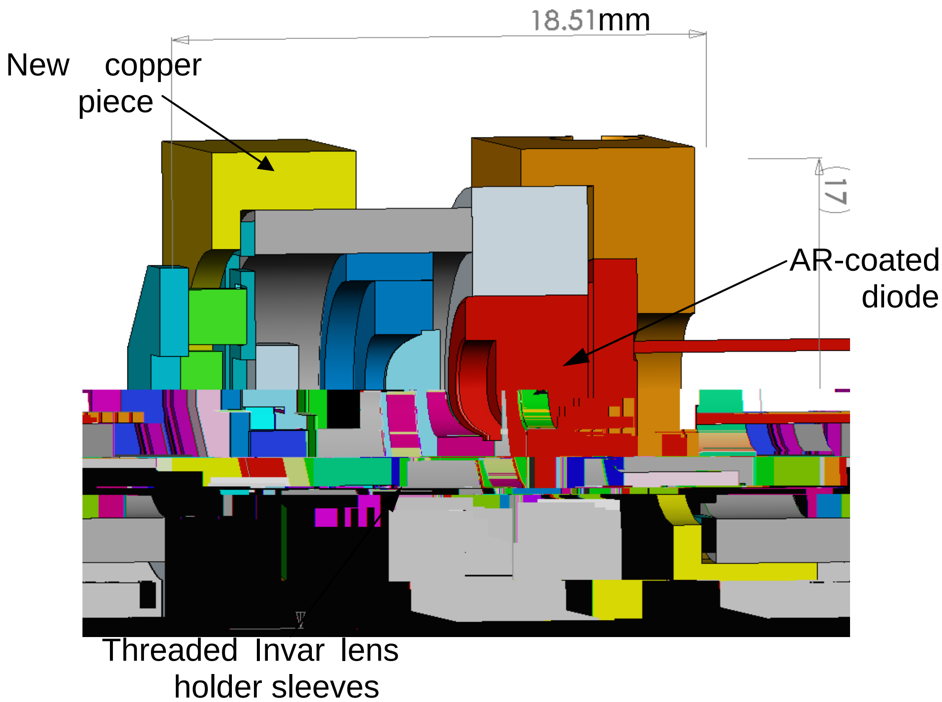


Fig. 14: Generation 3 VHG laser design with AR-Coated diode, a new copper piece for VHG temperature control through silicon flexure, and threaded invar sleeves for more precise collimation.

A generation 3 design, shown in Fig. 14, has been made with a similar cavity configuration to the generation 2 design. The primary change in this new model is a copper piece added to allow for temperature control of the VHG. As demonstrate in the generation 1 VHG laser, VHG temperature control would allow further fine tuning of the lasing frequency, and possibly decrease frequency drift due to temperature fluctuations caused by air currents [8]. Also, an AR-coated diode would be employed in the new laser design, providing a much improved mode-hop-free range and higher output power. Finally, the surface between the two invar lens holder sleeves would be threaded, allowing for more precise lens collimation.

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