External Cavity Diode Laser System for Cesium D1 (894 nm)

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We have developed an external cavity diode laser for use on the cesium D1 transition at 894 nm. Our system produces over 20 mW of single-mode power with a linewidth less than 3 MHz and a continuous tuning range of up to 25 GHz. Our mechanical design allows simple alignment and optimization of the cavity with very good passive stability, and could easily be used with diodes at other wavelengths. Our laser system has been in operation with minimal downtime for nearly three years. We detail the mechanical design and construction, and review the performance of the current system.

I. INTRODUCTION

Semiconductor diode lasers have become a mainstay of atomic physics research, with routine use in a wide variety of experiments.[1,2] External-cavity diode laser systems with diffraction-grating feedback were first developed over two decades ago,[3,4] and are now the most popular choice for applications requiring a narrow-linewidth tunable light source with moderate power. Systems have been developed for use at a large number of wavelengths, using a wide variety of laser diodes and cavity designs (see *e.g.* Refs. 5–8). One of the wavelength regions of considerable experimental interest for which relatively few diode laser systems have been developed is the region near the cesium D1 transition at 894 nm.[9,10] We have developed an external cavity diode laser for use in this region. We are using the same EG&G C86136E laser diode as other cesium D1 systems,[9] but with a significantly different mechanical design which allows easier and more precise optimization of the laser output. This results in a system with considerably more output power and much higher passive stability than commercially available 894 nm diode laser systems, at much lower cost.

Our design consists of a pair of custom-built kinematic mounts, one holding the diode and collimating lens and the other the diffraction grating, which is mounted in a Littrow configuration. Four stainless steel rods connect the back plates of these mounts, forming a stable cavity arrangement (Figure 1). The kinematic mounts facilitate simple alignment and optimization of the optical system. Our mechanical design could be used with other laser diodes, simply by modifying the diode mounting block to hold a different diode package. We use a two-stage thermoelectric heater/cooler, along with a well-insulated outer can, to provide long-term temperature stability of the laser cavity. Our system produces over 20 mW of single-mode power with a linewidth less than 3 MHz. A single-mode continuous tuning range of up to 25 GHz has been achieved, despite the sub-optimal factory anti-reflection (AR) coating on the diode, by simultaneously varying the diode current and the grating angle using computer D/A control. Our system has been in operation for almost three years, including near continuous, stable operation over the past two years. We have used this laser for Cs lineshape studies[11] and as the pump laser system for an optical pumping experiment on spontaneous polarization.[12]

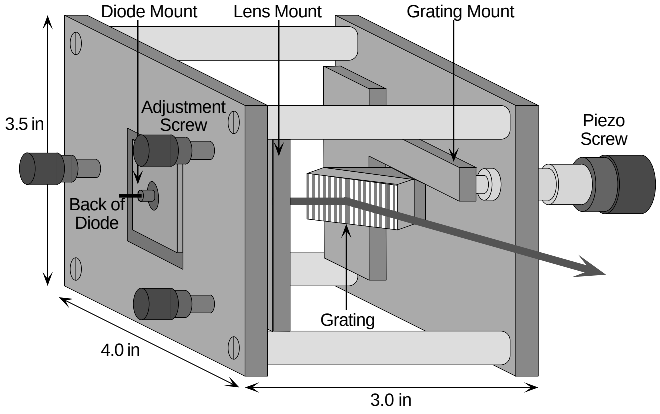

FIG. 1. Simplified 3D view of the external cavity. The outer can and thermoelectric coolers are not shown.

II. CONSTRUCTION

Details of the laser cavity arrangement are shown in Figures 1 and 2. It consists of two 1/4″ thick aluminum plates, 3.5″ by 4.0″, connected by four 3/8″ diameter, 2.5″ long stainless steel rods, all mounted inside a rectangular aluminum tube. A 1.4″ square hole is milled out in one plate, and a 1/4″ thick copper block just smaller than the hole is mounted in it, using a 1/8″ thick G10 (fiberglass) plate attached by eight screws to both aluminum plate and copper block. This ensures a mechanically rigid but thermally isolated connection. The laser diode is mounted in the center of the copper block, using a nut to secure the threaded tail of the diode so that it may be oriented properly (laser polarization vector vertical). A small thermoelectric cooler (TEC) with tinned faces (Melcor CP1.4-7-10TT) is soldered to the back of the copper block using low melting-point In-Sn eutectic solder. A length of 1/2″ wide copper ground strap is soldered in the same manner to the back side of the TEC, and the opposite end is clamped by a copper block to the outer can, which acts as a heatsink. This arrangement allows precise adjustment of the diode temperature without affecting the temperature of the laser cavity.

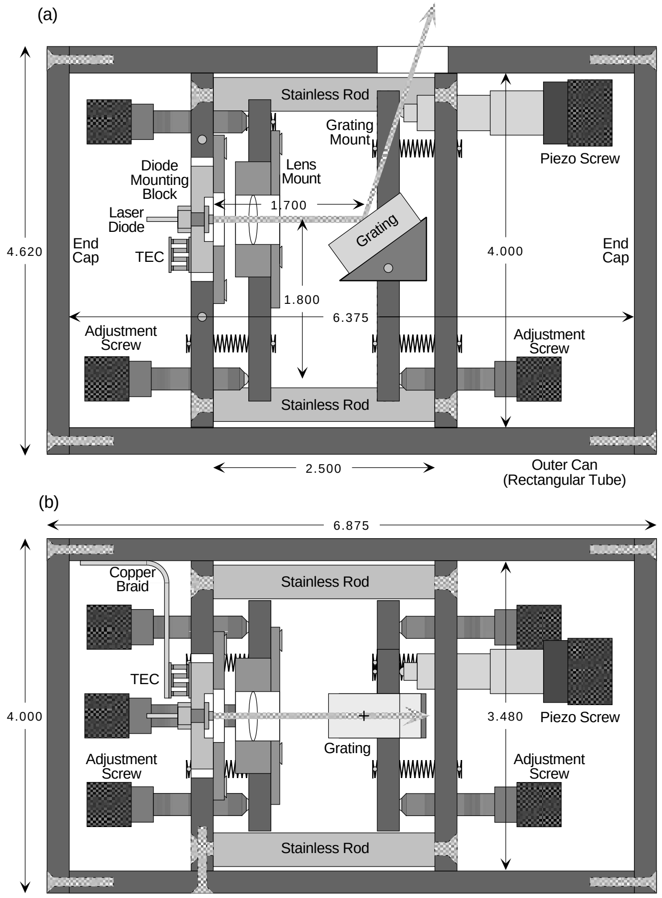

FIG. 2. Cutaway views of the external cavity and can from the bottom (a) and side (b) [dimensions in inches].

The aluminum plate holding the copper block is used as the fixed portion of the first kinematic mount. Another $1/4''$ thick aluminum plate is mounted to it using three ball-tipped 1/4–80 stainless steel adjustment screws (Thorlabs FAS100) and three springs, with the screw tips resting on a conical indent, groove, and flat on the moving plate to form a true kinematic mount. This plate has a $1.4''$ diameter hole centered in front of the diode, into which is mounted an aluminum lens holder with the collimating lens. The lens holder is held by three screws, with enough play to allow precise alignment of the lens to the diode while tightening the screws (see below). Note that the lens holder could easily be modified to accommodate a different size or type of collimating lens.

The aluminum plate at the other end of the stainless rods forms the fixed portion of the second kinematic mount which holds the diffraction grating. A T-shaped $1/4''$ thick aluminum plate is mounted to it in a similar manner to the lens holder plate. However, the adjustment screw at the foot of the T is replaced by a 3/16–100 actuator screw with an internal piezoelectric stack (Thorlabs PE4), to allow both coarse and fine adjustment of the grating angle. The grating itself is cemented to a triangular block cut at the appropriate angle for the specific grating and diode wavelength, which is screwed to the T-shaped arm so that the grating is centered in front of the collimated laser beam. The block has a raised edge against which the grating rests, and the arm has a milled relief cut for stable mounting of the block. Originally, the cavity length and the distance from the point of rotation of the grating arm to the point at which the laser beam intersects the grating were chosen so as to satisfy the continuous tuning criterion. This requires that the cavity length L and grating angle θ change together such that $\Delta\lambda/\lambda = \Delta L/L = \Delta\theta/\tan\theta$ (which follows from the diffraction grating equation, $m\lambda = 2d\sin\theta$ in the Littrow configuration). However, after running the laser for several weeks it was decided to shorten the cavity length as much as possible, to increase the spacing between longitudinal cavity modes and thus reduce the tendency to mode-hop (see Section III).

Extensive steps are taken during construction to ensure optimal mechanical stability of the two custom kinematic mounts and the complete laser cavity. All aluminum components are anodized prior to assembly of the laser, to prevent wear at the tips of the adjustment screws. The adjustment screws (other than the piezo screw) are mounted in tapped brass bushings instead of directly in the aluminum plates. The screws are greased lightly with fluorinated grease and threaded into the bushings, then the bushings are press-fit into undersized holes in the aluminum plates. The brass cold-flows into the threads of the screws, resulting in a tight and stable fit with minimal backlash. In addition, the springs which hold the kinematic mounts together are extremely stiff to reduce vibration of the plates. After mounting, socket heads are epoxied to the screw knobs to allow adjustment using an Allen wrench (hex key) from outside the can, thus minimizing any disturbances.

The laser cavity is housed in a well-insulated aluminum can for thermal and vibrational isolation (see Figure 3). The can is a $6.4''$ length of $3.5''$ by $4.0''$ (interior) rectangular aluminum tube with $1/4''$ walls, into which the cavity assembly slides easily. The laser cavity is affixed to the can by only two screws into the bottom edge of the plate holding the laser. This prevents any possible stresses on the cavity caused by differential thermal expansion of the stainless rods and aluminum can. A $1/2''$ by $1''$ slot is milled in the side of the can to allow the output beam to exit. The ends of the rectangular tube are closed with $1/4''$ aluminum plates, with three holes drilled in each at appropriate locations to allow access to the adjustment screws from outside the closed can.

Styrofoam panels $1''$ thick cover all sides of the can, with those over the end caps being removable. The screw adjustment holes extend through this insulation layer, to allow adjustment without loss of temperature stability. On top of the can is a small uninsulated area, in which two TECs (Melcor CP1.4-127-10L) are mounted above a copper spacer block. A large finned heatsink clamps the TECs in place and is screwed to the can, with fiberglass washers for thermal isolation. The entire can is mounted

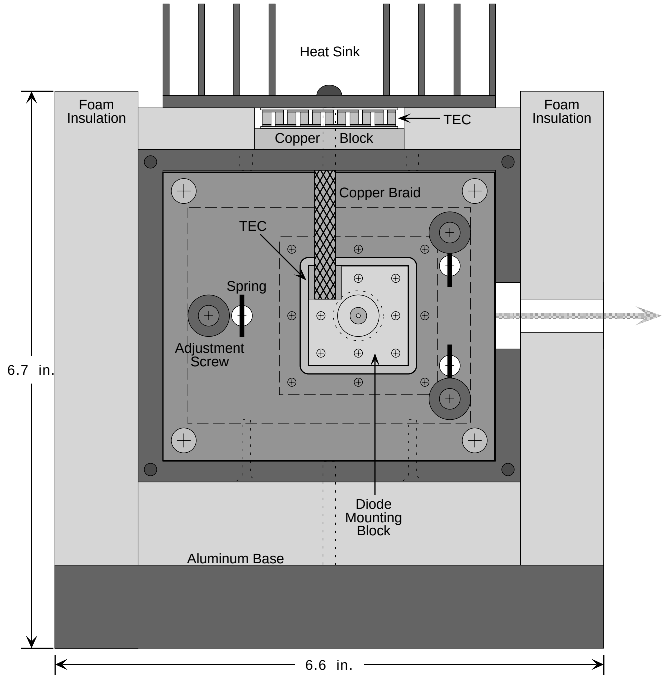

FIG. 3. Cutaway view of the laser enclosure, showing the laser diode mounting block and end plate. Outer slip-cover and lower portion of isolation mount are not shown.

on a vibration-isolation mount consisting of alternating layers of 2″ Styrofoam and 1″ aluminum plates. Long hold-down screws pass through holes in alternate layers, so that there is no direct metal-to-metal contact from optical table to laser can, yet the can is secured to the table. An outer slip-on cover constructed of 1″ Styrofoam covers the entire laser when in operation, except for the heatsink on top and the laser output port, providing an additional degree of thermal and acoustical isolation.

We assemble the laser cavity completely without the lens holder or grating block in place prior to installation of the diode. We remove the front window of the C86136E laser diode package (using a Thorlabs WR1 laser diode can opener) and mount it on the copper block. The beam of the C86136E has a divergence of about 40° in the plane perpendicular to its polarization vector and about 7° in the plane parallel. We use a Melles-Griot 06GLC001 multi-element collimating lens, which has the large numerical aperture needed for this laser. However, this lens has a very short rear working distance of less than 1 mm, necessitating removal of the window. In order to properly align the lens, the laser cavity is fastened down to a suitable surface (such as an optical table), and a card marked with a crosshair at the same height as the laser diode is mounted a meter or more directly in front. The lens holder is first attached finger-tight to its mount, gently nudged until the laser beam is centered on the crosshair, and then bolted down firmly. The collimation can then be fine tuned using the adjustment screws of the lens holder's kinematic mount.

The diffraction grating is now installed. We use an 1800 lines/mm holographic grating (Edmund Scientific D43221), mounted on a block set at 54° to the laser beam. The diode lasing threshold current is monitored while the grating angle is adjusted in both planes, until a drop in threshold indicates the onset of feedback from the grating. At this point the laser cavity is mounted inside the can and the temperature of the can stabilized near room temperature. All further adjustments can be made without access to the interior of the cavity. The laser wavelength is now monitored with a wavelength meter (scanning Michelson interferometer), and an optical spectrum analyzer (scanning Fabry-Perot) is helpful for confirming single-mode operation. The laser is now tuned towards the desired wavelength and an iterative process of minimizing the threshold current (and thus maximizing feedback) and adjusting the diode block temperature is used to optimize the laser output power.

External optics are needed to condition the output beam for most applications. The beam from the external-cavity is roughly collimated, but with a highly elliptical profile and residual astigmatism. We use a pair of Keplerian telescopes, the first with cylindrical lenses and the second with spherical, to eliminate astigmatism and produce a circular beam. The ratio of focal lengths in the cylindrical telescope must be roughly 5.5:1 in order to match the elliptical profile of the beam, and we use a system of three cylindrical lenses to allow adjustment of this ratio. The second telescope recollimates the beam and expands it to the required diameter. We have found it unnecessary to add an optical isolator to the system, since the laser appears to be unaffected by feedback from the surfaces of the telescope system. The laser is sensitive to feedback from more strongly reflecting optical elements such as attenuators and photodiodes, but this can be eliminated by angling the offending elements slightly off perpendicular to the beam.

The control electronics for this laser system were built in-house and use simple, standard circuits similar to those found elsewhere in the literature (see *e.g.* Ref. 2 for a list of references). Each of the two temperature controllers uses a thermistor in a bridge circuit as the sensor and a simple feedback loop to control the current to the TECs, providing a typical stability of better than 0.01 ℃. The laser current source uses an Ultraohm 0.01% sense resistor, with a standard MOSFET switch arrangement to control the current. A slow-starter circuit, ferrite beads, reverse-biased diodes, and a current limiting resistor provide protection against electrical spikes. The piezo driver consists of a dual power MOSFET arrangement which can supply 0-150 V at up to 300 Hz modulation into the large ($\sim 1\mu$F) capacitance of the Thorlabs piezo stack. The controller box incorporates an internal sweep generator to allow scanning the piezo voltage or laser current, which is useful during setup and alignment to monitor the threshold current of the laser, and includes external inputs for computer control of these parameters.

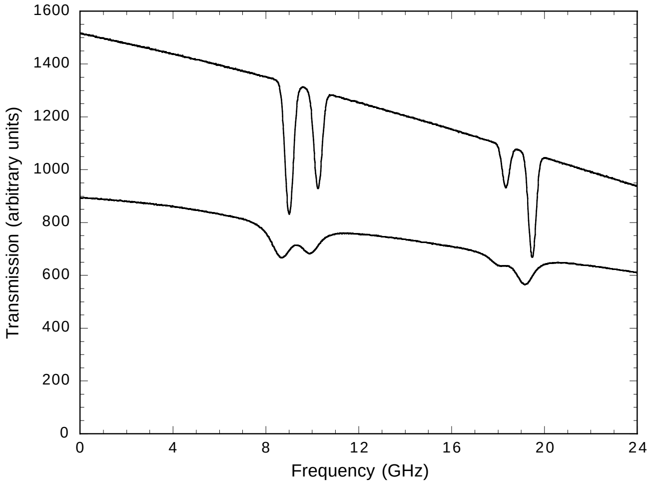

FIG. 4. Continuous scan of 24 GHz across the cesium D1 hyperfine spectrum, with transmission through vapor cells at 20 ℃ with zero (upper curve) and 40 Torr (lower curve) N_2 buffer gas. Intensity variation is due to varying diode current.

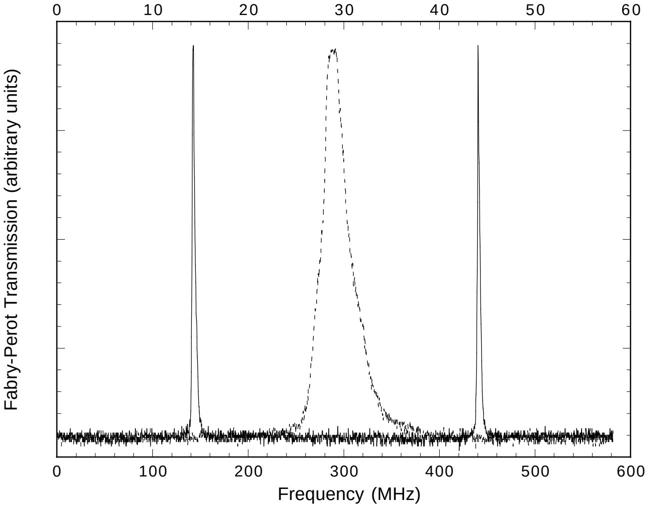

FIG. 5. Transmission through a scanning confocal Fabry-Perot etalon with FSR = 300 MHz. Solid line is a full scan across 2 FSR (scale at bottom). Dashed line is a single peak magnified 10× (scale at top), with FWHM = 3 MHz.

III. PERFORMANCE

The EG&G C86136E laser diode is specified to operate with a free-running center wavelength of 905 ± 10 nm at 25 ℃, shifting at a rate of about 0.3 nm/ ℃. It is desirable to run the diode slightly below room temperature (since the life span of the diode decreases when heated), while avoiding condensation which severely degrades the performance and life span of the diode. Since a typical C86136E would require cooling to less than 0 ℃ for optimal operation at 894 nm, it is necessary to frequency select individual diodes before purchase to ensure that their room-temperature center wavelength is close to 894 nm (the manufacturer will do this upon special request). The diodes we have used were selected for center wavelengths of 896-898 nm, and they typically run optimally near 894 nm at 17–20 ℃.

The continuous single-mode tuning range of the laser is limited to a few GHz if the grating angle alone is varied using the piezo, with multimode behavior preceding a complete mode hop. External cavity lasers using optimally AR-coated diodes (such as commercial systems from New Focus and others) have achieved continuous tuning ranges of tens of nanometers (i.e. several THz in frequency). Thus one of the limiting factors is clearly the factory AR coating (SiO) on the EG&G diode, which has a front facet reflectivity of 5%.[9] We attempted to reduce the reflectivity on our first diode by applying an additional layer of Sb_2O_3 in a simple evaporator (using a method similar to Ref. 5), but this did not appear to significantly improve the diode characteristics. Slight etalon effects between the two dissimilar coatings may have negated the benefits of any AR improvement. Consequently, we decided to shorten the laser cavity as much as the overall physical setup would allow, in order to increase the free spectral range (FSR) and thus the longitudinal mode separation. The cavity length was reduced from 4.2 to 3.0 cm by shortening the stainless steel rods, thus increasing mode separation from 3.5 to 5 GHz, which resulted in a noticeable improvement in single-mode performance. The resulting small mismatch in the tuning criterion does not appear to be a limiting factor on the continuous tuning range of the laser. We have not AR coated two subsequent replacement diodes for the same system, but performance has remained similar to or only slightly better than the first diode.

In order to extend the continuous tuning range, we simultaneously vary the laser injection current and the grating angle using a computer and two digital-to-analog (D/A) outputs, which allows simple, real-time optimization of the control voltages. The intensity variation this technique causes is not critical for our current experiment. We find that varying the current as a linear function of the piezo voltage is usually sufficient for all but the widest tuning ranges, with a small quadratic term added as necessary. Careful optimization is necessary to ensure single-mode performance across a wide tuning range. Using this method, we have achieved continuous single-mode scans of up to 25 GHz, several times the free spectral range of the laser cavity (Figure 4). We have tested the linearity of the frequency scan using the transmission through a Fabry-Perot etalon to produce marker fringes as the laser is scanned. As expected, the piezo exhibits some mechanical lag during the initial portion of a scan, but becomes quite linear as a steady-state scan is achieved. Also, the widest tuning ranges are usually only achieved for frequency scans in one direction, due to mechanical hysteresis in the piezo extension.

We have measured the linewidth of the laser using a scanning confocal Fabry-Perot etalon with a free spectral range of 300 MHz, and a manufacturer-specified finesse greater than 200. This data sets an upper limit of 3 MHz for the instantaneous laser linewidth (Figure 5). Using a different method, by monitoring the fluctuations in the transmission through a Cs vapor cell with the laser tuned half way down an absorption peak, we have measured a laser linewidth of about 4 MHz for a 500 ms averaging time. A Fourier transform of the transmission data shows that much of this width is due to residual line noise on the diode current supply. For our present application, a linewidth narrower than a few MHz is not important. Those requiring a narrower linewidth would need to use a lower-noise current supply, perhaps even a battery-powered one. Small oscillations of the laser frequency due to mechanical vibrations also contribute to this linewidth. The vibration isolation mount mentioned in Section II reduces this effect somewhat, and further improvements could be realized by floating the optical table on which the laser is mounted.

In day to day operation on our Cs spontaneous polarization experiment, the 894 nm pump laser needs to be tunable across a several GHz range of the D1 spectrum, since much of our data is not taken near line centers. Because of this requirement, it is impractical to lock the laser to an atomic transition using a saturated absorption spectrometer, and so it must be left free-running. The passive stability of the laser is thus an important characteristic. In general, when left overnight, the laser drifts a few tens of MHz, but generally remains single mode. Any slight multimode behavior which may appear can be corrected with a small adjustment of the diode current. Over longer periods, such as several weeks, the drift is typically a few hundred MHz. It is difficult to track the true long-term stability of the laser, since in the course of normal operation we adjust and optimize the laser on a nearly daily basis. However, one very noticeable characteristic is that the stability of the laser improves greatly during the first few weeks after assembly or re-assembly. We attribute this to metal creep following the tightening of bolts, as the cavity slowly achieves a long-term equilibrium position.

We have had varying results for diode lifetimes in this laser system. The first two diodes had lifespans of three and four months, the first killed by 120 VAC electrocution in a freak accident, while the second died of unknown causes. In both cases, the diodes continued to lase, but with severely degraded spectral qualities. Inspection of the bare diodes under a microscope revealed easily visible facet damage, more severe on the first. The third diode has now been in nearly continuous operation for about two years. Despite well over 10000 hours of operation, the spectral qualities of this diode have not degraded noticeably. We have generally run the laser at a current of 100-110 mA, somewhat less than the manufacturer's rated maximum of 125 mA. The threshold current has crept up slowly by several mA, but not enough to significantly reduce power output. We expect similar long lifetimes to be typical for diodes of this type if catastrophic failures are avoided.

IV. CONCLUSION

We have developed an 894 nm external cavity diode laser system and operated it nearly continuously for almost three years. Our design allows for simple optimization of the laser output, and the cavity is well stabilized thermally and mechanically. The single-mode power and long-term frequency stability exceed that of typical commercially available systems at this wavelength. More detailed construction diagrams are available upon request.

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