

# APPARATUS AND DEMONSTRATION NOTES

The downloaded PDF for any Note in this section contains all the Notes in this section.

Frank L. H. Wolfs, *Editor*

*Department of Physics and Astronomy, University of Rochester, Rochester, New York 14627*

This department welcomes brief communications reporting new demonstrations, laboratory equipment, techniques, or materials of interest to teachers of physics. Notes on new applications of older apparatus, measurements supplementing data supplied by manufacturers, information which, while not new, is not generally known, procurement information, and news about apparatus under development may be suitable for publication in this section. Neither the *American Journal of Physics* nor the Editors assume responsibility for the correctness of the information presented.

Manuscripts should be submitted using the web-based system that can be accessed via the *American Journal of Physics* home page, <http://ajp.dickinson.edu> and will be forwarded to the ADN editor for consideration.

---

## Design and construction of cost-effective tapered amplifier systems for laser cooling and trapping experiments

Jayampathi C. B. Kangara, Andrew J. Hachtel, Matthew C. Gillette, Jason T. Barkeloo, Ethan R. Clements, and Samir Bali<sup>a)</sup>

*Department of Physics, Miami University, Oxford, Ohio 45056-1866*

Brett E. Unks, Nicholas A. Proite, and Deniz D. Yavuz

*Department of Physics, University of Wisconsin, Madison, WI 53706*

Paul J. Martin, Jeremy J. Thorn, and Daniel A. Steck

*Department of Physics, 1274 University of Oregon, Eugene, Oregon 97403-1274*

(Received 6 June 2013; accepted 18 February 2014)

We present plans for the construction and operation of a tapered optical amplifier (TA) system seeded by a single-mode, frequency-tunable, near-IR external-cavity diode laser. Our plans include machine drawings for the parts, electronic circuit diagrams, and information on prices and vendors. Instructions are provided on how to safely couple light into and out of the TA chip. Practical aspects of handling the chip are discussed as well. Because many cold atom experiments require light beams with Gaussian spatial profiles, measurements of the tapered amplifier light output through a single-mode optical fiber are presented as a function of seed intensity, polarization, and driving current. © 2014 American Association of Physics Teachers.

[<http://dx.doi.org/10.1119/1.4867376>]

### I. INTRODUCTION

The ever-growing presence in the advanced undergraduate laboratory of the frequency-tunable external-cavity diode laser (ECDL), operating in single transverse and longitudinal mode with a linewidth of  $\leq 1$  MHz, is well documented.<sup>1-3</sup> These lasers have enabled the introduction of interesting topics in atomic and optical physics such as laser cooling and atom trapping,<sup>4-8</sup> electromagnetically induced transparency,<sup>9,10</sup> and novel techniques in Doppler-free and sub-natural linewidth spectroscopy.<sup>11-16</sup>

It is well known that while ECDLs offer important advantages such as low cost, narrow linewidth, and wide tunability, they are limited in output power; after manipulations such as beam-shaping, Faraday optical isolation, or fiber-coupling, one is typically left with less than 10 mW (Refs. 17 and 18) (although up to several tens of mW may be obtained by injecting the output into another “slave” diode laser<sup>19,20</sup>). This power limitation is due to the requirement that the light output be in a single spatial mode, which forces the transverse dimension of the diode laser used in the ECDL to be on the order of the optical wavelength. If one desires greater single-mode power, state-of-the-art systems using a narrow-linewidth fiber laser and low-noise fiber amplifier

in conjunction with frequency doubling through a nonlinear crystal, have recently been reported.<sup>21,22</sup> Commercial narrow-linewidth fiber lasers at 780 nm are still limited to  $< 100$  mW.<sup>23</sup> If the goal is to attain  $\sim 1$  W of single-mode optical power suitable for state-of-the-art experimentation in laser cooling and atom trapping at a modest price, the only method currently available is to use a tapered amplifier (TA) chip, which is a semiconductor device that achieves high power while retaining the narrow linewidth and stability of the ECDL.<sup>24</sup>

TA devices are available commercially in a price range of \$14,000–\$47,000 per unit, depending on whether the ECDL is included or not, and also depending on the choice of maximum output power (0.15–2.5 W), center wavelength (650–1190 nm), and desired accessories (for instance, Faraday isolation and/or fiber coupling into and out of the chip).<sup>25</sup>

In this paper we present detailed plans for the design and construction of a TA system at 780 nm, seeded by a continuous wave ECDL. We combine features from previous designs in important aspects such as mode coupling and current/temperature regulation, enabling the demonstration of a stable, compact, inexpensive TA system for laser-cooling and atom-trapping experiments at 780 nm. The total cost for

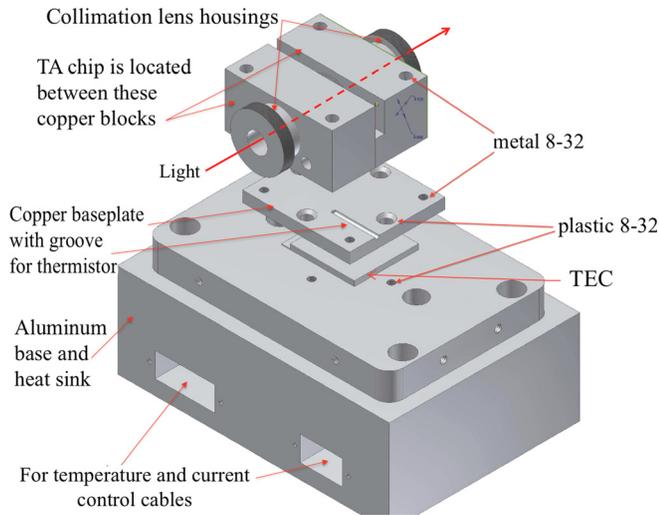


Fig. 1. View of the complete TA system after assembly. Reproduced from Ref. 26.

the TA system (not including the ECDL), is less than \$5000. Measurements of the TA output after collimation, as well as after passage through a single-mode optical fiber, are presented as a function of driving current and seed laser intensity. Since TA chips are notoriously susceptible to permanent damage by even small amounts of optical retroreflection and voltage fluctuation, various safety precautions are described to ensure that the TA system is suitable for implementation in advanced undergraduate laboratories.

## II. OVERVIEW OF COMPONENTS USED

The complete assembly for the TA system is shown in Fig. 1. The chip itself is located between two copper blocks

that house collimation lenses on the input and output sides of the chip. The copper blocks sit atop a copper baseplate in which a groove is cut to accommodate a thermistor. To the bottom of this plate is attached to a ceramic thermoelectric cooler (TEC) device, which itself sits on top of a large aluminum heat-sink. Holes and passageways are cut into the copper and aluminum pieces to allow electrical wires to pass through for the purpose of supplying current to the TA diode and for temperature regulation. Routing the electrical cords through the aluminum base in this fashion allows for the convenient installation of a protective Plexiglas housing that snugly fits the base. In this section, we go over each of the basic components of the TA system. A comprehensive list of parts and vendors can be found in Table II.

### A. The seed laser

For seeding the TA system, we employ a home-built continuous-wave ECDL in Littrow configuration. The laser used is an inexpensive single-mode diode laser (see Table II, line 1). The design and construction of the ECDL has been described in detail in many articles (see, e.g., Refs. 1–3, and 27). Seed powers typically should not exceed the point at which the TA output begins to saturate, which in our experience is about 15–20 mW. More power than this will slightly increase output power, but heightens the risk of destroying the TA.

### B. The TA chip

We have used TA chips made by m2k-Laser GmbH (see Table II, line 2). Photographs of C-mounted chips are shown in Fig. 2.

The basic structure of the TA chip has been described in detail before.<sup>20,24–26,28,29</sup> A working model, suitable for the purpose of this work, is depicted in Fig. 2(e). In this

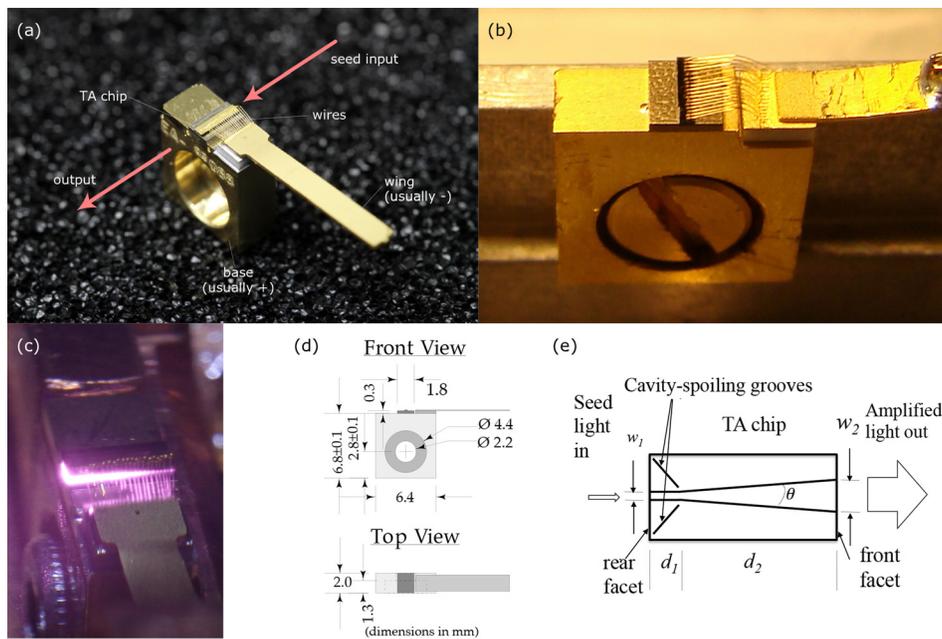


Fig. 2. (a) The TA chip (here, from Eagleyard) comes in a C-mount package, the base of which also serves as an electrical connection (usually the anode). The other connection is in the form of a thin, winged appendage (usually the cathode). Note the wires used to electrically pump the tapered region of the chip. (b) Another close-up photograph of a TA chip (here, from m2k-laser, with the chip still screwed into its original mount in the box supplied by the manufacturer), again showing the fine wires. (c) Photograph of a TA in operation (922 nm, output to the left). The straight narrow section of the chip on the right and the tapered section flaring out to the left are clearly visible. (d) A machine drawing of the C-mount, matching m2k-laser specifications. (e) A simplified top-view depiction of the straight index-guided section of the chip of length  $d_1$  and width  $w_1$ , and tapered gain-guided section of length  $d_2$  and output width  $w_2$  (note the different orientation with respect to the other illustrations here).

highly simplified picture, the TA chip consists of a short, straight, index-guided waveguide section ( $d_1 \sim 0.5$  mm typically) which is coupled to a longer gain-guided tapered section ( $d_2 \sim 1.5$ – $3$  mm typically). In our specific case,  $d_1 + d_2 = 2$  mm, although for the newer version of this chip, the value is 2.5 mm. Light is injected into the chip through the narrow aperture, of width  $w_1$ , of the straight index-guided section. Typically  $w_1 \sim 1$ – $3$   $\mu\text{m}$  but for our specific chip  $w_1 = 1.3$   $\mu\text{m}$  (for the latest version of our chip  $w_1 = 1.2$   $\mu\text{m}$  according to the manufacturer). The amplified output is emitted through the much wider aperture, of width  $w_2$ , of the tapered gain-guided section, as shown in Fig. 2(e). Typically  $w_2 \sim 200$   $\mu\text{m}$  but for our specific chip  $w_2 = 205$   $\mu\text{m}$  (for the latest version of our chip  $w_2 = 150$   $\mu\text{m}$ ). The taper angle  $\theta$  is approximately  $6^\circ$  and is chosen such that the beam from the straight section diffracts and expands to fill the entire tapered region. This is visible in Fig. 2(c), which is a photograph taken by the Oregon co-authors of one of their TA chips while in operation. In Figs. 2(a) and 2(b), note the presence of closely spaced wires in order to provide uniform electrical pumping to the tapered section of the chip. In Fig. 2(c), the amplified spontaneous emission (ASE) is brighter towards the output end of the TA chip due to the taper. Electrical contact is established by metallizing the top and bottom surfaces of the chip, thus connecting the top surface to the flat wire “wing” (typically serving as the cathode connection) and the bottom surface to the C-mount base (typically the anode connection). These connection polarities are common among currently available TAs, but there is no universal standard for C-mount connections. We advise to always check carefully against the manufacturer’s data sheet for your particular TA chip.

The small transverse dimensions of the straight section  $d_1$  ensures that only the fundamental transverse mode is excited, yet this section by itself would restrict the user to low output powers for a given energy density. Expansion into the broader gain region of the tapered section enables the production of high power for the same value of the energy density, and single-mode operation is maintained. Figure 2(e) also shows cavity-spoiling grooves etched into the chip outside the tapered region. The purpose of these grooves is to deflect and dissipate unwanted oscillating modes. Such modes—also known as Fabry-Perot cavity modes—propagate with wavefronts parallel to the two facets outside the tapered region. If allowed to oscillate, these modes would optically pump regions of the chip that are not electrically pumped, thus heating up the chip.<sup>28</sup>

### C. Collimating lenses and lens mount assembly

An aspherical lens (see Table II, line 5) is placed on either side of the TA chip, one to focus the seed beam from the ECDL into the tiny TA chip, and the other to collimate the highly divergent output from the TA. The lenses are housed inside custom-made mounting assemblies which are, in turn, housed inside the copper blocks shown in Figs. 3 and 4. These blocks are made out of oxygen-free high-conductivity copper because they are in direct electrical and thermal contact with the base of the TA chip. The C-mount of the TA chip is screwed into a slot machined in one of the blocks, as shown in Fig. 3. The slot dimensions are such that the TA chip fits snugly inside, and the gain medium of the chip is centered on the optical axis of the collimation lenses.

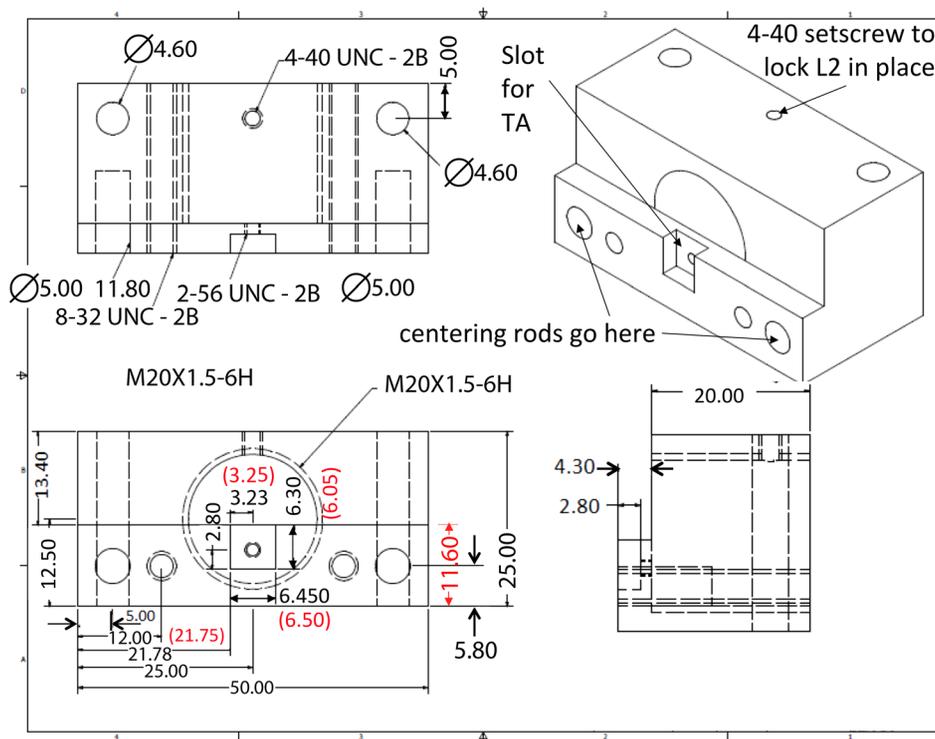


Fig. 3. Machine drawings (dimensions in mm) for the copper block that contains a U-shaped slot for the TA chip. The numbers in black are for the Eagleyard chip (see Table II, line 1) for which these drawings were originally made. The numbers in gray (red online) are modifications for the m2k-laser chip used in this paper. Note that in practice, from a machining standpoint, sharply-defined corners of the U-slot are not required; extra material may be removed to accommodate the finite radius of the end-mill, but the flatness of the main contact surfaces (large face and bottom, but not sides) with the TA chip is critical for efficient heat transfer.

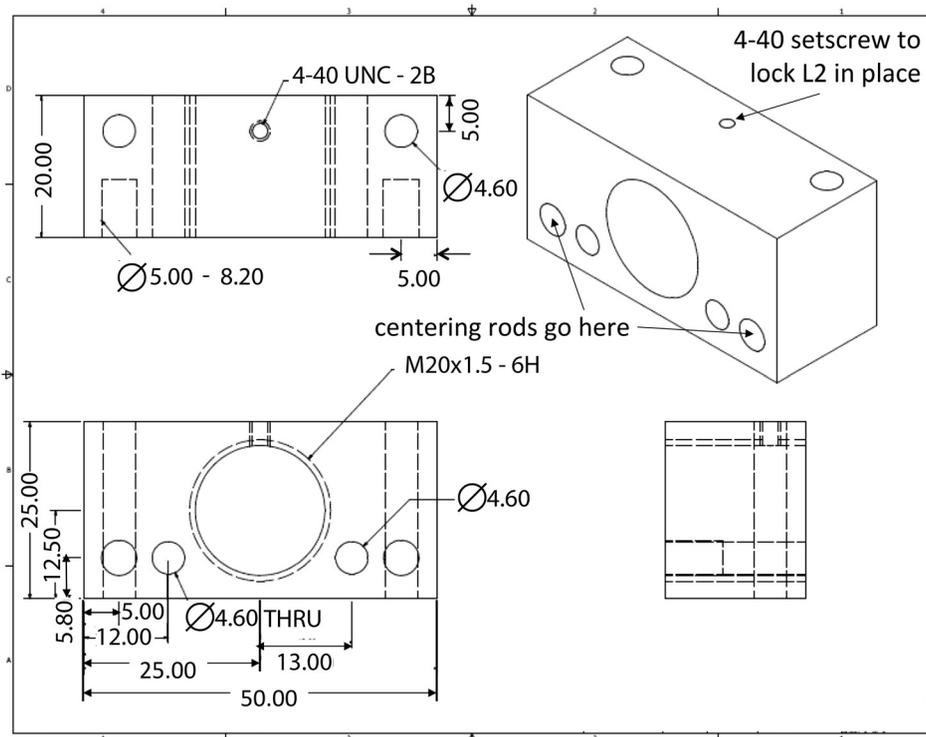


Fig. 4. Machine drawings (dimensions in mm) for the copper block facing the one that contains the TA chip.

The drawings for the other block are shown in Fig. 4. Both copper blocks in Figs. 3 and 4 have centrally-located, threaded holes for mounting the collimating lenses and their custom-built mount assemblies. Each lens mounting assembly is designed to sensitively optimize the position of each asphere while the TA is in operation and consists of two aluminum pieces L1 and L2 as shown in Fig. 5. The machining of these aluminum pieces is nontrivial because of the fine threads and can optionally be outsourced to a company such as Latitude Corp. (see Table II, line 6).<sup>30</sup> The asphere is mounted into the inside of L1, which is threaded to accept the Thorlabs mount for the aspherical lens. The outside of L1 has very fine threads that mate with the inside of L2 enabling L1 to thread into L2 to provide sensitive adjustment of the asphere during collimation. Meanwhile, L2 has coarse threads on the outside that thread into the copper block and allow for initial positioning of the lens assembly. Each block has an identical L1-L2 assembly. A set screw through the top of each copper block (see Figs. 3 and 4) locks L2 in place after coarse alignment of the aspheric lens, and a set screw in the knurled grip of L2 (see Fig. 5(c) and accompanying caption) holds L1 in place after fine adjustment of the collimation. Nylon-tipped set screws should be used to avoid damaging the fine threads of L1 and L2 (see Table II, line 7).

#### D. Thermoelectric cooler, thermistor, heat sink

Temperature regulation of the TA chip is of critical importance because during operation this small chip generates optical powers of  $\sim 1$  W while being electrically pumped by currents between 1.5–2.5 A (see Sec. IV A for relevant safety precautions). As shown in Fig. 1, the temperature is monitored by a thermistor (see Table II, line 8) affixed with heat-sink paste inside a groove cut into a copper plate that serves as a base for the copper mounts housing the chip and

collimation lenses. A machine drawing of this copper baseplate is provided in Fig. 6.

Figure 1 shows that temperature regulation is provided by a thermoelectric cooler (see Table II, line 9) inserted between the copper baseplate in Fig. 6 and a large aluminum base. In a previous design, water cooling of the copper blocks in Sec. II C was required,<sup>24</sup> but in our design, the aluminum base acts as an adequate heat-sink without the need for water cooling.<sup>20,26,31</sup> A machine drawing for the aluminum base is shown in Fig. 7. Note from Fig. 1, the slots that provide access for electrical signals from the TA controller are on the input side of the TA system, not on the output side, where the cables would obstruct the placement of a cylindrical lens immediately after the TA system (see Sec. II E).

It is crucial when applying the thermally conductive heat paste between both TEC-aluminum and TEC-copper interfaces, and putting these parts together, to not use too much paste. If the interfaces between the parts are smooth and contact is good, one may get away without using any heat paste at all. If one does use heat paste, a good rule is to use less than half a grain of rice. The reason is that heat paste is only moderately thermally conductive; it is only helpful for filling microscopic gaps where there would otherwise be no contact at all. Note also that outgassing from silicone-based heat-sink compounds may degrade the performance of the TA. Such outgassing can be mitigated by substituting a silicone-free vacuum grease (see Table II, line 10) performance, or a high-quality, silicone-free heat-sink compound (see Table II, line 11), which can be baked at low temperature to drive off most of the remaining oils before final assembly.

#### E. Cylindrical lens

The output beam from the TA chip is not only highly divergent but also highly asymmetric and astigmatic,<sup>20,24,28</sup>

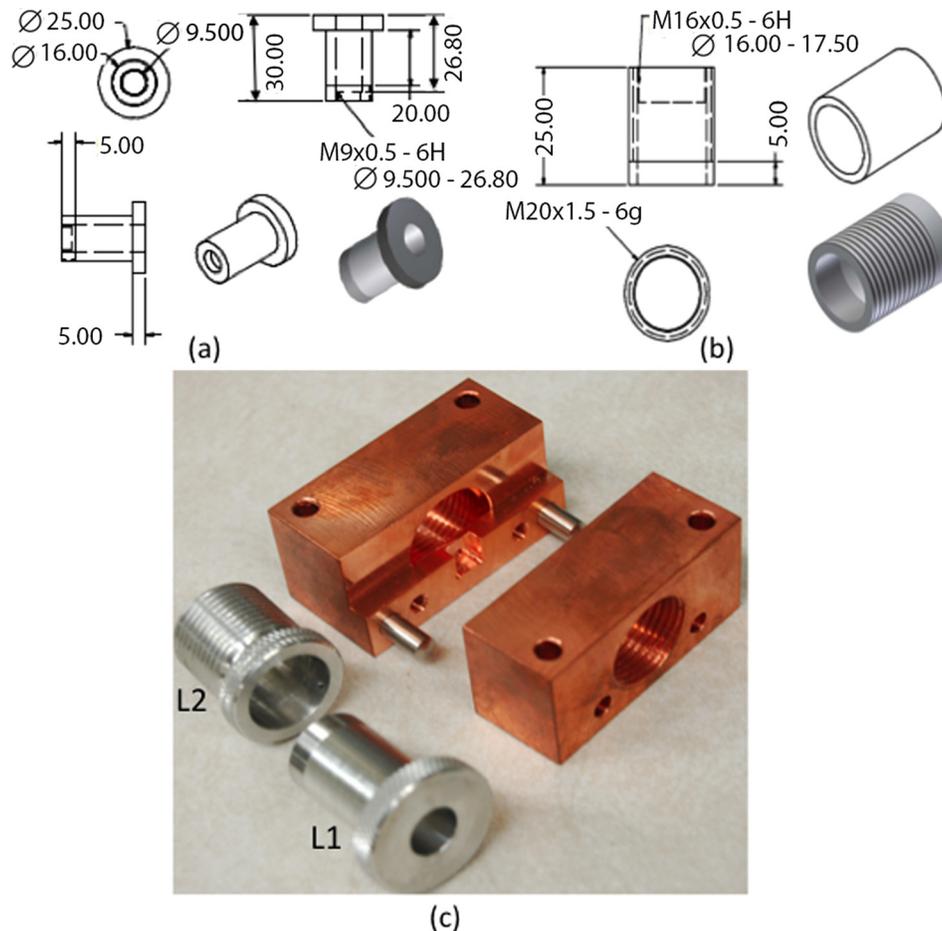


Fig. 5. (a) The asphere screws into a mating thread inside the mount L1. The fine thread (0.5-mm pitch) on the outside of L1 allows sensitive adjustment of the asphere during collimation. (b) L1 screws into L2, and L2 screws into the copper mounting block via a coarser thread (1.5-mm pitch). (c) The aluminum lens assembly for a collimating asphere, shown along side the copper blocks from Fig. 5. A knurled grip, not shown in the technical drawing in (b), was later added to L2 as seen in (c). A set screw in L2's grip, to lock L1 in place, is included. Missing in this picture are tapped holes for set screws in the copper blocks to lock L2 in place, but they are clearly visible and annotated in Figs. 3 and 4. (All dimensions in mm.)

meaning the beam divergences are very different in each of the perpendicular transverse directions. In our case, the divergence is  $6^\circ$  in the horizontal direction [see Sec. II B and Fig. 2(e)] and  $45^\circ$  in the vertical direction (this direction is not shown in Fig. 2(e); the active layer in the TA chip extends  $1\text{--}3\ \mu\text{m}$  in this direction, similar to  $w_1$ ). Additionally, there are different focal points for the two perpendicular directions after passage through a spherical converging lens. The aspherical lens in the previous subsection serves to collimate the output beam in the vertical direction. The horizontal component of the beam passes through a focus, and is then collimated by an anti-reflection coated cylindrical lens (see Table II, line 12), placed just outside the Plexiglas housing of the TA system (see Sec. II F). One should be careful to slightly tilt (i.e., misalign) the cylindrical lens so that any retroreflected light does not get sent back into the chip.

### F. Protective housing

It is important to operate the TA chip in a dust-free, draft-free environment. This is especially true at high TA currents ( $\geq 1\ \text{A}$ ) where the high intensities may effectively act as optical tweezers and attract dust particles, burning them permanently onto the faces of the chip's facets, and degrading the TA performance over time. A protective housing is therefore

necessary. We made such a housing by screwing (and/or gluing) together four Plexiglas pieces as walls and a fifth piece as a roof and snugly placing the Plexiglas enclosure on top of the aluminum base. The complete TA system with Plexiglas housing, including machine drawings of the housing, is shown in Fig. 8. A one-inch hole is made in two walls with a  $1/16''$  lip such that an AR-coated window (see Table II, line 13) fits snugly inside. The hole is bored such that the window sits at a  $4^\circ$  angle in order to avoid potentially dangerous backreflections into the chip.<sup>26</sup>

## III. ASSEMBLY OF COMPONENTS

### A. Handling the TA chip

Standard precautions similar to those observed while handling laser diodes need to be carefully followed. The operator must be electrically grounded before handling the mounted chip.

The wire connecting the protection circuit (see Sec. IV A) to the cathode needs to be carefully soldered to the metal wing protruding from the diode. We found this easiest to do with the chip still screwed into its original mount in the box supplied by the manufacturer. The chip is now ready to be removed from the box and settled into the U-shaped slot in the copper lens mount in Fig. 3, using a pair of small

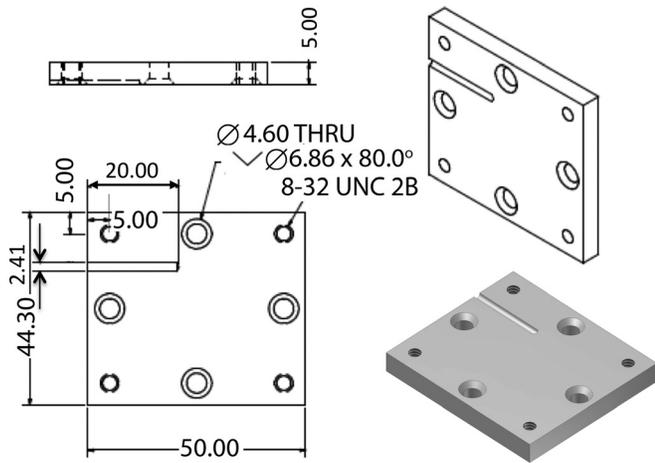


Fig. 6. The copper baseplate with a groove for the thermistor. The thermistor described in Sec. IID has a maximum diameter near its tip of 2.41 mm (the groove width and depth should be sized to just accommodate the thermistor).

needle-nosed pliers to grab the C-mount and hold the wire attached to the cathode wing for positioning. Before actually placing the chip in the U-slot, one must affix the centering rods into the lens mount in Fig. 3, as described in Sec. III B.

It is imperative that the input and output sides of the chip are correctly identified. Injecting the seed beam through the wrong end while operating the TA would instantly destroy the chip (see Sec. IV A); see Fig. 2(a) for the typical orientation, though this should be verified against the data sheet for each TA chip. Extreme caution must be taken to never, under any circumstances, touch the delicate wires shown in Figs. 2(a) and 2(b) that bond to the chip. Figure 9 shows a closeup image of damage to wires bonded to the cathode owing to

slight inadvertent mechanical contact by a user, which resulted in failure of the diode.

The wire from the protection circuit for the anode is soldered to a grounding lug that is attached to a metal 8-32 screw that goes through a clearance hole in the lens mount in Fig. 3, before screwing into the tapped hole in the copper baseplate in Fig. 7. As shown in Fig. 1, the C-mount (anode) for the TA chip is in direct electrical contact with the copper baseplate and lens mounts, but is electrically and thermally isolated from the aluminum base by nylon flathead 8-32 screws. The aluminum base is bolted to the optics table.

## B. Aligning the collimation lenses, and injecting the seed laser into the TA

The first step, before placing the TA chip in its U-slot in the lens mount (Fig. 3), is to insert the 5-mm steel centerless-ground centering rods into the lens mount. The rods are press-fit into the holes indicated (they need to be lightly hammered in). Once the TA chip is placed in its slot and the solder connection with the cathode made, the second lens mount (Fig. 4) is manually slid into position on the centering rods and screwed into the copper baseplate. The rods are indispensable for obtaining adequate axial co-alignment of the two aspheric lenses, given that there are no transverse adjustments available on the lens mounts. With the copper blocks screwed down and both aspheric lenses nominally in place, temperature control should be activated. The next step is to adjust the longitudinal separation of the lenses from the TA chip, starting with the input side.

The amplified spontaneous emission (ASE) emanating from the input end is used to provide the path along which the experimenter subsequently aligns the seed laser into the chip. We start by turning on the current to the TA, but

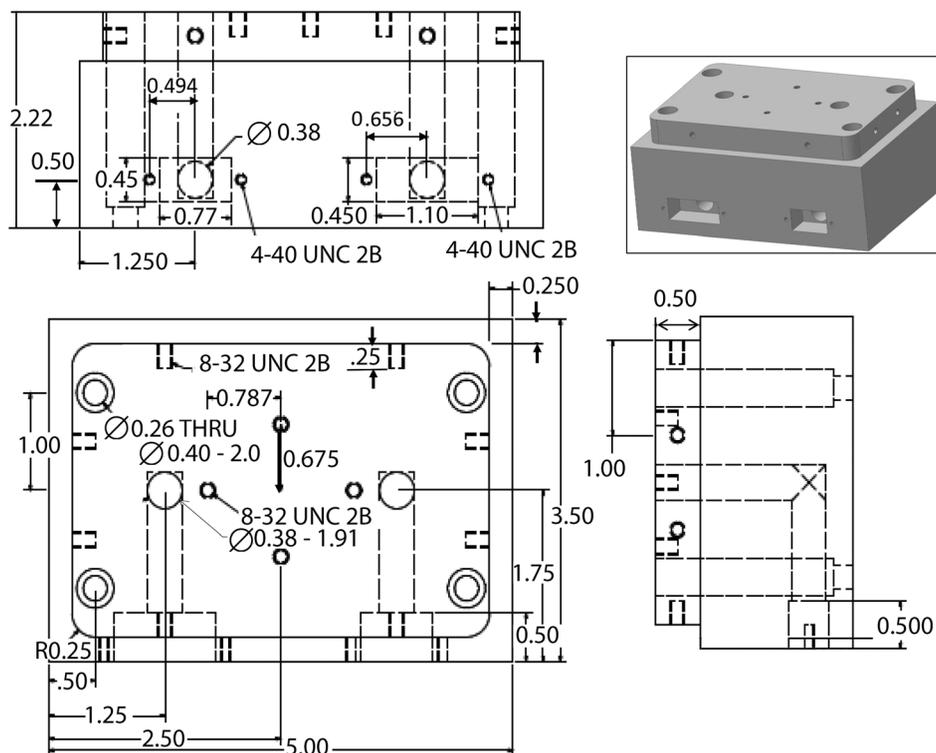


Fig. 7. The aluminum baseplate which serves as a heat-sink. The inset is meant to give an overall view and is not to scale with the other drawings in this figure. (All dimensions in mm.)

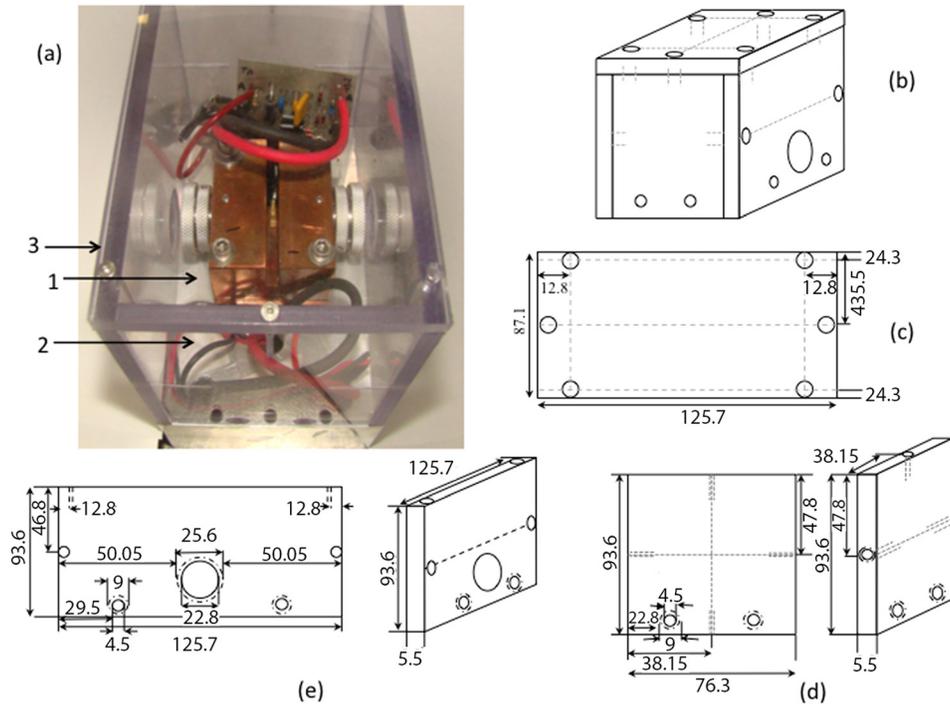


Fig. 8. Clockwise from left: (a) The complete TA system with Plexiglas housing. In this diagram, light enters from the left and exits on the right. The roof of the housing is denoted as 1, the front-and-back walls as 2, and the input-and-output walls as 3. The protection circuit is visible in the background. Machine drawings for (b) the Plexiglas housing, (c) 1 (d) 2, and (e) 3. (All dimensions in mm.)

because this particular adjustment is performed in the absence of a seed beam, we are careful not to exceed 1 A (see Sec. IV A) to avoid damage to the chip (in case ASE causes an excessively high power density at the input facet). As the chip is powered on, ASE is emitted from both ends of the unseeded chip. The ASE from the input is viewed several feet away and the aspheric lens mount L2 on this end (the coarse adjust for aspheric lens CL1, see Fig. 5) is carefully adjusted so that the beam-spot is as compact as possible. The path of this ASE beam is marked out by two pinholes P1 and P2 (see Fig. 10). We used standard irises (minimum diameter  $\sim 1$  mm; see Table II, line 14) placed as far apart as conveniently possible, typically 1–2 feet. Next, the seed beam from the ECDL is aligned through P1 and P2 into CL1 and the TA in a counter-propagating direction to the ASE. A Faraday isolator, FR1 in Fig. 10 (see Table II, line 15), is used to protect the ECDL from ASE produced by the TA, and from retro-reflections by intermediate optical components. Ensure correct polarization of the seed beam [see Fig. 13(d)], as TA chips have varying requirements for the input-seed

polarization. The ASE emanating from the output end is astigmatic (see Sec. II E) and is collimated only in the vertical direction by the output aspheric lens CL2. Thus the ASE therefore looks like a horizontal line. The longitudinal position of CL2 may now be adjusted via mount L2 to yield sharply focused top and bottom edges on the line. At this

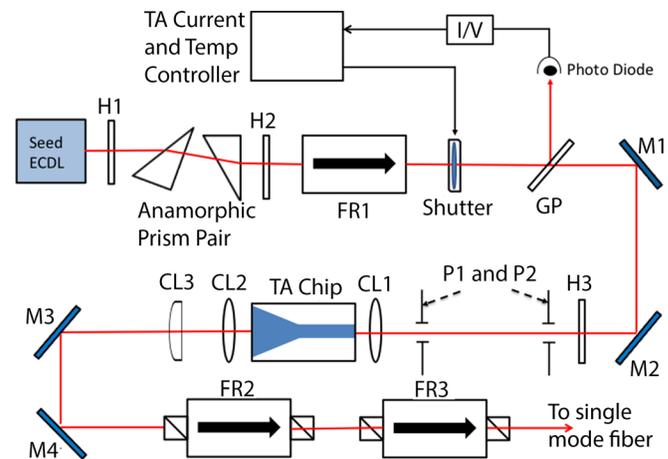


Fig. 10. The optical setup for coupling the linearly polarized seed laser into the TA (Sec. III B), and the TA output into a single-mode optical fiber (Sec. III C). H: half-waveplate; FR: Faraday Rotator; GP: Glass plate; M: Mirror; P: Pinhole; CL: Collimating lens. CL1 and CL2 are aspheres, each mounted inside lens mounts L2 from Fig. 5. CL3 is a cylindrical lens. The elliptical cross-section of the beam emanating from the ECDL is converted by the anamorphic prism pair into circular. H1 minimizes the Brewster losses through the prism pair. H2 maximizes the transmission through FR1, and H3 does the same through the TA chip. The shutter and GP-photodiode combination are employed as safety measures to protect the TA (see Sec. IV A). P1 and P2 mark out the path of the backward ASE emanating from the input end of the TA. M1 and M2 align the seed into the TA through these same pinholes.

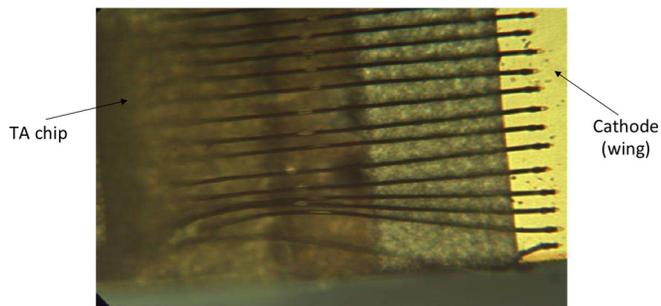


Fig. 9. Damage to wires electrically bonded to one of our chips. Photo courtesy m2k-laser.

point the longitudinal position of CL1 is fine-adjusted via L1 in order to couple the seed mode into the TA, yielding a bright spot located approximately in the middle of the horizontal line.

If a bright spot cannot be realized by adjusting CL1, this means the seed light is not coupled well into the TA. The pinhole-alignment procedure can be repeated, or an alternate method, which uses the TA diode as a photodetector, can be used. We note here that this approach requires coupling light into an unpowered chip (possibly dangerous, see Sec. IV A) but is suggested by a TA manufacturer.<sup>32</sup> This procedure is as follows. Adjust the input coupling asphere CL1 so that the ASE is slightly diverging, then disconnect the current source and attach an ammeter to measure photocurrent generated by a seed power of about 10 mW. If the pinholes are aligned appropriately, the current should be in the  $\mu\text{A}$  range. Then iterate the following two steps. First move CL1 toward the TA chip using L1 until the current peaks and begins to decrease. Second, adjust M1 and M2 to maximize current with the asphere in this location. A photocurrent of a few mA can be achieved in this way. Reconnect the TA's current source and verify that a bright spot appears in the center of the horizontal line generated by the output ASE.

The cylindrical lens CL3 in Sec. II E is placed so as to produce an image of the bright spot that is as compact as possible a few feet away. Place a power meter just after CL3, taking care to avoid reflecting light back into the diode. We now turn up the current and maximize the power output via fine adjustments to mount L1 for CL1 and coupling mirrors M1 and M2. The final location of the output asphere and cylindrical lens should be determined while running the TA at the desired current level. This is because the astigmatism is slightly different for given TA currents, owing to slight changes in the refractive index caused by differences in local thermal gradients in the gain medium. After optimizations are complete, tighten the set screws in the copper blocks in Fig. 3 that lock the aspheres in the L1 and L2 mounts. Subsequent fine-adjustment of the output asphere was found to affect beam shape but have little or no effect on output power. With both collimating aspheres locked down, put in place the protective housing for the TA (described in Sec. II F). It is now safe to run the TA at high currents ( $\geq 1\text{ A}$ ) over long periods of time.

### C. Interfacing the TA output with optics experiments

While aligning the TA output at high current through various optical components, it is critical to avoid backreflections. As mentioned in Secs. II E and II F, the output window on the Plexiglass housing and the cylindrical lens are both tilted for this reason. The next step is to provide Faraday isolation to the TA chip. The collimated output from the cylindrical lens is directed through two Faraday rotator-polarizer combinations (see FR2 and FR3 in Fig. 10 and see Table II, line 15) that provide a total of  $\sim 75\text{--}80\text{ dB}$  isolation and rotate the polarization by  $90^\circ$ .

Many optics experiments require a clean spatial mode profile. It is well-documented that the mode profile of the TA output departs significantly from that of a  $\text{TEM}_{00}$  mode.<sup>17,20,26</sup> We thought it would be useful to present our results for aligning the TA output into a single-mode optical fiber in order to clean up the spatial profile; the setup is indicated in Fig. 10. Measurements of output power from the TA, and coupling efficiency into the single-mode fiber, are presented in Sec. VI.

The single-mode fiber (see Table II, line 16) is connected on the input end to a fiberport (see Table II, line 17).

The focal length of the aspheric lens in the fiberport is chosen to yield maximum coupling efficiency into the fiber for the size of input beam. The maximum coupling efficiency we have been able to achieve is 40%, which is similar to what has been previously reported.<sup>17</sup> The fiberport to which the output end of the fiber is connected is chosen depending upon the desired size of the output beam from the fiber. Note that the geometry of the TA output is somewhat power-dependent, so while preliminary alignment with the fiber can be carried out at low operating current, final alignment should be carried out at normal operating current. Neutral density filters placed before the fiber coupler can help to guard against back-reflections during alignment (along with the optical isolators already described).

It is worth noting that there is one aspect of TA light that may make it unsuitable for certain applications in atomic physics. While most of the power is concentrated in a narrow spectral peak (corresponding to an amplified seed), there is also a significant ASE component, which appears as a low-level, spectrally broad “pedestal” that extends 10 or more nm away from the main peak.<sup>33</sup> While the power level of this pedestal is relatively small, it can still cause large problems in cases where any light resonant with the atoms is undesirable. This is best illustrated with an anecdote.

The Oregon co-authors constructed a (nominal) 780-nm TA system to act as a dipole trap (or “optical tweezers” for atoms, where a high-intensity, focused laser beam tuned far to the red of atomic resonance serves to confine atoms near the focus) for laser-cooled Rb atoms for some experiments realizing one-way barriers for atoms.<sup>34</sup> The laser was set up to be operated at 785 nm, 5 nm to the red of a principal Rb resonance. The authors were confused when they observed trapping lifetimes with this laser that were well under 100 ms, a symptom of a resonant component of the ASE pedestal heating the atoms (another experiment with a similar detuning, but from a Ti:sapphire laser reported  $\sim 10\text{ s}$  lifetimes<sup>35</sup>). Common tricks for dealing with the ASE pedestal include spatially filtering the light through a single-mode optical fiber (since the ASE is multimode) and passing the light through a Rb vapor cell to absorb any resonant component of the ASE. However, even after spatial filtering and triple-passing the light through a 10-cm Rb cell heated to  $>90^\circ\text{C}$ , the trapping lifetimes never exceeded 100 ms. By contrast, after switching to a 1090-nm fiber laser, the lifetime immediately jumped to around 20 s. The point is, if the intention is to use the light for very long, far-off-resonant interactions, TAs may not be the best choice. TAs are often ideal for shorter interactions with detunings of tens of GHz or less.

## IV. SAFETY PRECAUTIONS

### A. Protecting the laser

TA chips are notoriously delicate and susceptible to permanent damage by several mechanisms, such as dust accumulation on the TA facets, voltage spikes across the TA terminals, optical retroreflection, and malfunctions in the temperature regulation. We briefly discuss below, in this section and the next, how to safeguard against these damage mechanisms.

The use of a protective housing for the prevention of dust accumulation was discussed in Sec. II F, as was the use of Faraday isolators for preventing optical retroreflections in

Sec. III C. The use of an IR card (which typically has a reflective surface) to view the TA output before the light has passed through the isolators, for instance, can instantly kill the chip. Any backward-propagating field is amplified and focused by the tapered guide, potentially producing an excessively high intensity at the narrow input facet. Another straightforward mode of chip failure is if a voltage spike, or voltage of wrong polarity, is applied across the chip's terminals. In order to prevent this, one must connect a protection circuit across the terminals of the TA, a common practice with diode lasers, as noted in Ref. 2. The same circuit in Ref. 2 may be used here; we provide a variation of this circuit online.<sup>36</sup>

As mentioned in Sec. IID, the TA chip must never be operated at high current without proper temperature regulation. We turn on temperature control as soon as the diode is installed in the copper block, and leave it on indefinitely. Additional precautions to guard against condensation are necessary if the laser temperature is maintained far below room temperature (below 10–15 °C for typical laboratory humidity). These precautions could either include slow, continuous purging of the air in the TA housing with dry nitrogen or placing a desiccant material in the housing (which should be suitably contained to avoid releasing dust near the TA). Both must be checked regularly to avoid a spent nitrogen source or a saturated desiccant.

Two additional dangers lurk, both having to do with the seed beam. First, there is evidence to suggest that when the TA chip is completely powered off (the TA current and temperature regulation are both turned off), allowing a seed beam of 15–20 mW to propagate through the TA chip can instantly cause permanent damage.<sup>37</sup> Owing to the price of the chip, it is not easy to systematically test why this happens. It is possible, however, that this damage is caused because a disconnected TA chip acts like a photodiode and builds up charge on its leads that can electrocute it. Despite the instant degradation not being well-understood, it is relatively straightforward to implement a foolproof safeguard mechanism that can even protect against the possibility that the TA leads happen to be unshorted or unplugged at that time. We insert an electronic shutter (see Table II, line 18) in the path of the seed ECDL beam, as shown in Fig. 10, that automatically blocks the seed beam if the TA current drops below a certain value. Note that the photodiode in Fig. 10 only receives a signal when the shutter is open. As another part of the interlock described in Sec. V, the TA is only supplied with its full operating current if light is detected by the photodiode, but the driver circuit only opens the shutter when the current is high. Thus, when starting the TA, the shutter must be temporarily forced open (physically or by electronic override). Subsequently, any disruption in this chain will both bring down the TA current and block the seed input. On the other hand, note also that once the temperature control for the chip is on and has stabilized, injecting a moderate amount of seed power (less than 15–20 mW) into the chip while the current controller is still turned all the way down to zero should present no problems according to the TA chip manufacturers (Eagleyard and m2K). Note the alignment procedure in Sec. III B requires that the shutter be kept in the open position during alignment. Indeed, we have injected one TA (see Table II, line 4) over a period of months with normal (~10 mW) seed power always on and with the TA power mostly off, without problem. In any case, for safety when the TA is off (in addition to the temperature

always being stabilized), the TA leads are shorted by a relay in the current controller.

Second, it is well known that operating the TA chip at high currents without a seed laser causes eventual thermal degradation of the chip, even when the temperature regulation is on and performing satisfactorily. The reason is that while the TA is seeded, a significant portion of the electric input power is converted to optical power. However, while unseeded the optical power reduces to insignificant amounts of ASE, which means that most of the electrical power dissipates as heat. (It may be that in the absence of seed light and sufficiently high injection current, backwards-propagating ASE can be amplified to the point of damaging the input facet.) Problems arise when the TA is run unseeded at high currents for several hours. In this case, the temperature controller operates at its maximum design value and the aluminum heat-sink base becomes noticeably warm. This situation should be avoided. We decided to modify the current controller so that in the event that the seed for any reason drops to near-zero, the controller automatically disables the operating current. We achieve this by deflecting a small portion of the seed to a monitor photodiode using a glass plate (marked GP in Fig. 10). The photodiode current signal is converted into a voltage and fed into the TA current controller. If the photodiode signal drops below a certain value (set by an adjustable trimpot), the TA controller safely decreases the current (over a few milliseconds) to zero.

## B. Protecting the human

Though it is important to guard against damage to the TA, it is far *more* important to guard against damage to students, postdocs, faculty, visitors, etc. TAs involve dangerously large optical power levels, which can be particularly insidious for wavelengths beyond the range of human vision. Optical powers on the order of 1 W can easily burn skin and clothing, though this is usually not much more than an annoyance unless the rapid recoil of a body part to escape the heat leads to a secondary accident. The most serious risk, of course, is the near-instantaneous and permanent damage that can occur to your eye, even with a relatively weak partial reflection from an optical surface. Anyone *not* immediately scared of a high-power laser should read the visceral, first-hand account of laser eye damage by David Decker.<sup>38</sup> The dangers of lasers of this class are not to be dismissed casually, and laser neophytes should not work with these lasers until experienced with lower-power lasers (like grating-stabilized seed lasers) of the same wavelength as the TA.

Laser safety is an extensive subject, but literature that is specifically relevant to the work described here is difficult to find in one place. Here, in order to make this paper a stand-alone article, we summarize two key elements of basic, standard practice in atomic-physics laboratories.

The first basic safety measure is the strict use of proper laser eyewear. The glasses or goggles should be designed specifically to block the relevant laser wavelengths. They should also be lightweight, fit properly (this includes getting prescription glasses made, rather than over-the-glasses-type goggles, which are best relegated to temporary use for visitors), be well-enough vented (or treated with an anti-fog product) to avoid fogging, and allow for good overall visibility. These considerations are particularly important to reduce temptations to remove the eyewear while working with

lasers. The most important consideration is, after all, that laser eyewear should *always* be worn in the lab when a TA (or other high-power laser) is operating. There are no exceptions to this rule. (This rule can be relaxed somewhat by experienced users if only low-power light is present, but with TAs, it is never worth the risk.) Similarly, the working area should be blocked off with laser-opaque curtains, with the understanding (possibly with signs as reminders) that no one should enter the curtained-off area without proper eye-wear. Some labs go so far as to install interlocks that power down all lasers whenever the door to the lab is opened, which is an effective measure for safety though rather inconvenient.

The other standard practice is controlling the propagation of laser light, preventing stray beams and reflections that can cause injury in the first place. There are a number of techniques along these lines. First, all beams should propagate in a plane of constant height (a common choice is 4" or 100 mm above the optical table). Then stray reflections will tend to be confined to this plane, so you are relatively safe if you avoid stooping down to near-table level, at least without checking first for stray beams. A related issue that arises in diode-laser and TA setups is that optical isolators with exposed polarizers tend to generate problematic stray beams out of the standard plane. These can be blocked by mounting black-anodized metal tubes (e.g., lens tubes sold by Thorlabs) around each polarizer. In more complicated setups, multiple horizontal-beam planes may be necessary, in which case beams should be periscoped vertically in between planes. Within the horizontal planes, the beams should (as much as possible) run parallel to the table edges, and apertures (irises) should be placed to mark the beam paths and confine the beam. Not only do these practices guard against stray beams, but they also serve as useful diagnostic tools if an optic is bumped or the beams become otherwise misaligned.

In the same spirit, stray reflections should be meticulously tracked and blocked. Stray reflections that exit the table can be detected by taking a large piece of white paper, and sweeping it slowly in the dark around the perimeter of the table at various heights, while a lab mate watches it carefully for laser light (through an infrared viewer if necessary). Weak stray beams can be blocked with stiff pieces of cardboard or, better yet, black-anodized pieces of aluminum, securely bolted to the table for robustness against being bumped. Strong beams and reflections should be properly blocked using a high-absorbance beam dump. There are a

number of ready-made commercial and home-built possibilities for good beam dumps. High-power beam paths are best contained by black-anodized aluminum pipes (1/2" diameter or so), securely mounted to the table. This prevents human appendages and reflective optics from accidentally entering the beam path. And as extra insurance against stray reflections while working on the optical table, hand jewelry and wristwatches should stay securely pocketed while in the lab.

## V. CURRENT AND TEMPERATURE CONTROL

We use homebuilt circuits to control the temperature and current of the TA, and have documented the materials and designs online for easy reproduction.<sup>36</sup> The total cost of the required components, with the exception of an external high-current 12-V power supply, is approximately \$840.

The temperature control circuit is simply an interface for a Wavelength Electronics servo chip (see Table II, line 19). This chip monitors the temperature via a 50-k $\Omega$  thermistor and supplies current to the TEC to match a manual set point. The values of the error signal and TEC current can be monitored via front-panel BNC connections and a separate AD590 temperature transducer provides a reading on an LCD monitor (see Ref. 36). For two of our m2k-Laser TA setups that are each being operated at a driving current of 1.5 A while temperature-stabilized at 20 °C (with an ambient temperature of  $\sim 24^\circ$ ), we find the TEC current readout is 0.77 A in one case and 1.01 A in the other.

The more complex current-supply circuit is based around the high-voltage, high-current OPA549 operational amplifier, which is capable of a continuous 8-A output. A simplified (functional) schematic diagram of this circuit is shown in Fig. 11. This schematic is intended as a guide to help interpret the considerably more complex full schematic in Ref. 36. The input voltages  $V_{\text{set}}$  and  $V_{\text{mod}}$  corresponding to a front-panel knob setting and external modulation input are combined in a summing amplifier (IC2). This combined set-point value is limited by an adjustable-voltage limiter (IC4) to prevent overdriving the TA chip. These signals are fed into a proportional-integral servo amplifier (IC6), whose output is buffered by the high-current amplifier (IC7) and sent to the TA chip via a precision, four-point sense resistor (SR20, 0.1  $\Omega$ ). The output current is monitored by a precision, differential amplifier (IC9), which provides the feedback signal for the servo amplifier (IC6). Current-noise data is available online.<sup>36</sup> Other circuitry not shown implements several other features, including several features to reduce risk of

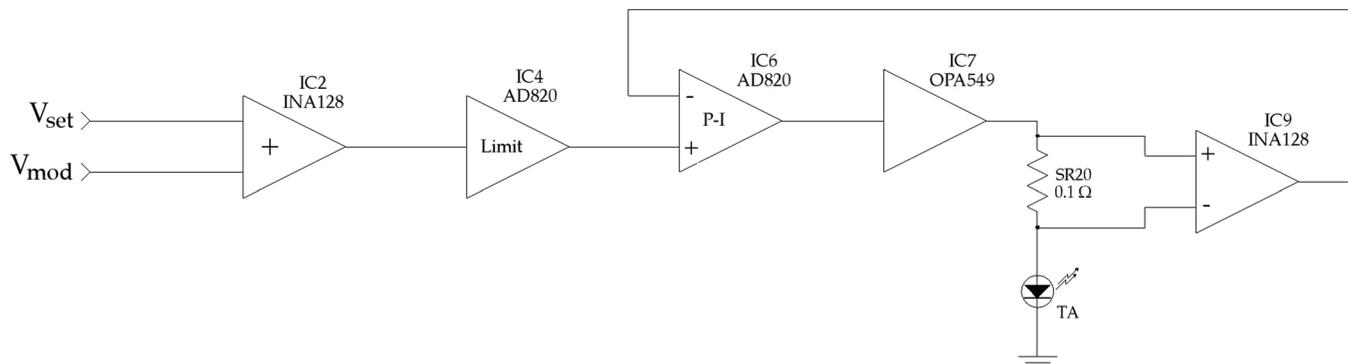


Fig. 11. Simplified schematic diagram of current-supply circuit for the TA chip. Component labels are the same as in the full schematic in Ref. 36.



Fig. 12. Photograph of front panels of complete systems for current and temperature control of two TAs.<sup>36</sup>

damaging the laser. To avoid overshoot, the current is ramped gently when switched on or off suddenly, and as mentioned, the current is limited by an adjustable maximum-current setting. Relays automatically short the diode contacts whenever the controller is not switched on (this is good general diode practice to avoid static-charge fatalities), as well as in the event of certain power-supply fault conditions. Additionally, a switch for manually shorting the TA leads is available, allowing the current set point to be adjusted without enabling the diode. To avoid operating the TA at high currents without a seed laser (see Sec. IV A), the output is disabled whenever the signal input from a monitor

photodiode (see Fig. 10) falls below an adjustable reference voltage (note that in initial alignment using ASE, as described in Sec. III B, this feature will need to be overridden either manually or with a false photodiode signal). Lastly, the front-panel BNC current monitor can be used in an external comparator circuit to drive the seed-blocking shutter mentioned previously.

The temperature and current controllers are both housed in an alodine-coated, fan-cooled aluminum box that fits a standard 19-inch rack. We black-anodized the front panel and etched labels using a 60-W laser cutter (Fig. 12). Front-panel connectors and switches are directly mounted onto the

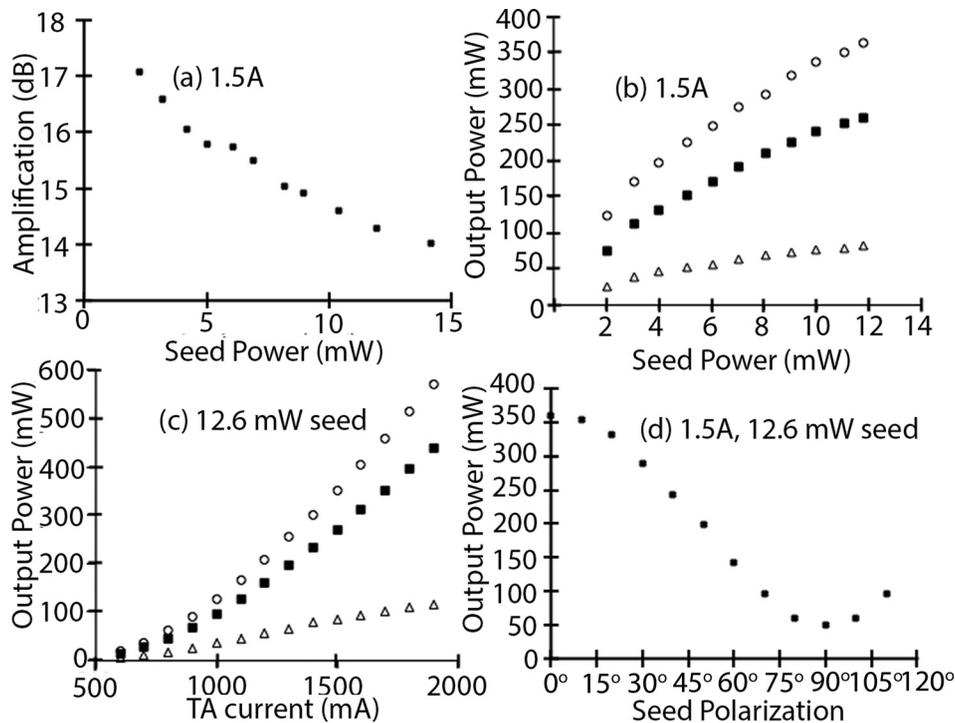


Fig. 13. (a) TA output versus seed power measured in dB-amplification just after the cylindrical lens CL3 in Fig. 10, for a fixed TA current of 1.5 A. (b) TA output in mW versus seed power, again for a fixed TA current of 1.5 A, measured at three different locations in Fig. 10, just after CL3 (circles), just before the optical fiber (squares), and just after the optical fiber (triangles). (c) TA output in mW measured at the same locations as in (b) but this time for many TA currents at a fixed seed power of 12.6 mW. (d) TA output power is strongly dependent on the seed polarization; here a polarization angle of zero corresponds to the light wave being TM-polarized, i.e., the electric field vector pointing in the vertical direction in our case. The TA current is again fixed at 1.5 A.

Table I. TA output measured in dB-amplification just after the cylindrical lens CL3 in Fig. 10. Our values compare favorably with those of the manufacturer (m2k-Laser). See also Fig. 13(a).

TA current	Seed power	Gain achieved
1.9 A	12.6 mW	16.5 dB (this work)
	20 mW	16.5 dB (m2k)
	30 mW	14.8 dB (m2k)
1.7 A	12.6 mW	15.6 dB (this work)
	20 mW	15.7 dB (m2k)
	30 mW	14 dB (m2k)
1.5 A	12.6 mW	14.3 dB (this work)
	20 mW	14.8 dB (m2k)
	30 mW	13.0 dB (m2k)

printed circuit board (PCB) for ease in assembly and troubleshooting, and important trimpots are accessible through the front panel.

## VI. MEASUREMENTS OF TA OUTPUT

In Figs. 13(a) and 13(b), we show how the measured TA output power changes with seed power at different currents for the m2k-Laser TA chip (see Table II, line 2). Meanwhile, Fig. 13(c) shows the dependence of TA output power on current at fixed seed power, and Fig. 13(d) shows how the TA output depends on seed polarization. The TA output, for various TA currents and seed powers, was measured in three different places (see Fig. 10): just after the cylindrical lens CL3, just before the optical fiber, and just after the optical fiber. Seed power was varied using a half-wave plate and

polarizer combination (not shown in Fig. 10) inserted between the ECDL and the TA.

The Wisconsin co-authors for this work are able to achieve a 1-W output (measured just after the cylindrical lens) with only 1–3 mW of seed power<sup>26,31</sup> (note that their seed beam is elliptical, since no anamorphic prism pair was used). Their result comfortably exceeds the manufacturer’s specifications. The chip used by them is from Eagleyard (see Table II, line 3) and the current was operated at 90% of its maximum value (Ref. 31 quotes a gain of 27 dB which is much greater than the 13 dB gain specified by Eagleyard.) The Miami co-authors for this work were unable to achieve this high degree of seed-TA coupling but their results (which are presented in Fig. 13 and Table I) compare with the specifications stated by the manufacturer (m2k-Laser).

Note that the power outputs are very different if the seed power is 12.6 mW, the maximum value the Miami co-authors had at their disposal, as compared to 20 or 30 mW (the seed value at which m2k supplied power output data is stated to lie somewhere between 20 and 30 mW). The dB-gain value gives us a reasonable parameter to compare TA performance across different seed powers.

The data in Fig. 13 show that the fiber coupling efficiency is in the 25–35% range, which is lower than, but not too different from, efficiencies reported earlier.<sup>17</sup> We find that the single-mode fiber coupling efficiency, if optimized for a certain TA current, decreases by several percent as the TA current is then increased or decreased over a 0.75–1.9 A range. This decrease in fiber-coupling efficiency likely comes from changes in the astigmatism of the TA output beam at different TA currents. The fiber coupling is optimized for a collimated beam and will decrease if the beam

Table II. Key components used for constructing the TA system. The \$5,000 price-tag quoted at the beginning of the paper does not include the Faraday isolators and fiberports.

	Description	Model	Cost
1	ECDL diode	Thorlabs L785P090	\$41.45
2	TA chip	Dilas Diode Laser:	
		m2k-TA-0780-1000-CM	\$2225
3		Eagleyard:	
		EYP-TPA-0780-01000	\$3200
4		EYP-TPA-915-01500-3006-CMT03-0000	\$3200
5	Collimating lens (2)	Thorlabs C230TME-B	\$79 ea
6	Lens assembly	Latitude Corporation <sup>30</sup>	\$694
7	Nylon-tipped setscrews	Thorlabs SS8N013 10 pk.	\$12
8	Thermistor	EPCOS B57861S0503F040	\$3
9	TEC	Digikey 926-1036-ND	\$27
10	Vacuum grease	Apiezon N	\$200
11	Heat paste	Artic Silver 5	\$5
12	Cylindrical lens	Thorlabs LJ182L1-B	\$85
13	AR window (2)	Thorlabs WG41050-B	\$114 ea
14	Iris	Thorlabs ID15	\$43
15	Faraday isolator (3)	Conoptics Model 712B	\$1985 ea
16	Single-mode fiber	Thorlabs P3-780A-FC-2	\$108
17	Fiberport	Thorlabs PAF-X-11-B	\$470
18	Shutter	Vincent Associates Uniblitz DSS10B1T0	\$420
19	Temperature controller	Wavelength Electronics WTC3243	\$97
		Wavelength Electronics WTC3293	\$150
		Custom design <sup>36</sup>	\$840
20	Gold mirrors (4)	Edmund Optics N45-606	\$68 ea
21	Photodiode	Hamamatsu S1336-18BK	\$19

becomes slightly divergent. The astigmatism is slightly different for different TA currents probably because of slight changes in the refractive index owing to differences in local thermal gradients in the gain medium at the different currents.

## VII. CONCLUSIONS

We have presented a user-manual-style description of how to build a cost-effective, fail-safe TA system suitable for a variety of optics experiments. Prices and vendor information are included in Table II.

## ACKNOWLEDGMENTS

The Miami University group would like to thank Michael Eldridge (former Instrument Maker, Physics Department) for machining their TA components, Lynn Johnson and Michael Weeks in the Instrumentation Laboratory for designing and implementing the electronic circuits to drive their TA system, and Diane Beamer for help with preparing some of the figures. S.B. gratefully acknowledges financial support from the Petroleum Research Fund. D.A.S. acknowledges support from the National Science Foundation. The Wisconsin group acknowledges support from the Air Force Office of Scientific Research and the National Science Foundation. The Miami co-authors wish to acknowledge Professor Georg Raithel for helpful discussions.

<sup>a)</sup>Electronic mail: balis@miamioh.edu

- <sup>1</sup>C. E. Wieman and L. Hollberg, "Using diode lasers for atomic physics," *Rev. Sci. Instrum.* **62**, 1–20 (1991).
- <sup>2</sup>K. B. MacAdam, A. Steinbach, and C. Wieman, "A narrow-band tunable diode laser system with grating feedback, and a saturated absorption spectrometer for Cs and Rb," *Am. J. Phys.* **60**, 1098–1111 (1992).
- <sup>3</sup>A. S. Arnold, J. S. Wilson, and M. G. Boshier, "A simple extended-cavity diode laser," *Rev. Sci. Instrum.* **69**, 1236–1239 (1998) and references therein.
- <sup>4</sup>C. E. Wieman, G. Flowers, and S. L. Gilbert, "Inexpensive laser cooling and trapping experiment for undergraduate laboratories," *Am. J. Phys.* **63**(4), 317–330 (1995).
- <sup>5</sup>A. S. Mellish and A. C. Wilson, "A simple laser cooling and trapping apparatus for undergraduate laboratories," *Am. J. Phys.* **70**, 965–971 (2002).
- <sup>6</sup>P. Feng and T. Walker, "Inexpensive diode laser microwave modulation for atom trapping," *Am. J. Phys.* **63**, 905–908 (1995).
- <sup>7</sup>Atom Trapping laboratory experiment, <[http://labs.physics.berkeley.edu/mediawiki/index.php/Main\\_Page](http://labs.physics.berkeley.edu/mediawiki/index.php/Main_Page)>, and references therein.
- <sup>8</sup>Laser Cooling advanced laboratory experiment, <<http://www.colorado.edu/physics/phys3340>>.
- <sup>9</sup>N. Belcher, E. Mikhailov, and I. Novikova, "Atomic clocks and coherent population trapping: Experiments for undergraduate laboratories," *Am. J. Phys.* **77**, 988–998 (2009).
- <sup>10</sup>A. J. Olson and S. K. Mayer, "Electromagnetically induced transparency in rubidium," *Am. J. Phys.* **77**, 116–119 (2009).
- <sup>11</sup>D. W. Preston, "Doppler-free saturated absorption: Laser spectroscopy," *Am. J. Phys.* **64**, 1432–1436 (1996).
- <sup>12</sup>D. Budker, D. J. Orlando, and V. Yashchuk, "Nonlinear laser spectroscopy and magneto-optics," *Am. J. Phys.* **67**, 584–592 (1999).
- <sup>13</sup>D. A. Smith and I. G. Hughes, "The role of hyperfine pumping in multilevel systems exhibiting saturated absorption," *Am. J. Phys.* **72**, 631–637 (2004).
- <sup>14</sup>A. J. Olson, E. J. Carlson, and S. K. Mayer, "Two-photon spectroscopy of rubidium using a grating-feedback diode laser," *Am. J. Phys.* **74**, 218–223 (2006).
- <sup>15</sup>J. D. Kleykamp, A. J. Hachtel, D. G. Kane, M. D. Marchall, N. J. Souther, P. K. Harnish, and S. Bali, "Measurement of sub-natural linewidth AC Stark shifts in cold atoms: An experiment for an advanced undergraduate laboratory," *Am. J. Phys.* **79**, 1211–1217 (2011).

- <sup>16</sup>A. J. Hachtel, J. D. Kleykamp, D. G. Kane, M. D. Marshall, B. W. Worth, J. T. Barkeloo, J. C. B. Kangara, J. C. Camenisch, M. C. Gillette, and S. Bali, "An undergraduate lab on measurement of radiative broadening in atomic vapor," *Am. J. Phys.* **80**, 740–743 (2012); Erratum, *ibid.*, **81**, 471 (2013).
- <sup>17</sup>Y. Xiong, S. Murphy, M. L. Carlsten, and K. Repasky, "Design and characteristics of a tapered amplifier diode system by seeding with continuous-wave and mode-locked external cavity diode laser," *Opt. Eng.* **45**(12), 124205-1–5 (2006).
- <sup>18</sup>A. C. Wilson, J. C. Sharpe, C. R. McKenzie, P. J. Manson, and D. M. Warrington, "Narrow-linewidth master-oscillator power amplifier based on a semiconductor tapered amplifier," *Appl. Opt.* **37**, 4871–4875 (1998).
- <sup>19</sup>See, for instance, T. Brzozowski, M. Brzozowska, J. Zachorowski, M. Zawada, and W. Gawlik, "Probe spectroscopy in an operating magneto-optical trap: The role of Raman transitions between discrete and continuum atomic states," *Phys. Rev. A* **71**, 013401-1–9 (2005).
- <sup>20</sup>Matthias Fuchs, M.S. thesis, University of Oregon, Eugene (2006).
- <sup>21</sup>S. S. Sane, S. Bennetts, J. E. Debs, C. C. N. Kuhn, D. G. McDonald, P. A. Altin, J. D. Close, and N. P. Robins, "11 W narrow linewidth laser source at 780 nm for laser cooling and manipulation of Rubidium," e-print [arXiv:1202.2657v1 \[physics.atom-ph\]](https://arxiv.org/abs/1202.2657v1).
- <sup>22</sup>R. J. Thompson, M. Tu, D. C. Aveline, N. Lundblad, and L. Maleki, "High power single frequency 780nm laser source from frequency doubling of a seeded fiber amplifier in a cascade of PPLN crystals," *Opt. Exp.* **11**, 1709–1713 (2003).
- <sup>23</sup>mW fiber laser at 780 nm, see Thorlabs catalog.
- <sup>24</sup>R. A. Nymann, G. Varoquaux, B. Villier, D. Sacchet, F. Moron, Y. LeCoq, A. Aspect, and P. Bouyer, "Tapered-amplifier antireflection-coated laser diodes for potassium and rubidium atomic-physics experiments," *Rev. Sci. Instrum.* **77**, 033105-1–7 (2006).
- <sup>25</sup>Commercial TA devices can be found at <<http://www.toptica.com>>, <<http://www.sacher-laser.com>>, <<http://www.dilas.com>>, or <<http://www.m2k-laser.de>>.
- <sup>26</sup>See Appendix A in Nicholas Proite, PhD thesis, Univ. of Wisconsin-Madison (2011).
- <sup>27</sup>E. C. Cook, P. J. Martin, T. L. Brown-Heft, J. C. Garman, and D. A. Steck, "High-passive-stability diode-laser design for use in atomic-physics experiments," *Rev. Sci. Instrum.* **83**, 043101-1–9 (2012).
- <sup>28</sup>J. N. Walpole, "Semiconductor amplifiers and lasers with tapered gain regions," *Opt. Quantum Electron.* **28**, 623–645 (1996).
- <sup>29</sup>M. T. Kelemen, J. Weber, S. Kallenbach, C. Pfahler, M. Mikulla, and G. Weimann, *Proc. SPIE* **5452**, 233–243 (2004).
- <sup>30</sup>Latitude Corp., 1003 American Way, Verona, <<http://www.latitudecorp.com>>.
- <sup>31</sup>B. E. Unks, N. A. Proite, and D. D. Yavuz, "Generation of high-power laser light with Gigahertz splitting," *Rev. Sci. Instrum.* **78**, 083108-1–4 (2007).
- <sup>32</sup>"Application Note: Alignment of a DFB MOPA System with DFB TPA Configuration," Rev. 2.0, Eagleyard Photonics, available at <<http://www.eagleyard.com/en/support/application-notes>>.
- <sup>33</sup>D. Voigt, E. C. Schilder, R. J. C. Spreeuw, and H. B. van Linden van den Heuvel, "Characterization of a high-power tapered semiconductor amplifier system," *Appl. Phys. B* **72**, 279–284 (2001).
- <sup>34</sup>J. J. Thorn, E. A. Schoene, T. Li, and D. A. Steck, "Dynamics of cold atoms crossing a one-way barrier," *Phys. Rev. A* **79**, 063402-1–19 (2009); Jeremy J. Thorn, Elizabeth A. Schoene, Tao Li, and Daniel A. Steck, "Dynamics of cold atoms crossing a one-way barrier," *Phys. Rev. Lett.* **100**, 240407-1–4 (2008).
- <sup>35</sup>K. L. Corwin, S. J. M. Kuppens, D. Cho, and C. E. Wieman, "Spin-polarized atoms in a circularly polarized optical dipole trap," *Phys. Rev. Lett.* **83**, 1311–1314 (1999).
- <sup>36</sup>More detailed information on our TA control electronics is available at <[http://atomoptics.uoregon.edu/ta\\_circuit](http://atomoptics.uoregon.edu/ta_circuit)>.
- <sup>37</sup>One of us (DAS) has observed this instantaneous damage. A nominally "full-power" seed beam (as inferred from the TA gain and output-power specifications from the manufacturer) caused catastrophic damage to the input facet of a TA chip. After replacing the chip, we settled on a much smaller seed power than we used in this first attempt.
- <sup>38</sup>C. D. Decker, "Accident victim's view," *Laser Focus* Aug. 1977, p. 6.