Laser Reference Guide

Lawerence Berkeley National Laboratory

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A U.S. Department of Energy National Laboratory Operated by the University of California

Laser Reference Guide

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Forward

The laser optics lab is an exciting place to work, but it has also been the scene of many laser accidents. The majority occur during beam or optics manipulations. The goal of this guide is to draw your attention to a mixture of good practice techniques and hazards from optics and common items found in a laser lab. If you have questions or suggestions, please contact the LBNL Laser Safety Program at (510) 495-2544.

Special thanks to:
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Disclaimer

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Chapter 1: On the Job Training (OJT)

One of the best ways to reduce the chance of a laser injury is through well thought-out on the job training (OJT). OJT is a mixture of instructions, observations and supervised activities. Because of the individual nature of the training, the duration and breath of the training will be different.

Contact the Ken Barat, LBNL Laser Safety Officer (LSO) for questions about this guide or about safety practices, (510) 495-2544.

OJT Trainer Responsibility

The Principle Investigator (PI) or designee shall train staff on the hazards of the specific experimental work to be performed. It is critical for the PI to determine the current level of staff competency for those requiring training in order to tailor the training to their needs. Training will include:

1. Locating and mitigating potentially hazardous beams and reflections
2. Identifying all hazards associated with the work
3. The use of all required Personal Protective Equipment (PPE)

For laser applications, OJT needs to include an emphasis on the following core laser safety principals:

- Selecting proper eyewear
- Examining the condition of eyewear
- Alerting others prior to turning on laser
- Alerting others about open beams
- Checking for stray reflections, thoroughly and often
- Blocking stray reflections
- Using various beam detection methods
- Employing controls for different intensity levels, especially those that apply to standard operating procedure or work authorization documents
- Familiarization with equipments
- Communication with others

OJT Trainee Responsibility

This training is meant to be a dialogue between the trainee and the trainer. The trainee should approach the OJT with an open mind, and take the opportunity to ask questions until satisfactory explanations have been provided. OJT may save the trainee from injuring themselves or others, and from damaging equipment.

For the Trainer

The booklet

The trainer should select relevant sections for the trainee and/or use the entire booklet as background material to review.

Two common errors in OJT are (1) Not using a checklist to guide the OJT process, and (2) simplifying OJT to focus on how to use equipment or how to insert samples without addressing safety elements. A checklist provides a consistent structure and helps to ensure that the trainer doesn't forget to cover important steps. The checklist should include safety elements as part of the process.

Training preparation

Preparation is extremely important for delivering OJT. This allows the trainer to have time to identify the behaviors critical to safety and operation, and to determine the best way to break up the learning tasks (smaller pieces rather than overwhelming the trainee with the shot gun approach). If the trainer does not feel qualified or comfortable to perform the OJT, they should get assistance or have a qualified person perform the training. If language is a barrier to communication and understanding, seek assistance.

Instructions

OJT is not a 15 minute or even 1 hour review; OJT is an ONGOING PROCESS which can last from days to months. The length of training depends on the complexity of the work to be covered and how often the person performs the task. With proper preparation the trainee has an action plan. For those who are already knowledgeable and skilled the trainer can ask the trainee to demonstrate skills in the contexts of the tasks to be learned.

One potential pitfall of OJT is that bad habits could be passed on to a new generation of users. Embrace peer review of training to avoid this error.

Observations

Learning is doing! Through the instruction process, time must be given to ensure that the trainee performs the tasks under direct supervision. Observation should be ONGOING, not just one time. See that tasks are performed in the correct order and manner. Observe safety steps and attitude. Potential observations include:

- If enclosures are to be open or beams to be accessed, does the trainee check that others are wearing laser protective eyewear?
- Is everyone present in the lab given adequate warning of the pending laser status?
- Does the trainee have the correct laser eyewear on?

- Does the trainee know how to hold a reflective sensor card?
- Is the trainee making safety suggestions to you, i.e. remote viewing?

Questions

Encourage a dialogue with the trainee and try to create an atmosphere that allows for questions. Some trainees may be reluctant to ask questions, and/or appear unknowledgeable. For example, in some cultures it is considered rude to ask questions because it could indicate the trainer has done a poor job explaining the material. Set aside time for observations and questions. Ask open ended questions, and ensure that the trainee responds (beyond simple yes or no answers).

Working with others

Working in a laser lab may involve working by one's self or most often working with others. Encourage communication and record keeping. Communication within a group is vital to laser safety. Keeping a record of what has been done and what has changed is often the difference between an accident prone lab and an accident free lab.

Chapter 2: General Considerations

Working with Lasers

Laser work can cause a life changing injury in less than the blink of an eye. Always follow safety rules to protect yourself and others working around you. In laser labs, non-laser hazards also exist, such as electrical shock, bumping ones head against low hanging shelves, and chemical hazards.

Communication

The quote “no man is an island” holds true for work in a laser lab. Communication between staff is extremely important. Your actions affect others who follow you. Document changes and conditions in a research log so others will not be surprised by changes to the system or equipment. Inform lab workers of the types of activities you will be engaged in and any precautions that need to be taken, for example, removal of barriers, need for protective eyewear, venting a chamber, using cryogens, etc.

Groups may choose to communicate through a log book, whiteboard or other means. The key is for all group members to understand and follow the agreed upon method.

Prior to Starting Work

Jewelry removal

Remove all watches, rings, bracelets, earrings and ID badges. These items can reflect light, which can be hazardous. If these items cannot be removed (i.e. a ring), cover it with tape, which will produce a diffuse reflection.

Opening the lab door

There should be no line of sight between the room entrance and optics on the optical table(s). In addition to actual safety precautions, it is also important to reduce the perception that passers-buy are at risk. Perimeter guards, enclosures around the table, and a curtain at the door also reduce the perception of risk to uninformed visitors.

Glass-door shelves on the wall, or laminated posters

Glass in the lab and even laminated posters are possible reflection hazards. They can send reflections to totally unexpected areas. Contain the beam to the optical table to avoid this hazard.

Workstations

When a computer workstation exists within the lab, laser protective eyewear may need to be removed so one can see the screen. Take steps to make sure the individual working there is protected from any stray reflection sources. Consider setting up a partition, placing a perimeter guard around the workstation, or moving the workstation altogether.

Eyewear storage

Laser protective eyewear needs to be located either outside the laser lab or right inside. This ensures eye protection is accessible without walking through a lab, past the optical hazards. Even with a designated storage area, eyewear sometimes migrates to people's offices or is left on optical tables. Pay attention to where eyewear is kept to avoid this.

Non-beam hazards

Many non-beam hazards also exist in the lab. Here are few common items for your consideration:

- Wires and equipment present electrical hazards.
- Paper viewing cards in beams can burn or char if positioned too close to a focus or left too long in the beam. While the cards rarely catch fire, smoke from burning can damage optics.
- Coaxial cable near the beam path can melt and gives off nasty fumes.
- If wires are disconnected or damaged, electrical pulsers for Pockels cells can be a hazard
- Cryogenic use creates potential hazards and requires the proper Personal Protective Equipment (PPE) such as gloves, face shield and clothing.
- Use caution during flash lamp change out.
- Equipment and wires create tripping hazards. Heavy duty bridges are available to cover wires and hoses. Plastic ones are better than metal bridges, which might have to be grounded. Contact the Laser Safety Officer (LSO) for literature.

Table grounding

All tables that have energized equipment on them and racks that contain energized equipment need to be grounded for your safety and to protect equipment.

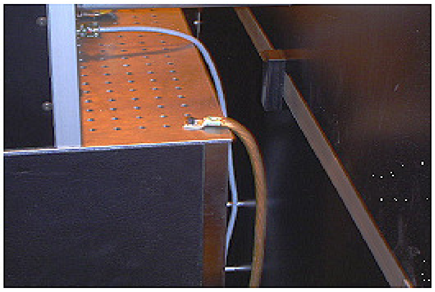


Figure: Grounded table

Oxygen Deficiency

LBNL has developed an oxygen deficiency calculation for laboratories using gases or cryogens. This will tell you if an oxygen sensor or other controls are required in the case of a catastrastic failure of the cryogenic or gas cylinders. Contact Industrial Hygiene for more information.

Tools

Avoid having tools cross the laser beam. Instead, block the beam for the mechanical step, and re-open the beam after removing the tool. For operations like alignment, where having a tool near the beam during operation is unavoidable, move the tool in such a way that the beam remains at normal incidence to the tool. The aligning user should be situated so that any stray reflection cannot hit them. Use non-reflective tools where possible to minimize stray reflections and store tools off the table.

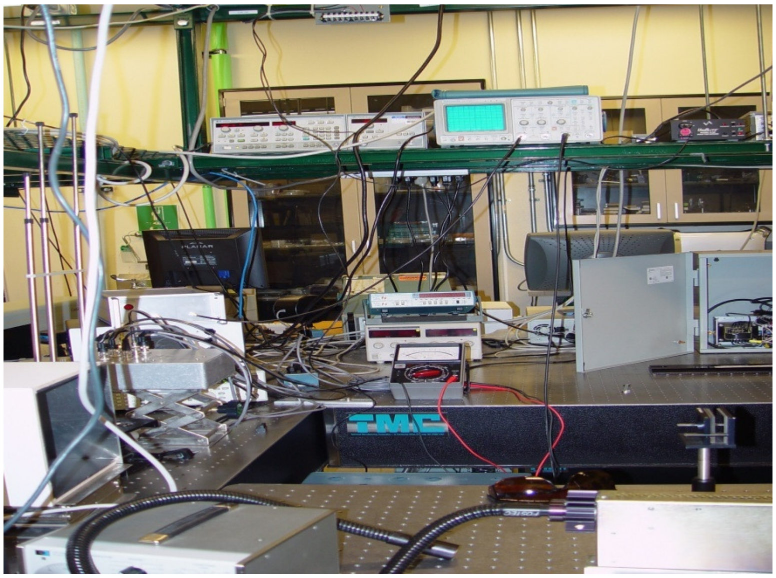
Interlocks/Access/Housings

The majority of room access interlocks need to be turned on in order for the lasers to work. Per LBNL policy, these units need an operational check at least twice a year and are not to be by-passed unless authorized by the LSO. The housings on commercial lasers themselves also have an interlock system. All interlocks should be checked for functionality after any service visits.

The majority of time there is no reason to operate the laser with the housing off.

Wires

Dangling wires can be a combustion source. They can also block your beam path. If you have wires hanging from shelves above the optical table, make sure they are clear of the beam.



Laser Location (human factors)

Experiment and equipment set up can be critical to safety. Think about the following questions: Can you reach optics that need to be moved? Does the work flow smoothly? Can you see monitors? Is remote viewing required to remove you from a hazard or awkward body position?

Your experimental setup should be well-planned to consider research needs and safety. Contact the LSO if you need assistance.

Cleanliness

Take steps to keep your experimental area clean and free from dust, including beam tubes, covered optics, hepa filter applications above optical table, plastic strips hanging around table, and enclosures.

- Avoid fingerprints on coated optics; acid from fingers permanently damages the coating when left on optics for a long time. Clean fingerprints immediately if you cause them.
- Wideband Ti:Sp oscillators are VERY sensitive to dust. Clean the cavity optics and the Ti:Sp crystal periodically. Never let the oscillator performance drop by more than 10%.
- Always use proper optic containers to store optics. If no container is available, wrap optics in lens tissues or temporarily deposit the optics FACE DOWN (on lens tissue layers) on a safe and clean flat surface, away from drop or damage risks.

Labeling of optics

Consider labeling optical mounts with the optics they are holding. This helps you check if the correct optics are where you expect or want them.

For any new optics received, mark the edge using a pencil or a permanent fine marker. Once the optic is removed or placed you will know what you have, as they can look similar. Label optics indicating, at a minimum:

a) Reflective/polished surface using an arrow (e.g. >)

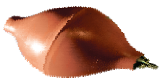
b) Coating parameters (e.g. AR.10 = UV, AR.14 = 532nm, AR.16 = 800nm)

c) Substrate details (e.g. FS, BK7, 0dur)

d) Other key details, as appropriate (e.g. s/n, PO#, ref#)

Cleaning Optics

- Only use a hand blower to clean optics. NEVER use dust blower cans. When tilted, the can sprays extremely cold liquid on optics and coatings, and it can also lift up dust from the bench top.



- For relatively small optics and mirrors, cleaning procedures vary. Refer to vendor documentation for best suggestions.

  Two common methods for cleaning small optics are:

  - Drag and Drop Method: http://www.coherent.com/Service/index.cfm?fuseaction=forms.page&pageID=38
  - The Hemostat and Lens Tissue Method http://www.coherent.com/Service/index.cfm?fuseaction=Forms.page&PageID=40

- NEVER CLEAN:

  - When laser beam is present
  - With the same lens tissue twice—always use fresh clean lens tissue
  - Large optics using small optics cleaning procedure. Multiple cleaning traces on large optics will lead to residue lines and possible beam profile issues
  - Diffraction gratings (unless using specific procedures)
  - Uncoated harmonic crystals (unless specified otherwise)

- Refresh your cleaning solvent bottle with new solvent every 1-2 months to ensure contamination free cleaning. 532nm AR coatings are particularly difficult to clean using contaminated solvent.

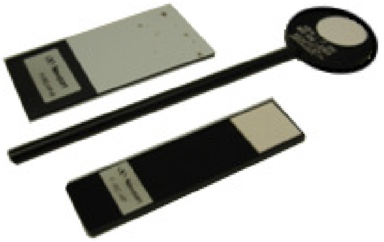
Chapter 3: Laser Safety Tools

This chapter focuses on tools that can help you be safe when working with lasers.

Indirect Laser Beam Viewing Tools

Laminated IR-viewing cards

The IR viewing card is designed to allow you to see invisible infrared beams. The majority of IR cards found in laser labs are covered with a plastic film to protect the fluorescent material from oxidation. Because they are often held by hand (possibly unsteadily) this can yield a specular reflector. One suggestion is to peel off the coating or use non-laminated cards. Sensor cards can also be found for ultra violet wavelengths, but are less commonly used. ALWAYS tilt the IR sensor card DOWN so that any reflection is directed away from you and anyone else standing in the area.



Sensor cards are not invincible. They present a fire hazard when burned through. Know your expected irradiance. As a general rule, NEVER leave an IR sensor card or any combustible card/plastic/beam blocks in a beam path unsupervised for an extended period of time.

IR Viewers

IR viewers have been a stable in laser labs for decades. There are two major safety concerns with IR viewers: (1) It can be difficult to use an IR viewer with protective eyewear and (2) the IR viewer can be mistaken for eye protection. Neither of these is a safe practice.

Depending on your eyewear the greenish view through a viewer may make it difficult to view the beam, prompting you to take your eyewear off. Although direct beam will not transmit through an IR viewer, a direct beam viewing through an IR viewer will likely have a blinding effect to the eye by overwhelming the sensor, as well as risking damaging the IR viewer.

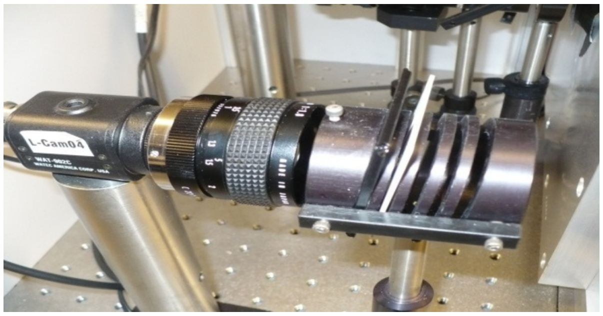
A superior, though more laborious, alternative is remote viewing with an IR camera, which removes you from standing in front of the beam or reflection.

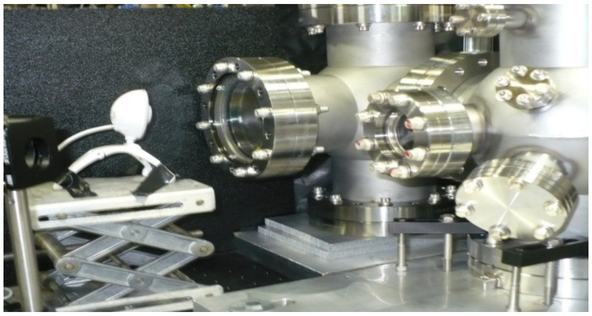
Remote viewing options

The majority of remote IR viewing systems that include a camera and monitor (similar to digital camera screen) are home-made systems. Commercial versions may be available in the future. At this time the LSO can provide you with information about making your own system.

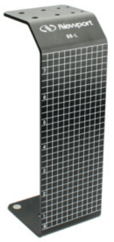
CCD/web cam

Home-made systems come in a number of varieties and can use web cameras and iPhone cameras to view visible and NIR beams. These devices promote safety because they remove users from the optical table. Remote viewers can be combined with motorized mounts to make alignment a simple activity.



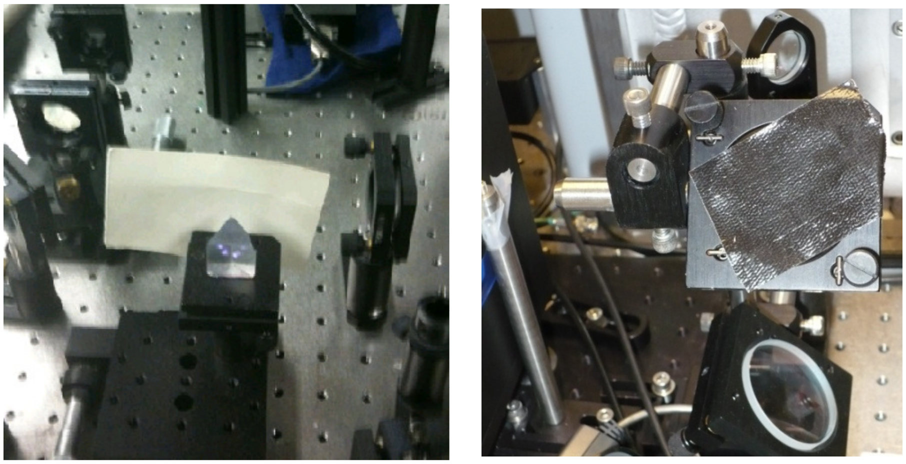


Beam Blocks



Many items can act as a beam block, though not all were designed to be. Note cards or post-it notes are inexpensive and on hand, and are commonly used as blocks for optic transmission, diffuse reflections, or primary beams.

These paper products can slowly (or not so slowly) burn through if placed at a point where the beam is intense enough. Pay attention to these ad-hoc beam blocks. If they burn through, they could cause an experimental or safety issue if they cease to block the intended beam.



Figures: Ad hoc beam block made from a piece of paper (left) and duct tape (right)

When using cards or paper as TEMPORARY laser shielding, it is essential to know which color to choose in order to avoid laser beam absorption in the card and therefore, risk of burning /heating. Also note that leaving a card as a block in front of an optic may outgas and leave residue on the optics which can ultimately damage the optics if not cleaned properly.

Unsecured Beam Blocks

The majority of beam blocks (metal) are designed to be secured to the optical table, either with a screw, magnetic base or just their weight. Bent sheet metal or folded cardboard can also be used as a block, but may be easily moved out of position or knocked down because it cannot be secured.

Figure: Unsecured beam block perched on the edge of a laser table

The range and size of protection of beam blocks vary. Contact the LSO for information on commercial units.

Beam Dumps

Beam dumps are different than beam blocks because they capture diverted beams. A beam dump can be considered a heat sink. These are either air or water cooled depending on the amount of energy they are indented to deal with.

Polycarbonate Sheets

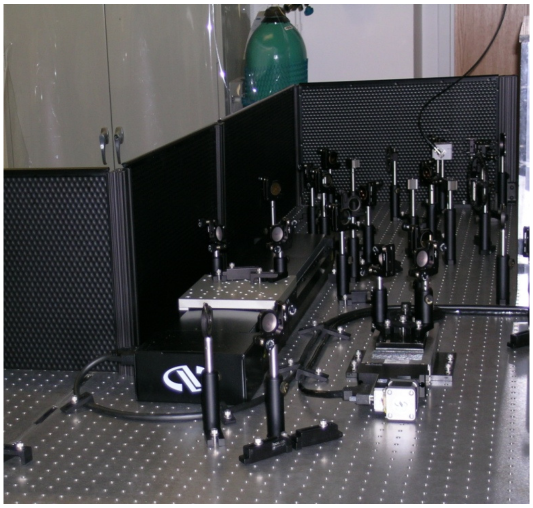
Polycarbonate sheets can be used as beam blocks and perimeter guards for UV & Carbon Dioxide wavelengths. These give a clear view of the optics on the table.

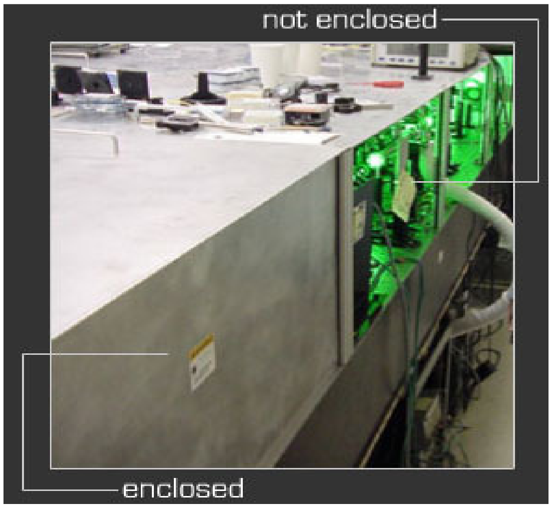
Plastic Laser Enclosures

Plastic/acrylic laser enclosures that are rated for certain wavelengths and provide a tested optical density (filtration) can be expensive. Most commonly people buy plastic or acrylic sheets from a supply catalog. Depending on the wavelengths being used this is effective containment for scatter or direct beams.

One of the better designs uses a diffuse film on the INTERIOR surface of the enclosure. You can self-test the materials using a spectrometer and/or power meter. The choice of a proper plastic laser enclosure should never be based just on a visual or “feel good” evaluation. Remember to reconfirm that the enclosure’s containment is suitable as you add new wavelengths to a system.

Metal Laser Enclosures





Left Figure: Metal barrier with diffuse surface to contain reflections
Right Figure: Beam path with both enclosed and exposed sections

While metal laser enclosures address the drawbacks of plastic enclosures, they have their own limitations. The coating of a metal enclosure can burn off. Also, when choosing a metal enclosure, make sure the enclosure will not present a specular reflection source.

Laser curtains

Laser curtain are most commonly used to segregate areas of a laser lab. A curtain commonly marks a zone that requires eyewear from one that does not. Do not use floor-to-ceiling laser curtains unless required for lighting conditions. At ceiling height curtains interfere with the fire suppression sprinklers.

Laser curtains can be certified laser curtains, or in some cases opaque welding curtains or metal curtains are used. Contact the LSO to discuss options. There is a considerable price and performance difference between the different options.

Laser Protective Eyewear

Laser protective eyewear is one last line of defense against laser beam exposure. See Appendix B: Eyewear Selection for more detailed information.

Chapter 4: Wavelength Specific Information and Best Practices

UV 200-266 nm beams

Always wear gloves and long sleeves when aligning UV beams to prevent skin exposure. Skin exposure to lasers could lead to possible skin cancer.

- Use CaF_2 substrate for transmissive optics to prevent nonlinear absorption of red fluorescence with high energy, high power UV beams. Red fluorescence ultimately leads to permanent increase of optical transmission loss (brownish coloring).
- Use fused Silica substrate for reflective optics to reduce coating absorption.
- Aluminum coated gratings, even when coated against oxidation, will degrade rapidly when used for UV high energy beams.
- Remember: the lower the wavelength, the smaller the spot size for a given focal length lens/optic. When looking at beam profile on camera, ensure ALL harmonics are filtered out.

Ultrafast OPA beams (166nm-20um)

- For NIR and IR beams, liquid crystals papers (from Thorlabs or Edmunds Optics) can be very helpful to detect the position of far IR beams, outside range of conventional beam viewers
- Don’t be fooled by harmonic components

800 nm beams

No wavelength has been involved in more LASER EYE INJURIES in the past 10 years as the Ti:sapphire 750-850 nm beam**.** The eyes lack perception of this wavelength band—less than 1% of these photons are perceived by the eye. A user may see a faint dot giving the false impression of low power.

- For alignment of an 800nm compressed beam (peak power), you can use a white bleached business cards (while wearing eyewear) to see the SHG (blue color) beam on the card.
- When aligning compressed or very intense large diameter beams use the SHG on a white business card to center the beam on alignment irises. Center the beam on the iris looking at the throughput beam (symmetrically clipped SHG blue beam).
- When aligning small diameter beams, use an IR viewer to look at the concentric beam around the hole of the iris or use an orange card looking at the throughput beam.
- Beware of the secondary lasing cavity caused by back reflections when introducing reflective surfaces in a pumped amplifier with flat (not Brewster) Ti:S crystals (valid for other type of gain medium).
- ALWAYS use a MINIMUM number of mirrors to realign an amplifier.
- White thin ceramic plates are useful for finding the beam. They are safe with both low and high power beams.

Case Study A

A 26 year old male student aligned optics in a university chemistry research lab. He used a "chirped pulse" Titanium-Sapphire laser operating at 815 nm with 1.2 mJ pulse energy at 1 KHz. Each pulse was about 200 picoseconds. The student was not wearing protective eyewear.

The laser beam backscattered off the REAR SIDE of a mirror (about 1% of total) and caused a foveal retinal lesion with hemorrhage and blind spot in central vision.

A retinal eye exam was done and confirmed the laser damage. Protective eyewear could have prevented the injury.

Case Study B

A postdoctoral employee received an eye exposure to spectral radiation from an 800 nm Class 4 laser beam. The extremely short pulse (100 fs) caused a 100-micron-diameter burn in the employee's retina. The accident occurred shortly after a mirror was removed from its mount and replaced with a corner cube during a realignment procedure. Although the beam had been blocked during several previous steps in the alignment, it was not blocked in this case. The employee was exposed to laser radiation from the corner cube mount when he leaned down to check the height of the mount.

Neither the employee that was injured nor another employee that was working on the alignment was wearing the appropriate laser eye protection. The researcher may have underestimated the hazard because the visible portion of the 800 nm beam only represented 1-2% of the beam.

Flash Lamp YAG high energy 532 nm beams

- Always align beams at LOW POWER (detune the QSW timing instead of LAMP timing to reduce green).
- Always verify the YAG beam profile PRIOR to sending it to a Ti:S crystal or other crystals. Hot spots will likely cause severe irreversible damages to the crystal lattice or the crystal coating. Dummy testing on Sapphire crystals can be an inexpensive way to ensure integrity of the Ti:S when pumped.
- White ceramic is the preferred permanent beam block material for YAG energetic beams.
- Practical “short term” beam blocks for YAG 10Hz green beam are white packing foams, which diffuse the green powerful beams temporarily during specific and approved alignment procedures.
- DO NOT USE black anodized metal surface as beam blocks. Photographic “burn paper” or non-developed black photo paper can be used to visualize the beam quality. Make sure to put the paper into a clear plastic bag to avoid debris blasts and avoid over-exposure. Beware of plastic bag laser reflections. Using back burns can help maintain information contained in the burn mark.

YAG/YLF high power 532/527 nm beams

- Wear LBNL approved alignment goggles that allow you to see a faint green beam. Goggles are very useful for avoiding burns during alignment.
- Remember that high power high rep rate beams will ablate black anodization of most beam blocks, leaving residues onto optics nearby.

Chapter 5: Precautions: Optics on Your Table

Optics can be used in your setup for a variety of functions: changing the beam’s polarization, focusing the beam, splitting the beam, changing its wavelength, expanding the beam, etc. During any of these operations, the optics can also be the source of unintended reflections and cause an incident. Checking for stray reflections is a crucial and ongoing task for users. Users should be checking optic to optic and often.

General items

Please pay special attention to the following items which have been involved in past injuries at Berkeley Lab.

Rotating elements

Rotating elements that reflect/transmit at angles (e.g. Glan-Thompson prisms or Berek's compensator) have been involved in more laser eye injuries than any other type of optic. Reflections often come from the unblocked window. Take special care with rotating elements to identify potential hazards as the beam is in operation.

Back reflections (Ghost Reflections)

Ghost /Back reflections are often overlooked. Back reflections from even an extremely low power beam can cause an eye hazard or damage laser equipment.

For example, doubling/wave mixing crystals often get tilted to optimize efficiency, which causes the stray back-reflection to also be moved. Anticipate potential back reflections during set up and work to prevent them.

Beam direction

The majority of laser beams on the optical table are following a horizontal path. However, it is not uncommon to have a periscope setup sending beams vertically. All vertical beams need to have a beam stop or shroud covering the receiving optic. It is extremely important to check vertical beams optics for stray reflections.

When setting up an optical trap on an inverted microscope or doing TIRF microscopy, it is easy to forget a vertical beam. Consider trying to place a fixed beam block below eye height to trap the beam and to serve as a reminder.

Has an optic moved?

Intentional repositioning of an optic from a previous setup needs to be communicated to others prior to start of work. This can be done through a log book; whiteboard or other means the group decides on, as described in the Communication section of Chapter 2. It never hurts to check items like flip mirrors to see that they are in the correct orientation prior to starting work with live laser beam.

Securing optics

It is to your advantage to secure your optics to the optical table and to the optical mount. If you manage to knock over an optic, RESIST the temptation to pick it right back up. Repositioning a shiny block could send reflections off in any direction. FIRST block the laser beam before reaching for or moving an optic.

Keeping optics clean

Nothing will end the useful life of optics faster than dirt from particles and fingerprints. Dirt can cause scratches and pits on the optics when it is vaporized off by the beam. When dirt absorbs heat from the laser beam, it can damage optical coatings, rendering the optics essentially useless. Dirty optics can also cause severe laser damage, as well as cause very bright scattering which can be harmful to the eyes.

Transporting the beam a “long distance”

The longer a beam, the more dangerous reflection can become. For example, a 12’ laser beam with just a small angle of reflection could easily end up at eye level once it has traveled 12’ back to the user.

When working with a long beam, tilt the optical component so that the reflection goes into some other optical mount. ALWAYS try to track back reflections and ensure the beams are reflected downwards to avoid eye exposures. When possible, long beams should be avoided because of the greater risk they pose. If necessary, try to enclose the beam in a beam tube.

Dropping and picking up items from the floor

A good practice is to turn your back to the optical table when bending down to pick up something from the floor. Alternatively, block your eye with your hand to avoid a direct line of sight with the optical table.

Optical Mounts

Optical mounts are not designed to yield diffuse reflections—most are either a flat black which is a great IR reflector or a shiny AL color. Please remember mounts can send beams off in any direction if struck. Having a laser beam hitting optical mounts proposes a safety and stability risk. Frequent high power beam exposure will cycle the optical mount temperature, and ultimately could loosen the optics which could fall or stir in an unsafe manner.

Chapter 6: Know your optics

Know the functionality and cautions of your optics. Review the list below for reference.

Polarizers

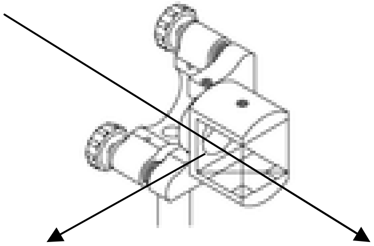
(AKA Laser User Enemy Number One)

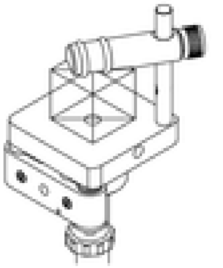
Polarizers are rotating elements that reflect/transmit at angles. These devices have been involved in more laser eye injuries than any other type of optic. A reflected/angled/rejected (ordinary) beam will sweep out a cone. It can come off any beam-stop and out of the plane of the table during adjustment of the device. They are extremely dangerous. Users must be very careful to trap the rejected beam before the device with a tube, a beam block or a cover window.

Typical polarizers found in a laser lab are:

- Glan Thompson Polarizers
- Glan Thompson linear polarizers
- Birefringent polarizers
- Polarizing beam splitter cubes
- Thin metal film polarizers
- Glan laser calcite polarizers
- Berek's compensators

Some polarizers can also reflect an additional beam back out the entrance (or exit) face at an angle. Be sure to understand the specific model prior to sending any beam into it. NEVER send the full power beam into a polarizer before ensuring proper alignment has been achieved.





Beam Splitter

A beam splitter is an optical device which can split an incident light beam into two or more beams, which may or may not have the same optical power.

Polarizing Cube-Beam Splitters

Polarizing Cube-Beam splitters separate polarization components of an incident beam into two highly polarized output beams separated by a 90-degree angle. They usually come in two varieties, broadband and laser line polarizing cubes. Anytime a beam is split, the users must take precautions for both beams.

Dichroic Elements

NOTE: Dichroic elements transmit 50% of unpolarized input light.

From the Encyclopedia of Laser Physics and Technology:

> Dielectric beam splitters can also have a strongly wavelength-dependent reflectivity. This can be used for dichroic beam splitters (dichroic mirrors), which can separate spectral components of a beam. For example, such a device may be used after a frequency doubler for separating the harmonic beam from residual pump light. The separation may occur based on the difference in wavelength or polarization.

Microscope comment

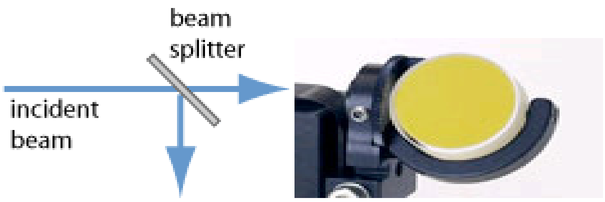
Dichroics used in fluorescence microscopy are not typically good reflectors and pass a lot of beam. 0.5% transmission is typical, though it could be more if the angle is not exactly 45°. They require a separate beam-stop.

This can be an especially serious problem for 2-photon microscopy, since the transmitted beam is near 800nm and practically invisible at powers that are still quite hazardous since pulses are femtosecond.

Types of Beam Splitters

The following information on dielectric mirrors, beam splitter cubes, fiber-optic beam splitters, and other types of splitters comes from the Encyclopedia of Laser Physics and Technology.

Dielectric Mirrors

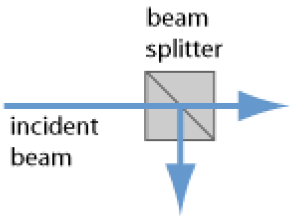


The image above shows a partially reflecting mirror, used as a beam splitter.

Any partially reflecting mirror can be used for splitting light beams. The angle of incidence determines the angular separation of the output beams and influences the characteristics of the beam splitter. A 45° angle (as s above) is often convenient, but the angle can also have other values. A wide range of power splitting ratios can be achieved via different designs of the dielectric coating.

In general, the reflectivity of a dichroic mirror depends on the polarization state of the beam. Such a device can be optimized to function as a THIN FILM POLARIZER. In some wavelength ranges a beam with a certain polarization can be nearly totally reflected, while a beam with different polarization is largely transmitted. On the other hand, it is also possible to optimize for a minimized polarization dependence to obtain a NON-POLARIZING BEAM SPLITTER. This is most easily achieved for near normal incidence.

Beam Splitter Cubes



Many beam splitters have the form of a cube, where the beam separation occurs at an interface within the cube (shown above). Such a cube is often made of two triangular glass prisms which are glued together with some transparent resin or cement. The thickness of that layer can be used to adjust the power splitting ratio for a given wavelength.

Birefringent crystalline media can be used in the splitter cube. This allows for construction of various types of polarizing beam splitter cubes such as Wollaston prisms and Nomarski prisms, where the two output beams emerge from the same face, with a typical angle between 15° and 45°. The Glan–Thompson prism and the Nicol prism (which actually has a rhombohedral form) are two more examples of this type of beam splitter.

It is also possible to use a multilayer coating within a cube. This further expands the possible device characteristics, such as operation bandwidth or polarizing properties.

In addition to simple light beams, beam splitter cubes can be used with beams carrying images, like those found in various types of cameras and projectors.

Fiber-optic Beam Splitters

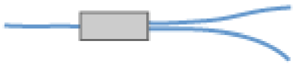


Figure: A fiber-optic beam splitter with a single input port and two output ports.

Various types of fiber couplers can be used as fiber-optic beam splitters. Such a device can be made by fusion-combining fibers, and may have two or more output ports. In bulk devices, the splitting ratio may or may not strongly depend on the wavelength and polarization of the input.

Fiber-optic splitters are required for fiber-optic interferometers, as used in optical coherence tomography. Splitters with many outputs are required for the distribution of data from a single source to many subscribers in a fiber-optic network, e.g. for cable-TV.

Other

Other types of beam splitters are:

- Metallic mirrors (e.g. half-silvered mirrors), where the metallic coating is made thin enough to obtain partial reflectance
- Pellicles, which are thin membranes, sometimes used in cameras
- Micro-optic beam splitters, often used for generating multiple output beams
- Waveguide beam splitters, used in photonic integrated circuits

Periscopes

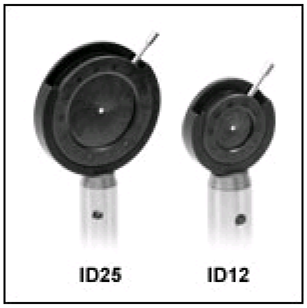
With a periscope, beams can be directed upward or downward. Either direction can be the source of misaligned reflections. Use shields and awareness labels to help prevent an accident.

Case History

An experimental setup included a 20 terawatt Ti:Sapphire amplifier, 800nm, 10Hz, 250ps, 50-100mJ, beam alignment thru a polarization rotator periscope. The beam was sent across the room to a vacuum compressor.

The periscope was aligned only by visual inspection. Once the beam was turned on, the last mirror sent the beam up to eye level and hit the eye of the laser engineer who was not wearing his laser protective eyewear.

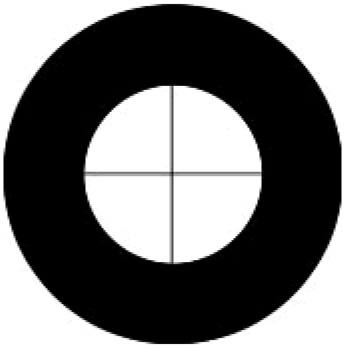
Iris



The iris is an extremely useful alignment aid. The following comes from the Newport product website:

> Iris Diaphragms provide continuously variable apertures for applications including setting the numerical aperture of a lens, controlling or measuring the intensity of a diffuse beam, or approximating beam diameters. They may also be used as baffles to reduce spurious reflections and scattered light.
>
> Designed for smooth adjustment and the best possible aperture shape, each iris consists of an array of curved, spring-steel leaves whose orientation is determined by the relative position of two rings. A pin handle on the inner ring lets you adjust the aperture without risk of obstructing the beam path.

Cross Wires (Cross Hairs)

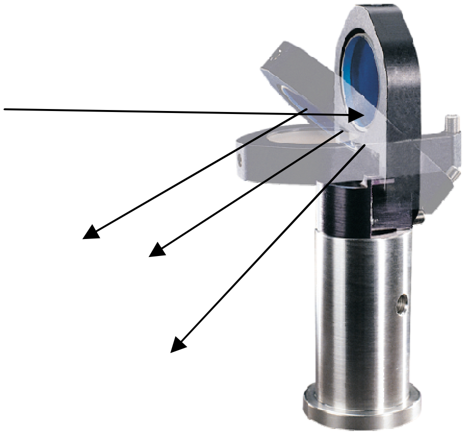


From the Photonics Buyer's Guide:

Fine lines, wires or threads used in the focal plane of many optical instruments to point out and locate particular objects in the field of view. They were formerly made from a single strand of spider web; later, fine-drawn threads of glass, quartz, silk, or plastic were substituted. Today it is more common to employ etched reticle lines on a glass plate. These can be illuminated from the side and they act in every way as a true cross wire, with the advantage of greatly increased rigidity and permanence.

Flip Mirror

ALWAYS consider reflected beam DURING flipping motion. NEVER flip while a laser beam is present!



The role of the flip mirror is to allow partial sharing of optics of a beam path. The mirror surface may not be perfectly perpendicular to the optical table due to machining imperfections, causing the reflected beam to deviate from being parallel to the table.

Mirrors

Dichroic laser mirrors

The angle of the mirror greatly affects the transmission of the beam, described with Optical Density. (See the Optical Density section for more information). Often the 0° interference mirrors are nearly perfect (OD6). However, the 45° ones are barely OD3. Watch out for some transmitted beam when using a high-power (e.g. regeneratively amplified) system, especially when using these mirrors at an angle with a non-opaque substrate (e.g. mirrors where the back is not ground glass). Even though these mirrors are 99.7% reflecting, the rest of the beam will transmit through the mirror. For a high power pump laser this can be significant: 0.3% of a 90 Watt pump lasers is still 270mW, which can burn skin if focused.

Metallic Mirrors

Metalilic mirrors have a broadband coating that is relatively insensitive to wavelength, angle of incidence, and polarization.

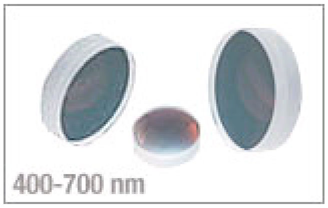
Parabolic Mirrors

In parabolic mirrors, the focal point is displaced from the mechanical axis, usually coated with aluminum or gold.

Diffraction Gratings

A beam bouncing off a grating is split into two or more beams. Typically more than 90% of the power goes into the useful beam, but remaining beam(s) have to be controlled too. For our high power grating stretcher/compressors, these beams typically stay in the horizontal and are easily controlled. Many dye lasers internally have gratings mounted with the diffracted beam going up/down which may cause an added safety concern.

Lens



Lenses may have between 0.25% (AR coated) and ~5% back-reflection (uncoated) from each surface.

Plano convex lenses

Plano convex lens have one flat and one convex surface and are used to converge incident light. They are commonly used in telescopes, collimators, magnifiers, condensers and optical transceivers. They can be made of a wide variety of materials.

Plano convex lenses cause one non-diverging and one diverging beam (possibly first converging through a focus). These can go off into nowhere if not controlled. They're also relatively weak, and hard to find with viewing devices in the glare of the main beam.

Other common lenses include bi-convex, plano concave, and bi-concave lens.

Slits

The use of mounted razor blades in DOE laser labs has contributed to several injuries to laser users, including an injury here at LBNL. In all cases the razor blade was being used as a knife edge in optical measurements. This practice has been going on for years. While this is convenient and affordable, commercial products have been developed to perform the same function safely. Alternatively, a thin dull metal plate in place of a sharp blade may be sufficient for the needed application.

Scanning Slit Measurement

The scanning slit technique is often used on commercial beam profile systems. In this method a detector measures the radiation passing through a narrow slit located between the detector and the laser beam source. The detector response is monitored as the slit is scanned across the beam. The beam diameter is calculated from the distance between the scan locations where the reading has dropped to approximately 36.8% of maximum. The accuracy of this type of measurement relies on the slit width being much smaller than the beam size. The scanning axis can be rotated to measure the beam size on different axes. For a uniform beam profile, the difference in positions on each side of the beam where the laser beam energy declines rapidly is the beam diameter.

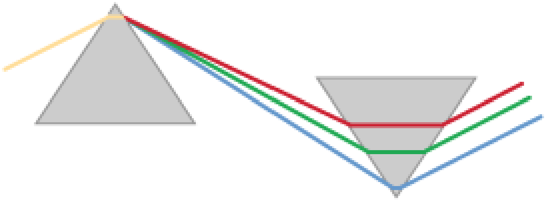
Scanning Knife Edge

This method is similar in principal to the scanning slit method except that a single knife edge is used instead of a slit. The output of the detector is then related to the integral (along one axis) of the irradiance distribution. Assuming a Gaussian beam profile, the knife edge is positioned at the location where 86.5% of the energy is transmitted to the detector and at the location where 13.5% of the energy is transmitted to the detector. The difference in these two positions provides the $1/e^2$ beam diameter. As with the scanning slit for a uniform beam profile, the difference in positions on each side of the beam where the laser beam energy begins to decline and where the beam energy is barely detectable is the beam diameter. Once the $1/e^2$ beam diameter is found, it can be converted to the 1/e beam diameter by dividing by $\sqrt{2}$.

Prisms

Prisms are blocks of optical material whose flat polished sides are arranged to deflect or deviate a beam path. They can also be used to separate states of polarization.

From the Encyclopedia of Laser Physics and Technology:

> Pairs of prisms (typically Brewster-angled) can be used for introducing anomalous chromatic dispersion without introducing significant power losses, e.g. into a laser resonator. A first prism refracts different wavelength components to slightly different angles. A second prism then refracts all components again to let them propagate in parallel directions after that prism (see figure below), but with a wavelength-dependent position (which is sometimes called a *spatial chirp*).
>
> 
>
> **Figure:** A prism pair for spatially dispersing different wavelength components; the prism introduces wavelength-dependent phase changes and chromatic dispersion.

With a second prism pair, or simply by reflecting the beams back through the original prism pair, all wavelength components can later be spatially recombined.

The spatial separation of different wavelength (or frequency) components can be utilized in different ways:

- An optical filter can be realized by inserting a knife edge from one side, attenuating primarily the short- or the long-wavelength components. This can be used. For wavelength tuning of lasers by placing such a prism pair within the laser resonator.
- The material dispersion of prisms can be used to offset anomalous dispersion which arises from the wavelength-dependent optical path lengths of such a dispersive delay line. The overall dispersion can be adjusted by varying the insertion of one or both crystals into the beam. This technique is often used to provide adjustable dispersion compensation in mode-locked lasers (see figure below), for example with soliton mode locking and for dispersive compression (or stretching) of optical pulses.

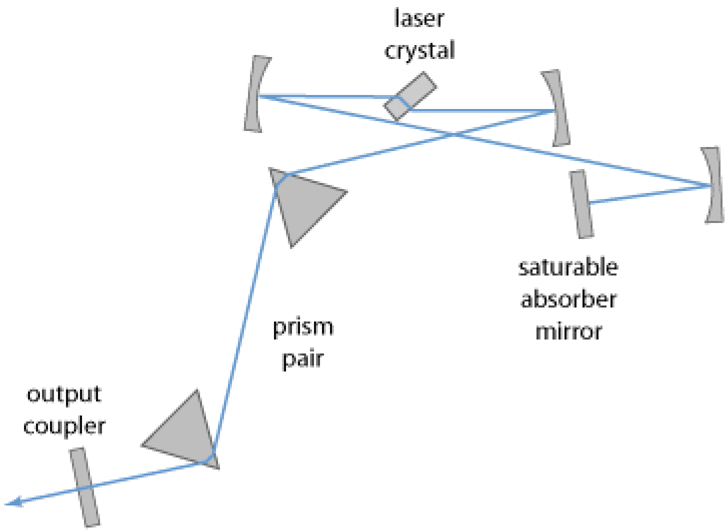


Figure: Resonator setup of a mode-locked laser. A prism pair is used for dispersion compensation. The overall anomalous chromatic dispersion allows for soliton mode locking, and can be adjusted via the prism insertion.

Typical amounts of anomalous dispersion from prism pairs are a few thousand fs2. For larger amounts of dispersion, a pair of diffraction gratings may be required. The attraction of using a prism pair, however, is that anomalous dispersion can be provided without introducing significant losses into a laser resonator.

For the compression of ultrashort pulses in the few-cycle region, prisms with a fairly small apex angle (and anti-reflection coatings) are sometimes used. Such configurations can achieve a lower residual chirp from higher-order dispersion. However, it is often necessary to compensate the higher-order dispersion with other means, for example with additional chirped mirrors.

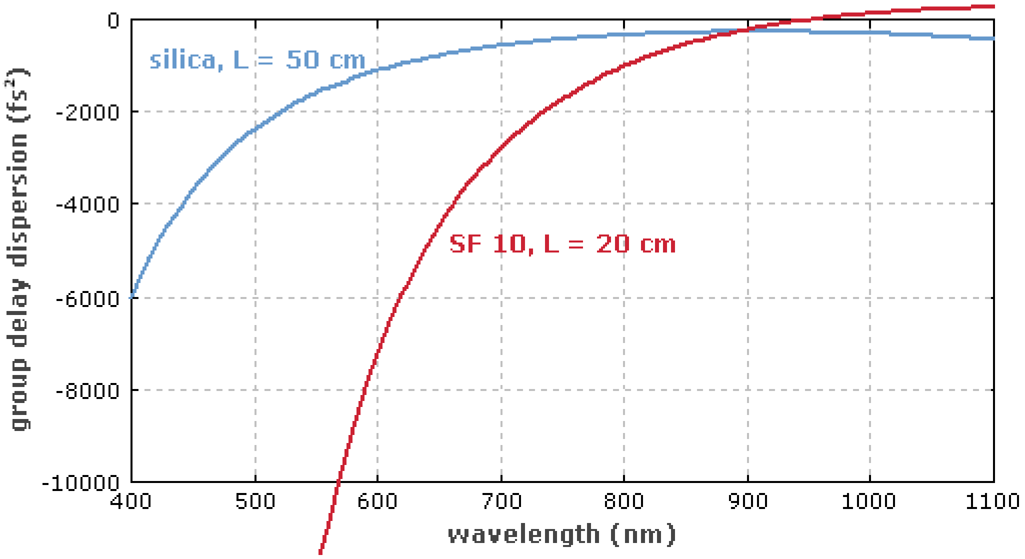


Figure: Group delay dispersion of prism pairs: comparison of a setup with silica prisms, 50 cm spacing, and another one with SF10 prisms, 20 cm spacing. The insertion of the prisms at 800 nm is 2 mm in both cases. The SF10 prisms can generate more dispersion, but the higher-order dispersion is significantly higher.

Birefringence

Birefringent crystals divide an entering beam into two beams having opposite polarization, propagating in different directions.

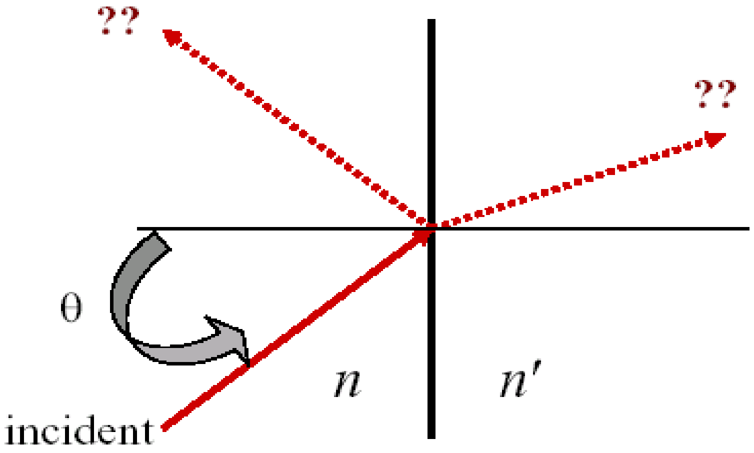


Figure: The angle of incidence at the dielectric interface.

Wave plates

Wave plates are optics that alter the polarization of a beam travelling through them. From The Encyclopedia of Laser Physics and Technology:

> These transparent plates have a carefully adjusted birefringence, which are mostly used for manipulating the polarization state of light beams. A waveplate has a slow axis and a fast axis, both being perpendicular to the surface and the beam direction, and also to each other. The phase velocity of light is slightly higher for polarization along the fast axis.

Half-wave plate

A half-wave plate can be used to rotate the plane of plane polarized light. They use birefringence to impart unequal phase shifts to the orthogonally polarized field component of an incident wave, causing the conversion of one polarization state into another

Quarter-Wave Plate

A quarter-wave plate can be used to turn plane polarized light into circularly polarized light and vice versa. One common application is to eliminate undesired reflections, especially when used with a polarizing beam splitter.

In addition to half-wave and quarter-wave plates, there are multiple-order wave plates and zero-Order Wave plates.

Etalons

Etalons are most commonly used as a line narrowing element in narrow band laser cavities or as bandwidth limiting and coarse tuning elements in broadband and picoseconds lasers. The Encyclopedia of Laser Physics and Technology defines etalons as: monolithic interferometric devices containing two parallel reflecting surfaces.

More from the Encyclopedia of Laser Physics and Technology:

> An optical etalon (also called Fabry–Pérot etalon) was originally known as a Fabry–Pérot interferometer in the form of a transparent plate (often made of fused silica) with parallel reflecting surfaces (solid etalon). However, the term is often also used for Fabry–Pérots consisting of two mirrors with some air gap in between (air-spaced etalon).When inserted into a laser beam, an etalon acts as an optical resonator (cavity), with the transmission periodically varying with optical frequency. (Strictly, the transmission is not exactly periodic in frequency due to chromatic dispersion.) In resonance, the reflections from the two surfaces cancel each other via destructive interference. The highest reflection losses occur in anti-resonance. The transmission versus frequency can be described with an Airy function, which approximately fits a simple sinusoidal function for not too high surface reflectivities.

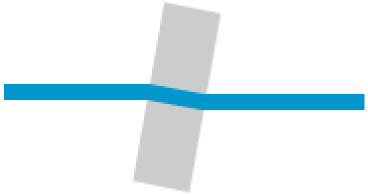


Figure: Tilted solid etalon in a laser beam.

The resonance effects occur even with some tilt provided that the tilt angle is so small that the overlap of counter propagating waves is not significantly reduced, as shown in the figure above. The tilt angle can then be used to control the resonance frequencies. An etalon can therefore be used as an adjustable optical filter for tuning the wavelength of a laser.

Spatial Filters

A spatial filter is an optical device that alters the structure of a beam. There are various modes of filtering.

Saturable Absorber

From The Encyclopedia of Laser Physics and Technology:

A saturable absorber is an optical component with a certain optical loss, which is reduced at high optical intensities. For example, this can occur in a medium with absorbing dopant ions, when a strong optical intensity leads to depletion of the ground state of these ions. Similar effects can occur in semiconductors, where excitation of electrons from the valence band into the conduction band reduces the absorption for photon energies just above the bandgap energy. The main applications of saturable absorbers are passive mode locking and Q switching of lasers, i.e., the generation of short pulses. However, saturable absorbers are also useful for purposes of nonlinear filtering outside laser resonators, e.g. for cleaning up pulse shapes, and in optical signal processing.

Planar waveguides

From The Encyclopedia of Laser Physics and Technology:

Planar waveguides have a planar geometry, which guide light only in one dimension. They are often fabricated in the form of a thin transparent film with increased refractive index on some substrate, or possibly embedded between two substrate layers. For example, a thin neodymium-doped YAG layer can be embedded in undoped YAG with slightly lower refractive index.

Such active planar waveguides are sometimes used for optical amplifiers with high gain (compared with that of bulk amplifiers) and relatively high power (at least multiple watts). There are also planar waveguide lasers. Some of these devices can be pumped with a proximity-coupled laser diode, not requiring any pump optics.

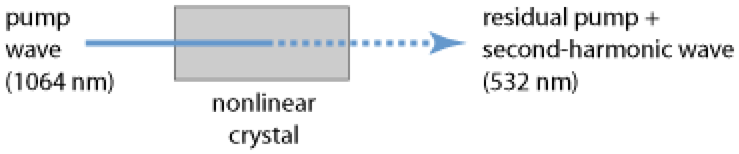
Frequency Doubling

(AKA: SHG = second-harmonic generation)

From The Encyclopedia of Laser Physics and Technology:

> Frequency Double is the phenomenon that an input wave in a nonlinear material can generate a wave with twice the optical frequency.

> Crystal materials lacking inversion symmetry can exhibit a so-called $\chi^{(2)}$ nonlinearity (→ *nonlinear crystal materials*). This can give rise to the phenomenon of frequency doubling [1], where an input (pump) wave generates another wave with twice the optical frequency (i.e. half the wavelength) in the medium. This process is also called *second-harmonic generation*. In most cases, the pump wave is delivered in the form of a laser beam, and the frequency-doubled (second-harmonic) wave is generated in the form of a beam propagating in a similar direction.



> **Figure:** A typical configuration for frequency doubling: an infrared input beam at 1064 nm generates a green 532-nm wave during its path through a nonlinear crystal.

Retroreflectors

Retroreflectors are used to reflect light back to its source.

Anti-reflection coatings- (AR Coating)

From The Encyclopedia of Laser Physics and Technology:

> An anti-reflection coating (AR coating) is an optical thin-film coatings for reducing reflections from surfaces. An anti-reflection coating (*AR coating*) is a dielectric thin-film coating applied to an optical surface in order to reduce the optical reflectivity of that surface in a certain wavelength range. In most cases, the basic principle of operation is that reflected waves from different optical interfaces largely cancel each other by destructive interference.

Single-layer Anti-reflection Coatings

In the simplest case, an antireflection thin-film coating designed for normal incidence consists of a single quarter-wave layer of a material the refractive index of which is close to the geometric mean value of the refractive indices of the two adjacent media. In that situation, two reflections of equal magnitude arise at the two interfaces, and these cancel each other by destructive interference.

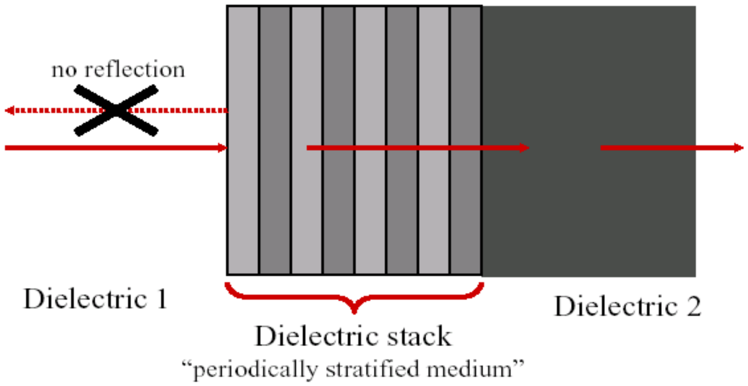
The limitations of this approach are twofold:

- It is not always possible to find a coating material with suitable refractive index, particularly in cases where the bulk medium has a relatively low refractive index.
- A single-layer coating works only in a limited bandwidth (wavelength range).

Single layer antireflection coatings

The intensity of the transmitted beam will approach the intensity of the incident beam.

Multilayer Coatings



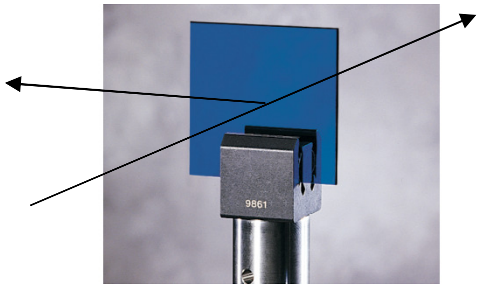
With proper design, the stack cancels the reflection for a wide range of incidence angles.

From The Encyclopedia of Laser Physics and Technology:

If no suitable medium for a single-layer coating can be found, or if anti-reflective properties are required for a very broad wavelength range (or for different wavelength ranges simultaneously, or for different angles of incidence), more complicated designs may be used, which usually have to be found using numerical techniques. A general tradeoff of such multilayer designs is between a low residual reflectivity and a large bandwidth.

Neutral Density (ND) Filter

BEWARE of reflected beams when you put an ND filters into a beam path.



From http://en.wikipedia.org/wiki/Neutral_density_filter:

A neutral density filter can be a colorless (clear) or grey filter. An ideal neutral density filter reduces and/or modifies intensity of all wavelengths or colors of light equally, giving no changes in hue of color rendition. The main purpose of using neutral density (i.e., ND) filters is to reduce the amount of light that can pass through the lens the deeper the color, the stronger the effect (i.e., reducing more light). The following shows Nikon's ND4 (font) and ND8 (rear) filters. From the shadows, it is clear that a ND8 blocks more light than a ND4 does. A graduated ND filter is similar except the intensity varies across the surface of the filter. This is useful when one region of the image is bright and the rest is not, as in a picture of a sunset.

ND Filter Wheel

From http://en.wikipedia.org/wiki/Neutral_density_filter:

It consists of two perforated glass disks which have progressively denser coating applied around the perforation on the face of each disk. When the two disks are counter-rotated in front of each other they gradually and evenly go from 100% transmission to 0% transmission. These are used on catadioptric telescopes mentioned above and in any system that is required to work at 100% of its aperture (usually because the system is required to work at its maximum angular resolution).

Practical ND filters are not perfect, as they do not reduce the intensity of all wavelengths equally. This can sometimes create color casts in recorded images, particularly with inexpensive filters. More significantly, most ND filters are only specified over the visible region of the spectrum, and do not proportionally block all wavelengths of ultraviolet or infrared radiation. This can be dangerous if using ND filters to view sources (such as the sun or white-hot metal or glass) which emit intense non-visible radiation, since the eye may be damaged even though the source does not look bright when viewed through the filter

Based on this understanding, ND filters help us in at least three situations: (1) reduce the intensity of light; (2) use slower shutter speed; and (3) use larger aperture.

Microscope

Because a beam may be as close as 12” from the height of the microscope eyepiece (and by extension near the chair you will be working from), take care with microscopes. You may casually bend down to tie your shoe or pick some dropped item and end up coming in contact with the laser beam. Minimize this danger by using lower tables and proper bean containment.

Another potential hazard related to a microscope is not having a variable attenuator for use in beam alignments. To decrease the hazard, use an ND wheel shortly after the laser exit to reduce power used during alignment to the minimum necessary

Some nonlinear optical setups may require full power to get the SHG you're trying to align, but for linear/CW systems this is an easy safety step.

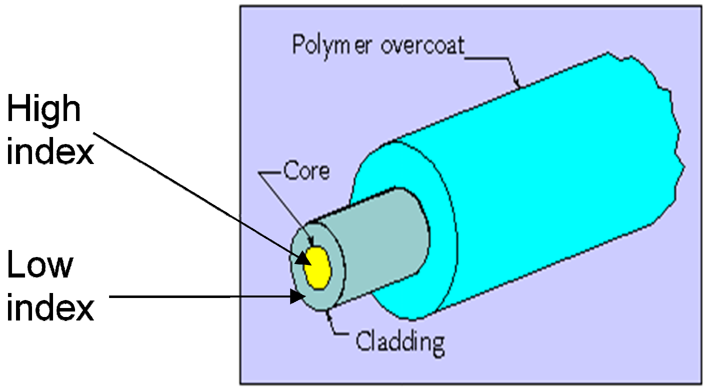
Use a Video/CCD camera for sample viewing rather than looking through eye pieces, which should contain a wavelength filter or be capped over.

Chapter 7: Fiber Optics

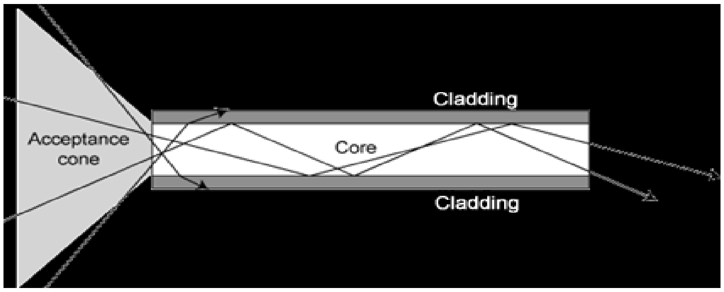
Fiber optics in the research setting are becoming more and more useful because they are:

- Compact
- Efficient
- High gain
- Good beam quality
- Robust
- Reliable
- Safe
- Space savers

However, fiber scraps are the same as glass splinters and can cause internal hemorrhaging if ingested.



optical fiber



General guidelines for working with fibers

- Keep all food and beverages out of the work area.
- Do not smoke in areas where fiber optic cables are being spliced or terminated, or where bare fibers are being handled.

- Do not bring cosmetics, lip balm, medicine, eye drops, chewing gum, chewing tobacco, hand creams, or lotions in areas where fiber optic cables are being spliced or terminated or where bare fibers are being handled.
- Prior to leaving the work area where fiber optic cables are being spliced or terminated or where bare fibers are being handled, check clothing to remove any stray pieces of bare fiber by patting yourself with clean pieces of double-sided tape, then properly dispose of this tape.
- Immediately and thoroughly wash your hands after leaving the work area, where fiber optic cables are being spliced or terminated, or where bare fibers are being handled.
- Work areas for splicing and terminating fiber optic cables must be provided with adequate lighting and ventilation.
- Wear a disposable apron if possible to minimize fiber particles from attaching to clothing. Fiber particles on your clothing can later get into food, drink, and/or be ingested by other means, or carried home on your clothing, exposing family members to the fiber splinters

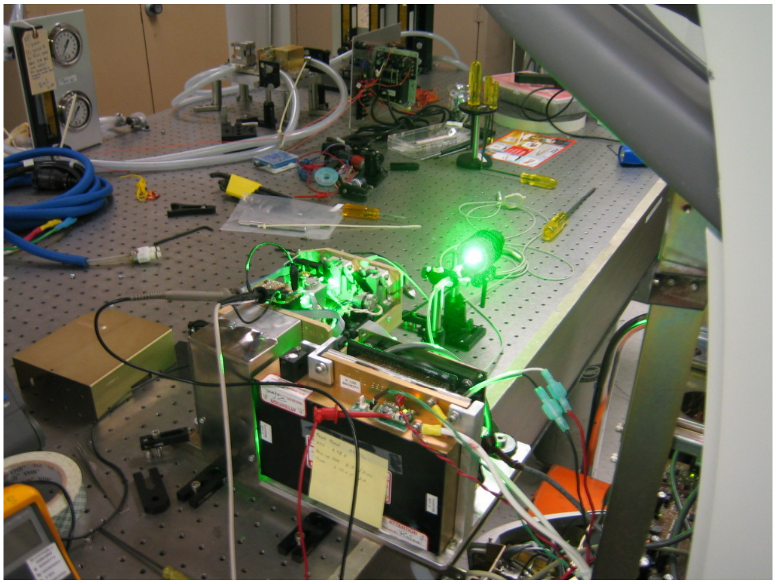


Figure: Application of fibers in a lab setting, with fiber contacting open air

Cutting & splicing

The most common injury associated with fiber optic work is getting fiber shards into the eyes or mouth. Fiber slivers will adhere to the natural oils on your fingers and can easily be transmitted to the eyes or mouth with a simple rub of the face. Safety glasses need to be worn when working with fibers and the use of gloves is recommended.

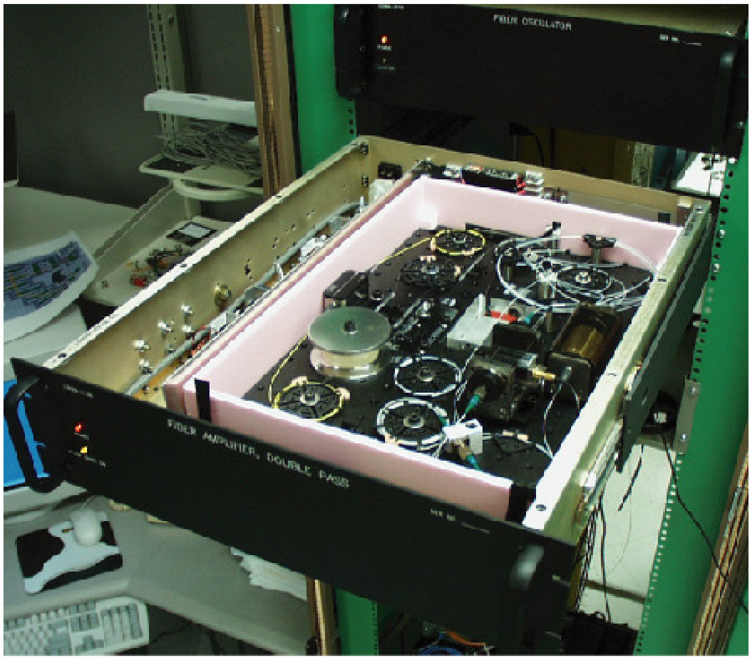


Figure: Fibers used with a spool to extend beam length.

In the fiber lab

- Here are a few common errors that can occur in the fiber based laser lab:
- Forgetting to shut down the fiber laser source.
- Leaving the fiber on and not blocking the exit end.
- Picking up the fiber to see if it is on.
- Failing to cover what may be a very short open beam path.

Fiber end viewing

Fiber end viewing should be done with a fiber connected to a camera and viewed on a remote monitor. DO NOT USE a fiber viewer regardless of whether or not it has a laser filter on it.

Appendix A: Alignment Guidelines

The techniques for laser alignment listed below are to be used to help prevent accidents during alignment of the laser or laser system.

Getting ready

- To reduce accidental reflections, watches, rings, dangling badges, necklaces and reflective jewelry are to be taken off before any alignment activities begin.
- Do not use any reflective tools.
- Limit access to the room or area to authorized personnel and supervised guests only.
- Consider having at least one other person present to help with the alignment.
- Plan ahead. All equipment and materials needed are present prior to beginning the alignment.
- Remove all unnecessary equipment, tools, combustible materials (if the risk of fire exists) to minimize the possibility of stray reflections and non-beam accidents.
- The Responsible Individual (RI) has authorized the persons conducting the alignment.
- A NOTICE sign is posted at entrances when temporary laser control areas are set up or unusual conditions warrant additional hazard information be available to personnel wishing to enter the area.
- Have all beam location devices such as sensor cards and viewers ready.

Recommended Alignment Methods

- There shall be no intentional intrabeam viewing with the eye.
- Coaxial low-power lasers should be used when practical for alignment of the primary beam.
- Reduce beam power with ND filters, beam splitters or dumps, or by reducing power at the power supply. Whenever practical, avoid the use of high-power settings during alignment.
- Laser protective eyewear shall be worn at all times during the alignment, either full protection for invisible beams or alignment for visible beams.
- Skin protection should be worn on the face, hands, and arms when aligning at UV wavelengths.
- The beam is enclosed as much as practical.
- The shutter is closed as much as practical during course adjustments.
- Optics and optics mounts are secured to the table as much as practical.
- Beam stops are secured to the table or optics mounts.
- Areas where the beam leaves the horizontal plane shall be labeled.
- Individuals performing alignment shall be responsible to search for stray reflections and contain such. Any stray or unused beams are terminated.
- Invisible beams are viewed with IR/UV cards, business cards, card stock, craft paper, viewers, 3 x 5 cards, thermal fax paper, or Polaroid film or by a similar technique. Operators are aware that such materials may produce specular reflections or may smoke or burn.
- Pulsed lasers are aligned by firing single pulses when practical.

- Intra-beam viewing is not allowed unless specifically evaluated and approved by the LSO.
- Intrabeam viewing is to be avoided by using cameras or fluorescent devices. Additional laser alignment controls are encouraged.

Post Alignment

- Normal laser hazard controls shall be restored when the alignment is completed. Controls include replacing all enclosures, covers, beam blocks, and barriers and checking affected interlocks for proper operation.
- Communicate with others in the lab that alignment is complete and full power operation is set to start.

Appendix B: Eyewear Selection

Selecting Laser Safety Eyewear

Laser safety eyewear is wavelength specific.

The following information is needed to select the appropriate laser safety eyewear:

- Wavelength(s)
- Mode of operation (continuous wave or pulsed)
- Maximum exposure duration (assume worst case scenario)
- Maximum irradiance (W/cm2) or radiant exposure (J/cm2)
- Maximum permissible exposure (MPE)
- Optical density (OD)

Contact the LSO to view sample frames and filter information.

Eyewear requirements

Per the ANSI standard, laser protective eyewear shall be specifically designed to withstand either direct or diffusely scattered beams depending upon the anticipated circumstances of exposure. In this case, the protective filter and frame shall exhibit a damage threshold for a specified exposure time, typically 10 seconds.

Types of Laser Safety Eyewear

Glass

Glass laser eyewear is heavier and more costly than plastic, but it provides better visible light transmittance. There are two types of glass lenses, those with absorptive glass filters and those with reflective coatings. Reflective coatings can create specular reflections and the coating can scratch, minimizing the protection level of the eyewear.

Polycarbonate

Polycarbonate laser eyewear is lighter, less expensive and offers higher impact resistance than glass, but allows less visible light transmittance.

Diffuse Viewing Only (DVO)

As the name implies, DVO eyewear is to be used when there is a potential for exposure to diffuse reflections only. DVO eyewear may not provide protection from the direct beam or specular reflections.

Alignment Eyewear

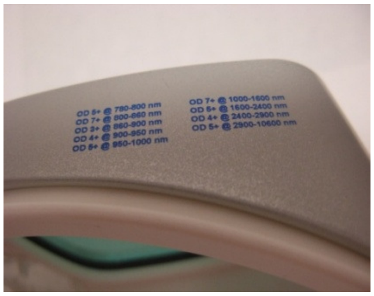
Alignment eyewear may be used when aligning low power visible laser beams. Alignment eyewear transmits enough of the specified wavelength to be seen for alignment purposes, but not enough to cause damage to the eyes. Alignment eyewear cannot be used during operation of high power or invisible beams and cannot be used with pulsed lasers.

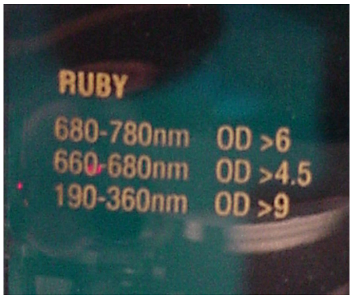
Laser Safety Eyewear for Ultra-Fast (Femtosecond) Lasers

Temporary bleaching may occur from high peak irradiances from ultra-fast laser pulses. Contact the manufacturer of the laser safety eyewear for test data to determine if the eyewear will provide adequate protection before using them.

Labeling of Laser Safety Eyewear

Laser safety eyewear shall be labeled with the optical density and the wavelength(s) the eyewear provides protection for. Additional labeling may be added for quick identification of eyewear in multiple laser laboratories.





Inspection and Cleaning of Laser Safety Eyewear

Laser safety eyewear should be inspected periodically for the following:

- Pitting, crazing, cracking and discoloration of the attenuation material
- Mechanical integrity of the frame
- Light leaks
- Coating damage

Follow manufacturers' instructions when cleaning laser safety eyewear. Use care when cleaning eyewear to avoid damage to absorbing filters or reflecting surfaces.

Considerations in choosing laser protective eyewear

The most important considerations for picking eyewear are listed below. There may be other considerations.

a) Optical density requirement of eyewear filters at laser output wavelength(s)
b) Comfort and fit of eyewear with no peepholes
c) Visible light transmission requirement and assessment of the effect of the eyewear on the ability to perform tasks while wearing the eyewear
d) Need for prescription glasses

The following items factor into calculating the Optical Density of the filter:

e) Largest laser power and/or pulse energy for which protection is required
f) Wavelength(s) of laser output

g) Exposure time criteria (e.g. 0.25, 10, 100, or 30,000 seconds)

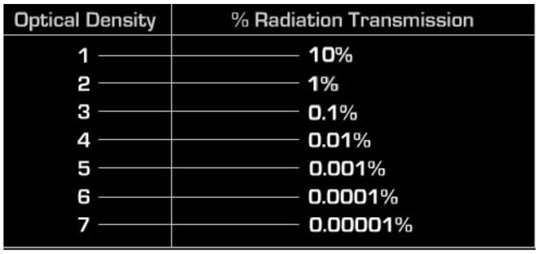
Comfort and fit

Comfort and fit is a personal preference. Consider overall comfort when evaluating in terms of short, moderate or protracted wearing times. If a pair of protective eyewear fits poorly, it will not work properly. Moreover, the likelihood of its use decreases. This is true for a respirator, facemask or laser protective eyewear.

One size does not fit all. Users do not want uncomfortable eyewear that is either too loose, too tight, too heavy, fogs up, or slips. The effort spent in finding proper fitting eyewear is well worth the time.

To help with fitting loose eyewear, you may need to place a strap across the back to keep the frame tight if necessary. Another option is to use flip-down eyewear over a user's owns glasses so the eyewear is familiar. Manufacturers offer a range of options in sizes, including new eyewear for slim faces to very large faces. There are options for fitting different nasal profiles, including flat or low nasal profiles, and combinations for small faces with flat nasal profiles. Adjustable temple lengths are also helpful, as well as temples with gripping ends. Bayonet temples (the straighter temple) also help in fitting large faces. Choices of laser protective eyewear have come a long way. All users should be able to an ideal pair.

Optical Density (OD)



Optical Density	% Radiation Transmission
1	10%
2	1%
3	0.1%
4	0.01%
5	0.001%
6	0.0001%
7	0.00001%

OD is a parameter for specifying the attenuation afforded by a transmitting medium. Since laser beam irradiances may be a factor of a thousand or a million above safe exposure levels, percent transmission notation can be tedious. For instance, goggles with a transmission of 0.000001 percent can be described as having an OD of 8.0. OD is a logarithmic expression and is described by the following:

$$OD = \log_{10} (M_i/M_t)$$

Where: M_i is the power of the incident beam and M_t is the power of the transmitted beam.

The Required OD (OD_{req}) for a particular laser device requires knowledge of the output power or energy. The following relationship may be used when radiant exposure (H) and irradiance (E) are averaged over the limiting aperture for classification:

$$OD_{req} = \log_{10} (E \text{ or } H)/MPE$$

When the entire beam could enter a person's eye, with or without optical aids, the following relationship is used:

$$OD_{req} = \log_{10} [\ 0 \text{ or } Q_0/AEL]$$

Where: AEL is the accessible emission limit (that is, the MPE multiplied by the area of the limiting aperture) and 0 and Q_0 are the radiant power or energy, respectively.

Alignment Eyewear

Many users confess they take off their eyewear because they cannot see the beam. Alignment eyewear provides a solution to this problem. For alignment of visible beams, conditions may arise that require the user to see the beam through their protective eyewear (cases where remote viewing is not possible). In these situations the use of alignment eyewear can be approved by the LSO. Alignment eyewear is assigned an OD lower than that which would provide full protection from a direct accidental exposure. For continuous wave lasers the alignment OD shall reduce irradiance to between Class 2 to Class 3R level. For pulse lasers the alignment OD shall be no less than the full protection OD minus 1.4.

Factors in Selecting Alignment Eyewear

Alignment eyewear by definition involves the use of visible laser light and requires the same attention and hazard analysis needed to adequately attenuate light from potential or accidental exposures to levels below MPEs by applying appropriate time base criteria. Ultimately the LSO shall approve the selection, use and appropriate OD values for all alignment tasks. The ultimate goal is to adequately attenuate light to levels safely below MPEs for all potential or accidental ocular exposures. Users must be aware that alignment eyewear will not provide full protection, but should be able to tell when they are being exposed, allowing them to turn away prior to causing injury.

Identification of Eyewear

To be considered legally certified laser protective eyewear, the eyewear must be labeled with its optical density and wavelength or wavelength range the eyewear is designed for. The laser manufacturer is only responsible for the wavelength marked on the eyewear.

NOTE:
Commercial laser protective eyewear may have a duplicate labeling compliant with European Norm 207 or 208 testing conditions where:

- D stands for continuous wave laser
- I stand for pulse laser
- R stands for Q Switched pulsed (pulse length 10-4 to 10-1 s)
- M stands for mode-coupled pulse laser (pulse length <10-9 s)
- L stands for Scale number equivalent to OD, L1 = OD 1, L2 = OD 2, etc.

Appendix C: Accidents

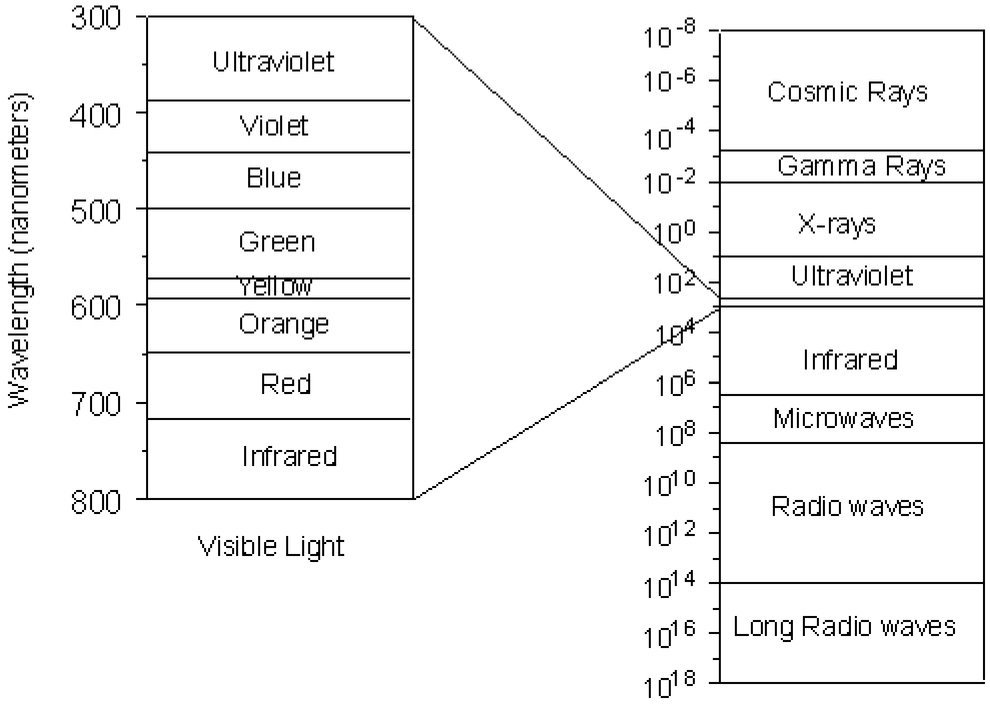
While Berkeley Lab strives to avoid laser accidents, they have occurred. Below is a listing of some common contributing factors that have led to past to laser eye injuries:

- Not checking for stray reflections
- Not blocking those stray reflections
- Failure to wear eyewear
- Selection of incorrect eyewear
- Misaligned optics and upwardly directed beams
- Equipment malfunction
- Out of position optics
- Improper restoration of equipment
- Lack of communication
- Failure to follow procedures
- Reflections off of surfaces
- Moving power meter into live beam
- Unblocked vertical beams
- Misuse of rotating polarizers
- Lack of awareness of hazard from wavelength(s) in use

Appendix D: Nature of Light

From *Properties of Light: Reflection, Refraction, Dispersion, and Refractive Indices.*

Light is electromagnetic radiation that has properties of waves. The electromagnetic spectrum can be divided into several bands based on the wavelength of the light waves. As we have discussed before, visible light represents a narrow group of wavelengths between about 380 nm (1 nm = 10^{-9} m) and 730 nm.



Our eyes interpret these wavelengths as different colors. If only a single wavelength or limited range of wavelengths are present and enter our eyes, they are interpreted as a certain color. If a single wavelength is present we say that we have ***monochromatic light***. If all wavelengths of visible light are present, our eyes interpret this as white light. If no wavelengths in the visible range are present, we interpret this as dark.

Interaction of Light with Matter

Velocity of Light and Refractive Index

The energy of light is related to its frequency and velocity as follows:

$E = h\nu = hC/\lambda$

where E = energy
h = Planck's constant, 6.62517 x 10-27 erg.sec
ν = frequency
C = velocity of light = 2.99793 x 1010 cm/sec
λ = wavelength

The velocity of light, C, in a vacuum is 2.99793 x 1010cm/sec. Light cannot travel faster than this, but if it travels through a substance, its velocity will decrease. Note that from the equation given above-

$C = h/\lambda$

The frequency of vibration, ν, remains constant when the light passes through a substance. Thus, if the velocity, C, is reduced on passage through a substance, the wavelength, λ, must also decrease.

We here define refractive index, n, of a material or substance as the ratio of the speed of light in a vacuum, C, to the speed of light in a material through which it passes, Cm.

$n = C/Cm$

Note that the value of refractive index will always be greater than 1.0, since Cm can never be greater than C. In general, Cm depends on the density of the material, with Cm decreasing with increasing density. Thus, higher density materials will have higher refractive indices.

The refractive index of any material depends on the wavelength of light because different wavelengths are interfered with to different extents by the atoms that make up the material. In general refractive index varies linearly with wavelength.

Materials can be divided into 2 classes based on how the velocity of light of a particular wavelength varies in the material.

1. Materials whose refractive index not depend on the direction that the light travels are called ***isotropic*** materials. In these materials the velocity of light does not depend on the direction that the light travels. Isotropic materials have a single, constant refractive index for each wavelength. Minerals that crystallize in the isometric system, by virtue of their symmetry, are isotropic. Similarly, glass, gases, most liquids and amorphous solids are isotropic.

2. Materials whose refractive index does depend on the direction that the light travels are called ***anisotropic*** materials. These types of materials will have a range of refractive indices between two extreme values for each wavelength. Anisotropic materials can be further divided into two subclasses, although the reasoning behind these subdivisions will become clear in a later lecture.

a. Minerals that crystallize in the tetragonal and hexagonal crystal systems (as well as some plastics) are ***uniaxial*** and are characterized by 2 extreme refractive indices for each wavelength.

b. Minerals that crystallize in the triclinic, monoclinic, and orthorhombic crystal systems are ***biaxial*** and are characterized by 3 refractive indices, one of which is intermediate between the other two.

Air, since it is a gas, is isotropic. The refractive index of air is usually taken as 1.0, although its true value is 1.0003.

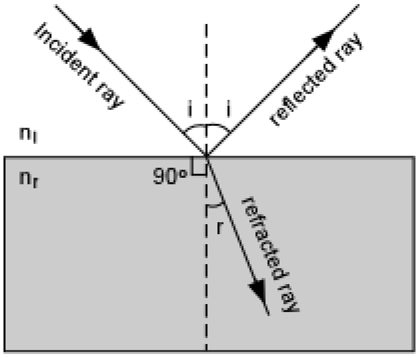
Reflection and Refraction of Light

When light strikes an interface between two substances with different refractive indices, two things occur. An incident ray of light striking the interface at an angle, i, measured between a line perpendicular to the interface and the propagation direction of the incident ray, will be reflected off the interface at the same angle, i. In other words the angle of reflection is equal to the angle of incidence.

If the second substance is transparent to light, then a ray of light will enter the substance with different refractive index, and will be refracted, or bent, at an angle r, the angle of refraction. The angle of refraction is dependent on the angle of incidence and the refractive index of the materials on either side of the interface according to ***Snell's Law***:

$ni \sin (i) = nr \sin (r)$

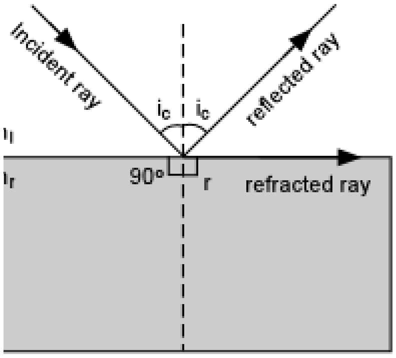
Note that if the angle of incidence is 0^o (i.e. the light enters perpendicular to the interface) that some of the light will be reflected directly back, and the refracted ray will continue along the same path. This can be seen from Snell's law, since $\sin(0^o) = 0$, making $\sin (r) = 0$, and resulting in $r = 0$.



There is also an angle, i_c, called the ***critical angle for total internal reflection*** where the refracted ray travels along the interface between the two substances. This occurs when the angle $r = 90^o$. In this case, applying Snell's law:

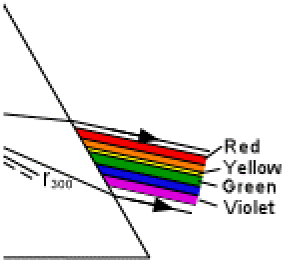
$n_i \sin (i_c) = n_r \sin (90^o) = n_r$ [since $\sin (90^o) = 1$]

$\sin (i_c) = n_r/n_i$



Dispersion of Light

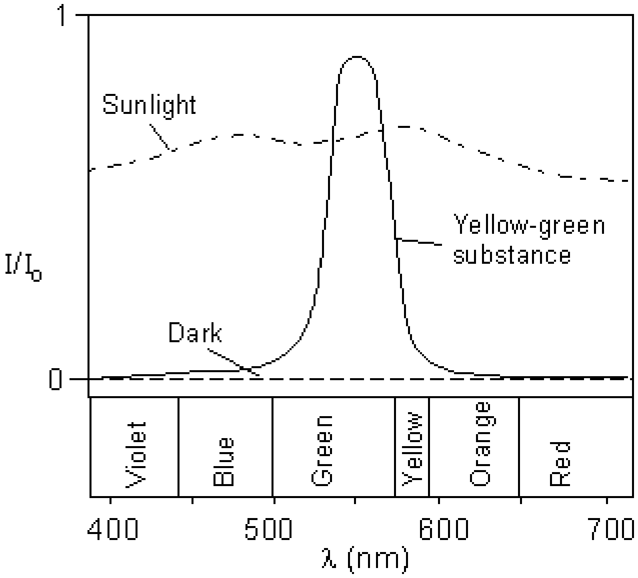
The fact that refractive indices differ for each wavelength of light produces an effect called ***dispersion***. This can be seen by shining a beam of white light into a triangular prism made of glass. White light entering such a prism will be refracted in the prism by different angles depending on the wavelength of the light. The refractive index for longer wavelengths (red) are lower than those for shorter wavelengths (violet). This results in a greater angle of refraction for the longer wavelengths than for the shorter wavelengths. (Shown here are the paths taken for a wavelength of 800 nm, angle r_{800} and for a wavelength of 300 nm, angle r_{300}). When the light exits from the other side of the prism, we see the different wavelengths dispersed to show the different colors of the spectrum.



Absorption of Light

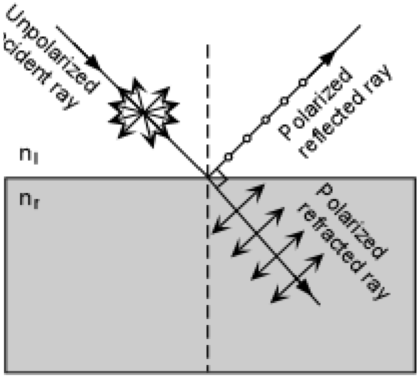
When light enters a transparent material some of its energy is dissipated as heat energy, and it thus loses some of its intensity. When this absorption of energy occurs selectively for different wavelengths of light, they light that gets transmitted through the material will show only those wavelengths of light that are not absorbed. The transmitted wavelengths will then be seen as color, called the ***absorption color*** of the material.

For example, if we measure the intensity of light, I_o, for each wavelength before it is transmitted through a material, and measure the intensity, I, for each wavelength after it has passed through the material, and plot I/I_o versus wavelength we obtain the absorption curve for that material as shown here. The absorption curve (continuous line) for the material in this example shows that the light exiting the material will have a yellow-green color, called the ***absorption color***. An opaque substance would have an absorption curve such as that labeled "Dark", i.e. no wavelengths would be transmitted. Sunlight, on passing through the atmosphere has absorption curve as shown, thus we see it as white light, since all wavelengths are present

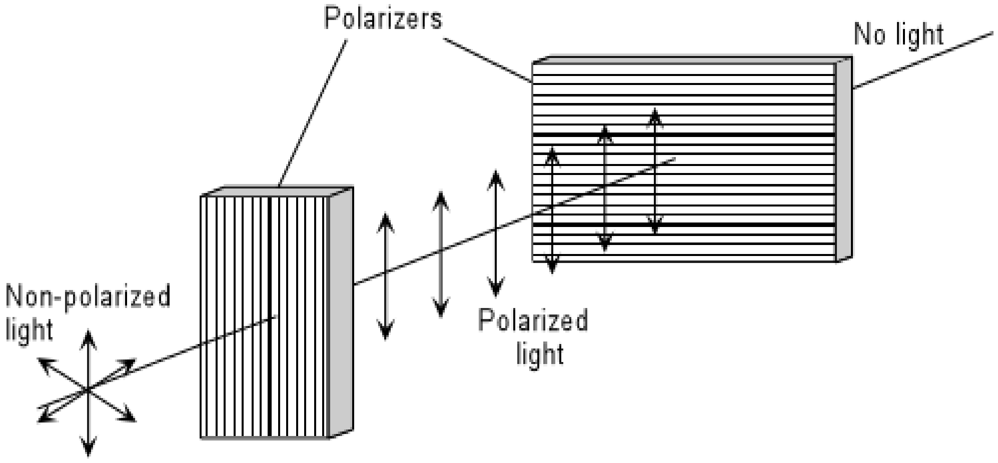


Polarization of Light

Normal light vibrates equally in all direction perpendicular to its path of propagation. If the light is constrained to vibrate in only on plane, however, we say that it is plane polarized light. The direction that the light vibrates is called the ***vibration direction***, which for now will be perpendicular to the direction. There are two common ways that light can become polarized. The first involves reflection off of a non-metallic surface, such as glass or paint. An unpolarized beam of light, vibrating in all directions perpendicular to its path strikes such a surface and is reflected. The reflected beam will be polarized with vibration directions parallel to the reflecting surface (perpendicular to the page as indicated by the open circles on the ray path). If some of this light also enters the material and is refracted at an angle 90^{o} to the path of the reflected ray, it too will become partially polarized, with vibration directions again perpendicular to the path of the refracted ray, but in the plane perpendicular to the direction of vibration in the reflected ray (the plane of the paper, as shown in the drawing).



Polarization can also be achieved by passing the light through a substance that absorbs light vibrating in all directions except one. Anisotropic crystals have this property in certain directions, called privileged directions, and we will discuss these properties when we discuss uniaxial and biaxial crystals. Crystals were used to produce polarized light in microscopes built before about 1950. The device used to make polarized light in modern microscopes is a Polaroid, a trade name for a plastic film made by the Polaroid Corporation. A Polaroid consists of long-chain organic molecules that are aligned in one direction and placed in a plastic sheet. They are placed close enough to form a closely spaced linear grid that allows the passage of light vibrating only in the same direction as the grid. Light vibrating in all other directions is absorbed. Such a device is also called a ***polarizer***.



If a beam on non-polarized light encounters a polarizer, only light vibrating parallel to the polarizing direction of the polarizer will be allowed to pass. The light coming out on the other side will then be plane polarized, and will be vibrating parallel to the polarizing direction of the polarizer. If another polarizer with its polarization direction oriented perpendicular to the first polarizer is placed in front of the beam of now polarized light, then no light will penetrate the second polarizer. In this case we say that the light has been extinguished.

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Polaroid sunglasses use these same principles. For example, incoming solar radiation is reflected off of the surface of the ocean or the painted hood of your car. Reflected light coming off of either of these surfaces will be polarized such that the vibration directions are parallel to the reflected surface, or approximately horizontal (as in the first method of polarization discussed above). Polaroid sunglasses contain polarizers with the polarization direction oriented vertically. Wearing such glasses will cut out all of the horizontally polarized light reflecting off the water surface or hood of your car.

Appendix E: How to Select Optical Mounts

The following material comes from Laser Safety: Tools & Training (Barat, 2008):

> The key to successfully choosing an optical mount is to prioritize the surrounding requirements. When critical alignment is of primary importance the user should choose kinematic mounts that offer high resolution and excellent position stability. Thermal stability is increased when all connecting components are constructed from the same material. In the majority of setups, this would consist of stainless steel hardware since most optical benches have stainless steel tops. However, a setup constructed entirely from stainless steel components can prove costly. When cost is more of a concern and alignment is less critical, aluminum is a perfectly suitable alternative.

Gimbal Mounts

Gimbal mounts are optical mounting device that permit adjustment around two perpendicular and intersecting axes of rotation.

From the Newport website:

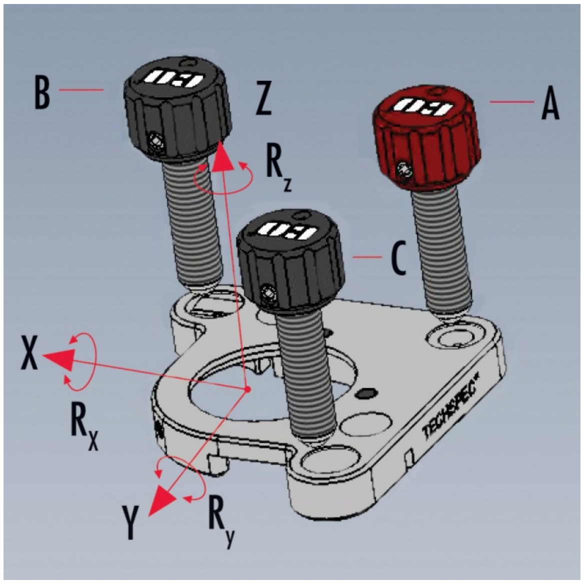
> They can be used for high-resolution azimuth and elevation adjustment of mirrors and beam splitters. The fixed rotational axes intersect at the front surface of the optic, allowing simple, non-coupled rotation without translation. The Gimbal design also greatly reduces beam wander and optical path-length changes. Mounts can be designed for maximum clear aperture of the transmitted beam at a 45° incident angle. Other Gimbal Mounts are designed for a single nominal optical diameter for positive, made-to-fit three-point mounting inside the Gimbal body.

Choosing optics

The following material comes from Laser Safety: Tools & Training (Barat, 2008):

When choosing optics, a common mistake among many engineers is overlooking the integration of optical mounts into their system. There are a variety of mounts available for holding lenses, prisms, mirrors, filters, and other common optical components. Some examples include bar-type mounts, Gimbal mounts, adjustable kinematic mounts, fixed mounts, and jaw clamp mounts just to name a few. When cost is a deciding factor, simple fixed mounts will be more than adequate. However, for applications that require fine positioning, adjustable, stable, kinematic mounts are essential to the integrity of a precision optical system.

A three-dimensional rigid body has exactly six degrees of freedom (DOF): X, Y, and Z are translational DOF and R_x, R_y, and R_z are rotational DOF. A mount is considered kinematic if all six DOF are fully constrained. Most laboratory kinematic optical mounts use the classic cone, groove, and flat constraint system, and use two or three adjustment screws. Two adjustment screws, at the groove and the flat, can be used to adjust the rotational degrees of freedom. Since the axis of rotation is behind the optic, there will be a slight translation of the optic when an adjustment is made. A third screw can be placed over the cone to compensate for unwanted translation. The three-screw configuration enables the optic to be rotated, as needed using the first two adjustments screws, and then returned to its original position along the Z-axis with the third.



To illustrate the importance of choosing the right optical mounts, consider an application that consists of a 25mm cube beam splitter and a 12mm focal length lens to combine and couple two 3mm beams into a 0.12 NA fiber. To ensure the highest coupling efficiency, assume that both focused spots need to be centered on the fiber to within ±2µm.

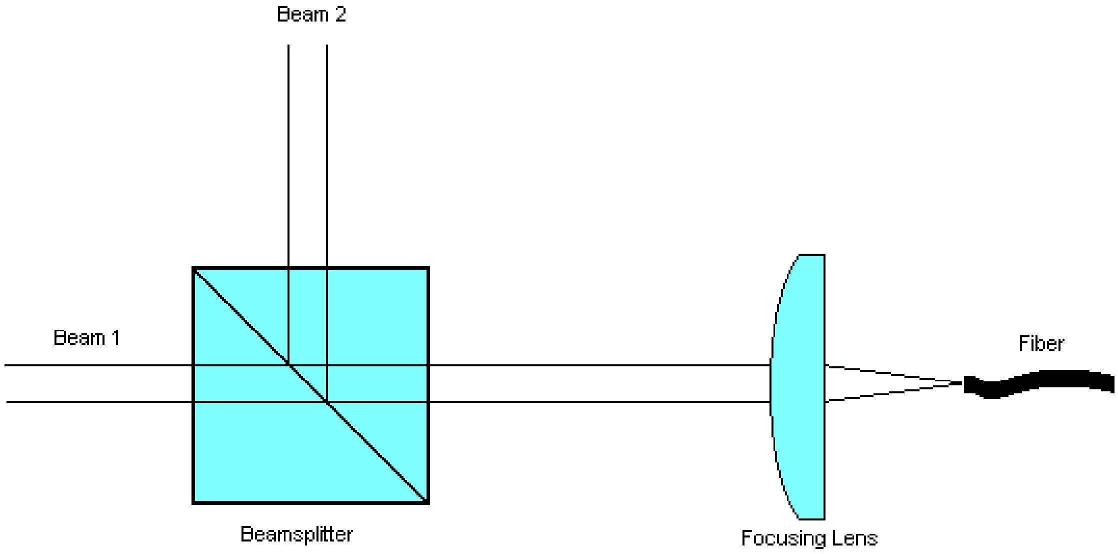
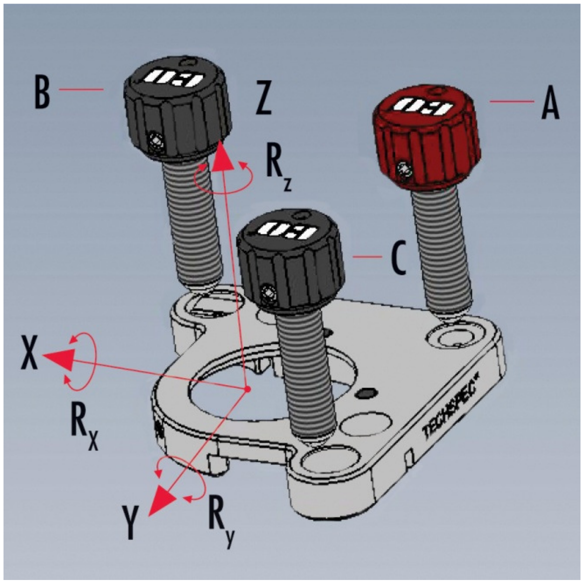


Figure: Fiber coupling system



Each component will contribute to the overall positioning error in the system, which can be calculated by the root sum square (RSS). Since each element potentially has six degrees of freedom, there are many combinations of movement that can occur. For simplicity, only the following movements will be considered:

1) Translation along the optical axis of the lens by 1µm.
2) Rotation of 400µrad of the focusing lens about a point 4mm from its nodal point.
3) Translation along the optical axis of the beam splitter by 2µm.
4) Rotation of 150µrad of the beam splitter about the optical axis.

5) Translation along the optical axis of the fiber by 1µm.

Table 1. Contributions of individual errors & RSS (total error)

Movement	Beam 1 (µm)	Beam 2 (µm)
1	1	1
2	2.4	1.6
3	0	0
4	0	3.6
5	1	1
RSS	2.14	4.19

Clearly, the system in the figure on the previous page of the fiber coupling system undergoes too much movement for beam 2 to maintain the ±2µm required for high coupling efficiency. Factors that may contribute to misalignment are mount resolution and instability from thermal effects, vibration, and gravity (often referred to as pointing stability).

Resolution of kinematic mounts is typically classified into two categories: linear resolution and angular resolution. The thread pitch of the adjustment screws determines the linear resolution, while the placement and thread pitch of the adjustment screws provides the angular resolution; 80-100 TPI adjustment screws are the industry standard. While higher resolution can be obtained by simply using adjustment screws with a larger TPI count, this isn’t always optimal since finer threads are easily damaged.

Sensitivity is another parameter, often provided by manufacturers, that is related to resolution. Since most kinematic mounts are manually driven it is helpful to know the minimum obtainable movement of the optic. Generally, fingertips are sensitive enough to resolve a 1º turn of the screw. The movement of the optic that corresponds to a 1º turn is what is used to define sensitivity.

Thermal stability indicates how well the mount will perform when subjected to changes in temperature. For minimum deflection from thermal affects, the mount’s coefficient of thermal expansion should be matched to that of the optic. Certain types of stainless steel match up very well to glass and are the preferred choice when thermal stability is of utmost importance. Although aluminum has a higher thermal expansion coefficient, kinematic mounts made from it still perform well in typical laboratory environments.

In addition to movement from thermal conditions, the affects of gravity over time will contribute to the overall misalignment error. Pointing stability is the measure of this error, specified as an angular movement, and is defined at a certain temperature, time-lapse, and applied load.

Vibration can also degrade optical system performance. Misalignment from low-level vibration will lead to blur in the image plane. Attempting to image with a high power microscope objective without using a vibration isolation platform will result in this phenomenon. Materials with higher stiffness values have greater fundamental or natural frequencies and faster settling times, resulting in less vibration disturbance.

A big drawback of many mounts is having to drop, rather than place, the optic into position. With the steep cost of precision optics, it’s highly undesirable to drop them into place even if it is only from a few millimeters. Choosing a mount with finger cuts incorporated into the design allows for guided placement of the optic, which will reduce chances of chipping and fracture.

Appendix F: Laser Bio-effects

From the LBNL Laser Safety Web Page:

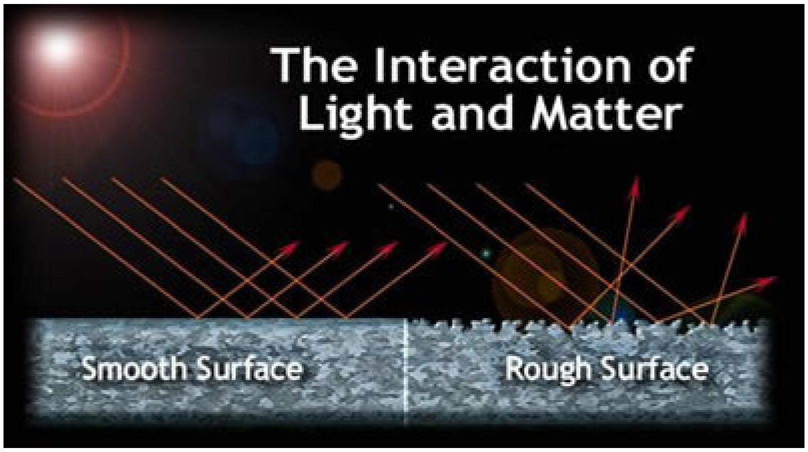
The chief concern over laser use has always been the possibility of eye injury. While skin presents a greater target, it is injury to one's eyes that drives laser safety, funding, controls and application. The effect of laser radiation will vary with the wavelength and part of the eye it interacts with. In addition biological effects from direct exposure and diffuse reflection exposure will differ. This article explains the anatomy of the eye and skin and issues associated with biological effects of laser exposure.

Exposure Type

One of the deciding factors on how hazardous a laser beam can be is how one is exposed: is it a direct or intrabeam exposure (where all the energy is directed right at one's eyes)?

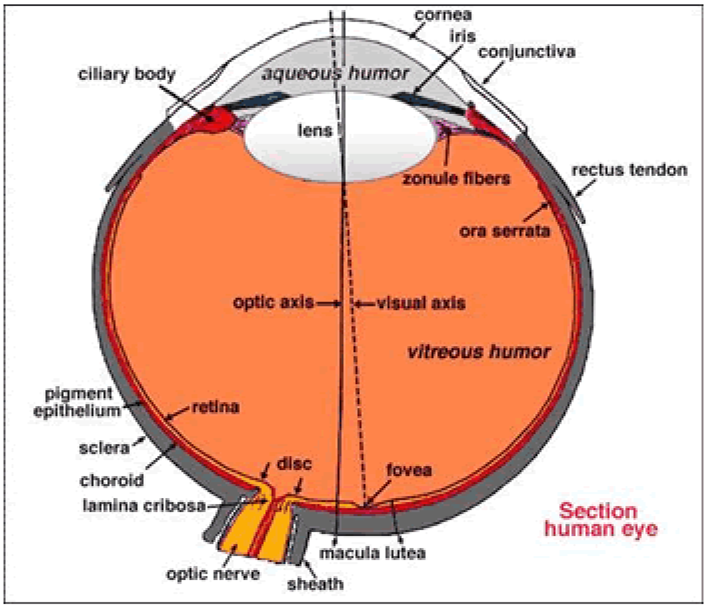
A specular reflection, which is a reflection off a mirror like surface (keeping in mind different surfaces to different wavelengths may or may not be mirror like). Specular reflection will result when the surface roughness is smaller than the wavelength. Specular reflections are generally less than 100%.

The safest reflection is the diffuse reflection, a reflection off a surface that spreads out the laser radiation reducing its irradiance. A diffuse surface will be one where the surface roughness is larger than the wavelength.



The Eye

The major danger of laser radiation is hazards from beams entering the eye. The eye is the organ most sensitive to light. A laser beam (400-1400 nm) with low divergence entering the eye can be focused down to an area 10 to 20 microns in diameter.



The energy density (measure of energy per unit of area) of the laser beam increases as the spot size decreases. This means that the energy of a laser beam can be intensified up to 100,000 times by the focusing action of the eye for visible and near infrared wavelengths. If the irradiance entering the eye is 1 mW/cm2, the irradiance at the retina will be 100 W/cm2. Even a 4% reflection off an optic can be a serious eye hazard. Remember a low power laser in the milliwatt range can cause a burn if focused directly onto the retina. A 40 mW laser is capable of producing enough energy (when focused) to instantly burn through paper.

The path of visible light

Light from an object (such as a tree) enters the eye first through the clear cornea and then through the pupil, the circular aperture (opening) in the iris. Next, the light is converged by the lens to a nodal point immediately behind the lens; at that point, the image becomes inverted. The light progresses through the gelatinous vitreous humor and, ideally, back to a clear focus on the retina, the central area of which is the macula. In the retina, light impulses are changed into electrical signals and then sent along the optic nerve and back to the occipital (posterior) lobe of the brain, which interprets these electrical signals as visual images

Major parts of the human eye

The cornea is the transparent layer of tissue covering the eye. Damage to the outer cornea may be uncomfortable (like a gritty feeling) or painful, but will usually heal quickly. Damage to deeper layers of the cornea may cause permanent injury.

The lens focuses light to form images onto the retina. Over time, the lens becomes less pliable, making it more difficult to focus on near objects. With age, the lens also becomes cloudy and eventually opacifies. This is known as a cataract. Every lens develops cataracts eventually.

Retina

The part of the eye that provides the most acute vision is the fovea centralis (also called the macula lutea). This is a relatively small area of the retina (3 to 4%) that provides the most detailed and acute vision as well as color perception. This explains why eyes move when you read—the image has to be focused on the fovea for detailed perception. The balance of the retina can perceive light and movement.

If a laser burn occurs on the fovea, most fine vision (reading and working) may be lost. If a laser burn occurs in the peripheral vision, it may produce little or no effect on vision.

Blink & aversion response

Fortunately the eye has a self-defense mechanism -- the blink and aversion response. Aversion response is the closing of the eyelid, or movement of the head to avoid exposure to bright light. The aversion response is commonly assumed to occur within 0.25 sec and is only applicable to visible laser wavelengths. This response may defend the eye from damage where lower power lasers are involved, but cannot help where higher power lasers are involved. With high power lasers, the damage can occur in less time than a quarter of a second.

The study “A Critical Consideration of the Blink Reflex as a Means for Laser Safety Regulations[1]” investigates the body’s natural defense mechanism against laser exposure and provides evidence indicating a need for stricter safety rules concerning laser class 2 products.

This study states that even for the larger spot size on the retina the frequency of the blink reflex has been shown to be less than 35 % and the same is true for the maximum of the pupil size, i. e. for low ambient light conditions. The study states 503 volunteers have been irradiated in the lab and 690 in 4 different field trials with laser radiation. Out of these trials, only 15.5 % or 18.26 % respectively have shown a blink reflex. The respective numbers as a function of wavelength are: 15.7 % (670 nm), 17.2 % (635 nm), and 22.4 % (532 nm). An increase from 4.2 % up to 28.1 % in blink reflex frequency was achieved when the ambient illuminance was decreased from 1 700 lx to 1 lx using an LED as a large extended stimulating optical source instead of a collimated laser beam.

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[1] The study “A Critical Consideration of the Blink Reflex as a Means for Laser Safety Regulations, byH.-D. Reidenbach”. 1,2,3, J. Hofmann1, K. Dollinger1,3, M. Seckler2.

A further dependency was found concerning the irradiated area on the retina, i.e. increasing the retinal spot from 6.4 to 9.4 mm^2 up to 33.7 to 46.8 mm^2 resulted in an increase of the blink reflex percentage from 20 % to 33.3 %.

Effects are wavelength-dependent

Ultraviolet-B+C (100 - 315 nm)

The surface of the cornea absorbs all UV of these wavelengths which produce a photokeratitis (welders flash) by a photochemical process. This causes a temporary denaturation of proteins in the cornea because the corneal tissues regenerate very quickly.

Ultraviolet -A (315 - 400 nm)

The cornea, lens and aqueous humour allow Ultraviolet radiation of these wavelengths and the principal absorber is the lens. Photochemical processes denature proteins in the lens resulting in the formation of cataracts.

Visible light and Infrared-A (400 - 1400 nm)

The cornea, lens and vitreous fluid are transparent to wavelengths. Damage to the retinal tissue occurs by absorption of light and its conversion to heat by the melanin granules in the pigmented epithelium or by photochemical action to the photoreceptor. The focusing effects of the cornea and lens will increase the irradiance on the retina by up to 100,000 times. For visible light 400 to 700 nm the aversion reflex which takes 0.25 seconds may reduce exposure causing the subject to turn away from a bright light source. However, this will not occur if the intensity of the laser is great enough to produce damage in less than 0.25 sec. or when light of 700 - 1400 nm (near infrared) is used, as the human eye is insensitive to these wavelengths.

Infrared-B and Infrared-C (1400 to 1.0 x 10+6 nm)

Corneal tissue will absorb light with a wavelength longer than 1400 nm. Damage to the cornea results from the absorption of energy by tears and tissue water causing a temperature rise and subsequent denaturation of protein in the corneal surface.

Signs of Eye Exposure

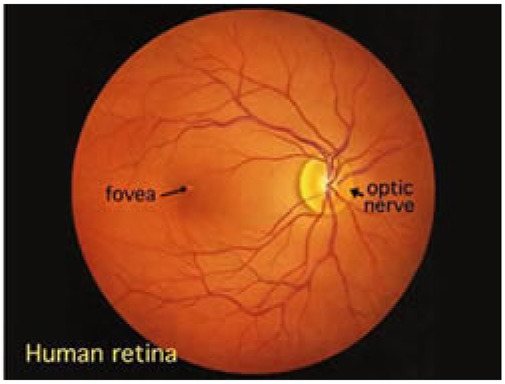


Figure: Normal Eye

Symptoms of a laser burn in the eye include a headache shortly after exposure, excessive watering of the eyes, and sudden appearance of floaters in your vision. Floaters are those swirling distortions that occur randomly in normal vision most often after a blink or when eyes have been closed for a couple of seconds. Floaters are caused by dead cell tissues that detach from the retina and choroid and float in the vitreous humor. Ophthalmologists often dismiss minor laser injuries as floaters due to the very difficult task of detecting minor retinal injuries. Minor corneal burns cause a gritty feeling, like sand in the eye.

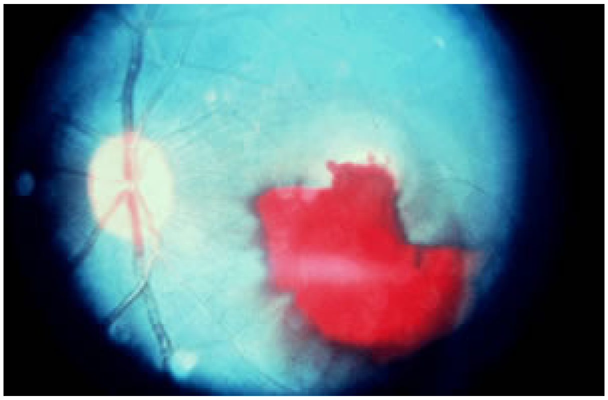


Figure: Vitreal Hemorrhage

The exposure to a visible laser beam can be detected by a bright color flash of the emitted wavelength and an after-image of its complementary color (e.g., a green 532 nm laser light would produce a green flash followed by a red after-image). When the retina is affected, there may be difficulty in detecting blue or green colors secondary to cone damage and pigmentation of the retina may be detected.

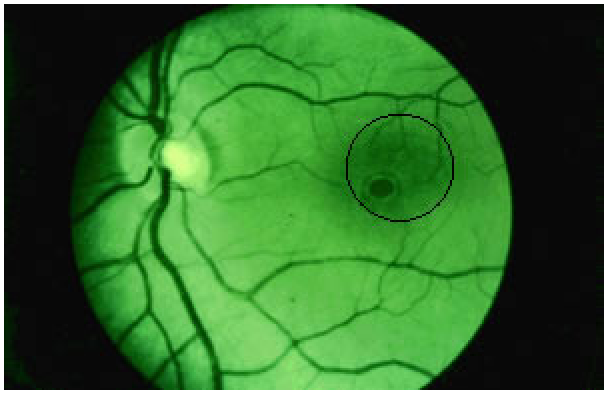


Figure: Large retinal burn from diffuse laser exposure Area of retinal burn

Exposure to the Q-switched Nd:YAG laser beam (1064 nm) is especially hazardous and may initially go undetected because the beam is invisible and the retina lacks pain sensory nerves. Photoacoustic retinal damage may be associated with an audible "pop" at the time of exposure. Visual disorientation due to retinal damage may not be apparent to the operator until considerable thermal damage has occurred.

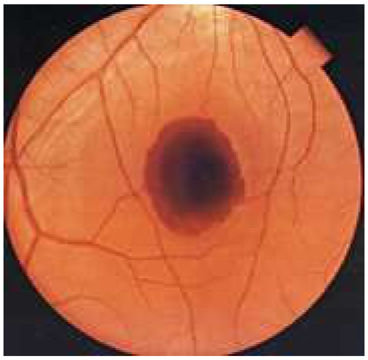


Figure: Blood pool 1 week post-injury

Exposure to the invisible carbon dioxide laser beam (10,600 nm) can be detected by a burning pain at the site of exposure on the cornea or sclera.

Damage Mechanisms

Electromechanical/Acoustic Damage

This type of damage requires beams of extremely high power density (109–1012 W/cm2) in extremely short pulses (ns) to delivery fluences of about 100 J/cm2 and very high electric fields (106–107 V/cm), comparable to the average atomic or intermolecular electric field. Such a pulse induces dielectric breakdown in tissue, resulting in a microplasma or ionized volume with a very large number of electrons. A localized mechanical rupture of tissue occurs due to the shock wave associated with the plasma expansion. Laser pulses of less than 10 microseconds duration can induce a shock wave in the retinal tissue that causes tissue rupture. This damage is permanent, as with a retinal burn. Acoustic damage is actually more destructive to the retina than a thermal burn. Acoustic damage usually affects a greater area of the retina, and the threshold energy for this effect is substantially lower. The ANSI MPE values are reduced for short laser pulses to protect against this effect.

Photoablation

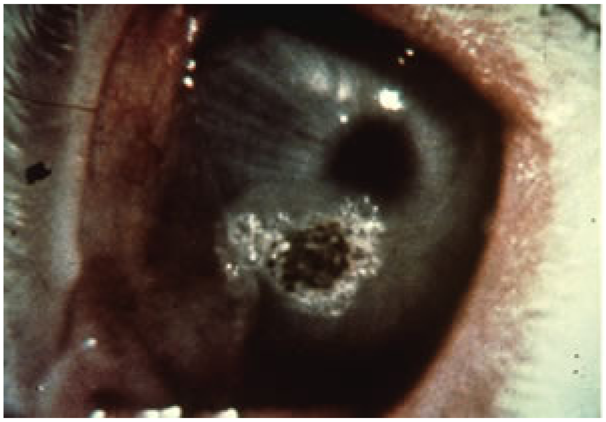


Figure: Corneal burn - Rabbit

Photoablation is the photodissociation or direct breaking of intramolecular bonds in biopolymers, caused by absorption of incident photons and subsequent release of biological material. Molecules of collagen, for example, may dissociate by absorption of single photons in the 5–7 eV energy range. Excimer lasers at several ultraviolet wavelengths (ArF, 193 nm/6.4 eV; KrF, 248 nm/5 eV; XeCl, 308 nm/4 eV) with nanosecond pulses focused on tissue at power densities of about 108 W/cm2 can produce this photoablative effect. Ultraviolet radiation is extremely strongly absorbed by biomolecules, and thus absorption depths are small, of the order of a few micrometers.

Thermal Damage

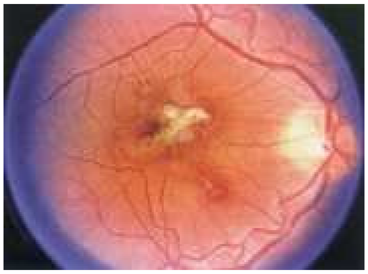


Figure: 3 Nd:YAG pulses

Thermal damage occurs because of the conversion of laser energy into heat. With the laser’s ability to focus on points a few micrometers or millimeters in diameter, high power densities can be spatially confined to heat target tissues. Depth of penetration into the tissue varies with wavelength of the incident radiation, determining the amount of tissue removal and bleeding control.

The photothermal process occurs first with the absorption of photon energy, producing a vibrational excited state in molecules, and then in elastic scattering with neighboring molecules, increasing their kinetic energy and creating a temperature rise. Under normal conditions the kinetic energy per molecule (kT) is about 0.025 eV. Heating effects are largely controlled by molecular target absorption such as free water, haemoproteins, melanin, and other macromolecules such as nucleic acids.

Photochemical Damage

Light below 400 nm does not focus on the retina. The light can be laser output, ultraviolet (UV) from the pump light, or blue light from a target interaction. The effect is cumulative over a period of days. The ANSI standard is designed to account only for exposure to laser light. If UV light from a pump light or blue light from a target interaction is emitted, additional precautions must be taken.

Key Advice: DO NOT look directly into the beam.

Laser Radiation Effects on Skin

Laser radiation injury to the skin is normally considered less serious than injury to the eye, since functional loss of the eye is more debilitating than damage to the skin, although the injury thresholds for both skin and eyes are comparable (except in the retinal hazard region, (400–1,400 nm). In the far-infrared and far-ultraviolet regions of the spectrum, where optical radiation is not focused on the retina, skin injury thresholds are about the same as corneal injury thresholds. Obviously, the possibility of skin exposure is greater than that of eye exposure because of the skin’s greater surface area.

The layers of the skin, which are of concern in a discussion of laser hazards to the skin, are the epidermis and the dermis. The epidermis layer lies beneath the stratum corneum and is the outermost living layer of the skin. The dermis mostly consists of connective tissue and lies beneath the epidermis.

Epidermis

The epidermis is the outer layer of skin. The thickness of the epidermis varies in different types of skin. It is the thinnest on the eyelids at .05 mm and the thickest on the palms and soles at 1.5 mm.

Dermis

The dermis also varies in thickness depending on the location of the skin. It is .3 mm on the eyelid and 3.0 mm on the back. The dermis is composed of three types of tissue that are present throughout - not in layers. The types of tissue are collagen, elastic tissue, and reticular fibers.

Subcutaneous Tissue

The subcutaneous tissue is a layer of fat and connective tissue that houses larger blood vessels and nerves. This layer is important is the regulation of temperature of the skin itself and the body. The size of this layer varies throughout the body and from person to person.

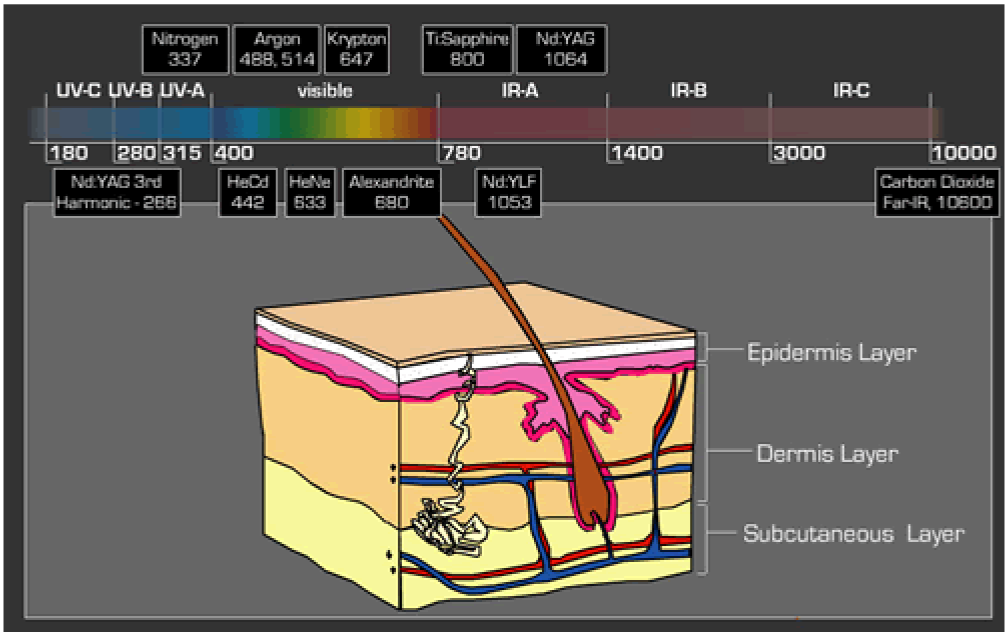


Figure: Skin penetration by laser type

There is quite a variation in depth of penetration over the range of wavelengths, with the maximum occurring around 700 to 1200 nm. Injury thresholds resulting from exposure of less than 10 seconds to the skin from far-infrared and far-ultraviolet radiation are superficial and may involve changes to the outer dead layer of the skin. A temporary skin injury may be painful if sufficiently severe, but it will eventually heal, often without any sign of injury. Burns to larger areas of the skin are more serious, as they may lead to serious loss of body fluids. Hazardous exposure of large areas of the skin is unlikely to be encountered in normal laser work.

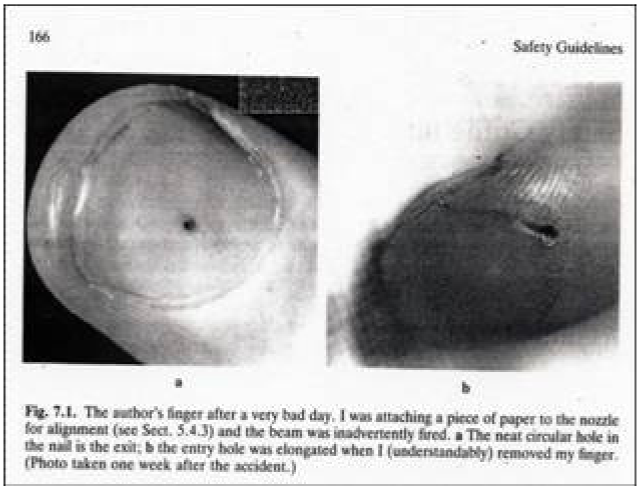
A sensation of warmth resulting from the absorption of laser energy normally provides adequate warning to prevent thermal injury to the skin from almost all lasers except for some high-power far-infrared lasers. Any irradiance of 0.1 W/cm2 produces a sensation of warmth at diameters larger than 1 cm. On the other hand, one tenth of this level can be readily sensed if a large portion of the body is exposed. Long-term exposure to UV lasers has been shown to cause long-term delayed effects such as accelerated skin aging and skin cancer.

To the skin, UV-A (0.315 µm-0.400 µm) can cause hyperpigmentation and erythema. UV-B and UV-C, often collectively referred to as "actinic UV," can cause erythema and blistering, as they are absorbed in the epidermis. UV-B is a component of sunlight that is thought to have carcinogenic effects on the skin. Exposure in the UV-B range is most injurious to skin. In addition to thermal injury caused by ultraviolet energy, there is the possibility of radiation carcinogenesis from UV-B (0.280 mm - 0.315 mm) either directly on DNA or from effects on potential carcinogenic intracellular viruses.

Exposure in the shorter UV-C (0.200 µm-0.280 µm) and the longer UV-A ranges seems less harmful to human skin. The shorter wavelengths are absorbed in the outer dead layers of the epidermis (stratum corium) and the longer wavelengths have an initial pigment-darkening effect followed by erythema if there is exposure to excessive levels.

IR-A wavelengths of light are absorbed by the dermis and can cause deep heating of skin tissue.

Figure: Twenty year evaluation of CO_2 laser (5 W/cm2, 1 sec. at 10,600 nm) exposure of human skin. NOTE: At long term follow up, burn regions display non-descript fibrous scarring. No other symptoms were observed over the twenty year period.



166 Safety Guidelines

a

b

Fig. 7.1. The author's finger after a very bad day. I was attaching a piece of paper to the nozzle for alignment (see Sect. 5.4.3) and the beam was inadvertently fired. **a** The neat circular hole in the nail is the exit; **b** the entry hole was elongated when I (understandably) removed my finger. (Photo taken one week after the accident.)

Figure: Burn through finger

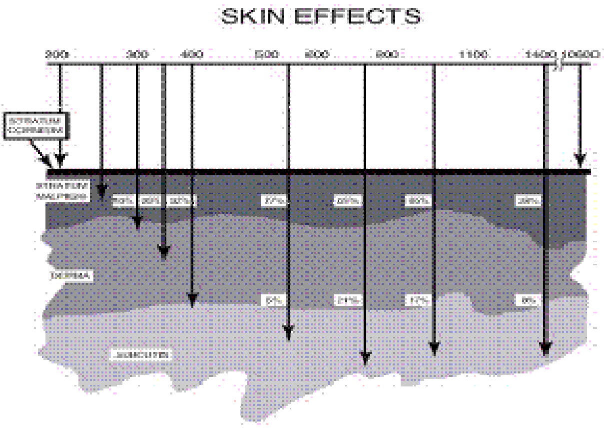


Figure: Wavelength penetration

Appendix G: Bibliographic References

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