

# Laser User Reference Guide

Second Edition

Lawrence Berkeley National Laboratory

Laser Safety Program



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



# Laser User Reference Guide

## Second Edition

### Foreword

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 user 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.

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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 LBNL Laser Safety Officer (LSO) for questions about this guide or about safety practices.

### OJT Trainer Responsibility

The Activity Lead (AL) or designee shall train staff on the hazards of the specific experimental work to be performed. It is critical for the AL 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 equipment
- 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.

## **Trainer's Corner**

### **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 into smaller pieces rather than overwhelming the trainee. 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, working with chemicals, or bumping the head against low hanging shelves.

### **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 cryogenics, 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 passerby 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 Shelves in the Lab**

Glass shelves in the lab and even laminated posters are possible reflection hazards. They can send reflections to 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 outside the laser-controlled area. This can be either on the door outside the laser lab or inside the lab, between the door and the curtain or partition. 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.



*Examples of Eyewear Storage*

## 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 proper Personal Protective Equipment (PPE) such as gloves, face shield and clothing.

- Use caution during flash lamp change out, there is explosion hazard when a warm lamp comes into contact with bare hands.
- 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.

### **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.

### **Oxygen Deficiency**

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



*Example of Electrical Ground on the Optical Table*

### **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 person aligning the laser beam should be situated to avoid stray reflection. Use non-reflective tools where possible to minimize stray reflections and store tools off the table.

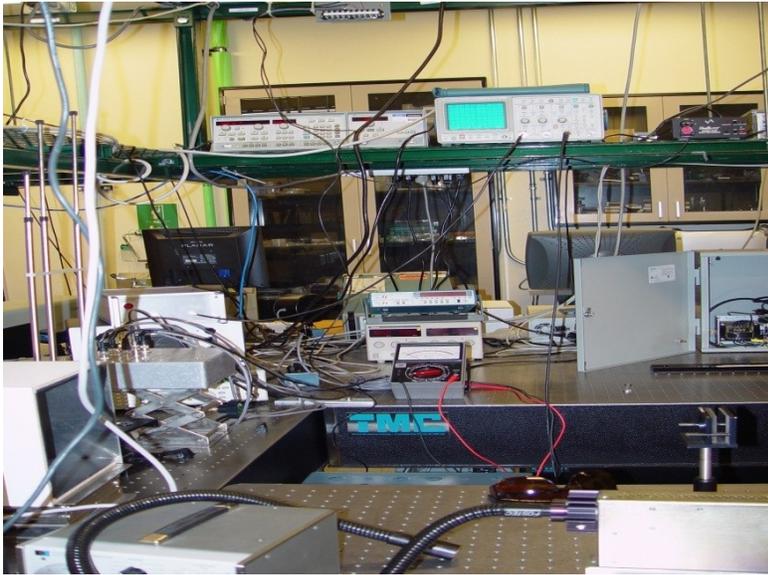
### **Interlocks**

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 once a year and are not to be bypassed unless authorized by the LSO. The housings on commercial lasers 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 removed.

### **Wires**

Dangling wires can present a number of hazards. 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.



*Example of Dangling Wires*

## 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, high efficiency particulate air (HEPA) filters 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:Sapphire oscillators are VERY sensitive to dust. Clean the cavity optics and the Ti:Sapphire 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.

## Handling Optics

Never handle optics with bare hands, as skin oils can permanently damage the optical surface quality. Instead, wear gloves; alternatively, for smaller optical components, it may be helpful to

use optical or vacuum tweezers. If possible, hold the optic along non-optical surfaces, such as the ground edges of the optic.

Most crystals (e.g., calcite polarizers, beam displacers, lithium niobate wafers) are temperature sensitive and can crack if exposed to thermal shock. It is important to allow the package and contents to come to thermal equilibrium prior to opening. These crystals are also much softer than conventional optics, and thus, need to be handled more carefully when cleaning.

## Storage

Never place optics on hard surfaces. Instead, most optics should be wrapped in lens tissue and then stored inside an optic storage box designed for the optic. Typically, the box should be kept in a low humidity, low contaminant, and temperature-controlled environment. Optics are easily scratched or contaminated, and some optical coatings are hygroscopic, so proper storage is important for preserving the optical component.



*Example of lens storage*

## Labeling 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 in holder, you will know what you have, as they can look similar. Label optics indicating, at a minimum:

- Reflective/polished surface using an arrow (e.g. >)
- Coating parameters (e.g. AR.10 = UV, AR.14 = 532nm, AR.16 = 800nm)
- Substrate details (e.g. FS, BK7, Oduur)
- Other key details, as appropriate (e.g. s/n, PO#, ref#)

## Cleaning Optics

Through everyday use, optics can come in contact with contaminants such as dust, water, and skin oils. These contaminants increase scatter off the optical surface and absorb incident radiation, which can create hot spots on the optical surface, resulting in permanent damage. Optical components with coatings are particularly susceptible to this sort of damage.

Always read the manufacturer's recommended cleaning and handling procedures if available.

Typical solvents employed during cleaning are acetone, methanol, and isopropyl alcohol (isopropanol). Use all solvents with caution since most are poisonous, flammable, or both. Read product data sheets and SDS sheets carefully before using any solvents.

Before cleaning optics, consult the optic’s manufacturer. They provide information on how to handle and clean different optics. Very often, you can find there detailed tutorials for cleaning optics. Some links are provided in the reference page.

Some common methods for cleaning optics are:

1. Blowing Off the Surface of an Optic

- 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.



*Example of hand blower*



*Example of dust blower can*

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

2. Drop and Drag Method - Ideal for unmounted optics

- Drop some solvent onto a piece of unfolded lens tissue.
- Slowly but steadily drag the damp lens tissue across the optic being careful not to lift the lens tissue off of the surface. Continue dragging the lens tissue until it is off of the optical surface.



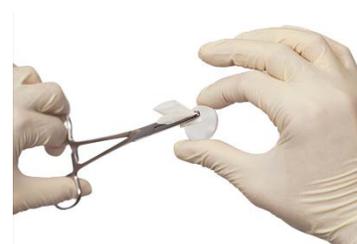
*Illustration of Drop and Drag method*

[https://www.thorlabs.com/newgrouppage9.cfm?objectgroup\\_id=9025](https://www.thorlabs.com/newgrouppage9.cfm?objectgroup_id=9025)

<https://www.youtube.com/watch?reload=9&v=9Pq4SeNmFYw#action=share>

3. The “Brush” Technique – ideal for smaller optics

- Create a “brush” by folding the lens tissue so that the fold is as wide as the optic. It is important to fold and clamp the tissue in such a way that the portion of tissue that comes into contact with the optic is not touched.
- Apply a couple of drops of solvent to the lens tissue. The tissue should be damp, but not dripping. If too much solvent was added, safely shake the excess solvent from the lens tissue.
- Wipe straight across, from one edge of the surface to another.



*Illustration of Brush method*

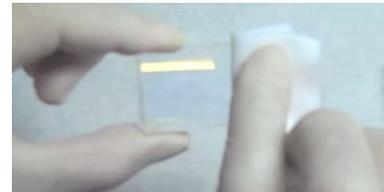


- For small-diameter mounted optics, wrap a tissue around the soft tip of a synthetic low-lint swab to create a “brush”.
- Use the swab to “paint” or “brush” the optic perimeter and sweep across the center of the optic.
- Brushing in a continuous motion will prevent drying marks.



*Illustration of how to wrap a tissue around a swab and wipe or brush*

4. The “wipe” technique – ideal for stains
- Fold the lens tissue as described in the “brush” technique but grip it with your fingers.
  - Apply uniform pressure on the optic edge and slowly wipe across the optic’s face.



*Illustration of Wipe technique*

**NEVER CLEAN:**

- When laser beam is present, block the laser beam and then reach to clean optics.
- 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

#### Viewing Cards

There are variety of detector cards for use with UV, Visible, Near IR (NIR), or Mid IR (MIR) radiation. These cards are fabricated from plastic with a liquid crystal photosensitive region. Each card's light-sensitive detector area allows for the easy location of a UV, Visible, NIR, or MIR laser beam and its focal point. To facilitate their use during alignment procedures, every card is marked with a detection region and

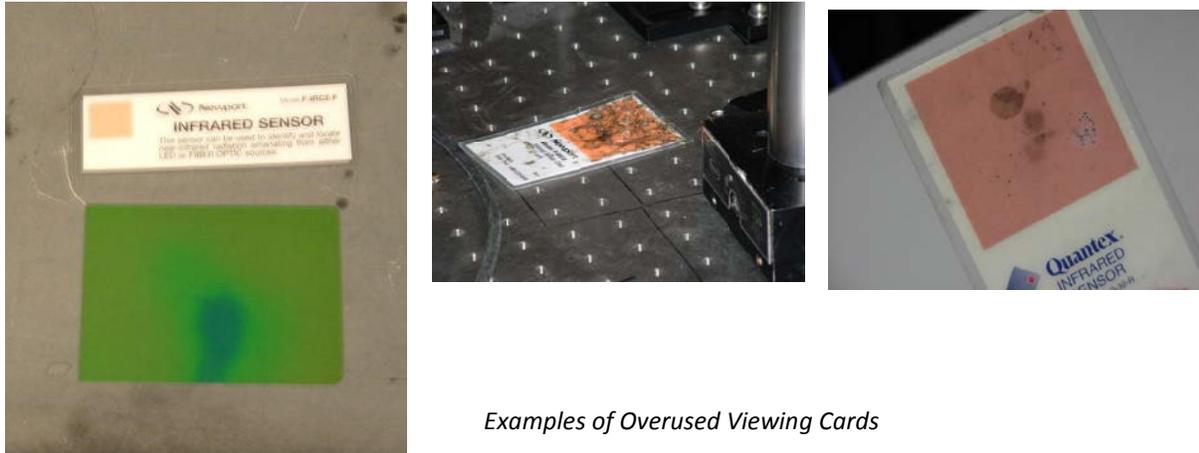
Please note that these detector cards are not intended to be used as laser beam blocks, and appropriate safety measures should be taken when working with laser beams. See the *Laser Safety* tab for details.

#### 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.



*Examples of Viewing Cards*



*Examples of Overused Viewing Cards*

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



*Example of IR viewer*

IR viewers have been a staple 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.

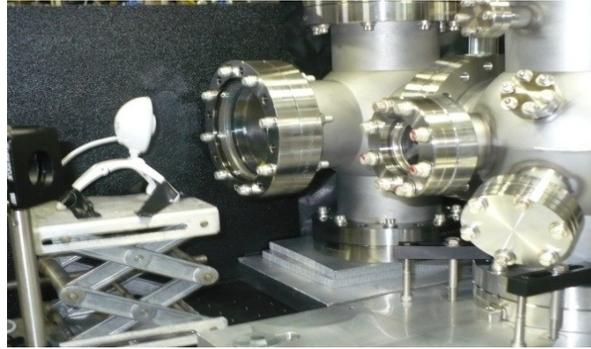
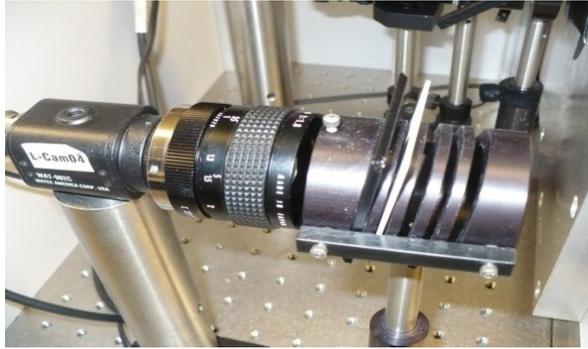
A superior, though more laborious, alternative is remote viewing with an IR camera, which removes you from standing in front of the beam or reflection.

## 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 Cameras

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.



*Examples of Remote viewing Systems*

## 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.



*Examples of Beam Blocks*

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.



*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



*Example of unsecured beam block perched on the edge of a laser table.*

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.

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

## Beam Dumps



*Examples of 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 intended to deal with.

## Laser Enclosures and Perimeter Guards

### Polycarbonate Sheets for Enclosures

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.



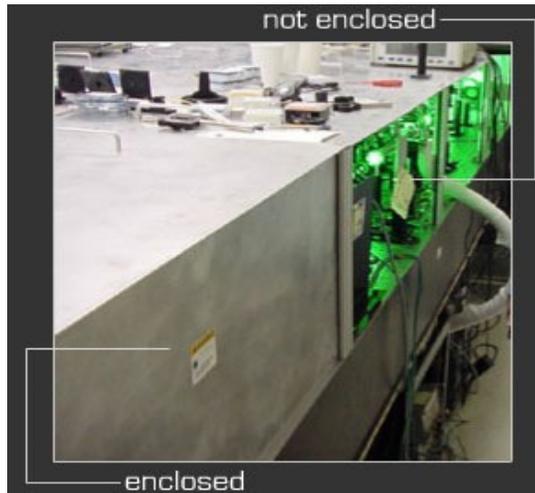
*Examples for enclosures using polycarbonate sheets*

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



*Examples for metal 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



*Examples of installed laser curtains*

Laser curtains 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 (LPE) is one last line of defense against laser beam exposure.

### Selecting Laser Protective Eyewear

Laser protective eyewear is wavelength specific.

The following information is needed to select the appropriate LPE:

- Wavelength(s)
- Mode of operation (continuous wave or pulsed)
- Maximum exposure duration (assume worst case scenario)
- Maximum irradiance (W/cm<sup>2</sup>) or radiant exposure (J/cm<sup>2</sup>)
- Maximum permissible exposure (MPE)
- Optical density (OD)

### 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 Protective 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 Protective 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 and Identification of Laser Protective Eyewear

LPE shall be labeled with the optical density and the wavelength(s) the eyewear provides protection for. The laser manufacturer is only responsible for the wavelength marked on the eyewear.



*Examples of LPE labeling*

Additional labeling may be added for quick identification of eyewear in multiple laser laboratories.

### NOTE:

Commercial LPE 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.

### **Inspection and Cleaning of Laser Protective Eyewear**

PLE 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 LPE. 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 LPE are listed below. There may be other considerations.

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

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

- Largest laser power and/or pulse energy for which protection is required
- Wavelength(s) of laser output
- 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 LPE 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 own 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 LPEr have come a long way. All users should be able to find 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%

*Optical Density table*

Optical density (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:

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

Where: AEL is the accessible emission limit (that is, the MPE multiplied by the area of the limiting aperture) and Q 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 attenuate adequately 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. Users must be aware that alignment eyewear will not provide full protection.

## 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<sub>2</sub> 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 (166 nm-20 um)

- 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.

### IR: 800 nm Beams

- No wavelength has been involved in more LASER EYE INJURIES in the past 15 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), one 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:Sapphire 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.

### **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:Sapphire 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:Sapphire 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 repetition 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. Laser users should be checking optic to optic and often.

### General Items

Special attention should be paid to the following items:

#### 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 incidents 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.



*Example of mounted polarizing prism*

#### Back Reflections (Ghost Reflections)

Ghost or 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 are tilted to optimize efficiency, which causes the stray back-reflection to 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 common 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 beam optics for stray reflections.

When setting up an optical trap on an inverted microscope, 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.

## **Moving Optics**

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 logbook, whiteboard or other means the group decides on. 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 the beam vaporizes it. 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 the 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 aluminum color. Please remember mounts can send beams off in any direction if struck. Having a laser beam hitting optical mounts introduces 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.

The mirrors are generally mounted in one of several ways:

- Internal fixed - The mirror is fastened in place with no means of adjustment possible. Epoxy was often used on older HeNe (and no doubt other) laser tubes.
- Internal adjustable 1 - The mirror is mounted on an extension of the end of the tube which has a restricted or narrowed region designed to be bent or flexed. External stabilizers (three-screw collars found on some tubes) can provide some degree of adjustment.
- Internal adjustable 2 - The mirror is mounted on a highly flexible tube requiring external adjustment screws. Some Ar/Kr ion and HeCd lasers use this arrangement.
- External kinematic - The mirror is mounted on a plate which can be tilted in X and Y via a pair of thumb screws or set screws. This arrangement is probably the most common for high quality lasers and other precision mirrors since it is intuitive to use. Variations include the use of a large spherical bearing tiltable in X and Y instead of a spring mounted plate.
- External gimbal - The entire mirror mount rotates on a (partial) spherical bearing so that both axes rotate about a common point. Like the kinematic mount, X and Y motion are independent. This design is more elegant than the kinematic mount and more complex to manufacture.
- External three-screw - The mirror is mounted on a plate with three equally spaced thumb screws or set screws. This is also quite common but not quite as easy to use.
- External X-Y position - Where the mirror has a concave surface, moving it up/down or left/right (rather than tilting it as is done with all the previous techniques) will also precisely adjust the alignment. This approach is used in some lasers for user fine tuning (with kinematic or three-screw adjusters used for factory alignment).

Some lasers use a combination of several of these approaches.

## How to Select Optical Mounts

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.

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  $45^\circ$  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.



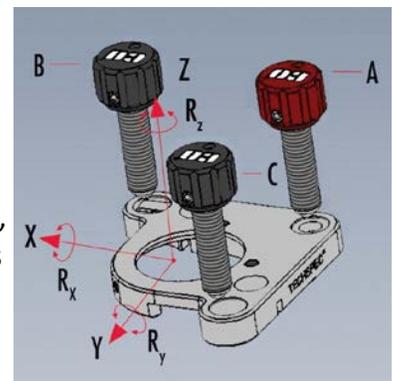
*Example of Gimbal mounts*

### Choosing Optics

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.

### Kinematic Optical Mounts

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.



*Example of kinematic optical mount*

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.

Sensitivity is another parameter related to resolution, and is often provided by manufacturers. 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  $1^\circ$  turn of the screw. The movement of the optic that corresponds to a  $1^\circ$  turn is what is used to define sensitivity.

Thermal stability, gravity over time, vibration can affect the optical system performance.

## Chapter 6. Know Your Optics

Know the functionality and limitations of your optics. For reference, some of the basic optics are listed below. Self-study is strongly recommended.

### Polarizers

A polarizer is a type of optical filter where the light transmission depends strongly on the polarization state. Normally, light with linear polarization in a certain direction is passed, and light polarized in an orthogonal direction is blocked: it may be absorbed or redirected.

### Types of Optical Polarizers

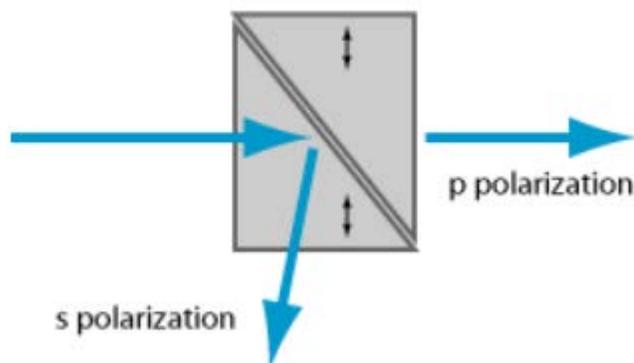
#### Absorptive Polarizers (Dichroic Polarizers)

Absorptive polarizers are used for low-power applications. They consist of a special doped plastic sheet (a polymer materials), which has been stretched in one direction, such that the polymer chains are more or less aligned along one axis. Light in polarization direction along the chains is strongly absorbed, whereas the absorption is weak for light with a perpendicular polarization direction.

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

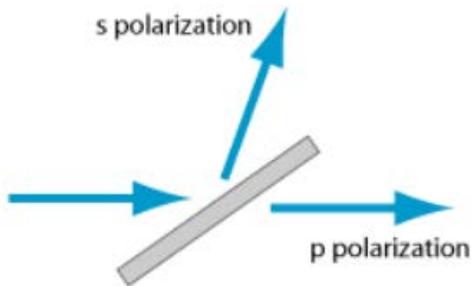
#### Polarizing Beam Splitters Based on Birefringence

Polarizers where light with the “rejected” polarization state is not absorbed but only sent to some other direction can handle much higher optical powers. The most common type of polarizing beam splitters exploit birefringence of a transparent crystalline material such as quartz ( $\text{SiO}_2$ ), calcite ( $\text{CaCO}_3$ ), yttrium vanadate ( $\text{YVO}_4$ ), beta barium borate (BBO) or magnesium fluoride ( $\text{MgF}_2$ ). Often, two pieces of such material with different orientations of the optical axis are cemented together (or joined with a small air space). The device is often mounted in a polymer housing, which may also contain a beam dump for light with the rejected polarization direction.



*A Glan–Taylor prism. Total internal reflection occurs for the s polarization, whereas there is little reflection for p polarization due to operation close to Brewster's angle.*

## Thin-Film Polarizers



*Illustration of thin-film plate polarizers*

There are different kinds of thin-film polarizers. Thin-film plate polarizers (on the figure above) consist of a dielectric coating on some glass substrate. For non-normal incidence (in a certain range of incidence angles), the reflectivity of the coating can be strongly polarization-dependent. It is possible to have the “rejected” beam at a deflection angle of  $90^\circ$ , which is often convenient. However, many thin-film plate polarizers are operated at Brewster's angle, so that no anti-reflection coating is required on one side.

There are *polarizing cube beam splitters* where the dielectric coating is applied to one  $45^\circ$  prism and another  $45^\circ$  prism is cemented to the coating, such that overall one obtains a cube.

## 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.



*Examples of cube-beam splitters*

Some polarizers are rotating elements that reflect/transmit at angles. 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 and contain the rejected beam.

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 Splitters

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

Beam splitters are used in laser systems, optical interferometry, fluorescence, and biomedical instrumentation. They come in three basic forms: plate, pellicle, and cube. All are made using a partially reflecting coating, but due to differences in construction, they differ in power handling. Plate beam splitters are made using a coated substrate, and thus exhibit beam offset and ghost reflections from the second surface. Cube beam splitters avoid beam displacement by working at  $0^\circ$  angle of incidence and placing the coated surface between two right angle prisms, but power handling can be limited if epoxy is used to bond the prisms. Optical contacting can increase the laser damage threshold, though ghost reflections from the entry and exit faces can still occur. A pellicle beamsplitter may appear to solve these problems by stretching an elastic membrane (sometimes coated) over a metal frame until it is very thin, but in reality, coating options are limited, and they offer lower power handling than cube beam splitters. When working with laser light, a plate or cube beamsplitter offers the best combination of optical performance and power handling.

## Types of Beam Splitters

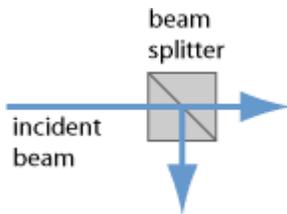
### Dielectric Mirrors



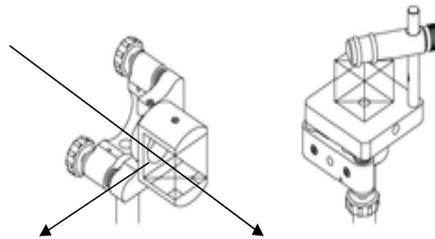
Illustration of *partially reflecting mirror, used as a beam splitter*

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 in the picture 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.

### Beam Splitter Cubes



*Schematics of cube beam splitters*



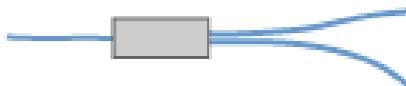
*Illustration of mounted cube beam splitters*

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.

### Fiber Optic Beam Splitters



*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.

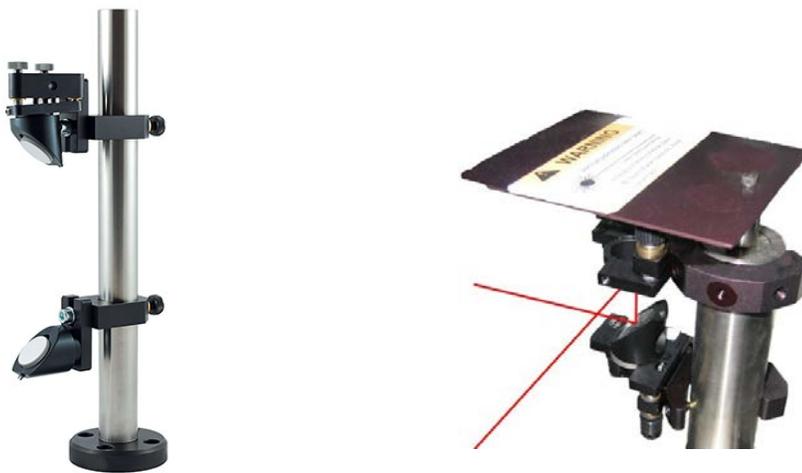
## Other

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.



*Illustration of periscope assembly without and with external beam block*

## Iris

The iris is an extremely useful alignment aid. 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.



*Examples of irises*

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 helps to adjust the aperture without risk of obstructing the beam path.

## Flip Mirror



*Example of flip mirror*

The role of the flip mirror is to allow moving an optic in and out of the 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. Always mount the mirror to flip downward to prevent unexpected redirection of the beam.

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

## Mirrors

### Dielectric (Dichroic) Laser Mirrors

Mirrors used inside the laser resonator are almost always of the so-called dielectric variety using multiple layers of transparent insulating materials rather than metal films. (These may also be called dichroic.)

There are many types of dielectric mirrors but the most common are:

- **Narrowband Dielectric Mirrors.** These are designed for a specific reflectivity at a single wavelength or narrow range of wavelengths. They are suitable for lasers outputting a single, fixed wavelength like HeNe and single line Ar/Kr ion types.



*Examples of mirrors*

- **Broadband Dielectric Mirrors.** These are designed to be reflective over a wide range of wavelengths. They are used where a laser can be set up for one of several wavelengths or where multiple wavelengths may be generated simultaneously. For example, a mixed-gas (Ar/Kr) ion laser producing RGB lines for a full color laser show or an argon ion laser with an adjustable intra-cavity line selecting prism.

The angle of the mirror greatly affects the transmission of the beam, described with Optical Density. Often the 0° interference mirrors are nearly perfect (OD6). However, the 45° ones are barely OD3.

### **Metallic Mirrors**

Metallic 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.

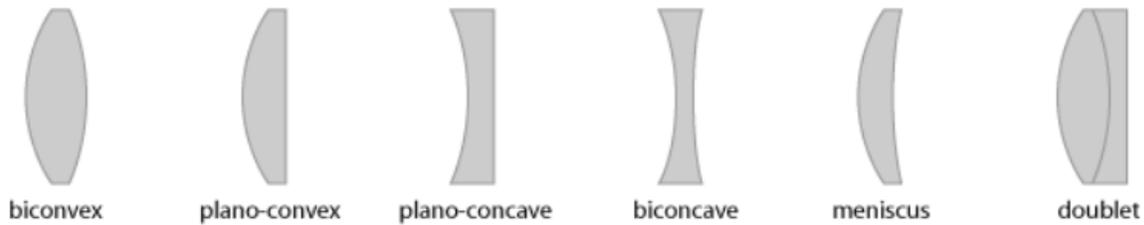
### **Diffraction Gratings**

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 the 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**

The lenses are transparent optical devices affecting the wavefront curvature of light. An optical lens consists of a transparent medium, where light enters on one side and exits on the opposite side. Often, but not always, it has at least one curved surface. Its purpose is to modify the wavefront curvature of the light, which implies that light is focused or defocused.

Optical lenses come in different types as shown on the picture.



*Different types of lenses*

Many lenses have anti-reflection coatings on their surfaces, which substantially reduce the reflections caused by the refractive index change at the surface. Note, however, that this works only in a limited wavelength range. There is a trade-off between a high suppression of reflections and a broad operation bandwidth.

There are also abrasion-resistant coatings, making lenses more robust.

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



*Examples of lenses*

### **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.

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

## **Slits**

### **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.



*Example of a slit*

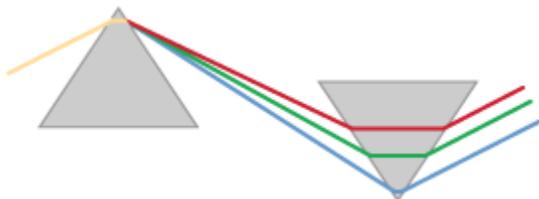
## Scanning Knife Edge

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  $\sqrt{2}$ .

## 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.

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*).



*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.

## Wedge Prism

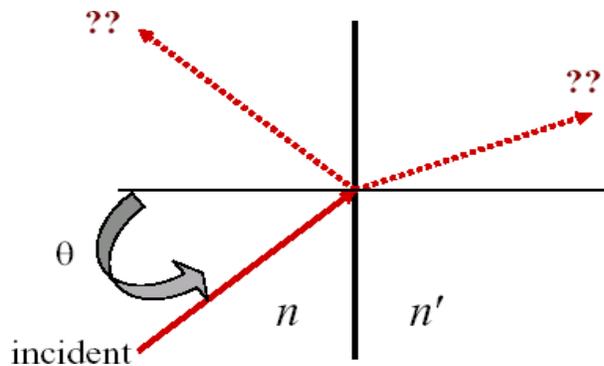
Wedge prisms are designed to be used, either individually or in a pair, for beam steering applications. This is done by individually controlling the rotation of each.

*Examples of wedge prism*



## Birefringence

Birefringence is the polarization dependence of the refractive index of a medium. Birefringent crystals divide an entering beam into two beams having opposite polarization, propagating in different directions.



*The angle of incidence at the dielectric interface*

## Wave Plates

Wave plates are optics that alter the polarization of a beam travelling through them.

These transparent plates have a carefully adjusted birefringence, which are mostly used for manipulating the polarization state of light beams. A wave plate 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.



*Wave plates*

### Half-Wave Plate

A half-wave plate can be used to rotate the plane of 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.



*Illustration of tilted solid etalon in a laser beam*

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.

## Filters

### Spatial Filters

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

### Saturable Absorber

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, for cleaning up pulse shapes, and in optical signal processing.

### Planar Waveguides

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

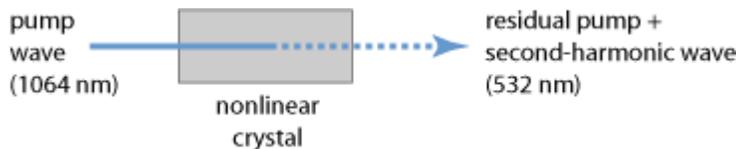
neodymium-doped YAG layer can be embedded in undoped YAG with slightly lower refractive index.

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

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 ( $\rightarrow$  *nonlinear crystal materials*). This can give rise to the phenomenon of frequency doubling, 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 (SHG)*. 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.



*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.*

## Band-pass Filters

A band-pass filter is a device that passes frequencies within a certain range and rejects (attenuates) frequencies outside that range.

There is an engraved arrow on the edge of the filter to indicate the recommended direction for the transmission of light through the filter. Although the filter will function with either side facing the source, it is better to place the coated side toward the source. This will minimize any thermal effects or possible thermal damage.

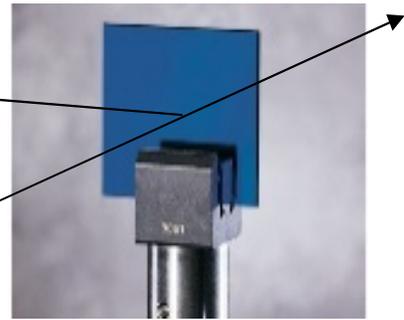
The filter is intended to be used with collimated light normally incident on the surface of the filter. For uncollimated light or light striking the surface at an angle not normally incident to the surface the central wavelength (wavelength corresponding to peak transmission) will shift toward lower wavelengths and the shape of the transmission region (passband) will change. Varying the angle of incidence by a small amount can be used to effectively tune the passband over a narrow range.

## Neutral Density (ND) 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 ND filters is to reduce the amount of light that can pass through the lens.

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.

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



*Example of ND filter*

## Neutral Density Filter Wheel



*Example of ND filter wheel*

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 and in any system that is required to work at 100% of its aperture.

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.

## Retroreflectors

Retroreflectors are used to reflect light back to its source.

## Anti-Reflection Coatings (AR Coating)

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).

### Multilayer Coatings

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, more complicated designs may be used. A general tradeoff of such multilayer designs is between a low residual reflectivity and a large bandwidth.

## Microscope

Microscopes have certain hazards associated with them. The beam may be as close as 12" from the height of the microscope eyepiece. You may casually bend down to pick some dropped item and end up coming in contact with the laser beam. Minimize this danger by using lower tables and proper beam 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 right after the laser exit to reduce power used during alignment to the minimum necessary.

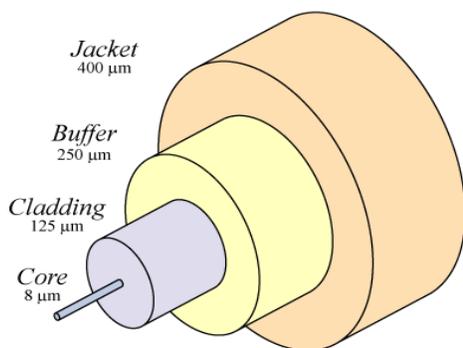
Some nonlinear optical setups may require full power to get the SHG you're trying to align, but for linear/CW systems this is an easy safety step. Use a Video/CCD camera for sample viewing rather than looking through eye pieces.

## Chapter 7. Fiber Optics

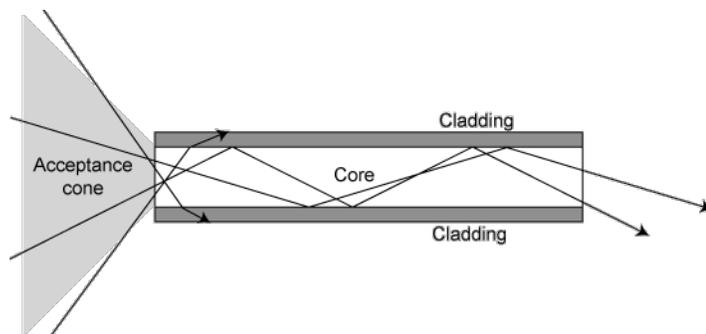
Fiber optics is the technology based on optical fibers, i.e., on mostly flexible waveguides for light. Optical fiber is a flexible, transparent fiber made of glass (silica) or plastic, slightly thicker than a human hair. It functions as a waveguide, or “light pipe”, to transmit light between two ends of the fiber.

Optical fibers typically include a transparent core surrounded by a transparent cladding material with a lower index of refraction. Light is kept in the core by total internal reflection. This causes the fiber to act as waveguide. When light traveling in an optically dense medium hits a boundary at a steep angle, the light will be completely reflected. This is called total internal reflection. Light travels through the fiber core, bouncing back and forth off the boundary between the core and cladding. Because the light must strike the boundary with an angle greater than the critical angle, only light that enters the fiber within a certain range of angles can travel down the fiber without leaking out. This range of angles is called the acceptance cone of the fiber.

Optical fiber can be used as a medium for telecommunication and computer networking because it is flexible and can be bundled as cables. It is especially advantageous for long-distance communications, because light propagates through the fiber with little attenuation compared to electrical cables. Each fiber can carry many independent channels, each using a different wavelength of light.



*Illustration of a typical single-mode fiber*



*Illustration of a total internal reflection*

The most common type of single-mode propagation fiber has a core diameter of 8–10 micrometers and is designed for use in the near infrared waveband. The mode structure depends on the wavelength of the light used, so that this fiber actually supports a small number of additional modes at visible wavelengths. They are used in a long-haul communications.

Apart from the fibers, there are various types of fiber-optic elements, which may be connected with each other using optical fibers. Some of these are essentially made of fibers, whereas others consist of utterly different materials but are coupled to fibers, i.e., they offer fibers for input and output purposes. Some examples for fiber-optical components:

- Fiber-coupled laser diodes can be used as light sources for fiber optics.
- Fiber couplers can be used e.g. for combining light from different sources into one fiber, or as fiber splitters e.g. for distributing television (cable-TV) signals to different users.
- Fiber Bragg gratings can be used as strongly wavelength-selective fiber-optic reflectors.
- Fiber connectors allow one to have removable and reconfigurable connections between fiber devices – similar to electrical connections, although often more sensitive.
- Fiber collimators provide a connection between fiber optics and free-space optics: they can collimate the output from a fiber, or launch a collimated beam into a fiber.
- Fiber-coupled Faraday isolators, rotators and circulators can be used for manipulations based on beam polarization.
- There are various others fiber-coupled components for beam manipulation, such as fiber-optic modulators and saturable absorbers.
- There are fiber-coupled power meters and spectrometers for monitoring optical powers and optical spectra. Other devices can monitor the polarization state.

There are some hazards everyone working with optical fibers should be aware of:

- Hard to tell if fiber is live or not
- Failure to cap connection points
- Non-laser hazards: sharps, chemicals, confined space

The best safety control when using optical fiber is to shut off the laser before working with fiber.

## Eye Protection

To be certain fibers are safe to inspect or work with, always check fibers with a fiber optic viewer to ensure no light is present, or treat the fiber as if it is alive and do not look at its end.



*Fiber optic viewer*

## Fiber Fragment Control

A common problem is getting scraps of fiber in your eye when working with fiber. Every termination and splice produces shards (scraps) of optical fiber which is potentially very harmful to your eyes and skin or may stick in your clothing and be carried to other locations where it may be harmful to others. These shards of fiber can easily puncture your skin, burying themselves deep enough to be difficult to pull out.

## Use of Chemicals

Fiber optic splicing and termination use various chemical cleaners and adhesives as part of the processes. Normal handling procedures for these substances should be observed. If you are not certain of how to deal with them, ask the manufacturer for a SDS. Always work in well-ventilated areas. Avoid skin contact as much as possible, and stop using chemicals that cause allergic reactions. Even simple isopropyl alcohol, used as a cleaner, is flammable and should be handled carefully.

## General Guidelines for Working with Fibers

- Always wear safety glasses with side shields and protective gloves. Treat fiber optic splinters the same, as you would glass splinters.
- Keep all food and beverages out of the work area or table where the fibers are cleaved and spliced. If fiber particles are ingested, they can cause internal hemorrhaging.
- Wear disposable aprons to minimize fiber particles on your clothing. Fiber particles on your clothing can later get into food, drinks, and/or be ingested by other means.
- Never look directly into the end of fiber cables until you are positive that there is no light source at the other end. Use a fiber optic viewer to make certain the fiber is dark.
- Do not touch your eyes while working with fiber optic systems until your hands have been thoroughly washed. Contact lens wearers must not handle their lenses until they have thoroughly washed their hands.
- Keep all combustible materials safely away from the curing ovens.
- Put all cut fiber pieces in a properly marked container for disposal.
- Thoroughly clean your work area when you are done.
- Do not smoke while working with fiber optic systems. The ashes from smoking contribute to the dirt problems with fibers, in addition to the possible presence of combustible substances.

## Chapter 8. Laser Beam 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, remove watches, rings, dangling badges, necklaces and reflective jewelry 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, have all equipment and materials 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.
- Post the area with appropriate warning sign.

### 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.
- Skin protection should be worn on the face, hands, and arms when aligning at UV wavelengths.
- Enclose the beam as much as practical.
- Close the shutter as much as practical during course adjustments.
- Secure optics and optics mounts to the table as much as practical.
- Secure beam stops to the table or optics mounts.
- Label areas where the beam leaves the horizontal plane.
- Individuals performing alignment are responsible to search for stray reflections and contain them. Any stray or unused beams must be terminated.

- Visualize invisible beams with cameras, IR/UV cards, cards, thermal fax paper, or Polaroid film or by a similar technique. Laser users should be aware that such materials may produce specular reflections or may smoke or burn.
- Pulsed lasers are aligned by firing single pulses when practical.

Additional laser alignment controls are encouraged.

## Post-Alignment

- Normal laser hazard controls shall be restored when the alignment is complete. 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.

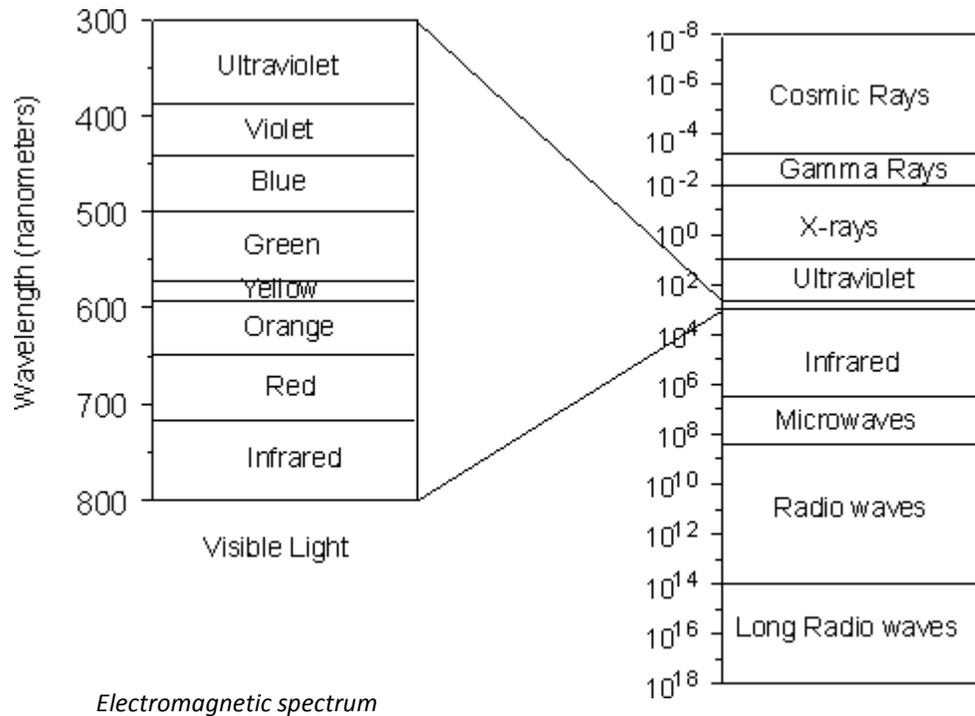
## Accidents

The highest probability for an accident is while aligning laser beams. While Berkeley Lab strives to avoid laser accidents, they have occurred. Below is a listing of some common contributing factors that lead to laser related accident:

- 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 A. Nature of Light

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. Visible light represents a narrow group of wavelengths between about 380 nm and 730 nm (1 nm =  $10^{-9}$  m).



Our eyes interpret these wavelengths as different colors. 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,  $6.62517 \times 10^{-27}$  erg.sec

$\nu$  = frequency

C = velocity of light =  $2.99793 \times 10^{10}$  cm/sec

$\lambda$  = wavelength

The velocity of light,  $C$ , in a vacuum is  $2.99793 \times 10^{10}$  cm/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,  $\nu$ , remains constant when the light passes through a substance. Thus, if the velocity,  $C$ , is reduced on passage through a substance, the wavelength,  $\lambda$ , must also decrease.

Here, we define the 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,  $C_m$ .

$$n = C/C_m$$

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

### 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:

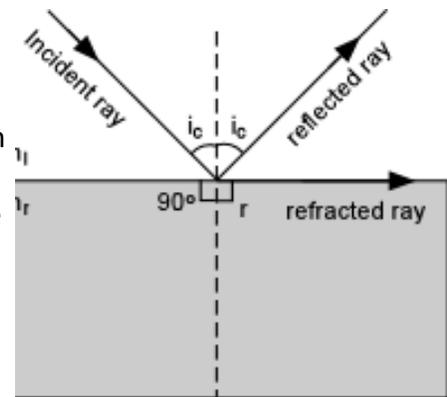
$$n_i \sin (i) = n_r \sin (r)$$

Note that if the angle of incidence is  $0^\circ$  (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  $\sin(0^\circ) = 0$ , 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  $r = 90^\circ$ . In this case, applying Snell's law:

$$n_i \sin (i_c) = n_r \sin (90^\circ) = n_r, \text{ since } \sin (90^\circ) = 1$$

$$\sin (i_c) = n_r/n_i$$



*Illustration of reflection and refraction of light*

## 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.

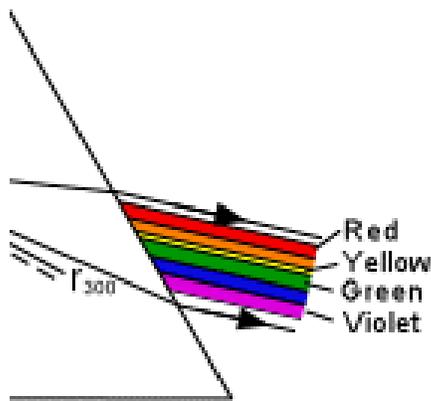


Illustration of dispersion of light

## 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, the 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,  $I_0$ , 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  $I/I_0$

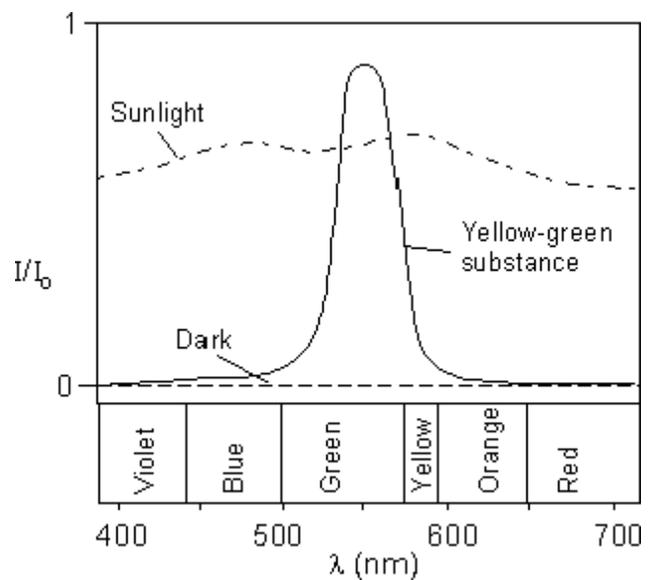


Illustration of absorption of light

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  $90^\circ$  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).

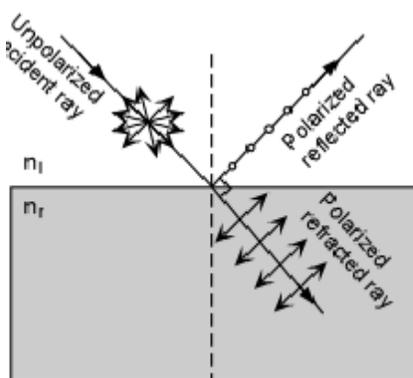
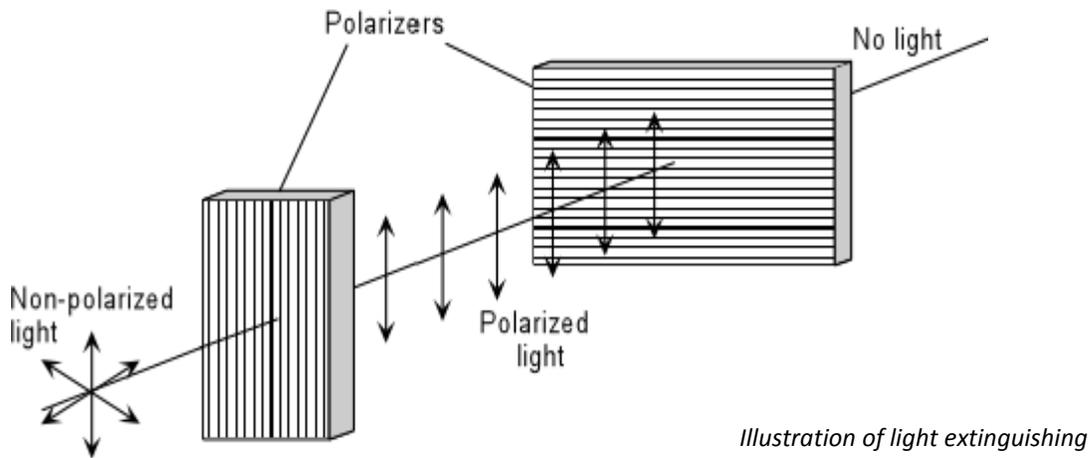


Illustration of light polarization

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. 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.



Polaroid sunglasses use these same principles. 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 B. Laser Bio-effects

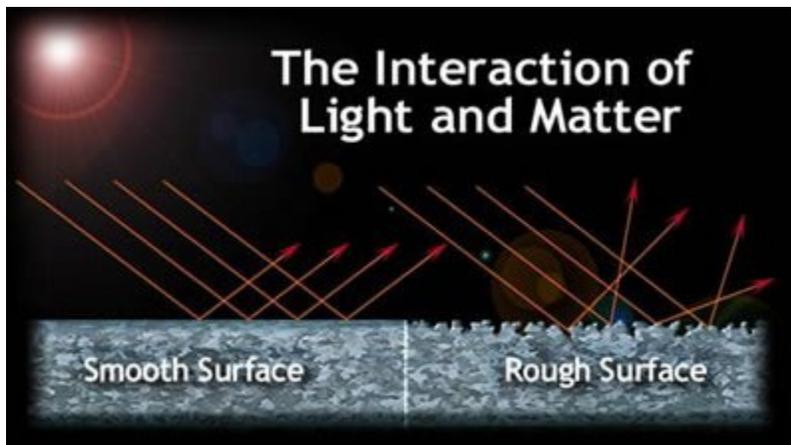
The main concern over laser use has always been the possibility of eye injury. While skin presents a greater target, the injury to the eye is that drives laser safety and controls. The effects of laser radiation vary with the wavelength and part of the eye it interacts with. In addition, biological effects from direct exposure and diffuse reflection exposure differ.

### Exposure Type

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

A specular reflection, which is a reflection off a mirror like surface has the same effect as a direct exposure. Specular reflections are generally less than 100%.

A diffuse reflection is 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.



*Illustration of specular (from smooth surface) and diffuse (from rough surface) reflection*

### 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  $1 \text{ mW/cm}^2$ , the irradiance at the retina will be  $100 \text{ W/cm}^2$ . Even a 4% reflection off an optic can be a serious eye hazard. 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.

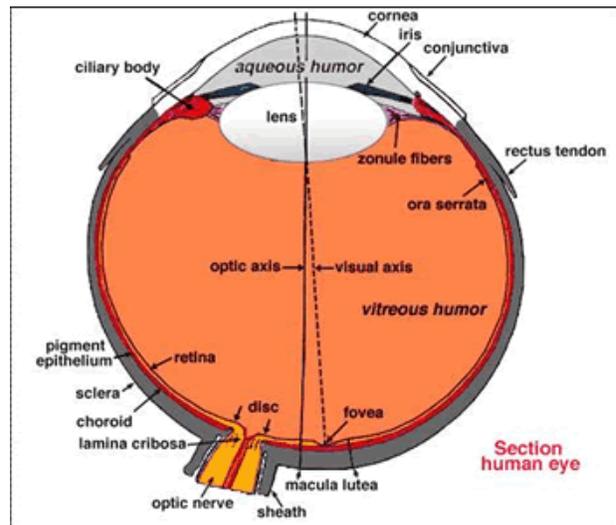
## The Path of Visible Light

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.

## Human Eye Structure

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.



*Illustration of eye structure*

### 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 and 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.

## 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 denaturation of proteins in the lens resulting in the formation of cataracts.

Wavelength	Eye	Skin
UV-C (100-280 nm)	Photokeratitis "Welder Flash"	Erythema (sunburn) Skin cancer
UV-B (280-315 nm)	Photokeratitis "Welder Flash"	Accelerated skin aging Increased pigmentation Skin cancer
UV-A (400-400 nm)	Photochemical cataract	Pigment darkening Photosensitive reaction
Visible (400-780 nm)	Photochemical and Thermal retinal injury	Photosensitive reaction Skin burn
IR-A (780-1400 nm)	Retinal burn, possible cataract	Skin burn
IR-B (1400-3000 nm)	Corneal burn, aqueous flare, possibly cataract	Skin burn
IR-C (3000-10 <sup>6</sup> nm)	Corneal burn only	Skin burn

*Summary of basic laser biological effects*

### Visible Light and Infrared A (400 - 1400 nm)

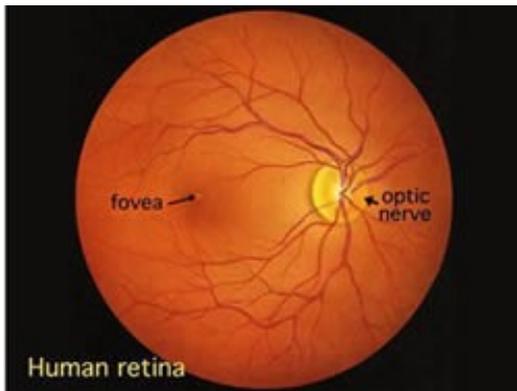
The cornea, lens and vitreous fluid are transparent to wavelengths. Damage to the retinal tissue occurs by absorption of light and its conversion to heat by the melanin granules in the pigmented epithelium or by photochemical action to the photoreceptor. The focusing effects of the cornea and lens will 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 $1.0 \times 10^6$ nm)

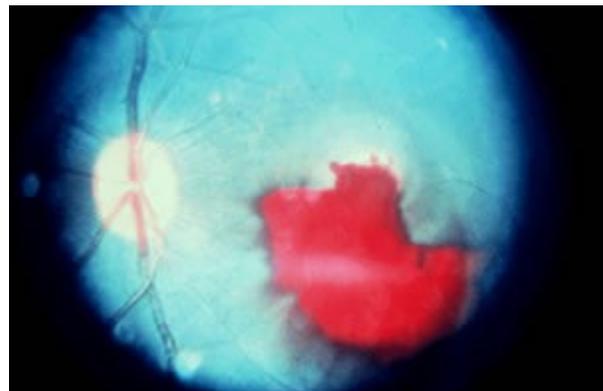
Corneal tissue will absorb light with a wavelength longer than 1400 nm. Damage to the cornea results from the absorption of energy by tears and tissue water causing a temperature rise and subsequent denaturation of protein in the corneal surface.

### Signs of Eye Exposure

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.

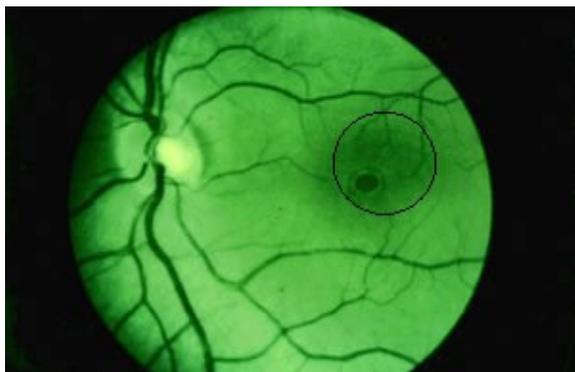


*Normal eye*



*Vitreous Hemorrhage*

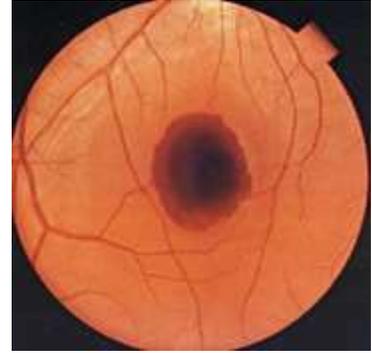
The exposure to a visible laser beam can be detected by a bright color flash of the emitted wavelength and an after-image of its complementary color (e.g., a green 532 nm laser light would produce a green flash followed by a red after-image). When the retina is affected, there may be difficulty in detecting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



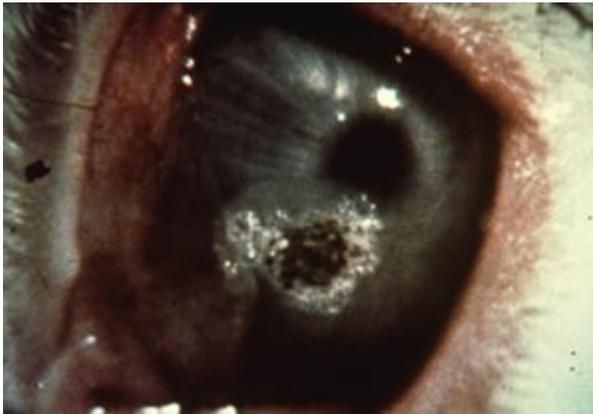
*Large retinal burn from diffuse laser exposure Area of retinal burn*

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.

Exposure to the invisible carbon dioxide (CO<sub>2</sub>) laser beam (10,600 nm) can be detected by a burning pain at the site of exposure on the cornea or sclera.



*Blood pool, one week post-injury*



*Corneal burn from CO<sub>2</sub> laser exposure (Rabbit eye)*

## Damage Mechanisms

### Electromechanical/Acoustic Damage

This type of damage requires beams of extremely high power density ( $10^9$ – $10^{12}$  W/cm<sup>2</sup>) in extremely short pulses (ns) to delivery fluencies of about 100 J/cm<sup>2</sup> and very high electric fields ( $10^6$ – $10^7$  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.

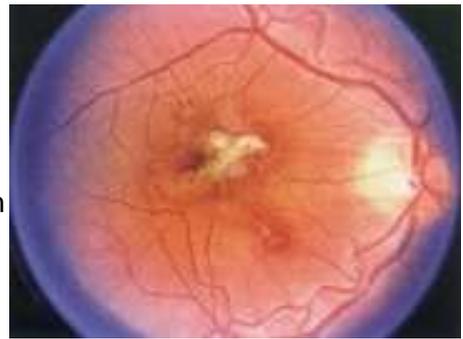
### Photoablation

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  $10^8$  W/cm<sup>2</sup> 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

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.



*Thermal damage from Nd:YAG pulses*

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, hemoproteins, 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.

### 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

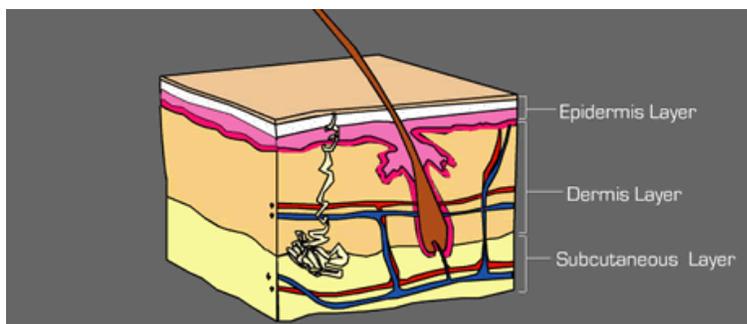
The epidermis is the outer layer of skin. The thickness of the epidermis varies in different types of skin. It is the thinnest on the eyelids at 0.05 mm and the thickest on the palms and soles at 1.5 mm.

## Dermis

The dermis also varies in thickness depending on the location of the skin. It is 0.3 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

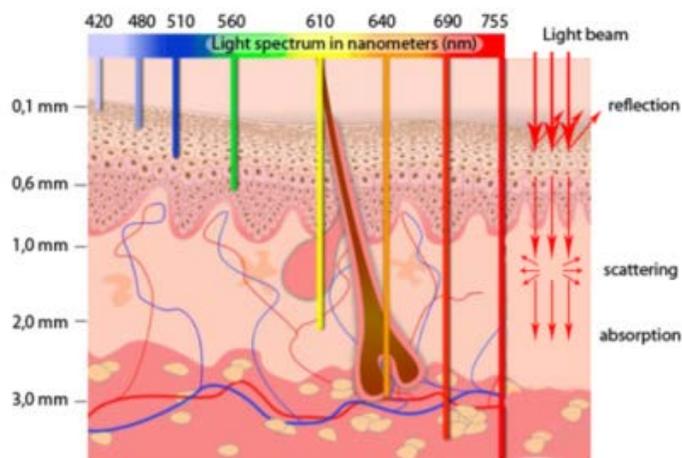
The subcutaneous tissue is a layer of fat and connective tissue that houses larger blood vessels and nerves. This layer is important in the regulation of temperature of the skin itself and the body. The size of this layer varies throughout the body and from person to person.



*Skin structure*

## Wavelength Dependence in Absorption by the Skin

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



*Skin penetration by wavelength*

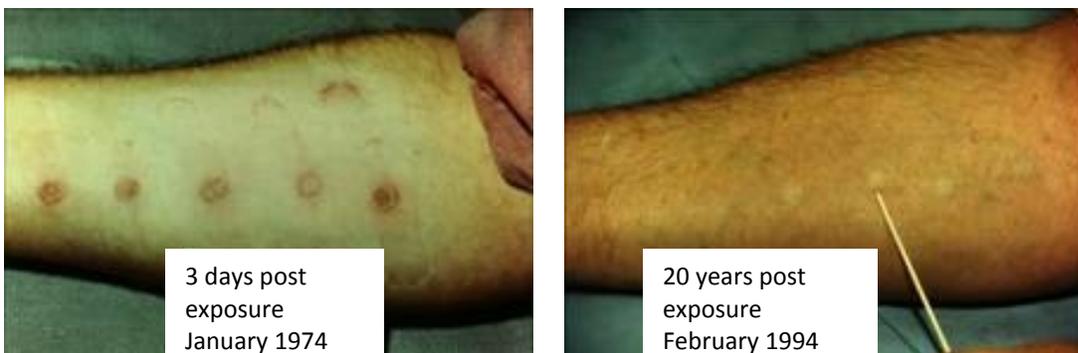
than 10 seconds to the skin from far-infrared and far-ultraviolet radiation are superficial and may involve changes to the outer dead layer of the skin. A temporary skin injury may be painful if sufficiently severe, but it will eventually heal, often without any sign of injury. Burns to larger areas 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  $0.1 \text{ W/cm}^2$  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 (315 nm - 400 nm) 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 (280 nm - 315 nm) either directly on DNA or from effects on potential carcinogenic intracellular viruses.

Exposure in the shorter UV-C (200 nm - 280 nm) 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.



*Twenty year evaluation of CO<sub>2</sub> laser ( $5 \text{ W/cm}^2$ , 1 sec. at 10,600 nm) exposure of human skin.*

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