# Lasers, Eyeballs, and Peaceful *Cohabitation*

*Peter N. Saeta*

28 August 2013

When you are little, your parents and teachers tell you not to look at the Sun: it will blind you. The Sun is the "kinder blinder." It takes a few moments to cause permanent damage to your retina, time for your reflexes to close your eyes, avert your gaze, and save your vision.

Most research lasers are unforgiving and unkind. Most pulsed lasers systems emit many pulses before your reflexes can kick in, any one of which has enough energy to destroy the portion of your retina upon which it is focused. Like any piece of dangerous equipment (automobiles, high-voltage circuits, radioactive sources), you need to understand the hazards and how to avoid them before you begin working in the laboratory.

The following provides a brief introduction to lasers in general and how to operate them safely. Besides discussing some of the optical physics of lasers, it concentrates on how your eye responds to light and how it can be damaged by laser beam. A second document summarizing safe operating procedures accompanies this one, and concludes with an informed consent form. As you work through this document, feel free to ask questions and make comments. Also, please work the exercises to gain familiarity with the magnitudes involved.

## 1 How a laser operates

A laser produces an extremely bright beam by channeling the optical emission of an excited medium into a nearly **collimated** (parallel) beam. The light source is called the gain medium, and may be a neutral gas (as in a helium-neon, or HeNe, laser); an ionized gas (as in an argon-ion laser); a liquid dye; a doped crystal or glass (e.g., titanium-sapphire, Nd:YAG, or Nd:glass); a semiconductor quantum well (diode lasers). The gain medium must be pumped either electrically or optically to produce a **population inversion**, meaning that there are more atoms (or molecules or ions or electrons) in the excited state than in the de-excited state. An inverted medium provides gain to a wave of appropriate wavelength passing through it, since it has greater probability of stimulating an emission from an excited state than being absorbed by a de-excited state.

A laser oscillator also requires feedback so that a beam passes through the gain medium many times. By surrounding the gain medium with high-reflectivity mirrors to form a resonant cavity, it is possible to arrange that on a round trip through the gain medium, the average intensity of a beam that is heading in the right direction will be increased. As the gain medium is pumped to produce a significant population in the excited state, photons will be emitted spontaneously in all directions. Virtually all head in directions that prevent them from passing again through

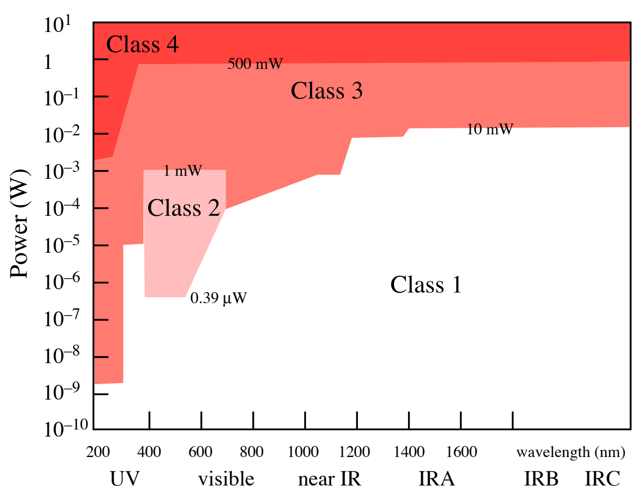
| Class | Conditions | Danger Level |
|---|---|---|
| Class 1 | $P \le 0.39\,\mu W$ | safe under all circumstances |
| Class 2 | $0.39\,\mu W \le P \le 1\,mW$ | no danger for an exposure of less than 0.25 seconds |
| Class 3A | $1\,mW \le P \le 5\,mW$ | Do not look into the beam, especially through an optical instrument |
| Class 3B | $5\,mW < P \le 0.5\,W$ | |
| Class 4 | $P > 0.5\,W$ | Dangerous to both the eye and the skin, either by a direct beam or a diffusely scattered one |

Table 1: Laser classifications

the gain medium; only a few happen to head toward the mirrors in just the right way to return to the gain medium to be amplified. If the net gain in passing through the medium exceeds the scattering and absorption losses distributed throughout the cavity, the intensity in that "optical mode" will grow exponentially. The mode *oscillates* or *lases*. Stimulated emission dominates over spontaneous emission and a narrow beam is produced, typically leaking out of one of the mirrors which is designed to transmit a few percent of the light incident upon it. Because of the small cross section of the beam, a 5-mW HeNe laser beam is much brighter than a 100-W light bulb, despite being 4 orders of magnitude weaker in average power.

## 2 Classification of Lasers

Lasers are classified according to the danger their beams pose to the skin and eyes. The following table and Fig. 1, show how power and wavelength get mapped into classes. Class 1 lasers are so weak that they are safe under all circumstances. I'm not sure that I have ever met such a laser. Rapidly pulsed lasers pose additional risks associated with the high *instantaneous* power at the




Source: Sécurité Laser, 2001

Figure 1: Lasers are classified according to their wavelength and power. The weakest beams are designated Class 1, and are generally safe under all circumstances. There are few such lasers! They have powers below 0.39 μW, which is considerably weaker than a typical helium-neon laser. Higher-numbered classes are progressively more dangerous.

pulse peak, even when the average power is more modest.

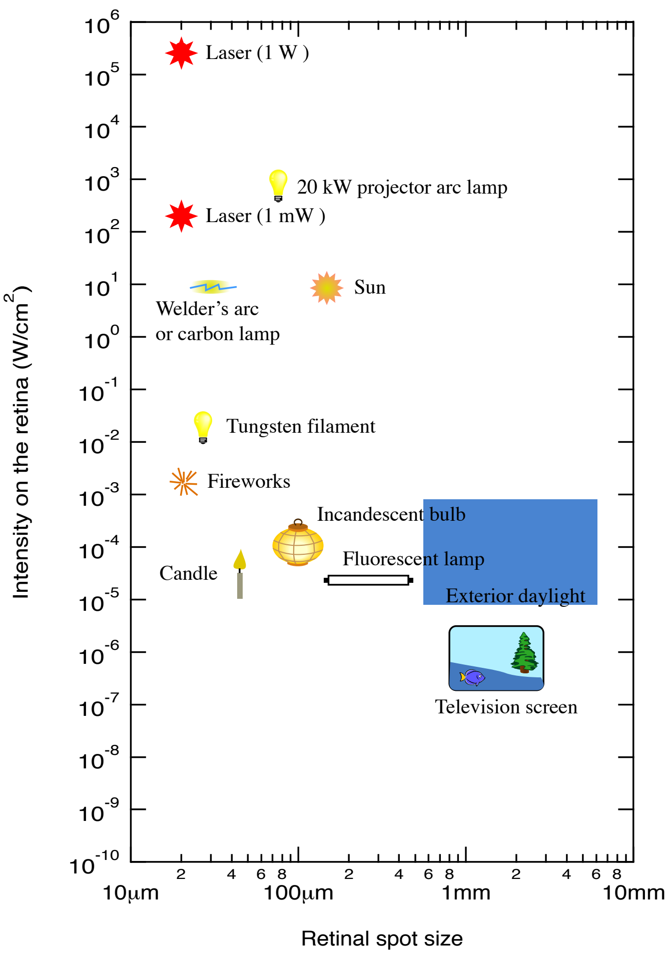
# 3 Eye safety

The retina is the sensor responsible for the translation of visible photons into chemical signals that can be sent down the optic nerve to the brain for processing into vision. The retina must cope with a tremendous range in signal strength, from darkness to bright sunlight, over ten orders of magnitude. Perhaps not surprisingly, bright (indirect) sunlight is about the maximum our eyes can handle; the minimum depends on the individual and the wavelength, but under optimal conditions the human eye can detect a signal of just a few photons.

Because the eye includes a high-quality lens, the "optical gain" of the eye is quite high, up to about half a million. This means that the intensity on the retina may be hundreds of thousands of times greater than the intensity of the beam that arrives at the eye. For a uniform beam focused by a lens of focal length $f$ and diameter $\phi$, the central region of the Airy pattern in the focal plane has a radius given by

$$r = 1.22\frac{\lambda f}{\phi} \tag{1}$$

**Exercise 1** Estimate the factor by which the intensity of a uniform beam is increased on focusing by a human eye.




Source: CEA, Sécurité Laser, 2001

Figure 2: Approximate intensities on the retina of various common sources of illumination.

The danger a laser beam poses to the eye depends on its average power, wavelength, and size. Depending on the wavelength, the light may be absorbed by the front layer of tissue, may pass through all tissues of the eye, including the retina, without coming to a focus, or may be focused on the retina. Figure 3 shows the intensity on the retina of various sources of light. Two issues are at

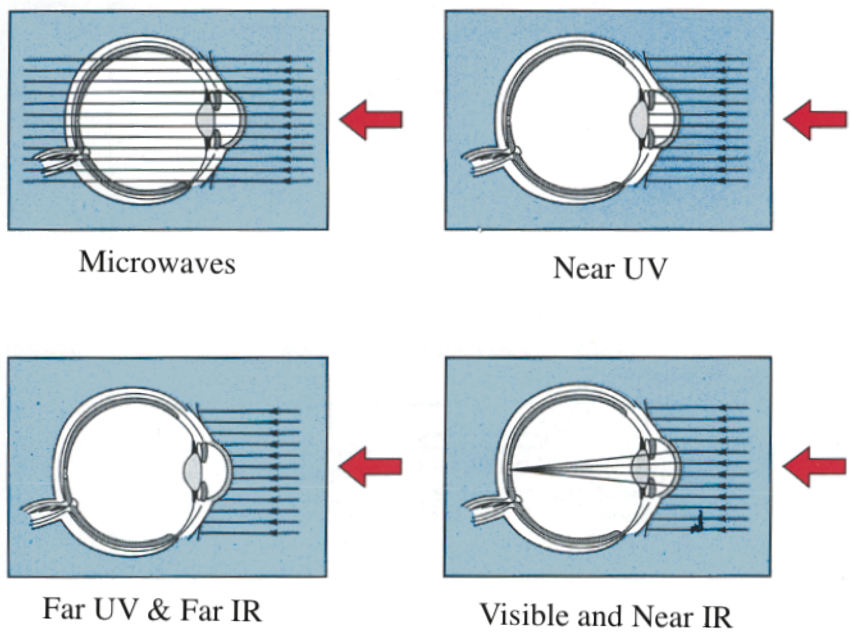



Figure 3: How the eye absorbs different wavelengths of light.

play: the tightness of the focus and the power of the source. For a diffuse source such as a fluorescent tube, the total amount of light emitted may be significant, but the source extends over a large area, so that the concentration of power on any location of the retina is small. Because a laser beam tends to be very nearly collimated (parallel), the focal spot on the retina for a relaxed eye focused at infinity is very small, making the intensity (power per unit area) high enough to cause damage.

How the eye becomes damaged depends upon details of the laser source and the exposure the retina receives. The main mechanisms are heating (often explosive, accompanied by a blast that detaches the retina) and photochemical degradation. I have yet to speak with a doctor or laser safety expert who can give me a convincing assessment of which mechanisms operate when an eye is blinded by looking too long at the Sun. However, with a laser beam the mechanism is often easier to determine.

The first consideration is wavelength. As shown in Fig. 3, which eye tissues absorb laser light depends on the wavelength.

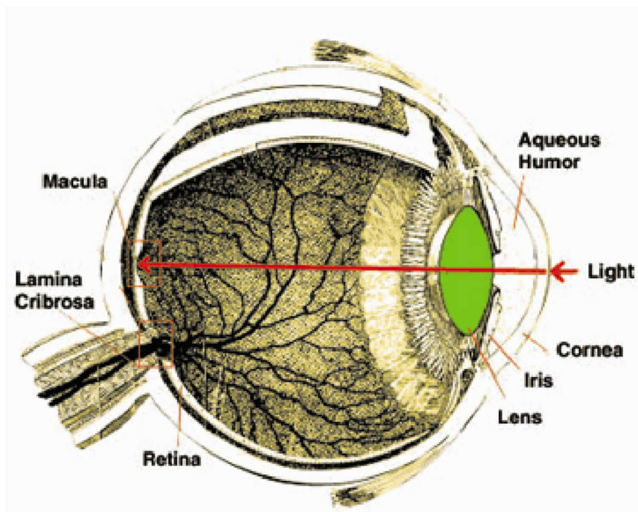
As shown in Fig. 3, which eye tissues absorb laser light depends on the wavelength.

- In the microwave region, as well as in the x-ray region, the radiation passes unfocused through all tissues of the eye and on into the cranial cavity.
- Light in the far UV (roughly 100–315 nm) and the far IR ($\lambda > 1.4\mu$m) is absorbed in the outer layer of the eye, the **cornea**, where it can cause burns and permanent damage of the corneal tissue. When slightly damaged, such as when scratched, the cornea is the fast part of the body to heal. It heals by producing new cells at the periphery of the eye, and these

migrate to the damaged region and replace damaged cells, which are sloughed off by tears. When the "active" regions where new cells are produced become damaged, no healing of the cornea can take place. In some cases, it is possible to transplant a healthy cornea to restore sight; in others this fails by rejection of the transplanted tissue.

- Light in the near UV penetrates the cornea but is absorbed in the lens, where it can cause a degradation of the proteins of the lens that turns them cloudy and opaque. This condition is called a cataract; before the hazards of UV exposure were well understood, many atomic physicists working with UV sources, including Hg lamps, developed cataracts and had to have cataract surgery to replace the lenses of their eyes.

- In the visible and near infrared spectral region, which includes the spectrum of the Ti:sapphire laser and the undoubled Nd:YAG laser (which is truly invisible, unlike the Ti:sapphire), light is well focused by the cornea and lens onto the retina, leading to very high intensities at the focal spot. *This kind of laser is the most dangerous for permanent retinal damage.*




With an intense, pulsed laser in the visible or near IR, a single shot from the laser may be sufficient to destroy a patch at the focal spot and in the surrounding area. If the beam arrives straight on, as shown in the figure, the region of the retina that is damaged is called the *fovea*, which is the region responsible for visual acuity and detailed color vision. In this region of the retina, which is only about 100 $\mu$m across, the density of the cones responsible for color vision is greatest, leading to the greatest resolution and clarity in the entire visual field of view.

The optic nerve leaves the eye in a region 1.5 mm or so below the fovea. If this region is destroyed by a laser shot, the eye is irreparably blinded. Laser spots on other regions of the retina, such as arise by misdirected laser beams and stray reflections that enter the eye away from the forward direction, tend not to be as severe as hits to the fovea and optic nerve. Typically, a region surrounding the spot is damaged and goes blind. It is also common that with the laser heating of the retinal cells, blood vessels explode and blood enters the *vitreous humor* (the fluid that fills the eyeball between the lens and the retina). Those who have suffered such laser shots describe how terrifying it is to see one's vision streaked with blood as though shot in battle. Chunks of retinal tissue can float around in the vitreous humor for years, clouding vision and causing "holes" in one's field of vision that wander around. According to Prof. Donnelly's personal experience, floaters can persist for years and can be more annoying than the permanent blind spots.

# 4 Upshot

Laser physics is enormously rich and varied, and lasers have become an absolute commonplace with CD players and laser pointers. The dangers should not intimidate us but sober us. This exposition should persuade you of the positively enormous risks of careless behavior in a laser laboratory. One thoughtless mistake can destroy an eye. That eye might be yours, or it might belong to someone else in the room. Most experiments involve teamwork, and it is therefore essential that everyone understand the risks and dangers, and that we all work to minimize them.

# 5 Safe Practices

Now that you are convinced that the equipment is dangerous, it is time to learn how to operate it safely.

1. **Remove bling**. Belt buckles, necklaces, bracelets, and other shiny objects can reflect a stray beam in unexpected directions. Remove or tape any reflective surfaces.
2. **Wear appropriate laser glasses or goggles**. Make sure that the glasses are designed for the laser wavelength in use. The glasses should have an optical density rating for the laser that brings the transmitted intensity down to a safe level. Optical density is the negative base-10 logarithm of the ratio of the transmitted to incident intensity; OD6 means that the lens attenuates the beam by a factor of $10^6$.
3. **Keep the beam parallel to the table**. In most circumstances, the beam can remain at the same height above the table throughout an optical setup. In rare situations, it may be necessary to use a periscope to change the height of the beam, or to rotate its polarization. These are potential hazards. When the beam moves vertically, it has a chance of missing a mirror and either bouncing off the table or heading straight up into an eye.
4. **Keep your head above the beam plane**. Even with safety glasses on, do not put your head at beam level. If you must pick something up off the floor, train yourself to close your eyes as you pass through the beam plane, regardless of your safety glasses.
5. **Block any beam that you are not using**. If you are working elsewhere in the laboratory and don't need the beam on your setup, block the beam as close to the source as possible without disturbing others' work.
6. **Fasten optics securely**. A leading cause of accidents is the stray reflection from a mirror, lens, or other optic that is moved into or out of the beam, by accident or on purpose. Block the beam, insert the optic, verify its position with the beam briefly using a card or viewer, and fasten the optic/mount firmly to the table before unblocking the beam.
7. **Eliminate stray reflections**. Even the stray reflection from a portion of the beam can be sufficient to blind. Carefully track down stray beams using a card or viewer. Use beam blocks, black paper, iris diaphragms, and glass filters to remove them.
8. **Ask**. When in doubt about the operation of any piece of laboratory equipment, ask another student or a professor.
9. **Assume the worst**. When you enter the laboratory, assume the laser is on, not off.
10. **Get instruction**. Before operating a new piece of equipment, have someone show you have it works and explain potential problems. Read the manual. It may take you several times watching the procedure before you are ready to handle it on your own. This is normal. I watched folks in France perform the start-up procedure plenty of times before I was ready to make more than trivial adjustments. No shame there.
11. **Think!** It takes one split-second misstep to destroy an eye. If you are tired and having a hard time concentrating, it is time to pack up for the day. Accidents can happen at any time, but when you're tired or doing something unfamiliar they are much more likely. When it doubt, discretion is the better part of valor. **Think!**

# Informed Consent

The purpose of this document has been to acquaint you with the hazards of working with lasers and to help you learn how to work safely with them. When you work alone on a laser, you alone are at risk. Usually, more than one person is present in a laser laboratory, either collaborating on a single setup or working on independent experiments with independent beams. In this case, you are responsible for your safety and the safety of others in the room.

I have read this document, studied the list of safe procedures for working with lasers, consent to abide by them, and asked a professor for clarification on any specific policies appropriate for the laser system(s) with which I will be working.

Signature: ______________________________________________

Name: ______________________________________________

Date: ______________________________________________