<==== Sam's Laser FAQ ====>

Safety, Info, Links, Parts, Types, Drive, Construction

A Practical Guide to Lasers for Experimenters and Hobbyists

Back to Sam's Laser FAQ Welcome Page.

- Expanded Table of Contents - HTML, diagrams, photos, and schematics.
- Comprehensive Table of Contents - Direct links to every chapter and section.

Table of Contents

PART I - Basics, Safety, General Information, Print/Web Resources, Parts, Manufacturers

PART II - Lasers Based on Commercial Components - Diode, HeNe, Ar/Kr Ion, CO2

PART III - Lasers Constructed from Basic Materials, Hardware, Optics, and Electronic Parts

Laser Equipment Gallery

Back to Sam's Laser FAQ Table of Contents.

Forward

Sam's Laser FAQ evolved to become what it is today from a short note on safely powering the laser diodes ripped from dead CD players which I had written in conjunction with the CD player repair guide (part of the Sci.Electronics.Repair FAQ). It is only about 3 years old at this point. Chapters were added as I acquired a variety of lasers and related equipment. Thus, much of this information comes from first-hand experience. First, those little laser diodes and driver circuits, then Helium-Neon (HeNe) lasers and power supplies, followed by argon ion lasers, and who knows what else the future will bring.

However, many others have contributed in one form or another (newsgroup postings, email, laser parts, etc.). They are cited in the Acknowledgements and/or in the individual sections which contain their material. And, by the way, the name: "Sam's Laser FAQ" was more or less created by those who have read and commented on it via the newsgroups or direct email. The name stuck in part because the original one: LASERS: Safety, Info, Links, Parts, Types, Drive, Construction" was just way too long. :)

While I had kept in touch with laser technology since their invention in the early 1960s, my direct contact with lasers was relatively limited until much more recently. Although there was that glass working I did for someone else's home-built HeNe laser, the ruby laser I inherited at my high school because no one else wanted it, and the little commercial HeNe laser there used to view the hologram in an issue of Scientific American, but I was not yet really hooked on lasers.

In fact, the first real lasers that I actually owned were purchased from a surplus outfit in 1990 or so - a couple of small helium-neon laser tubes and power supplies. I only bought those because a friend of mine had casually mentioned that I didn't have any lasers. I couldn't let that statement stand without doing something! Well, after mounting, wiring (which wasn't much), and testing them, I thought to myself: Well, these are kind of cool and might even come in handy someday. (My friend quickly lost interest once he realized they weren't powerful enough to burn anything!) I dragged them out every so often to make sure they still worked but that was about it, laser-wise, for awhile.

Then a few years later, having spent a lot of time on the USENET newsgroups answering questions (mostly those in the sci.electronics hierarchy, sci.optics, and the like), it became clear that there was virtually NO practical laser related information on the Web. Even with my somewhat limited contact with lasers, the scary thing was that it would appear that I already had more of this sort of hands-on knowledge than was available in cyberspace - and probably anywhere else outside the laser industry. Sure, the major laser manufacturers were beginning to discover the Internet for their sales and advertising, and there were some academic and research sites as well. But, if what you wanted was to be able to power a HeNe laser tube or build a power supply for one, or wire up a laser diode without blowing it out - forget it. There was virtually nothing to be found on-line and only a bit more in print. Much of what did exist was incorrect, incomplete, dangerous, or all of the above.

Sam's Laser FAQ is NOT an academic paper or reference work on quantum mechanics, gas discharges, or solid state physics. You can relax. It is about getting your hands into lasers safely and on a realistic budget. There is only a bare minimum of heavy math and only a few equations. The dozens of thick, expensive technical books and thousands of research papers on basic laser science and advanced laser technology exist to handle that! Sam's Laser FAQ is for the experimenter, hobbyist, weekend tinkerer, and budding mad scientist. For you! Enjoy. :)

Back to Sam's Laser FAQ Table of Contents.

Preface

Sub-Table of Contents

Back to Preface Sub-TOC.

Author and Copyright

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Back to Preface Sub-TOC.

DISCLAIMER

This document is still under development and will probably continue to be in this state until will beyond the time when the Sun turns into a red giant or Hell freezes over, though the Engineers may be able to prevent the latter, at least. :-)

Many of the circuits have been reverse engineered - traced from various schematics or actual hardware. There may be errors in transcription, interpretation, analysis, or voltage or current values listed. They are provided solely as the basis for your own designs and are not guaranteed to be 'plans' that will work for your needs without some tweaking.

Many power supplies and other laser components operate at extremely lethal voltage and current levels. The optical output from even modest power lasers can result in instant and irreversible damage to vision. No one ever should attempt to operate, troubleshoot, repair, or modify such equipment without understanding and following ALL of the relevant safety guidelines for lasers and high voltage and/or line connected electrical and electronic systems.

We will not be responsible for damage to equipment, your ego, county wide power outages, spontaneously generated mini (or larger) black holes, planetary disruptions, or personal injury or worse that may result from the use of this material.

Note that I have no business relationship (financial or otherwise) with any of the laser product manufacturers, sales, or service companies, referenced in this document and benefit in no way by recommendations or suggestions to check out their Web sites. In addition, a requirement of any Sci.Electronics.Repair FAQ or Sam's Laser FAQ mirror site is that there be no advertising of any kind forced on you within the pages of these documents - even for those that are hosted on commercial servers.

And, yes, flattery will get you everywhere but I am almost as eager to have any feedback (good or bad), corrections, suggestions, or additions. Please feel free to Email Me. I will reply, usually within less than 24 hours. Sam's Laser FAQ has been and continues to be a labor of love. My only reward is the knowledge that someone, somewhere, is using this material and is hopefully enjoying the fruits of my effort and making use of them in a productive way.

Back to Preface Sub-TOC.

Acknowledgements

While I have written a good portion Sam's Laser FAQ from my first-hand knowledge and experiences, information from many other sources has been invaluable in filling gaps and even constructing some of the foundations. Much of this has been from postings to USENET newsgroup and other discussion groups, as well as via private email. Wherever possible, I have acknowledged these individual contributions. However, if you feel that there is something here you wrote without being recognized, please send me Mail.

There are a few people who have gone well beyond the level of these casual or passive contributions:

- Special thanks to Don Klipstein (Email: don@misty.com) for his comments and additions to this document in the early stages of its development. His Web site (http://www.misty.com/~don/) is a valuable resource for information relating to lighting and related technology in general.

- Special thanks to Steve Roberts (osteven@akrobiz.com for much of the material in the chapters on Argon/Krypton Ion Lasers including direct contributions of text and photos, as well as via extensive email discussions. He has also developed an interest in high power CO2 lasers and is knowledgeable in many aspects of laser technology so his contributions can now be found in many other chapters as well.

- Special thanks to Chris Chagaris (Email: pyro@grolen.com) for his comments and additions to this document. His first-hand experience in constructing several lasers from scratch has been extremely valuable in polishing and enhancing the chapters on Amateur Laser Construction.

Back to Preface Sub-TOC.

Please Don't Scrap Your Unwanted or Broken Lasers or Laser Related Equipment and Parts!

I am interested in obtaining lasers and laser parts of all types and sizes in almost any condition (dead, partially dead, broken, in need of alignment, adjustment, or repair, etc.)

including but not limited to: diode laser modules (even laser pointers), laser diodes, and laser diode drivers; HeNe, Ar/Kr ion, CO2 or other laser tubes, power supplies, and power supply components; laser rods and other solid state laser parts; optics and accessories; modulators, deflectors, and sensors; other types of power and control circuits; and almost anything else related to lasers. Of particular interest are external mirror gas lasers (for the chassis, optics, and power supplies) even if the tubes themselves are beyond hope (though I do have fantasies about trying some regassing in the far distant future).

Obviously I would love to get working units as well but since this effort is primarily for non-profit use to expand knowledge and further enhance the FAQ, all I can really pay is slug mail shipping and maybe a wee bit more for something of sufficient entertainment value (mine). :-)

Any information found during my dissection or repairs would would eventually find its way into this continually evolving document. While I rarely sell anything that I have revived or restored (how could I part with such things?!) if I were to do so with any items obtained via this request, I would be happy to share any net proceeds with the contributor.

In addition to hardware, schematics for laser diode drivers, HeNe, Ar/Kr, and other laser power supplies, as well as other laser related circuits are also of particular interest. Where permitted, these would be added to the FAQ and/or made available at the Web sites (i.e., they are not proprietary or in violation of copyright restrictions if made public).

So, please send me Mail if you have any of this sort of stuff cluttering up your basement, garage, or attic, and really need the space. :)

Back to Sam's Laser FAQ Table of Contents.
Back to Preface Sub-TOC.
Forward to Introduction.

Introduction

Sub-Table of Contents

Back to Introduction Sub-TOC.

Scope and Purpose of This Document

Many types of lasers are used in conjunction with popular hobbyist projects, basement experimentation, and just plain old late night tinkering. Diode and helium-neon (HeNe) lasers in particular are very common due to several factors including the wide availability of inexpensive components and systems (new and surplus) and the relative ease of constructing working devices. A greater number of argon (and krypton) ion lasers will be turning up on the surplus market at very affordable prices as they are replaced with more modern (but still very expensive) solid state alternatives. There is often interest in carbon dioxide lasers because of their higher power capability.

However, on-line and print resources with detailed information on driving laser diodes and powering helium-neon lasers seem to be scarce. Some of those that do exist are incorrect and potentially dangerous (or at least destructive). There appears to be virtually nothing at all on argon/krypton ion and CO2 lasers. And, even less on the nitty-gritty of amateur laser construction.

This document was written in the hopes of rectifying this situation.

Contributions in almost any form are always welcome and will be acknowledged appropriately.

Back to Introduction Sub-TOC.

Organization of This Document

For the most part, we assume that you are at least familiar with the basic concept of what a laser is and have an idea of your intended application - be it for optics experimentation, communications, ranging, simple curiosity, or just being able to say you have a working laser in the house. :-)

PART I includes some general information on lasers and laser related topics. In addition to essential laser safety information, there are extensive lists of references and Web links to laser safety sites, tutorials on lasers and laser related topics, and laser and optics organizations and manufacturers.

There isn't much in the way of laser physics and other theoretical topics. (You can now breath a sigh of relief!) Nor will there be much in the way of the design of laser shows, holography experiments, interferometers, or other laser applications - though a bit is provided just to stimulate your interest. I leave these to the many excellent books and articles that have been published over the years.

Our major emphasis is on the practical aspects of the types of diode, HeNe, and argon/krypton ion lasers (with CO2 lasers under development), that may be found outside of a well funded research lab - those available at reasonable cost on the used or surplus market, for example.

If you are interested in detailed information on other types of lasers, laser applications, laser physics, laser experiments, or laser research, consult the chapter: Laser Information

Resources for a list of books, magazine articles, and Web links covering everything laser related from basic questions like "What is a laser" or "How do lasers work" to "Spectra in stimulated emission of rare gases" and "Dissociative excitation transfer and laser oscillation in RF discharges" - and everything in between. A quick check of some of the educational Web sites may provide everything you need.

PART II deals with the care and feeding of lasers constructed from readily available components like helium-neon tubes and laser diodes. There is also extensive information on the design and construction of power supply, driver, and other circuits.

The chapters on specific types of lasers includes *8* circuits for driving laser diodes, *16* complete schematics for helium-neon laser power supplies, as well as simple modulators and other useful goodies. Most of these have been tested and/or came from working commercial designs and can be constructed using readily available inexpensive parts.

The material on argon/krypton ion lasers includes extensive information on the general characteristics and features, power supply requirements and design considerations including circuit descriptions, and maintenance and alignment of these highly prized devices. There are even complete ion laser power schematics of varying levels of sophistication which can be replicated using readily available parts or used as the basis for a custom design of your own!

There is even some coverage of CO2 lasers including a discussion of sealed CO2 tubes which are powered in a very similar way to helium-neon lasers.

To the best of my knowledge, no other resource in the explored universe (or elsewhere) currently comes close to providing as much practical information on these topics in a form which is both easy to read and readily accessible in one place - if at all.

PART III is for the true basement experimenter and provides information on actually constructing entire lasers from basic materials like beach sand and copper ore. :-) Well, maybe not quite that basic but: glass tubing, mirrors, hardware, gasses, chemicals, and electronic components like transformers, resistors, capacitors, diodes, and high voltage warning signs!

Where you really think constructing a laser from scratch would be a challenge, fun, and educational, first keep in mind that such an endeavor is generally a LOT of work and depending on the type of laser, may require access to fairly sophisticated facilities and equipment (at least compared to the average kitchen sink - and that, too, may be needed!). These may include the need for glass blowing, a high vacuum system, access to a machine shop, and sources for assorted lab supplies, chemicals, pure gases, and specialized optical and electronic components. This is not to say that your dream is unrealistic or impossible - just that one must be quite determined to see such a project through to a successful conclusion and the information in this document will get you started.

Back to Introduction Sub-TOC.

Related Information

See the chapter: Laser Information Resources for books, magazine articles, newsgroups, technical forums, and links to other laser related Web sites.

There are many other documents at the Sci.Electronics.Repair (S.E.R) FAQ Web site or one of its mirror sites which may be of use in the design, testing, and repair of laser equipment. The Main Table of Contents (ToC) provides links to a variety of information on troubleshooting and repair of many types of equipment, general electronics, an assortment of schematics, over 1,000 technology links, and much more. Most of these documents are nicely formatted, indexed, and cross-referenced. (Silicon Sam's Technology Resource, which may be present at this site and others, usually contains slightly more recent versions of many of these same documents but most of those under the S.E.R FAQ Main ToC are easier to use and the actual content differences are likely to be minor.)

The first one below, is also part of Sam's Laser FAQ itself: Make sure you study it if at all relevant to what you will be doing!

- Safety Guidelines for High Voltage and/or Line Powered Equipment should be thoroughly studied before even thinking about working on any of the power supplies for gas or solid state lasers. (At least with small diode lasers, about all you can easily do is destroy the laser diode itself.)

- Notes on the Troubleshooting and Repair of Compact Disc Players and CDROM Drives provides more info on how the laser diodes in CD players and CDROM drives worked originally.

  Where the manufacturer and part number for your laser diode are known, by all means take advantage of the extensive applications information that is likely to be available. Start with a search at ThorLabs. Driving laser diodes without blowing them out is often not easy - even for an experienced design engineer!

- Notes on the Troubleshooting and Repair of Electronic Flash Units and Strobe Lights includes design information and sample circuits that may be useful for flash lamp pumped lasers.

- Various Schematics and Diagrams includes a variety of circuits that may be useful in generating the high voltage for helium-neon lasers (in addition to those found in the chapter: Complete HeNe Laser Power Supply Schematics.

- Salvaging Interesting Gadgets, Components, and Subsystems for unconventional sources and uses for neat, useful, and otherwise discarded or neglected parts and equipment.

See the Home and Mirror Site Locations for other possibilities which may be faster from where you live.

Back to Sam's Laser FAQ Table of Contents.

Back to Introduction Sub-TOC.
Forward to What is a Laser and How Does It Work?.

What is a Laser and How Does It Work?

Sub-Table of Contents

Back to What is a Laser and How Does it Work Sub-TOC.

A Brief Introduction to Lasers Principles and Structure

The Laser Age

Since every document on lasers must have a discussion of basic principles, this is it! If you know anything at all about lasers, you can skip to the section: Characteristics of Some Common Lasers since the summary below will probably just put you to sleep and then you might miss the rest of the excitement. :-) If you want a more in-depth on-line course, see the section: On-Line Introduction to Lasers.

A laser is a source of light but unlike anything that had ever been seen or implemented before 1960 when Theodore H. Maiman of Hughes Aircraft mounted a specially prepared synthetic ruby rod inside a powerful flash lamp similar to the type used for high speed photography. When his flash lamp was activated, an intense pulse of red light burst forth from the end of the rod that was both monochromatic (a single color) and coherent (all of the waves were precisely in step). The difference between the output of a laser and that of an incandescent light bulb is like the difference between white noise and a single tone.

The laser age was born. Within a very short time, in addition to many more solid state materials, laser action was demonstrated in gasses (the ubiquitous helium-neon laser was the first gas laser though it originally only produced invisible IR wavelengths), liquids, and semiconductor crystals. Almost every conceivable material was tried in the frenzy to produce new and interesting lasers. Even some varieties of Jello(tm) brand dessert were blasted with xenon light, and according to this legend, are supposed to work fairly well. I wonder whether the flavors have to be all natural. :-) (See the section: Comments on the Jello Laser Legend for a discussion on this very exciting topic.)

See Laser Stars - LASER HISTORY (1917-1996) for an interesting chronology of laser development, discovery, and applications.

In many ways, the laser was a solution looking for a problem. Well, the problems soon followed in huge numbers. It would be hard to imagine the modern world without lasers - used in everything from CD players and laser printers, fiber-optic and free-space communications, industrial cutting and welding, medical and surgical treatment, holography and light shows, basic scientific investigation in dozens of fields, industrial cutting and welding, and fusion power and Star Wars weapons research. The unique characterisics of laser light - monochromicity (the light is very nearly a single wavelength or color), coherence (all the waves are in step), and directionality (the beam is either well collimated to start or can easily be collimated or otherwise manipulated) make these and numerous other applications possible. In fact, it is safe to say that the vast majority of laser applications have not yet even been contemplated. For an idea of the extensive and diversified applications for which the laser has become an essential tool or component, see for example: Rami Aliei - The Laser Adventure: Laser Applications and Lasers On-Line: Some Applications.

General Physical Characteristics of Lasers

The word 'LASER' is an acronym standing for 'Light Amplification by Stimulated Emission of Radiation'. In some ways, this is somewhat confusing since most lasers are actually oscillators (generators or sources of light) and not amplifiers (devices for increasing the strength of a signal), though such lasers are also possible and used for some applications.

The output of a laser can be pulsed or a continuous beam; visible, IR, or UV; less than a milliwatt - or millions of watts of power. However, nearly all lasers have the following in common. (One notable exception is the 'free electron laser' which operates on a totally different principle - in fact, it is probably not really accurate to call it a laser at all except for the fact that its output is intense coherent monochromatic light!):

1. A lasing medium. This can be a solid, liquid, gas, or semiconductor material which can be pumped to a higher energy state.
    - It must be possible to boost a majority of the lasing medium to an upper energy level (electron, ion, vibrational) called a population inversion.
    - There must be a downward transition triggerable by stimulated emission.
    - Most lasers are based on 3 or 4 level energy level systems. Which of these are possible depends on the lasing medium:
        - 3 level: Pump to level (3) which decays rapidly to level (2). Stimulated emission from level (2) to level (1).

        - 4 level: Pump to level (4) which decays rapidly to level (3). Stimulated emission from level (3) to level (2). Decays to level (1).

        - The intuitively simpler 2 energy level system does not work well in practice since it is difficult to produce a population inversion.

2. A means of pumping energy into the lasing medium. This can be optical, electrical, mechanical, chemical, etc.

    - Gas lasers use an AC or DC electrical discharge through the gas medium, or external RF excitation, electron beam bombardment, or a chemical reaction. Other pumping means are also possible. The DC electrical discharge is most common for 'small' gas lasers (e.g., helium-neon, argon ion, etc.).

      For a description of a really LARGE chemically pumped laser, see the Mid-Infra Red Advanced Chemical Laser (MIRACL). This sort of laser is sometimes described as a rocket engine between a pair of mirrors!

    - Solid state lasers usually use optical pumping from high energy xenon flash lamps (e.g., ruby, Nd:YAG) or from a second pump laser or laser diode array (e.g., DPSS frequency doubled green lasers). Continuous solar or xenon arc pumping may be used for some types of lasers.

      By far the largest solid state laser on the face of the earth (at least for awhile) will be at the National Ignition Facility being constructed at Lawrence Livermore National Laboratory. It will produce about 1.8 MJ per pulse with a peak output power of over 500 Terawatts. The NIF laser will be about the size of a football STADIUM with 192 beam lines and over 7,300 major optical components including some 3,000 Nd:Glass slab amplifiers nearly a meter across! Its estimated construction cost is more than $1,200,000,000 with an annual operating budget of about $60,000,000. No, the NIF laser isn't portable. :-)

    - Semiconductor lasers are most often pumped by DC current but optical and electron beam pumping may also be possible.

    - Liquid (dye) lasers are usually pumped optically.

    - X-ray lasers are supposedly pumped using small nuclear devices. Although tests may have been performed (underground), there is controversy as to whether they were successful. (There may be smaller X-ray lasers today that use other pumping means and don't self destruct with every shot.)

    - Free Electron Lasers (FELs) are 'pumped' by multimillion (or multibillion) dollar particle accelerators (though, as noted above, these 'lasers' are not based on quite the same principles as the other types. The charged particle beam from the accelerator is passed through a structure called an 'undulator' or 'wiggler' array - a series of powerful magnets of alternating polarity. As the particles oscillate back and forth in response to the magnetic field, photons are emitted in all direction -

some along the axis of the beam. (Electromagnetic radiation can be emitted whenever a charged particle is accelerated in a magnetic field.) Mirrors before and after the magnets complete the laser resonator. (Additional magnets route the electron beam around the mirrors at each end of the resonator.) As the photons in line with the beam axis bounce back and forth, they 'encourage' new photons to be emitted in the same direction - a form of stimulated emission - though the concept of a population inversion probably doesn't apply here. Voila - an FEL! The wavelength of the laser 'light' depends on many factors including the type of charged particle (electron, proton, etc. - the same principle can be applied to particles other than electrons though I don't know if this has been done or is even practical), strength and spacing of the magnets, and energy of the beam. The coherent output of the FEL can span the electromagnetic spectrum ranging from far IR to X-Rays.

For more information on FELs than you probably really want, check out the links returned by a Lycos Search for "Free Electron Laser" and the UCSB FEL Link Page.

3. A resonator. In most cases this is some form of a Fabry-Perot cavity, a pair of mirrors, one at each end of the laser, which allow stimulated light to bounce back and forth through the lasing medium. Usually, one of the mirrors is totally reflective while the other is partially transparent to allow the laser beam to escape. The mirrors are either perfectly flat (plane) or one or both may be very slightly concave. Other configurations are possible:

   - Some lasers have a mirror at one end only (e.g., nitrogen laser) or no mirrors at all (e.g., X-ray laser since it is nearly impossible to reflect electromagnetic radiation at X-ray wavelengths).

   - Lasers constructed in the shape of a triangle or rectangle (mirrors at the corners) may have no output beam but use interference from a pair of counter-rotating laser beams at one location internally to sense the assembly's orientation in a ring laser gyro platform. See the section: Ring laser gyros.

   - Optical slabs are often used in high power laser amplifiers. In one common configuration, the slab is oriented at the Brewster angle (see the section: What is a Brewster Window?) so that virtually no energy is lost due to reflections from its surfaces as the beam passes through. Slabs may also in such a way that the laser beam follows a zig-zag path through the slab reflecting back and forth from its flat faces. In both cases, the large surface area of the slab means that it is able to dissipate a large amount of power without damage. The largest pulsed lasers in the world (used for inertial fusion and nuclear bomb research) employ slab type laser amplifiers extensively.

     See: Lawrence Livermore National Laboratory Laser Programs for more information.

   - Lasers may be constructed with 'distributed feedback' which replaces one of the mirrors with a diffraction grating. See the section: Difference Between Fabry-Perot and DFB Lasers. Adjusting the angle of the grating can be used to select the wavelength of the output in some lasers. (An 'intra-cavity' prism can also be used for this purpose.)

- Additional optical elements like prisms, modulators, Q-switches, Kerr cells, and so forth may also be present inside the resonator.

Basic Laser Operation

Relax! This will be short and simple. There are numerous references with extensive information - at all levels of sophistication - on laser theory. See the chapter: Laser Information Resources for references and links to all sorts of material which will cure insomnia. :-)

We present only the briefest of summaries. Some additional more specific material is presented in the chapters: Helium-Neon Lasers and Diode Lasers.

Please refer to the diagram: Basic Laser Operation whlle reading the following explanation. The numbers in () denote each step in the lasing process.

Normally, nearly all atoms, ions, or molecules (depending on the particular laser) of the lasing medium are at their lowest energy level or 'ground state' (1).

To produce laser action, the energy pumping device must achieve a population inversion in the lasing medium so that there are a majority of atoms/ions/or molecules at the upper energy level of the pair that participates in the stimulated emission. Note that those designated 'Energy Level 2' in the diagram are the ones of interest; some have been raised to 'Energy Level 1' and just sit there taking up space. :-)

At random times, some of these excited atoms/ions/molecules will decay to the lower energy state on their on. In the process each one emits a single photon of light. This is called 'spontaneous emission' and by itself isn't terribly useful. It is basically the same process that accounts for the glow of a neon sign, or the phosphor coating of a fluorescent lamp or screen of a CRT (3).

However, Einstein showed that if one of these photons happens to encounter an excited atom/ion/molecule in just the right way, it will drop down to a lower energy state and emit a photon with several amazing properties compared to the original one. Among these are:

- The new photon will be of exactly the same wavelength.
- The new photon will have exactly the same phase.
- The new photon will be emitted in exactly the same direction.

The new photon will have exactly the same polarization as well, though this is not a requirement to create a laser. However, where the resonator favors a particular polarization orientation (e.g., there is a Brewster angle window or plate in the beam path or the cavity is highly asymmetric), or in some cases, there is a particular magnetic field configuration, the output beam will also be polarized - but this is for the advanced course. :-)

So, imagine the lasing medium (perhaps, it is easiest to visualize it like the glowing gas in a neon sign) spontaneously emitting these photons in all direction at random times. Most will be lost exiting the side of the discharge tube or hitting one of the mirrors at an angle and then escaping its confines.

Occasionally, however, a photon will happen to be emitted nearly parallel to the long direction of the resonator (3,4). In this case it will travel down to one of the mirrors and be able to bounce back and forth many times (with some configuration of slightly concave mirrors, if there were no losses, it could even do this indefinitely). So far, pretty boring! However, along the way, it encounters excited atoms/ions/molecules and STIMULATES them to give up their photons. As this progresses, what was once a single photon is now an avalanche of more and more photons via this stimulated emission process (5).

The resulting beam is highly monochromatic (nearly entirely one wavelength) and coherent (all the waves are in-step). It is also either well collimated (nearly parallel rays for most lasers including gas and solid state types) or appears to originate from a point source (diode lasers). In either case, the beam can easily be manipulated in ways impossible with more common light sources.

If the pumping source is adequate and enough atoms/ions/molecules are being raised to the upper energy level to maintain the population inversion while this is happening, the laser action will continue indefinitely (barring trivial problems like overheating or depletion of the power available on the National Electric Grid). This results in a continuous wave laser. If the pumping cannot be maintained or some energy levels get clogged up, the result is a pulsed laser. (Therefore, Basic Laser Operation actually illustrates a pulsed laser since pumping is not sustained.)

There you have it! Everything else is just details. :-)

For some (still easy to understand) details on the principles of operation of the ubiquitous helium-neon laser, see the section: Theory of Operation, Modes, Coherence Length, On-Line Course as well as the chapters on other specific types of lasers. Additional information on general laser characteristics may also be found in the chapter: Items of Interest.

Back to What is a Laser and How Does It Work? Sub-Table of Contents.

On-Line Introduction to Lasers

There are a number of Web sites with laser information and tutorials. Many are of marginal value at best. However, there are a few that stand out as being well worth bookmarking:

- The best that I have found by far is the Laser/Electro-Optics Technology Series being developed by CORD Communications, 324 Kelly Drive, P.O. Box 21206, Waco, Texas 76702-1206. This is essentially a complete on-line textbook with over 100 diagrams, many basic equations (you can't have everything!), detailed laboratory experiments, and extensive lists of references for further study.

There are several (mostly complete) courses (some are still under development and there are a few rough edges). While the original material was developed in the early 1970s (there are a number of diagrams with tube circuits!), it has been updated and has a lot to offer including by far the most complete on-line presentation of laser technology (e.g., resonator structures and power supply example schematics) that I know of - though not to the level of detail present in Sam's Laser FAQ! :)

The blurb that goes along with the courses states:

> "The LEOT (Laser/Electro-Optics Technology) curriculum was developed by CORD in 1970-1974 with funding from the U.S. Office of Education. At that time many books on lasers were available for physicists and engineers. Those books contained the rigorous theoretical information needed to develop new designs and applications for lasers. The LEOT curriculum does not provide that kind of information, but instead, is written for the technicians who will build, modify, install, operate, troubleshoot, and repair lasers.
>
> Technicians are a vital link in the advancement of photonics technology. They are the workers in the laboratories, plants, and fields who ensure that lasers, and other photonics related equipment, operate properly and reliably."

So these course are very practical in nature and provide a nice companion to Sam's Laser FAQ's practical orientation.

Here are the main table of contents (list of modules) for each course that presently exists or is under development:

Course 1: Intro to Lasers

1-1 Elements and Operation of a Laser
1-2 Elements and Operation of an Optical Power Meter
1-3 Introduction to Laser Safety
1-4 Properties of Light
1-5 Emission and Absorption of Light
1-6 Lasing Action
1-7 Optical Cavaties and Modes of Oscillation
1-8 Temporal Characteristics of Lasers
1-9 Spatial Characteristics of Lasers
1-10 Helium-Neon Gas Laser--A Case Study
1-11 Laser Classifications and Characteristics

Course 3: Laser Technology

3-1 Power Sources for CW Lasers
3-2 Pulsed Laser Flashlamps and Power Supplies
3-3 Energy Transfer in Solid-State Lasers
3-4 CW Nd:YAG Laser Systems
3-5 Pulsed Solid-State Laser Systems
3-6 Energy Transfer in Ion Lasers

3-7 Argon Ion Laser Systems
3-8 Energy Transfer in Molecular Lasers
3-9 CO2 Laser Systems
3-10 Liquid Dye Lasers
3-11 Semiconductor Lasers
3-12 Laser Q-Switching-Giant Pulses
3-13 Measurements of Laser Outputs
3-14 Laser Safety Hazards Evaluation

Course 4: Laser Electronics

4-1 Electrical Safety
4-2 Gas Laser Power Supplies
4-3 Ion Laser Power Supplies
4-4 Flashlamps for Pulsed Lasers and Flashlamps
4-5 Arc-Lamp Power Supplies
4-6 Diode Laser Power Supplies
4-7 Electro-Optic and Acousto-Optic Devices
4-8 Optical Detectors
4-9 Electro-Optic Instrumentation

Course 6: Laser and Electro-Optic Components

6-1 Optical Tables and Benches
6-2 Component Supports
6-3 Photographic Recording Mediums
6-4 Windows
6-5 Mirrors and Etalons
6-6 Filters and Beam Splitters
6-7 Prisms
6-8 Lenses
6-9 Gratings
6-10 Polarizers
6-11 Nonlinear Materials

Course 10: Laser and Electro-Optic Measurements (under construction)

10-1 Spectrometers
10-2 Monochromators
10-3 Spectrophotometers

The current Laser/Electro-Optics Technology (LEOT) curriculum materials are also available in print from CORD Communications.

With permission of CORD Communcations, I have made a complete copy of the text and graphics available at: Laser/Electro-Optics Series - S.E.R FAQ (Kent Lee) Mirror. I have also fixed some of the rough edges. :)

I would suggest that one of these sites be bookmarked so you can refer to it for additional info on all sorts of laser related topics.

This is all great educational content for those who wish to gain a better understanding of the principles of laser operation, find out what is in a laser, see examples of power supply circuits, and much more. But, it is designed at a level that shouldn't put you to sleep with too much heavy math. :-)

- Another site which provides an outline of a course on lasers including summaries of laser types, applications, and laboratory experiments is: The Laser Adventure by Rami Arieli. I call it an outline because although most of the major topics are included, their coverage is quite brief and the serious student would need to find details elsewhere - perhaps from the CORD Communications Lasers and Electro-Optics courses described above. :-)

  Some specific links with the most general interest are:

  - Table of Contents (Links to all chapters and sections of the course)
  - Laser Types (Summaries of major characteristics of most common lasers)
  - Laser Applications (Daily use, military, medical, scientific, industry, special)
  - Laboratory Experiments (Divergence, diffraction, measuring wavelength with a ruler, etc.)

- Rockwell Laser International has a variety of short articles and summaries with info on laser theory, common laser types, wavelengths, and applications, a glossary, and more at their Laser Tutorials page.

- Also see the section: General Laser Information and Tutorial Sites for other sites that may be worth visiting.

Back to What is a Laser and How Does It Work? Sub-Table of Contents.

Characteristics of Some Common Lasers

Here is a summary of the features, power output, power supply requirements, wavelengths, beam quality, cost, and applications of diode, helium-neon, argon/krypton ion, and carbon dioxide lasers.

- Diode lasers. Semiconductor laser diode 'chip' driven by low voltage power supply. Optical feedback from a monitor photodiode (commonly in the same package as the laser diode) is generally used for precise regulation of laser diode current.

  Wavelengths: Red (635 nm, actually may appear slightly orange-red) through deep Red (670 nm) and beyond, IR (780 nm, 800 nm, 900 nm, 1,550 nm, etc.) up to several um). Green and blue laser diodes have been produced in various research labs but until recently, only operated at liquid nitrogen temperatures, had very limited lifespans (~100 hours or worse), or both. Recent developments suggest that long lived room temperature blue and green diode lasers will be commercially available very soon.

Beam quality: Fair to high depending on design. The raw beam is elliptical or wedge shaped and astigmatic. Correction requires some external optics. Coherence length anywhere from a few mm to many meters.

Power: .1 mW to 5 mW (most common), up to 100 W or more available. The highest power units are composed of arrays of laser diodes, not a single device.

Some applications: CD players and CDROM drives, LaserDisc, MiniDisc, other optical storage drives; laser printers and laser fax machines; laser pointers; sighting and alignment scopes; measurement equipment; high speed fiber optic and free space communication systems; pump source for other lasers; bar code and UPC scanners; high performance imagers and typesetters, small (mostly) light shows.

Cost: $15 to $10,000 or more.

Comments: Inexpensive, low (input) power, very compact, but critical drive requirements. Many types of diode lasers are not suitable for holography or interferometry where a high degree of coherence and stability are required. However, see the section: Interferometers Using Inexpensive Laser Diodes since these common CD player and visible laser diodes may in fact be much better than is generally assumed.

- Helium-neon (HeNe) lasers. Sealed HeNe plasma tube with internal mirrors, high voltage power supply.

  Wavelengths: Red (632.8 nm) is most common by far. Orange (611.9), yellow (594.1 nm), green (543.5 nm), and IR (1,523.1 nm) HeNe lasers are also readily available (but these are less efficient and therefore more costly for the same beam power).

  Beam quality: Extremely high. The output is well collimated without external optics, and has excellent coherence length (10 cm to several meters or more) and monochromicity. Most small tubes operate single mode (TEM00).

  Power: .5 to 10 mW (most common), up to 250 mW or more available.

  Some applications: Industrial alignment and measurement; blood cell counting and analysis); medical positioning and surgical sighting (for higher power lasers); high resolution printing, scanning, and digitization; bar code and UPC scanners, interferometric metrology and velocimetry; non-contact measuring and monitoring; general optics and holography; small to medium size light shows, laser pointers, LaserDisc and optical data storage.

  Cost: $25 to $5,000 or more depending on size, quality, new or surplus.

  Comments: Inexpensive, components widely available, robust, long life.

- Argon (Ar) and krypton (Kr) ion lasers. These differ mainly in gas fill. Sealed plasma tube with internal or external mirrors and high current (10 amps or more at around 100 VDC) regulated power supply (constant current or optical power based). Combined Ar/Kr produces lines in red, green, and blue, and is therefore considered a 'white light laser'. All are electrical power guzzlers and larger units are water cooled.

Wavelengths: Violet blue (457.9 nm), blue (488 nm - single line), green (514 nm), Red (Kr or Ar/Kr types only, 646 nm). Many other lines throughout the visible spectrum (and beyond) are available (but generally weaker) and may be 'dialed up' on some models.

Power: 10 mW to 10 W. Research lasers up to 100 W.

Beam quality: High to very high. Single and multimode types available.

Some applications: very high performance printing, copying, typesetting, photoplotting, and image generation; forensic medicine, general and ophthalmic surgery; entertainment; holography; electrooptics research; and as an optical 'pumping' source for other lasers.

Cost: $500 (surplus 100 mW) to $50,000 (multi-watt new) or more.

Comments: High performance for someone who is truly serious about either optics experiments like holography or medium to high power light shows.

- Carbon dioxide (CO_2) lasers. Sealed (small) or flowing gas design. High voltage DC, RF, electron beam or other power supply.

  Wavelength: mid-IR (10.6 um, 10,600 nm).

  Beam quality: High.

  Power: A few watts to 100 KW or more.

  Some applications: Industrial metal cutting, welding, heat treatment and annealing; marking of plastics, wood, and composites, and other materials processing, and medicine including surgery.

Back to What is a Laser and How Does It Work? Sub-Table of Contents.

Lasers for the Hobbyiest and Experimenter

Commercial Lasers Versus Amateur Laser Construction

Diode, helium-neon (HeNe), and argon/krypton (Ar/Kr) ion lasers are probably the most popular types of lasers generally available to hobbyists and experimenter (see the section: Characteristics of Some Common Lasers). This is due to the wide availability of complete lasers and laser components (new as well as surplus), and their desirable optical and physical characteristics, including the generation (in most cases) of a continuous beam, manageable power and cooling requirements, and the fact that there is no need for sophisticated laboratory facilities to keep them healthy. A major portion of this document is devoted to the practical aspects of these types of laser systems, their power sources, and related optics and electronics.

While many other types of lasers may be constructed including mercury vapor ion, nitrogen, excimer, dye, ruby, Nd/YAG, chemical, free electron, and X-ray, most of these are less commonly available as surplus. There could also be problems obtaining the 100 million volt particle accelerator required for the free electron laser and the small thermonuclear device needed to pump the X-ray laser. :-)

Now, back down to earth....

Where you are really interested in actually constructing any of these types of lasers from basic materials (e.g., not by simply hooking together commercial laser tubes and power supplies), check out the chapters beginning with: Amateur Laser Construction which include general information on the types and requirements for home-built lasers, setting up a laser lab, introduction to vacuum systems and glass working, and other really exciting topics.

General Comments on Lasers as a Hobby

(From: Richard Alexander (RAlexan290@gnn.com).)

How much do you like to build things? Would you prefer to assemble a bunch of parts, or do you want to blow your own glass tubes, too? Do you have any mechanical experience? Do you build electronic kits? Keep in mind that you will often be working with intense light (enough to instantly damage your unprotected eyes, and maybe your unprotected skin) and high voltages.

All laser experimenters (and optics types, too) should have a copy of "Scientific American"'s "Light and Its Uses." [5] It gives construction plans for a Helium-Neon (you blow the glass tube yourself), an argon ion (even more complicated), a CO2 (designed and built by a high school student, and able to cut through metal), a dye, a nitrogen (a great first laser, but watch out for UV light) and a diode laser (obviously, you buy the diode laser and assemble the driver circuit from the plans they supply). They also explain how to make holograms using visible and infrared light, microwaves and sound. There are other projects, too. The book is getting fairly old (the HeNe dates to the '60s), but it's still a great reference.

A nitrogen laser may be built for under $200 (maybe less than half that amount if you are lucky). It requires no mirror alignment (since it has no mirrors). The technology for building this laser was available to Ben Franklin, so there is nothing too critical in it. The hazards it presents are lots of ultraviolet light (spark discharges and laser beam), high voltage (necessary to arc across a 1/4 inch spark gap in a nitrogen environment) and circuit etcher (the main capacitor is made from an etch circuit board).

Once built, the nitrogen laser can drive many other projects. It can be used as a pump for the dye laser, for example. It will light up anything fluorescent. It is a pulse laser (10 ns) that can be repetitively pulsed (120 Hz is a likely frequency). Megawatt power is possible, but the total energy is low (due to the short pulses).

"Electronics Now" (formerly, Radio Electronics) has a laser projects column that started several months ago. I'm trying to think up a project I can submit to them. They said they would welcome projects for the laser column.

Helium-Neon laser tubes may be bought from many mail-order companies. I bought one from Meredith Instruments in Arizona. They cost about $15, and the power supply can be built or bought for about another $20. You have the option of buying tubes with mirrors attached or not. You might want to buy the mirrors attached, because aligning those mirrors is extremely tedious. I was given an "A" for constructing a working Helium-Neon laser from the parts in the Laser Lab in less than an hour. The class was given two semesters to gain the experience they needed to do that.

If you want more than one color from lasers, there are various ways to do it, but none of them are as nice as one might like. For $3000 or so, you can buy a Helium-Neon laser that will produce laser light ranging from infrared to blue. All you have to do is turn a dial on the back.

Laser light shows usually use argon ion or krypton lasers. These are able to produce most of the colors of visible light, and they can also be dialed to the desired color. However, they usually cost several thousand dollars ($40,000 is not too unusual) and require either forced air or water cooling or a combination.

A dye laser is the usual solution to the multi-color problem. They are inexpensive and simple. They aren't especially tunable, unless you change the dye, although a diffraction grating can be used to tune a particular dye to various colors. One common dye that can be used in a dye laser is the green dye found in radiator antifreeze.

Back to Sam's Laser FAQ Table of Contents.
Back to What is a Laser and How Does It Work? Sub-TOC.
Forward to Laser Safety.

Laser Safety

Sub-Table of Contents

Back to Laser Safety Sub-TOC.

Introduction to Laser Safety

You Only Received One Set of Eyeballs?

Lasers have tended to be high glamor devices popular with with hobbyists, experimenters, entertainers, and serious researchers alike. However, except for very low power lasers - those with less than a fraction of a mW of beam power - they do pose some unique hazards particularly with respect to instant and permanent damage to vision.

Here we only discuss the hazards with respect to vision. There are other safety issues - such as the danger from the high voltages used to power certain types of laser. These are summarized later in this chapter and dealt with in more detail in the chapters on the lasers for which they apply. There are several reasons that even small lasers which do not represent any sort of burning or fire risk can instantly and permanently damage vision:

- The output of many lasers is a nearly parallel - highly collimated - beam which means that not only is the energy concentrated in a small area but the lens of the eye will focus it to a microscopic point on the retina instantly vaporizing tissue in much less than the blink of an eye. A collimated beam represents the rays from an object at infinity so if your eye is focused for distance, the laser will be in focus as well. Even a common helium-neon laser without external optics will approximate a point source a .5 meter or more behind the exit window of the laser. Where your are working in a small room, this approximate distance would likely be where your eyes are focused. While purists might argue that the lens of the eye isn't perfect and will not produce a diffraction limited spot on the retina, this won't save your vision! The power density in a sub-optimal spot can still be astronomical.

  A cheap laser pointer also produces a highly collimated beam.

  Even at power levels considered relatively safe, one shouldn't deliberately stare into the beam for any reason. For these relatively low power lasers, permanent eye damage is not that likely but why take chances? For these lasers, viewing the spot projected on a white surface is perfectly safe.

  A 100 W light bulb puts out about 5 to 7 W of visible light (the rest is mostly IR and heat) more or less uniformly distributed in all directions. However, at any reasonable distance from the light bulb, the power density (e.g., W/sq. mm) is much lower than for a collimated laser beam of even very low power. And, it takes significant effort to produce any sort of truly collimated beam from such a non-point source such as is present with even the filament of a clear light bulb. However, for a helium-neon laser, the collimation is such that the entire beam (total power output of the laser) will still be small enough to enter the eye even at a distance of several meters.

For example, at 10 cm from a 100 W bulb (which would be a very uncomfortable place to be just due to the heat), the power density assuming 6 total watts of light would be only about .05 mW/sq. mm. At 1 m, it would be only .0005 mW/sq. mm or 500 mW/sq. m. Based on this back-of-the-envelope calculation, a 5 mW laser beam spread out to a circular spot of .1 m diameter (i.e., 1 mR divergence at a distance of 50 m - without external optics) will be brighter than the 100 W light bulb at 1 m! And, close to the laser itself, that beam may be only 1 *mm* in diameter and thus 10,000 times more intense!

- As another point of reference, the mid-day Sun at the Earth's equator on a clear day has a power density of about 1 KW/square meter or about 1 mW/sq. mm. It would not take very long staring into the Sun to burn out your eyeballs!

See the section: Laser Safety Sites for links to much more information on general laser safety, laser safety organizations, and regulatory agencies.

A popular graveyard joke in the laser industry is: "Do not stare into the beam with your remaining good eye". Nonetheless, laser safety is no laughing matter.

Why a 1 mW Helium-Neon Laser Still Appears Bright a Mile Away

At a distance of 1 mile (1,609 m), the beam from a typical helium-neon laser (which is a quite well collimated source) will have spread to a diameter of roughly 4 feet (48 inches, 1.3 m). However, it will still appear quite bright. Why is this so?

(Portions of the following from: Don Klipstein (don@Misty.com).)

The fraction of light entering the eye for a large diameter beam is pupil area divided by beam area.

Assuming a pupil diameter of 1/4 inch (6.3 mm, rather dilated but not fully dark adapted which may approach 1 cm). The portion of the beam entering the eye would then be the square of (1/4)/(48), which is about 27 millionths of the total. Since the 4 foot diameter beam is not uniform but dimmer towards the edges, I would say the eye could get about 35 millionths of the beam near the center or 35 nanowatts (35 nW).

Note that close to the laser, the pupil size is going to be larger than the beam diameter (which is typically less than 1 mm) and pupil size larger than this will not affect the maximum possible power entering the eye (though it will affect the probability of this occurring. (One suggested laser safety practice is to brightly illuminate the laser lab to make your pupils smaller. Even though there are times this will not reduce the severity of the worst case, a smaller target reduces likelihood of this happening.)

However, where the beam diameter is equal to or larger than the pupil diameter, the difference in pupil diameter between bright and dark adapted eyes will be very significant -

more than a 30-fold difference in power entering the eye for this analysis.

I calculate that a 4 foot diameter 1 mW 632.8 nM beam appears about as bright as a 100 W bulb does 88 feet away.

Although 35 nW is definitely eye-safe, it may look quite bright against pitch black surroundings especially when the eye is fully dark adapted (the pupil is wide open and the combined retinal/neural sensitivity is maximum as it is after awhile when out at night) and may quickly result in a noticeable afterimage. The effect is probably enhanced by the knowledge that the light source is a laser and thus potentially damaging to your eyesight.

As a side note, the 1,710 lumen output of a typical 100 watt incandescent bulb is about the same lumens as *10 Watts* of 632.8 nm light!

Also see the section: How Much Light Does a 5 W Laser Really Produce?.

Back to Laser Safety Sub-TOC.

Safety Issues With Respect to Hobbyist Lasers

Low, Medium, and High Power Lasers

The most common types of lasers generally available to hobbyists - CD laser diodes, visible laser diodes, laser pointers, and small HeNe lasers, are all rated Class II or IIIa. See the section: Laser Safety Classifications. Class II lasers should be relatively low risk if even minimal precautions are taken. However, Class IIIa lasers must be taken much more seriously if the beam is well collimated - as it would be from a laser pointer or HeNe laser tube.

When you graduate to higher power lasers (e.g., argon ion) rated Class IIIb or more, additional very real dangers are present of both instant damage to vision and with Class IV lasers - the possibility of burning or setting fire to flesh and other things. The smallest CO2 laser is going to be rated Class IV!

Higher power diode lasers (above 5 mW) are becoming more readily available both as surplus or pulls from optical drives and high performance laser printers, and also at not totally unreasonable prices even new. Their small size may lead one to assume that a diode laser can't be dangerous. WRONG! A 100 mW laser diode operating on battery power can blow a hole in your retina as easily as a 100 mW argon ion laser consuming the same electrical power as a space heater! And, higher power laser diodes are more likely to be infra-red (IR) and invisible - and thus more dangerous because the aversion response won't work - you have no idea your vision is being destroyed until it it way too late! (CO2 lasers are also IR but the much longer wavelength will only vaporize the front of your eye since the beam is blocked by the cornea.)

In addition to their vision hazards, gas lasers generally use high voltage or line connected power supplies so there is the added shock hazard resulting from touching or accidentally coming in contact with uninsulated connections. See the document: Safety Guidelines for High

Voltage and/or Line Powered Equipment before working on any type of equipment which uses line voltage or produces high voltage. (With diode lasers, you can easily fry the laser diode but the low voltage power supplies don't generally pose much of a shock hazard.)

- Small HeNe lasers (say, under 5 mW) at least require low current (a few mA) so the risk of actual electrocution from the a commercial high voltage power supply is relatively small but there may be AC line voltage involved and there can be collateral damage from a reflex response to the shock. But, a homemade power supply may use components which are grossly oversized for the application (due to low cost availability) like a 15,000 V, 400 W neon sign transformer even though only under 10 W of power is actually needed (we definitely do NOT recommend this approach). However, all power supplies for larger HeNe lasers can be quite lethal.

- Small Ar/Kr ion lasers operate at relatively modest voltage - 100 to 110 VDC across the tube - but due to the high current (up to 10 A), are usually directly line connected (no line isolation) and therefore the power supplies are extremely dangerous.

- Small CO2 lasers do indeed use high voltage and possibly much higher current than HeNe lasers - that neon sign transformer may be appropriate - and deadly!

Note that some of these 'small' lasers are only small in comparison to their higher power cousins and small doesn't equate to safe!

Furthermore, you may come across a truly high power CO2 or argon ion laser, or even a 100 mW HeNe laser tube. These, rated at the upper end of Class IIIb or Class IV, represent even more significant risks of both instant permanent eye damage even from momentary reflections from shiny (specular) surfaces as well an actual fire hazard. The possibility of electrocution from their power supplies is correspondingly greater as well. You must handle them properly for your own safety and the safety of others around you and your surroundings.

See the specific chapters on each of these types of lasers for additional hazards and precautions Note that other people in the area may actually be more likely to get caught by the beam. The reason? You will be aware of what NOT to look at while they will be looking in the direction of the action not having a clue of what to expect! Don't take chances.

The following very large number is designed to impress: The power density of a 1 mW laser beam when focused to a spot of around 2 um (which isn't difficult with a simple convex lens) is around 250,000,000 W per square meter! Don't let that spot be in the back of one of your own or someone else's eyeballs!

Be extremely careful when working with any laser!

(From: Tjpoulton (tjpoulton@aol.com).)

A 1 mW diode will probably not cause damage if you briefly look into it, but I wouldn't encourage you to try it. While it probably won't do anything bad, it is not good to become comfortable with the idea of checking the operation of lasers by looking into them. If you are a hobbyist who uses lasers quite a bit, there is a good chance you will, at some point, end up with an unmarked diode. It could emit any wavelength at any power level, and how bright the beam appears when you shine it on something has no bearing on the power level. Looking into an unmarked diode just because the beam is dim could (and probably will) have disastrous results. I have a 1 W 808 nm laser diode, and it appears much dimmer than a .5 mW 670nm beam when focused into a .2 mm spot. When focused in that way, it will easily engrave plastic and burn paper and wood (and skin). Just because it looks dim doesn't mean it won't instantly blind you.

(From: Daniel P. B. Smith (dpbsmith@world.std.com).)

Be aware that eye damage that is localized to a small area of the eye is not very noticeable. For example, few people ever notice the existence of the large blind spot where the optic nerve enters the eye even though it is rather huge (10 degrees or so) and not all that far from central vision. A laser wouldn't necessarily have to make you totally blind; it could just wipe out a teeny patch here and a teeny patch there. This kind of damage would be very insidious; each time you'd say "Wow! That was bright! lucky I didn't get blinded" - while slowly and cumulatively losing your sight...

General Laser Safety Guidelines

These guidelines are for your own protection and that of others around you. Lasers have a unique set of dangers not present with other equipment common at work or at home. And, yes, some of these guidelines even apply to those $9.95 laser pointers!

- Never look into the beam of any laser. OK, there might be exceptions if you are *absolutely* sure the beam has been attenuated or diverged enough to be totally eye-safe. For example, the beam from the optical pickup in a DVD player is safe to view from an oblique angle at a distance of at least 6 inches since it is highly divergent; the beam from a supermarket barcode scanner is safe because it is scanning rapidly.) Distance alone isn't a guarantee - some lasers maintain a tightly collimated beams for 100s of feet or more. IR lasers may be invisible but can still cause instant damage to vision and are even more dangerous than visible laser because your blink and aversion reflexes don't work if you can't see the beam. Specular reflections (from shiny surfaces like glass and metal) may be just as dangerous as the raw beam. Viewing the reflection from a diffuse surface like a white card is much safer though for higher power lasers, even if the card doesn't burst into flames, the reflection may still be unbearably bright.

- Wearing proper laser safety goggles is always a good idea for any laser but especially for those rated Class IIIb or higher. Each type of laser requires its own specific protection depending on wavelength and power. Just because you have a piece of colored glass or dark visor from a welding outfit doesn't mean it will protect you from a laser beam!

- Be aware of the wavelength(s) power of your laser(s). A 100 W CO2 laser and 100 mW Ar ion laser are quite different and require different sets of precautions but one is not necessarily more dangerous than the other. Specific laser classifications and precautions depend on both wavelength and power.

- Always terminate the laser beam with a light absorbing material or diffuse screen. Don't just let it fly wildly around the room to end up who-knows-where.

- Clearly mark the path of the beam and provide barriers to prevent accidental contact with eyes (all lasers) and other body parts (high power lasers).

- Follow all relevant electrical safety regulations with respect to wire sizes, equipment grounding, and proper hookup, as well as providing essential fuses, circuit breakers, GFCIs, and other protection devices. Insulate or block access to all AC line connected and/or high voltage terminals.

- Provide a 'kill' switch in an accessible location away from the laser and its beam path just in case you need to cut power in a hurry.

- Put appropriate laser safety and electrical safety warning/danger stickers near the laser emission aperture and other beam path locations, on the laser, and on power supply components.

- Never randomly aim a laser out the window. In fact, your laser lab or workshop should have shades or blinds over all windows to prevent this from happening by accident. Someone across the street may inadvertently look into the beam. And, deliberately directing a laser toward an aircraft is not only incredibly stupid but also highly illegal - pilots take their eyesight quite seriously! There may be specific applications or experiments that depend on using lasers outside (professional laser light shows, line-of-site laser communications, surveying, LIDAR, etc.) but each will have its additional specific safety precautions and regulations.

- Instruct anyone else with you as to the hazards of laser light and make sure they understand all of these guidelines. Those with you may actually be in MORE danger because they will be looking toward the direction of the action while you will know what to expect and avoid.

Also see the additional comments below, and the more specific information on laser safety in each chapter for the specific laser(s) you will be using.

Laser Pointer Safety

There have been some recent articles (mainly in the UK) about eye injuries resulting from careless or malicious use of common laser pointers. In the U.S., there have been numerous news reports which would lead the average person to believe that the absolute end of civilization as we know it will result from the proliferation of these devices. Although the potential for eye injury is typically what comes to mind when one thinks of a laser, the possible side effects - or collateral damage - that may result from aiming one at somebody is at least as likely a cause for the current wave of hysteria.

Keep in mind that what gets reported in the popular press is not exactly what you would call rigorously reviewed for scientific accuracy. And, if it turns out that the outcome wasn't quite as reported originally, any correction for a front page story is usually to be found in fine print buried on page 17! Actual substantiated instances of long term or permanent effects on vision resulting from momentary or unintentional exposure to a laser pointer's beam - or even from prolonged intentional misuse - appear to be all but non-existent. Flash blindness IS possible, but this is temporary and will clear up on its own.

With respect to direct personal danger, potential damage to vision is the only real consideration - there is no risk from radiation or enough power in a beam of less than 5 mW to burn anything. However, from a public policy and regulatory perspective, there are actually three areas of concern:

1. Flash blindness from momentary exposure or permanent damage to vision from prolonged intentional misuse. Laser pointers are usually rated Class IIIa or less which means that the power is low enough that the eye should be protected from permanent damage by natural pupil contraction, blink, and aversion reflexes.

2. Distraction and collateral damage - you wreck your car because someone pointed a laser pointer at you while you were driving.

3. Misinterpretation of intent - you get blown away by someone with a BIG gun who thinks you are targeting them with a laser sight. Or, you are arrested and thrown in the slammer for aiming a laser pointer at a cop (this happened recently).

I am in favor of tough laws to make (2) and (3) crimes and require at least full restitution (maybe even 2X or 3X) for any resulting damages in addition to disciplinary action or jail time. Such behavior should not be tolerated. However, in the remainder of this section, I only really want to address the vision issues (1).

While I absolutely agree that intentionally aiming a laser of any kind into someone's eye is basically stupid (unless you are having laser eye surgery), one must be careful in interpreting the meaning of press reports that describe momentary exposure to the beam from a laser pointer waved around an auditorium resulting in instant total loss of vision in all three eyes. One would have to direct the beam into the pupil of the eye from a close distance for a few seconds or more without either the eye or pointer moving, twitching, or blinking. Distance is significant both because even laser pointer beams diverge (especially cheap ones) so less energy is able to enter the pupil of the eye as the source moves further away and it is harder/less likely for it to remain stationary and centered on such a target a few mm across. This is not really possible by accident and even takes significant effort to do intentionally since the eye's natural pupil contraction, blink, and aversion reflexes will prevent the beam from focusing on a single spot on the retina with a sufficient concentration of energy for more than an instant - not enough time for damage to result. There would have to be cooperation which can only really happen in a game of chicken - but it is hard to protect people from their own stupidity. This does mean, however, as if it isn't already obvious, that laser pointers should be kept from infants - period, and away from children unless adequately supervised. Adults, on the other hand, presumably know not to stare into painfully bright lights and some may even read the warning labels!

Though momentary exposure may indeed result in temporary flash blindness, disorientation, multiple afterimages, and a headache, such effects, while not to be minimized in importance, should not be permanent. And, as the distance between the eye and the pointer increases, their severity and duration diminishes greatly. To suggest any long term eye injury from a pointer's beam originating on the other side of a football stadium is simply not plausible.

In fact, despite the great amount of press coverage lately - and such reports resulting in the passage of laws in some places banning laser pointer sales to minors (or to anyone), there are very few if any confirmed reports of permanent vision damage attributable to these things. The irresponsible aiming of a laser pointer at a person that might result in tragic consequences from distraction or misinterpretation of intent is far more likely to be a problem in today's world - and justifiably so.

Laser pointer manufacturers and resellers make all sorts of claims about power levels and there may be deliberate (power is, after all, a major feature) or unintended (due to poor quality control) sale of devices with power even beyond the approved safety limits and these could indeed be much more dangerous. However, simply enforcing existing regulations could go a long way toward reducing this possibility. But, of course, the prices would likely go up if more sophiticated laser power control circuitry were required and every unit had to be more fully tested, adjusted, and certified to be compliant.

To further minimize the chance of vision damage, I think a maximum power limit of 1 mW would be more than adequate for most purposes with the newer 635 nm pointers. These appear 5 to 7 times brighter than previous 670 nm models and green laser pointers (which should be available at affordable prices in the not to distant future) will appear even brighter by another factor of 5 or so. Staring into the noonday Sun would result in the same order of magnitude of power focused on the retina as a 1 mW laser pointer against your eyeball and we don't even bother to regulate THAT! :)

Don't get me wrong - I am definitely NOT recommending that laser pointers be treated as toys and handed out to all the neighborhood kids as party favors. They can still be dangerous and at least a niusance even if eye injury isn't the primary risk. I fully agree that any use of such a device in a way that annoys other people or puts them at risk - even if it is a small risk - is valid grounds for confiscation and possible severe disciplinary action.

For that matter, how come no one has banned butane lighters or matches? :-) They are cheaper, more readily available, and certainly result in more injury, death, and destruction in the hands of kids than laser pointers! Or, how about cigarettes.... Sorry, I will get off my soap box now....... No, I don't expect an answer. :-)

For more information on laser pointer safety, see the NRPB Laser Pointer Article, ISHN Putting Risks into Perspective, and other links in the section: Laser Safety Sites.

(From: Gregory Makhov (lsdi@gate.net).)

As chair of the ILDA (International Laser Display Association) laser safety committee, I have been carefully following the thread on laser pointer safety (in the sci.optics newsgroup - search at DejaNews for the complete saga). I have seen most of the articles in the press on laser incidents/accidents in the UK. If you have a source of factual evidence concerning these 'injuries', I would greatly appreciate the information. My own experience with laser pointers would indicate that a level of 5 milliwatts and below is unlikely to cause injury unless self-inflicted and for a substantial duration (several seconds). I say self-inflicted, as it is unlikely that another person could direct the laser accurately into someone's eye at any significant range. Almost immediately after the initial exposure to the beam, the pupil shrinks to a very small size (a few millimeters) which is an awfully small target to illuminate from a distance of even a few meters.

However, if there is any medical evidence of these injuries, and some documentation of how they occurred (laser power, range, duration, etc.) I am most interested.

How Does Wavelength Affect Laser Safety?

Laser hazards and laser safety classifications depend on wavelength but not just because some colors are much more visible than others.

For wavelengths within the visible spectrum and near IR where the cornea, lens, and vitreous of the eye are transparent, 1 mW is the same amount of power whether it is near IR, red, or green. There will be slight differences in damage threshold depending on wavelength (spot size on the retina, absorption) but green is really not more dangerous than red, mW per mW for a beam that reaches the back of the eye. Since green light at 555 nm *appears* about 30 times brighter than red light at 670 nm, the green laser may actually be slightly less of a hazard since you will likely respond to it faster (and, in the case of laser pointers in particular, a lower power unit may be adequate).

Beyond the visible - IR and UV - there are other issues. UV laser light, like UV Sunlight can indeed have effects beyond just those due to the power density. Fortunately, there aren't likely to be UV any laser pointers any time soon even if there were a use for them (phosphorescent white boards?)! :-) Most other UV lasers (excimer, helium-cadmium, frequency quadrupled YAG, etc.) are not that common either (at least not that the typical hobbyist will acquire). However, should you consider building the nitrogen laser (among the easiest of home-built lasers), its output is at 337.1 nm which near UV (UV-A range).

Near IR is perhaps the most dangerous since it progressively less visible the longer the wavelength starting at about 1/250th visibility compared to 555 nm and going down to 3E-14 visibility (estimated) at 1,064 nm. Yet, until well beyond this (maybe 1,500 nm), the light can still pass through the anterior structures of the eye to reach the retina and will focus reasonably sharply despite not being visible. There will be no blink or aversion reflex so damage can be done even for modest power lasers without any immediate symptoms. Only later, will the pretty patterns engraved on your retina(s) become evident (since your brain will initially tend to fill in and mask their effects). And, they won't go away - ever!

At mid IR, the beam can still penetrate to the lens, heating it, which may produce a cataract. Far far IR such as the 10.6 um (10,600 nm) from a carbon dioxide (CO_2) laser is effectively absorbed and blocked by the cornea of the eye - and it can be damaged in a similar way. And, almost all CO_2 lasers produce enough power (a few W to 10s of KW) that they are also hazardous with respect to burning things (including other types of flesh) as well as actually setting fires.

The long and short of it is that there is a threshold of laser power that will be dangerous in various ways at ANY wavelength and no laser can be treated as totally safe until the detailed specifications of the laser and its optical system are known.

Caution About Depending on Neutral Density Filters for Protection

(From: Don Klipstein (don@Misty.com).)

While thumbing through some gel filter sample packs, it has occurred to me that there are neutral density gel filters - and that they are not truly neutral. Both Gam and Rosco ones are somewhat neutral through to about 700 nM - and become more transparent as wavelength increases through the low and mid 700's. They are nearly transparant above about 750 nM.

They also have a slight peak at 380 nM, where they are a bit more transparent than they are to visible light. Transmission at 380 can exceed the average visible transmission for darker grays.

This is because these filters are made gray with some kludge of dyes rather than something truly neutral-density. They also do not equally attenuate all visible wavelengths; they have transmission peaks around 480 (greenish blue) and 600 (orange), and absorption peaks around 450 (mid-blue) and the mid 500's (yellowish green). Different brands may have some differences, as well as having some similarities. They probably have some but not all dyes in common.

I do not know whether the infrared transparency is an unavoidable consequence of dying plastics/gels, or something intentional to reduce filter heating. I do know that the colored filter gels are also nearly transparent to most wavelengths from the upper 700's (sometimes low 700's) through probably at least around 1500 nM.

Because of this, dark filter gel combinations are probably unsafe for directly viewing the sun, and are probably unsafe for attempting to protect eyes from infrared lasers.

Accidents Can Happen

(From: Brian Sutin (sutin@sol.ucolick.org).)

Several years ago there was a long thread in rec.guns, where people posted their stories about all the accidents or near accidents they had experienced with firearms. These were all seemingly intelligent people like computer programmers and scientists and engineers. Still, while dealing with a simple device with only a few knobs, they managed somehow, sooner or later, and while trying to obey all the safety rules, to blast a hole in something or someone. Educational reading.

There was a really good story recently posted right here (sci.optics). Some guy was working with a laser and then took off his goggles, and blew out some of his eye. Dumb. Then, rather than realizing that the goggles don't work if they are not worn, he decided that he just wouldn't wear them at all, and he would Be Real Careful. This is called People Who Don't Learn From Their Mistakes. Let's hope he doesn't take up firearms.

When you have goggles on (assuming that they are the right kind, and you should make damn sure they are), you have very good protection against loss of vision. When you take them off, you don't. A movement of a mirror, lens, or baffle can cause a specular reflection, total internal reflection, or refraction right into your eye. This isn't something to anticipate -- that's why it is called an accident. Even with all the appropriate precautions, accidents can still happen.

Imagine that you are working with the laser off, aligning some mirror, no goggles, and you spill your coffee over the on-off switch to the laser power. Oops. Collect insurance.

Back to Laser Safety Sub-TOC.

Laser Safety Classifications

A Smorgasbord of Acronyms

There are ANSI, OSHA, FDA (CDRH), NRPB, and military standards. The best discussion of these, plus general treatment of the topic, is a book by Sliney and Wolbarsht, "Safety with Lasers and Other Optical Sources," Plenum Press, New York. While they will agree with each other in most respects, some differences will result in a particular laser changing classes depending on which standard is used. The major criteria are summarized below.

The following is based on material from the University of Waterloo - Laser Safety Manual.

All lasers are classified by the manufacturer and labelled with the appropriate warning labels. Any modification of an existing laser or an unclassified laser must be classified by the Laser Safety Officer prior to use. The following criteria are used to classify lasers:

1. Wavelength. If the laser is designed to emit multiple wavelengths the classification is based on the most hazardous wavelength.

2. For continuous wave (CW) or repetitively pulsed lasers the average power output (Watts) and limiting exposure time inherent in the design are considered.

3. For pulsed lasers the total energy per pulse (Joule), pulse duration, pulse repetition frequency and emergent beam radiant exposure are considered.

Lasers are generally classified and controlled according to the following criteria:

- Class I lasers - Lasers that are not hazardous for continuous viewing or are designed in such a way that prevent human access to laser radiation. These consist of low power lasers or higher power embedded lasers (i.e. laser printers).

- Class II visible lasers (400 to 700 nm) - Lasers emitting visible light which because of normal human aversion responses, do not normally present a hazard, but would if viewed directly for extended periods of time. (like many conventional light sources).

- Class IIa visible lasers (400 to 700 nm) - Lasers emitting visible light not intended for viewing, and under normal operating conditions would not produce a injury to the eye if viewed directly for less than 1000 seconds. (i.e. bar code scanners).

- Class IIIa lasers - Lasers that normally would not cause injury to the eye if viewed momentarily but would present a hazard if viewed using collecting optics (fibre optics loupe or telescope).

- Class IIIb lasers - Lasers that present an eye and skin hazard if viewed directly. This includes both intrabeam viewing and specular reflections. Class IIIb lasers do not produce a hazardous diffuse reflection except when viewed at close proximity.
- Class IV lasers - Lasers that present an eye hazard from direct, specular and diffuse reflections. In addition such lasers may be fire hazards and produce skin burns.

The following is paraphrased from the CORD course: "Intro to Lasers". (On-line version at: Course 1 - Intro to Lasers. See the section: On-Line Introduction to Lasers.) It relates the laser classifications to common laser types and power levels:

- Class I - EXEMPT LASERS, considered 'safe' for intrabeam viewing. Visible beam.

  Maximum power less than 0.4 uW. This will not cause damage even where the entire beam enters the eye and it is being stared continuously.

- Class II - LOW-POWERED VISIBLE (CW) OR HIGH PRF LASERS, won't damage your eye if viewed momentarily. Visible beam.

  Maximum power less than 1 mW for HeNe laser.

- Class IIIa - MEDIUM POWER LASERS, focused beam can injure the eye.

  HeNe laser power 1.0 to 5.0 mW.

- Class IIIb - MEDIUM POWER LASERS, diffuse reflection is not hazardous, doesn't present a fire hazard.

  Visible Argon laser power 5.0 mW to 500 mW.

- Class IV - HIGH POWER LASERS, diffuse reflection is hazardous and/or a fire hazard.

The classifications depend on the wavelength of the light as well and as noted, there may be additional considerations for each class depending on which agency is making the rules. For example, the NRPB (British) adds a requirement for Class IIIa that the power density for a visible laser not exceed 25 W/m^2 which would thus bump some laser pointers with tightly focused beams from Class IIIa to Class IIIb. For more information on laser pointer safety and the NRPB classifications, see the NRPB Laser Ponter Article.

In the US, start with the Center for Devices and Radiological Health (CDRH), part of the Food and Drug Administration (FDA). See the section: Regulations for Sale of Lasers and Laser Based Products for more info on how to find the relevant guidance documents.

For additional information on laser safety and laser safety classifications, see the section: Laser Safety Sites (May Also Include Other Laser Information).

(From: Johannes Swartling (Johannes.Swartling@fysik.lth.se).)

It is not the laser in itself that is given a class number, but the whole system. A system which is built around a very powerful laser can still be specified as Class I, if there is no risk of injury when operating the system under normal conditions. For example, CD players are of class I, but the (IR) laser diode may in itself be powerful enough to harm the eye. CD players are designed so that the laser light won't escape the casing.

When it comes to laser safety and exposure levels the regulations are fairly complicated and I will not go into details. Basically, there are tables with 'safe' levels of exposures. The exposure has to be calculated in a certain way which is unique to each case, depending on among other things: laser power, divergence, distance, wavelength, pulse duration, peak power, and exposure time.. Although it is true that near infrared lasers are potentially more dangerous than visible because you can't see the radiation, it is incorrect to say that it must be, say, Class III. The level of exposure may be so low that it can be a class I (note that Class II lasers are always visible though, so infrared lasers are either of Class I or Class III or higher).

You can probably get a copy of the regulations from a university institution that works with lasers or from the government agency in your country that is responsible for safety at workplaces.

Hobbyist Projects and Laser Safety Classifications

While many of the partial circuits and complete schematics in this document can and have been used in commercial laser products, important safety equipment has generally been omitted to simplify their presentation. These range from simple warning labels for low power lasers (Class I, II, IIIa) to keyswitch and case interlocks, beam-on indicators, and other electrical and mechanical safety devices for higher power lasers. Laser safety is taken very seriously by the regulatory agencies. Each classification has its own set of requirements.

The following brief summary is just meant to be a guide for personal projects and experimentation (non-commercial use) - the specifics for each laser class may be even more stringent:

- For diode lasers and HeNe lasers outputting 5 mW or less (Classes 1, II, IIIa), packaging to minimize the chances of accidental exposure to the beam and standard laser warning labels should be provided.

- Where the case can be opened without the use of tools, interlocks which disable the beam are essential to prevent accidental exposure to laser radiation (Class IIIa and above). Their activation should also remove power and bleed off any dangerous voltages (ALL HeNe and argon/krypton lasers).

- A beam-on indication is highly desirable especially for lasers emitting invisible IR (or UV).

Aside from their essential safety function, laser warning or danger stickers DO add something in the professional and high-tech appearance department. Companies selling laser accessories will likely offer genuine CDRH approved stickers. If you are selling any laser based equipment, you'll need them (and a lot more - see below). For hobbyist use some semi-standard unofficial samples can be found at many laser related Web sites. One fairly complete set including all laser classes can be found at University of Illinois at Urbana Champlain Laser Safety Signs. Starting from these, the specific type of laser and maximum output power for your particular equipment can be further customized using a graphics editor.

Regulations for Sale of Lasers and Laser Based Products

Where you plan to offer a product commercially, there are very specific requirements - and equally severe penalties for non-compliance!

(From: Steve Roberts (osteven@akrobiz.com).)

> "CDRH has fangs and will use them. I have a friend who sold helium-neon laser power supply kits without stickers, certification, and registering. His legal bills alone were $8,000, not to mention the hefty fine his company paid."

CDRH will gladly send out a complete copy of the guidelines for manufacturing laser systems free of charge if you request it. Ask them to throw in the laser show stuff as it makes even more interesting reading. The hardcopy from CDRH will include the exposure tables and how to calculate MPEs, etc. It's free to all US citizens and probably free to overseas corporations as well.

Many if not all of these documents are now available on-line (although some are just the scanned paper documents in .pdf format). Go to the CDRH Guidance on Electronic Products which Emit Radiation page. This has all the categories of radiation emitting devices and some of the detours may prove interesting. If you have enough discipline to ignore them, click on "Lasers, Including Light Shows" which takes you to the Laser Products, Including Laser Light Shows and Displays page with its list of available documents. The one you probably want to begin with is: Performance Standard - Lasers and Products Incorporating Lasers. This includes the always very popular detailed information on laser classifiactions! :)

For a more interactive experience, spend an afternoon (more or less) starting at the CDRH Device Advice page. According to their blurb: "Device Advice is set up with pages that describe these procedures and link you to the appropriate documents on the CDRH Homepage such as guidance documents, databases, and manuals that will both assist in meeting marketing requirements and answer many questions you may have."

Also, see the chapters on 'Control Measures' in the laser safety manuals at the Laser Safety Links Web site and the other laser safety links in the chapter: Laser Information Resources of this document.

How Large a Laser Can You Legally Own?

(From: Steve Roberts (osteven@akrobiz.com).) As long as you don't use the laser for public displays or shows, put it where the general public can access more then the Class I exposure limits, don't do anything that risks illuminating an aircraft or other vehicle and don't practice medicine (including general surgery and dentistry!) with it, the sky is the limit. You can legally use some Class II lasers and some Class IIIa lasers in public, as long as you comply with the safety instructions that came with the device. This is for the US. However, if you wish to do laser shows, other rules apply. See the sections starting with: Some Basic Info on Light Show Lasers for more info.

Back to Sam's Laser FAQ Table of Contents.
Back to Laser Safety Sub-TOC.
Forward to Items of Interest.