Photonics-Enabled Technologies

Lasers in Medicine and Surgery

OP-TEC

Optics and Photonics Series

Lasers in Medicine and Surgery

Photonics-Enabled Technologies

OPTICS AND PHOTONICS SERIES

STEP (Scientific and Technological Education in Photonics), an NSF ATE Project

National Center for Optics and Photonics Education

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PREFACE

This module is part of the STEP series on *photonics-enabled* technologies. The combined series on photonics-enabled technologies (comprising both STEP and OP-TEC materials) consists of modules in the areas of manufacturing, biomedicine, forensic science and homeland security, environmental monitoring, and optoelectronics, as listed below. (This list will expand as the OP-TEC series grows. For the most up-to-date list of modules, visit http://www.op-tec.org.)

Manufacturing

Laser Welding and Surface Treatment

Laser Material Removal: Drilling, Cutting, and Marking

Lasers in Testing and Measurement: Alignment Profiling and Position Sensing

Lasers in Testing and Measurement: Interferometric Methods and Nondestructive Testing

Environmental Monitoring

Basics of Spectroscopy

Spectroscopy and Remote Sensing

Spectroscopy and Pollution Monitoring

Biomedicine

Lasers in Medicine and Surgery

Therapeutic Applications of Lasers

Diagnostic Applications of Lasers

Forensic Science and Homeland Security

Lasers in Forensic Science and Homeland Security

Infrared Systems for Homeland Security

Imaging System Performance for Homeland Security Applications

Optoelectronics

Photonics in Nanotechnology

For students who may need assistance with or review of relevant mathematics concepts, a review and study guide entitled *Mathematics for Photonics Education* (available from CORD) is highly recommended.

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Lasers in Medicine and Surgery

INTRODUCTION

Since the invention of the first laser in 1959, lasers have moved from the realm of the science fiction "death ray" to an everyday and often indispensable part of the medical/surgical armamentarium in practically every medical specialty. The unique qualities of laser energy are being utilized in an ever-growing number of applications. Lasers have been the driving force behind innovations in many surgical specialties. Competition from lasers has also lead to significant improvements in many competing, non-laser devices.

Lasers are now available with output wavelengths ranging from the far ultraviolet to the mid infrared. A growing number of these laser wavelengths are being applied in medicine and surgery. In some cases, new procedures are being developed around the unique characteristics of laser energy. In other cases, a new wavelength or laser may be replacing less efficient or more expensive systems. Absorption characteristics of the many available wavelengths vary across the laser spectrum. For a laser to have a desired effect, its energy must be absorbed in the targeted tissue. As such, lasers are selected for specific applications based on the absorption characteristics of their wavelength(s) in tissue and the means available to get the laser energy to the treatment site. This chapter will provide a general overview of the role lasers play in medical and surgical applications. The various effects that can be achieved, the types of lasers generally used, the common delivery systems and accessories will all be included.

PREREQUISITES

Course 1: *Fundamentals of Light and Lasers*

Module 1-1: *Nature and Properties of Light*

Module 1-3: *Light Sources and Laser Safety*

Module 1-6: *Principles of Lasers*

OBJECTIVES

Upon completion of this module, you should be able to do the following:

- Describe the process of absorption of laser light by human tissue. The description should include:
  - Identification of the approximate wavelength ranges at which absorption is relatively low and relatively high.
  - Description of the effect on skin pigmentation.
- Describe reflection of laser light by human tissue. The description should include:
  - Identification of the approximate wavelength ranges at which reflection is relatively low and relatively high.
  - Description of the effect on skin pigmentation.
- For a particular laser and tissue type, determine the temperature rise resulting from a laser exposure. State whether this exposure is likely to cause tissue destruction.
- Measure the absorption coefficient of an organic tissue at several laser wavelengths.
- Name the most widely used lasers in medicine, along with the output wavelength(s) for each and the type of applications where they are most suited.
- For given values of beam power and target spotsize, calculate the irradiance of a laser beam on target.
- Describe the use of fiber optics in medicine.
- For given values of indices of refraction, calculate the critical angle for total internal reflection in a fiber.

SCENARIO

Jerome, who graduated from a community college with an associate degree in photonics and has been working in the telecommunication industry, decided he wanted to make a career change. Jerome has always been interested in the medical field and began to investigate and acquire knowledge in photonics as it relates to medicine and surgery. The Cleveland Clinic Hospital, which is near where Jerome lives, uses CO_2, argon, Nd:YAG, and excimer lasers for surgical procedures. Jerome did some reading on lasers in medicine and discovered that to make the career change he anticipates, he will need to review laser fundamentals such as laser properties, optics, types of lasers, and laser safety. He also discovered that medical lasers are fundamentally the same as industrial lasers but much different in their shapes, styles, and components. Jerome will have to acquaint himself with these new systems. He made several contacts with medical laser manufacturers such as Sharplan Medical Laser Systems in Allendale, N.J., to ask for information and brochures on medical laser systems. He also inquired at the Laser Institute of America in Orlando, Fl.; Rockwell Laser Industries in Cincinnati, Ohio; and CORD (producer of laser curriculum materials) in Waco, Texas, for materials on photonics as it relates to medicine and surgery. At the same time he asked these organizations for schedules of short courses being offered in this discipline. He contacted the Cleveland Clinic Hospital's employment office, which informed him that the hospital needs a photonics medical technician *and* a medical laser safety officer. Jerome realized he had basic laser safety knowledge from his training in college and his present job, but had little knowledge of laser safety as it pertains to medical environments. Since he will be working with nurses, doctors, and patients, he certainly needs training in medical laser safety. The hospital said that if Jerome is hired, it would sponsor his attendance at a medical laser safety short course. This course would include topics such as hazards and controls, personal protection equipment, engineering controls, maximum permissible exposures (MPE), and nominal hazard zones (NHZ). Jerome decides to apply for the position of photonics medical technician with all the other duties involved. Good luck, Jerome, with your new career move and a successful application at the Cleveland Clinic Hospital.

BASIC CONCEPTS

Properties of Laser Light

It is laser light's unique characteristics that give it much of its utility. Normal light is incoherent. Consider the average light bulb. The photons emitted cover a broad range of wavelengths from the infrared through the visible and into the ultraviolet. These photons spread out randomly in all directions. The light bulb is useful for illuminating broad areas but that is about all. Light from a laser is very different.

Laser light is *monochromatic, coherent,* and *collimated*. While many laser mediums are capable of fluorescing at several different wavelengths, generally lasers are designed to use the most efficient wavelength(s), i.e., the most intense line of fluorescence.

While lasers can be designed to produce multiple wavelengths simultaneously, each line of fluorescence is *monochromatic*—of a single wavelength. Therefore, laser light can be monochromatic even when multiple lines are lasing at the same time. Each wavelength can be separated from the others by passing the beam through a prism or a grating, thereby producing a beam of a single wavelength.

Another characteristic of laser light is its *coherence*. Because of the way the emission of photons is stimulated within the medium, the photons are in phase—that is, in step—with each other. Comparing incoherent light to coherent light would be like comparing a rain shower to an ocean wave. Raindrops fall randomly in no particular sequence, so their impact is diffused over space and time. By comparison, an ocean wave of the same volume, with all its "drops" in phase with one another, hits the same place at the same time. The impact of all of those drops is magnified by their coherence. (See Figure 1.)

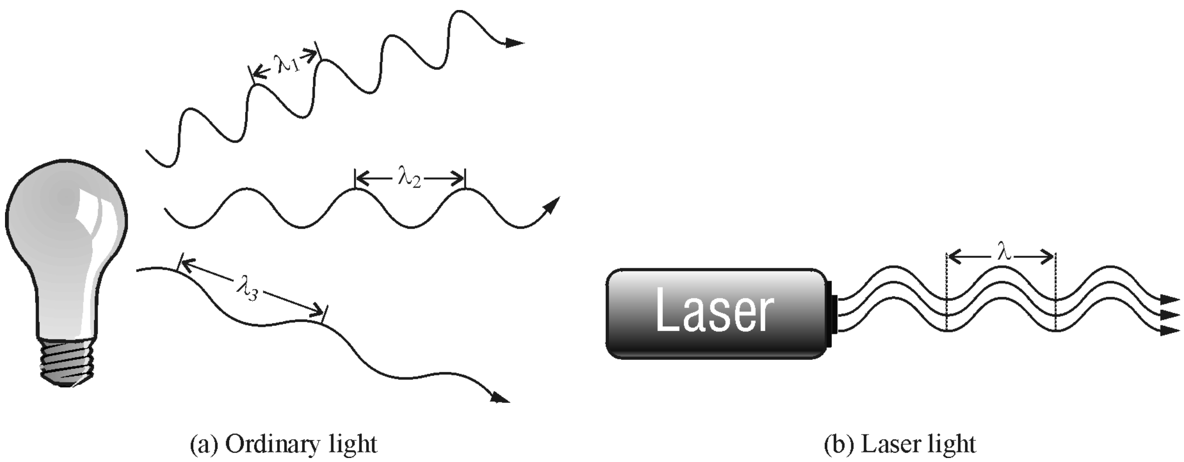
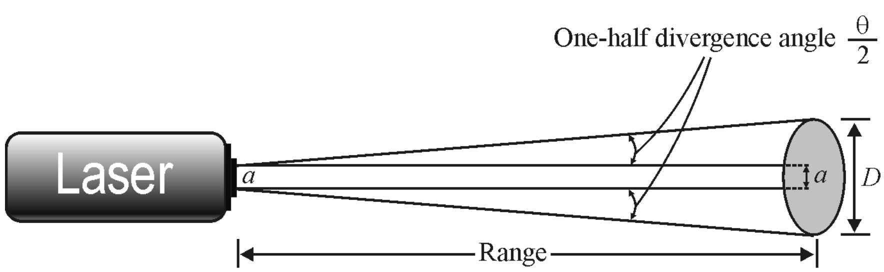


Figure 1 *A comparison of ordinary light and monochromatic, coherent light (a)* ***Light bulb:*** *incoherent light; different wavelengths [colors] (b)* ***Laser:*** *coherent and monochromatic light; same wavelength [monochromatic]; light waves in phase [coherent])*

The third unique characteristic of laser light is *collimation*. Collimated light consists of photons all traveling in the same direction with minimal divergence. Laser light is emitted in a narrow, well-defined beam that does not spread rapidly. This characteristic makes it easier to focus the laser's output to a very small, well-defined spot. (See Figure 2.)



$$\text{Spot diameter } D = [\text{Divergence angle} \times \text{Range}] + a = [2(\frac{\theta}{2}) \times \text{Range}] + a$$

Figure 2 *The spot size diameter of a laser beam on target depends on the beam divergence and the distance from the laser to the target.*

Tissue Effects

When laser energy is incident on tissue, three things happen. Some of the light will be *reflected,* some will be *absorbed* at the treatment site, and some will be *transmitted* into tissues beyond the treatment site. (See Figure 3.) For the laser to be effective the light must be absorbed by the targeted tissues. The degree to which each occurs is a function of the laser wavelength and how the laser energy interacts with the tissue being irradiated. If the laser wavelength has been selected properly, the majority of energy is absorbed in the targeted tissue. Reflection of some of the laser energy simply reduces the laser's efficiency. Any energy not reflected or absorbed is transmitted through and eventually dissipated in the underlying tissues.

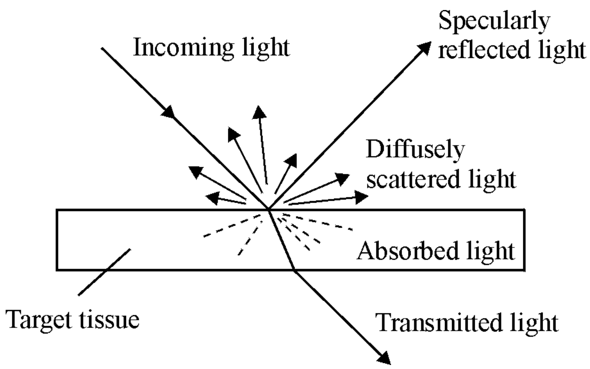


Figure 3 *Interaction of light on target tissue*

The tendency of different types of tissues to reflect, absorb or transmit laser energy is a function of both the laser's wavelength and the makeup of the tissue. While all soft tissue is made up of over 90% water, other components of tissue such as *melanin* and *hemoglobin* can vary greatly. Absorption, reflection and transmission values can be established for low levels of irradiance. These characteristics can be useful in determining the most suitable wavelength for a specific application.

Again, throughout the visible spectrum there are appreciable differences in the amount of light reflected, depending on the pigmentation level of the skin. This means that, for an argon laser or a ruby laser, much more light will be reflected from the skin of a fair-skinned person than from a darker-skinned person. (See Figure 4.) Note that in the infrared—around 3 μm—the two curves come together. There and beyond, the reflectance drops to a low value and is not strongly dependent on the pigmentation level of the skin. Therefore, for the CO_2 laser at 10.6 um, very little radiation will be reflected, regardless of the pigmentation. This means that absorption can be high.

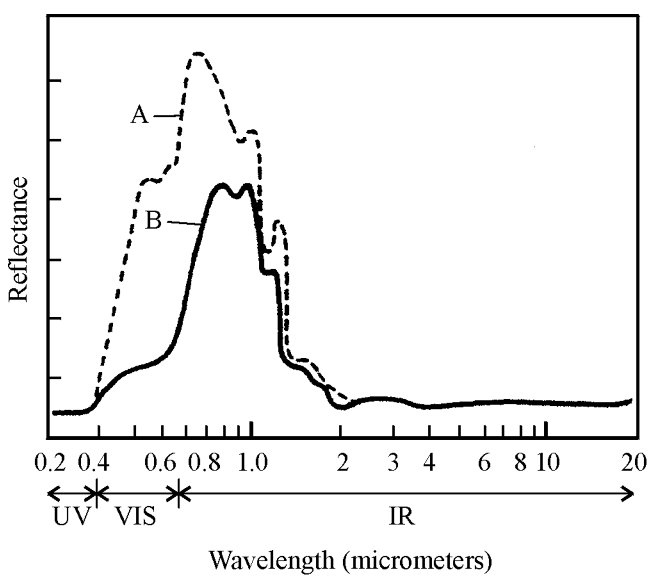


Figure 4 *Reflectance of skin as a function of wavelength. Curve A is for fair skin; curve B is for heavily pigmented skin. The visible region (VIS) extends from 0.4 to 0.7 μm.*

The reflectance value is important because reflected light is lost and is not available for heating or cutting the tissue. For example, with a ruby laser incident on a fair-skinned person, 60% of the incident energy may be reflected. However, exposure to sufficiently high concentrations of laser energy will damage exposed tissue. Once tissue has been damaged, its characteristics are altered, and this alteration can significantly affect the ratios of reflected, absorbed, and transmitted energy.

Transmitted energy raises some interesting issues. It will tend to scatter as it passes through tissue. It generally penetrates into the surrounding tissue where it is absorbed. If enough laser energy is absorbed in the surrounding tissues, it can cause undesirable *collateral damage*. This is a major safety concern with some laser wavelengths.

In certain cases, a laser wavelength may be selected so that it will transmit through surface tissues to reach underlying target tissues, where it will be absorbed. Lightly pigmented tissues will reflect or transmit visible and near-visible wavelengths that heavily pigmented tissues would absorb. Since hemoglobin and oxyhemoglobin appear as red, they will tend to reflect red light and absorb its complement, green light. For this reason, in the past, lasers emitting green wavelengths were often used to treat vascular lesions such as port wine stain. The energy is transmitted through the skin to the underlying lesion where it is absorbed by the hemoglobin, thereby destroying the vascular structure that makes up the lesion. While this is easily accomplished on a fair-skinned person, it becomes more complicated as the concentration of melanin in the skin increases. Melanin and hemoglobin have similar absorption curves. Depending on the laser wavelength being applied, the energy may be absorbed in the skin's melanin before it reaches the lesion. This can lead to a bleaching effect over the treated area. Today, newer vascular lasers such as the Candela V-Beam operate in the near IR at 755 nm.

Returning to Figure 4, one can see clearly that where reflection is high, absorption will be correspondingly low. Comparing both graphs in Figure 4, one sees that tissue destruction occurs more rapidly for laser wavelengths that are more strongly absorbed (less reflected). Thus, wavelengths above 1.0 μm are strongly absorbed and more prone to cause tissue damage more quickly, for both fair-skinned and dark-skinned persons.

Lasers for surgery

In surgical applications the goal is generally to destroy tissue. How that is accomplished depends on the wavelength used and how it is applied to the tissue. Table 1 shows absorption coefficients for different wavelengths. The higher the absorption coefficient, the more incident laser energy is absorbed in the tissue.

Table 1. Absorption Coefficient for Human Tissue

Laser	Wavelength (μm)	Absorption Coefficient (cm^{-1})
ArF	0.193	>400
KrF	0.249	600
XeCl	0.308	200
XeF	0.351	40
Argon	0.488	20
Argon	0.5145	14
Doubled Nd:YAG	0.532	12
Ruby	0.6943	5
Nd:YAG	1.06	4
HF	2.7	1000
Er:YAG	2.94	2700
CO_2	10.6	600

A major consideration when using lasers in a surgical application is the degree of collateral damage that results. With some wavelengths, the amount of transmitted light and its effect on underlying tissues is a concern. The interaction of laser radiation with tissue produces a thermal response. If the absorption of the thermal energy raises the tissue to a high enough temperature for a long enough time, cells will be destroyed. Figure 5 shows the amount of heating needed to cause tissue destruction. It shows how long a cell can survive at elevated temperatures before cell viability is compromised sufficiently to render it non-viable.

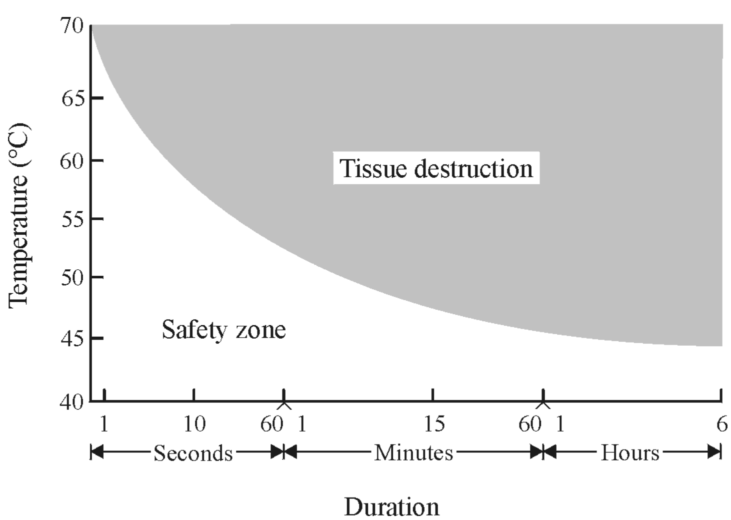


Figure 5 *Relationship of temperature and time for tissue destruction to occur (Normal body temperature is about 37°C. In the region below the shaded area in the figure, tissue destruction and cell death should not occur.)*

Normal body temperature is 37 degrees C or 98.6 degrees F. From the curve in Figure 5, cell death should not occur even after six hours at 45°C or 113°F. However, if the tissue temperature is raised to between 55 and 60 degrees C (130–140 degrees F), cell death can occur in as little as a few seconds.

When underlying tissue is sufficiently heated by transmitted laser energy, it will be destroyed. As a result, a layer of necrotic (dead) tissue will remain after the targeted tissue has been destroyed. The depth of the dead tissue is called “the zone of thermal necrosis.” The depth of this zone is a function of the wavelength and how it is applied. Which wavelength is chosen and how the energy will be applied often depend on the application and absorption coefficients, as illustrated in Table 1. For decades, the workhorses of laser surgery have been the CO_2, Nd:YAG, and Argon lasers. Their outputs range from the mid IR to the visible. Each laser has a different wavelength or range of wavelengths with their attendant advantages and limitations. Let us now consider each in turn.

The CO_2 laser—The CO_2 is generally considered the WYSIWYG (What You See Is What You Get) laser. Due to the transmission characteristics of its wavelength(s) in the mid IR, it is limited to use with an *articulated arm* or *hollow waveguide*. Its most common wavelength is 10,600 nm (10.6 μm), though a special CO_2 laser using the C^{13} isotope of CO_2 produces an 11,100 nm wavelength designed for laparoscopy. Both wavelengths are strongly absorbed by water. (See Table 2.)

Table 2. Selected Absorption Coefficients (cm^{-1}) for Different Biological Tissues

	Laser Types		
Tissue	**Argon 0.488 μm**	**Nd:YAG 1.06 μm**	**CO_2 10.6 μm**
Water	0.00025	0.363	1106
Skin	55	15	911
Liver	50	12.5	200
Blood	105	9.9	—

The *extinction range* of the CO_2 laser at a water interface is about 100 microns. Used to cut or ablate (vaporize) tissue, the CO_2 laser boils the water inside and between the cells causing them to explode. All remaining solid components will be carbonized. Because the CO_2 laser energy only penetrates 100 microns deep, the zone of thermal necrosis can be very thin. While the CO_2 laser can seal off small capillaries, thereby providing a relatively bloodless field due largely to its shallow penetration, it is not applicable for controlling bleeding in larger blood vessels. At medium power levels a focused beam can cut through tissue rapidly. At high power levels a relatively diffuse beam can efficiently ablate large areas. However, when used at milliwatt levels, the CO_2 laser can be used to virtually “weld” viable tissues together to close a wound.

The Nd:YAG laser—Though its applications have been broadened considerably with the advent of contact tips and fibers, the Nd:YAG (Neodymium: Yttrium Aluminum Garnet) laser was originally designated as a “photo-coagulator” because of its ability to coagulate blood and control bleeding. Often referred to simply as a “YAG” laser, the Nd:YAG has a principal wavelength in the near IR at 1064 nm, approximately 1/10 that of the CO_2 wavelength. It also has a rarely used secondary wavelength at 1320 nm. The 1064 nm wavelength is primarily absorbed by pigmented components such as melanin and hemoglobin and proteins. It transmits well through fiber optics and was originally used for controlling bleeding in the bowel, debulking gastro-intestinal (GI) and pulmonary obstructions (tumors), and treating a number of urinary tract conditions.

Unlike the CO_2 laser, when used as a “free beam” laser, the Nd:YAG laser’s wavelength can penetrate up to 14 mm into surrounding tissues. Its penetration is dependant on the degree of pigmentation and the amount of energy delivered. Due to its depth of penetration, it can denature (kill) tissues without necessarily vaporizing them. (See Table 3.)

Table 3. Depth of Skin Penetration for Medical Lasers

Laser	Laser Output wavelength	Absorption coefficient, cm^{-1}	% of beam that penetrates through 1 mm	Depth of tissue in which 1/2 light will be absorbed
KrF (excimer)	249 nm	600	negligible	0.012 mm or 12μm
Argon	488 nm 514.5 nm	20 14	7.8% 14.0%	0.347 mm 0.495 mm
Ruby	694.3 nm	5	21.8%	1.386 mm
Dye	631 nm (typically)	4	24%	1.73 mm
Nd:YAG	1.06 μm	4	33.5%	1.73 mm
Er:YAG	2.94 μm	2700	negligible	less than 1 μm
CO_2	10.6 μm	600	negligible	0.012 mm or 12 μm

The treated tissue will blanch during application of the laser energy. It is possible to destroy several millimeters of tissue without ever vaporizing the surface cells. This damaged tissue will either slough off or be resorbed by the body’s immune system. The potential for a deep zone of necrosis makes it important to track the amount of YAG energy delivered to tissue. As such, most Nd:YAG lasers record the number of pulses fired and the total energy delivered for each procedure. With the advent of contact tips and fibers, the range of applications for the YAG laser was greatly expanded. Like the CO_2 laser, the YAG can also be used at very low powers to weld viable tissues.

Q-switched Nd:YAG lasers are used for very delicate work in ophthalmology. Short, high-energy pulses are used to drill precise holes in structures internal to the eye. A very common application is treatment of secondary cataracts.

The Argon laser—Like the Nd:YAG, the Argon laser was also originally designated as a photo-coagulator and like the Nd:YAG, the introduction of contact fibers has greatly expanded its utility as a surgical device. Due to lower efficiency in converting input power to laser output, the Argon laser is generally a lower power laser than either the CO_2 or the Nd:YAG laser. The Argon laser can produce multiple wavelengths across the visible spectrum and into the UV. Most often they operate between 454.6 and 514.5 nm. Within this range the argon laser can simultaneously produce nine different wavelengths with the strongest lines at 488 nm (light blue) and 514.5 nm (green). Many argon lasers allow the operator to switch between full spectrum output and green only output for different applications. The zone of thermal necrosis is largely dependant on the degree of tissue pigmentation but is generally midway between the CO_2 and the Nd:YAG. In surgical applications it is used similarly to the Nd:YAG laser. In addition to its surgical applications, it is widely used in ophthalmology for coagulating intra-ocular bleeders and treating torn or detached retinas. The argon laser has about half its multi-line output at 514.5 nm. This wavelength is strongly absorbed by melanin, hemoglobin, and oxyhemoglobin. Used as a coagulator or surgical laser, the argon has faced stiff competition from the *frequency doubled* Nd:YAG laser operating at 532 nm.

The frequency-doubled Nd:YAG laser—This laser has higher potential output powers and similar tissue effects to the argon laser. Lithium bromide crystals—as well as potassium titanyl phosphate crystals—can also be used to achieve frequency doubling of the Nd:YAG wavelength. (See Table 4 for established lasers in the medical field.)

Table 4. Laser Types Established in Medical Applications

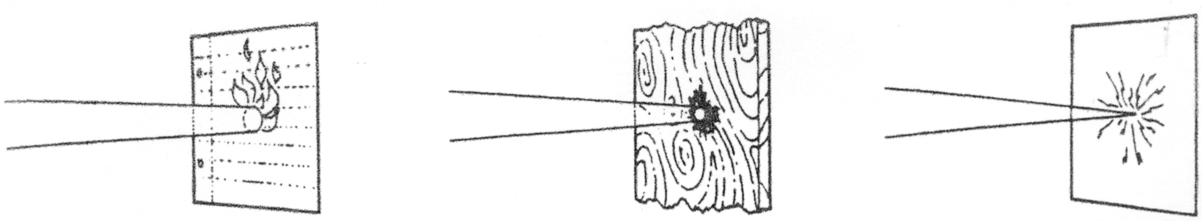
Laser type	Wavelength (μm)	Feature	Typical application
CO_2	10.6	High absorption in tissue	Cutting and vaporization
Argon	0.4880 and 0.5145	High absorption in hemoglobin	Retinal surgery
Nd:YAG	1.06	High power short pulses, fiber trans	Eye procedures, cauterization
Dye	Tunable—often 0.131	Tunability	Activation of dyes
Excimer	0.249, 0.308, 0.351	High absorption in tissue	Angioplasty tissue removal
Er:YAG	2.91	Very high absorption in tissue	Angioplasty
Free electron	Tunable	Wide tenability with high power	Tumor removal

One of the properties that makes laser energy unique is the laser's ability to target specific types of tissue for destruction while leaving the surrounding tissues intact. This helps reduce postoperative pain and swelling, and in many cases can reduce healing time.

Effects of irradiance

Regardless of the laser being used, the work done is a direct function of both the *wavelength* and the *irradiance*. Often called *power density*, irradiance is the degree to which laser energy is concentrated on the targeted tissues. Irradiance on target is laser power divided by target area, and the unit of measurement is watts/cm^2. Since the vast majority of surgical laser output beams are round, and the area of a circle is defined as πr^2, if the target spot *radius* is increased or decreased, the resultant change in irradiance will be increased or decreased as an inverse function of r^2. Therefore, a small change in spot size can have a dramatic effect on target irradiance and correspondingly the rate at which the laser will destroy tissue.

Figure 6 illustrates the effect of decreasing the target spot size on the irradiance.



A lens focuses a laser beam by bringing it to a small point. The area of the beam is reduced, and so the irradiance is increased.

(a) One watt concentrated on one square centimeter (1 W/cm^2) is enough power to burn paper.

(b) One watt concentrated on an area one tenth of a square centimeter (10 W/cm^2) will burn a wooden door.

(c) One watt concentrated on an area one-hundredth of a square centimeter (100 W/cm^2) will begin to work its way through metal.

Figure 6 *The effect of a reduced area on target irradiance for one watt of laser power*

Since irradiance E_{irrad} is defined as the power on target divided by the area of the target, we can write Equation 1:

$$E_{irrad} = \frac{P}{A} \qquad (1)$$

where E_{irrad} = irradiance in units like $watts/cm^2$
P = power in watts
A = target area in units like cm^2

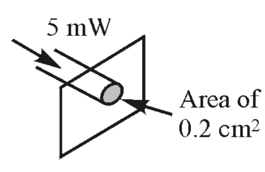
Equation 1 is used in Example 1 to find the irradiance of a HeNe beam on target.

Example 1: HeNe laser beam irradiance

Given: A 5-mW laser beam illuminates an area of 0.2 cm^2.

Find: The irradiance E_{irrad}

Solution



$$E_{irrad} = \frac{P}{A}$$

$$E_{irrad} = \frac{5 \text{ mW}}{0.2 \text{ cm}^2}$$

$E_{irrad} = 25 \text{ mW/cm}^2 = 0.025 \text{ W/cm}^2$

Example 2 shows how the irradiance depends critically on target spot size.

Example 2: Target irradiance dependence on target size

Consider a laser that emits a beam with 12.5 watts of power. What is the beam irradiance if the *beam diameter* is

(a) 2 mm?
(b) 4 mm?
(c) 1 mm?

Solutions

Using Equation 1, the three beam irradiances are:

(a) for d = 2 mm, r = 1 mm = 0.1 cm

$$\therefore E_{\text{irrad}} = \frac{P}{A} = \frac{12.5\text{ W}}{\pi r^2} = \frac{12.5\text{ W}}{(3.14)(0.1)^2} = \frac{12.5}{0.0314\text{ cm}^2} = 398\text{ W/cm}^2$$

(b) for d = 4 mm, r = 2 mm = 0.2 cm

$$\therefore E_{\text{irrad}} = \frac{P}{A} = \frac{12.5\text{ W}}{\pi(0.2)^2} = \frac{12.5}{(3.14)(0.04)\text{ cm}^2} = 99.5\text{ W/cm}^2$$

(c) for d = 1 mm, r = 0.50 mm = 0.05 cm

$$\therefore E_{\text{irrad}} = \frac{P}{A} = \frac{12.5\text{ W}}{\pi(0.05)^2} = \frac{12.5}{(3.14)(0.0025)} = 1592\text{ W/cm}^2$$

Irradiance is only one factor in achieving precision in the application of laser energy. The other factor is time. While many lasers are capable of operating in the *continuous output mode,* they are rarely used that way. Debulking of large tumors or growths and destruction of pre-cancerous lesions that require removal of significant volumes of tissue are the exception. Even the most skilled surgeon cannot maintain adequate control of a continuous laser output for very long. Control is best maintained by *pulsing* the output. Pulsed exposures may be a timed output programmed into the laser or simply the clinician tapping the power footswitch on and off. The more critical the application, the more desirable a precisely timed pulse becomes. A third factor is continuous movement of the beam over the area to be treated.

A growing number of applications require a high degree of precision. In general, too little irradiance may be ineffective while too much can result in excessive destruction of tissue and/or collateral damage. In the first case, retreatment will usually provide the desired results. This is actually the cautious approach to laser surgery, since once tissue is vaporized or denatured, you can't put it back. Application of too much irradiance can have catastrophic results. It is better to have too little and return to add more.

Controlling exposure

There are a couple of ways to control the degree of tissue destruction. One obvious way is to increase or decrease the power setting. A second way is to vary the spotsize. Both affect the irradiance on tissue. In many cases these two are all that is necessary to achieve the desired results. In a growing number of applications, a greater degree of control is required. This leads us to a third way, *pulsing the output*. (A fourth way—computerized scanning devices—will be discussed separately.)

Some types of lasers can only be operated with a pulsed output. For instance, Er:YAG lasers and some small Nd:YAG lasers only operate in a free-running pulsed mode. In some cases, such as the Er:YAG, this is the only way in which this type of laser can be operated. For purposes of achieving control over tissue effects, a second pulse, a limited exposure time, can be superimposed over the pulsed output.

Some lasers—such as the pulsed dye lasers, the Q-switched Nd:YAG, and the kilowatt, CO_2 Heart laser—operate in only a single-pulse mode. When the footswitch is depressed, the laser fires a single, precisely timed pulse. These lasers are designed for very precise applications of laser energy.

Other systems offer the user more delivery options. There are two means by which a laser output can be pulsed and very often they are both referred to as "pulsed mode." Obviously, this can lead, and has led, to confusion. Most commonly, this occurs with the CO_2 laser, so we will use it as an example.

Even the most basic CO_2 lasers can usually be set to operate in a continuous, single-pulse, or repeat-pulse mode. These modes refer to how the laser reacts i.e., the delivery mode, when the footswitch is depressed.

- In *continuous mode,* the laser output will continue for as long as the footswitch is depressed.
- In *single-pulse mode,* as the name implies, one pulse of laser energy of a fixed duration is emitted regardless of how long the footswitch is depressed.
- In the *repeat-pulse mode,* a series of timed pulses is emitted. The operator usually has the option of selecting the length of each exposure or pulse duration. The interval between the pulses may be fixed or variable. Early CO_2 lasers fired at 1 Hz (once a second) with exposure times of 0.1, 0.2, or 0.5 seconds.

Figure 7 gives a graphic picture of the various modes.

Continuous, single-pulse, and repeat-pulse deliveries can be superimposed on different excitation modes, as described below:

- For continuous wave (cw), the laser tube lights and stays lit continuously. The output would be graphed as a straight horizontal line of *x* watts. (See Figure 7b.) The power level is varied by increasing or decreasing the tube current and can be set anywhere within the operating range for the laser tube.
- For a chopped or gated pulse, the excitation current to the laser tube is pulsed turning the tube on briefly and then off again. The output would be graphed as a square wave. (See Figure 7c.) The maximum output power level would normally be the maximum cw power of the laser. The output power level may be varied either by adjusting pulse duration or frequency. These parameters may be set by the operator or may be preset by the manufacturer. Since this type of output requires some off time between pulses, the maximum output power will be, or should be, less than the laser's maximum cw power.
- For a so-called "super pulse," the output versus time would graph as a series of very narrow spikes with a long interval between the spikes. Super pulsing a laser takes

advantage of the very brief spike in output energy that occurs when the population inversion in the laser medium first breaks down and lasing begins. The peak power of that naturally occurring spike or peak can be increased by briefly over driving the laser medium and then shutting the current off. A proper super pulse has a peak power many times the maximum cw power for the laser. Pulse durations are fixed and generally measured in nanoseconds. Output power is adjusted by changing the frequency of the pulses. Ideally the number of pulses possible is limited to allow for sufficient thermal relaxation of the surrounding tissues between pulses. If the frequency is set too high, the advantages of a super pulse can be diminished and the degree of necrosis will increase.

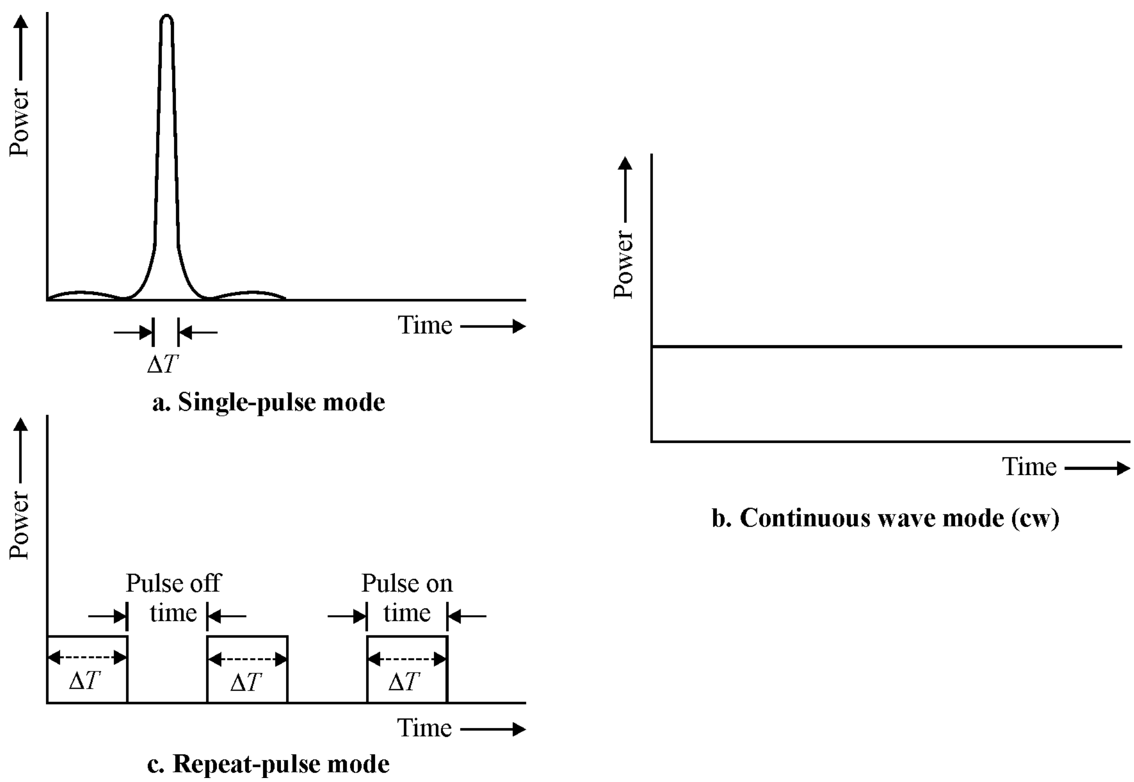


Figure 7 *Graphic drawing of difference between single-pulse, cw, and repeat-pulse modes of operation*

Thus, by combining various excitation modes with different pulse variation modes, one can operate a CO_2 laser in continuous/continuous, pulsed/continuous, or continuous/pulsed mode. It is easy to see why it is important to be specific as to which “mode” is to be used. As a technician or nurse setting the controls for a surgeon, or as a surgeon requesting a particular setting, it is important to communicate intent clearly. Verbal feedback of instructions is the best way to avoid problems.

Range of tissue effects

For many wavelengths, a range of tissue effects can be achieved by varying exposure levels and time-on the tissue. Again, as an example we will discuss the CO_2 laser. At very low irradiance levels, the CO_2 laser can be used for low-level laser therapy (LLLT). Used to accelerate healing and to reduce pain, LLLT is widely accepted and used in most parts of the world as both a palliative and curative therapy. In the United States it is widely accepted for veterinary use, especially with horses.

At somewhat higher irradiance levels, the CO_2 laser has been used experimentally—in lieu of sutures—for welding viable tissues together. Tissue welding or *anastomosis* requires power levels in the milliwatt range, focused to a small spotsize. The laser is used to heat precisely the tissues to be welded. The laser energy denatures proteins in the tissue, thereby creating a "glue" that bonds the tissues together while healing takes place. More recent research has focused on the use of various substances including albumen as a sort of biological solder for this process. The potential applications for this technique range from repairing severed nerves and blood vessels to closing surgical wounds.

At high irradiance levels, the CO_2 laser is used to destroy tissues by vaporization. It can be focused to sub-millimeter spotsizes or defocused to a beam of 8-10 mm or more. In its focused mode, it is used for making incisions and excising tissue with minimal bleeding, reducing postoperative pain and swelling. In its defocused mode, with high power levels it can rapidly ablate (vaporize) large volumes of tissue to debulk tumors and debride wounds and ulcers while sealing off capillaries, lymphatics, and nerves.

As with the CO_2 laser, many laser wavelengths are suitable, to one degree or another for a variety of applications. In such a competitive and potentially lucrative field, everyone wants their laser or their wavelength to be capable of performing as wide a range of procedures as possible. When evaluating a particular laser or when considering the purchase of a laser for a particular application, it is important to cut through the marketing hype to find the most suitable wavelength and laser system. Argon, CO_2, IR, diode, Er:YAG, Hol:YAG, KTP, Nd:YAG and free electron lasers can all be used for soft tissue surgery. (See Table 4.) The only way to make an informed decision is to understand the absorption characteristics of the various wavelengths, the mode of delivery, and how each interacts with tissue. Research is the only way to narrow down the field of suitable candidates.

Commonly Used Lasers

The heart of the laser is the active laser medium, a material that will absorb and emit radiation (fluoresce) when excited with the appropriate type and intensity of excitation energy. It is the particular medium that gives each type of laser its wavelength characteristics. As such it is customary to refer to a laser by the wavelength producing component of its active medium. In some cases this is only part of the active medium.

A CO_2 laser uses a combination of three or more gases to achieve the laser output. It is the CO_2 gas that produces the wavelength so it is called a CO_2 laser. In the Nd:YAG laser, it is the neodymium (Nd) which fluoresces, producing the output wavelength. The mineral YAG (yttrium aluminum garnet) is simply a host crystal for the neodymium. One aspect that can be confusing is that YAG is used as a host crystal for a variety of fluorescing elements designated as Er:YAG (erbium) and Hol:YAG (holmium). In medical circles, the term "YAG laser" is generally used to refer to the Nd:YAG. The others are referred to as either the "erbium" or "holmium" laser.

The active laser medium—as we know—may be solid, liquid, or gas. The excitation energy may (in the case of medical lasers) be in the form of an electric current, intense light or radio frequency, electromagnetic (EM) radiation. Which of the three is appropriate depends on the nature of the medium. Laser mediums may be crystals (solid), dyes (liquid), gases or semi-conductors. The crystals and dyes require exposure to intense light to stimulate fluorescence. In some cases another laser may be used as the light source. Semi-conductor or diode lasers require an electric current to stimulate them. Gas mediums may be excited using either an electrical discharge or radio frequency radiation depending on the type of gas(es) being used. The resulting florescence from the energized medium produces the wavelength(s) characteristic of the medium—the laser output wavelength(s).

This section will provide an overview of many of the different lasers being used therapeutically. In some cases, examples of certain procedures will be described for illustrative purposes related to wavelength or tissue effects. A complete listing of the procedures that can be performed using each laser would be too exhaustive for this text.

Below is a listing of commonly used lasers including special characteristics: wavelength, applicable delivery systems, accessories, and examples of applications.

Characteristics of commonly used lasers

CO_2 Laser (See Figure 8.)

Wavelength(s): 10.6 um and 11.1 um

Tissue effects by irradiance level

- Low—LLLT to promote healing
- Medium—Tissue welding to close wounds
- High—Destruction of tissue, incision, excision, or ablation

Delivery system(s)

- Direct—Yes, with focusing OC
- Articulated arm—Yes
- Fiber optic—No
- Waveguide—Yes, rigid or flexible

Accessories

- Handpieces—Yes
- Microscope mounted manipulators—Yes
- Endoscopes—Rigid: Yes; Flexible: No
- Scanners—Yes

Contra-indications: Strong absorption in water and short extinction range in all tissues limits laser-to-surface use. Not specific to any pigmenting component of tissue.

Figure 8 *A modern CO_2 laser system with an articulated-arm delivery (Photo courtesy Lumenis [www.lumenis.com])*

Nd:YAG Laser (See Figure 9.)

Wavelength(s): 1064 nm and 1320 nm

Tissue effects by irradiance level

Low—LLLT to promote healing

Medium—Tissue welding to close wounds

High—Destruction of tissue, incision, excision, or ablation

Delivery system(s)

Direct—No

Articulated arm—Yes, but rarely used

Fiber optic—Yes

Waveguide—No

Accessories

Handpieces—Yes, contact and noncontact

Microscope mounted manipulators—Yes

Endoscopes—Rigid: Yes; Flexible; Yes

Scanners—No

Figure 9 *A continuous wave (cw) Nd:YAG laser with control panel for laser beam settings (Photo courtesy Lumenis [www.lumenis.com])*

Argon Laser

Wavelength(s): 488 nm and 514.5 nm

Tissue effects by irradiance level

Low—Repairs to detached retinas

Medium—Coagulation of retinal bleeders

High—Destruction of tissue, incision, excision, or ablation

Delivery system(s)

Direct—No

Articulated arm—Not usually

Fiber optic—Yes

Waveguide—No

Accessories

Handpieces—Yes

Microscope mounted manipulators—Yes, and slit lamps for ophthalmology

Endoscopes—Rigid: Yes; Flexible: Yes

Scanners—Yes

Delivery Systems

Delivery systems for laser energy present a number of challenges depending on the application. (See Figure 10.) To be effective, the appropriate levels of laser energy must be delivered to treatment sites both outside and inside of the body. For some applications it is important to maintain all of the output characteristics of laser energy. In others, one or more of the unique qualities of laser light can be, and often are, sacrificed. While some procedural sites are easily accessed, others require a high degree of flexibility. Primary means of delivery include *direct output* from the laser resonator, *articulated arms, fiber optics* (some of which are highly specialized), and *hollow waveguides*.

In many cases, the distal (far) end of fiber optics and hollow waveguides are used to deliver the energy directly to the target tissue. However, in other applications, as with articulated arms, a secondary delivery device must be attached. These secondary delivery devices can vary from a specially designed diamond or sapphire tip for a fiber optic—to be used in direct contact with tissue—to a single- or multiple-lensed device that collects and focuses the energy for *noncontact* applications. Common lensed devices include *surgical handpieces*, *microscope adaptors,* and *scanners*.

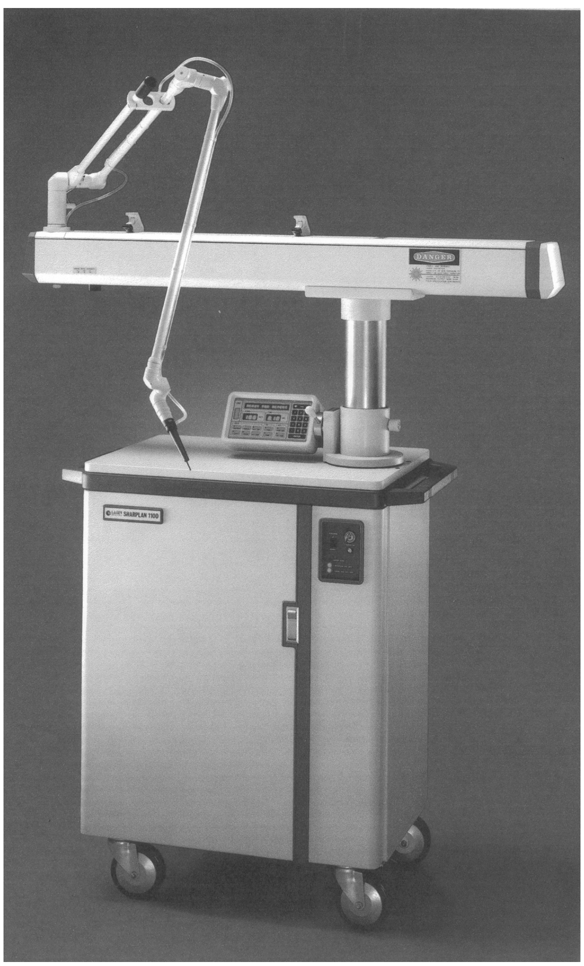


Figure 10 *A complete laser delivery system with control panel (Photo courtesy Lumenis [www.lumenis.com])*

Direct delivery

The least complicated way to deliver laser energy is for the clinician to simply hold the laser in his or her hand and direct the output onto the treatment site—a *direct delivery*. A number of systems—from the CO_2 to the latest diode lasers—use this means of delivery. Of course this severely limits the size and potential output power available from such systems. In some cases this means a fairly bulky handpiece.

For direct delivery systems, focusing optics can be included within the laser tube or the optics may be attached at the laser aperture. Special tips may be available with different angled mirrors to help deliver the laser energy to less accessible areas. Typical output levels for a CO_2 laser of this type of delivery system would generally produce a maximum output of about 10-15 Watts. Anything larger would be too unwieldy to be used effectively. Direct delivery systems are generally limited to fields such as dermatology, podiatry, gynecology (external), ENT and dental/oral surgery. One drawback to this delivery system is that it generally lacks a visible aiming beam. Delivery tips with small *guide tips* are provided for some systems to aid the clinician in determining the proper focal distance and some indication of where the beam will impact tissue. It is not uncommon for a clinician to fire a CO_2 laser onto a tongue depressor prior to surgery to determine the relative location of the beam to the special tip. While useful for a wide range of procedures, these lasers are not intended for surgeries that require a very high degree of accuracy.

One system that uses direct delivery of laser energy is designed for hair removal. The handpiece contains an array of IR laser diodes and a chiller tip. The delivery tip is pressed against the skin. When fired as a brief pulse, the laser energy is sufficient to kill the follicle(s). The chiller serves to lower the skin temperature at the treatment site. This helps to reduce pain and limit collateral thermal damage to tissue surrounding the follicle(s).

Articulated arms

Articulated arms can be designed for use with any laser beam. All that is required is the presence of a correct reflective coating on the mirrors and a laser beam with a low divergence angle. For some wavelengths, such as in the mid-range IR and UV, articulated arms are the only option. This is the only other delivery system that maintains all of the unique characteristics of the laser beam.

An articulating arm is essentially two long sections of straight tubing that are joined together by a series of precision bearings, each connected at a 90-degree angle. Each 90-degree joint or knuckle has an adjustable front surface mirror that reflects the laser beam down the center of the next section of tubing. Between each pair of mirrors there is a precision bearing that allows a free, 360-degree rotation of each successive mirror and arm segment. A typical articulated arm has 8 bearings and seven mirrors. In some designs, an eighth mirror is used to align or launch the beam into the arm while other systems simply align the arm to the laser by adjusting the centering and tilt angle of the arm to the laser beam. The first section of the arm is relatively short and is mounted vertically to allow the arm to be rotated completely around the laser. The second section is horizontal and allows for a range of vertical movements. At the end of the second long section of the arm, the last three mirrors and four bearings are designed to allow a full range of motion for the laser accessory. (See Figure 11.)

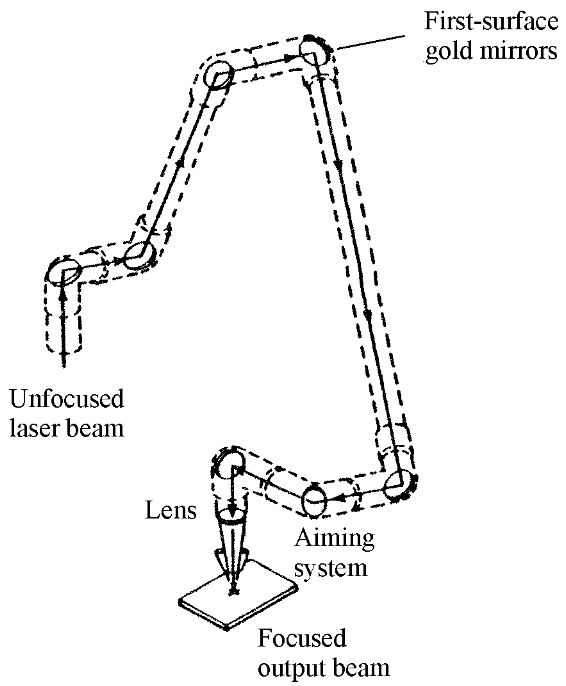


Figure 11 *Articulated arm and component parts*

Early articulated arms were made of heavy, stainless steel tubing with large diameter bearings. Due to their weight, a heavy, adjustable counter-balancing weight was used to make the arm seem weightless to the clinician. Even with their robust construction, these arms were often prone to alignment problems. Newer arms are constructed of aluminum alloys or space-age materials such as carbon fiber reinforced composites. Combined with high-precision bearings these improvements have dramatically improved the flexibility and reliability of articulated arms. While some arms still rely on a counterweight, others incorporate a spring balance device. In either case the counterbalances are adjustable to compensate for various accessories such as handpieces or laparoscopes that will be used with the laser. The idea is to make the arm and accessory seem relatively weightless to the clinician.

Generally, all articulated arms are susceptible to alignment problems. Arm alignment problems were a major factor in the promotion of many fiber-delivered laser systems in the 1980s. Today, misalignment of the arm is an ever-present problem since most common lasers that use articulating arms—such as the CO_2 laser—have output wavelengths that are not visible. These systems usually incorporate a low-power visible laser, such as a HeNe, or visible diode laser, as a marker or aiming beam to show where the working laser target spot will impact tissue. The output of these low-power "guide" lasers is combined with the surgical beam so that they follow the same path through the arm and accessory. If the working laser beam is off center in the arm, diffraction and a resulting separation of the beams will occur as the two lasers pass through the focusing optics of the accessory. As the beams pass through the lens off center, the prismatic effect causes the beams to separate. Beam coincidence at the treatment site will be affected. This is especially true for devices using longer focal lengths such as microscopes and laparoscopes. The relationship between guiding and cutting beams is critical for accuracy in many surgical procedures.

Sometimes trying to situate a laser in a crowded surgical field with microscopes, OR lights and other accoutrements results in flexural stresses that are applied to the arm. If a section of the arm is stressed sufficiently, an alignment problem becomes evident. These problems are generally resolved when the stress in removed.

Even arms that are promoted as “permanently aligned” have some means by which they can be adjusted. There are two aspects to aligning an articulated arm. The first and most obvious is the angular adjustment of the mirrors. If the angle of a mirror is off, the beam will tend to wander at the distal end of the arm as the arm is moved. In bad cases, the beam may be clipped by the arm or even lost inside the arm.

The second aspect, and one that can be affected by improperly adjusting the angular aspect is mirror location. If a mirror is at the proper location in the joint, its center is aligned with the center of both adjacent arm sections. If the mirror is too deep in the joint or too shallow, an alignment problem can occur. This type of alignment error is most problematic with narrow lumen endoscopes such as the laparoscope. While this type of error can appear to be adjusted through appropriate angular movements, the problem may persist. Beyond a mirror that is “off depth,” the laser beam will travel through each successive arm section at an angle. As a result, while the beam appears to be centered at the distal end of the arm, it is exiting the arm at an angle to the center line. Rotation of the joints of the arm will cause the beam to wander, as it describes a cone, inside the laparoscope lumen—to the point where it can clip the aperture or reflect off the inner wall of the lumen. A special lensed tube must be attached to the arm to evaluate and correct this type of problem.

Some arms use a four-point adjusting system with two hold-down screws and two standoff screws. The mirror assembly is mounted in the joint and the beam is observed as the adjustments are made. The screws are worked in pairs to adjust the angle of the mirror in an *x*-*y* pattern. If one screw is to be tightened to correct an alignment error, the opposing screw must first be loosened the same amount. By adjusting the *x*- and *y*-axes separately, and maintaining proper screw tension, mirror depth can be maintained during angular alignment.

A more common mirror adjustment design uses three adjusting screws. As three points describe a plane, any one screw can be adjusted to move the beam. In this system the mirror is mounted in the joint cover and must be removed to access the screws. Some sort of tensioning device such as a wave washer or disk spring is mounted behind the mirror to hold it firmly against the adjusting screws. Generally, one of the three screws is offset from the others. The offset screw is only adjusted when it is necessary to correct a mirror depth problem. All angular corrections are made using the other two screws. In these systems, the mirror is often offset in its cap to match the offset of the adjusting screws. It is important that the mirror and cap be re-installed in its correct orientation.

The actual techniques for evaluating and properly aligning an articulated arm are beyond the scope of this text. In brief, both *evaluation* and *alignment* must begin at the laser aperture. Coincidence between the surgical beam and any visible guiding beam device (HeNe or diode laser) at two different points (near and far) must first be ascertained. Once beam coincidence at the two locations is verified, with the arms bearings immobilized, each bearing is rotated individually to check for errors. The checks proceed from the laser head to the end of the arm. Any adjustment needed is made on the mirror immediately before the bearing being rotated.

Fiber optics

Fiber optics play an important role in a number of surgical applications, not all of which involve lasers. Fiber optic bundles are used to transmit light through both rigid and flexible endoscopes in order to illuminate surgical sites inside the body. (See Figure 12.) In flexible endoscopes a second fiber bundle transmits a view of the surgical site back to the clinician. In laser procedures, a single fiber is used to deliver the energy to cut, coagulate and ablate tissue. This section addresses the application of fibers in delivering laser energy to the surgical site.

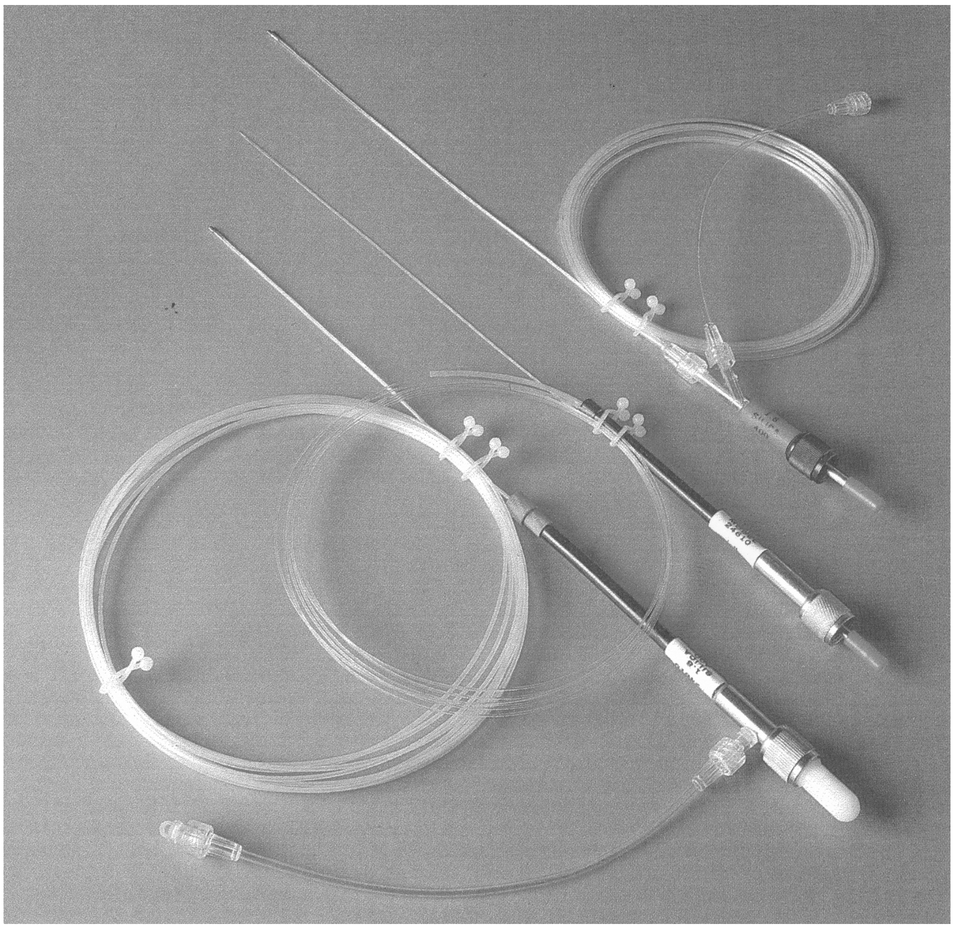


Figure 12 *Optical fibers for flexible delivery systems (Photo courtesy Lumenis [www.lumenis.com])*

Optical fibers provide a flexible means of delivering laser energy to otherwise inaccessible areas of the interior body. While fibers provide great utility, in most surgical applications, some of the unique characteristics of laser light can be lost as the energy passes through the fiber. While laser light retains its monochromatic characteristic after passing through an optical fiber, it may no longer be collimated. Light from a fiber can *diverge* rapidly, depending on the numerical aperture (NA) of the fiber—that is, on the *effective light-gathering cone* at the ends of the fiber.

While fibers can be made of a number of exotic materials for special applications, the vast majority of fibers are made of glass. Most fibers consist of three distinct layers: *core, cladding,* and *buffer*. The core transmits the laser energy. The cladding—which has a lower index of refraction—is applied over the core and acts to keep the energy in the core from leaking out through a process called "total internal reflection." The buffer is generally a tough plastic and acts as a protective covering to prevent damage to the fiber as it is passed through endoscopes and similar secondary delivery devices.

The two primary types of fibers used are *silica/silica,* where both the core and cladding are made of glass, and *plastic clad silica* (PCS). In either case, the cladding material is selected so that it has a lower index of refraction than the core. Total internal reflection (TIR) is a function of the difference between the higher index of refraction of the core material and lower index of refraction of the cladding material. The difference in the indices of refraction creates a mirror-like surface at the core-cladding interface. At this interface, a light ray is incident at an angle ϕ. (See Figure 13.) If ϕ is greater than a certain *critical angle,* ϕ_c, *all of the incident light* is reflected back into the fiber. This reflection obeys the ordinary law of reflection, with the reflected angle equaling the incident angle, in effect, treating the core-cladding interface as a *mirror*. If the incident angle ϕ is less that the critical angle ϕ_c, the incident ray partially penetrates the interface in accordance with Snell's law, thereby losing photons to the cladding. As usual, according to Fresnel's equation, some of the light is also reflected, but not much, so the loss of laser light in the core is significant.

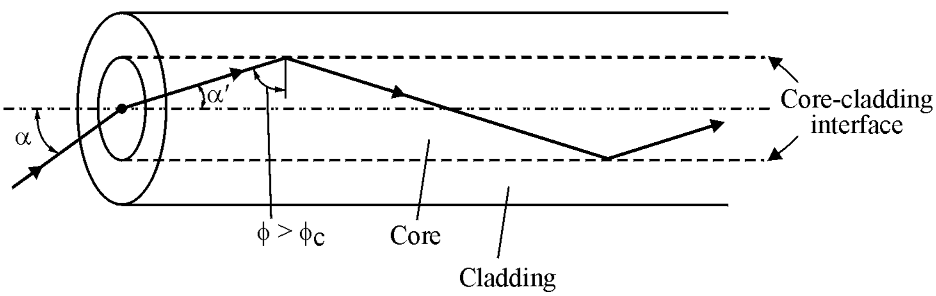


Figure 13

Equation 2 provides the definition for a critical angle. The geometry at the core-cladding interface was shown in Figure 13.

$$\phi_c = \sin^{-1}\left(\frac{n_{clad}}{n_{core}}\right) \qquad (2)$$

where ϕ_c is the critical angle in degrees
$\sin^{-1}$ represents the inverse or arc sine function
n_{clad} is the index of refraction of the cladding material
n_{core} is the index of refraction of the core material

Example 3 shows how the critical angle ϕ_c is calculated.

Example 3: Calculating a critical angle

A fiber and cladding arrangement, such as that shown in Figure 13, has a core index of refraction of $n_{\text{core}} = 1.55$ and a cladding index of refraction of $n_{\text{clad}} = 1.50$. What is the critical angle for a light ray in the core that is incident on the core-cladding interface?

Solution

Use Equation 2.

Then $$\phi_c = \sin^{-1}\left(\frac{n_{\text{clad}}}{n_{\text{core}}}\right)$$

$$\phi_c = \sin^{-1}\left(\frac{1.50}{1.55}\right) = \sin^{-1}(0.9677)$$

$$\therefore \phi_c \simeq 75°$$

This means that any ray of light incident at the core-cladding interface with an angle greater than 75° will be totally reflected, and remain in the core.

Severe bending of the fiber will change the angle of incidence and can affect the amount of power lost. Losses in optical fibers are rated in *decibels per kilometer* (dB/Km). Since most surgical fibers are only a few meters in length, this rating means very little. Losses in short fibers occur at the fiber ends, and refractions occurring at the air/core interface account for most of the normal losses. There is also a phenomenon called cladding modes where light that leaks from the core becomes trapped between the core and buffer. In longer fibers this light usually leaks out of the cladding but in short surgical fibers it can be transmitted to the surgical site. This can sometimes be seen as a halo effect when viewing the transmitted energy.

There are two classifications for laser fibers, *jacketed* or *bare,* sometimes called *cooled* or *uncooled*. A jacketed fiber has a Teflon sleeve covering its full length with a metal ferrule at its distal (far) end. At the proximal (near) end there is a fitting that can be connected to either an air/gas source or a liquid source as a purging agent. This purging agent does two things. By flowing along the length of the fiber and over the distal tip, it helps to keep the tip cool, but perhaps more importantly, it keeps the fiber tip clean. Smoke or other debris coming in contact with the fiber tip can rapidly degrade fiber transmission. Either liquid or gas may be used in gastrointestinal procedures. For pulmonary procedures, only air purge is used for obvious reasons. For urologic procedures, a bare fiber is used since the treatment site is a liquid-filled field.

Fiber optic core diameters can vary from a few microns to over a millimeter. Most medical/surgical fibers are at the larger end of the scale. The larger sizes are used for a number of reasons. Larger fibers, while more rigid, are also more robust and less likely to fracture when passed through a secondary device. Many fibers are used in contact with tissue and as such need to be fairly rigid. Also, most higher-power lasers have large-diameter beams. The fibers selected for use with a particular laser must be large enough to accept the spot size to which the beam can be focused and have a numerical aperture, NA, which determines the entrance "cone angle of acceptance." The entrance cone angle is shown as angle α in Figure 13. The minimum spot size to which a laser beam can be focused is a function of the wavelength and the angle of divergence of the unfocused beam.

Once the laser energy has been transmitted through the fiber it can be used in two ways. It can be applied in either a *free-beam* or a *contact* mode. Using just the fiber in the free-beam mode, the energy can be directed onto the target tissue without making contact. The spot size applied to the tissue can be varied by adjusting the distance from the fiber tip to the tissue. Varying the diameter of the spot size dramatically affects the intensity of the incident energy, as we have already seen. Alternately, the light diverging from the fiber can be captured by a lens—or a series of lenses—to recollimate or focus the light for use with a handpiece, microscope, slit lamp, or other secondary device.

In the contact mode, the fiber itself or a special tip can be used in contact with tissue. In essence, when used in the contact mode, the laser becomes nothing more than a very expensive heat source. The tip of a bare fiber can be used directly in contact with tissue for cutting or ablation. Or, a special sapphire or diamond tip can be attached to the ferrule of a jacketed fiber. In either case the tip will become coated with carbonized matter. Many tips are manufactured with a frosted or precarbonized surface. Generally, these tips are carbonized prior to use on a patient. The laser energy is absorbed by the carbonized matter, thereby heating the tip to a very high temperature. Once carbonized, very little of the laser wavelength escapes the tip or fiber to interact with the surrounding tissue. For this reason, when used in a contact mode, there is no appreciable difference in tissue effects between lasers of different wavelengths. There are a variety of special tip shapes available for contact applications including hemispherical, cylindrical, conical, flat and chisel shapes.

Hollow waveguides

A *hollow waveguide* is essentially a special case of the optical fiber. Used primarily with the CO_2 and Er:YAG lasers, a waveguide is basically a fiber without a core—or a core of air. Since the far-IR wavelength of the CO_2 laser does not transmit through glass or other materials suitable for making a flexible fiber, the only viable option as of this writing is to use a flexible hollow tube with a reflective lining. These waveguides have fairly high losses compared to glass fibers and are limited in length—with most being under two meters. An air purge is used to help cool the waveguide, prevent damage to the coating, and prevent debris from collecting on and eventually clogging the surgical tip. Since the CO_2 laser is always used in a noncontact mode, this type of delivery system is never used in contact with tissue. The Er:YAG laser—using a hollow waveguide—may have a sapphire tip at the distal end to allow contact applications such as soft tissue cutting or cavity removal in dentistry.

Another issue with water-absorbed wavelengths is the hygroscopic nature of many glass fibers. Nd:YAG operating at 1320 nm, Hol:YAG at 2100 nm, and the several wavelengths of Er:YAG would be greatly attenuated by a fiber that has absorbed water from environmental exposure. Much research has been done to find a suitable fiber material for the CO_2 laser. While several materials have been tested, to date the hollow waveguide remains the best option for a flexible delivery system. Research to find the best type of hollow waveguide for these wavelengths is ongoing.

Laser Accessories

Laser accessories are secondary delivery devices. They connect to the primary delivery device, such as an articulated arm or optical fiber, or they provide a delivery mechanism for an optical fiber. These devices include

- Handpieces,
- Microscopes or adaptors for microscopes,
- Rigid and flexible endoscopes,
- Scanners, and
- Catheters.

It is these devices that make feasible such a broad range of applications for laser energy. Whether it's a hand-held scanner for removing wrinkles or unwanted hair, or a special catheter for opening blocked coronary arteries, it is the accessory that gets the energy where it is needed and may even control the exposure.

Handpieces

The simplest of these secondary delivery devices is the *handpiece*. A handpiece may attach to the distal end of an articulated arm or it may be designed for use with an optical fiber. Many handpieces contain one or more lenses that can focus and/or defocus the beam. The optics in a handpiece, or any other accessory, must be designed for use with the particular laser's wavelength. The simplest handpiece is nothing more than a means of holding onto an optical fiber. The most sophisticated handpieces actually scan the laser output over a treatment site.

The simplest forms of the handpiece are used with optical fibers. While focusing handpieces are available, contact and nonfocusing handpieces are far more common. For contact surgery, the handpiece is simply a stylus, generally with a thin metal tube protruding from its distal end. The metal tubes can range from as short as 10 or 20 mm to as long as 300 or 400 mm, depending on their intended application. An unjacketed surgical fiber is inserted through the handpiece so that its tip extends beyond the tubular metal tip. A single-use fiber may have the handpiece permanently attached. In other cases there is a clamping device on the proximal end of the handpiece, thereby allowing adjustment of the fiber length and a tightening to hold the fiber in place. Handpieces with short tips are used for a variety of surgical applications. Those with long (200–400 mm) tips are generally used with rigid endoscopes such as in laparoscopy.

A noncontact fiber optic handpiece may not contain any optics, but simply provide a means to hold the fiber for free beam delivery of the diverging laser energy. The handpiece is usually a straight tube with a clear plastic tip. As with the contact surgical handpiece, the fiber passes through a clamping device. The tip of the fiber is recessed inside of the handpiece a distance sufficient to provide the desired spot size at the end of the handpiece tube. The handpiece is generally pressed against the treatment site and the laser is fired. The handpiece is then moved to a different site and the laser fired again. These are commonly used with a variety or wavelengths for treating superficial conditions such as vascular lesions, age spots or hair removal.

More complex fiber optic handpieces use lenses to either collimate or focus the fiber's output. By collimating the output of the laser, a consistent spot size can be achieved without undue concern for the distance of the handpiece from the treatment site. For the majority of applications for unfocused, noncontact fiber optic lasers, this design is unnecessarily complex. While not a surgical application, this type of handpiece was used with the first blue argon lasers, developed for curing light-activated resins used in dentistry. By refocusing the beam, fairly small spotsizes can be achieved. This type of handpiece is designed for strictly noncontact use in cutting or ablating tissue. Since many of the more common fiber-delivered wavelengths can penetrate a significant distance into tissue, technique with these handpieces is very important. Unlike the more common, non-contact applications, more of the laser's energy is actually absorbed during the incision/ablation due primarily to absorption in the plume and carbonized tissue. However, the more defocused the beam becomes, the more likely collateral damage becomes. Because of this, focusing handpieces for fiber-delivered wavelengths are not widely used.

More common are focusing handpieces for articulated-arm-delivered lasers, primarily the CO_2 laser. In its simplest form this hand piece is a tubular housing with a single lens that focuses the laser beam. A conical tube or handpiece barrel somewhat shorter than the focal length of the lens is attached to the lens housing. This provides a hand hold and places the focus of the beam at a comfortable distance for the clinician . Usually, a removable tip is provided to help the clinician judge the distance for optimal focus of the beam. The size of the spot applied to tissue is controlled by adjusting the distance the handpiece is held from the target tissue. For procedures requiring a sterile field, the lens housing and arm can be covered with a sterile drape and the barrel and tip can be sterilized.

There are various focal lengths available for these handpieces. Typical focal lengths for CO_2 lasers are 50 mm, 125 mm and 200 mm. Some adjustable handpieces use a two-lens system to provide a variable spot size. The very short 50 mm handpiece, while it will provide the smallest spot size, is generally used for working with the beam defocused. The short focal length allows the clinician to significantly defocus the beam by withdrawing the handpiece a short distance from the treatment site. This is also the principal application for adjustable focus handpieces.

The *125-mm handpiece* is the workhorse for freehand surgery. It is ideal for incisional and excisional cutting and can be moderately defocused by withdrawing the handpiece a reasonable distance. The longer 200-mm handpiece is fairly rare, even though it provides a little better reach in some applications. One problem shared by all focusing handpieces is the presence of a laser plume. Due to the density of the laser energy and the explosive action of tissue being vaporized, the laser plume will invariably travel back along the beam path and up the handpiece barrel where the debris will tend to collect on the focusing lens. If the plume debris collects on the focusing lens and absorbs laser energy, the antireflective coatings on the lens and the lens itself can be damaged. This problem is overcome by using a purge gas.

All focusing laser handpieces have a fitting for a tube which will supply a purge gas just beyond the focusing lens. The flow of the purge gas creates a positive pressure within the handpiece barrel, thereby preventing the laser plume from entering. At higher flow rates, the purge gas can be used to displace the plume from the surgical field. But such use tends to scatter the plume, making it more difficult to capture it with suction or evacuation equipment.

Microscopes

Surgical microscopes are widely used in a variety of medical specialties. (See Figure 14.) They provide the surgeon with a well-illuminated, magnified view of the treatment site. One of the first—if not *the* first—applications of lasers in medicine was in *ophthalmology*. For this, a laser adapted to a slit lamp is used to deliver the laser energy to the treatment site within the eye. To visualize the treatment site, an ophthalmologist would use a microscope with a slit lamp to illuminate the retina or other internal structures. Since the microscope cannot be manipulated on three axes, a mirror connected to a small joystick allows the clinician to move the beam throughout the microscope's field of view. A focusing mechanism allows adjustment of the focal spot within the eye. In ophthalmology, the focusing power of the eye's own lens must also be considered. Today, argon, dye, krypton and Nd:YAG lasers mounted to slit lamps are commonplace.

Figure 14 *A modern CO_2 laser micromanipulator use in microsurgery (Photo courtesy Lumenis [www.lumenis.com])*

Surgical microscopes provide a stable platform for the precise application of laser energy. The most common surgical applications for microscope-mounted lasers are in ENT, neurosurgery, and gynecology. Often referred to as a *microman* (short for *micromanipulator*) or *microslad* (short for *microscope laser adaptor device*), these devices are integrated with a microscope on an "as needed" basis. They are available for both fiber- and arm-delivered wavelengths. The optic train usually consists of two lenses mounted in a telescope-like focusing device. One lens is moved relative to the other in order to focus or defocus the laser beam at the surgical site. Ideally, the longest focal length is matched to the microscope's objective lens and movement of the micromanipulator's focusing telescope moves the focus closer to the microscope and away from the surgical site. The beam is then reflected by a movable mirror connected to a joystick that the surgeon uses to direct the laser beam.

To be used with a microscope, an adaptor for the micromanipulator must be installed on the microscope. Generally, this is attached around the objective lens of the microscope. In most cases, the microscope's objective lens is removed and an adaptor ring threaded in its place. The objective lens is then screwed into the adaptor ring and the micromanipulator clamps to the adaptor ring.

Both surgical microscopes and micromanipulators are available with a variety of focal length lenses. Most laser surgery is performed at 200 mm, 300 mm, or 400 mm, though other focal lengths are available. It is important that the focal length of the microscope's objective lens be matched to that of the micromanipulator. It is also important that the laser/microscope be set at the proper distance from the surgical site for everything to work properly.

When first starting to use a laser with a microscope, it is not uncommon to find that the sharpest focus of the microscope is not set at the distance of the objective lens. In nonlaser surgery, it is common for the microscope to be set at an approximate distance from the patient and the oculars then adjusted so the clinician sees clearly. This simply does not work when the focus of the microscope and the optimal focus of the laser must coincide. If the oculars are set incorrectly, the microscope may be set too far away to achieve the optimal spotsize for cutting. If too close, the optimal focus may be midway through the range of the focus-defocus adjustment.

Microscope-adapted lasers may be used as an adjunct in conventional surgery or they may be the principal surgical tool. They are often used with a speculum for gynecological or rectal surgery. In ENT they can be used through a suspension laryngoscope or a nasal speculum. Since these accessories are generally shining metal, accidental reflections can be a concern, especially when working in the airway.

Endoscopes

An *endoscope* is primarily a viewing instrument. Endoscopes are available in both rigid and flexible designs. They may or may not have an operating channel or lumen through which a surgical instrument, or in this case a laser, may be passed. Those discussed here do have such a lumen. Some endoscopes can be adapted for use with either an articulated arm or a fiber optic delivery system. Flexible endoscopes and some rigid one will be limited to use with fiber optic lasers.

Rigid endoscopes—Rigid endoscopes are inserted either through a small puncture or through a natural bodily orifice. They are conventional surgical instruments that can be used with or adapted for use with a laser. All operating scopes have a lumen or operating channel through which surgical instruments are passed. They also have a fiber optic bundle that passes light to the distal end of the scope to illuminate the treatment site. If used with a fiber optic, no modification or coupler is generally necessary. If they are used with a CO_2 or other free-beam laser, a laser coupler must be used to adapt the endoscope to the laser. Depending on the type of application, a CO_2 laser coupler may be little more than a focusing lens situated in a housing. In other cases, the coupler may be a combination surgical microscope and micromanipulator used to direct the laser beam down the endoscope lumen.

Cytoscopes. The *cystoscope* is a simple adaptation of a laser endoscope for surgery. Used to access the bladder or prostate, the cystoscope sheath is passed through the urethra. This sheath has a fitting for pressurizing and thus distending the bladder to effect visualization. All this is accomplished with an irrigating fluid. Usually all that is needed is a bag of fluid hanging from and IV pole. An inflatable cuff may be fitted over the bag to provide additional pressure. Due to the fluid-filled field, cystoscopes are not suited for use with the CO_2 laser or other free-beam lasers. Unjacketed optical fibers or fibers fitted with contact tips can be passed through the operating channel to treat areas in the bladder or the prostate. Cystoscopes have a flexible device called an Albarran bridge that allows the clinician to deflect a flexible surgical instrument or an optical fiber to treat areas not directly in line with the cystoscope's lumen. A variety of lasers may be used in a non-contact mode with the cystoscope. Perhaps most common is the Nd:YAG laser.

Urethroscopes. A *urethroscope* is basically a longer, thinner version of a cystoscope. It is passed through the urethra into the bladder and then into the ureter to reach the kidney. The principal use for laser applications is destruction and removal of kidney stones. Conventionally, forceps or a basket-like instrument are used to crush and remove small stones. Larger kidney stones may become stuck in the ureter just after leaving the kidney. The clinician may push the stone back up into the kidney. Once the stone is back in the kidney, the stone may be broken up. Conventional approaches involve the use of forceps or percutaneous nephrolithotomy or extracorporeal shock wave lithotripsy (ESWL) to crush the stones. Pulsed dye, laser lithotripters provide a means of crushing the stones using a photo-acoustic shockwave. The laser fiber is passed through the lumen and brought into contact with the stone. When the laser is fired, the laser pulses chip away at the stone. The sand like residue then passes out through the urinary tract.

Bronchoscopes. As their name implies, *bronchoscopes* are used to access the bronchial tubes, primarily the main bronchi. (See Figure 15.) As mentioned earlier, these are conventional instruments that can be used with fiber optic lasers or adapted to a free-beam laser such as the CO_2 by means of a laser coupler. Since mobility of the scope is limited by the fairly narrow and rigid structure, a laser coupler with a microscope and joystick manipulated mirror is used to direct the CO_2 laser beam down the operating channel to the treatment site.

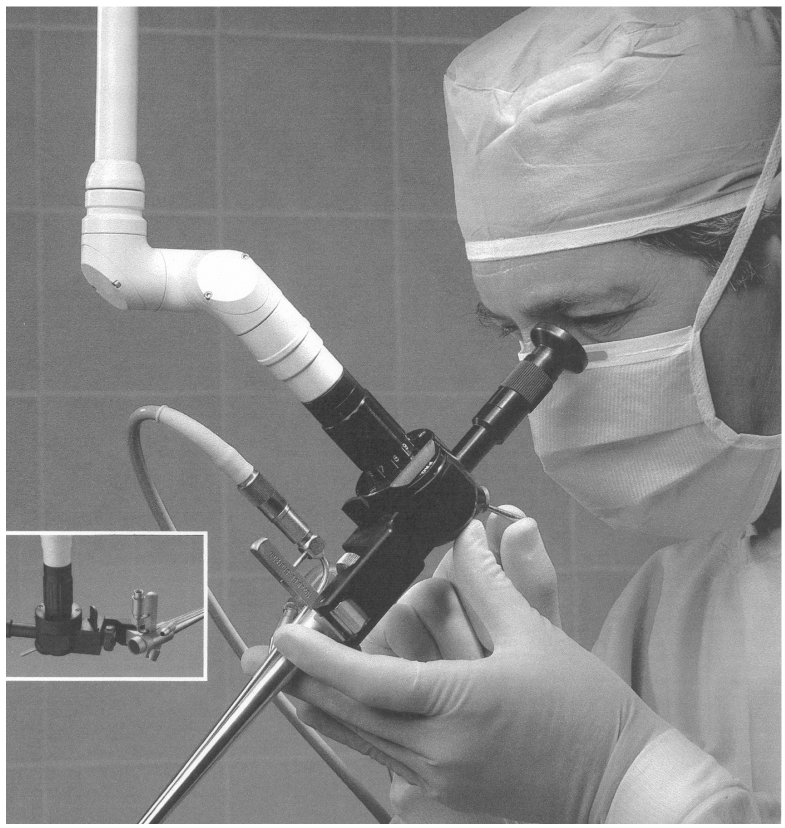


Figure 15 *A bronchoscope in the hands of a surgeon (Photo courtesy Lumenis [www.lumenis.com])*

Rectoscopes. *Rectoscopes* are used to access areas in the rectum. While there is somewhat greater mobility in the rectum, these endoscopes may also use a coupler similar to the bronchoscope for the CO_2 laser.

Laparascopes. The *laparoscope* is perhaps the most widely used of all the rigid endoscopes. (See Figure 16.) Once used mainly in gynecology, they are now being used widely in other specialties as well. Both fiber optic and free beam lasers can be used with the laparoscope. Unlike the previously discussed endoscopes, laparoscopies involve at least one incision, or more accurately a puncture, made in the abdomen. This is usually, if not always, made through the umbilicus or navel, the naturally occurring opening in the musculature of the abdominal wall.

More involved laparoscopies often require the use of multiple instruments that are passed through additional punctures made through the muscles of the abdomen.

Laparoscopies like cystoscopies require distension to allow visualization of the organs and structures within the abdomen. This is most commonly achieved through the use of a pressurized gas, normally CO_2, though N_2O has also been used. To maintain intra-abdominal pressure, a seal must be maintained between the laparoscope and the abdominal wall. This is achieved by making a puncture rather than cutting into the abdomen. The abdomen is first inflated by passing a hollow insufflation needle through the umbilicus. The needle is connected to a device called an insufflator which supplies the pressurized gas necessary to distend the abdomen. Regulation of the pressure is very important since too much pressure can inhibit respiration. Once the abdomen is adequately inflated, the needle is removed and a *trocar* (a large, sharp nail) is pushed through the umbilicus. The trocar is then withdrawn, leaving behind the trocar sheath, and hollow tube with a trumpet-type valve through which the laparoscope will be passed. The gas line from the insufflator would be switched to a fitting on the trocar sheath to maintain insufflation.

In most simple cases, an instrument or the laser can be passed through the operating lumen of the laparoscope. Very often two or more additional punctures are made to permit introduction of laser fibers, graspers, scissors, probes or other instruments. Sometimes a laparoscope without a lumen is used. In that case, the laser or another instrument would be used through one of the additional punctures. For laser surgery, a surgical fiber may be passed through the operating lumen of the laparoscope or through one of the secondary punctures. Surgical fibers or contact tips are used exclusively in the contact mode during these procedures.

Figure 16 *Laserscope KTP/YAG surgical laser system, a versatile laser system used in urology, ENT, gynecology, orthopedics, neurosurgery, gastro-intestinal, and pulmonary disorders (Photo courtesy Laserscope, 800-356-7600)*

Use of a CO_2 laser with the laparoscope has presented a number of challenges. One of the early problems involved proper alignment of the beam to the laparoscope. Most older laparoscopes were not intended for use with lasers. Consequently, the proximal end to which the laser coupler was attached was not necessarily machined perpendicular to the lumen. This required some adjustment to ensure that the beam would pass through the scope. A second problem involved the alignment of the laser's articulated arm. Due to the length and small diameter of most laparoscope lumens, any irregularity in the arm's alignment would result in losing the beam as the laparoscope and arm were manipulated. A third problem had to do with interaction of the CO_2 wavelength and the insufflating gas.

If a CO_2 laser is to be used, a sealed coupler with the appropriate focal length lens is connected to the laparoscope. There are a number of designs available. Some feature a joystick which allow adjustment of the laser beam within the lumen. Others are designed to automatically align the laser beam with the lumen. Provided the arm is properly aligned, any of these will work. Historically, once the laparoscope was inserted into the trocar sheath, the insufflator was moved from the trocar sheath to a fitting on the laparoscope lumen. This was done to prevent the laser plume from entering the lumen and diffusing the laser energy or collecting on the optics. However, this presented a second problem. As surgeons became more proficient in the use of the laser with the laparoscope, they began increasing the laser power. Rather than noticing an increase in cutting efficiency, they noticed an increase in the laser spotsize and lower efficiency. The problem was that the gas being used to inflate the abdomen was the same gas being used to generate the laser wavelength, CO_2. As the laser beam passed down the lumen, a portion of the energy was absorbed by the insufflation gas. Since the beam irradiance profile of most CO_2 lasers is *gaussian* (bell-shaped), the gas near the center of the beam was heated more then the gas near the edges. As the gas was heated, it expanded. Being partially trapped by the walls of the lumen, the gas became more dense at the edges of the beam and less dense near its center. In effect, the laser beam passing through the CO_2 gas in the lumen created a gas lens that defocused the laser beam. The degree of defocus was dependent on the laser's power level.

To address this problem, Coherent Lasers, Inc. developed and patented a CO_2 laser that used the C^{13} isotope of the CO_2 gas (along with any other isotope of CO_2 that could be used for a laser). The conventional CO_2 laser uses the C^{12} isotope and produces a principal wavelength at 10,600 nanometers. The C^{13} isotope produces a wavelength at 11,100 nm, which is outside the absorption range of the insufflating gas. Another approach was taken by Laser Engineering, Inc., which received a patent for using an inert, nonabsorbing gas such a argon at a very low flow rate as a purge gas in the laparoscope lumen. In this case, the insufflator remained connected to the trocar sheath. This approach worked well with the conventional CO_2 lasers and was far more economical.

Arthroscopes. Like cystoscopes and laparoscopes, *arthroscopes* require distension for visualization. They are used to visualize and treat problems within joints, primarily the shoulder and knee. These joints can be distended with either gas or liquid. In most cases fluid is used, which means that the CO_2 laser cannot be used. Contact fibers or contact tips are most commonly used for surgery. As with the laparoscope, a puncture must be made to gain entry to the joint and a trocar sheath is used to pass the arthroscope into the joint.

Flexible endoscopes—Like rigid endoscopes, *flexible endoscopes* have a fiber bundle for delivering radiation to the treatment site. They also have one or more operating lumens through which instruments or a laser fiber may be passed. Unlike the rigid endoscopes, they use a bundle of optical fibers to capture and transmit an image to the clinician, and of course, they are semiflexible. They must be stiff enough to be pushed through the internal passages of the body and flexible enough to be maneuvered. Some have a tip that can be flexed or deflected on two axes to facilitate viewing and to help in guiding the scope around bends as it is passes through the bowel, lungs, etc. The most flexible bundles can be turned to look back on themselves.

The primary difference between the different semiflexible endoscopes is size. They come in various lengths and diameters with the longest being the *colonoscopes,* some two meters in length and about 15 mm in diameter. The *urethroscope* is small enough to be passed through the bladder and up the urethra to the kidneys. *Gastroscopes*, typically about a meter in length and 12 to 14 mm in diameter, are used in the upper digestive tract, including the esophagus, stomach, and duodenum. *Bronchoscopes* generally have a working length of about a 500–600 cm. Their diameters range from less than 3 mm to 5 mm. The smaller diameters are small enough for insertion into the peripheral bronchi.

Scanners

Scanners provide a means of automating the delivery of laser energy to tissue. (See Figure 17.) They allow uniform application of laser energy over large areas that would be difficult, if not impossible, to achieve manually. They also provide repeatability in tissue effects. Generally, scanners are integrated to some extent with the laser's control circuitry. When the laser's on-off footswitch is depressed, the scanner will pass the beam over the treatment site. Movement of the beam is accomplished through use of one or two electronically controlled mirrors. Scanners may be hand held, free standing or microscope-mounted.

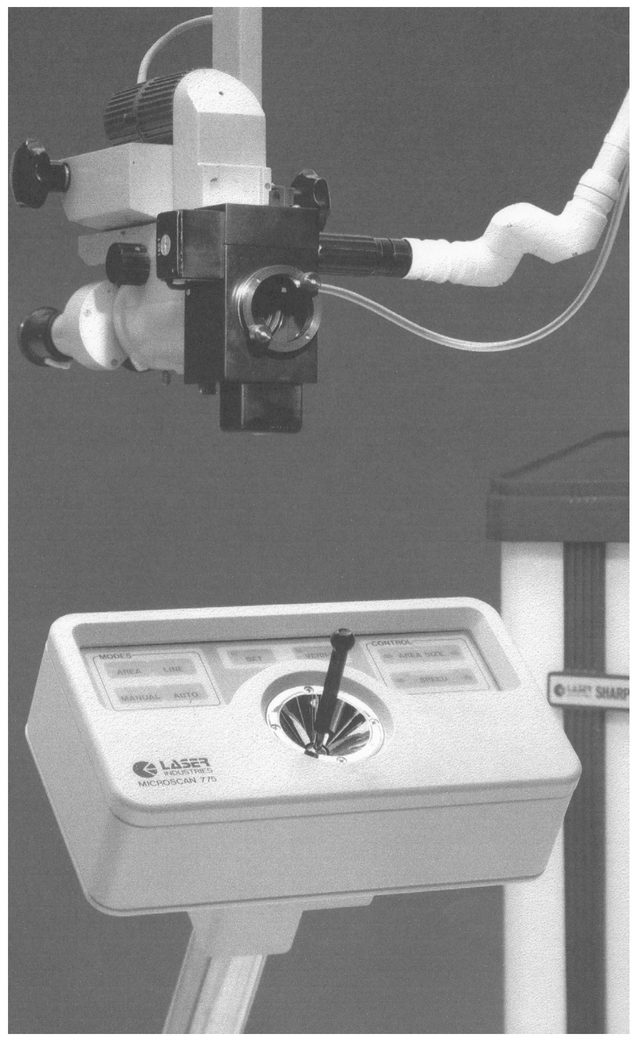


Figure 17 *A computerized laser scanner with a joystick control (Photo courtesy Lumenis [www.lumenis.com])*

The simplest scanners are the hand-held designs. They may scan in either a spiral or an *x-y* pattern. A scanner doesn't really have to be integrated with the laser if the duration of the laser exposure can be set to coincide with a single scan of the mirror, or if the scanning handpiece itself has a shutter that controls exposure. These are most commonly used for superficial treatments such as laser skin peels for rhytide (wrinkle) reduction or treatment of blemishes. (See Figure 18.) CO_2 and Er:YAG lasers are commonly used with hand-held scanners for these applications. Argon, KTP, copper, and gold vapor lasers have been used with this type of scanner for treating vascular lesions and, in some cases, tattoo removal.

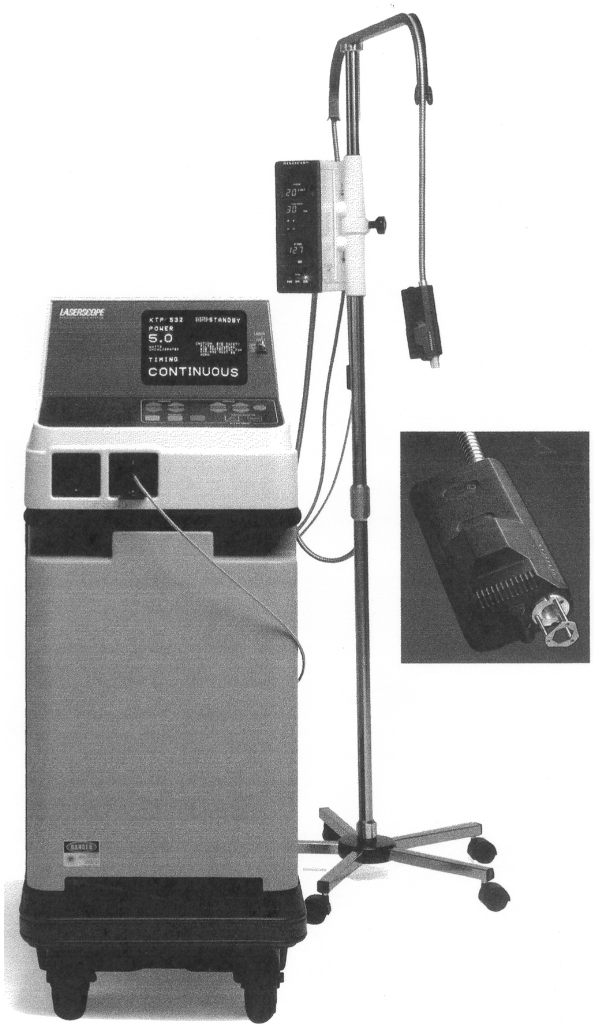


Figure 18 *Laserscope KTP/532 surgical laser system, for the effective removal of benign vascular and pigmented lesions, showing the handpiece used by a surgeon (Photo courtesy Laserscope, 800-356-7600)*

More sophisticated scanners are designed for use with the operating microscope. Microscope mounted scanners are generally programmable to some extent. These scanners may allow the operator to outline an irregular shape and designate separate areas within the larger area. When the footswitch is depressed, the laser fires as the scanner makes incremental passes over the area. The laser turns off, or the shutter closes, as the beam passes over the smaller, outlined areas, thereby avoiding application of laser energy to these sites.

One aspect of laser surgery that can be a problem is involuntary movement of the target tissue during non-contact laser application. This is most noticeable during procedures where patient respiration causes movement of the target tissue. Attempts have been made to design a motion tracking system to increase the precision of laser incisions by tracking and predicting tissue movement.

Perhaps the most sophisticated scanners in common use today are those used for the *LASIK* procedure. This application requires complete integration and control of the laser by a sophisticated computer. To achieve a simple spherical correction of the corneal surface, the laser must remove a precise amount of tissue from the cornea. The amount of tissue to be removed changes as the laser scans across the cornea. To perform *photorefractive keratectomy* (PRK) for myopia, where a spherical correction is required, more tissue is removed from the center of the cornea than is removed from the periphery. To address more complex abnormalities such as cylindrical corrections for astigmatism, the treatment becomes much more complex.

A typical LASIK procedure may take twenty minutes to perform. The majority of that time is used to prepare the patient and program the laser equipment. The actual laser may fire for as few as thirty seconds or for as long as two minutes.

Laser catheters

Catheters provide a means of delivering laser energy to areas of the body that would otherwise be inaccessible by any other means short of major surgery. These catheters are generally introduced into an artery in the groin and directed, to the blockage site (say, the heart) under fluoroscopy.

An example involves the treatment of vascular blockages such as clots or stenosis of major vessels like the coronary or peripheral arteries. Early versions of these devices used argon laser energy to vaporize plaque that forms the blockage, thereby creating a path for an integrated balloon catheter. The balloon catheter is then used to compress arterial plaque and further open the channel through the blockage site. More recently, excimer lasers and frequency-tripled Nd:YAG lasers have been investigated for this application, since they do not cause localized heating, which in itself can damage the delicate tissues lining the vessels.

These devices can be used to treat stroke victims who are not candidates for the so called “clot busting drugs”. The action of the laser breaks up and emulsifies the clot allowing it to be sucked up by the catheter.

Connectors

Many laser manufacturers use accessory connections that are unique to their systems. While one may use a standard thread to connect an accessory to an articulated arm, another may use a spring clip design, a twist lock or a multi-start thread. Fiber optic lasers have different pin arrangements on their connectors to “tell” the laser which type of fiber is attached.

There are some companies that specialize in manufacturing laser accessories. These companies usually can provide adaptors that will permit use of their product(s) on the most common lasers. Additionally, adaptors usually can be obtained that allow the use of one manufacturer’s accessory with a laser from a different manufacturer. For this reason, it is important to ensure the compatibility of the accessory with the laser to be used. Mixing an accessory designed for one wavelength with a laser of a different wavelength may result in little or no effect on tissue and destruction of some very expensive optics. As long as there is wavelength compatibility, using accessories from one manufacturer with a laser from another usually isn’t a problem with simple accessories such as handpieces, microscope adaptors or endoscopes. However, this could be problematic with more sophisticated devices. As an example, if a scanner is designed to be used with a particular laser, it may very well interface with the laser’s control circuitry for trigger, scan speed, and exposure time. Some may require installation of an interface PC card and/or upgrades in system software before the device can be used with a laser.

LABORATORIES

Basic Laboratory: Exponential Law of Absorption

Objective

In this experiment the student will measure the transmission of three filter materials as a function of filter thickness.

Equipment

Laser pointer or 1–2 milliwatt HeNe laser

Plastic filters of equal thickness (6 red, 6 blue, and 6 green)

Power meter

Filter holder

Lab jack

Procedure

1. Mount the laser on a lab jack near one end of the optical bench. Attach the beam expander to the output aperture. (See Figure 19.)

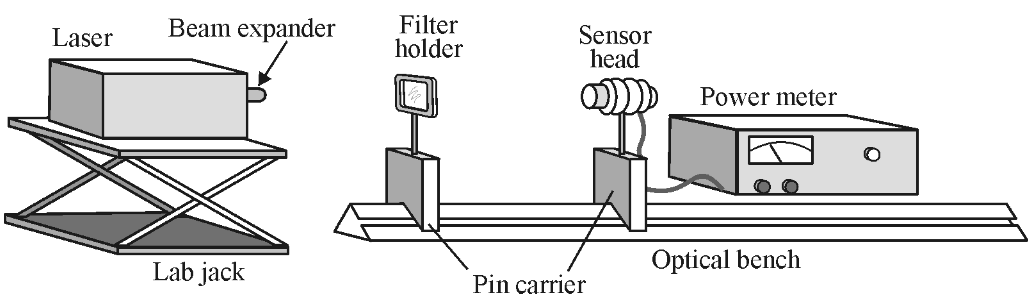


Figure 19 *Experimental setup for absorption measurements*

2. Using a pin carrier, mount the sensor head of the power meter about 15 cm to the right of the laser. Between the laser and the sensor head, use another pin carrier to attach the filter holder to the bench, as illustrated in Figure 19.
3. With the micrometer, measure the thickness of several filters. Record the average thickness in the data table.
4. Using the proper safety precautions, plug in and turn on the laser. Adjust the range selector on the power meter to 10 mw full scale and turn on the power meter. Position the sensor head in such a manner that the active area of the detector is fully illuminated; however, do not overfill the detector.
5. Measure and record the power output (P_o) of the laser.

6. Place a blue filter sheet in the holder and measure the power transmitted (P_t) by the filter. Repeat with two, three, four, five, and six sheets of blue filter. Record the results in the data table.
7. Repeat Step 6 for green and red filters. Note: The range switch on the power meter will have to be adjusted to obtain some of the readings, since the power levels to be measured will vary over a range from about 2–3 mw to < 100uw.
8. From the data obtained in Step 7, plot a curve of transmitted power versus thickness (number of filters) for each of the three types of color filters. The resultant curves should provide verification of the exponential law of absorption. (Your first data point on each curve should be the output power of the laser, P_o, that is, the power when no filters are in the beam path.)

Data Table: Exponential Law of Absorption

Equipment	**Manufacture/model number**		
Laser optical power meter			
Laser power output, P_o _______________ mW **Average filter thickness** _______________ mm			
	Transmitted power, P_t		
Number of filters	**Blue**	**Green**	**Red**
1			
2			
3			
4			
5			
6			

Advanced CO_2 Laser Laboratory

Objective

The purpose of this lab is to become familiar with power settings, spot sizes and time settings using a CO_2 laser and tongue depressor to represent the effects on tissue.

Equipment

Laser safety glasses for the appropriate laser wavelength(s)

CO_2 laser system (as depicted in Figure 8)

125 mm handpiece with focusing guide/tip

Scalpel

Gauze pads

Cotton swabs

Wet towels and/or a bowl of water

Smoke evacuator or suction device with filter.

Various colored markers (black, blue, red, yellow)

Target materials: Tongue depressors (some dry, some soaked in water) (The tongue depressor is the small wooden blade typically used by doctors in routine examinations of the mouth and throat.)

Procedure

The CO_2 laser is used in a strictly freebeam or non-contact mode. This exercise may be performed with either the handpiece or a micromanipulator. While other accessories are available for articulated arm equipped models, the effects will be similar.

The CO_2 laser may be used focused for incision/excision or defocused for ablation. The end results will depend largely on the power setting, spot size and time on tissue.

In this lab you will fire the laser on a tongue depressor in lieu of actual tissue specimens. (See Figure 20.) The effects of focused and defocused laser energy at various power levels will be noted. Any differences between tissue effects in lightly pigmented and darkly pigmented tissues will also be observed. Also, note the appearance of the aiming laser on the tongue depressor and other specimens. The differences, if any, between continuous and any available enhanced-pulse modes will also be observed.

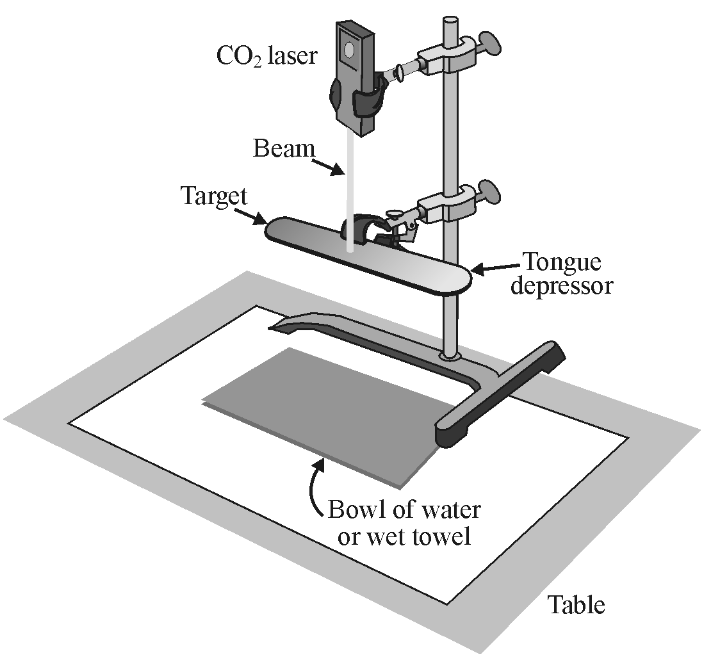


Figure 20 *Lab setup*

To ensure safety, approved goggles and a smoke evacuator are required. It is best that at least two people work together during this lab. One person should act as the laser operator setting power, exposure and mode while another is using the laser. If working in larger groups each person should take a turn at each position.

Part I

Start with a dry tongue depressor as the target. Since a focused CO_2 laser can burn through a tongue depressor at relatively low powers, work over a wet towel or a container of water to absorb any excess energy. Never point the handpiece at anyone. To help control the odor of burning wood, hold the evacuator wand or suction device as close as possible to the impact point of the laser beam.

To begin, set the laser for 2–3 Watts. Select a single pulse of 0.1 second. Place the handpiece with its focusing guide against the tongue depressor. Depress the footswitch. Exciting, isn't it? Now put the laser in *standby* and inspect the results.

Did it burn through the tongue depressor?

Duplicate this with another tongue depressor that has been soaking in water to compare to living tissue. Wipe any excess water from the surface of the wood.

How do the burns compare?

Now, hold the handpiece back an inch and fire the laser on both tongue depressors.

Note the difference in the size of the burn.

Repeat this holding the handpiece at increasing distances until there is no effect on the tongue depressor. Did water content have an effect on the results?

Repeat this process for longer pulse widths and higher power settings of 5W, 10W, 20W. Note the differences in the increase in power makes.

Switch the laser to repeat pulse, 2–3 Watts.

Depress the footswitch as you move the handpiece along the tongue depressor.

Repeat using various powers and spotsizes.

Mark off an area on the tongue depressor of 1 cm^2 and try to uniformly ablate the surface leaving a uniform char layer.

Part II

Switch the laser to continuous (cw) mode and repeat the previous exercise.

Which mode is easier to control?

If SuperPulse or another enhanced pulse mode is available, compare its effects with the cw mode using the same power level(s) and spot size(s).

Make a series of lines across a dry tongue depressor using colored markers. Use a beam sufficiently defocused so that it barely marks the wood as you scan across the tongue depressor. Scan across the marks from lightest color to darkest. Does one color react more strongly than another? What can you deduce from this?

Prepare a detailed report of your results, making comparisons of data and observations for Part I and Part II.

EXERCISES

1. Define the following terms:
    a. Power
    b. Energy
    c. Irradiance
    d. Coherence

2. A CO_2 laser beam has a power of 250w and a diameter of 1.5cm. Determine the irradiance at a target struck by this beam in W/cm$^{2.}$
3. Define monochromatic light
4. List the commonly used lasers in medicine and surgery giving their wavelengths and applications.
5. Identify the four optical interactions take place when laser light strikes tissue?
6. Tissue can be changed several ways with laser light. List them.
7. List four optical beam delivery systems
8. A medical laser can operate in three modes. List them.
9. How does the interaction of time and temperature result in tissue destruction?
10. Which wavelengths reflect most for fair skin? Are these the same for dark skin? Answer the same question for skin absorption of laser light.
11. An optical fiber has a core with an index of refraction of 1.45 and a cladding of 1.40. What is the critical angle necessary for transmission in the fiber.

REFERENCES

CORD. *Introduction to Lasers*. Waco, Texas: CORD, 2000.

Dover, Jeffrey S., Kenneth A. Arndt, Scott M. Dinehart, Richard E. Fitzpatrick, Ernesto Gonzalez. *Guidelines of Care for Laser Surgery*. American Academy of Dermatology Association, Practice Management. (http://www.aadassociation.org/Guidelines/laser.html)

ETI. *Medical Lasers and Safety.* Waco, Texas: ETI, 1992.

Fisher, J.C. *Principles of Safety in Laser Surgery and Therapy*. Appleton Century Crofts, 1985.

Harrington, James. A.. "A Review of IR Transmitting, Hollow Waveguides," *Fiber and Integrated Optics,* 19 (2000), 211–17.

Hunter, I.W., C.J.H. Brenan, and E.L. Sebern. "Design and Characterization of a Laser-based Instrument to Treat Hemangiomas Using Spectroscopic Feedback: The 'Smart Scalpel.'" Progress Report No. 2-4: October 1, 1999, MIT Home Automation and Healthcare Consortium, d'Arbeloff Laboratory for Information Systems and Technology, MIT.

Mainster, Martin A. "Laser Wavelength Selection," *Iris Medical Products, Applications Newsletter,* Vol. 8, Number 1, 2003.

Petty, Howard. "A Survey of Laser Applications in Biomedicine," *Lasers and Optronics,* April, 1990.

Resar, Jon R. *Direct Laser Myocardial Revascularization.* Cardiac Catheterization Laboratory, Johns Hopkins School of Medicine, Baltimore, Md. (Ital Heart J 2000; 1 [Suppl 3]: S120–S123).

Sliney, David, and Stephen Trokel. *Medical Lasers and their Safe Use.* Springer-Verlage, 1992.