1

Laser Fundamental Principles

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LASER is an acronym of "Light Amplification by Stimulated Emission of Radiation." Laser is light with specific properties and may interact with tissues and materials. Light is an electromagnetic wave, which is a coupling of electric and magnetic fields, traveling as waves at a speed equal to the known speed of light (velocity, c). Both fields oscillate at the same frequency, with a number of oscillations per second, which is well known as frequency (f). The speed of light is a universal constant, which is about 300 000 km/s.

Since medical professionals are interested in the applications of laser devices and not the internal physics, here we describe fundamental information, which is foundation knowledge, before the use of lasers in clinical settings.

A laser light is a *monochromatic*, *coherent* light in the visible and nonvisible (infrared or ultraviolet [UV]) parts on the electromagnetic spectrum. Laser light is optical radiation and is termed non-ionizing radiation to be differentiated from ionizing radiation, such as gamma- and X-rays, which may cause biological effects in the cells and tissues. The human eye associates a color to a group of specific wavelengths from violet, blue, green, yellow, orange, red based on the increase of the wavelengths. Invisible wavelengths for the human eye are wavelengths of radios and television (infrared) or in the UV parts of the spectrum, the gamma- and x-rays (Figure 1.1).

The spectrum is divided into two major zones: the short wavelength ionizing radiation (nonvisible to the human eye) and the non-ionizing radiation (visible light and non-visible infrared radiation) with longer wavelengths. The ionizing radiation can penetrate tissue and damage cells. In low doses it can be used for diagnostic purposes (i.e. X-rays). The non-ionizing range of radiation can be used for superficial heating of tissues, and for treatment of skin disorders and musculoskeletal injuries.

The power of lasers can range from milliwatts to almost 20 W for commercial lasers. In addition, higher levels of power in megawatts may be used for military purposes.

The sizes of lasers can have dimensions larger than 100 m. Lasers in this size can be used for nuclear experiments using laser beams to squeeze hydrogen atoms in order to release a high amount of energy (laser fusion). The biggest facilities in the world so far are the NIF (National Ignition Facility) in California and the Laser Megajoule (LMJ) in France, near Bordeaux.

In contrast to large lasers, the smallest lasers today are 5000 times smaller than the tip of a pen. Scientists have created the world's smallest laser after they squeezed light into a space smaller than a protein molecule. The so-called "spacer" generates stimulated emission of surface plasmons (oscillations of free electrons in metallic nanostructures) in resonating metallic nanostructures adjacent to an active medium. It is anticipated that, at least experimentally, the spacer (wavelength of 531 nm) will advance our fundamental understanding of nano-plasmonics and the development of new opportunities due to the photothermal properties in the therapy of malignant lesions (Chon et al. 2014).

In general, there is a broad diversity in laser applications, which can be used for industrial, commercial, research, and military interests.

Some areas where lasers can be used are:

- Material cutting and welding
- Measurements
- Communications
- Entertaining and performing arts
- Holography
- Spectroscopy and atomic physics
- Environment protection
- Plasma diagnostics
- Medical applications

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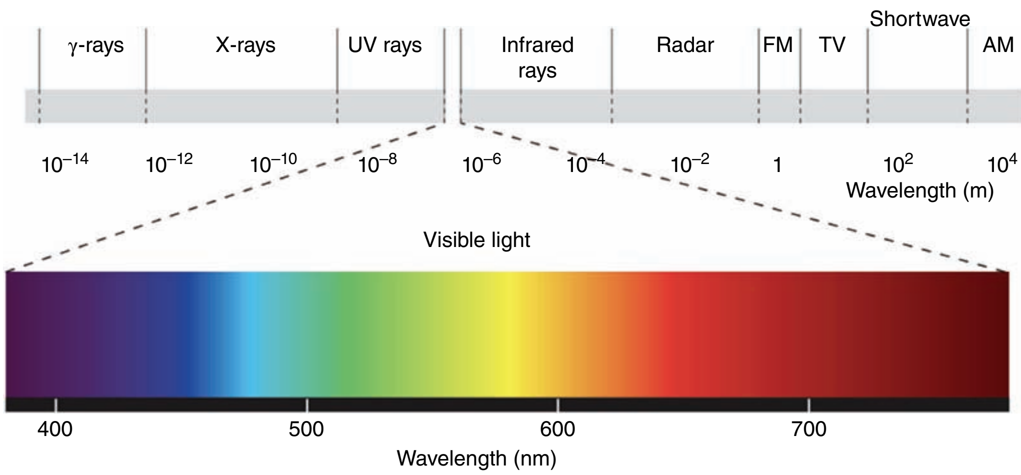


Figure 1.1 Electromagnetic spectrum and the different wavelengths.

There is no way to think about modern life without the internet, mobile phones, and technology. Therefore, lasers are everywhere in our lives since lasers are fundamental in all these technological advances.

Lasers can do a lot, for example measuring distances, such as the depth of oceans and in aerospace, based on the principle that laser light is sent to a target, which will then be reflected and sent backward. For instance, laser light can be sent to the moon, collecting a few photons reflected back by mirrors placed on the lunar surface (such as during the Apollo missions), and then we know the distance between the moon and the Earth.

The coherent properties of laser light will be used in ring laser gyroscopes allowing distance measurement in aircrafts, helicopters, missiles, ships, etc. Bar code readers and scanners exist only in conjunction with diode lasers. Also, optical storage capacity from compact discs (CDs) to digital video discs (DVDs) and today Blu-ray discs depends on the density of coding elements (pits) and the laser spot after focusing. The shorter the wavelength, the smaller the laser spot and the engraved surface of the disc. In addition, partial or complete absorption of the light can be at resonance with the material medium and create distinguished resonance frequencies (signals), characterizing the medium composition (spectroscopy).

In medicine, cornea surgery, removal of wrinkles, and coagulation of blood vessels in abdominal surgery accommodate lasers in daily practice. Also, other applications in laser medical imaging, like the phenomena of scattering and absorption of light by tissues, have been used extensively the last few years establishing excellent opportunities in the field of diagnostics. Specifically, optical coherence tomography (OCT) today allows a high-resolution cross-sectional imaging compared to the conventional diagnostics due to the reflected light by a mirror and by measuring backscattered or back-reflected light.

Figure 1.2 OCT device for clinical and diagnostic applications. *Source:* Dr. Georgios E Romanos.

OCT (Figure 1.2) can provide cross-sectional images of tissue structure on the micron scale in situ and in real time. This relatively new technology is very helpful today in biomedical and clinical sciences. Especially in ophthalmology, it provides treatment guidance for glaucoma and diseases of the retina, including age-related macular degeneration (AMD) and diabetic eye disease (Fujimoto et al. 2000).

1.1 Historical Background

The precursor of the laser, namely the "Maser," was developed in the United States by the physicist Theodore H. Maiman (1960). It consisted of an one-crystal-rod from artificial ruby and could emit red light with a wavelength of 694 nm in the microwave band. The Maser, an acronym for Microwave Amplification by Stimulated Emission of Radiation, is today generally known under the name *laser*. In its name is summarized the basic principle after which all laser systems work. Charles H. Townes (1964) received the Nobel Prize for the development of the laser; Townes was the first to achieve, due to stimulated emission, the fortification of the radiation in the microwave band.

Moreover, Albert Einstein (1917) had already argued in his thesis "Quantum Theory of Radiation," that parts of the electromagnetic field can be stimulated in such a way that through it fortified light originates. The first lasers were called optical masers.

1.2 Energy Levels and Stimulated Emission

Based on Niels Bohr and the Planck-quantum hypothesis, the following two postulates were formulated:

- Electrons move only on certain, firm orbits around the nuclear core
- Electrons can jump only from orbit to orbit and deliver energy in the form of radiation, as for example light (emission of radiation), or take up energy (absorption of radiation).

Therefore, in the interaction between light and matter three different optical concepts may occur: *absorption*, *spontaneous emission,* and *stimulated emission*.

Absorption is the process when electrons transfer from a low energy level (E1) (stable) to a higher energy level (E1) (unstable). Energy levels E1 are called the ground state and E2 called the excited state.

Spontaneous emission is the process, when electrons transit from a higher energy level (E2) to a lower energy level (E1). When E2 > E1, the energy difference satisfies the relation E2-E1 = h ν. The constant h ($= 6.63 \times 10^{-34}$ J/s) is known as Planck's constant, and ν is the radiation frequency. Spontaneous emission is responsible for the production of conventional visible sunlight.

Stimulated emission is the process when atoms initially from the excited stage fall down to the ground state emitting photons. An atom can be stimulated (excited stage) by an external source, so that its electrons of a low energy can jump to a higher energy orbit. This source can be of an electric kind, e.g. a flashbulb, and serves as "a pumping mechanism." Other pumping methods can be also chemical or optical, depending on the energy source (Figure 1.3).

1.3 Properties of the Laser Light

With the term *laser* is identified a physical principle leading to the production of electromagnetic radiation, which differs from the usual light in the following properties (Figure 1.4):

- *Coherence:* Wave streaks remain parallel and well-defined even in large distances. The light has spatially the same phase (the waves are "in tune").

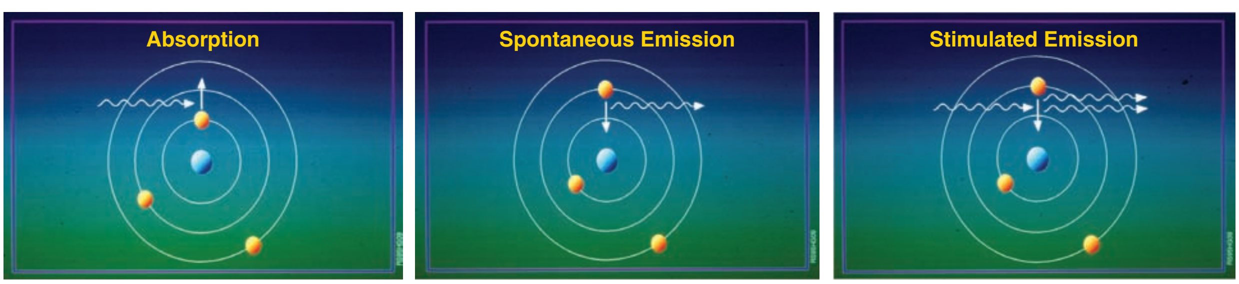


Figure 1.3 Spontaneous and stimulated emission principles.

- *Collimation:* The laser beam can give a localized spot when something is in its way. This has the practical advantage that the light can be well focused.
- *Monochromatism:* All wave streaks have the same wavelength, the same frequency, and thus the same energy. The wavelength of the light plays a critical role in medicine and determines today the exact clinical ranges of application.

A high energy density is produced when the generated electromagnetic radiation bundles in the narrowest space, due to the coherence and the collimation. The light can be focused precisely and have, because of its high energy density, different effects on the tissues. Therefore, vaporization, coagulation, and also carbonization of tissues are possible. Light with such qualities does not exist in nature. The photons of usual light exhibit different wavelengths, and they are emitted in all directions (Figure 1.4) of space (polychromatic, incoherent light).

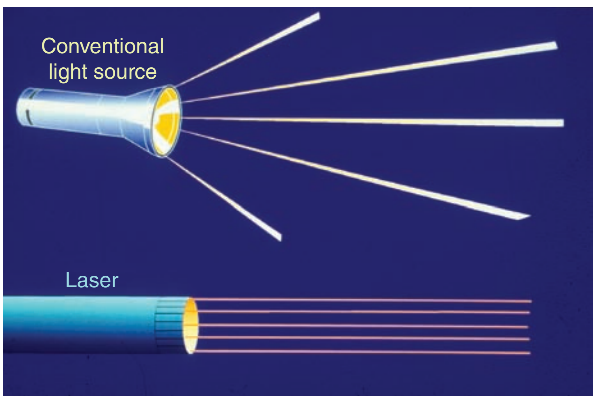


Figure 1.4 Collimated light of the laser versus non-collimated light of the conventional light source

The concurrent combination from the above-mentioned physical properties permits very high capacity density. In this way, for example, the sunlight striking our earth has power of on an average 0.1 W/cm^2; on the contrary, surgical laser systems easily reach a power of 100 000 W/cm^2. Lighting a match produces energy of 200 J. With the energy of only 1 J of coherent light generated by a ruby laser – focused by means of a plane optical lens – it is possible to cut a hole in a metal plate (Frank 1989).

The three basic criteria of light are: brightness (amplitude), color (frequency), and polarization (angle of vibration).

1.4 The Laser Cavity

From the practical standpoint, a laser device (Figure 1.5) contains the following components:

- The laser medium (active medium), which generates the laser light (this is the "brain" of the system).
- The optical resonator (reflecting system)
- The laser pumping mechanism

1.4.1 Active Medium

Atoms are stimulated to the production of the laser radiation. These atoms are components of the so-called **"active (gain) medium."** This can be a gas, a solid body (crystal), a liquid, or a semiconductor. Different lasers systems can be classified based on the active medium.

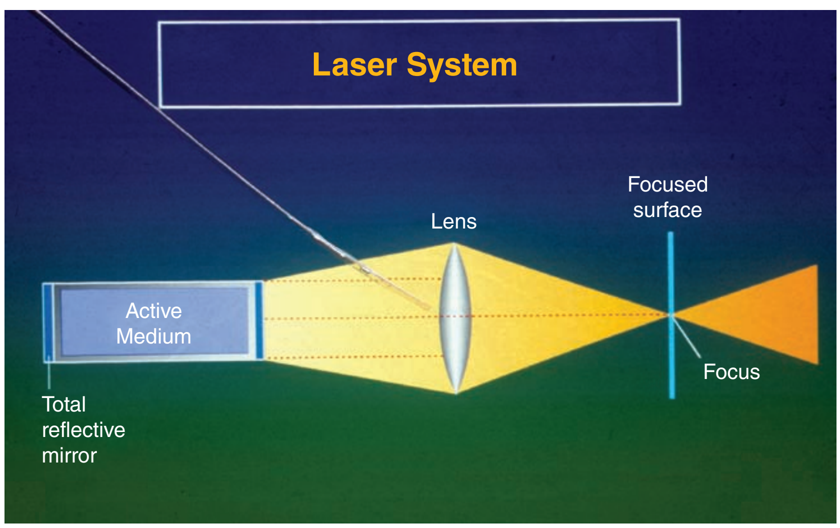


Figure 1.5 Schematic demonstration of a laser device.

1.4.2 Pumping Mechanism

The **laser pumping mechanism** is the act of energy transfer from an external source into the active medium of the laser. The pump energy is usually provided in the form of light (optic) energy, or electrical current, but also other sources have been used, such as chemical or nuclear reactions.

1.4.3 Lenses – Resonator

The **optical resonator** is the reflecting system of the laser device. With the use of two parallel, arranged mirrors (mostly concave shaped) at a specific distance, the light will be reflected. The exact radius of curvature characterizes the optical resonator. A certain curvature controls better the light reflections, modifying the distribution of light within the laser output beam.

The resonators with a stable reflecting distance are also called also stable resonators and differentiate themselves from the unstable ones, which obtain a variable reflecting distance. According to the distance and shape of the mirrors as well as their position, there are concentric, confocal, hemi-confocal, and hemispherical resonators. Energy loss can happen if mirrors (especially output mirrors) do not perfectly reflect light, and this should happen as much as possible. Concave mirrors are needed in order to focus light transversely.

The simplest laser cavity is formed by two parallel mirrors facing each other. This is called a *Fabry-Perot Cavity*.

The laser resonator has two different types of modes: transverse and longitudinal. Transverse modes can be explained by the cross section of the beam profile and represents the intensity pattern. This distribution of power is also referred to as transverse electromagnetic mode (TEM).

1.5 Laser Application Modes

The operation mode of a laser can be switched to *pulsed* or *continuous* (Figure 1.6). The pulsed mode is also known as normal mode. A continuous beam is referred to as continuous wave ("continuous-wave laser") or *CW laser*, when light will be constantly emitted over an uninterrupted period of time due to continuous pumping. These lasers have usually low peak energy and low power. They are usually gas lasers, i.e. CO_2 lasers.

The type of the operating mode, namely the length or width of a pulse is dependent on the pumping mechanism and the laser medium. The pulsed laser light (gated, chopped) can be achieved when a mechanical shutter opens and closes in front of the beam.

Pulses can be short or ultrashort dependent on the pulse duration. A superpulse mode is associated with good ablation and wide residual thermal damage (RTD) compared to the ultrapulse mode, where the ablation is precise and the RTD is shallow. The latter may be also called char-free mode.

Usually pulses have a pulse duration in the μs-ms range. *Free-running* (*FR*) *lasers* are pulsed lasers with shorter pulse durations than the conventional pulsed lasers. Such lasers can be used in areas when risk of overheating has to be avoided. For instance, a FR-Nd:YAG is used for the LANAP protocol in periodontal therapy (see also Chapter 5).

Shorter pulses with pulse duration from microseconds (10^{-6}) to nanoseconds (10^{-9}) define the *Q-switched* lasers (*Q-switching*). Compression or shortening of pulses can be done with this technique. This kind of laser can be used in industry for metal drilling, cutting, and marking with extremely high peak power.

The second compression technique of pulses is to create pulses with extremely short duration; sometimes referred to as *ultrashort pulses*. These are pulses with a width in picosecond (10^{-12} seconds), femtosecond (10^{-15} seconds), or attosecond (10^{-18} seconds) defining the *mode-locking*. This can be used for cutting or melting of metals due to the high penetration depth. Pulse repetition rate (frequency) also varies widely.

Pulse modes control the heat transfer to the tissues, providing vaporization without overheating and, as a consequence, melting. High peak power pulses can create defects with sharp edges in the matter (or tissues) without damage.

There is great interest in the *pulse duration,* also called pulse width, of the laser beam in order to avoid negative effects and damage in biological tissues.

Chopped (shuttered) pulses usually have a duration of 100–500 ms. Superpulses have a shorter width, usually of 60–200 μs and higher peak power. The width can be controlled electrically using mechanical shutters and other devices, like shutters and Q-switches. These devices are placed in the laser cavity.

The pulse width must be shorter or equal than the *thermal relaxation time* (*TRT*) of the target chromophore. This time is directly proportional to the square size of the chromophore. Therefore, small objects cool

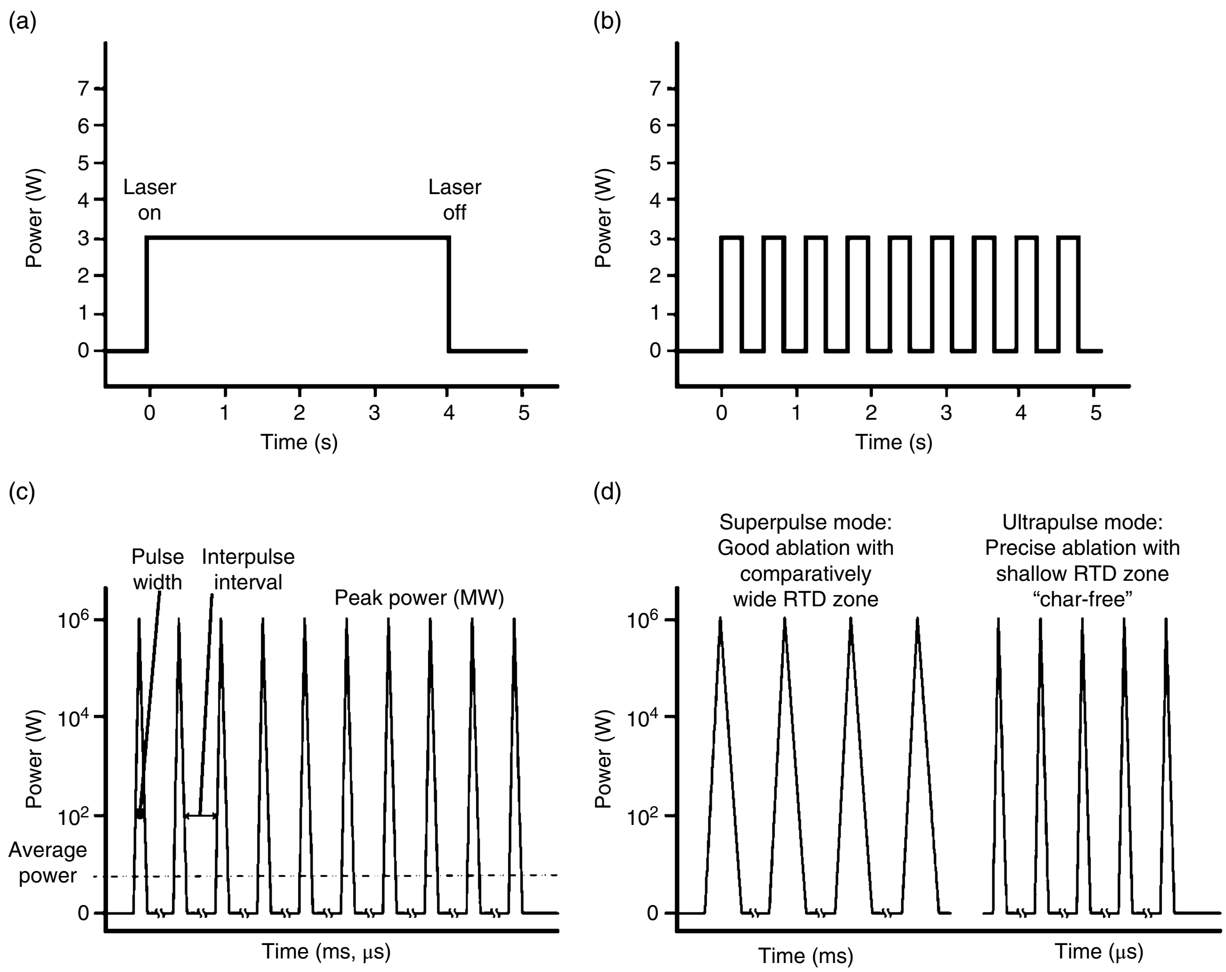


Figure 1.6 Continuous (CW) and pulsed (chopped, gated) laser application modes compared to pulsed, superpulse, and ultrapulse mode.

faster than large ones, while larger chromophores have a longer TRT than smaller chromophores.

The TRT is defined as the time needed for the target chromophore to dissipate 63% of its peak temperature. Bogdan Allemann and Kaufman (2011) showed different TRTs of importance based on the chromophore size in dermatology (see Table 1.1).

Contact and *non-contact laser* modes can be defined dependent on the position of the optic fiber or tip in relation to the tissue or material.

Important parameters, when continuous lasers are used, are the irradiation period, power, and spot size. In contrast, for pulsed lasers maximum energy per pulse, pulse duration, frequency, and spot size are fundamental. Power (in watts) is defined by the transmitted energy (in joules) per unit time.

Therefore,

$$P = E/t(\text{Frequency} = 1/t, \text{in Hz})$$

Also:

meanP = Pmax × tpulse × frequency
Pmax is the maximum power (watt)
tpulse is pulse duration (second)
frequency (Hz)

Table 1.1 Thermal relaxation times for different chromophores of various size.

	Size, µm	Thermal relaxation times (approx.)
Tattoo ink particle	0.5–4	10 ns
Melanosome	0.5–1	1 µs
Erythrocyte	7	2 µs
Blood vessel	50	1 ms
Blood vessel	100	5 ms
Blood vessel	200	20 ms
Hair follicle	200	10–100 ms

The energy per area is the power density (PD, or fluence) and expressed in joules/cm^2

PD = meanP/S
PD is Power Density (watt/cm^2); mean power (watt); S is the irradiated surface (cm^2)
r is the radius of the glass fiber; ($S = \pi \cdot r^2$), $\pi = 3.14$

All parameters that must be included in different laser studies should be: power density, energy of the laser beam, pulse width and frequency, irradiation period, diameter of the glass fiber (or tip), beam profile, distance to the irradiation object, and tip angulation.

Peak Power is the energy flow in every pulse

$$Ppeak : E/\Delta t$$

Average Power is the energy flow over one full time period.

$$Pavg = E/T$$

Therefore:

$$Ppeak\ \Delta t = Pavg\ T$$

Also, *Duty Cycle* is the fractional amount of time the laser is "on" during a specific given period.

Therefore:

$$\text{Duty Cycle} = \Delta t/t = Pavg/Ppeak$$

1.5.1 Beam Profiles

The energy distribution across the beam (transverse electromagnetic mode) determines the nature of laser focus (focal spot size). This focus can have a circular, clean pattern (TEM_{00}), or an irregular pattern (multi-mode, TEM_{xx}). The circular spot is the fundamental mode, with Gaussian (normal distribution) in the beam profile, which has the highest concentration of power and can be focused into the smallest, most concentrated focal spot (Figure 1.7). The TEM_{00} mode is the most desirable beam. The fundamental mode with the maximum intensity peak at the center of the beam is the TEM_{00} and contains roughly 86% of the power in the spot.

Longitudinal modes correspond to different resonances along the length of the laser cavity which occur at different frequencies or wavelengths. The transverse modes are classified according to the number of nulls that appear across the beam cross-section. However, multimode beams can have high power but lower quality.

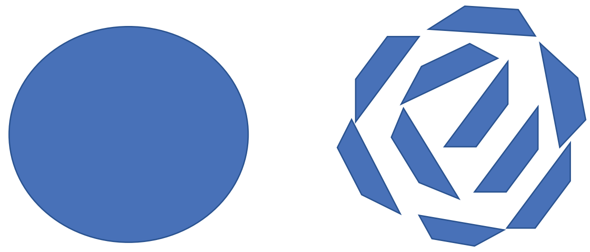


Figure 1.7 Transverse electromagnetic modes with regular, high concentrated beam (TEM_{00}) and irregular (TEM_{xx}) pattern with less concentration of the maximum energy in the beam.

1.6 Delivery Systems

The laser beam is used as a handpiece by means of different guide systems (the so-called beam guide systems), allowing the surgeon to perform a perfect, with minimal complications, and practical, laser application. A direct coupling, an articulated arm, a flexible hollow guide as an optical fiber, or a fiber system are currently available for this purpose.

1.6.1 Direct Coupling

A direct coupling is possible only in extremely compact systems (e.g. He:Ne target lasers, soft lasers, laser pointers). In such systems the laser unit corresponds to the handpiece of the system.

1.6.2 Articulated Arms

The laser beam can be used as a handpiece by means of articulated arms (Figure 1.8) at specific wavelengths (e.g. in the UV range and the wavelength of the CO_2 laser). In such systems, mirrors are used for beam deflection. For this reason, such articulated arms are also called transmission arms.

Articulated arm beam delivery dates back to the 1970s; it features a cumbersome four-elbow, seven-mirror articulation, which can rotate to different angles for the transmission of the laser beam, but it can have limitations in accessibility. A lens in the base of the handpiece focuses the laser beam 2–3 cm from the exit aperture of the handpiece. An articulated arm is unusable without an aiming beam – the only visible indicator of the focused CO_2 laser beam location on the target tissue.

Although, the beam quality can be described as a very good one, disadvantages are the large weight of the articulated arm and thus the entire laser unit, the

Figure 1.8 Articulated arm for a CO_2 laser application in the modern CO_2 laser (Denta 2, Lutronic, GPT dental, Fairfield, NE, USA).

Figure 1.9 Hollow guide of a CO_2 laser presenting the flexible delivery system for oral applications. *Source:* Dr. Georgios E Romanos.

relatively inflexible operation, and the relatively expensive reconstruction. To reduce the heavy weight, a technical modification is needed. A weight balance with gas pressure springs or counterweights can also positively affect the clinical use of endoscopes, surgical microscopes, or handpieces.

1.6.3 Fiber Systems and Flexible Hollow Guides

These fiber systems are flexible light guides made of glass fibers (high-purity fused quartz glass) coated with transparent plastic or piping systems, the so-called waveguides (Figure 1.9).

Flexible hollow guides are also used in the construction of CO_2 lasers, instead of more expensive and relatively inflexible articulated arms. The flexible hollow fiber for CO_2 laser wavelength was developed in the 1990s; it features an unprecedented reach and accessibility unattainable with articulated arm lasers. A pen-size, scalpel-like handpiece is held very close to the target tissue. It focuses the CO_2 laser beam 1–3 mm away from handpiece's distal end; no aiming of the beam is needed. The handpiece is autoclavable, and the latest designs use no disposable tips.

The optical fiber (Figure 1.10) works by a total internal reflection in which the index of reflection inside the core of the fiber is higher than the index of reflection of the cladding (Ghatak and Thyagarajan 1998). They are currently used in many laser systems, because they are reasonably priced. These light pipes can be quite long, so that the laser unit and the surgical area can be physically separated.

They have a broad clinical application possibility, among others in gastroenterology, vascular surgery, gynecology, and also in dentistry.

A disadvantage of these waveguides is the relative loss of power at high deflection of the fiber and the limitations in focusing. Of particular clinical importance is the intracorporeal application of the fiber, due to the high quartz fiber flexibility. Flexible fibers can nowadays be inserted, by means of endoscopy, in difficult to access areas, and there they can be therapeutically used.

For intracorporeal clinical use an optical fiber is essential. Waveguides are not currently used intracorporeally, as combustion products in the case of not-with-window-closed waveguides can contaminate the inner surfaces. Technological efforts for the optimization of beam control systems are intensively carried out in the various fields of clinical medicine.

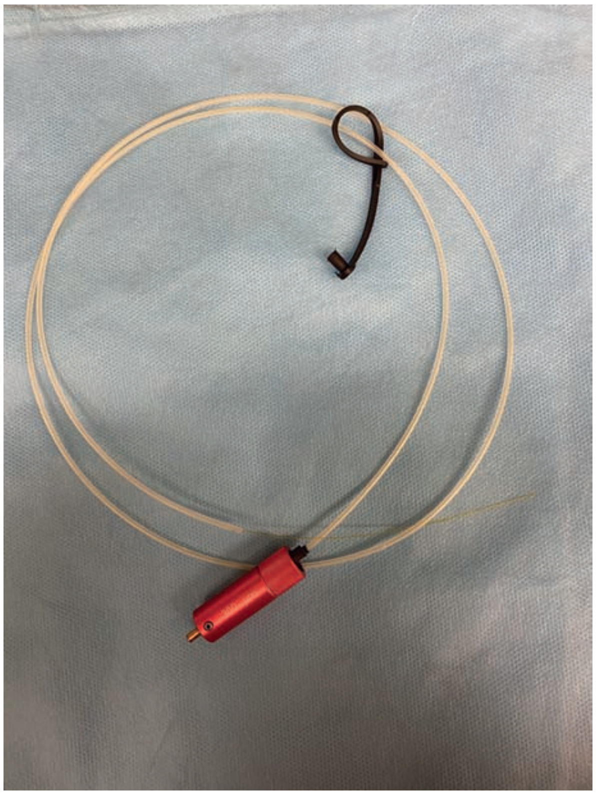


Figure 1.10 Flexible optical fibers for medical and dental applications. *Source:* Dr. Georgios E Romanos.

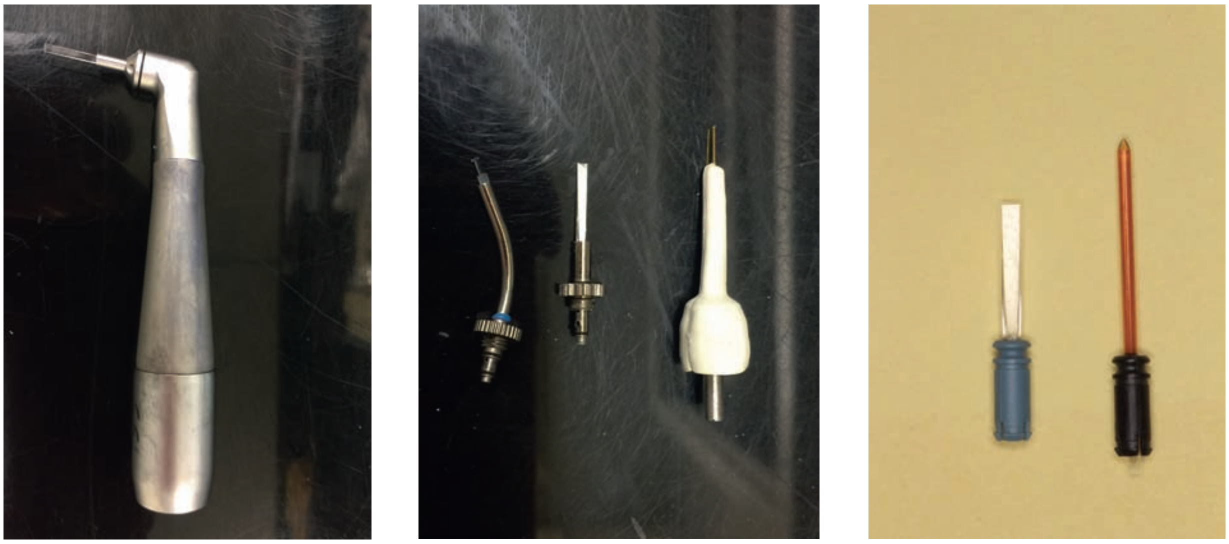
1.7 Applicators

Applicators are technical devices of the laser unit, which allow direct transmission of the laser beam in the tissue. They have the shape of a handpiece or a tube (fiber applicator).

1.7.1 Handpieces

Handpieces are primarily used for mirror swivel arms and make possible the transmission and focusing of the beam on a tissue area without contact (noncontact). They can shrink the irradiated area considerably, depending on the manufacturer and by means of special tips made of ceramic or metal (Figures 1.11–1.14). Bent

Figure 1.11 Irradiation of soft tissues in the lamb vestibule using a ceramic tip and CO_2 laser (left) and a glass flexible fiber of a diode laser (right). Observe the superficial carbonization of the CO_2 laser excision compared to the diode ablation. Different diameter applicators were used (ceramic cylindrical tip for the CO_2 and narrow glass fiber for the diode laser). *Source:* Dr. Georgios E Romanos.



Figures 1.12–1.14 Special tips for direct connection with the hand piece (left) for Er:YAG laser made by sapphire or glass fiber for Er:YAG or diode lasers (middle) and for Er,Cr:YSGG laser (right). *Source:* Dr. Georgios E Romanos.

metal spikes can be also used for less accessible regions of the oral cavity. Likewise, there are handpieces with beam deflection.

1.7.2 Fiber Applicators

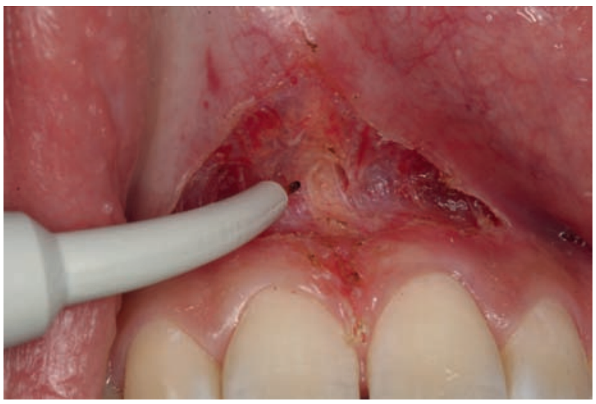
Fiber applicators are straight or curved tubes that allow contact of the flexible fibers with the tissues. The fiber can be fixed in the applicator by a simple screw. During a contact application, the fiber tip is worn out over time, which reduces the beam profile and decreases the available power density (Figures 1.15 and 1.16). Thus, an optimal ablation is prevented.

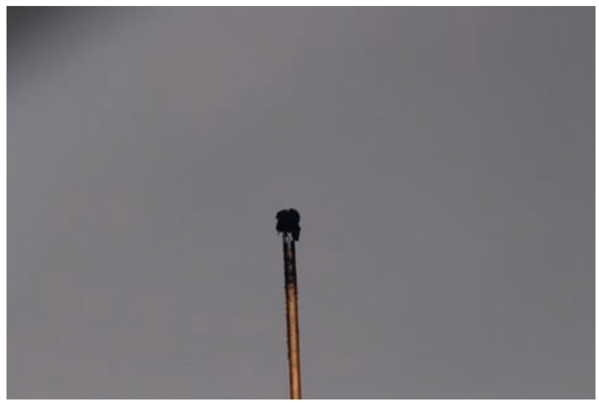
A fiber cable consists of the main core (8 μm), the cladding (125 μm) covered by the coating (approx. 250 μm), and the jacket (400 μm), which protects the entire fiber optic.

Laser manufacturers have special tools (Figure 1.17) for cutting the glass fibers after removal of the plastic coating (clearing).

With new laser developments, the industry grows, and laser devices become smaller and more powerful every day. An example is the growth of the Er,Cr:YSGG lasers (Biolase Inc.) over the last 20 years demonstrating a significant reduction of the size of the devices.

The spot size is very important since smaller spot sizes are associated with higher fluence. Thermal transfer in small spot sizes can be more effective without damage to the surrounding tissues. In contrast to this, a larger spot size requires higher energy levels or longer irradiation periods, which may have side effects to the surrounding tissues (i.e. carbonization or overheating). In this case, when clinicians try to avoid overheating





Figures 1.15 and 1.16 Diode laser irradiation during frenectomy and partial vestibuloplasty using a contact of the fiber tip with the tissues (left). This may allow damage of the tip, decrease of the power density, and, due to overheating, potential scar tissue formation. For this specific indication, initiated tips are strongly recommended (right). *Source:* Dr. Georgios E Romanos.

Figure 1.17 Special tools to remove plastic coating around glass fiber without damaging the fiberoptic. *Source:* Dr. Georgios E Romanos.

tissues, the therapeutic energy level cannot be achieved and, therefore, the final outcome is insufficient.

1.8 Laser Types Based on the Active Medium

The currently known laser systems are, according to their active medium, divided into the following types (Table 1.2):

- Gas lasers (He:Ne, CO_2, excimer [ArF or KrF] or argon laser)
- Solid state lasers (Nd:YAG, Ho:YAG, Er:YAG, Er,Cr:YSGG, rubin, alexandrite laser)
- Liquid (dye) lasers (containing liquid colorant as the medium, e.g. Rhodamine G6, Coumarin, etc.)
- Semiconductor (diode) lasers, so-called GaAs, GaAlAs lasers (containing semiconductor as the medium)
- “Free-electron” lasers (using an electron accelerator, not available for dentistry)

Physically seen, the change of energy levels of electrons in an atom produces the laser radiation. With the gas and solid-state lasers, the atoms are stimulated by electron collisions. On the contrary, in the excimer, or in the dye lasers, a transition of electrons to molecules takes place.

All lasers used in medicine, including their wavelengths, are in the Table 1.2.

Below are described those types of lasers, which are primarily used in surgical dentistry.

1.8.1 Gas Lasers

Such lasers use gas as the active medium. These lasers are relatively inexpensive and can achieve high power in continuous wave mode. Known systems are the CO_2, the argon, the He:Ne, and the excimer laser. In these types of lasers, the active medium is stimulated by an optical pumping mechanism or by electrical discharge. Flowing gas is required, and usually there is no need for gas refill for a long lifetime. Such lasers are the main

Table 1.2 Laser systems with applications in medicine.

Wavelength (nm)	Laser	Active Medium	Mode	Application
193	Argon fluoride Excimer	ArF	Pulsed	Ophthalmology
308	Xenon chloride Excimer	XeCl	Pulsed	Vascular surgery
488	Argon ion	Ar	CW	Various surgeries
511	Copper vapor	Cu ions	Pulsed	Dermatology
514	Argon	Ar	CW	Various surgeries
532	KTP (frequency doubled Nd:YAG)	Nd:YAG KTP crystal	Pulsed	Various surgeries
627.3	Gold vapor	Au ions	Pulsed	PDT
632.8	Helium-neon	Neon gas	CW	Biostimulation
647	Krypton	Ionized Kr gas	CW	Retinal coagulation
694.3	Ruby	Cr^{3+}:Al_2O_3	Pulsed	Dermatology
500–800	Dye	Dyes	CW/pulsed	PDT, Dermatology
670–1550	Diode	Ga-As	CW/pulsed	various surgeries
798	Alexandrite	Crystal	Pulsed	Research
1064	Neodymium:YAG	Crystal	Pulsed	Various surgeries
1070	Ytterbium:YAG	Crystal	Pulsed	Dermatology
2010	Thulium	Tm:YAG crystal	Pulsed	Urology
2140	Holmium	ThHoCr:YAG crystal	Pulsed	Cartilage surgery
2940	Er:YAG	Er:YAG crystal	Pulsed	Ophthalmology
10 600 (or 9300)	CO_2	CO_2	CW/pulsed	Various surgeries

lasers for general surgery especially the carbon dioxide laser. However, the bulky size of these devices and the fragile construction make these lasers not the first choice of application in private practices.

1.8.1.1 CO_2 Laser (10 600 nm)

This type of laser was developed in the US between the early 1960s and the early 1980s. The active medium consists of carbon dioxide (CO_2), nitrogen, and helium. The mixing ratio of the laser medium is 4.5% CO_2, 13.5% N_2, and 82% He and represents a nontoxic gas mixture. Nitrogen molecules are pumped by an external energy source, which by its energy activates the molecules of the active medium (CO_2). For this reason, this type of laser is also called a molecular laser.

Depending on the type of discharge, they are currently operated as continuous (CW) or pulsed systems. During the production of the laser light, an excessive overheating of the optical resonator is prevented by the cooling effect of helium. Optical materials for the CO_2 laser are, among others used, germanium, zinc selenide, and gallium arsenide. Even the slightest dirt on the lenses can cause destruction.

In terms of CO_2 laser construction characteristics, there are different types of CO_2 lasers including glass tubes dating back to the 1960s; this technology features a relatively short lifetime and high maintenance costs; it requires up to 20 000 volts and flowing liquid coolant, both of which are expensive in service. Innovative technology with all-metal tubes was developed in 1990s; it features rugged an all-metal air-cooled resonator design, long lifetime (up to 45 000 hours), low cost, low voltage RF transistor-operated power supplies, and excellent laser pulsing capabilities (Figure 1.18).

With a wavelength of 10 600 nm (invisible infrared range), the beam can be well absorbed by the enamel, so that at first it was considered to use this type of laser in the cavity preparation, the conditioning of dental enamel, and treatment of caries (Lobene and Fine 1966; Lobene et al. 1968; Stern et al. 1972). Significant increases in temperature on the tooth surface strongly limited the use of conventional CO_2 lasers (CW or pulsed) at the processing of hard tissues (Stewart et al. 1985). On the contrary, Melcer et al. (1984) demonstrated in a clinical trial with 1000 patients positive observations in the removal of caries. In an animal study Melcer et al. (1987) histologically confirmed the formation of secondary dentin and the sterilization of dentin and pulp during the application of CO_2 laser.

The absorption of the laser beam increases by water. Since its penetration depth is low (ca. 0.1–0.3 mm) and the surrounding tissue is hardly heated, modern CO_2 lasers can be primarily used in the superficial manipulating of soft tissues (Figure 1.19). The coagulating effect on small blood vessels allows a blood-free and clear surgical field.

1.8.1.2 CO_2 Laser (9300 nm)

This is a relatively new development of the CO_2 (9300 nm) laser with applications in hard and soft tissues in dentistry. Due to the relatively high absorption by hydroxyapatite, this wavelength can be used for removal of enamel and dentin.

The first laser with FDA clearance for soft and hard tissue applications in dentistry is the SOLEA (Convergent Dental). Compared to the conventional CO_2 lasers and the Er:YAG lasers, which vaporize water and enamel, this new laser uses an oxygen-18 isotope

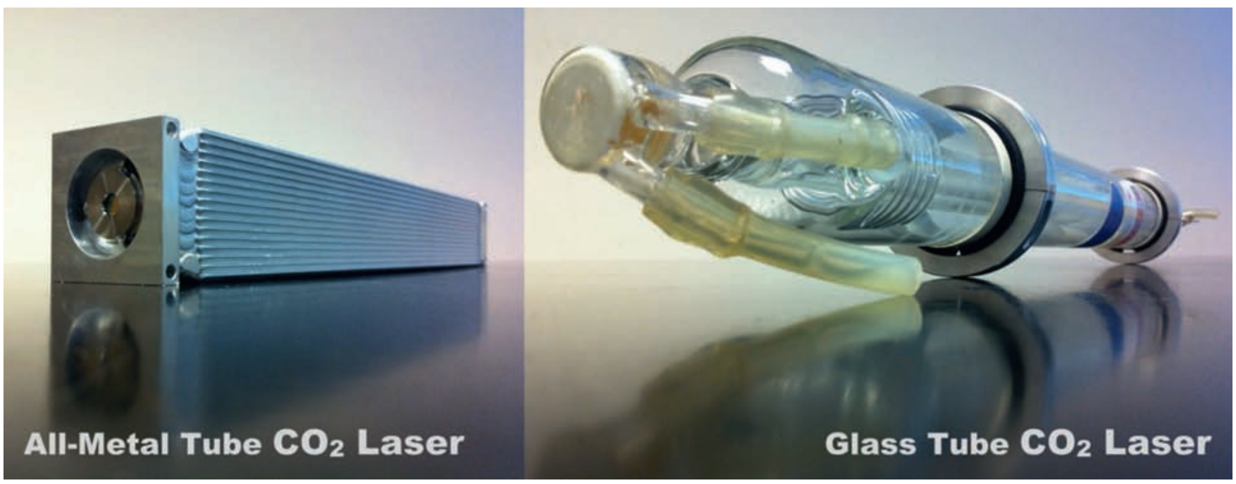


Figure 1.18 Innovative all metal-tube compared to the classic old glass tube of CO_2 laser systems (courtesy: LightScalpel, Inc.).

Luxar (MegaPulse, Lightscalpel)

Figure 1.19 Development of CO_2 lasers over time by LightScalpel, Inc. demonstrates the modern and robust design for surgical applications using hollow guide technology. Luxar (MegaPulse, Lightscalpel)

and other modifications to emit 9.3 μm, matching the peak absorption of hydroxyapatite. Therefore, it can be used for removal of decay and also soft tissue excisions with controlled bleeding. Since this wavelength is relatively new in dentistry, more case series and clinical applications are needed to demonstrate the long-term effects of this wavelength on the tissues.

1.8.1.3 Argon-Laser

The argon laser is an ion laser and is currently not popular in dentistry. Its wavelength is in the visible range of light (488 nm blue or 514.5 nm green light) and its capacity is up to 30 W. Almost all its power is converted into heat, which is why adequate water cooling is necessary.

Initially in the 1960s the argon laser was introduced in gynecology, dermatology, ENT, and ophthalmology. In dentistry, it is useful for caries diagnosis; it reduces the polymerizing time in the therapy with hybrid or micro-filled composite fillings (Kelsey et al. 1989; Powell et al. 1989; Severin and Maquin 1989; Blankenau et al. 1991a, 1991b; Powell et al. 1995) and can also be used in surgery for the removal of vascular lesions (White et al. 1993) (Figure 1.20).

The high absorption of the argon laser light from hemoglobin, hemosiderin, and melanin allows both intra- and extraoral, a complication-free hemostasis of strongly vascular tissues, and the removal of pigmented lesions (Dixon et al. 1986; Hohenleutner and Landthaler 1990; Kutsch and Blankenau 1995; Poetke et al. 1996). Vessels up to a diameter of 1 mm can be coagulated. The optical penetration depth of the argon laser is limited to about 1 mm. The superficial water cooling allows a doubling of the thermal impact depth by about 2 mm. Thermal damage to the skin can be minimized by the use of saline solution and pressing with a glass spatula (Poetke et al. 1996).

Figure 1.20 Argon laser device (Premier, Irvine, CA).

1.8.1.4 He:Ne Laser

This laser is a neutral atom laser. It contains neon as the active medium and helium as pumping gas at a ratio of 1 : 10. The light is emitted at a wavelength of 633 nm. He:Ne lasers operate in continuous wave mode. The output power is at 0.5 to 50 mW relatively low. Reliability, manageability, and a relatively low price compensate for the low working efficiency of this laser. The He:Ne laser is currently used as a target (the so-called pilot laser), as well as a laser light pointer in holography. In medicine, it belongs to the group of soft lasers that are used to support wound healing and pain reduction. Further possible applications are found in the counting of cells and measuring of the eye in ophthalmology.

1.8.2 Crystal Lasers

Crystal lasers (usually named as "solid-state" lasers) are lasers with a crystal as an active medium. Usually, the YAG (yttrium-aluminum-garnet) crystal is used in these lasers. Approximately 1% of the yttrium atoms is replaced ("doped") with neodymium, to have the Nd:YAG (Neodymium: yttrium, aluminum, garnet) laser, which is the most known laser type of this group. The invisible 1064 nm wavelength penetrates deeply into biological tissues, compared to the 532 nm (half of 1064 nm) which penetrates far less and is visible. Such crystals are KTP (potassium triphosphate), producing the frequency-doubled Nd:YAG (KTP) lasers (green output) with many applications in the treatment of vascularized tissues due to the high absorption by hemoglobin.

Similarly, there are Er:YAG (erbium: yttrium, aluminum, garnet), Er,Cr:YSGG (erbium, chromium: yttrium, scandium, gallium, garnet) and the alexandrite lasers. Less popular crystal dental lasers and some no longer commercially available are the Ho:YAG (holmium: yttrium, aluminum, garnet; 2120 nm), the ruby (694.3 nm), the Nd:CGSGG (neodymium: chromium, gadolinium, scandium, gallium, garnet; 1061 nm) and the Nd:YAP (neodymium: yttrium, aluminum, perovskite; 1340 nm) laser.

These lasers or any glass lasers cannot operate in a CW mode in order to avoid risks of overheating and damage of the laser crystal.

1.8.2.1 Nd:YAG Laser

The Nd:YAG laser was used in dentistry for the first time in 1977 in animal studies in order to test its effect on the pulp (Adrian 1977). Nowadays, it is the most important known solid-state laser with a wavelength of 1064 nm. In the normal pulse mode, it provides energies up to 50 J, and has as a continuous beam (CW laser) and an output power up to 150 W. It is also used as an industrial laser for material processing (Abdurrochman et al. 2014). However, in dentistry the Nd:YAG laser can be used only in pulsed mode due to the high risk of tissue overheating and deep tissue penetration. The laser beam is absorbed from only a small amount of water and works in contact with the tissue. The heat effect occurs deep in the tissue of the irradiated area and has a strong coagulation effect. This leads to the shrinkage of the tissue, and vessels up to a diameter of 2– 3 mm can be closed. This hemostatic effect of the Nd:YAG laser is used in many ways in clinical surgery. Its biological effects are coagulation, carbonization, and vaporization (Frank 1989).

The application of Nd:YAG laser in medicine was tested by extensive clinical studies and is scientifically validated. One can currently use it in hepatectomy and in the removal of hemorrhoids and highly vascularized tissues, as hemangiomas, without major complications in contact with the tissue used in a fiber optic system (Kiefhaber et al. 1977; Iwasaki et al. 1985; Joffe 1986; Joffe et al. 1986; Poetke et al. 1996).

The first studies in dentistry were carried out by Myers and Myers (1985), and their purpose was the removal of dental caries, concluding that superficial carious enamel lesions can be removed with the Nd:YAG laser. The fine fiber of the Nd:YAG laser system can be used both in the excision of soft tissue, as well as for coagulation (Figures 1.21 and 1.22). In endodontics the positive effect of the laser was shown by means of bacterial reduction in the root canal (Dederich et al. 1984, 1985; Melcer et al. 1987; Hardee et al. 1994; Gutknecht et al. 1996). In various clinical articles it was shown that the application of the Nd:YAG laser is also possible in the surgical excision of the labial frenulum (frenectomy) in periodontology and in the excision of benign tumors in the oral cavity (Romanos 1994; Goldstein et al. 1995).

1.8.2.2 Er:YAG Laser

The Er:YAG laser with a wavelength of 2940 nm plays an important role in medicine and dentistry. Its active medium is as for the Nd:YAG laser, a crystal, although the Er:YAG laser with 30–40 wt% is relatively high doped, and yttrium atoms are replaced by erbium atoms. In total the Er:YAG system, including the pumping mechanism (using a pulsed linear xenon flash lamp), is similar to the Nd:YAG laser system (Figures 1.23 and 1.24).

The penetration depth of the radiation in the tissue is only approx. 1 μm (10^{-3} mm), so that a selective photoablation occurs, and the tissue is removed layer by layer.

Figure 1.21 Classic Nd:YAG laser (Pulsemaster 1000; American Dental Technologies, Southfield, MI, USA). *Source:* Dr. Georgios E. Romanos.

Figure 1.22 Nd:YAG laser device (American Dental Technologies, Southfield, MI, USA). *Source:* Dr. Georgios E. Romanos

Er:YAG (Syneron, Israel)

Er:YAG (KaVo Key III, Germany)

Figures 1.23 and 1.24 Representative Er:YAG laser devices for dental clinical applications. *Source:* Dr. Georgios E. Romanos.

This wavelength is used primarily in the field of microsurgery and hard tissue surgery. Soft tissue incisions and removal can be achieved due to the low penetration depth. Due to the high absorption rate of the laser beam in water, this wavelength can be used for the ablation of enamel, dentin, or bone. Discoloration and carbonized zones appear in the tissue only at the margins of the irradiated area. This can be prevented through an integrated water-cooling (Keller and Hibst 1995).

Although different experimental animal and clinical studies have been conducted (Keller and Hibst 1990; Keller et al. 1990, 1991), the scientific substantiation through a broad clinical application of this system is lacking, in contrast to other dental lasers.

In osteotomies with the Er:YAG laser, Keller et al. (1991) observed a minimal zone of necrosis, which compared to the osteotomies made with the CO_2 laser, and led to no wound healing delay. In contrast to these studies, Nelson et al. (1989) found a delay of wound healing (similar to the CO_2 laser) after the application of the Er:YAG laser, when no water cooling was utilized.

Regarding the treatment of the soft tissue, the wavelength of this laser is recommended for the ablation of oral mucosa (e.g. surgical removal of leukoplakia or lichen planus) (Keller et al. 1990). A clinical application in areas where there is no major bleeding tendency (Keller et al. 1990) (e.g. in the removal of benign soft tissue tumors, gingivoplasty, and extraorally on the skin) is possible without the need of additional suturing (Kautzky et al. 1992). The Er:YAG laser can be also applied, as shown in in vitro studies in periodontology, for the removal of calculus from the root surface (Aoki et al. 1994).

Experimental tests with this wavelength were also performed successfully in temporomandibular-joint (TMJ) arthroscopy, as conventional arthroscopy is highly time consuming and complex and is associated with significant trauma (Mordon et al. 1995).

1.8.2.3 Er,Cr:YSGG Laser

Great efforts have been made with the development of the Er,Cr:YSGG laser (2780 nm) for bone cutting. This wavelength has been used in oral surgery for osteotomies, osteoplasties, and removal of supernumerary teeth utilizing water and air spray in different ratios. Further applications in implant dentistry, like the preparation of the lateral maxillary sinus window, the implant uncovering, and implant site preparation have also been reported (see also Chapter 6). In addition, in pediatric dentistry and orthodontics, for removal of the frenum, gingivectomies, and operculectomies, is an opportunity for soft tissue excisions with low complication rates. The Er,Cr:YSGG laser has a lower water absorption coefficient compared to the Er:YAG laser and therefore a better penetration depth in the soft tissues. Therefore, the cutting efficiency is better. Furthermore, this wavelength can be used in operative dentistry for enamel conditioning before etching and cavity preparation. Due to the increased interest for use, the company Biolase, Inc. has developed numerous devices for different clinical applications (Figures 1.25–1.27).

1.8.2.4 Ho:YAG Laser

The Ho:YAG laser has a wavelength of 2.1 μm or 2.01 μm and in the water a penetration depth of 0.3 mm. It is used for hard and soft tissue excisions. Currently there is only the Ho:YAG laser for dental applications in some countries. This unit contains two laser sources, making

Waterlase MD
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Waterlase iPlus
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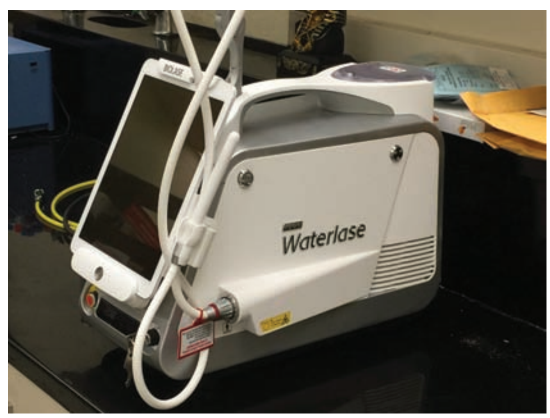

Waterlase Xpress
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Figures 1.25–1.27 Different Er,Cr:YSGG laser devices developed in the last 20 years by Biolase, Inc. The size of the device has been decreased, providing innovative opportunities for clinical settings. *Source:* Biolase, Inc.

the application of two different wavelengths possible. A Ho:YAG (2090 nm) and a Nd:YAG (1064 nm) laser can be adjusted for use, depending on the therapeutic requirements, at the touch of a button. The Ho:YAG laser (formerly DuoPulse®) system can achieve up to 4 W output power, and it also allows easier handling through a flexible silica fiber. This type of laser is in used in the fields of vascular surgery (Mehmet et al. 1989; Hardee et al. 1994), ophthalmology (Iwasaki and Inomata 1986), urology (Johnson et al. 1992), ENT (Shapshay et al. 1990; April et al. 1991; Oswald and Bingham 1992), gastroenterology (Nishioka et al. 1989; Bass et al. 1991; Rubio 1991), gynecology (Rosenberg et al. 1990), and orthopedics, especially for arthroscopy (Trauner et al. 1990; Shi et al. 1993).

In the arthroscopic surgery of the TMJ, the use of this laser type was tested and clinically studied by Hendler et al. (1992) and Koslin and Martin (1993). It has been proven that the Ho:YAG laser is currently a low-invasive treatment alternative in arthroscopic surgical procedures. Examinations of the irradiated tissue and the adjacent areas showed only a slight thermal effect.

In dentistry, the Ho:YAG laser is used for the conditioning of dentine, the removal of the dentin surface (White et al. 1993), the effective ablation of dentine from the root canal (Stevens et al. 1994), and for in vitro root apex resections (Komori et al. 1997). Under certain circumstances it can remove enamel, dentin, and calculus (Mani 1992).

Physically seen, the Ho:YAG laser beam is very well absorbed by water, although its absorption coefficient is about 19 times lower in comparison to the CO_2 laser. Due to the high amount of water in enamel and dentin, the removal of hard tissue is minimally possible. One can achieve with it an efficient management of soft tissue without complications, either highly pigmented or white (with or without contact with the tissue). In regard to the coagulation of vessels, the coagulation zone is in comparison to CO_2 laser bigger, but smaller than the one of Nd:YAG laser.

1.8.2.5 Alexandrite Laser

The design principle of the frequency-doubled alexandrite laser (comprised of a $Cr:BeAl_2O_4$ crystal) corresponds to the Nd:YAG laser. The alexandrite laser has a fundamental wavelength between 720 and 800 nm (typically 755 nm). The frequency-doubled Alexandrite laser corresponds to ca. 578 nm. Its application, which was previously only experimental, takes place in the salivary duct stone lithotripsy. Its advantages are the high stone fragmentation rate and the low trauma, as it is a minimally invasive procedure (Gundlach et al. 1995).

1.8.3 Liquid (Dye) Lasers

Liquid (dye) laser systems have a dye as the active medium. They need other lasers or intense light for optical pumping. The laser light has a wavelength ranging from UV, through the visible, to infrared spectral range. A medium is used, usually rhodamine 6G, which flows at high velocity through the pump beam. In this way heating during the operation is avoided. The concentration of the dye is 10^{-4} mol/I. Another laser (e.g. an excimer laser) or a flash lamp is used as the pumping mechanism. This allows a pulse mode, and the corresponding output power ranges from a few mW to 10^6 W. When an argon or krypton laser is used as a pump laser, a continuous laser beam (CW) with a capacity of up to 1 W is possible. The wavelength of the laser beam is then in the range of 570–620 nm.

In medicine, such laser systems are used in the field of ophthalmology (for surgeries of the retina, for instance, coagulation of the retina) and in dermatology (e.g. in pigmentation and tattoo removal).

1.8.4 Semiconductor (Diode) Lasers

Laser dentistry has specific, sometimes unique, other times rather standard requirements for laser parameters and design of laser systems. Common desired features of laser systems for such widespread procedures as hard and soft tissue microsurgery, bacteria reduction, tissue regeneration, and tooth whitening are small size and low cost of ownership. These demands stimulated the growth in popularity of semiconductor (diode) lasers due to their high efficiency, small package size, convenient ergonomics, high reliability, and reasonable costs. Such lasers fulfill the needs of the vast majority of dental practices very well.

A semiconductor (diode) is a crystal in which the individual atoms are arranged periodically and has an electrical conductivity, which stands between insulators and metals. Semiconductor lasers are relatively small, compact, and practice-friendly devices (Figure 1.28) and have as the active medium semiconductors (diodes). This diode can be a GaAlAs (gallium aluminum arsenide) or GaAs (gallium arsenide) diode. Such lasers are relatively small, but relatively high-energy densities can be achieved. Therefore, they can also be used for medical purposes. Diode lasers have been used widely outside the United States as therapeutic devices for pain control with controversial efficacy.

The GaAs diode lasers generate pulses with an average power of 10–20 mW and are used for biostimulation. The GaAlAs diodes can be modulated and pulsed as

Figure 1.28 Various diode lasers for oral applications (from left to right): Sirona blue light; KaVo 980 nm; Spectralaser (980 nm); Ivoclar 810 nm; Epic (940 nm, Biolase); and the Alta Diode (975 nm) laser with automatic power control (APC) (Biolase). *Source:* Dr. Georgios E. Romanos.

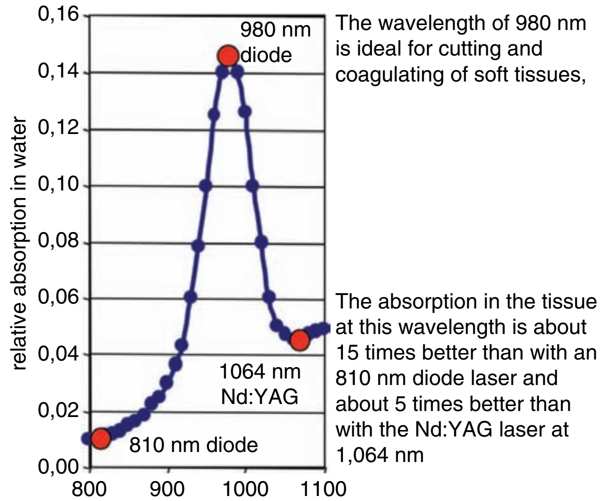


Figure 1.29 Water absorption spectrum in the wavelengths of 980, 810, and 1064 nm.

desired. In the continuous mode, the performance is lower than in the pulsed mode. The lifetime of the diode in continuous operation is approximately 500 hours.

Diode lasers can be used not only as biostimulation devices (soft lasers), but also as surgical (hard) lasers (Cetinkaya et al. 2015; Hermann et al. 2015; Arroyo-Ramos et al. 2019; Serra and Silveira 2019).

The laser light is generated in semiconductors at a suitable geometry of a semiconductor (parallel end surfaces as a resonator) under the application of electric energy. By applying an operating voltage, the electrons are injected into the different transition zone between two mirrors, and for this reason, such laser systems are referred to by some authors as "injection laser diodes." The wavelength of this laser light is typically in the range of 810–980 nm, but it can be, however, substantially lower (635 nm) when used as a low power (soft) laser. The working mode is both "continuous" and "pulsed." An external cooling of the laser system is not necessary because usually the performance is low.

In microsurgery (e.g. vascular surgery) they are used for an effective vascular anastomosis with minimal complication (Tang et al. 1994; Mordon et al. 1995), in ophthalmology for surgery of the retina, and very early in dentistry (Bach and Krekeler 1996). The diode laser is currently unsuitable for the manipulation of the hard tissue, due to the thermal load on the pulp and the periodontal tissues. Pilot studies showed potential benefits in the treatment of peri-implantitis (Bach et al. 2000).

New diode lasers have been developed recently in order to control the potential risk of thermal collateral tissue damage (overheating), allowing at the same time an efficient cutting of soft tissues. The tissue will be excised faster with sufficient hemostasis in a contact surgery mode compared to the other surgical lasers working in noncontact mode. The new advances in diode laser technology will definitely provide more opportunities in the future for the dental profession.

Currently available mainstream diode lasers are not free of limitations. Specifically, their peak power is usually low, whereas selection of available wavelengths is narrow and limited to spectral regions with low absorption of light by soft and hard tissues. Until very recently, these factors seriously limited competitiveness of the diode lasers vs. other more expensive technological approaches. The absorption of water in the 980 nm is 15 times better than with an 810 nm diode laser and approximately five times better than in the Nd:YAG (1064 nm) laser (Figure 1.29).

Recent developments in laser technology have resulted in the advent of several new laser platforms with the same unique combination of small size and low cost as traditional diode lasers, but with power characteristics and wavelength versatility making them capable of replacing conventional flash-lamp-pumped solid-state Nd:YAG, Ho:YAG, and Er:YAG lasers as well as the CO_2 lasers.

1.8.4.1 Blue Light (445 nm)

The development of a diode laser in the blue wavelength range (445 nm) promises good energy coupling to pigmented cells and tissue, combined with low absorption in water, improves cutting quality for surgical procedures, and provides deep decontamination for periodontal and endodontic lesions (Braun et al. 2015).

Shuji Nakamura was the first person to present the gallium nitride laser diode in the blue light range with a wavelength of 405 nm. He and his colleagues, Isamu Aksaki and Hiroshi Amano, were awarded the Nobel Prize for Physics in 2014. In such procedures, one of the most important advantages of blue laser light (Figure 1.30) is that, due to its shorter wavelength, it penetrates less deeply into the tissues with minimal scattering (Wilson 2014). Due to this low penetration depth, the risk of accidental injuries in deeper layers is drastically reduced, and the beam can be guided more precisely. At the same time, the thermal input to surrounding tissue from the scattering of the laser light is reduced. The absorption maximum for blood cells is in the range of approximately 430 nm (Beard 2011; Niemz 2019), which leads to a high energy input and can thus cause rapid hemostasis.

The wavelength of 445 nm displays a high level of direct coupling to tissue during incision or excision that is achieved by the favorable biophysical properties of this radiation. Comparison of the cutting effectiveness shows advantages with 445 nm in comparison to 980 nm (Frentzen et al. 2016). The consistent results from the histological investigations and the cell culture tests showed that with both lasers tested, damage in the sense of an unspecific thermal interaction occurs. The width of the coagulation zone is, at the same cutting speed, larger at 980 nm compared to the 445 nm. With 445 nm, the width of the coagulation zone increases with rising power, in particular at a low cutting speed. At a high cutting speed, the cutting depth is the same for 445 nm at 2 W and 980 nm at 3 W (output power). The width of the coagulation zone is smaller with all 445 nm parameters than with 980 nm. Evaluation of the blue light incision quality in our lab showed minimal carbonization and good depth of the surgical incision, providing promising results in surgical applications (Figures 1.31 and 1.32).

Figure 1.30 Blue-light laser (SIROLaser Blue, Dentsply Sirona, Charlotte, NC), the main market representative for blue laser diode laser in dentistry. *Source:* Dr. Georgios E. Romanos

The blue diode laser seems to be a promising technology for clinical application due to high absorption of blue light without major side effects in adjacent tissues even by reduced power settings. No increase of devitalized cells was documented with higher distances between laser tip and cell layer. Temperature development during laser irradiation was measured with a thermographic infrared camera and showed no negative thermal interactions (Reichelt et al. 2017).

1.8.5 New Developments in Laser Technology

1.8.5.1 Fiber Laser

A fiber laser is a laser in which the active gain medium is an optical fiber doped with active centers rare-earth elements such as ytterbium (Yt), neodymium (Nd), erbium (Er), thulium (Tm), and others. Unlike most other types of lasers, the laser cavity in fiber lasers (Figure 1.33) is constructed monolithically by fusion splicing rear and output reflectors (Bragg gratings), which replace conventional dielectric mirrors to provide optical feedback. Fiber lasers are pumped by pigtailed CW or QCW diodes with pumping wavelength λ_P typically in the range 960–975 nm or by other fiber lasers. Pumping light from the diode laser is propagated through a silica end cap of the fiber laser and is coupled into transparent cladding of the fiber laser with a typical diameter 100–300 μm. The core of the fiber laser has diameter of just 10–20 μm and is doped by active centers which absorb diode laser radiation. Diode laser radiation is propagated through the full fiber laser length (10–30 m) and is gradually absorbed in the core to create inversion and gain of active centers. Lasing-effect at the new laser wavelength λ_L is achieved by multipass circulation of the laser photons between rear and output

Figure 1.31 Incisions using blue laser light (445 nm) and average power of 2 W (continuous wave) in chicken breast showing minimal carbonization zone. *Source:* Dr. Georgios E. Romanos.

Figure 1.32 Comparative incisions using blue laser light (left), pulsed CO_2 laser with microsecond pulses (middle, char-free), and CO_2 laser (continuous wave and average power of 2 W (continuous wave) in chicken breast showing minimal carbonization zone but sufficient incision depth. *Source:* Dr. Georgios E. Romanos.

reflectors into core of the fiber laser. The fiber laser has several unique characteristics. Firstly, the fiber laser is the brightest (in terms of output radiance) laser due to the very small diameter of the output beam. It means than fiber laser beam can be focused at the smallest spot size and coupled into smallest-diameter silica fiber for delivery to the treatment zone. Secondly, fiber laser has a very high conversion efficiency and converts almost every pumping photon into laser photons. Thirdly, the fiber laser is the most stable and reliable laser design because it does not need mirror alignment; is not sensitive to variations in environmental conditions; and does not have mechanics for alignment, water flow, lamp, gas, electrodes, and other components that usually cause instability or failure regimes typical for solid-state or gas lasers. Fourthly, the fiber laser, much like the diode laser, can be manufactured in a mass production environment with very high yield, stringent quality control, and low cost typical for the electronics industry. In short, fiber lasers offer a compact, electrically efficient, low-cost alternative to solid-state and gas laser technologies.

Fiber lasers can generate a variety of wavelengths, which can be used for standard and new medical applications. For medical applications, one of the most important considerations is that the fiber laser produces wavelengths which can be delivered through silica fibers transparent in wavelength range 300–2600 nm with high throughput. The Figure 1.34 shows the spectrum of absorption of water, which is a major tissue chromophore in NIR and MIR spectral ranges. Also shown are bands of emission of Yt (1020–1180 nm), Er (1530–1565 nm), and Tm (1900–2040 nm) fiber lasers. The ytterbium fiber laser (1070 nm) has been used in dentistry for debonding of ceramic orthodontic brackets without thermal increase and enamel damage (Sarp and Gülsoy 2011) or to treat zirconia surfaces before cementation (Unal et al. 2015). As one can see from this figure, these three lasers invoke three different mechanisms of light-tissue interaction with low (Yt), medium (Er), and high (Tm) tissue absorption. Tm line has the highest coefficient of tissue absorption in the band of transparency of silica fiber. This coefficient is about 160 cm^{-1} at 1908 nm, which is almost five times higher than that for the Ho:YAG laser at 2140 nm. Fiber lasers can be used for laser pumping of external laser crystals to extend the output spectrum into the longer-wavelength IR range for even higher absorption in soft and hard tissues. Such hybrid systems can be packaged into a medical handpiece with pumping power delivered from a fiber laser through silica fiber. It has been demonstrated that such hybrid systems are feasible with standard laser crystals doped by Er, Ho, and other rare earth ions. IPG Photonics Corp. (Oxford, MA) has developed a new Cr^{+2}: Zn Ce laser crystal, which can be pumped by an Er or Tm fiber laser. These systems can generate wavelengths in the range 1800–3000 nm, which includes strong absorption bands of water (2700–2940 nm). This laser can be used for hard tissue cutting to achieve efficiency similar to classic Er:YAG or Er,Cr:YSSG and for soft tissue cutting with efficiency similar to that of the CO_2 laser.

Ytterbium high-power fiber lasers (YDF) in a power range from 1 to 10 kW, can be used in industry in continuous or pulsed mode in advanced materials-processing applications requiring extremely high power and brightness, such as fine cutting and surface structuring, cutting high-reflectivity metals, microwelding, sintering, and engraving, as well as remote processing and directed-energy applications (Figure 1.35).

1.8.5.2 Thulium (Tm:YAP) Laser

Relatively new laser systems have been developed recently and used in soft tissue dissections in ENT. The thermal damage is greater than that from the CO_2 laser, but the thulium laser (1940 nm wavelength) has the

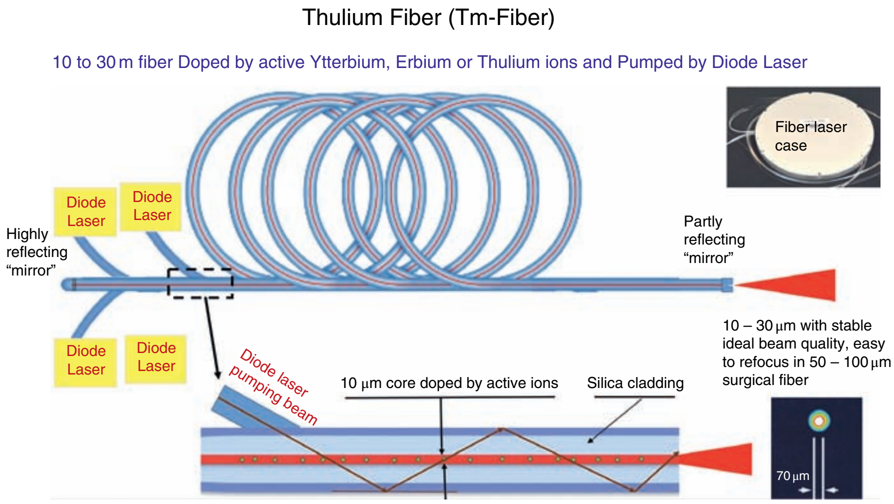


Figure 1.33 Basic concept of a fiber laser. *Source:* IPG Photonics (Oxford, MA).

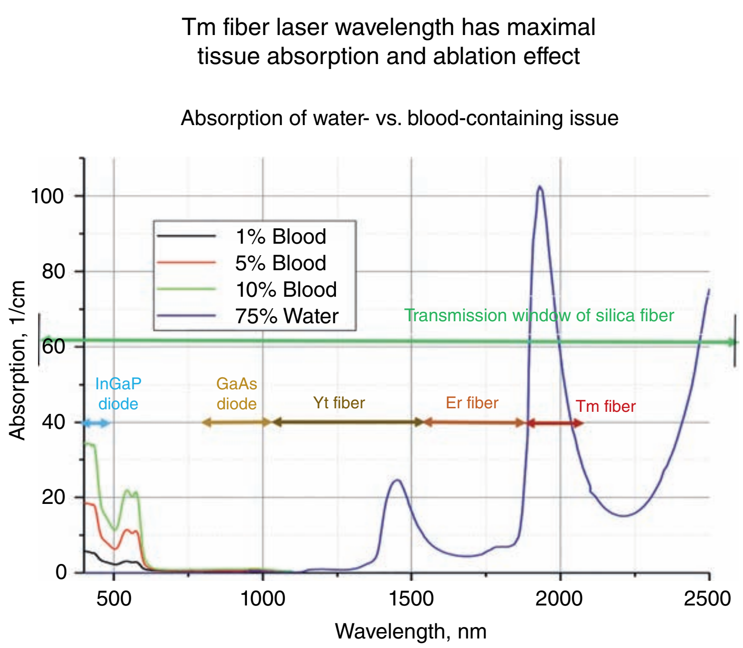


Figure 1.34 Absorption spectrum of water and blood. *Source:* IPG Photonics (Oxford, MA).

primary advantage of a silica fiber optic delivering thulium laser energy. The fiber-based delivery system offers the advantages of tangential cutting and office-based applications, because the laser energy is not delivered in a "line-of-sight" mode (Burns et al. 2007). Therefore, air-cooling has been used to reduce the extent of thermal trauma associated with thulium laser surgery of the vocal folds, and the high-temperature plume generated during laser cutting is effectively cleared.

In addition, the thulium laser has been used extensively in urology, especially in prostate surgery, providing benefits in comparison to the conventional methods. This new wavelength has been determined as a safe and effective method for the treatment of symptomatic benign prostate hyperplasia (Sun et al. 2015). Recent studies demonstrate much better outcomes in lithotripsy compared to the Ho:YAG laser applications (Traxer and Keller 2019).

In dentistry, two studies present applications of the thulium fiber laser in oral surgical procedures (Guney et al. 2014) and also for the debonding of ceramic brackets (Dostalova et al. 2011). The Tm:YAP fiber laser seems to be a promising tool for intraoral surgery, due to the excellent absorption by tissue, good coagulative qualities, easy to manipulate fiber output, and its use as an incisional tool with very little to no carbonization. Also promising solutions in hermetic connections between metals with polymers seem to be new innovative industrial applications.

1.8.5.3 Superpulse Diode Laser

The superpulse (SP) diode or quasi continuous wave (QCW) diode laser can generate very high peak powers comparable to that of an Nd:YAG laser (on order of 100–400 W in the range of pulse widths 5 μs to 10 ms and duty cycle about 10%). It is a fundamental departure from a standard diode laser which normally operates either in a continuous wave (CW) mode with power up to 10 W or in a pulsed (modulated) mode with peak power not much different from that in CW mode (i.e. 10–15 W). The SP laser is characterized by a unique design featuring a special quantum structure of semiconductor emitters, high number of emitters coupled into single fiber (up to 12 vs. one or two of a typical mainstream dental diode laser), special packaging for efficient cooling, and a high threshold of optical damage of all light train materials.

Figure 1.36 shows a picture of a standard CW diode laser rated at 10 W of optical power and a new superpulse QCW diode laser with peak optical power up to 200 W, both emitting at wavelength of 975 nm. They are both produced by IPG Photonics Corporation (Oxford, MA), the largest manufacturer of high-power diodes and fiber lasers in the world. The 10 W laser, PLD-10, has a single CW diode laser emitter inside the package, its output coupled into a 110 μm core diameter fiber. The superpulse diode laser, PLD-120QCW, has six QCW diode laser emitters inside.

The superpulse diode laser can be expected to be similar in terms of optical output to a standard dental Nd:YAG laser, which has average power of about 6 W

Figure 1.35 Ytterbium high-power laser developed by IPG Photonics Co. *Source:* IPG Photonics Co.

Figure 1.36 Superpulse diode laser (Alta-ST, Surgical Laser System, IPG Photonics Co.).

and peak power of about 400 W. These parameters (average and peak power) have been shown to be effective in terms of tissue heating and antibacterial effect. Table 1.2 compared optical output characteristics and heat generation efficiency on the major soft-tissue chromophores (water and blood) of CW diode, SP diode, and Nd:YAG laser with typical parameters for dental systems.

In Table 1.3, we used blood and water optical characteristics (Das et al. 1985; Edge and Carruth 1988; Feyh et al. 1989) and calculated temperature rise for 1 ms pulse width and spot size or fiber diameter 200 μm for the peak power of the respective laser. As one can see from Table 1.3, a CW laser in modulated pulse mode can produce negligible temperature rise in water and temperature rise in blood just on the threshold of blood coagulation. In contrast the SP diode laser can elevate temperature in water up to 45 °C, whereas the Nd:YAG laser achieves a water temperature rise of ~32 °C, which has been shown sufficient for bacteria deactivation. Both the superpulse diode and Nd:YAG laser with 1 ms pulse can be used for ablation of blood vessels as well.

Superpulse lasers can produce faster tissue cutting with lower collateral damage than standard CW or modulated diode lasers (Dahlman et al. 1983; Aronoff 1986; Anneroth et al. 1988; Castro et al. 1988; Basford 1990; Beer et al. 2012) because tissue ablation efficiency increases with peak power and a similar cutting effect can be achieved in pulse mode with lower average power, which in turn reduces collateral tissue heating and residual damage.

Superpulsed lasers with high-power pulses of short duration minimize the protein coagulation effects of the laser. The vaporization will be controlled without significant peripheral heating. In the surgical field, superpulsed mode permits the surgeon to advance the handpiece as slowly and as accurately as desired, while experiencing a fraction of the necrosis which occurs using conventional continuous-wave lasers. The superpulse feature may significantly change the way in which the carbon dioxide laser is used in cutaneous surgery. The superpulse diode laser has a stronger antibacterial effect than the CW diode laser because temperature elevation during biofilm illumination is higher.

However, superpulse mode was compared with ultrapulse mode of a fractional carbon dioxide laser on normal back skin of seven healthy Chinese women (split design). Clinical outcomes and side effects were evaluated. Biopsies were taken for histologic evaluation. There was no significant difference between the two sides with regard to pain, edema, crust formation, erythema, or pigmentation. The histopathological findings showed similar penetration depth for superpulse and ultrapulse mode (Xu et al. 2013).

In summary, advent of the superpulse diode lasers and fiber lasers opens up new opportunities for medical (and dental, in particular) applications. At the same time, these novel laser systems have a significant potential of competing with and eventually replacing existing solid-state and gas laser sources for many standard applications.

Table 1.3 Optical output characteristics and heat generation efficiency on the major soft-tissue chromophores (water and blood) of CW diode, SP diode, and Nd:YAG laser.

Laser type	CW Diode laser		Super Pulse Diode laser (PLD 120)	Nd:YAG laser
Wavelength, nm	800	975	975	1064
Maximum average power	10	10	60	6
Minimal pulse width, μs	5	5	5	100
Maximal pulse width, ms	100	100	100	1
Maximum average power	10	10	60	6
Maximal peak power for short pulse, W	15	15	220	1000
Maximal energy of 1 ms pulse, mJ	12	12	120	300
Water absorption coefficient, cm^{-1}	0.02	0.49	0.49	0.14
Maximal temperature increase, in water per 1 ms pulse	0.2	4.5	45	32
Arterial blood absorption coefficient, cm^{-1}	4.8	6.3	6.3	3.4
Maximal temperature increase, in blood per 1 ms pulse	44	58	575	776

1.8.6 Lasers for Research Applications

1.8.6.1 Free-Electron Laser

The free-electron laser (FEL) is a very large device, which extracts light energy from a beam of free very-high-speed electrons passing through a spatially periodic magnetic field. The electron beam must be maintained in a vacuum, which requires the use of numerous vacuum pumps along the beam path. While this equipment is bulky and expensive, FELs can achieve very high peak powers, and the tunability of FELs makes them highly desirable in many disciplines, including chemistry, structure determination of molecules in biology, and in medical diagnosis.

This laser type is not used in dentistry due to its size, high costs, and lack of practicality (more specialists are required for its application).

1.8.6.2 Nuclear-Pumped Gas Lasers

These are gas lasers in which the excitation energy is transferred from products of a nuclear reaction.

1.8.6.3 X-Ray Laser

An X-ray laser is a device that uses stimulated emission to generate or amplify electromagnetic radiation in the near X-ray or extreme UV region of the spectrum. Applications of coherent X-ray radiation include coherent diffraction imaging, research into dense plasmas (not transparent to visible radiation), X-ray microscopy, phase-resolved medical imaging, and material surface research.

1.9 Laser and Biological Tissue Interactions

The contact of the laser beam with tissue leads to different effects. These effects are distinguished in:

- photochemical
- photothermal
- ionizing or nonlinear (photoablation and photodisruption).

At the contact of light with a surface of body tissue, various optical phenomena occur (reflection, transmission, scattering, and absorption).

Depending on the surface of the irradiated object, a more or less pronounced *reflection* of the radiation takes place. This small part of radiation, which will be reflected remains without therapeutic effect. Smooth surfaces reflect the light very intensively; rough surfaces scatter it diffusely back (Figure 1.37).

The orientation of the reflection may be direct or diffuse depending on various factors, such as the surface structure, the tissue reflective index, and the angle of incidence. As an example, the reflection of the laser beam in the oral cavity on dental mirrors and metal restorations, such as amalgam fillings, crowns, and/or implant surfaces may lead to undesirable effects in not directly irradiated tissues.

The *absorption* of the ray is defined as an impairment of the radiation intensity during the transit through the substance. It is based on the transition of the radiation energy in another form of energy. The potency of the absorption is dependent on the absorption coefficient of the irradiated object. The wavelength of the laser light is an important factor in this correlation. For example, the absorption of hemoglobin under the wavelength of the argon laser light is high, and therefore this laser is clinically widely used for the coagulation of blood vessels and vascular lesions (Figure 1.37).

By definition, *scattering* of light means the deflection (dispersion) of a part of a bundled radiation from its original direction within the tissue in different directions. It takes place mainly within the irradiated body and can be deflected in every direction due to lack of homogeneity in the tissue or body structure (Figure 1.37).

The change of the path of the light (*refraction*) and the spreading of waves around an obstacle (*diffraction*) are additional phenomena in the interaction of light with matter or tissues.

At the irradiation of an object, apart from the reflection, *transmission* also occurs, which is the transfer of the light through the tissue (medium) without being absorbed or scattered. This is prominent for transparent objects, compared to opaque objects, because the high absorption of the beam is significantly reduced (Figure 1.37).

The interaction of laser light with biological tissues is always associated with the presence of chromophores within the tissues, which influence the absorption, transmission, scattering, and reflection from the tissues. We can talk about a phenomenon of "selective photothermolysis" between the wavelength and the chromophore. The absorption spectrum of water, (oxy) hemoglobin, and melanin (pigmented tissues) in relationship to the light wavelengths is presented in Figure 1.38. The absorption by (oxy)hemoglobin in the connective tissue is 1000 times weaker than the absorption by water at the CO_2 (10,600 nm) laser. A primary goal of laser therapy is to allow the maximum transmission to the target tissue (or chromophore) without conduction to the healthy surrounding tissues. For instance,

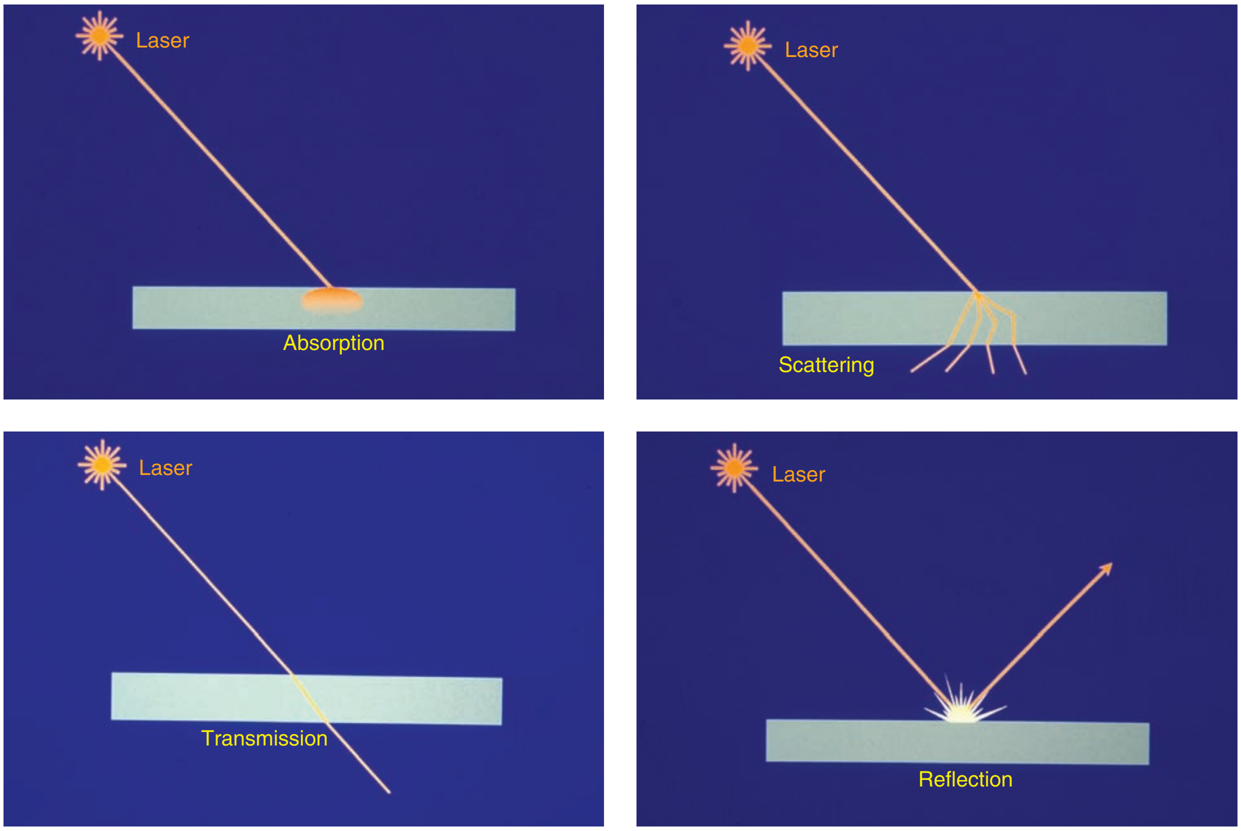


Figure 1.37 Physical properties of the light in contact with matter or biological tissues.

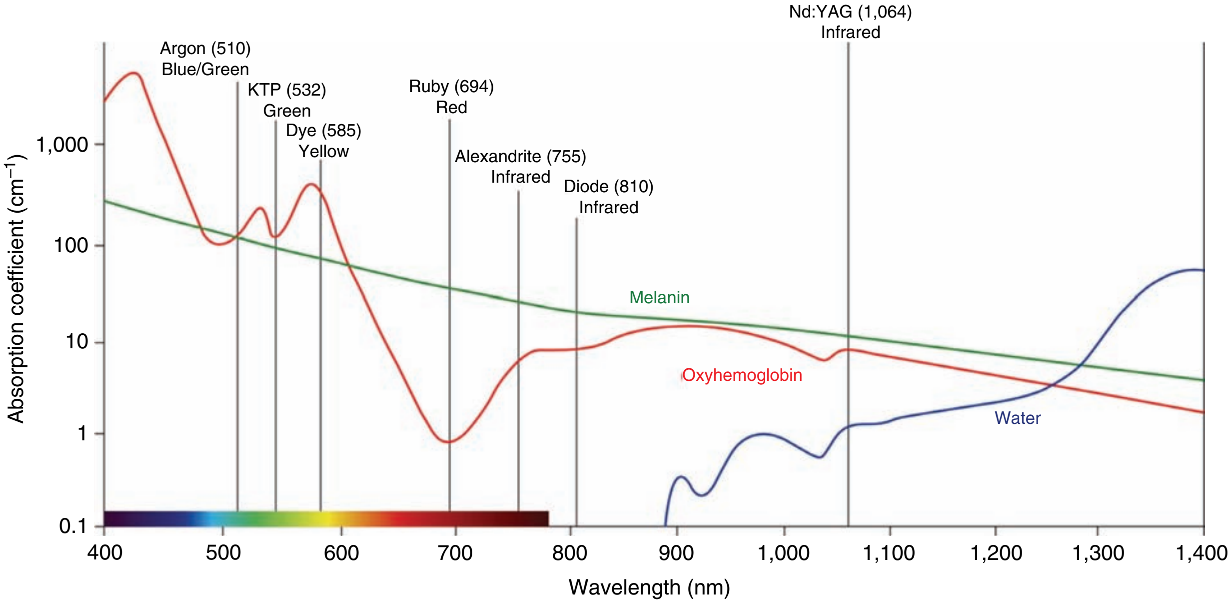


Figure 1.38 The absorption spectrum of water, (oxy)hemoglobin, and melanin depends on the different wavelengths, characterizing the specific laser-tissue interactions.

in clinical scenarios with vascular lesions, a selective irradiation of blood vessels to achieve effective coagulation without damage or structural alteration of the surrounding tissues is the primary goal of treatment. Similarly, hair removal is associated with the absorption of the laser by the melanin located in the hair follicle (and not the hair) as the main chromophore to have a therapeutic value.

The lasers and the interactions with the tissues have high importance especially in the interaction of the laser light with the eye. There are differences in the reflective and absorptive properties of the different laser wavelengths from the retina and the cornea. Since the cornea is highly concentrated in water, laser wavelengths in the mid-infrared and far infrared (1400 nm–1 mm) and middle UV (180–315 nm) and near UV (315–390 nm) wavelengths are highly absorbed. In contrast to these wavelengths, in the range of visible light and near infrared (400–1400 nm) light spectrum, there is absorption by the macula lutea of the retina (oval-shaped pigmented area near the center of the retina of the human eye and some other animal eyes) (Figure 1.39).

In order to avoid hazardous effects in the eye, special safety measures are followed. Use of goggles specific for

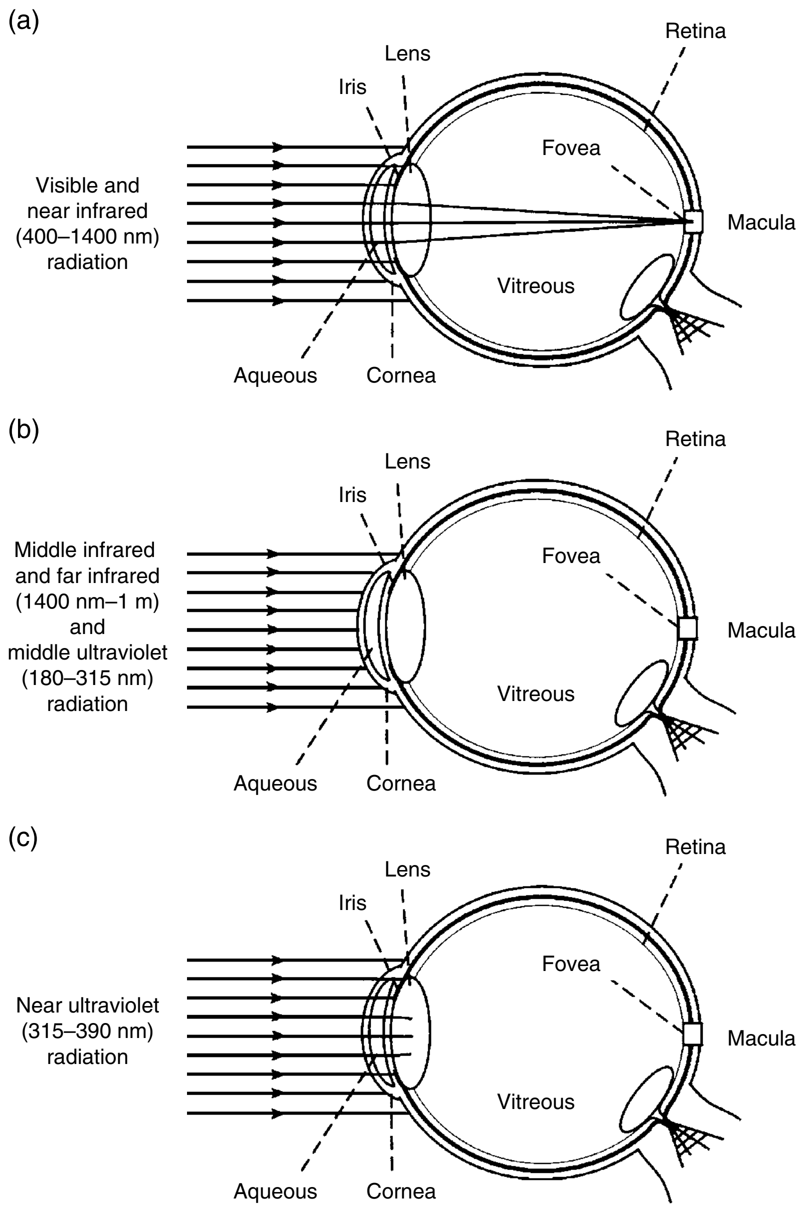


Figure 1.39 Absorption areas of the visible and near infrared (a), mid-infrared and far infrared (b), middle ultraviolet and near ultraviolet (c) wavelengths.

the individual wavelengths (see also Chapter 8), as well as curved mirror systems (reflectors) within the laser device, control direct reflections and irreversible eye damage (Figure 1.40).

1.9.1 Photochemical Effects

The laser beam can chemically change a tissue's molecules or warm a tissue, when higher power densities are applied. As a result, different effects may occur:

- formation of ions (photo-ionization)
- isomerization of the macromolecules (photo-isomerization)
- decomposition of the molecules (photo-dissociation).

These effects of the laser energy can be applied during biostimulation, photodynamic therapy, or also acupuncture.

The chemical changes of the tissue molecules due to the photochemical effect of the laser light can be shown schematically as follows:

- photo-ionization: AB → AB+
- photo-isomerization: AB → BA
- photo-dissociation: AB → A + B

1.9.1.1 Biostimulation

The absorption of the laser light in the tissue is for biostimulation an essential condition. Within the cells, the light is absorbed in the area of the mitochondria, and thereby the tissue is stimulated. In contrast to the surgical use of the laser, there are no fabric-damaging side effects known during biostimulation.

For the phenomenon of the biostimulation (or "photobiomodulation"), only lasers with a low power are used (1–5 mW), the so-called "soft" lasers. Examples for this, are the He:Ne laser or the GaAs and the GaAlAs laser diodes. For this reason, these lasers are also called "low-level-therapy lasers" (LLTL) or "low power," "low-energy," "over-the-counter" lasers, or "low-intensity-laser therapy" (LILT) lasers, and the technology is noninvasive. The biomodulation has been used for pain reduction, acceleration of wound healing and blood flow, and treating a variety of inflammatory-related conditions (Chung et al. 2012). In this case, because the temperature in the tissue is slightly increased (less than 0.1–0.5 °C), the effect is only of a chemical (not thermal) nature.

The currently available trials of these laser types indicate no significant clinical effect. Anneroth et al. (1988) did not ascertain any difference in the wound healing of the rat skin between the test (with GaAs laser) and the control group.

On the other hand, other studies ascertained a stimulating effect of the laser light on wound healing or collagen synthesis with the He: Ne laser on pigs. Because of the stimulation of wound healing, this phenomenon is referred to as biostimulation. Moreover, in addition to the differentiation of the connective tissue, it has been proven that the migration of the epithelium cells is, under the effect of the He: Ne laser, more intensive, and the tissue's wound healing is thereby faster. Hargate (2006) showed in studies that using this technology, acute wounds (cold sores on the lips) as a result of herpes labialis can treated with complete closure. Nather et al. (2007) tried to treat chronic wounds in the legs of diabetic patients who did not respond to previous treatments

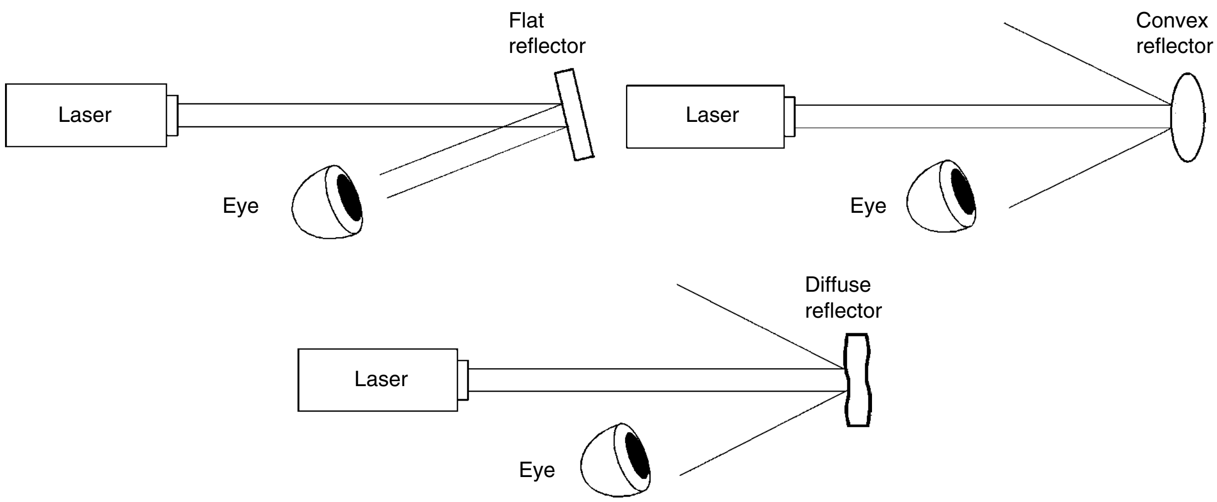


Figure 1.40 Use of flat reflectors can produce direct reflections having hazardous effects in the eye. Therefore, convex or diffuse reflectors are recommended.

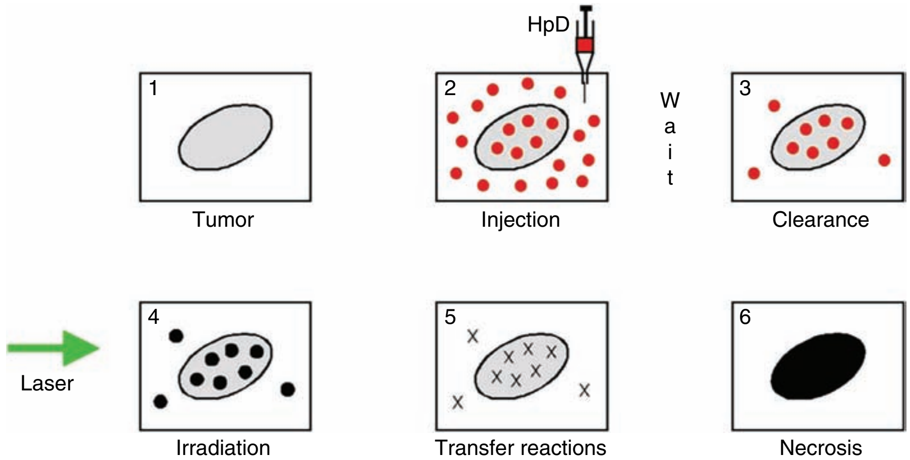


Figure 1.41 Concept of the photodynamic therapy of tumors (from Niemz 2019).

and showed favorable results after biostimulation. Usually the treatment period depends on the medical condition and ranges from a few days to several weeks.

The exact mechanism of biostimulation is still unknown. Some authors have implicated a "placebo," and furthermore there is a lot of speculative discussion about the biostimulatory effects of the light. More trials are necessary to better clarify the effect of biostimulation on tissues. Governments are encouraging programs that support self-management from home, reducing the load in the healthcare system (Renner et al. 2015).

Japanese researchers, focused on the phototherapeutic effects of the light, described the stimulation of specific light sensory receptors at the cell surface, which promote intracellular changes in the cell nucleus (Aleksic et al. 2010). Specifically, low level Er:YAG lasers may enhance the osteoblastic proliferation via MAPK/ERK pathway in the nucleus.

1.9.1.2 Photodynamic Therapy (PDT)

Photodynamic therapy represents a special technology of modern laser use, which finds its use particularly in the noninvasive treatment of superficial malignant tumors. The principle of photodynamic therapy is the resorption of a photosensitive substance (the so-called "photosensitizer") from the tumor's cells and later the selective destruction of the tumor with the help of a laser. First a photosensitizer is injected in the vein of the patient. The photosensitizer is distributed within a few hours in the entire soft tissue. After about 48–72 hours, the injected substance (photosensitizer) is eliminated by the healthy, normal cells; however, in the tumor cells, it remains for approximately seven to 10 days. With the help of a dye label of the tumor cells, they can be destroyed selectively by means of laser beams (Figure 1.41). The pathological tissue will be rejected after successful PDT within 5–15 days. The resulting defect will be then – without leaving a scar – epithelialized (Herzog et al. 1992).

This therapy does not have the disadvantages of a chemotherapy or radiotherapy and provokes no damage to the normal tissue areas, but it has the disadvantage that patients have to stay in darkness for days.

Red coloring or diodes lasers are used for photodynamic therapy. The photosensitive substances can be derivatives of hematoporphyrin (HPD), merocyanine 540 (MC-540) or rhodamin-I23 (Rh-123). Lipson and Blades (1961) were the first to describe the photodynamic properties of hematoporphyrin and its derivatives, as well as its ability to provoke a rapid necrosis of the tumor tissue after exposition to light.

Although the effects of the PDT are already long known, the exact mechanism of action is not yet completely clear. Early on, Tappenier and Jesionek (1903) observed a positive therapeutic effect of skin carcinomas after use of eosin and fluorescein under simultaneous light radiotherapy.

Today the bonding of the sensitizer with different cellular components is controversial. The cell membrane, the nucleus, the mitochondria, the lysosome or microsome are decisive for the selective resorption of the photosensitizer.

In the maxillofacial surgery, the clinical value of photodynamic therapy has been often investigated. It could be used for the improvement of the surgical therapy result, particularly for hardly recoverable structures, like the carotid artery and the facial nerve, as well as other important anatomical structures.

A comprehensive review of the literature of the antimicrobial effects of photodynamic therapy in periodontal and peri-implant diseases with the entire spectrum of existing photosensitizers has been published by Takasaki et al. (2009). The review presents the existing preclinical and clinical evidence on the effects of photodynamic therapy in the treatment as a promising novel therapeutic approach for eradicating pathogenic bacteria in periodontal and peri-implant diseases.

A systematic review of the literature demonstrates also that photodynamic therapy in periodontology as an adjunctive treatment to the standard therapy enhances the antibacterial effects in dentistry (Javed and Romanos 2013).

1.9.2 Photothermal Effects

The photothermal effects of the laser beam on tissue are dependent on several factors (Niemz 2019). The power of the beam, its energy, and the respective exposure time can accordingly raise the temperature of the tissue and cause thereby coagulation, carbonization, or melting in the hard tissue and vaporization (Figure 1.42).

The irradiation of tissue by laser light results in the absorption of energy. This energy is expressed entirely as a heat transfer absorbed by the tissue. Laser light will be transferred to the tissues ablating inflamed soft tissues and supporting wound healing via photomodulation. Due to heat transfer, the liquid will boil into vapor, causing changes in the tissue. Since the main liquid in the tissues is water and, in case of inflammation, blood, the impact of heat transfer to the tissues is vaporization of water and later on denaturation of proteins. The tissue will become firm. Common example of this denaturation phenomenon is that boiled eggs become hard and cooked meat becomes firm (see Tables 1.4 and 1.5).

Thermal *conductivity* and thermal *diffusivity* are two tissue properties that are temperature dependent. The conductivity of the living tissues is higher compared to dead tissues, indicating the dominant role played by blood transfusion enhancing the heat transfer in living tissues (Bhattacharaya and Mahajan 2003). Water has the highest thermal conductivity of any liquid.

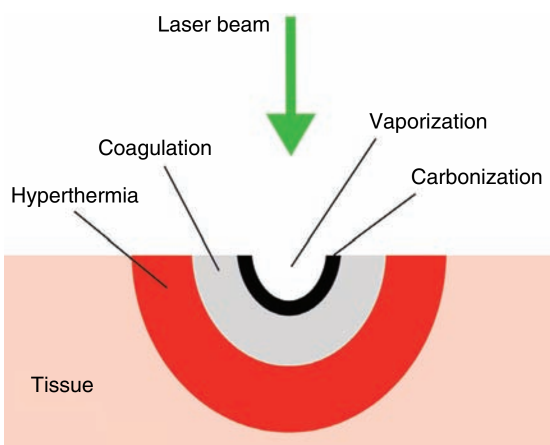
Considering the rules of physics, the *thermal conductivity coefficient K* is larger in muscles than in the liver and smaller in water and blood (Ponder 1962).

Also, the thermal *diffusivity* is the ability of an object to conduct heat during change of temperature. Thermal conductivity and diffusivity increase when temperature increases (Valvano 2011). Collagen has lower thermal properties and acts as a thermal insulator (Valvano 2011). Therefore, in clinical medicine it is more difficult to cut hypertrophic tissues and tissues containing more collagen using the laser beam.

However, thermal damage due to high temperature or longer heating time leads to collapse of the tissue. First, cellular death occurs and later on the extracellular matrix will be replaced by a scar.

In the laser-mediated tissue ablation high energy will be transferred with short pulses. Water vaporization appears as the temperature approaches 100 °C. When the water vaporization is faster than the diffusion of the heat out of the tissue, the vapor (steam) stays in the tissue forming steam vacuoles (Thomsen and Pearce 2011). This creates histologically a "popcorn" effect. When the temperature exceeds 200 °C, a carbonization (carbon formation) will be formed with a layer of a thin black membrane (5–20 μm) covering the defect.

The ablative effects of the laser radiation on the tissue are variously used in medicine. Thus, strong bleeding can be controlled and a blood-free operation area can be



temperature	effect
37 °C	–
>42 °C	hyperthermia
>60 °C	coagulation
100 °C	vaporization
>100 °C	carbonization

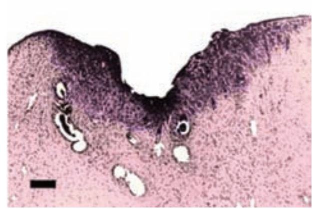


Figure 1.42 Effects of temperature distribution in the tissues (from Niemz 2019).

Table 1.4 Biological effects in soft tissues based on temperature increase (according to Niemz 2019).

Temperature (°C)	Effect
37	Normal
45	Hyperthermia
50	Reduction in enzyme activity, cell immobility
60	Protein (collagen) denaturation, coagulation
80	Permeability of membranes
100–140	Tissue vaporization, Thermal decomposition (ablation)
>150	Carbonization
>300	Melting

Table 1.5 Biological effects in hard tissues based on temperature increase (according to Bachmann et al. 2004).

Temperature (°C)	Effect
140	Elimination of water
200	Collagen denaturation
300–400	Organic material loss
400–1000	Carbonate loss
200–800	Cyanate formation
800–1000	Cyanate loss
200–1000	Changes in hydroxyapatite structure
1100	$Ca_4(PO_4)_2O$ formation
1300	Elimination of structural water, Hydroxyapatite melting

achieved. With the use of lasers it is also possible to remove superficial tissue alterations by means of carbonizing and vaporizing. Using different modes (i.e. continuous or pulsed mode and various pulse characteristics), we can have effects in the tissue of clinical significance (Figure 1.43). If during the laser use, the tissue reaches the temperature of approximately 150 °C, the tissue is carbonized (charred). From the clinical point of view, first a coagulation of the respective layers of the tissue is provoked, and afterwards a necrosis and carbonization. Higher temperatures alter the surface to a large extent and lead to pronounced irreversible changes, like melting of the hard tissue and vaporization.

Similar effects can be found in soft tissues. The use of water and air supply in different ratios can change the thermal effects and provide a reduced overheating, improving the cut efficiency. Some lasers can be used in conjunction with an air/water supply. The use of water and air provides new opportunities in clinical dentistry (Figure 1.44).

Recent studies on dental tissues showed that heat application changes the physicochemical properties of enamel contributing to positive effects due to the reduced adhesion of some bacterial species (Hu et al. 2011). Specifically, heating reduced the adhesion force of both *Streptococcus mitis* and *Streptococcus oralis* to enamel (with or without saliva coating), but heating did not affect the adhesion of *Streptococcus sanguis* with or without saliva coating.

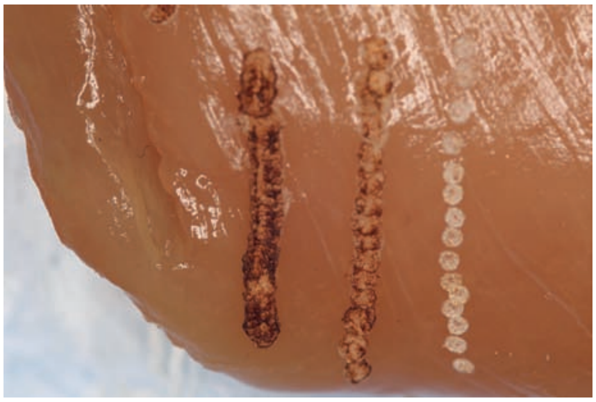


Figure 1.43 Photothermal effects of a 3 W-CO_2 laser on soft tissues (chicken breast) using a continuous wave (left), pulsed mode (middle), and superpulsed mode (right). The thermal effects demonstrate changes in the tissue. *Source:* Dr. Georgios E Romanos

Bacterial photo-elimination has been described as a novel modality in the eradication of *Streptococcus mutans* colonies in the near future; significant reduction of *Streptococcus mutans* was observed in planktonic cultures after photodynamic and photothermal therapy (Fekrazad et al. 2013).

The penetration depth of laser light within the oral soft tissues depends on the laser wavelength and can schematically be demonstrated in Figure 1.45.

Figure 1.44 Photothermal effects of lasers on soft tissues (chicken breast) using a 6 W Er,Cr:YSGG laser (15 Hz, no air/no water, [a], pulsed mode, 70% air/30% water [b]). With higher frequency in pulsed mode (50 Hz) and no air or water, there is a carbonization effect due to overheating (c). This can be reduced significantly using a sufficient air/water (70%/30%) supply (d). *Source:* Dr. Georgios E Romanos.

Dependent on the contact or noncontact mode, but also the used wavelength, different thermal effects may occur within the tissues. Figure 1.46 demonstrates these effects as an example for clinical use. The glass fiber of the pulsed Nd:YAG or diode laser is associated with irradiation with deep penetration, creating a carbonized, coagulation, and stimulation zone. However, a carbonized fiber tip (on the 810, 940, 975 980, and the 1064 nm lasers) transforms the laser-tissue effect of a laser with high water absorption, i.e. the light is absorbed in the carbon layer, resulting in a "hot" fiber tip. This property should be carefully considered when using the 810–1064 nm lasers. When superficial ablation is needed, a carbonized tip is absolutely necessary. Therefore, initiated tips are recommended to avoid scattering and improve light absorption (see also Chapter 3).

1.9.2.1 Fractional (Photo)-Thermolysis

Fractional (photo)-thermolysis (FT) is a relatively new technique with applications in dermatology and plastic reconstructive surgery. This novel, nonablative method was introduced in the market by Dieter Manstein and Rox Anderson and published by Huzaira et al. (2003). Compared to conventional skin resurfacing methods, FT allows treatment of a fraction of the skin leaving up to 95% of the skin uninvolved.

Basically, FT is the production of an "injury pattern" to the soft tissue (i.e. skin) with skip areas repeated over and over again, which, as they heal, promote an

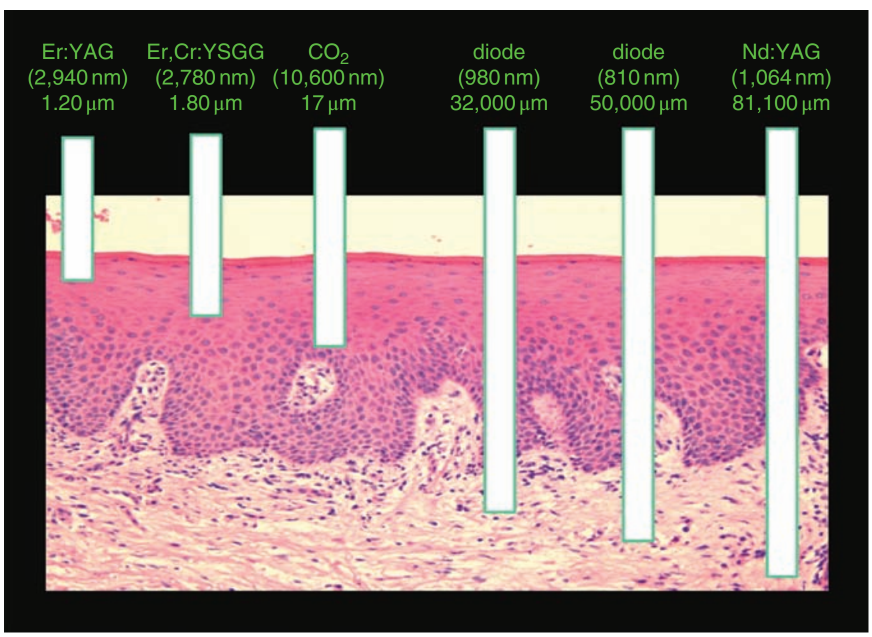


Figure 1.45 Schematic drawing of the penetration depth of different laser wavelengths in the oral mucosa based on the laser wavelength. *Source:* Dr. Georgios E Romanos.

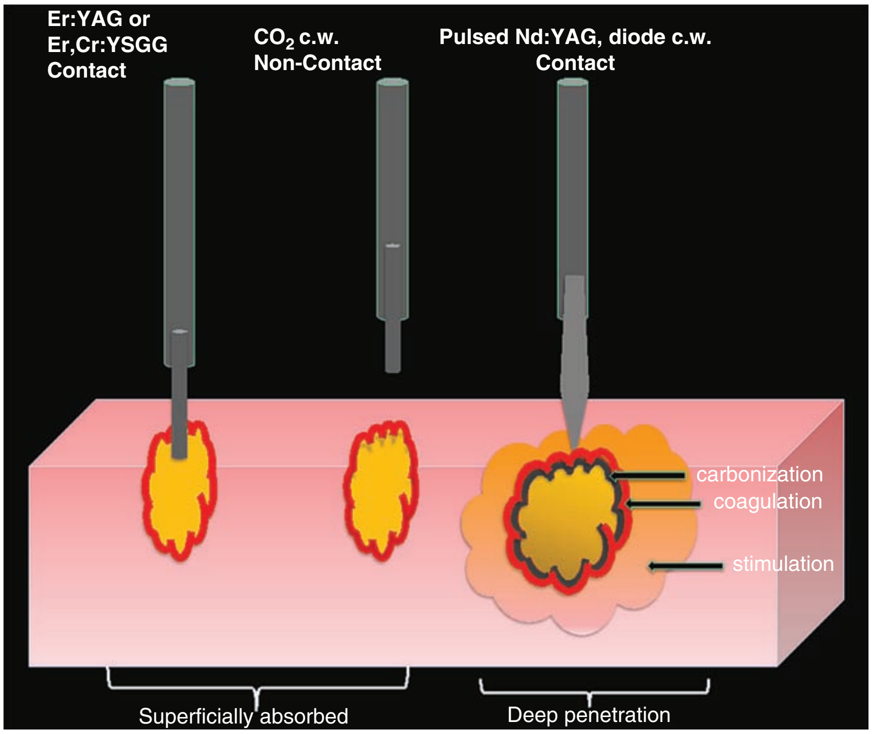


Figure 1.46 Laser-tissue effects based on the wavelength and the application mode. *Source:* Dr. Georgios E Romanos.

improvement in the tone and texture of the tissue. This technology triggers the body's natural healing process, accelerating the production of collagen and new, healthy skin cells.

In more technical terms, all of these devices produce small columns of thermal injury to the skin, which are known as microthermal zones (MTZs). These MTZs vary from device to device. Some are nonablative dermal injuries only; whereas, others are associated with ablative changes in the skin, causing both epidermal and dermal injury patterns. MTZs also vary greatly in their diameter of effect and in the degree of depth they achieve to create the injury. Once injured, the skin begins a very rapid process of repair (Figure 1.47).

In dermatology, lines and wrinkles, as well as pigmentary concerns including melasma, and in scars, especially acne and traumatic scars, can be removed and generally improve skin's appearance. This concept of therapy was applied using a prototype device (1.5 μm laser, Reliant MTZ SR prototype, Palo Alto, CA) for skin restoration of photoaged skin in the periorbital area of 30 subjects and 15 subjects with injuries in the forearm. These first clinical results showed 18% improvement of the wrinkle score after three months of therapy (Manstein et al. 2004).

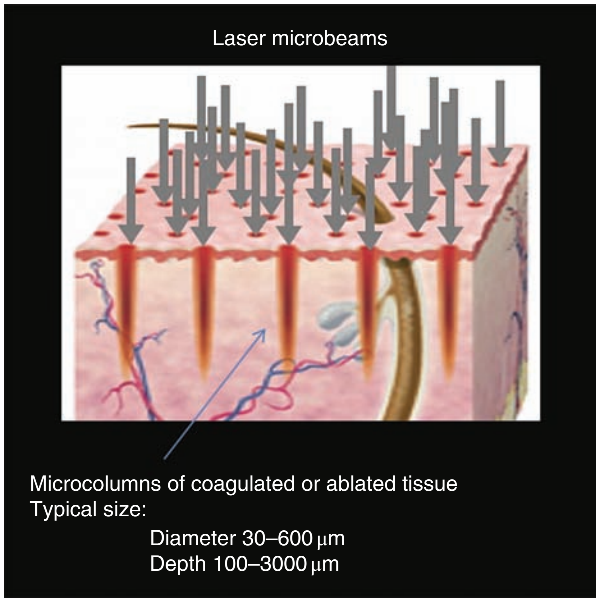


Figure 1.47 Principle of the fractional photothermolysis in the soft tissue. *Source:* IPG Photonics Inc.

Laser skin resurfacing began with the application of the carbon dioxide (CO_2) laser to facial rejuvenation, initiating a new era in the field of photorejuvenation (Alexiades-Armenakas et al. 2008). However, the major long-lasting side effect of nonfractionated CO_2 lasers is permanent skin hypopigmentation, although permanent hyperpigmentation can rarely occur (Ward and Baker 2008). In general, the CO_2 laser can vaporize the superficial epidermis without having an impact on the superficial dermal layer. Serious thermal damages can occur, especially if such procedures are performed by nonskilled clinicians. In contrast, Er:YAG or Er,Cr:YSGG lasers can ablate the epidermis superficially using short pulses and accomplish a "pure" ablation of the epidermis.

Recently, studies have looked at the use of FT in the treatment of hypertrophic scars, keloids, and burn hypertrophic scars. Ablative CO_2 fractional laser (Lumenis UltraPulse Encore, Fraxel re:pair) and ablative Er:YAG fractional lasers have been used with similar postoperative effects and comparable cosmetic improvements (Karsai et al. 2010; Preissig et al. 2012).

Erbium fiber lasers with wavelength 1550 nm (Fraxel, Reliant Technologies Inc., San Diego, CA) have been used in photomedicine for FT treatment of tissue. FT was developed as a way for laser surgeons to get closer to ablative laser resurfacing clinical outcomes with less patient downtime and fewer overall adverse events. Currently available devices vary in the way in which they produce their injury patterns, their wavelength, and their intensity. Recent studies showed that atrophic scars can be effectively and safely reduced with 1550 nm erbium-doped fiber laser treatment (Alster et al. 2007).

Of interest is the use of a similar concept in dentistry, as a minimally invasive microsurgical approach to initiate gingival and oral mucosal tissue regeneration. A *laser patterned microcoagulation (LPM)* was used in the rabbit oral mucosa using a diode laser at a wavelength 980 nm and a power of up to 20 W. The laser irradiation applied to the gingival and oral mucosa at multiple time points.

A single LPM treatment induces a wound healing response in the oral mucosa, showing the potential of LPM for the initiation of oral mucosa and gingival regeneration. This technology stimulates significantly the fibroblast activity and may lead to periodontal reattachment in periodontal tissues. Complete healing was observed in 3 months after treatment with no change in keratinization or scar tissue formation (Romanos et al. 2013).

Using this concept in clinical practice, ablation of soft tissues may be avoided and only coagulation zones underneath the epithelium surface may stimulate the matrix for new connective tissue formation. With the correct selection of laser wavelength, microbeam column diameter, and power and pulse width, there is a potential innovative mechanism to improve dense collagen fibers formation (Figure 1.48).

This concept has been initially used to improve the quality of periodontal tissues and increase the width of keratinized, attached gingiva (Figure 1.49). Clinical trials are encouraging to test this technology in specific patient populations.

1.9.3 Ionizing or Nonlinear Effects

1.9.3.1 Photoablation

The phenomenon of *photoablation* (nonlinear process) was until recently not clearly defined and was described for the first time by Srinivasan and Leigh (1982) (photodecomposition). A tissue ablation takes place as soon as

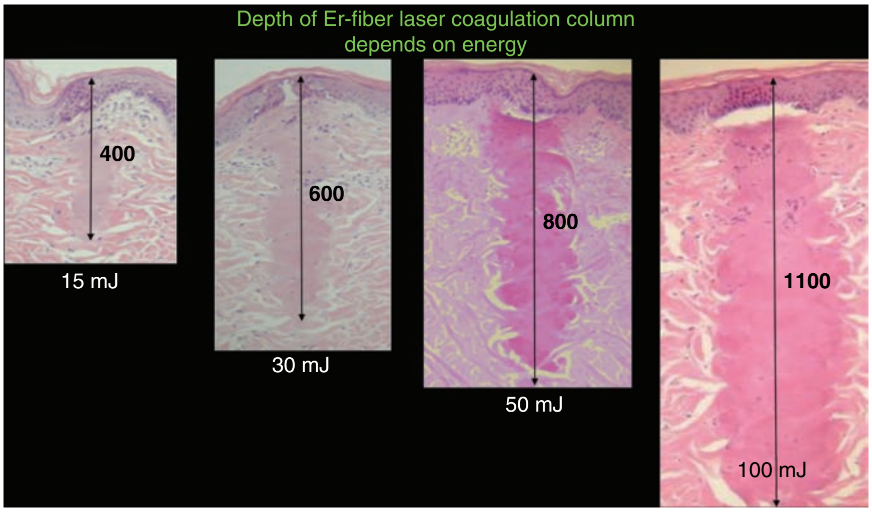


Figure 1.48 Histological demonstration of the coagulation zones in the soft tissues without ablation based on the concept of fractional photothermolysis. *Source:* Dr. Georgios E Romanos.

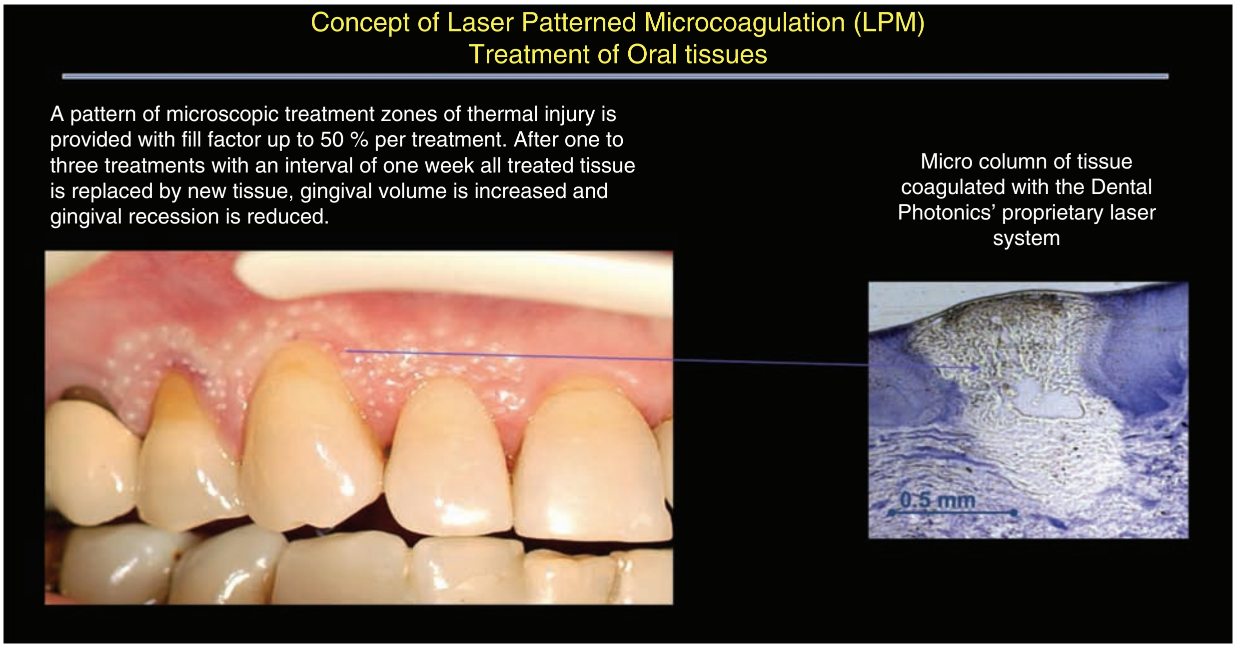


Figure 1.49 Concept of the Laser patterned micro-coagulation (LPM) for improvement of keratinized and attached gingiva. *Source:* Dr. Georgios E Romanos.

photons fall on the tissue. As a result, molecular connections are broken. The broken molecular structure suffers a volume enlargement and expands rapidly. An optimum photoablation can occur only with a wavelength of 193 nm (ArF, excimer laser). The extent of the photoablation increases with smaller wavelengths. This happens on the condition that the photon energy is greater than the molecular binding energy ($E = h \times r$). Free electrons are accelerated in the field of the laser beam and form a rise of free electrons as well as ions (formation of plasma and tissue overheating). At all other wavelengths a concurrent thermal change occurs in the tissue. It has been discussed that the ablative effect of the laser beam can lead to mutagen changes of the molecules. Studies showed that the 193 nm excimer laser beam does not transform corneal keratocytes and that the energies emitted by this beam will not cause cell transformation when the excimer laser is used as a surgical tool in human eyes (Gebhardt et al. 1990).

The conditions for photoablation are a short-pulse duration (in the area of nano- to microseconds) and a low penetration depth in the tissue, which is in the UV (<400 nm) and middle infrared (>2.5 pm) range of the spectrum. An ablative effect on the surface of the matter (e.g. dental surface) thereby takes place, and thermal damages of nonirradiated areas are avoided. This phenomenon is today clinically applied during caries removal with a laser using different (short, medium-short, and supershort) pulses. According to recent studies the effect of supershort laser pulses was the most efficient in ablation of caries in dentin, providing a smear layer-free surface with open dentinal tubules (Baraba et al. 2012).

Other biomedical applications of the photoablative photodecomposition are the irradiation of a KrF excimer laser pulses (wavelength: 248 nm; fluence: $1\,J/cm^2$ pulse) onto several polymer films resulting in the formation of an etched pit on the irradiated surface (Nakayama and Matsuda 1995).

1.9.3.2 Photodisruption

Plasma, in physics, is an electrically conducting medium in which there are roughly equal numbers of positively and negatively charged particles, produced when the atoms in a gas become ionized. It is sometimes referred to as the fourth state of matter, distinct from the solid, liquid, and gaseous states. Modifications to the process can be made by introducing different gases to the chamber. Commonly used gases include O_2, N_2, Ar, H_2, and CF_4. These five gases are used singularly or in combination in the majority of the labs around the world for plasma processing.

After the formation of plasma, a wave spreads out explosively and is able to destroy by means of mechanical forces the surrounding tissues. This phenomenon is known as *photodisruption* and is, as a nonlinear pro-

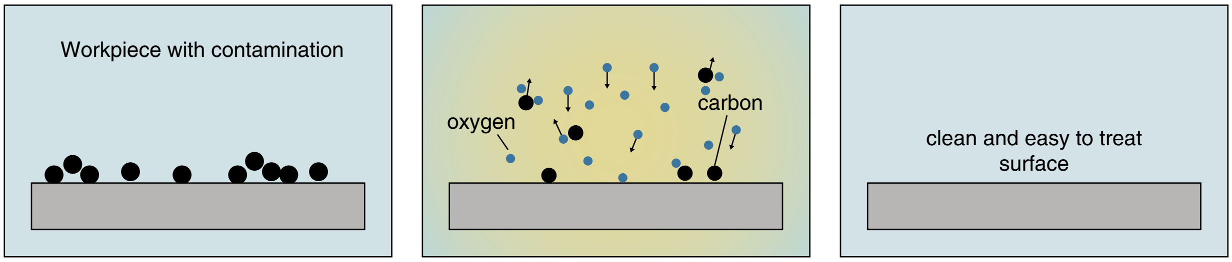


Figure 1.50 Principle of plasma cleaning process of a metal. *Source:* Thierry Plasma Science and Technology, Royal Oak, MI.

cess, closely related to the photoablative effect of the laser beam. No energy absorption has to take place for photodisruption in the tissue, because the laser energy is absorbed in the plasma of the tissue surface. Such phenomena can thereby also appear in transparent materials. Today, this interaction with the tissue is clinically applied in the ophthalmology (i.e. corneal surgery and cataract therapy) and in lithotripsy (e.g. the removal of salivary stones). The femtosecond laser especially (Sacks et al. 2003; Nuzzo et al. 2010; Rossi et al. 2015) but also the picosecond (ps) and nanosecond laser were used earlier (Vogel et al. 1994). Specifically, the use of ps pulses improved the precision of intraocular Nd:YAG laser surgery and diminished unwanted disruptive side effects.

Gas plasma technology has played a variety of roles in this scope of innovative work. These roles vary widely depending on the product market application. However, they do fall into the four categories of plasma cleaning, plasma activation, plasma etching, and plasma coating. Many plasma applications have been used in medicine for cleaning of metals using the so-called plasma cleaners (plasma treatment), but also using the plasma surface technology, there is the ability to change the surface of materials on the microscopic level, giving them different characteristics. One method that plasma *surface technology* can employ to change a surface's traits is called micro-sandblasting. **Plasma cleaning** is the process of removing all organic matter from the surface of an object through the use of an ionized gas (so-called **plasma)**. This is generally performed in a vacuum chamber utilizing oxygen and/or argon gas.

In plasma cleaning (Figure 1.50) the surface is cleaned by ion bombardment and chemical reactions. After plasma activation, the nonpolar surfaces are changed into adhesive surfaces, and the surface energy increases. To plasma etch or to remove material, the surface is etched with an etchant gas.

This innovative technology seems to have many applications in surgical dentistry in industrial but also clinical settings.

Low pressure plasma cleaners are an economical way to uniformly, safely, and completely plasma clean, removing contaminants from the surface of treated substrates without affecting the bulk material properties. This process of decontamination is used in industry before packaging and works for a large range of materials (metals, plastics, glass, ceramics, etc.). Plasma cleaning is an environmentally friendly procedure since there is no need for hazardous chemical solvents. The processing eliminates mold-releasing agents, antioxidants, carbon residues, oils, and all varieties of organic compounds.

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