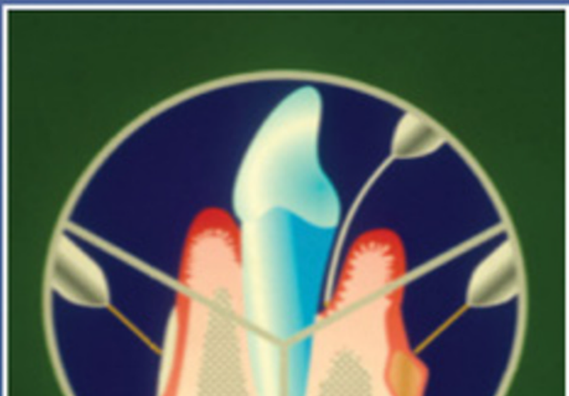
ADVANCED LASER SURGERY IN DENTISTRY

GEORGIOS E. ROMANOS

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To my focused beam, little star, my daughter Stella

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Preface

Lasers are novel and innovative technologies with many benefits for clinicians, patients, and applications in surgical dentistry. It is a significant contribution to the modern medical field that laser light can be used effectively in clinical dentistry based on present scientific developments and technological advances.

Scientific evaluation of this technology presents a lack of strong evidence in specific areas of dentistry, but there is no doubt that lasers are beneficial as clinical tools in a variety of clinical scenarios based on the appropriate laser-tissue interactions and the challenges in daily practice.

The first part of the book will provide the fundamental and advanced uses of lasers as surgical tools for improvement of clinical outcomes and is focused on the intraoral applications of a variety of laser wavelengths and devices.

The book presents the clinical impact of the use of lasers on the different fields of surgical dentistry in a modern way with clinical photographs and step-by-step documentation. The strength of the book is the discussions of the use of different lasers and novel fiber-optics in the treatment of a variety of clinical problems and the contribution of top specialists in the field of antimicrobial, photodynamic therapy, and laser safety.

For instance, the use of laser light to excise or coagulate tumors, the impact of lasers on periodontal surgical procedures, as well as in implant dentistry, from the implant uncovering to the treatment of peri-implant diseases, are discussed. The highlights of the book for the new decade are the modification of traditional concepts of treatment and using a patient friendlier method leading to less postoperative complications and excellent wound healing.

The book explains systematically the protocols of treatment with clinical cases and illustrates the way of thinking and treatment methodology in the different surgical fields. It is an excellent resource for clinicians who want to improve their experience in surgical dentistry and advance their practice. In addition, the book is a strong foundation for the specialist who wants to learn more about this novel technology and how it can fit in their practice.

Enjoy reading but also practice, and you will recognize the pearls and jewels in *Advanced Laser Surgery in Dentistry*.

Georgios E. Romanos, DDS, PhD, Prof Dr med dent

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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

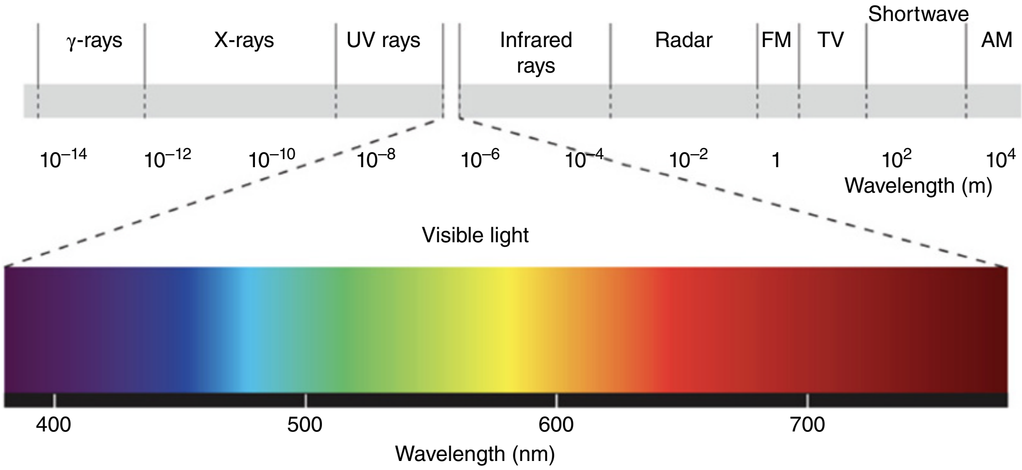

Figure 1.1 Electromagnetic spectrum and the different wavelengths.

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 (= 6.63×10^{-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").

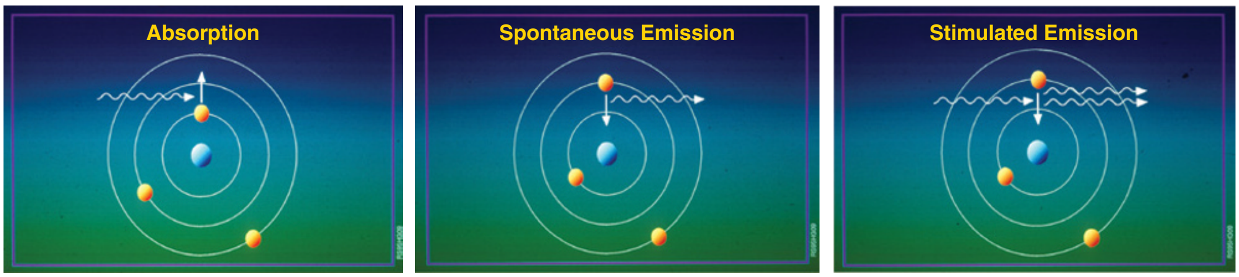

Figure 1.3 Spontaneous and stimulated emission principles.

- *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).

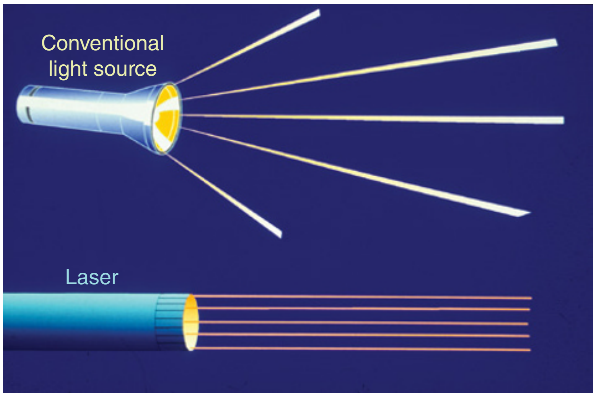

Figure 1.4 Collimated light of the laser versus non-collimated light of the conventional light source

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.

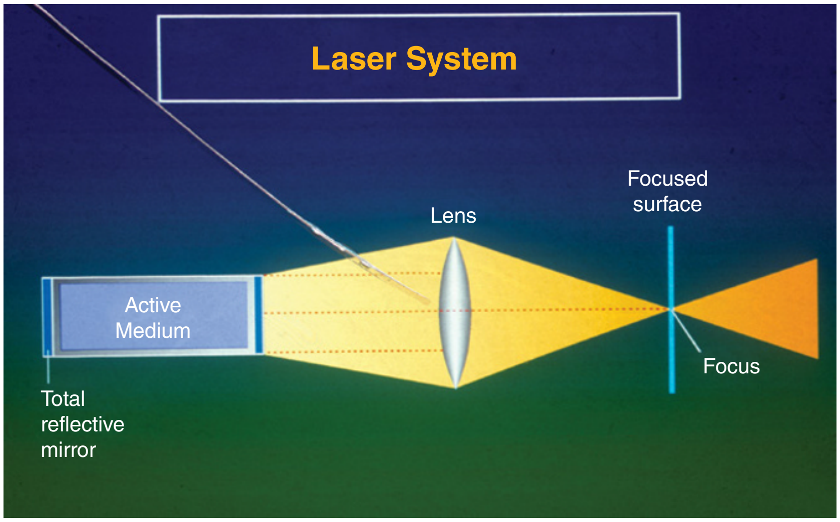

Figure 1.5 Schematic demonstration of a laser device.

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

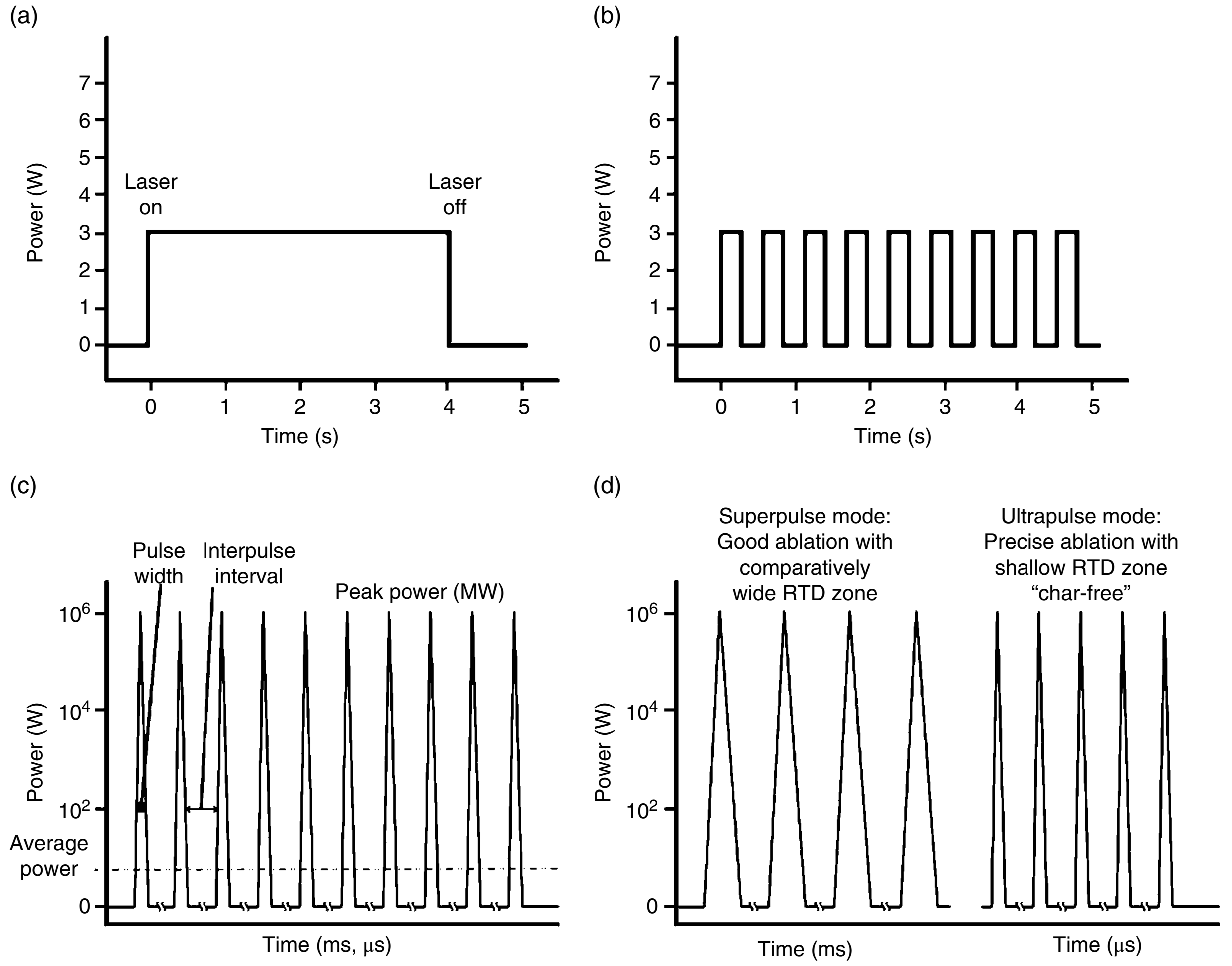

Figure 1.6 Continuous (CW) and pulsed (chopped, gated) laser application modes compared to pulsed, superpulse, and ultrapulse mode.

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