Laser and Light Fundamentals

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Core Message

The word LASER is an acronym for light amplification by stimulated emission of radiation. The theory was postulated by Albert Einstein in 1916. A brief description of each of those five words will begin to explain the unique qualities of a laser instrument.

Once the laser beam is created, it is delivered to the target tissue. Furthermore, each device has certain controls that the clinician can operate during the procedure.

An understanding of these fundamentals will become the foundation for further elaboration of the basic concepts of how lasers are used in dentistry.

2.1 Light

2.1.1 Origins and Curiosities of Light

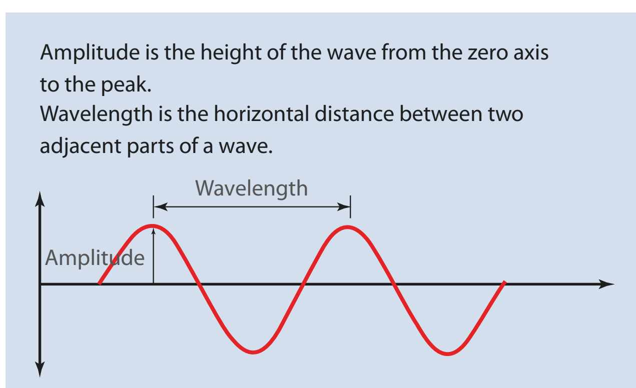
The word light has been used for many centuries, including biblical references such as in the beginning sentences of the Book of Genesis. Early civilization seemed to understand that the cycle of day and night with the sun, the moon, and the stars produced differences in ambient brightness. Historical investigations into the nature of light produced interesting and sometimes conflicting studies. Ancient peoples were curious about this brightness: the Greek philosopher, Pythagoras, began to develop wave equations about 400 B.C. Over a century later, the Greek mathematician Euclid claimed that light is emitted in rays from the eye; he then proclaimed the law of reflection of those waves. It took until 1021 for a mathematician from Basra, Ibn al-Haytham, to correct the concept and prove that light enters rather than emanates from the eye. In addition, al-Haytham postulated that there are tiny particles of energy coming from the Sun that produce light. In 1672, British physicist Isaac Newton was studying the laws of reflection and refraction and concluded that light was made of particles, which he called «corpuscles» [1]. He concluded that light is a combination of seven colored particles—violet, indigo, blue, green, yellow, orange, and red (in keeping with the belief that seven is a mystical number.) Those particles combine to produce white light [2]. A few years later in 1678, the Dutch physicist Christiaan Huygens insisted that light was made up only of waves and published the «Huygens» Principle [3]. As history would have it, both Newton and Huygens were at best half correct.

Over a hundred years later, new discoveries of light emerged. In 1800, William Herschel, a German-born musician and astronomer, moved to England and investigated individual temperatures of the visible colors. From those experiments, he discovered infrared light [4]. Johann Ritter, from a region of Eastern Europe now known as Poland, discovered ultraviolet light in 1801, by observing how the common chemical silver chloride changes color when exposed to sunlight [5]. The British physicist Michael Faraday produced evidence that light and electromagnetism were related [6]. In 1865 his Scottish colleague James Maxwell then explained electromagnetic radiation: that is, electricity, magnetism, and light are in fact interrelated in the same phenomenon [7]. His discovery quantified the different wavelengths of radiation and thus helped to explain our current understanding of the existence of light in more than just the visible spectrum of Newton's colors. In 1895 Wilhelm Roentgen, a German professor of physics, added X-radiation to the electromagnetic spectrum, after studying many experiments from colleagues such as Philipp Lenard and Nikola Tesla [8]. He used the terminology of X to signify an unknown quantity. A theoretical physicist Max Planck, also from Germany, proposed that light energy is emitted in packets he termed quanta in 1900 [9]. He formulated an equation that gave a relationship between energy and wavelength or frequency. In 1905 the German scientist Albert Einstein discovered what he termed the photoelectric effect. He observed that shining light on many metals causes them to emit electrons, and he termed them photoelectrons. He then deduced that the beam of light is not just a wave traveling through space but must also be composed of discrete packets of energy, as described by Planck. Einstein called these tiny particles photons [10], thus crystallizing the particle-wave dual nature of light.

2.1.2 The Duality of Light

Based on the discoveries and arguments over the last three millennia, it can now be stated that light is a form of electromagnetic energy with a dual nature. It behaves as a particle and travels in waves at a constant velocity. The basic packet or quantum of this particle of radiant energy is called a photon [11]; a photon is a stable particle that only exists when moving at the speed of light in a vacuum. By implication of the theory of relativity, it has no mass. When decelerated, it no longer exists, and its energy is transformed.

The wave of photons which travels at the speed of light can be defined by two basic properties, as shown in ◘ Fig. 2.1. The first is amplitude, which is defined the vertical height of the wave oscillation from the zero axis to its peak. This



◘ **Fig. 2.1** A depiction of electromagnetic waves showing the two important quantities of amplitude and wavelength correlates to the amount of energy carried in the wave: the larger the amplitude, the greater the amount of energy available that can do useful work. The second property of a wave is wavelength, which is the horizontal distance between any two corresponding points on the wave. This measurement is very important both in respect to how the laser energy is delivered to the tissue and what the interaction will be. Wavelength is measured in meters, and dental lasers have wavelengths on the order of much smaller units using terminology of either nanometers (10^{-9} m) or microns (10^{-6} m.) As waves travel, they oscillate several times per second, which is termed frequency. Frequency is inversely proportional to wavelength: the shorter the wavelength, the higher the frequency and vice versa.

2.1.3 Properties of Light and Laser Energy

Ordinary light produced by a table lamp, as an example, is usually a white glow. The white color seen by the human eye is really a sum of the many colors of the visible spectrum—for example: red, orange, yellow, green, blue, and violet, as first described by Isaac Newton. The light is usually diffuse, and not well focused.

Laser energy is distinguished from ordinary light by two properties. One is *monochromaticity* which means the generated light wave is a single specific color. For dental instruments, that color is usually invisible to our eyes. Secondly, each wave has *coherency*, identical in physical size and shape along its axis, producing a specific form of electromagnetic energy. This wave is characterized by spatial coherency—that is, the beam can be well defined; the beam's intensity and amplitude follow the Gaussian beam's bell curve in that most of the energy is in the center, with rapid drop-off at the edges. There is also temporal coherency, meaning that the single wavelength's emission has identical oscillations over a time period. The final laser beam begins in collimated form and can be emitted over a long distance in that fashion. However, beams emanating from optical fibers usually diverge at the tip. By using lenses, all the beams can be precisely focused, and this monochromatic, coherent beam of light energy can accomplish the treatment objective.

Using a household fixture as an example, a 100-watt lamp will produce a moderate amount of light and proportionally more heat in a room. On the other hand, two watts of laser power can be used for a precise excision of an irritation fibroma, providing adequate hemostasis on the surgical site without disturbing the surrounding tissue.

2.2 Emission

2.2.1 Spontaneous Emission

In 1913, Niels Bohr, a Danish physicist, developed his model of an atom, applying the quantum principle of Planck. He proposed distinct energy orbits or levels of energy around the nucleus of that atom. Bohr found that an electron could «jump» to a higher (and unstable) level by absorbing a photon and then the electron would return to a lower (more stable) level while releasing a photon [12]. He termed this spontaneous emission. The nuance to this emission is that, since there are several possible orbital levels in the atom, the wavelength of the photonic emission would be determined by the energy of the emitted photon, according to Planck's equation. It should also be noted that the emitted photon will likely have a random direction and phase. In more simple terms, spontaneous emission can be demonstrated when a conventional electric light bulb is switched on. The filament glows brightly emitting light and heat as the electrons are excited to higher energy states and then return to their ground conditions. Different broad groups of wavelengths (e.g., white light) will be produced during emission from the higher energy levels. A light-emitting diode also produces spontaneous emitted light by using a flow of energized electrons recombining on the positive side of the wafer to produce luminescence. The color (wavelength) of the emitted light will depend on the chemical composition of the diode wafer [13].

2.2.2 Stimulated Emission

In 1916 Albert Einstein postulated the theory of lasers [14]. Using Bohr's model, he postulated that during the process of spontaneous emission, an additional photon, if present in the field of the already excited atom with the same excitation level, would stimulate a release of two quanta. These would be identical in phase, direction, and wavelength. In addition, these emission photons would share monochromatic and coherent properties—thus a laser is born.

2.3 Amplification

Amplification is part of a process that occurs inside the laser. Once stimulated emission occurs, the process should theoretically continue as more photons enter the field both to excite the atoms and to interact with the excited photons returning to their ground state. One could imagine a geometric progression of the number of emitted photons, and, at some point, a population inversion occurs, meaning that a majority of atoms are in the elevated rather than the resting state. As Bohr implied, there can be several potential levels of energy available in most atoms. Having multiple levels (more than two) would aid in maintaining a population inversion because there would be no possibility of equal rates of absorption back into the ground state and stimulated emission. This amplification effect can only occur if there is a constant and sufficient source of energy, which is supplied by a pumping mechanism.

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2.4 Radiation

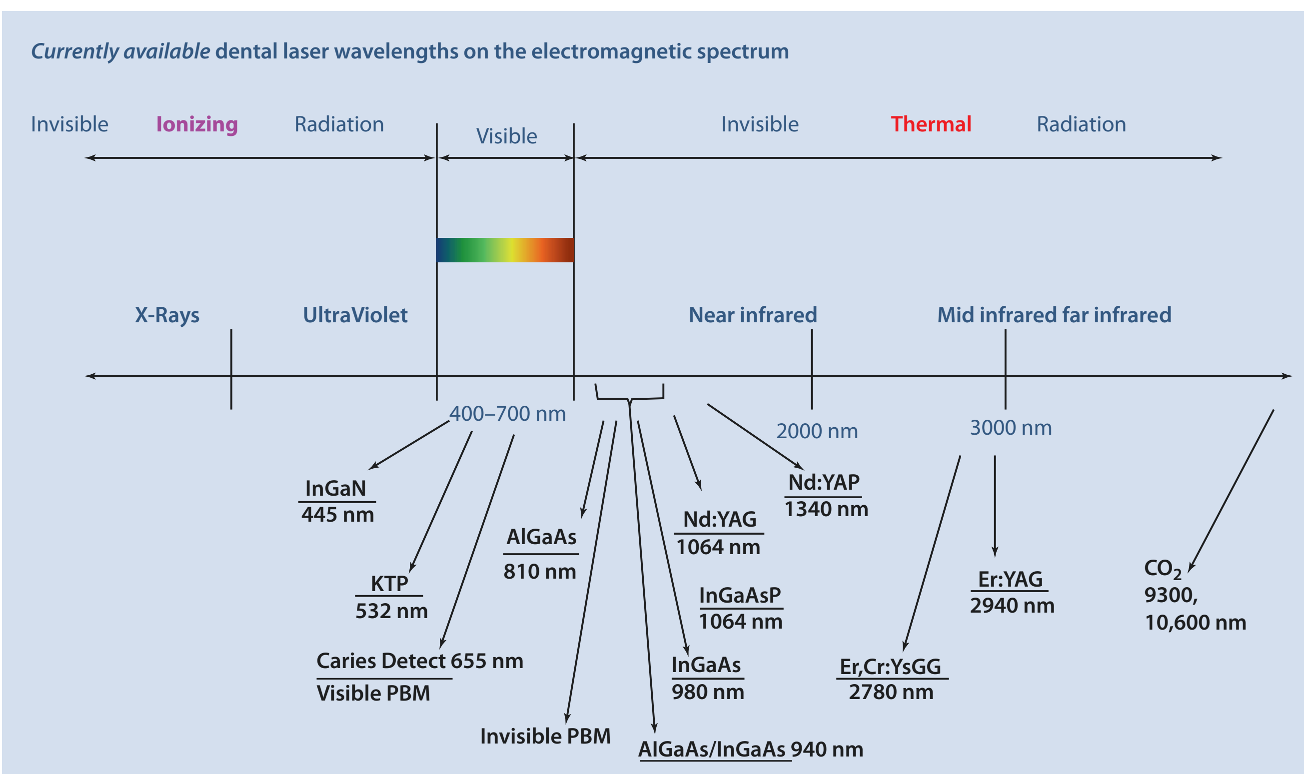
The basic properties of a wave were discussed in ▶ Sect. 2.1.2. The entire array of wave energy is described by the electromagnetic spectrum (ES)—in other words, all frequencies and wavelengths of radiation [15]. The ES has several regions with rough boundaries of wavelength or frequency. There are seven general classes, with increasing order of wavelength to describe the radiation: gamma rays, X-rays, ultraviolet radiation, visible radiation, infrared radiation, microwaves, and radiofrequency waves. These wavelengths range in size: gamma rays measure about 10^{-12} m; on the other end of the spectrum, radio waves have wavelengths up to thousands of meters. The ES can be more broadly divided into two divisions with gamma rays, X-rays, and ultraviolet light in a group termed ionizing radiation, while all the other wavelengths are termed nonionizing. Ionizing simply means that the radiant wave has enough photon energy to remove an electron from an atom, and those wavelengths can cause mutagenic changes in cellular DNA. The human eye responds to wavelengths from approximately 380–750 nm, with those two numbers representing deep violet and dark red, respectively. That range is termed the visible spectrum. The term thermal radiation can be applied to many wavelengths. For example, an infrared lamp generates heat; the sun provides both light and heat; and the ionization present in plasma can also produce high temperatures.

The energy of a photon can be calculated using the equation from Max Planck. It states that the energy is directly related to the frequency of wave or inversely proportional to the wavelength. Thus, gamma or X-radiation with very short wavelengths (ranging from 10^{-12} to 10^{-10} m) has very high energy, while radio waves (approximately 3 m to 1 km) have significantly lower energy by comparison.

2.5 Components of a Laser

Identifying the components of a laser instrument is useful in understanding how the energy is produced. For dentistry, there are two basic types of lasers: (1) one that operates as a semiconductor and is compact in size and (2) one that has distinct components that, when assembled, occupy a larger footprint. The first type is generally known as a diode laser; the second type encompasses all other lasers. Both of these types share common features—an active medium, a pumping mechanism, and a resonator. In addition, a cooling system, controls, and a delivery system complete the laser device.

All available dental laser devices have emission wavelengths of approximately 0.45 microns, or 450 nanometers to 10.6 microns or 10,600 nanometers. That places them in either the visible or the invisible nonionizing portion of the electromagnetic spectrum. ◻ Figure 2.2 is a graphic depiction of those lasers on a portion of the electromagnetic spectrum.



◻ **Fig. 2.2** A graphic showing the currently available dental wavelengths' position on the visible and invisible nonionizing portion of the electromagnetic spectrum. Note that most of the wavelengths also include the composition of the active medium which produces that wavelength. PBM is an abbreviation for photobiomodulation, and those instruments use various active media

2.5.1 Active Medium

Lasers are generically named for the material that is being stimulated; such material is called the active medium. As mentioned above, the atoms (or molecules) of that material absorb photonic energy and then begin to spontaneously emit. Subsequently under the right conditions, the process of stimulated emission will begin. Common materials for dental lasers can be broadly designated as one of three types: a container of gas, a solid-state crystal, or a semiconductor. The active medium is at the center or core of the laser, termed the optical cavity.

Gas Lasers

The most common gas dental laser is carbon dioxide, which contains a gas mixture of carbon dioxide, helium, and nitrogen. Helium is not directly involved in the lasing process, but nitrogen does interact with the excitation process and ultimately transfers that energy to the carbon dioxide molecules.

A second gaseous laser is the argon ion instrument. A tube of this noble gas when excited can produce several radiant emissions, the most common being a visible blue and blue-green beam of collimated light. The physical demands of power and cooling have rendered this laser to a very limited application in dentistry.

One of the first lasers developed was the helium-neon gas laser, which has a visible red color emission.

Solid-State Crystal Lasers

Various solid-state crystals are used in dental lasers. The host material is composed of yttrium aluminum garnet (YAG), yttrium aluminum perovskite (YAP), or yttrium scandium gallium garnet (YSGG.) Any of these can then be «doped» with ions of neodymium, erbium, and chromium. The resulting designation would be written as Nd:YAG, for example, which would be a neodymium-doped yttrium aluminum garnet crystal.

Semiconductor Dental Lasers

A semiconductor laser utilizes the basic positive-negative (p-n) junction of everyday electronic circuits—the diode: that is, a two pole oppositely charged wafer. The flow of negatively charged electrons into the positively charged holes diffuses across the junction. The lasing action takes place between the charged layers, called the depletion region. This small rectangle will emit coherent and monochromatic light, but collimation must be performed by an external lens. Current diode lasers consist of various atomic elements in binary, ternary, or quaternary form arranged in a wafer-like structure. Examples would be gallium arsenide (GaAs), aluminum gallium arsenide (AlGaAs), indium gallium arsenide (AlGaAs), and indium gallium arsenide phosphate (InGaAsP.) These elements provide a checkerboard-like crystalline structure to allow lasing to occur; the usual silicon-based semiconductor is not used because of its symmetry. The single diode wafer just described is then arranged in a linear array for cooling, and the number of wafers determines the power output.

2.5.2 Pumping Mechanism

Surrounding this optical cavity with its active medium is an excitation source, known as the pumping mechanism. Pumping is used to transfer energy into the optical cavity, and that energy must be of sufficient quantity and duration so that the occupation of a higher energy level exceeds that of a lower level. This condition is called a population inversion and it allows amplification to occur.

Although the above-described process occurs rapidly, it still takes some time. Most lasers are described as three-level or four-level. A three-level system describes the basic concept: level one would be the stable, ground state, sometimes designated as energy level zero, a pumped level (energy level 2), and a lasing level (energy level.) Despite rapid decay from level 2, with enough pumped energy, there will be a population inversion between level 1 and 2. A four-level system is similar with the pumped level designated as 3, the upper lasing level as 2, and the lower lasing level as 1. The difference between these two lasing levels will aid in producing a population inversion. Certain active media operate as either three- or four-level systems.

In the laser industry, there are a wide variety of pumping mechanisms. The pumping of dental lasers is usually performed with optical devices—high-power lamps or lasers or by electricity—either with direct current mains or with electronic modulation of alternating current. Currently diode lasers are electronically pumped; solid-state crystal lasers use high-powered strobes (flash lamps); and carbon dioxide lasers can be operated with AC or DC current or radiofrequency (RF) pumping methods. As a variation in pumping, one form of carbon dioxide technology uses very high pressure gas and many electrodes along the length of the gas tube. This is known as a transversely excited atmosphere (TEA) laser.

2.5.3 Resonator

The resonator, sometimes known as the optical cavity or optical resonator, is the laser component surrounding the active medium. In most lasers, there are two mirrors one at each end of the optical cavity, placed parallel to each other, or in the case of a semiconductor, either a cleaved and polished surface exists at the end of the wafer or there is reflection within the wafer. In all cases, these mirrored surfaces then produce constructive interference of the waves: that is, the incident wave and the reflected wave can superimpose on each other producing an increase in their combined amplitude. Clearly some waves will not combine and will soon lose their intensity, but others will continue to be amplified in this resonator. With the mirror system, this continued effect will help to collimate the developing beam. As mentioned previously, a diode laser collimation occurs externally.

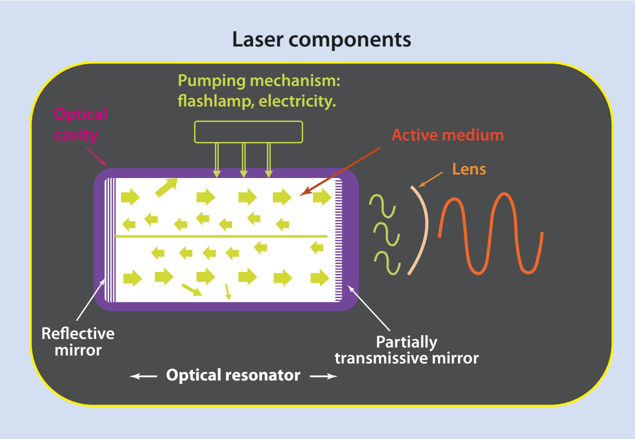


Fig. 2.3 General schematic of a laser. The active medium can be solid state (like Nd:YAG) or a gas (like carbon dioxide.) The pumping mechanism provides the initial energy, and the resonator consists of the active medium and axial mirrors. One mirror is totally reflective and the opposite one is partially transmissive. When a sufficient population inversion is present, laser photonic energy is produced and focused by lenses

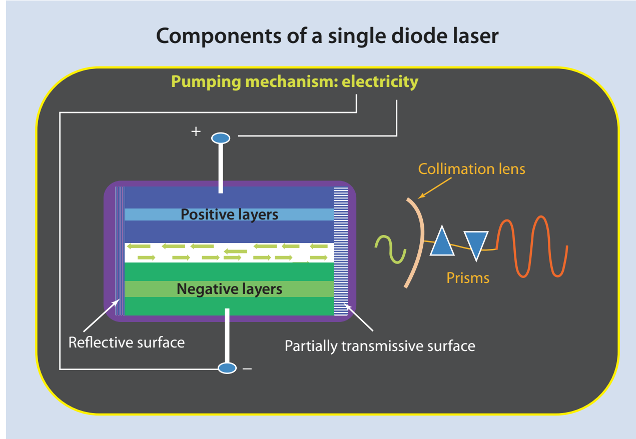


Fig. 2.4 Schematic of a single (individual) diode laser wafer. There are layers of positively and negatively charged compounds, pumped by electricity. The white layer with the yellow arrows represents the active layer where stimulated emission takes place. In this example, a reflective coating is applied to opposite ends of the wafer. In the right area are examples of lenses and prisms that would be placed at the emission end of an array of wafers to produce useful powers of diode laser photonic energy

2.5.4 Other Mechanical Components

A cooling system is necessary for all lasers, and higher output power requires increasing dissipation of the heat produced by pumping and stimulated emission. Air circulation around the active medium can control the heat, especially with diode lasers; the sold state crystal lasers and some gaseous lasers require additional circulating water cooling.

Focusing lenses are employed for each beam, and in the case of diode lasers, for collimation. The delivery system will ultimately determine the diameter of the emitted wavelength.

The laser control panel allows the user to adjust the parameters of energy emission, along with a foot or finger switch for «on-off» or variable output operation on some devices.

2.5.5 Components Assembled

Laser energy is produced because the active medium is energized by the pumping mechanism. That energy in the form of photons is absorbed into the active medium, raising its atomic electrons to higher orbital levels. As the electrons return to their stable ground state, photons are emitted while other entering photons can produce stimulated emission. The resonator allows more numbers of these photonic interactions and will continue the amplification process.

The operation is temperature controlled, the beam is focused, and the clinician can control the laser used. Figure 2.3 shows a graphic of a solid-state laser such as an Nd:YAG or a gas laser such as carbon dioxide, and Fig. 2.4 depicts a schematic of a single semiconductor laser wafer. Tables 2.1 and 2.2 provide details of the currently available dental lasers with their active medium, common usage, and emission wavelength.

Table 2.1 Currently available visible spectrum dental lasers

Type of laser and emission spectrum	General uses	Active medium	Wavelength	Emission mode
Semiconductor diode, visible blue	Soft tissue procedures, tooth whitening	Indium gallium nitride	445 nm	CW, GP
KTP solid-state visible light emission	Soft tissue procedures, tooth whitening	Neodymium-doped yttrium aluminum garnet (Nd:YAG) and potassium titanyl phosphate (KTP)	532 nm	CW, GP
Low-level lasers, visible red light emission semiconductor or gas lasers	Photobiomodulation therapy (PBM), photodynamic therapy (PDT), or carious lesion detection.	Variations of gallium arsenide or indium gallium arsenide phosphorus diodes Helium-neon gas	600–670 nm 632 nm	CW, GP

The type of laser and its emission spectrum is listed in column 1; column 2 indicates the general usage in dentistry; column 3 describes the active medium; column 4 shows the emission mode with the following abbreviations: *CW* continuous wave, *GP* acquired pulse

Table 2.2 Currently available invisible infrared dental lasers

Type of laser and emission spectrum	General uses	Active medium	Wavelength	Emission mode
Low-level lasers, (invisible) near infrared	Photobiomodulation therapy (PBM) , photodynamic therapy (PDT)	Variations of aluminum gallium arsenide diodes	800–900 nm	CW, GP
Semiconductor diode, near infrared	Soft tissue procedures	Aluminum gallium arsenide	800–830 nm	CW, GP
Semiconductor diode, near infrared	Soft tissue procedures	Aluminum/indium gallium arsenide	940 nm	CW, GP
Semiconductor diode, near infrared	Soft tissue procedures	Indium gallium arsenide	980 nm	CW, GP
Semiconductor diode, near infrared	Soft tissue procedures	Indium gallium arsenide phosphorus	1064 nm	CW, GP
Solid state, near infrared	Soft tissue procedures	Neodymium-doped yttrium aluminum garnet (Nd:YAG)	1064 nm	FRP
Solid state, near infrared	Soft tissue procedures, endoscopic procedures	Neodymium-doped yttrium aluminum perovskite (Nd:YAP)	1340 nm	FRP
Solid state, mid infrared	Soft tissue procedures, hard tissue procedures	Erbium, chromium-doped yttrium scandium gallium garnet (Er,Cr:YSGG)	2780 nm	FRP
Solid state, mid infrared	Soft tissue procedures, hard tissue procedures	Erbium-doped yttrium aluminum garnet (Er:YAG)	2940 nm	FRP
Gas, far infrared	Soft tissue procedures, hard tissue procedures	Carbon dioxide (CO_2) laser, with an active medium isotopic gas	9300 nm	FRP
Gas, far infrared	Soft tissue procedures	Carbon dioxide (CO_2) laser with an active medium of a mixture of gases	10,600 nm	CW, GP, FRP

The type of laser and its emission spectrum is listed in column 1; column 2 indicates the general usage in dentistry; column 3 describes the active medium; column 4 shows the emission mode with the following abbreviations: *CW* continuous wave, *GP* acquired pulse, *FRP* free-running pulse

2.6 History of Laser Development

After Einstein's laser theory was published, experiments to build a device didn't appear until the 1950s. Charles Townes of Columbia University in New York began working with a microwave amplification in 1951. In 1957 another Columbia graduate student Gordon Gould described in his laboratory notebook the basic idea of how to build a laser. That was considered the first time the term was used. The first laser was built by Dr. Theodore Maiman in 1960 at Hughes laboratory [16]. He used a 1 × 2 cm synthetic ruby cylinder for the active medium and photographic flash lamps for the pumping mechanism and produced a brilliant red light pulsed emission. At the end of that year, three other scientists at Bell labs developed the helium-neon gas laser with a continuous output of red light. Other wavelength instruments were rapidly developed during that decade. Notable is the 1964 invention of the carbon dioxide laser, with a 10.6 micron wavelength, by Kumar Patel, and, in the same year, the Nd:YAG laser was built by Joseph Geusic and Richard Smith, all at Bell labs. In the spring of 1970, a team of Russian and American scientists independently developed a continuous wave room temperature semiconductor laser [17]. The first laser specifically designed for dentistry was marketed in 1989 [18].

2.7 Laser Delivery Systems

Laser energy can be delivered to the surgical site by various means that should be ergonomic and precise. There are three general modalities:

- **An optical fiber**
- **A hollow waveguide**
- **An articulated arm**

Fig. 2.5 An optical fiber assembly

Fig. 2.6 A hollow waveguide assembly

2.7.1 Optical Fiber

An optical glass fiber usually made of quartz-silica. This glass core conducts the laser beam along its length. A thin polyamide coating surrounds the core to contain the light, and a pliable thicker jacket covers both to protect the integrity of the system. A specific connector couples the fiber to the laser instrument; a handpiece and tip are added to the operative end. Figure 2.5 shows a typical optical fiber assembly.

2.7.2 Hollow Waveguide

A hollow waveguide is a jacketed flexible tube. The internal surface has a reflective coating like silver iodide to allow the beam's transmission. A series of protective jackets complete the system. The waveguide is connected to the emission port on the laser, and a handpiece and optional tip are connected to the operative end. Figure 2.6 shows a typical hollow waveguide assembly.

2.7.3 Articulated Arm

An articulated arm consists of a series of reflective hollow tubes with pivoting internally mirrored joints along its length. The arm has a counterweight to provide ease in movement. The laser emission port is coupled with the first tube, and a handpiece and optional tip are added to the operative end of the distal tube. Figure 2.7 shows the basic arm assembly.

Shorter wavelength instruments, such as KTP, diode, and Nd:YAG lasers, have small, flexible fiber-optic systems

Fig. 2.7 An articulated arm delivery system

with bare glass fibers or disposable tips that deliver the laser energy to the target tissue. A few low-powered diode lasers are offered as handheld units with disposable glass tips.

Erbium devices are constructed with more rigid glass fibers, semiflexible hollow waveguides, or articulated arms. Carbon dioxide lasers use waveguides or articulated arms. Some of the erbium systems employ small quartz or sapphire tips, and carbon dioxide instruments employ metal cylinders that attach to the handpiece. All of the tips are used for contact with target tissue, although they can direct the beam toward the tissue when not directly touching it. Other lasers in these wavelengths use tip less (and therefore noncontact) delivery systems. In addition, some procedures demand that a clinician not directly contact the tissue. In addition, the erbium lasers and the 9.3 micron carbon dioxide laser employ a water spray for cooling hard tissue.

2.7.4 Contact and Noncontact Procedures

All conventional dental instrumentation, either hand or rotary, must physically touch the tissue being treated, giving the operator instant feedback. As mentioned, dental lasers can be used either in contact or out of contact. Clinically, a laser used in contact can provide easy access to otherwise difficult-to-reach areas of tissue. The fiber tip can easily be inserted into a periodontal pocket to remove small amounts of granulation tissue, for example. In noncontact, the beam is aimed at the target at some distance away from it. This modality is useful for following various tissue contours, but the loss of tactile sensation demands that the surgeon pays close attention to the tissue interaction with the laser energy.

The active beam is focused by lenses. With the hollow waveguide or articulated arm, there will be a precise spot at the focal point where the energy is the greatest, and that spot should be used for incisional and excisional surgery. For the optic fiber, the focal point is at or near the tip of the fiber, which again has the greatest energy. When the handpiece is moved away from the tissue and away from the focal point, the beam is defocused and becomes more divergent. At a small divergent distance, the beam can cover a wider area, which would be useful in achieving hemostasis. At a greater distance away, the beam will lose its effectiveness because the energy will dissipate. This concept will be further discussed in ► Sect. 2.8.

2.7.5 Aiming Beam

All the invisible dental lasers are equipped with a separate aiming beam, which can either be laser or conventional light. The aiming beam is delivered coaxially along the fiber or waveguide and shows the operator the exact spot where the laser energy will be focused.

2.8 Emission Modes

There are two natural modes of wavelength emission for dental lasers, based on the excitation source: continuous wave and free-running pulse. A subset of continuous wave mode is a gated pulsed emission, where there is some means of modification performed after the beam is initially generated.

2.8.1 Continuous Wave

Continuous wave emission means that laser energy is emitted continuously when the laser is switched on and produces constant tissue interaction. These lasers are pumped with a constant direct current electrical field source. KTP, diode, and older model CO_2 lasers operate in this manner. The energy and/or power have a level output.

2.8.2 Free-Running Pulse

Free-running pulse emission occurs with very short bursts of laser energy due to a very rapid on-off pumping mechanism. Two examples are a high-powered strobing lamp or a radiofrequency electronic field. The usual pulse durations of energy can be measured in microseconds, and there is a relatively long interval between pulses. The power produced has a high peak and low average level, which will be discussed in ► Sect. 2.9. Nd:YAG, Nd:YAP, Er:YAG, and Er,Cr:YSGG and some carbon dioxide devices operate as free-running, direct pulsed lasers.

2.8.3 Gated Pulsed Mode

Some laser instruments are equipped with a mechanical shutter with a time circuit or a digital mechanism to produce pulsed energy. Pulse durations can range from tenths of a second to several hundred microseconds. Some diode and carbon dioxide lasers have these gated pulses from their continuous wave emission. There can be high peak and low average power levels produced.

Another method to produce very short pulses is called Q switching (the Q indicates the quality factor of the optical resonator.) An attenuating mechanism modulates the rate of stimulated emission, while the pumping mechanism continues to provide energy into the resonator. When the Q switch is turned off (opened), the result is a very short pulse of light, on the order of tens of nanoseconds. Peak powers can be very high.

Alternatively, an acousto-optic modulator can be placed in the laser cavity to ensure that the phases of emission all constructively interfere with each other. This is called mode-locking and can produce pico- or femtosecond pulse durations with resulting extremely high peak powers.

Current dental lasers do not utilize Q switching or mode-locking emission modes.

2.9 Terminology

The laser instrument's wavelength has a unique and unchangeable photon energy emission. However, the clinician can adjust various parameters of that emission from both the control panel and the handpiece's position on the target tissue. Throughout the remainder of this book, various terms will be used to describe the laser procedures. The Glossary at the end of this chapter contains many of the terms and definitions that are standard for lasers.

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Table 2.3 Important terminology for laser use

Term	Definition	Abbreviation
Energy	The ability to do work	J (joule) or mJ (millijoule)
Fluence	Energy per area	J/cm^2
Power	Work performed over time	W (watt)
Power density	Power per area	W/cm^2
Beam size	The area of the projected laser beam on the tissue	(Usually measured in microns or millimeters)

Table 2.3 describes the fundamental terms that are common notations found in clinical procedures. A few of those terms will be described in more detail in this section.

2.9.1 Energy and Fluence

Energy is a fundamental physics term defined as the ability to do work. This energy is usually delivered in a pulse. A joule (J) is a unit of energy; a useful quantity for dentistry is a millijoule (mJ), which is one-one thousandth of a joule. Pulse energy is therefore the amount of energy in one pulse.

Fluence is a measurement of energy per area and is expressed as J/cm^2. This is also known as energy density. Procedures on different dental tissues will require various fluences for both efficiency and safety.

2.9.2 Power and Power Density

Power is the measurement of work completed over a period of time and is measured in watts (W.) One watt equals 1 joule delivered for 1 s.

Power density is the measurement of power used per unit of area and is expressed as W/cm^2. Alternate terms are intensity or radiance.

2.9.3 Pulses

Except for continuous wave operation, all lasers can produce pulsed emission; that is, several bursts of energy can occur in a second. The number of pulses per second (pps) is the usual term applied, and an alternate word is hertz. That word could be confused with the description of the number of cycles per second of alternating electrical current.

Pulse Duration, Pulse Interval, and Emission Cycle

The length of each pulse is called the pulse duration or sometimes pulse width and can be as short as one microsecond (10^{-6} s.) The pulse interval is that time period between the pulses, when no laser energy is emitted. The emission cycle is the ratio, usually expressed as a percentage of the individual pulse duration to the total time of that pulse duration plus the subsequent pulse interval. In other words, if the pulse duration is 0.5 s and the pulse interval is 0.5 s, that is one pulse per second and the emission cycle is 50%. The emission cycle is sometimes referred to as the duty cycle. Similar to hertz, that similarity is unfortunate since the phrase duty cycle actually refers to how long on a device can remain on and working before it must be switched off for cooling.

2.9.4 Average and Peak Power

Average power is what the tissue experiences during the duration of the procedure. Peak power is the power of each pulse. Obviously, with continuous wave lasers, there is really no peak power. For any pulsed laser, the average power will be less than the peak power.

The calculation of peak power is the result of dividing the pulse energy by the pulse duration. For example, a 100 mJ pulse with a duration of 100 µs would have a peak power of 1000 W. This a common peak power achieved in free-running pulsed dental lasers. However, those same lasers are generally used with a low pulses per second parameter, which means that the pulse interval is relatively large. This results in a correspondingly low percentage emission cycle. Using the above example of a pulse duration of 100 µs at 50 pulses per second, the total emission time is 5/1000 of a second, which means the total pulse interval is 995/1000 of a second. The duty cycle is then calculated at approximately 1%. Figure 2.8 shows a graphic depicting the relationship between peak and average power with basic laser parameters.

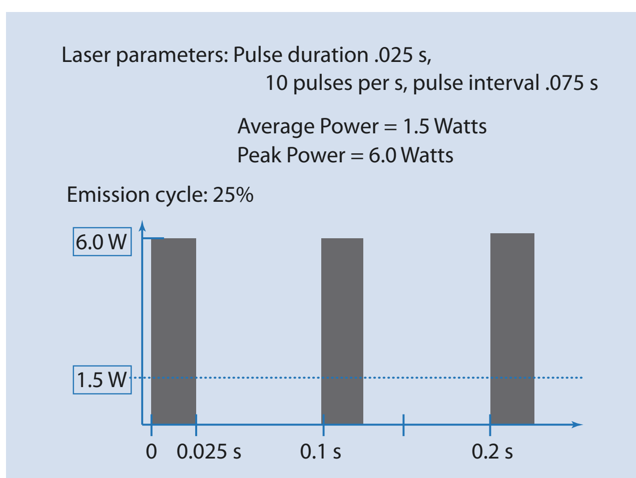

Fig. 2.8 This graphic shows the relationship between peak and average power along with the emission cycle. The pulses of laser energy are depicted in *dark gray* bars. The individual pulse duration is 0.025 s and the pulse interval is 0.075 s. Each pulse has a peak power of 6 watts, but the average power is 1.5 watts, due to the emission cycle of 25%

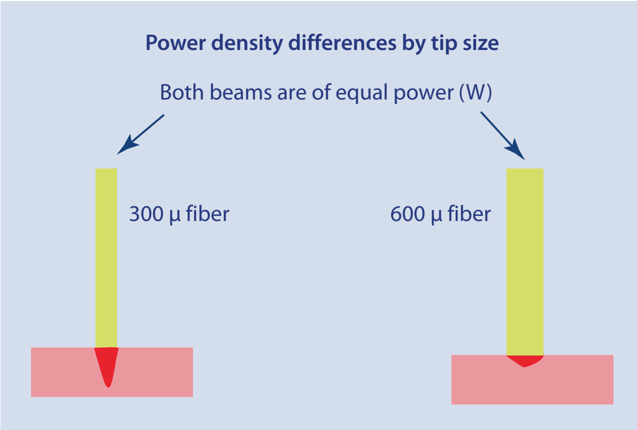

Fig. 2.9 This graphic shows the difference between power density areas using a 300 micron tip/beam size and a 600 micron tip/beam size. The smaller fiber has a larger area of interaction because of the larger power density calculation

2.9.5 Beam Size

This is the area of the photonic emission that will interact with the target tissue. Lasers that employ tips have their nominal size indicated on the tip, and noncontact lasers also have an area of focus. Laser tips are available in several diameters; typical sizes are 200, 300, 400, and 600 microns. Other tip less lasers can produce beam sizes with similar measurements. Clearly, the fluence and power density measurements will be based on that beam size. As mentioned previously, the laser beam will diverge at a prescribed angle from a quartz or sapphire tip, increasing its area. Likewise a focused beam from a tip less delivery system will have a larger area when the beam is defocused. If the average power remains the same, both the fluence and the power density will be reduced.

Conversely, choosing a smaller diameter tip or producing a smaller focused area would increase the fluence or power density with the same laser output setting. This could affect the tissue interaction. Figure 2.9 is a graphic showing how the difference in tip sizes would affect the power density.

2.9.6 Hand Speed

In addition to the above parameter adjustments, an important principle of laser use is the speed at which the beam moves on the target tissue. A slower speed will increase the power density because of the longer time the energy remains in the tissue and could result in a larger area of interaction. This may or may not be a desirable effect, especially if the treatment objective is a minimally invasive procedure. Figure 2.10 shows a laboratory comparison of hand speed for soft tissue incision.

Fig. 2.10 An 810 nm diode laser with a 400 micron contact fiber was used at 1.0 W continuous wave for both incisions on a porcine maxilla specimen. The left incision was made with a faster vertical movement than the right incision. The left incision is narrower; the right incision is wider and more ragged and produced a higher temperature in the tissue. Thus, the power density was larger for that incision

Summary
This chapter provided details of light and lasers. From basic experiments with light to the sophisticated development of different instruments, it should be clear that laser photonic energy can be precisely produced and controlled to be used for dental procedures.

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