Lasers in Oral and Maxillofacial Surgery

Stefan Stübinger
Florian Klämpfl
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Hans-Florian Zeilhofer
Editors

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Preface

In 2020, the laser will celebrate its 60th anniversary. While in the beginning, it was a solution looking for a problem; it is meanwhile widely spread in industry, science, medicine, in offices, or even at home. It is used to weld car bodies, to prove the existence of gravitational waves, to treat eyes, or to measure distances. These are only a few examples of its applications. This wide use results from its unique properties. It is a light source which can be focused on a very small spot; it is typically highly monochromatic, and there are lasers which produce pulses with a duration in the fs second regime. These pulses are among the shortest events created by humans. Light, which takes only a second to travel almost eight times around the earth, travels less than the diameter of a human hair during the duration of these pulses. While for a long time these so-called ultrafast lasers were used only in scientific laboratories, they have found these days their way into application, even medical application. Today, they are used in fs-Lasik systems to carry out the flap cut during refractive cornea surgery, which is probably the most famous application of lasers in medicine. Refractive cornea surgery is only possible with a laser. It requires high precision. The error must be in the range of micrometers or less. This is only possible by an automated system, even the most capable surgeon cannot work with such precision. And a laser is the perfect tool for automated processes as it works contact free. This is an advantage which is also taken by car manufactures when they weld car bodies with lasers or one by speakers using a laser pointer to emphasize important parts of slides projected on a wall. Working contact free however has not only advantages regarding automation it also has medical advantages during surgeries not limited to eye surgery. Applying no force reduces the damage to surrounding tissues, after the surgery fewer edemas develop, and it is easier to maintain sterility during surgery. Besides this, studies showed also that the healing process after a surgery is quicker than in the conventional surgery. However after all these advantages, one cannot neglect the disadvantages of using a laser for surgery. First of all, lasers are expensive. Even the example of the laser pointer proves this. A simple wooden stick for pointing costs less than a laser pointer. But advantages of the laser pointer count in this case. Second, lasers require safety measures; this does not apply to a laser pointer, but it is easily understandable that a laser which can ablate tissue is highly dangerous for the human eye. This applies even to lasers which cannot ablate tissue but which exceed a certain power limit. Third, a laser used for surgery requires new skills of surgeons. The techniques they trained and learned using traditional instruments over years do not apply anymore to lasers, so they start again from the beginning in this case. But these disadvantages can be overcome, and one can benefit from the advantages a laser provides. This is also one of the points where this book tries to help. It will help physicians and engineers to understand how to take advantage of lasers especially in the area of maxillofacial applications and to give an impression of what can be done with lasers in this area today.

The book is split into two parts. The first part covers the physical fundamentals. It cannot replace more detailed studies in physics or even a good book about laser physics, optics, or laser tissue interaction, but it should help the reader without previous knowledge to understand the second part of the book which covers a broad range of applications. The first part itself is divided into four chapters. After this introduction, one chapter offers a brief revision of the necessary physical fundamentals so the understanding of the following two chapters is easier. The third chapter gives an introduction to lasers, their design, and function with regard to the systems normally used in maxillofacial surgery. The fourth chapter describes the basics of how these lasers interact with tissue, so it lays the foundation for the second part.

Overall, the second part covers five major clinical and technical topics. Firstly, different laser treatment regimes of skin and mucosa are presented. Thereby, the authors set a clear focus on the usage of lasers for cancer therapy and oral rehabilitation. The second key aspect addresses the application of various laser wavelengths for hard tissue ablation. Besides enamel and dentin, state-of-the-art and innovative developments in laser bone surgery are also described. The third part summarizes special applications of lasers in oral and cranio-maxillofacial surgery. The goal is to provide the reader with current and approved clinical procedures of surgical and non-surgical laser applications. In this respect, two chapters also give an overview of implementing laser light for diagnostic or planning issues. The fourth part gives an insight into current research and future trends in laser technology. Novel and advanced potentials and scopes for manufacturing processes are discussed. Finally, the book closes with a chapter on general laser safety.

We hope that you enjoy this first edition of *Lasers in Oral and Maxillofacial Surgery* and that it becomes a trusted partner in your clinical and educational experience. It is hoped that the information and techniques included in the present work will provide clinicians with sufficient knowledge to help them achieve successful and sustainable results and provide their patients with satisfaction and comfort as a result of the treatment.

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Part I

Laser Fundamentals

Physical Fundamentals

1

Florian Klämpfl

Contents

Abstract

The chapter gives a short introduction into the physical fundamentals of light propagation and the interaction of light with matter. The chapter is neither a strict scientific description nor does it replace a textbook. It should only help the reader to understand the book more easily, and it should be a starting point for further studies.

Keywords

Physical fundamentals of light
Light propagation · Light-matter interaction

1.1 Prequel

This chapter tries to summarize important physical fundamentals to enable the reader to understand the remainder of this book. However, it cannot replace a good textbook on optics or describe these fundamentals in a strict scientific manner. For this, the bibliography of the chapter contains several references: [1–3].

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Light is a physical phenomenon that is fundamental to human life. For example, the energy from the sun is transferred to the earth by light, and furthermore, approximately 80% of the information input to humans is by light through the eyes. Due to this, for several millennia, humans have been thinking about the nature, behavior, and properties of light.

1.2 Basic Properties of Light

Over time, several models have been developed, which allow to explain light. The simplest model uses the so-called geometrical optics.

1.2.1 Geometrical Optics: Light as Rays

Geometrical optics assumes that light consists of rays. This means that light starts at a certain point and propagates in a straight line until it hits a surface that absorbs it or changes its direction. Geometrical or ray optics can be used to explain phenomena of light reflection or refraction, so the basic behavior of optical elements like lenses, mirrors, or prisms can be explained. However, effects like diffraction or polarization cannot be described by ray optics, neither is there a good explanation for the idea of "color" in terms of ray optics. To explain these effects, a different model is needed, which describes light as waves.

1.2.2 Wave Optics

The base of wave optics is the *Maxwell equations* [4]. This is a set of partial differential equations that describe the behavior of electromagnetic fields, and as light is an electromagnetic field, light propagation can be described by the Maxwell equations. Making a few assumptions (nonconducting medium, no space charges), two equations can be derived from the Maxwell equations, which are similar to wave equations, and thus, light can be described as a wave. Two equations are needed because light consists of both an electric field/wave and a magnetic field/wave in terms of wave optics. These two waves oscillate perpendicular to each other as well as to the propagation direction of light, so light is a traversal wave: it oscillates perpendicular to its propagation direction. As the electric and magnetic radiation fills the whole space, they are also called fields. Thus, in terms of wave optics, light consists of an electric field and a magnetic field, which both contribute to the behavior of light. Both fields are vector fields, i.e., at each point, the field has not only a value but also a direction.

The remainder of this chapter will concentrate on the electric field because the electric field/wave is often better suited for an explanation for the behavior of light. Besides this, the direction of the electric field also defines the polarization of a light wave. A light wave with linear polarization has an electric field where the vectors of the field always point in the same direction. Another important property is the wavelength of light: it is a physical unit associated with its color. By dividing the speed of light by its wavelength, one gets the associated frequency of the light wave.

While wave optics covers many effects, some effects cannot be explained by it. One example is the photoelectric effect: by irradiating matter with light, it is possible to break away electrons. If this effect is present, it shows a threshold regarding the wavelength: above a certain wavelength, it does not happen, not even at higher intensities.

1.2.3 Photons

This photoelectric effect can be explained by assuming that light consists of particles, so-called photons. A photon has a certain energy depending on its wavelength. If this energy exceeds the energy needed to break the bonding of an electron to its atom, the electron can be released from the atom when the photon is absorbed by the atom. This effect is hard to explain by ray or wave optics. So in this case, it is useful to assume that light consists of photons.

In general, it cannot be said that a certain model of light is the best model for all purposes. It depends on the application and/or the effect that shall be explained which model is the most useful.

1.3 Light Propagation

When working with light or lasers, it is important to be able to influence the direction of the light. The simplest means to change the direction of light is a mirror. It reflects the incoming light back following the law that the angle of incident equals the angle of reflection. This is illustrated by Fig. 1.1: $\Theta_1 = \Theta_2$.

A mirror typically consists of a substrate that defines its shape and a highly reflective coating that is responsible for reflecting the light. The simplest case of a mirror is a plane mirror. A plane mirror does not change the angle between the rays of a beam of light; a parallel beam reflected by a plane mirror stays a parallel beam. Plane mirrors are, for example, used to guide a laser beam from the laser source to the processing/treatment area. If the angle between the rays of a beam of light needs to be changed, a curved mirror can be used. For example, a curved mirror with a concave, spherical shape can be used to focus a parallel beam into a small spot.

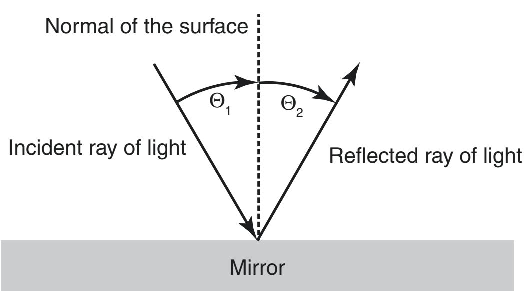
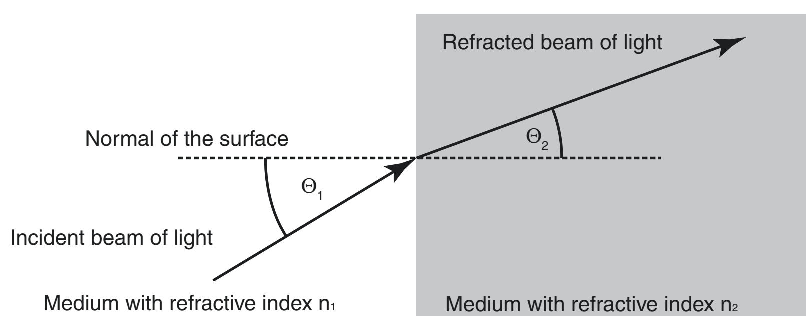


Fig. 1.1 Principle of a plane mirror

Another phenomenon that can be used to change the direction of light is refraction. Refraction happens when light propagates from one medium to another where it has a different propagation speed. The propagation speed of light in a medium is described by the index of refraction. The refractive index is a factor that describes how much faster the light propagates in vacuum than in the medium at hand. So, to get the velocity of light in a medium, the speed of light in vacuum must be divided by the refractive index. Typical values for the refractive index of glasses and tissue are around 1.5. The change in direction by refraction is described by Snell's law; see Fig. 1.2. It says that the refractive index of the medium where the light beam comes from (n_1) multiplied by the sine of the angle of incident (θ_1) is equal to the refractive index of the medium where the light goes to (n_2) multiplied by the sine of the angle of the refracted light beam (θ_2) or written as a formula $n_1 \bullet \sin \theta_1 = n_2 \bullet \sin \theta_2$.

So, when light propagates from air to glass, it is always refracted toward the normal surface. In case that light propagates perpendicular to the surface of the interface from one medium to the other, refraction does not change its direction. The effect of refraction is used by lenses to change the direction of light. Almost any optical system makes use of lenses; the human eye uses lenses for imaging, cameras typically use lenses for imaging, and laser system uses lenses for focusing the laser beam into a small spot. A lens is made out of a material that is transparent with regard to the wavelength at hand. It has two optically relevant surfaces with a defined shape,

Fig. 1.2 Snell's law



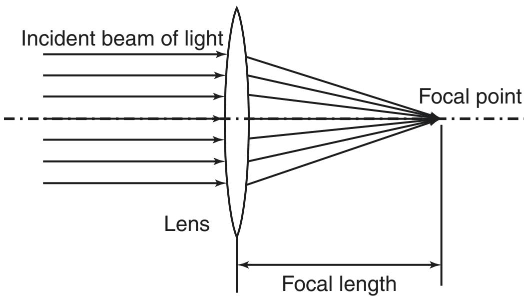


Fig. 1.3 Focal length of a lens

which define the properties of the lens. Those surfaces can be plane, spherical, or aspherically curved, and they can be concave or convex; what shape the surfaces have depends on the purpose of the lens. The shape of the surface together with the refractive index of the lens material defines one important property of a lens: its focal length. The focal length is the distance at which a parallel beam of light is focused by the lens into a single spot. This is illustrated in Fig. 1.3.

This property of a lens is used, for example, to focus a laser beam into a single spot. However, a real lens does not work as well as the drawing suggests. It has aberrations. For example, if the surface is spherical, not all rays meet in one point, and the outer rays are focused at a shorter focal length. This property is called spherical aberration. Another aberration is wavelength dependent. The refractive index of a material is not constant with the wavelength; this effect is called dispersion. Due to dispersion, light of different colors is refracted less or more. While for a lens this effect is not desired, it is used by prisms to split up light into its components depending on the wavelength.

1.4 Light-Matter Interaction

When discussing the behavior of light, it is not only necessary to have a model of light, but it is also necessary to have a model of the objects with which light is interacting. For matter, different models exist at different levels of detail. For the understanding of this chapter, it is sufficient to know that matter consists of atoms, and these atoms consist of a nucleus that is positively charged and of electrons that are negatively charged. This simple model allows already to explain sufficiently well phenomena like the absorption of light by matter or certain types of scattering. The electric field of the light wave accelerates the electrons, and they start to oscillate with the frequency of the incident light wave. Depending on the material and the incident frequency, the energy is transferred to the lattice of the material, so the lattice starts to vibrate, which means the material is heated. It could also be that, by the movement of the electrons, the energy is reemitted—as by an antenna where also moving charges are responsible for the emission of a wave. If a charge moves back and forth emitting energy/a wave, this is called a Hertzian dipole. The emitted field and the resulting wave of a Hertzian dipole have a very characteristic appearance: in the direction of the oscillation vector, the *dipole moment vector*, no electric field is emitted. In all other directions, lines of the electric field form a plane with the dipole moment vector. So the direction of the electric field vector does not change over time at a given location, so the emitted light is linearly polarized.

1.5 Scattering of Light

When light interacts with matter, different effects happen: for example, the light might be reflected, absorbed, refracted, or scattered. All these effects happen in tissue. When talking about light propagation in the tissue, scattering is one of the dominant effects. Scattering means that incident light changes its direction when hitting a *scattering center*. In the simplest case, nothing else happens. This is *elastic scattering*. However, it is also possible that the light changes not only its direction but also its wavelength. This is *inelastic scattering*.

1.5.1 Elastic Scattering

Elastic scattering is something that can be experienced daily. Elastic scattering is the reason why the sky is blue, but it is also the reason why clouds or milk appear white. It is the reason why a finger appears to glow red when it is irradiated even with a low-power (class 1) red laser pointer. In case of the blue sky, the molecules of the atmosphere are the scattering centers; in case of the cloud, it is the small water droplets a cloud consists of. In case of tissue, scattering centers are the cells or parts of them. While scattering is an interesting effect, it is something that is unwelcome when doing diagnostics or therapeutics with light: the incident light does not only reach the tissue at which it is aimed; it might also affect the surrounding tissue, or in case of diagnostics, the received light is not only received by the target structure but also by other structures. While the effect cannot be avoided, understanding it helps to deal with it. The most suitable model to describe elastic scattering in light is *Mie theory* [5]. It is an approach to solve the Maxwell equations in the environment of spherical particles. While understanding this theory involves a lot of mathematics, the overall approach can be easily understood and some conclusions can be drawn from it. Mie theory assumes that the incident wave is absorbed by dipole structures in the particle. Those dipoles remit the wave again. The number of dipoles that absorb the wave depends on the size of the particle. So, the bigger the particle, the more dipoles are involved. The radiations of the dipoles interfere, so interference patterns appear inside the reemitted radiation. Furthermore, as a dipole emits in all directions, the light wave is deflected from its incident direction. However, this happens not in one fixed direction, but in all directions with different intensities. The detailed angular intensity distribution depends on several parameters like wavelength, size of the particle, refraction index of the particle, and refraction index of the environment. For example, the shorter the wavelength is, the more deviation happens, or the bigger the particle is, the less the light is deflected. Significant elastic scattering happens only if the particle has a size in the magnitude of the wavelength or below. When the particles are very small, the deviation is the highest: in this case, only one dipole is excited, and in this case, the intensity of the scattered light follows exactly the characteristics of a dipole. This happens, for example, if the scattering centers are only single molecules. This type of scattering is called Rayleigh scattering. While it can be also described by Mie theory, it has a separate name due to historic reasons: it was discovered and investigated independently of Mie theory, and it took some time until it was understood that both types of elastic scattering can be described by the same mathematical model. The effect that the red laser pointer makes the whole fingertip glow is mostly Mie scattering.

1.5.2 Inelastic Scattering

When the light changes not only its direction but also its “color,” i.e., its wavelength, it is called inelastic scattering. Several mechanisms and types for inelastic scattering are known. For medical applications, two types are the most important ones: Raman scattering and fluorescence. In case of Raman scattering, the wavelength can be increased or decreased, i.e., the photons can gain or lose energy. The energy difference is left or comes from the scattering center. Those are atoms or molecules that might change their vibrational state. Raman scattering is something that happens normally together with Rayleigh scattering. However, the intensity of the Raman scattered light is magnitudes lower than that of the Rayleigh scattered light, so it is something that is not experienced in daily life. Raman scattering can only be measured with an appropriate setup. In case of Raman scattering, the scattered light is not limited to one wavelength or a small band, but the scattered light has a rather broad spectrum with certain peaks. This spectrum is very characteristic of the matter of the scattering center, and it can be considered as a fingerprint of the material. So, Raman scattering can be used for the identification of materials.

Fluorescence is very similar to Raman scattering. However, the wavelength of the scattered light is always longer, i.e., the photon energy is lower. In case of fluorescence, the incoming photon is absorbed by a resonant transition of the molecule or atom, which enters an excited state.

After a short time (~nanoseconds), the excited particle returns through several intermediate levels to the ground state by releasing the absorbed energy of the photon again. Part of this energy is released or emitted as a photon. As this photon must have a lower energy than the incident photon, the wavelength of the scattered light is shorter. Fluorescence is something that can be experienced daily. For example, neon tubes use this effect to generate white light. But fluorescence also has its application in medicine: in diagnostics, it is used by fluorescence microscopy. Furthermore, photodynamic therapy takes advantage of it to generate highly reactive molecules and treat certain diseases.

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An Introduction to Laser

2

Gholamreza Shayeganrad

Contents

Abstract

For a better understanding of the special advantages of laser light in oral and maxillofacial surgery, we need to know the principle of generation of laser light and the properties that distinguishes it from conventional light or other energy sources, as well as, how a laser works and the different types of lasers that can be used in medical applications. Light theory branches into the physics of quantum mechanics, which was conceptualized in the twentieth century. Quantum mechanics deals with behavior of nature on the atomic scale or smaller.

This chapter briefly deals with an introduction to laser, properties of laser light, and laser-beam propagation. It begins with a short overview of the theory about the dual nature of light (particle or wave) and discusses the propagation of laser beam, special properties of laser light, and the different types of lasers that are used in medical applications.

Keywords

Laser principle · Coherence · Gaussian beam optics · Laser medicine · Laser surgery

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2.1 Introduction

Light is electromagnetic radiation within a certain portion of the electromagnetic spectrum that includes radio waves (AM, FM, and SW), microwaves, THz, IR, visible light, UV, X-rays, and gamma rays. The primary properties of light are intensity, brightness, wave vector, frequency or wavelength, phase, polarization, and its speed in a vacuum, c = 299, 792, 458 m/s. The speed of light in a medium depends on the refractive index of the medium, which is c/n. Intensity is the absolute measure of power density of light wave and defines the rate at which energy is delivered to a surface. Brightness is perceptive of intensity of light coming from a light source and depends on the quality of the light wave as well. The frequency of a light wave determines its energy. The wavelength of a light wave is inversely proportional to its frequency. The wave vector is inversely proportional to the wavelength and is defined as the propagation direction of the light wave. Phase cannot be measured directly; however, relative phase can be measured by interferometry. A light wave that vibrates in more than one plane like sunlight is referred to as unpolarized light. Such light waves are created by electric charges that vibrate in a variety of directions. Depending on how the electric field is oriented, we classify polarized light into: linear polarization, circular polarization, elliptical polarization, radial and azimuthal polarization. We say a light wave is linearly polarized if the electric field oscillates in a single plane. If electric field of the wave has a constant magnitude but its direction rotates with time at a steady rate in a plane perpendicular to the direction of the wave, it is called a circular polarized wave. In general case, electric field sweeps out an ellipse in which both magnitude and direction change with time, which is called elliptical polarized wave. Radially and azimuthally polarized beams have been increasingly studied in recent years because of their unique characteristic of axial polarization symmetry, and they can break the diffraction limit with a strong longitudinal electromagnetic field in focus [1–3]. The unpolarized light can be transformed into polarized light by wire grid, polaroid filter, molecular scattering, birefringent materials, retarder waveplates, reflection at Brewster's angle, polarizing cubes, total internal reflection, optical activity, electro-optic effect, or liquid crystals.

The understanding of light refers to the late 1600s with raising important questions about the dual nature of light (particle or wave). Sir Isaac Newton held the idea that light travels as a stream of particles. In 1678, Dutch physicist and astronomer Christiaan Huygens believed that light travels in waves. Huygens' principle was the successful theory to introduce the appearance of the spectrum, as well as the phenomena of reflection and refraction, which indicated that light was a wave. Huygens suggested that the light waves from point sources are spherical with wavefronts, which travel at the speed of light. This theory explains why light bends around corners or spreads out when shining through a pinhole or slit rather than going in a straight line. This phenomenon is called diffraction. Huygens stated that each point on the wavefront behaves as a new source of radiation of the same frequency and phase. Although Newton's particle theory came first, the wave theory of Huygens better described early experiments. Huygens' principle predicts that a given wavefront in the present will be in the future.

None of these theories could explain the complete blackbody spectrum, a body with absolute temperature $T > 0$ that absorbs all the radiation falling on it and emits radiation of all wavelengths. In 1900, Max Planck proposed the existence of a light quantum to explain the blackbody radiation spectrum. In 1905, Albert Einstein individually proposed a solution to the problem of observations made on photoelectric phenomena. Einstein suggested that light is composed of tiny particles called "photons," and each photon has energy of $h\nu$, where $h = 6.63 \times 10^{-34}$ J/s is Planck's constant and ν is the frequency of photons.

In 1924, de Broglie proposed his theory of wave–particle duality in which he said that not only photons of light but also particles of matter such as electrons and atoms possess a dual character, sometimes behaving like a particle and sometimes as a wave. He gave a formula, $\lambda = h/p$, to connect particle characteristics (momentum, p) and wave characteristics (wavelength, λ). Light as well as particle can exhibit both wave and particle properties at the same time. Light waves are also called electromagnetic waves because they are made up of both electric (E) and magnetic (H) fields. Electromagnetic radiation waves can transport energy from one location to another based on Maxwell's equations. Maxwell's equations describe the electromagnetic wave at the classical level. Light is a transverse wave and electromagnetic fields E and H are always perpendicular to each other and oscillate perpendicular to the direction of the traveling wave. The particle properties of light can also be described in terms of a stream of photons that are massless particles and traveling with wavelike properties at the speed of light. A photon is the smallest quantity (quantum) of energy that can be transported.

In 1803, Thomas Young studied the wave properties of light by interference of light through shining two narrow slits separated equally from the center axis. The light emerging from the double-slit spreads out according to Huygens' principle, and the interference pattern appears after overlapping two wavefronts as shown in Fig. 2.1. The two beams exiting from the two slits are electromagnetic waves and can be described by $A_0\sin(2\pi\nu t)$ and $A_0\sin(2\pi\nu t + \delta)$, respectively, where A_0 is the field amplitude, ν is the frequency of light, t is the time, and $\delta = d\bullet\sin(\theta)$ is the path difference between the two beams at angle θ.

2.2 Physics of Laser

Although there are many different types of lasers, most lasers follow similar operation principle. The Light Amplification by Stimulated Emission of Radiation (LASER) was developed by Theodore Maiman first [4]. Since then, laser have found a wide range of different scientific and technical applications from the industrial to applied and fundamental research including information technology, consumer electronics, medicine, industry, military, law enforcement, and research. The invention of the laser in 1960 dates from the nineteenth century, when Albert Einstein explained the concept of "stimulated emission of radiation" in a paper delivered in 1916 and German physicist Max Planck proposed the quantum theory of light in 1900. As mentioned before, Planck assumed energy should be composed of discrete packets, or quanta, in the form of photons. According to Planck's radiation law, when an oscillator changes from an energy state E_2 to a state of lower energy E_1, a photon

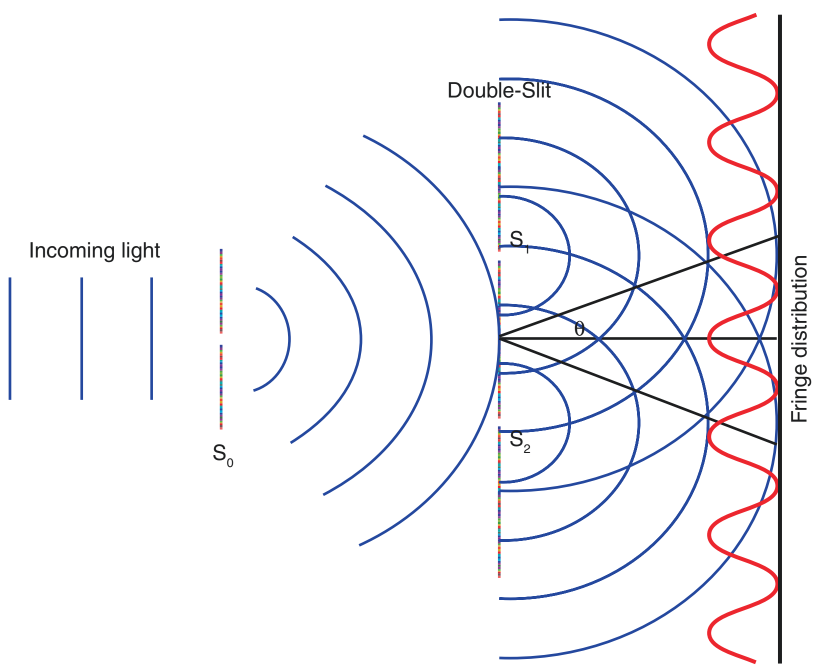

Fig. 2.1 Thomas Young's double-slit interference experiment

with discrete amount of energy $E_2 - E_1 = h\nu$ emits.

The Danish physicist Niels Bohr expanded the quantum theory to help explain the structure of atoms called Bohr's model. In Bohr's model, the nucleus of an atom is surrounded by orbiting electrons that are confined to specific energy states depending on the chemical structure of the atom. In other words, electrons can only occupy certain energy states, which are fingerprints of each atom. An electron can absorb a photon and thereby can be pushed into a higher energy state, called absorption. When an electron is in an exited state, it is inherently unstable and will spontaneously drop to the lower energy states by releasing a photon, called spontaneous emission. The underlying principle of the laser phenomenon stimulated emission is purely a quantum effect. Einstein postulated that emission would be triggered by other photons, in which, an incoming photon of a specific frequency can interact with an excited electron causing it to drop to a lower energy state and release two photons with specific properties, including identical phase, frequency, polarization, and similar direction of propagation. The process of absorption, spontaneous emission, and stimulated emission is depicted in Fig. 2.2.

Notice that the root of the invention of laser lies in fundamental physics research, specifically, a 1917 paper by Albert Einstein on the quantum theory of radiation or stimulated emission, but it was a paper on laser theory published in 1958 by two physicists, Charles Townes and Arthur L. Schawlow, which spurred the race to make the first working laser. According to the Einstein principle, there is an equal probability that a photon will absorb or emit. Thereby, according to the

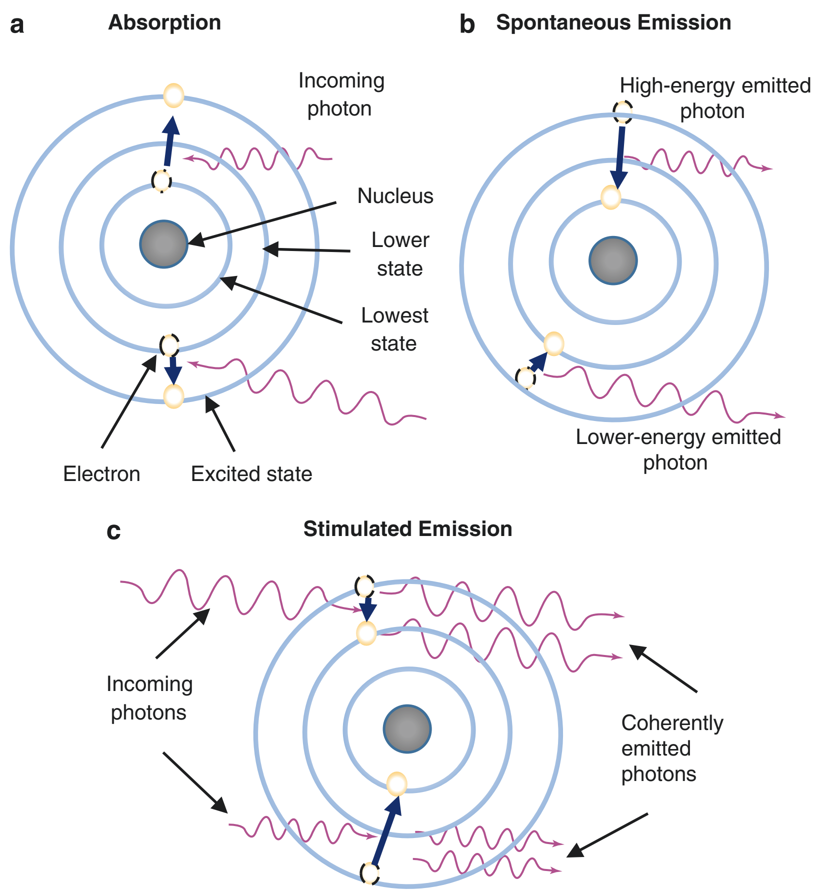

Fig. 2.2 Schematic of absorption (**a**), spontaneous emission (**b**), and stimulated emission (**c**) of two photons with different frequencies

Boltzmann distribution that when there are more atoms in the ground state than in the excited states and light is incident on the system of atoms, in thermal equilibrium, the probability of absorption of energy is much higher than emission. However, in the case that more atoms are in an excited state than in a ground state and strike with photons of energy similar to the excited atoms, many of atoms will induce the process of stimulated emission, whereby a single excited atom would emit a photon identical to the interacting photon. Under the proper conditions, a single input photon can result in a cascade of stimulated photons, and thereby amplification of photons will result. All of the photons generated in this way are in phase, traveling in the same direction, and have the same frequency as the input photon.

As shown in Fig. 2.3, a laser requires three major parts: (1) gain medium (e.g., gas, solid, liquid dye or semiconductor); (2) pump source (e.g., an electric discharge, flashlamp, or laser diode); and (3) the feedback system, e.g., optical resonator. For instance, in the case of the first invented laser, the gain medium was ruby, and the population inversion was produced by intense broadband illumination from a xenon flashlamp. However, in the case of diode-pumped lasers, the population inversion is produced by laser diode that benefits from higher total conversion efficiency. Laser wavelength emission is determined by the gain medium and the characteristics of the optical resonator (see, for example, [5–12]). It is noticeable that some high-gain lasers do not use an optical oscillator and work based on amplified spontaneous emission (ASE) without needing feedback of the light back into the gain medium. Such lasers emit light with low coherence but high bandwidth.

For optical frequencies, population inversion cannot be achieved in a two-level system. In 1956, Bloembergen proposed a mechanism in which atoms are pumped into an excited state by an external source of energy. A lasing medium consists of at least three energy levels: a ground state E_1, an intermediate (metastable) state; E_2, with a relatively long lifetime, t_s, and a high energy pump state; and E_3, as shown in Fig. 2.4. To obtain population inversion, t_s must be greater than t_3, the lifetime of the pump state E_3. Note

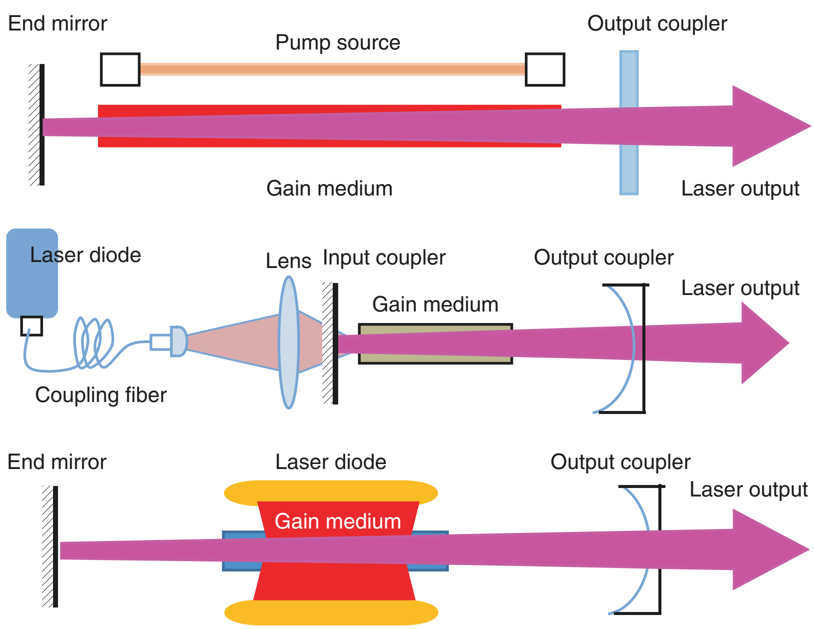

Fig. 2.3 Schematic diagram of a typical laser (top) flashlamp pumped, (middle) laser-diode end-pumped, and (bottom) laser-diode side-pumped configurations, showing the three major parts: (1) laser gain medium, (2) pump source, and (3) optical resonator

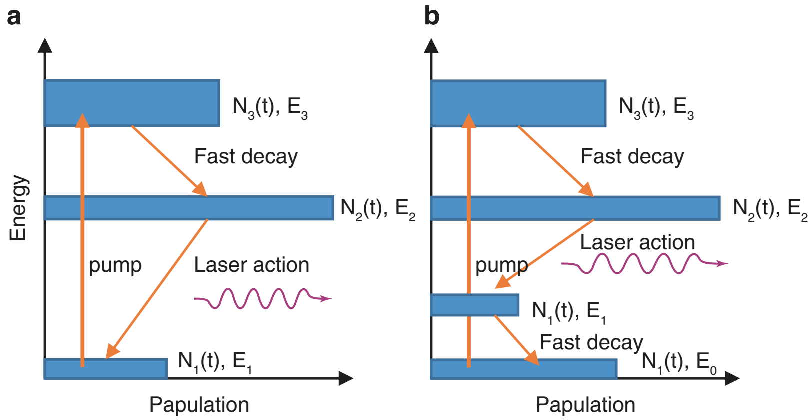

Fig. 2.4 Schematic diagram of three-level laser (**a**) and four-level laser (**b**)

that a characteristic of the three-level laser material is that the laser transition takes place between the excited laser level E_2 and the final ground state E_1, the lowest energy level of the system. The three-level system has low efficiency. The four-level system avoids this disadvantage.

Figure 2.4 compares schematically the three-level and four-level laser systems. In three-level lasers, initially, all atoms of the laser material are in the ground state level E_1. The pump radiation rises the ground state atoms to a short-lived pump state E_3. Atoms from this state undergo fast decay (radiationless transition) to a metastable state E_2. In this process, the energy lost by the electron is transferred to the lattice. A population inversion takes place between ground state and the metastable state where the lasing transition occurs. In general, the "pumping" level 3 is actually made up of a number of bands, so that the optical pumping can be accomplished over a broad spectral range. If pumping intensity is below laser threshold, atoms in level 2 predominantly return to the ground state by spontaneous emission. While, when the pump intensity is above laser threshold, the stimulated emission is the dominated processes compared with spontaneous emission. The stimulated radiation produces the laser output beam.

In the case of four-level lasers, the pump excitation extends again by radiation from the ground state (now level E_0) to a broad absorption band E_3. As in the case of the three-level system, the atoms so excited will transfer fast radiationless transitions into the intermediate sharp level 2. The electrons return to the fourth level E_1, which is situated above the ground state E_0, by the emission of a photon to proceed the laser action. Finally, the electrons return to the ground level E_0 by radiationless transition. In a true four-level system, the terminal laser level E_1 will be empty. To qualify as a four-level system, a material must possess a relaxation time between the terminal laser level and the ground level, which is fast compared to the fluorescence lifetime, t_s. In addition, the terminal laser level E_1 would be far above the ground state E_0 so that its thermal population can be considered as negligible. In a kind of situation, where the lower laser level is so close to the ground state that an appreciable population in that level occurs in thermal equilibrium at the operating temperature, the laser called quasi-three-level laser. As a consequence, the unpumped gain medium causes some reabsorption loss at the laser wavelength same as three-level lasers.

The purpose of the resonator is to provide the positive feedback necessary to cause oscillation. The resonator has mirror at the ends so that photons are reflected back and forth and are constantly renewing the process of stimulated emission as they strike more of the excited atoms in the laser medium. The mirrors also align the photons so that they force to travel in the same direction. Typically, one will be a high reflector (HR) and the other will be a partial reflector (PR). The latter is called output coupler that allows some of the light to transmit out of the resonator to produce the laser output beam. The buildup of oscillation is triggered by spontaneous emission. The produced photons by spontaneous emission are reflected by the mirrors back into the laser medium and amplified by stimulated emission. Other optical devices, such as prism, Q-switch modulators, filters, etalon, and lens, may be placed within the optical resonator to produce a tunable laser, pulsed laser, and narrow bandwidth laser or shape the laser beam.

If the gain medium has a homogeneous (Lorentzian) gain profile, as the oscillating intensity grows and the population of excited atoms depletes by causing sufficient stimulated emission, photons oscillating at ν_0 can emit from all atoms in the medium, and oscillation at frequency ν_0 can suppress oscillation at any other frequency under the gain profile. Generally, the oscillation will build up with frequency, which has maximum emission probability. However, in an inhomogeneously broadened gaseous medium, the additional oscillation at frequencies far away from ν_0 is also possible.

2.3 Laser Light Properties

The laser happens when stimulated-emission process is dominant compared with absorption and spontaneous emission. It means, in laser, stimulated emission leads to the unique characteristics, e.g., (1) coherence, (2) divergence and directionality, (3) monochromatic, and (4) brightness. These properties differentiate laser light from ordinary light and make it very interesting for a range of applications.

2.3.1 Coherence

Coherence of electromagnetic radiation means maintaining a constant phase difference between two points of wavefront of the wave in space (spatial coherence) and in time (temporal coherence). Coherence is one of the most important concepts in optics and is strongly related to the ability of light to exhibit interference effects. Temporal coherence is related to the intrinsic spectrum bandwidth of the light source, while spatial coherence can be affected by size of the light source. Laser radiation has high spatial and temporal coherence compared with ordinary light sources. In ordinary light sources like bubble lamp, sodium lamp, and torchlight, the electron transition from higher energy level to lower energy level occurs in spontaneous process. In other words, electron transition in ordinary light sources is random in time. In these sources, no phase relation exists between the emitted photons, and the phase difference between different atoms changes in time. Thus, the photons emitted by an ordinary light source are out of phase as illustrated schematically in Fig. 2.5.

In contrast to incoherent sources, in laser, a phase relation between electron transitions exists. In other words, in laser, electron transition occurs in specific time. Therefore, the emission of laser is in phase in space and time as illustrated schematically in Fig. 2.5. In laser, the stimulated emission process produces coherence light. Because of the coherence, a large amount of power can be concentrated in a narrow space. For a light source with a Gaussian emission spectrum, the coherence length can be obtained as follows:

$$l_c = c\tau_c = \sqrt{\frac{2\ln 2}{\pi n}}\frac{\lambda^2}{\Delta\lambda} = \sqrt{\frac{2\ln 2}{\pi n}}\frac{c}{\Delta\nu} \quad (2.1)$$

where c is the speed of light, n is the refractive index of the medium, λ is the central wavelength, and $\Delta\lambda$ is the full-width half-maximum (FWHM) of the emission peak in wavelength spectrum. The light sources with a small $\Delta\lambda$ such as lasers are highly temporally coherent, while the light sources with a large $\Delta\lambda$ such as white light lamps are

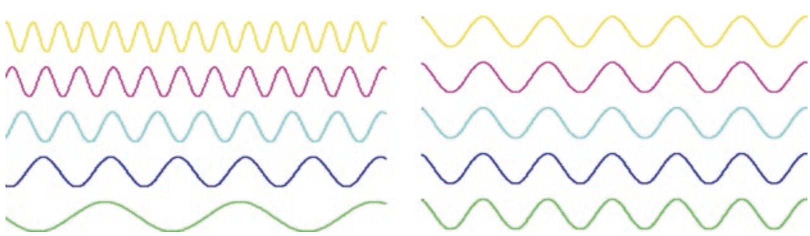

Fig. 2.5 Schematic of incoherent (left) and (right) coherent light waves

Table 2.1 Comparing the coherence length and coherence time of some medical laser systems and ordinary sources

Source	$\Delta\nu_c$ (THz)	τ_c	$l_c = c\tau_c$
Filtered sunlight (400–800 nm, $\lambda_0 = 550$ nm)	374	1.8 fs	0.32 μm
InGaAs ($E_g = 0.9$ eV, $\lambda_0 = 1300$ nm)	6.2	0.11 ps	17.7 μm
Low-pressure sodium lamp ($\lambda_0 = 589$ nm)	0.5	1.33 ps	0.399 mm
Single-mode He-Ne laser ($\lambda_0 = 633$ nm)	1×10^{-6}	0.66 μs	198 m
CO_2 laser ($\lambda_0 = 10.6$ μm)	40×10^{-6}	0.16 ns	4.8 m
Ruby laser ($\lambda_0 = 694$ nm)	0.36	1.85 ps	0.555 mm
Nd:YAG ($\lambda_0 = 1064$ nm)	0.18	3.7 ps	1.11 mm
Nd:Glass ($\lambda_0 = 1059$ nm)	9	73.8 fs	22.2 μm
Dye laser (Typ. R6G $\lambda_0 = 570$–610 nm)	100	6.6 fs	1.98 μm

temporally incoherent. The coherence length and coherence time of some medical optical sources and ordinary sources are compared in Table 2.1.

There is not a single universal technique to measure laser linewidth or coherence length. Temporal coherence can be measured by the Michelson interferometer, while spatial coherence can be measured by Young's double-slit experiment. The van Cittert-Zernike theorem states that the spatial coherence area, A_c, is given by the following:

$$A_c = \frac{d^2\lambda^2}{\pi D^2} \tag{2.2}$$

where D is the diameter of the light source, and d is the distance away. The spatial coherence area is large for sources with small diameter and large wavelength.

2.3.2 Divergence and Directionality

The propagation and directionality of radiation is described by diffraction theory. Maximum intensity of radiation is limited by the angle of divergence. In conventional light sources, photons emit and travel in random direction. Therefore, the radiation from these light sources has a large divergence angle. However, in laser, the optical resonator leads to travel all photons in the same direction with low beam divergence, which results in a high directionality. In contrast, the collimated light waves from a laser diverge little over relatively great distances. For example, a laser beam can be pointed at the moon, which is ~4×10^5 km away from earth. For diffraction-limited laser radiation with wavelength λ and diameter D, the divergence angle is given from diffraction theory by the following:

$$\theta_d = 1.22\frac{\lambda}{D} \tag{2.3}$$

If a free-aberration positive lens is used for focusing a laser light, the radius of the central lobe behind the lens on the focal plane is $a \approx f \bullet \theta_d \approx 1.22 f \bullet \lambda / D$, where f is the focal length of the lens. For a multimode beam, TEM_{pl}, the minimum diameter of the focal spot is given by the following:

$$a = 1.22\frac{\lambda f\left(2p+l+1\right)}{D} \tag{2.4}$$

2.3.3 Monochromaticity

Monochromatic light means a light containing a single color or frequency. In ordinary light sources, the emitted photons have many different energies, frequencies, wavelengths, or colors with a wide spectrum bandwidth. However, in laser, stimulated emission leads all the emitted photons to have the same energy, frequency, or wavelength. Therefore, laser radiation has a very narrow spectrum bandwidth. This means that the radiation emitted by the laser is nearly monochromatic. This purity is unique to laser light in contrast to all other light sources which are of mixed wavelengths. Monochromaticity enables great precision when a laser is used for medical or surgical purposes because components of human tissue preferentially absorb electromagnetic energy of specific wavelengths. Further, monochromatic aspect of lasers is essential for temporal coherence.

According to the Heisenberg's uncertainty principle, if the momentum of a particle is precisely known, it is impossible to know the position precisely and vice versa. This relationship also applies to energy and time. It means one cannot measure the precise energy of a system in a finite amount of time. Uncertainties in the products of "conjugate pairs" (momentum and position, and energy and time) are as below:

$$\Delta x \Delta p \geq \frac{\hbar}{2} \tag{2.5a}$$

$$\Delta t \Delta E \geq \frac{\hbar}{2} \tag{2.5b}$$

where Δ refers to the uncertainty in that variable and $\hbar = h/2\pi$ is reduced Planck's constant in which h is Planck's constant. For a monochromatic light with $\Delta E \approx 0$, Heisenberg's uncertainty principle results to $\Delta t \to \infty$. It means a perfectly monochromatic source (if it existed!) would give an infinitely long wavetrain which is uniformly distributed over the infinite constant-phase planes.

2.3.4 Brightness

The brightness is characterized by a light source that takes into account the power that can convey into the laser spot. It is defined as the power emitted per unit area and unit solid angle as follows:

$$B = \frac{p}{A.\Omega} \tag{2.6}$$

where P is power, $A = \pi D^2/4$ is area of laser spot, and Ω is solid angle defined as below:

$$\Omega = 2\pi\left(1 - \cos\theta\right) \approx \pi\theta^2 \tag{2.7}$$

Maximum brightness is obtained if $\theta = \theta_d$. From Eqs. (2.6) and (2.3), maximum brightness can be simplified as follows:

$$B = \frac{4p}{\pi^2\left(1.22\right)^2 \lambda^2} \tag{2.8}$$

One can see that maximum brightness is proportional to the inverse square of the center wavelength of radiation. Notice that in an ordinary light source, the light spreads out uniformly in all directions, while, in laser, the light due to *directionality* spreads in small region of space. Thereby, laser light has greater intensity and brightness when compared to the ordinary light.

2.4 Gaussian Beam Optics

In most laser applications, it is necessary to know the propagation characteristics of laser beam. The propagation of a laser beam is a paraxial solution of the Maxwell's equations. In general, laser beam propagation can be approximated by assuming that the laser beam has a Gaussian intensity profile. A Gaussian beam has a radially symmetrical distribution whose electric field variation is given by the following:

$$E\left(r,z\right) = E_0\left(z\right)\exp\left[-r^2 / w^2\left(z\right)\right] \tag{2.9}$$

with a Gaussian intensity distribution in a cross-sectional plane at z, r as follows:

$$I\left(r,z\right) = I_0\left(z\right)\exp\left[-2r^2 / w^2\left(z\right)\right] \tag{2.10}$$

where $I_0(z)$ is the beam peak intensity in a cross-sectional plane at z. Many lasers emit beams with a Gaussian profile. The fundamental transverse mode, or TEM_{00} mode, is a perfect Gaussian beam. In most cases, the laser output beam deviates from TEM_{00} mode. When a Gaussian beam propagates into an optical medium like lens, a Gaussian beam is transformed into another Gaussian beam characterized by a different set of parameters.

A simple and commonly used measure to evaluate laser beam propagation is the beam propagation ratio M-square factor M^2, which compares the propagation properties of a real beam to those of a perfect diffraction-limited Gaussian beam. In other words, the $M^2 \geq 1$ describes the deviation of a laser beam from a perfect Gaussian beam. For a perfect laser beam, $M^2 = 1$. Most gas lasers have $M^2 \approx 1$. Although most solid-state lasers have an M^2 value between 1.1 and 1.5, some lasers, such as flashlamp pumped lasers and high-power solid-state lasers, have an M^2 value over 10.

A Gaussian beam can be fully described with the use of the complex beam parameter, q, and ABCD matrix. It facilitates the study of Gaussian beams in the presence of optical elements such as lenses, spherical mirrors, etc. The general form of the complex beam parameter, q, can be written in terms of two real parameters, R and w, as follows:

$$\frac{1}{q(z)} = \frac{1}{R(z)} - i\frac{\lambda M^2}{n\pi w^2(z)} \tag{2.11}$$

where $R(z)$ is the radius of curvature of beam wavefront and $w(z)$ is the spot radius of the beam at z. For the Gaussian beam, spot radius w is considered the radius where $I = I_0/e^2$. At focusing point, a Gaussian beam achieves a minimum spot size (called waist with radius w_0) when the wavefront becomes a plane ($R = \infty$). Therefore:

$$\frac{1}{q_0} = -i\frac{\lambda M^2}{n\pi w_0^2} \tag{2.12}$$

The transformation of a Gaussian beam can be described by the following:

$$q_2 = \frac{Aq_1 + B}{Cq_1 + D} \tag{2.13}$$

where A, B, C, and D are the elements of the $ABCD$ transform matrix characterizing the optical medium. From $ABCD$ matrix of free space ($A = 1$, $B = z$, $C = 0$, $D = 1$) with thickness of z, the value of q at z away from the waist in free space are given by the following:

$$q = q_0 + z \tag{2.14}$$

or we can obtain the following equation by applying Eq. (2.13) and considering $ABCD$ matrix of a thin lens with focal length f ($A = 1$, $B = 0$, $C = -1/f$, $D = 1$) as follows:

$$\frac{1}{q_2} = \frac{1}{q_1} - \frac{1}{f} \tag{2.15}$$

Figure 2.6 illustrates propagation characteristics of a Gaussian beam showing spherical wave-

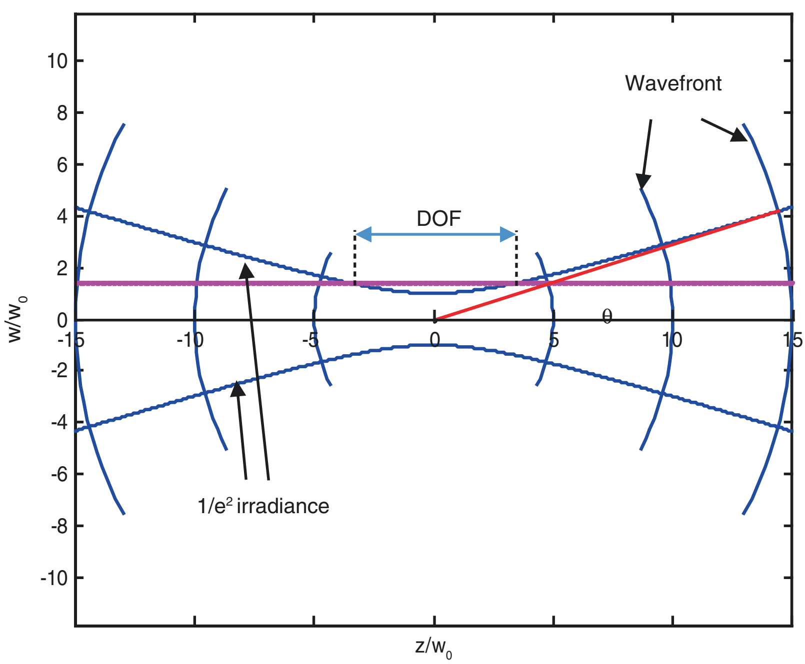

Fig. 2.6 Propagation characteristics of a Gaussian beam with parameters $w_0 = 50$ μm, $\lambda = 2.94$ μm, and $M^2 = 15$, showing spherical wavefronts. DOF is depth of focus

fronts. Once again, a Gaussian beam does not come to a focus at a point but rather achieves a minimum spot size w_0 where the wavefront becomes a plane. From Eqs. (2.11)–(2.14), one can obtain the following:

$$w(z) = w_0 \left[1 + \left(\frac{M^2 \lambda z}{n\pi w_0^2} \right)^2 \right]^{1/2} \tag{2.16}$$

$$R(z) = z \left[1 + \left(\frac{n\pi w_0^2}{M^2 \lambda z} \right)^2 \right] \tag{2.17}$$

Equations (2.16) and (2.17) can be simplified in the following forms:

$$w(z) = w_0 \left(1 + \frac{z^2}{z_R^2} \right)^{1/2} \tag{2.18}$$

$$R(z) = z \left(1 + \frac{z_R^2}{z^2} \right) \tag{2.19}$$

where:

$$z_R = \frac{n\pi w_0^2}{\lambda M^2} \tag{2.20}$$

is the Rayleigh length that reflects the distance from the waist to the place where the spot size increases by a factor of $\sqrt{2}$.

The divergence of a Gaussian laser beam in the depth of focus (DOF) is negligible, and it can be considered as parallel beam. The DOF or confocal parameter is twice the Rayleigh length:

$$\mathrm{DOF} = \frac{2n\pi w_0^2}{\lambda M^2} \tag{2.21}$$

The parameter $w(z)$ approaches a straight line for $z >> z_R$. The angle between this straight line and the central axis of the beam is called far-field divergence:

$$\theta \simeq \frac{\lambda M^2}{\pi w_0} \tag{2.22}$$

The angle θ is inversely proportional to the beam waist w_0 and proportional to the *M*-square factor M^2 and the wavelength λ.

As mentioned in Sect. 2.2, according to the gain material, lasers can be divided into solid-state, gas, dye (liquid), or semiconductor. In the following, the commonly used lasers with typical applications and wavelengths are listed in each type.

2.5 Solid-State Lasers

The first functional laser was invented by Maiman in 1960. It was a ruby laser in visible region (694.3 nm) pumped by a xenon flashlamp; the first laser was used in medicine in 1960 by Leon Goldman, the "father of laser medicine," who tried to lighten tattoos by aiming a ruby laser at the pigmented skin until the pigment granules broke apart. In 1963, Charles Campbell used a ruby laser to treat a detached retina. In 1980s, the Nd:YAG flashlamp pumped laser was developed. Soon after, novel laser diode-pumped solid-stare lasers with different gain medium were constructed. So far, continuous-wave (CW) or pulsed solid-state lasers from different crystals, mainly Nd^{3+} doped, such as Nd:YAG, Nd:YLF, Nd:YVO_4, (Er, Nd):YAG, (Ho, Nd):YAG, Nd:$GdVO_4$, Nd:LYSO, Nd:YAP, Nd:YAB, Nd:Mgo:$LiNbO_3$, Nd:GSAG, Nd:$LuVO_4$ Nd:$YAIO_3$, Ti:sapphire, Yb:KGD$(WO_4)_2$, and Nd,La:SrF_2, with different laser emission wavelength has been demonstrated (see, for instance, [6, 7, 13–20]). In ref. [21] influence of length of gain medium and pump beam quality on performance of the laser and required design parameters has been investigated. The active ion of Nd^{3+} has mainly three allowed transitions of $^4F_{3/2} \rightarrow {}^4I_{9/2}$, $^4F_{3/2} \rightarrow {}^4I_{11/2}$, and $^4F_{3/2} \rightarrow {}^4I_{13/2}$, corresponding to the emitting wavelengths around 0.9, 1.06, and 1.3 μm, respectively, which makes it possible to achieve single- and multi-wavelength operations of an Nd^{3+} laser through a proper design of the laser. The capability of a laser can be extended by multiple wavelength engineered emission. Notice that dual- or multi-wavelength simultaneously emission laser sources have been used in different scientific and technical applications in optical coherence tomography (OCT) [22, 23],

Table 2.2 The most important solid-state lasers with wavelength and typical applications

Laser type	Wavelength(s)	Applications
Ruby	694.3 nm	Pulsed holography, tattoo removal and cosmetic dermatology, high-speed photography, hair removal
Nd:YAG	1.064 μm, (1.32 μm, 946 nm)	Material processing, laser target designation, glaucoma surgery, dentistry, research, pumping other lasers, cataract surgery, water vapour remote sensing, underwater communication
Erbium-doped glass/fiber	1.53–1.56 μm	Optical amplifiers for telecommunications
Ho:YAG	2.1	Surgery, dentistry, material processing, arthroscopic surgery, remote sensing
Er:YAG	2.94 μm, 1.53–1.56 μm	Surgery, resurfacing of human skin, oral surgery, dentistry, osteotomy, removal of warts, soft tissue
Er,Cr:YSGG	2.790 μm	Surgery, dentistry, soft tissue
Tm:YAG	2.01 μm	Remote sensing, material processing, optical communication, dentistry

optical testing [24], atom interferometry [25], spectroscopy [26], THz radiation generation [27, 28], and remote sensing [29–31]. Table 2.2 summarizes the most important solid-state lasers with their wavelength emission and typical applications.

2.6 Gas Lasers

The gas lasers can be basically categorized into three distinct families: (i) the neutral gas laser, (ii) the ionized gas laser, and (iii) the molecular gas laser. Table 2.3 summarizes the most important gas lasers with their wavelength and typical applications. He-Ne laser is the first invented gas laser in 1960 by Ali Javan. This laser radiates in a continuous regime CW and uses electric discharge excitation in a neutral gaseous environment. It soon became the first commercial laser with a power of 1 mW. The argon laser operating in the visible and ultraviolet spectral regions was invented in 1964 by William Bridge. CO_2 laser was developed by Kumar Patel in 1964 at Bell Laboratories. The CO_2 laser operates both pulsed and CW mode in the middle infrared region on rotational-vibrational transitions of carbon dioxide at 10.6 and 9.4 μm wavelengths. It is one of the most powerful and efficient lasers available.

Table 2.3 The most important gas lasers with wavelength and typical applications

Laser type	Wavelength(s)	Applications
He-Ne laser	632.8 nm	Interferometry, holography, spectroscopy, barcode scanning, laboratory testing, aiming beam
Ar^+ ion laser	454.6 nm, 488.0 nm, 514.5 nm	Retinal phototherapy (for diabetes), plastic surgery, dermatology, lithography, confocal microscopy, spectroscopy pumping other lasers
CO_2 laser	10.6 μm, (9.4 μm)	Material processing (cutting, welding, etc.), dentistry, osteotomy, vaporization and coagulation, gynecology
Excimer laser	193 nm (ArF), 248 nm (KrF), 308 nm (XeCl), 353 nm (XeF)	Ultraviolet lithography for semiconductor manufacturing, surgery, skin treatment, material processing, lithography, nanofabrication, LASIK

2.7 Semiconductor Lasers

Semiconductor lasers or diode lasers are a special type of solid-state lasers. They are portable, compact, and efficient with wavelength versatility and reliable benefits. This type of laser can be operated in a CW or pulsed mode. The frequency of the emitted photons depends on the gain material composition. Typical operation wavelengths of different diode lasers are summarized in Table 2.4. Diode lasers were developed very soon after solid-state and gas lasers. The first laser