2nd Edition

Principles and Practice of LASER DENTISTRY

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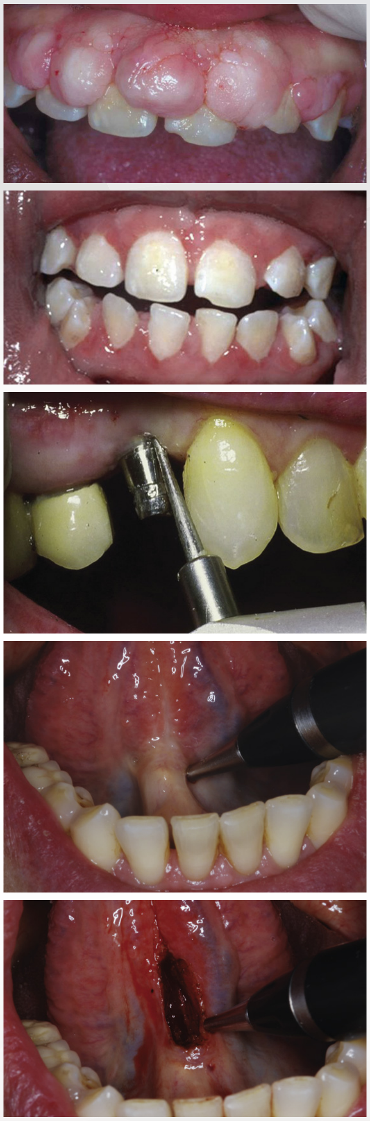

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To my wife, partner, and source of inspiration
not just in dentistry, but in life:
Dr. Ellen Goldstein Convissar

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Foreword

When the first dental laser came on the market in the late 1980s, there was great excitement in the world of dentistry. Unfortunately, the laser wavelength for that first device was chosen because it was available, not because it was the best one for the purpose desired. Laser dentistry has come a long way since then, with accumulation of an extensive science base on laser interactions with both soft and hard tissues. In recent years, lasers have been developed for medicine and dentistry based on the best evidence to date, including the optimal conditions for these clinical applications. A whole new energy has emerged regarding the use of lasers in dentistry and much of it is captured in this second edition of Dr. Robert Convissar's *Principles and Practice of Laser Dentistry.*

Dr. Convissar is one of the pioneers of the clinical use of lasers in dentistry, with almost 25 years of experience with carbon dioxide, neodymium-doped yttrium-aluminum-garnet (Nd:YAG), diode, and erbium wavelengths. He has presented more than 300 laser seminars on five continents. For this revised edition, he has brought together a team of authors whose knowledge base and skills are state of the art, for preparation of a treatise worth reading.

In these days of electronic communication and indeed electronic books, journals, media, music, and much more, it is hard to imagine that yet another textbook could be useful. On the contrary, this is a great read for anyone who wants a comprehensive review of the world of lasers and their use in dentistry. The attentive reader will gain an understanding of how lasers work, how they interact with the tissues, and thus how best to apply this knowledge in clinical practice.

I started my research into the possibilities of using lasers in dentistry in 1980, well before there was even much use of these devices for surgery and treatments in the rest of the human body. Things were very primitive at that time, with much unknown. My team has worked for more than 30 years on laser interactions with hard tissues. Together with other groups across the world, we were able to contribute to an in-depth understanding of how to use lasers for teeth and bone applications. Only recently was all of this work brought together by a company to build and then market a new laser that takes advantage of this science and the clinical research that followed. This new technology has helped to set the stage for the next big move forward in the everyday adoption of lasers in dental practice.

Other big steps forward have been achieved in recent years, as detailed in the following pages. There is definitely more to come in the future, as a dream of more than 25 years ago for some of us is realized.

John D.B. Featherstone, MSc, PhD

Preface

In the five years since the publication of the first edition of this book, the field of laser dentistry has made great strides in delivering superior patient care. Manufacturers new to the industry have entered the field with state-of-the-art devices. Well-established companies have come out with new models that offer significant improvements over previous versions. A new wavelength on the market, a 9300-nm carbon dioxide laser with both hard- and soft-tissue applications, may revolutionize dentistry—or may fall by the wayside, as did the argon and holmium wavelengths in the context of general dentistry. As usual, the clinical experience will determine this outcome.

Clinicians are finding ever more procedures that have a positive impact on the lives of their patients. Five years ago, just a handful of pediatric laser dentistry pioneers were performing lingual tongue-tie and maxillary frenectomy procedures on newborn babies to help them latch onto their mothers' nipples and nurse. It was rare for dentists to receive referrals from other health care professionals for this type of procedure. Today, laser dentists are receiving referrals from pediatricians, neonatologists, pediatric otolaryngologists, lactation specialists, and many more to help babies nurse more successfully. For treating teenagers and older patients, dentists are receiving referrals on a regular basis from speech therapists, orofacial myologists, specialists in osteopathic manipulative medicine, and many more. For drug-induced gingival hyperplasia treatment, dentists are working with transplant surgeons and primary care physicians of organ transplant recipients. The list keeps growing.

As with the first edition, this book is written both for the clinician who wants to learn how to use a laser and for the established laser user who wants to expand the range of procedures for the practice's instrument or to add a device with different capabilities. For each procedure described, the peer-reviewed literature that validates its use also is presented. Procedures that are neither supported by the peer-reviewed literature nor based on sound biologic foundations are not included in this book. Each of the chapters is written by a "wet-fingered" practitioner with extensive laser experience—and, in most cases, with specialty board certification in his or her field of expertise. Virtually every procedure is fully documented with preoperative, intraoperative, and postoperative photographs. Suggestions and "Clinical Tips" are highlighted throughout, making the most pertinent clinical information for the practitioner readily available.

A textbook of any scope and depth cannot be written without the dedication of a number of people. Thanks are due to each and every contributing author, who gave up months of valuable time away from their practices and families to work on this most worthwhile project. Thanks also to the best team in dental textbook publishing: Brian Loehr, Jaime Pendill, Sara Alsup, and Kathy Falk. Finally, this book would never have been possible without the love, encouragement, and support of my wife and partner, Dr. Ellen Goldstein, and our children Craig, Alex, and Dana.

1

Einstein's "Splendid Light": Origins and Dental Applications

JOHN G. SULEWSKI

Humankind's fascination with the properties of light and its applications in medicine can be traced to ancient times. Developments in physics at the beginning of the twentieth century laid the foundation for laser theory postulated by Albert Einstein, culminating in the invention of this special form of light in 1960. Soon thereafter, researchers began to explore possible applications of laser technology in medical and dental treatment.

The medicinal use of light for diagnostic and therapeutic purposes dates from antiquity. Light allowed early physicians to observe skin color, inspect wounds, and choose a suitable therapeutic course of action. Heat from sunlight or campfires was used for therapy. Greeks and Romans took daily sunbaths, and the solarium was a feature of many Roman houses.[1] Ancient Egyptians, Chinese, and Indians used light to treat rickets, psoriasis, skin cancer, and even psychosis.[2]

The ancient Egyptians, Indians, and Greeks also used natural sunlight to repigment affected skin in patients with vitiligo by activating the naturally occurring photosensitizer *psoralen,* found in parsley and other plants.[3-5] In the eighteenth and nineteenth centuries, European physicians used sunlight and artificial light to treat cutaneous tuberculosis, psoriasis, eczema, and mycosis fungoides.[3] These and other applications of light were precursors to the invention and subsequent use of optical amplifier devices that generate a special form of light—*lasers*—in the medical field over the past several decades.

This chapter examines the efforts of select laser pioneers in dentistry and summarizes current intraoral clinical applications of lasers.

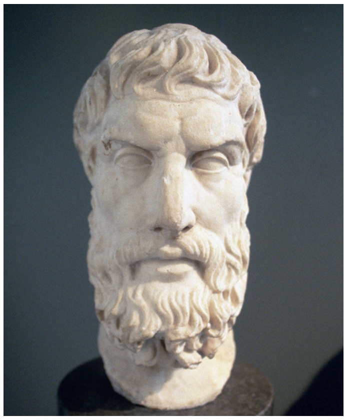
Early Published Theories of Light

Philosophers and scientists long pondered the nature of light: Was it composed of particles, waves, pressure, or some other substance or force?

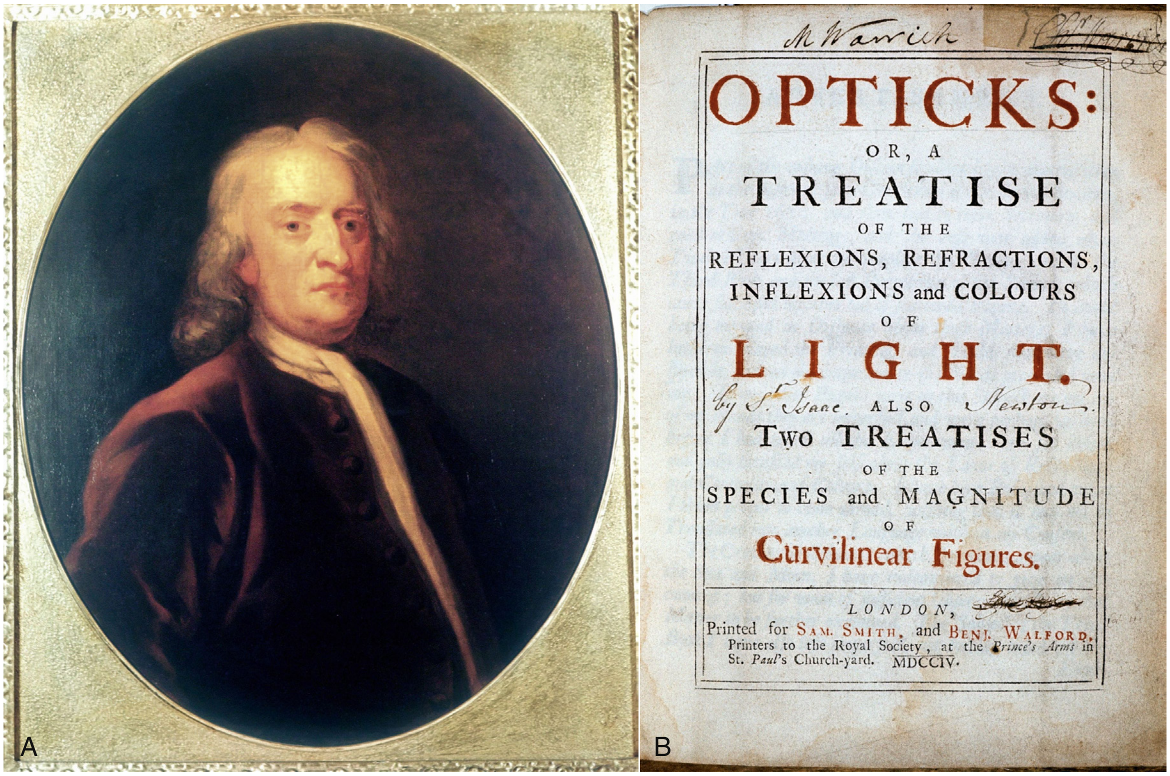
In his *Book of Optics,* published in 1021, Persian mathematician, scientist, and philosopher Ibn al-Haytham described light as being composed of a stream of tiny particles that travel in straight lines and bounce off objects that they strike.[6] Pierre Gassendi, a French philosopher, scientist, astronomer, and mathematician, described his particle theory of light (published posthumously in 1658 in Lyon, France, as part of the six volumes of his collected works, the *Opera Omnia*), in effect introducing to European scholars the atomism view of the universe identified by the ancient Greek philosopher Epicurus (341-270 BCE)[7] (Figure 1-1).

Gassendi's work influenced English physicist Sir Isaac Newton (1642-1727), who described light as "corpuscles" or particles of matter that "were emitted in all directions from a source"[8,9] (Figure 1-2). Newton proposed the theory of particle dynamics, which later would be developed to describe the behavior of particles reacting to the influence of arbitrary forces.[10] The particle view of light differed from that of French philosopher and scientist René Descartes, who in his 1637 *Discourse* saw light as a type of "pressure," which foreshadowed the postulation of the wave theory of light[11] (Figure 1-3).

In 1665, English scientist Robert Hooke suggested his wave theory of light, likening the spread of light vibrations



• Figure 1-1 Greek philosopher Epicurus (341-270 BCE).



M Warwick

OPTICKS:
OR, A
TREATISE
OF THE
REFLEXIONS, REFRACTIONS,
INFLEXIONS and COLOURS
OF
LIGHT.
by Sr. Isaac ALSO Newton
Two TREATISES
OF THE
SPECIES and MAGNITUDE
OF
Curvilinear Figures.

LONDON,
Printed for SAM. SMITH, and BENJ. WALFORD,
Printers to the Royal Society, at the *Prince's Arms* in
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• **Figure 1-2** **A,** Sir Isaac Newton (1642-1727). **B,** Title page from Newton's work *Opticks*, 1704.

to that of waves in water: "every pulse or vitration of the luminous body will generate a sphere, which will continually increase, and grow bigger, just after the same manner (though infinitely swifter) as the waves or rings on the surface of the water do swell into bigger and bigger circles about a point."[12] The wave concept subsequently was proved experimentally by Scottish physicist James Clerk Maxwell, who in 1865 proposed an electromagnetic wave theory of light and demonstrated that electromagnetic waves traveled at precisely the speed of light.[13]

• **Figure 1-3** René Descartes (1596-1650).

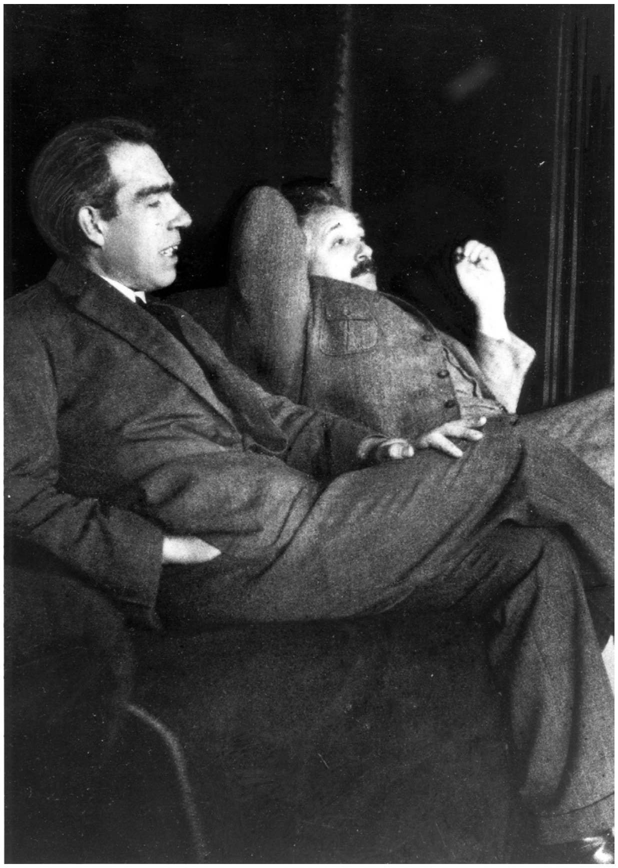
Development of Quantum Theory

The previous theories, useful as they might have been before 1900, did not entirely or satisfactorily describe the characteristics of light observed by the scientific community: Light behaved as particles in some cases and as waves in others. This context of inquiry led to the field of *quantum theory.*

On December 14, 1900, German physicist Max Planck delivered a lecture before the German Physical Society (Deutsche Physikalische Gesellschaft) in which he theorized that light consisted of discrete and indivisible packets of radiant energy that he named *quanta.* He described what eventually became known as the elemental unit of energy *(E)*, as $E = hv$, where h is a constant of nature with the dimension of action (= energy × time, with a value of 6.626×10^{-34} joule-second), subsequently called Planck's constant, and v is the frequency of radiation. Planck's theory was published late in 1900.[14-16] Eleven years later, British physicist Ernest Rutherford contributed to quantum theory when he postulated a planetary model of the atom based on his experimental observations of the scattering of alpha particles by atoms. In his view an atom comprises a central charge surrounded by a distribution of electrons orbiting within a sphere.[17]

Danish physicist Niels Bohr synthesized Rutherford's atom model with Planck's quantum hypothesis (Figure 1-4). In a series of papers published in 1913, Bohr proposed a theory in which electrons revolve in specific orbits around a nucleus without emitting radiant energy. He described the stable, "ground state" of an atom, when all of its electrons are at their lowest energy level. Bohr also theorized that an electron may suddenly jump from one specific orbital level to a higher level; to do so, an electron must gain energy. Conversely, an electron must lose energy to move from a higher energy level to a lower energy level. Thus an electron can move from one energy level to another by either absorbing or emitting radiant energy or light.[18,19]

It was in this burgeoning milieu of nascent quantum theory that Albert Einstein made three significant contributions. First, in 1905, Einstein developed his light quantum theory: "In the propagation of a light ray emitted from a point source, the energy is not distributed continuously over ever-increasing volumes of space, but consists of a finite number of energy quanta localized at points of space that move without dividing, and can be absorbed or generated as complete units."[20] Singh[21] points out that this paper on photoelectric effect was the first that Einstein published during his *annus mirabilis* ("extraordinary year"), in the scientific journal *Annalen der Physik* in 1905; his other papers that year treated Brownian motion, special theory of relativity, and matter and energy equivalence ($E = mc^2$). Notably, Einstein himself regarded his light quantum paper as the "most revolutionary" of those that he had published in 1905. He was awarded the 1921 Nobel Prize in physics for this paper. Hallmark and Horn[22] stated that Einstein's light quantum theory was so radical in comparison with other contemporary theories of light that it was not generally accepted until American physicist Robert A. Millikan performed additional experiments in 1916 to support the theory.


• **Figure 1-4** Niels Bohr and Albert Einstein in 1925.

Einstein's 1905 paper made the case for the particle nature of light. In 1909, Einstein made his second significant contribution to laser theory by publishing the first reference in physics to the *wave-particle duality* of light radiation, using Planck's radiation law. Einstein stated: "It is my opinion that the next phase in the development of theoretical physics will bring us a theory of light which can be interpreted as a kind of fusion of the wave and emission theory. … Wave structure and quantum structure … are not to be considered as mutually incompatible. … We will have to modify our current theories, not to abandon them completely."[21,23] British mathematician and physicist Banesh Hoffmann fancifully characterized the quandary for many early twentieth-century physicists regarding the apparent wave-particle duality of light: "They could but make the best of it, and went around with woebegone faces sadly complaining that on Mondays, Wednesdays, and Fridays they must look on light as a wave; on Tuesdays, Thursdays, and Saturdays, as a particle. On Sundays they simply prayed." [24]

In 1916-1917, Einstein made his third important contribution to laser theory by providing a new derivation of Planck's radiation law,[25-27] with vast implications. As he wrote to his friend Michele Angelo Besso in 1916, "A splendid light has dawned on me about the absorption and emission of radiation."[21] Indeed, his new idea provided the basis for subsequent laser development.

Based on quantum theory, two fundamental radiation processes associated with light and matter were known before Einstein's new derivation: (1) *stimulated absorption,* a process in which an atom can be excited to a higher energy state through such means as heating, light interaction, or particle interaction; and (2) *spontaneous emission,* the process of an excited atom decaying to a lower energy state spontaneously, by itself. Einstein's breakthrough was the addition of a third alternative: *stimulated emission,* the reverse of the stimulated absorption process. In the presence of other incoming radiation of the same frequency, excited atoms are stimulated to make a transition to the lower energy state—more quickly than in spontaneous emission—and in the process release light energy identical to the incoming form of light. The emitted light has the same frequency and is *in phase* (i.e., coherent) with the stimulating radiation wave. Stimulated emission occurs when there are more excited atoms than atoms that are not excited (i.e., more atoms in upper of two energy levels than in lower level), a condition called *population inversion.* Einstein also showed that the process of stimulated emission occurs with the same probability as for absorption from the lower state.[28-31] Hey et al.[32] summarized the significance of Einstein's insight as follows:

> For over 35 years this stimulated emission process gained hardly more than a cursory comment in quantum mechanics textbooks, since it seemed to have no practical application. What had been overlooked, however, was the special nature of the light that is emitted in this way. The photons that are emitted have exactly the same phase as the photons that induce the transition. This is because the varying electric fields of the applied light wave cause the charge distribution of the excited atom to oscillate in phase with this radiation. The emitted photons are all in phase—they are coherent—and, furthermore, they travel in the same direction as the inducing photon.

At this point, it should be clarified that the term *photon* was not used by Planck, Bohr, or Einstein up to the time of Einstein's 1916-1917 papers. American chemist Gilbert Lewis[33] apparently was the first to use the term when he argued, in a letter to the editor of *Nature* magazine in 1926, for the need for new nomenclature to describe discrete units of radiant energy:

> It would seem inappropriate to speak of one of these hypothetical entities as a particle of light, a corpuscle of light, a light quantum, or a light quant, if we are to assume that it spends only a minute fraction of its existence as a carrier of radiant energy, while the rest of the time it remains as an important structural element within the atom. It would also cause confusion to call it merely a quantum, for later it will be necessary to distinguish between the number of these entities present in an atom and the so-called quantum number. I therefore take the liberty of proposing for this hypothetical new atom, which is not light, but plays an essential part in every process of radiation, the name *photon.*

The following accepted definition appears in the *American Heritage Dictionary*[34]:

> **photon** n. *Physics.* The quantum of electromagnetic energy, regarded as a discrete particle having zero mass, no electric charge, and an indefinitely long lifetime.

Decades followed Einstein's 1916-1917 articles on stimulated emission before significant progress was made in laser development, both theoretically and practically, in the 1950s and 1960s, partly because of the outlook and training of physicists at that time, as suggested by American physicist Arthur L. Schawlow and later observers. Schooled in the idea that "thermodynamic equilibrium," a state of energy balance, was the normal condition of matter throughout the universe, these scientists tended to believe that population inversion was merely an unusual event or brief permutation, not something particularly significant.[35,36]

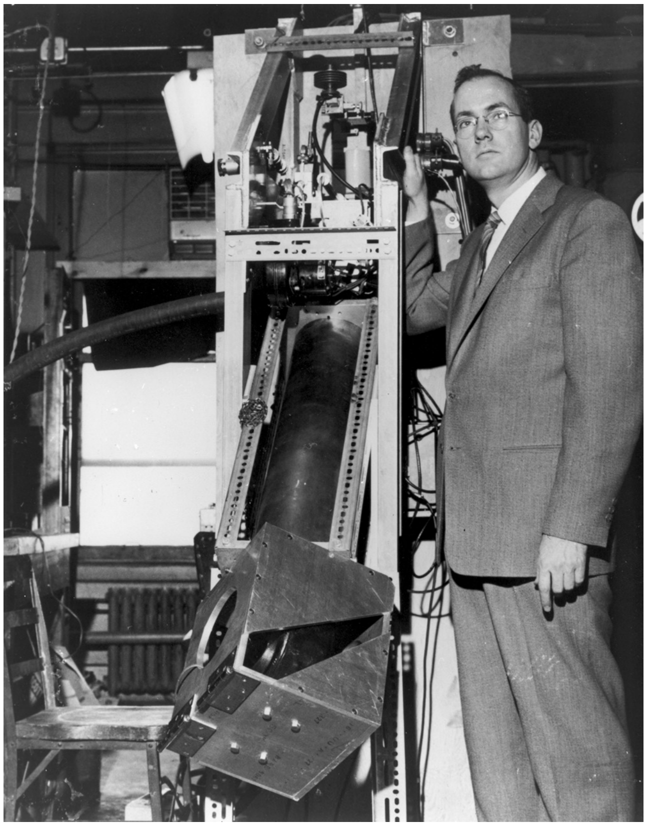
However, the 1920s and 1930s were not entirely bereft of discovery and insight. In 1928, German physicist Rudolf Ladenburg indirectly observed stimulated emission while studying the optical properties of neon gas at wavelengths near a transition where the gas absorbed and emitted light. This was the first evidence that stimulated emission existed.[35,37] In his 1939 doctoral dissertation, Soviet physicist Valentin A. Fabrikant had envisioned a way to produce a population inversion, writing that "such a ratio of populations is in principle attainable. … Under such conditions we would obtain a radiation output greater than the incident radiation."[35,36,38]

Nevertheless, the works of Ladenburg and that of Fabrikant were isolated incidents. Another impediment to laser development after Einstein was two world wars, although World War II then actually accelerated research toward laser development. Efforts of physicists were diverted from performing fundamental research to helping propel technology that would help win the war. Afterward, the sophisticated equipment developed for the war effort became military surplus, and physicists accustomed to low budgets received some of this equipment as they resumed their research.

Masers and Lasers

The impact of the wartime research focus on laser development is exemplified by the work of American physicist Charles H. Townes at Bell Telephone Laboratories in Manhattan and later at Columbia University, which he joined in 1948 (Figure 1-5). In 1941, Townes was assigned to work on a military radar project. Modern radar, a system of using transmitted and reflected radio waves for detecting a reflected object to determine its direction, distance, height, or speed, was developed in the 1930s, when systems used radio waves about a meter long and could not discern much detail. During the war, the military was interested in developing a radar system that used much higher radio frequencies to attain greater sensitivity, tighter radio beams, and transmitting antennas small enough to fit on an airplane. Townes began working on microwave frequencies of 3, 10, and 24 gigahertz (GHz).[35] Although none of these systems was used in battle, Townes' experience with the 24-GHz system, interest in microwave spectroscopy, and use of surplus equipment guided him toward subsequent development.

In 1951, at the spring meeting of the American Physical Society in Washington, D.C., Townes proposed the concept of a *maser,* an acronym he and his students coined for *m*icrowave *a*mplification by *s*timulated *e*mission of *r*adiation. He indicated that the "primary object of the work that led to the maser was to get shorter wavelengths so we could do better spectroscopy in a new spectral region."[39] Townes elaborated on April 26, 1951: "I sketched out and calculated requirements for a molecular-beam system to separate high-energy molecules from lower [-energy] ones and send them through a cavity which would contain the electromagnetic radiation [photons] to stimulate further emission from the molecules, thus providing feedback and continuous oscillation."[40] On May 11, Townes sketched the idea in his laboratory notebook, dated it, and signed it "Chas. H. Townes." In February 1952, his colleague and brother-in-law Arthur L. Schawlow also signed the page.[35,36]



• Figure 1-5 Charles H. Townes with a ruby microwave maser amplifier developed for radio astronomy in 1957. (Courtesy Alcatel-Lucent USA.)

On his return to Columbia University after the April 1951 conference, Townes and postdoctoral fellow Herbert J. Zeiger and doctoral student James P. Gordon commenced work on building a maser. They began to experiment with a beam of ammonia molecules, a compound familiar to Townes from his work on the 24-GHz radar system. It was known that ammonia molecules absorb microwaves at a frequency of 24 GHz, causing the nitrogen atom of that molecule to vibrate. Initial success was achieved in late 1953, when Gordon saw evidence of stimulated emission and amplification from their device; then, in early April 1954, they achieved the desired oscillation.[35] They reported their success in a late paper presented at a meeting of the American Physical Society on May 1 and then in a short paper published in the journal *Physical Review.*[41]

While on sabbatical from Columbia University in 1955, Townes worked with French physicist Alfred Kastler at the École Normale Supérieure in Paris. Kastler developed the technique of "optical pumping," a process by which light is used to raise (or pump) electrons from a lower to a higher energy level, as a new way to excite materials for microwave spectroscopy.[35] Townes recognized that optical pumping might excite the optical energy levels necessary for an optical maser. In fall 1957, Townes and Schawlow, a postdoctoral fellow under Townes at Columbia until he joined Bell Labs in 1951, proposed extending maser principles to the infrared and visible regions of the electromagnetic spectrum.[36,39] They subsequently published their influential paper in *Physical Review* in 1958.[42]

Meanwhile, another American physicist, Gordon Gould, a Columbia graduate student in 1957, asked whether optical pumping could excite light emission. He recorded his ideas in nine handwritten pages of a laboratory notebook, with the first page titled "Some rough calculations on the feasibility of a LASER: Light Amplification by Stimulated Emission of Radiation"—the first time the term *laser* was used. Gould had his notes notarized on November 13, 1957, which he saw as a necessary step in applying for a patent. His patent defense efforts were finally recognized after 30 years of delays, challenges, and litigation.[35,39,43]

The Schawlow and Townes paper stirred a number of organizations to conduct additional research into optical masers as follows[35]:

- In September 1958, Townes and Columbia University received funding from the U.S. Air Force Office of Scientific Research to pursue investigation of a potassium-vapor laser.
- Schawlow began to work with crystals (including synthetic pink ruby, composed of aluminum oxide doped with chromium atoms) at Bell Labs, which was interested in developing the technology to expand the transmission capacity of Bell's communications network.
- Ali Javan and William R. Bennett, Jr., also at Bell, worked on employing an electrical discharge tube filled with helium and neon gas.
- Gould had joined the Technical Research Group (TRG) in Manhattan, a military contractor that secured funding from the Pentagon to research the potential military applications of a laser, including communications, marking targets for weapons, and measuring the range to targets. Gould's group explored the potential of a laser using alkali metal vapors.
- Westinghouse Research Laboratories in Pittsburgh had an Air Force contract to examine solid-state microwave masers. Irwin Wieder and Bruce McAvoy explored the characteristics of ruby using bright tungsten lamps and (unsuccessfully) pulsed light sources.
- IBM entered the laser race with Peter Sorokin and Mirek Stevenson at the T.J. Watson Research Center in Yorktown Heights, N.Y.

Numerous other companies also had joined the quest for building the first laser, including aerospace company Hughes Research Laboratories in California, which was under a maser development contract with the U.S. Army Signal Corps. The Corps became interested in developing a more practical version of a previously developed ruby solid-state microwave maser, one that could serve as a low-noise microwave amplifier aboard an airplane. American physicist Theodore H. Maiman, who joined Hughes in 1956, and his assistant, Irnee D'Haenens, were assigned to the project. Their task was daunting; the existing desk-size device weighed 2.5 tons. They succeeded in developing a 4-pound version, but the continuing need to incorporate cryogenic cooling of the device limited its practicality.

Nevertheless, Maiman used this experience with ruby in his later work on the laser. Some investigators, including Wieder at Westinghouse as well as Schawlow and others at Bell Labs, had dismissed ruby as an unsuitably inefficient laser material, but their calculations were based on inadequate data. Maiman conducted his own investigation and found that ruby could indeed be suitable, provided that it could be optically pumped with an intensely bright light source. His calculations showed that a pulsed flashlamp would provide enough light to excite a ruby laser. His experimental laser design ultimately was elegant, incorporated in a device that could fit in the palm of the hand: a ruby rod 1 cm in diameter and 2 cm long placed within the coils of a small flashlamp, and an aluminum cylinder with reflective interior surface that slipped around the lamp to reflect light toward the ruby rod. The ends of the rod were polished flat, perpendicular to the length of the rod and parallel to each other. Maiman applied a reflective silver coating to both ends and then removed the silver from the center of one end, to allow a transparent opening for the laser beam to escape and subsequently be detected. The apparatus was connected to a separate power supply.[35]

On May 16, 1960, Maiman and D'Haenens aimed the laser cylinder toward a white poster board. They started firing the flashlamp with pulses of 500 volts (V), gradually increasing the voltage to produce progressively more intense light flashes, and measured the laser's output tracing on an oscilloscope. Finally, with the power supply set above 950 V, the oscilloscope's trace surged, a red glow filled the room, and a brilliant red spot appeared on the poster board. After 9 months of intense effort, Maiman accomplished his goal, and the laser was born. In so doing, he beat out Bell Labs, TRG, Westinghouse, IBM, Siemens, RCA Labs, Massachusetts Institute of Technology's Lincoln Laboratory, General Electric, and all others in contention.[35,36,39,44] Maiman submitted a paper reporting his evidence for a ruby laser to *Physical Review Letters,* the leading U.S. journal for publishing new physics research. Its editor, Samuel Goudsmit, rejected the manuscript, apparently not appreciating the breakthrough Maiman had achieved, perhaps mistakenly believing it was just a follow-up to previously published work on masers. Maiman then submitted his report to the British weekly journal *Nature,* which accepted it immediately and published it on August 6, 1960.[45,46]

Other laser types followed[36,39,46]:

- Sorokin and Stevenson demonstrated the solid-state uranium laser in November 1960.[47]
- Javan, Bennett, and Herriott demonstrated the first gas laser, a helium-neon (HeNe) laser emitting at 1.15 μm, in December 1960 at Bell's Murray Hill, New Jersey, laboratory.[48]
- In 1961, Johnson and Nassau at Bell Labs demonstrated a 1.06-μm laser from neodymium (Nd) ions in a host crystal of calcium tungstate.[49]
- Also in 1961, Snitzer of American Optical (Southbridge, Massachusetts) built an Nd laser in optical glass. [50]
- White and Rigden developed the 632.8-nm-wavelength HeNe laser at Bell Labs in 1962.[51]
- Also in 1962, Rabinowitz, Jacobs, and Gould demonstrated the optically pumped cesium laser at TRG.[52]
- Further in 1962, Hall and colleagues of the General Electric Research Center (Schenectady, NY) developed a cryogenically cooled gallium-arsenide (GaAs) semiconductor laser.[53]
- The year 1964 marked the demonstration of the neodymium-doped yttrium-aluminum-garnet (Nd:YAG) laser by Geusic, Marcos, and van Uitert at Bell Labs.[54]
- Patel developed the carbon dioxide (CO_2) laser at Bell Labs in 1964.[55]
- Also in 1964, Bridges of Hughes Research Laboratories developed the argon ion laser.[56]
- Silfvast and colleagues at the University of Utah conducted extensive research with metal-vapor lasers in the mid-1960s.[57]
- Sorokin and Lankard developed the dye laser in the mid-1960s.[58,59]
- Ewing and Brau of the Avco Everett Research Laboratory (Everett, Massachusetts) were the first to demonstrate three excimer lasers: krypton fluoride, xenon fluoride, and xenon chloride lasers.[60]
- Madey of Stanford University demonstrated the free electron laser on January 7, 1975.[61]
- Schawlow and one of his students even concocted a Jello-O laser by firing a ruby laser into a bowl of Jell-O doped with the organic dye rhodamine 6G.[35,39]

During a July 7, 1960, press conference announcing his accomplishment, Maiman identified five potential uses for the laser:

1. The first true amplification of light
2. A tool to probe matter for basic research
3. High-power beams for space communications
4. Increasing the number of available communication channels
5. Concentrating light for industry, chemistry, and medicine

The accuracy of his insight was affirmed in subsequent discoveries and applications; only his third prediction has not been put into regular use.[35] A few years later, when commenting on the outlook for medical applications of the laser, Maiman foresaw the use of the device as a "bloodless" surgical tool, in the treatment of malignancies, and as a dentist's drill.[62] He cited the interconnection of blood vessels to relieve arterial blockage as one example of successful experimentation. He also discussed microsurgical laser equipment capable of destroying individual red blood cells, as well as a laser destroying single genes and other tiny masses, with practically no effect on surrounding tissue.[63]

Lasers In Dentistry and Oral Surgery

Soon after his invention was demonstrated, researchers began to examine Maiman's vision of the laser as a useful instrument for medicine. Their efforts laid the foundation for the present clinical use of lasers in ophthalmology, neurosurgery, urology, gynecology, gastroenterology, general surgery, cardiovascular surgery, orthopedics, esthetic/dermatologic/plastic surgery, otorhinolaryngology, oral surgery and dentistry, and veterinary medicine. This section briefly outlines select pioneering efforts in the application of laser technology to dentistry and oral surgery and then summarizes the types of lasers and current range of intraoral clinical applications. (See also Chapter 2.)

To find new and effective methods of removing caries, pioneering examinations into the interactions of ruby laser energy with tooth structure were reported in the mid-1960s.[64-72] Investigators discovered that the ruby laser could vaporize caries, but that the high energy densities caused irreversible necrotic changes in pulpal tissues. Years later, the development of erbium (Er) laser wavelengths and CO_2 lasers operating at 9300 and 9600 nm, better suited to the clinical requirements for cavity preparation without the detrimental effects on pulp, led to further investigations.[73-84]

Early intraoral soft tissue investigations were conducted using the ruby laser.[71,85,86] The development of the CO_2 laser with its ability to ablate soft tissue with minimal hemorrhage led to studies in oral surgery.[87-99] Other groups of workers followed up with soft tissue studies involving the Nd:YAG laser.[100-103]

Other researchers examined the photopolymerization of dental composites[104-109] with the argon laser, the possible use of Nd:YAG lasers in the welding of prosthetic devices and gold alloys,[107-110] and the application of various lasers in endodontics.[111-113] An extensive survey of the published scientific research and clinical reports on the use of lasers in dentistry discusses the first experimental uses in 1964 through the numerous clinical applications into 2000.[114]

Otolaryngologists, oral surgeons, and periodontists were among the first practitioners to use medical lasers intraorally to perform a variety of soft tissue surgical applications. On May 3, 1990, the first laser designed specifically for general dentistry, the dLase 300 Nd:YAG laser, developed by Myers and Myers, was introduced in the United States.[115] This event marked the beginning of the clinical use of lasers by dentists—a development anticipated by a pioneer in laser surgery, Leon Goldman (1905-1997).

Goldman had been reporting on the biomedical aspects of the laser since 1963 and had published findings on the effect of the laser on dental caries, teeth, and other tissues as part of his early research. Concerning the prospects of laser applications in dentistry, Goldman[116] wrote in 1967:

> Although the possibilities of the development of laser dentistry appear to us to be excellent, there has been too little interest in the clinical and applied phases of laser dentistry by dentists and dental research groups. … These studies at present then indicate that a significant portion of the laser laboratory should be devoted to the field of laser dentistry. Unlike many dentists, we feel that this is a profitable area for research, especially in the treatment of caries and perhaps even of calculus. The dentist and especially dental histopathologist and electron microscopist must work with the biologists and the physicians and the engineers engaged in laser research. The purpose of this cooperative study is to develop flexible, effective and safe laser instrumentation needed for laser dentistry. Dentists should be active in this program, not wait until other disciplines do the work for them.

Almost 2 decades later, a dental practitioner heeded Dr. Goldman's call to develop what became the first laser designed specifically for general dentistry. Michigan dentist Dr. Terry D. Myers joined with his ophthalmologist brother Dr. William D. Myers, himself among the first to incorporate a laser into his ophthalmic practice, in exploring the advances in lasers, electronics, and optics to produce a device appropriate for the dental operatory. In contrast with a medical laser adapted for dental use, their instrument would be designed for the specific needs of the dental practitioner. It would feature an easy-to-use control panel that selected safe and effective operational parameters for the lasers' numerous clinical indications. It would be portable, with a self-contained cooling system, requiring no special electrical hookups, and would be simple to set up and maintain. It would have built-in self-diagnostics, autoclavable or disposable components, and a flexible fiberoptic delivery system to facilitate intraoral access and provide the necessary tactile feedback to which dental professionals are accustomed.

Currently, a number of laser wavelengths are used in oral surgery and dentistry, including two CO_2 wavelengths, Nd:YAG, argon, various diode wavelengths, two Er wavelengths, and potassium titanyl phosphate (KTP). Applications include the following[117-121]:

- Soft tissue procedures: gingivectomy/gingivoplasty, uvulopalatoplasty, excision of tumors and other lesions, incision/excision biopsies, frenectomy, removal of hyperplastic/granulation tissue, second-stage recovery of implants, guided tissue regeneration, and treatment of periodontal disease, aphthous ulcers, herpetic lesions, leukoplakia, and verrucous carcinoma
- Control of bleeding in vascular lesions
- Arthroscopic temporomandibular joint surgery
- Caries diagnosis and removal
- Curing of composites
- Activation of tooth-bleaching solutions
- Caries diagnosis and removal
- Root canal debridement and preparation
- Osteotomy and osseous crown lengthening
- Detection of subgingival dental calculus

Many professional societies are dedicated to the use of lasers in medicine and dentistry (Table 1-1). All have international representation, and some have links to their component societies or country representatives. Affiliated selected journals of interest to dentists who use lasers in their practice include the following and are listed in Table 1-2.

TABLE 1-1 **Professional Societies Dedicated to the Use of Lasers in Medicine and Dentistry**

Organization	Web Address	Year Formed
Academy of Laser Dentistry	www.laserdentistry.org	1993
American Society for Laser Medicine and Surgery	www.aslms.org	1981
Deutsche Gesellschaft für Laserzahnheilkunde	www.dgl-online.de	1991
Japanese Society for Laser Dentistry	http://jsld.jp	1989
Society for Oral Laser Applications	www.sola-int.org	ca. 2000
Laser Institute of America	www.laserinstitute.org	1968
SPIE* (an international society for optics and photonics)	www.spie.org	1955
World Association for Laser Therapy	www.walt.nu	1994
World Federation for Laser Dentistry	www.wfld-org.infolaser.com	1988

*Originally founded as the "*S*ociety of *P*hotographic *I*nstrumentation *E*ngineers."

TABLE 1-2 **Selected Journals of Interest to Dental Laser Practitioners**

Journal	Web Address	Years of Publication
International Journal of Laser Dentistry	www.jaypeejournals.com/eJournals	2011-present
Journal of Biomedical Optics	www.spie.org/x866.xml	1996-present
Journal of Dental Lasers	www.jdentlasers.org	2007-present
Journal of Laser Applications	www.lia.org/subscriptions/jla	1988-present
Journal of Laser Dentistry	www.laserdentistry.org	1992-present
Journal of Oral Laser Applications	www.quintpub.com/journals/jola/gp.php?journal_name=jola	2001-2010
Journal of the Japanese Society for Laser Dentistry	www.jstage.jst.go.jp/browse/jjpnsoclaserdent	1990-present
Journal of the Laser and Health Academy	www.laserandhealthacademy.com/en/journal	2007-present
Laser International	www.dental-tribune.com/epaper/issues/product/33	2010-present
Laser Journal	http://www.zwp-online-info/de/publikationen/laser-journal	2003-present
Lasers in Medical Science	http://link.springer.com/journal/10103	1986-present
Lasers in Surgery and Medicine	http://onlinelibrary.wiley.com/journal/10.1002/(ISSN)1096-9101	1980-present
Optical Engineering	http://spie.org/x867.xml	1962-present
Photochemistry and Photobiology	http://onlinelibrary.wiley.com/journal/10.1111/(ISSN)1751-1097	1962-present
Photomedicine and Laser Surgery	http://www.libertpub.com/overview/photomedicine-and-laser-surgery/128	1983-present
Zeitschrift für Laser Zahnheilkunde	http://lzhk.quintessenz.de	2004-2008

Conclusions

Fifty years after their initial experimental use in dentistry, and almost 25 years after their practical introduction into the dental operatory, lasers are becoming more commonplace and even routine, either as adjunctive treatment methodologies or as stand-alone additions to the dental armamentarium. Researchers continue to investigate new laser wavelengths and clinical applications as they apply to dentistry, extending the vision of Maiman and other pioneers. The growing number of dental laser practitioners, propelled by the increasing body of evidence concerning the safe, effective, and appropriate use of lasers in dentistry, will continue to advance the application of Einstein's "splendid light" in their operatories, to the benefit of patient and practitioner alike.

If laser clinicians find themselves simultaneously awed over the multifaceted capabilities of laser light and confounded in their attempts to fully explain it, they might find consolation in the knowledge that others have expressed similar fascination. Einstein himself wrote to Besso on December 12, 1951: "All the fifty years of conscious brooding have brought me no closer to the answer to the question, 'What are light quanta?' Of course today every rascal thinks he knows the answer, but he is deluding himself."[122] Rascals or not, laser clinicians are in good company in their sense of wonder!

References

1. Katzir A: *Lasers and optical fibers in medicine*, San Diego, 1993, Academic Press.
2. Daniell MD, Hill JS: A history of photodynamic therapy, *Aust NZ J Surg* 61(5):340–348, 1991.
3. Wheeland RG: History of lasers in dermatology, *Clin Dermatol* 13(1):3–10, 1995.
4. Fitzpatrick TB, Pathak MA: Historical aspects of methoxsalen and other furocoumarins, *J Invest Dermatol* 32(2, pt 2): 229–231, 1959.
5. Kalka K, Merk H, Mukhtar H: Photodynamic therapy in dermatology, *J Am Acad Dermatol* 42(3):389–413, 414–416 (quiz), 2000, errata, 43(4):609, 2000, and 44(1):150, 2001.
6. Gribbin JR: *Q is for quantum: an encyclopedia of particle physics*, New York, 2000, Touchstone.
7. *Opera omnia* … haetenus edita auctor ante obitum recensuit … posthuma vero, totius naturae explicationen complectentia, in lucem nunc primum proderunt ex bibliotheca … Henrici-Ludovici-Haberti Mon-Morii … [*Accesit* Samuelis Sorberii praefatio, in qua de vita et moribus Petri Gassendi disseritur], Lyon, 1658, Laurent Anisson and Jean Baptiste Devenet, I, pp 422a–432b.
8. Newton I: Correspondence: Isaac Newton to Henry Oldenburg, Cambridge, Dec 7, 1675. In Turnbull HW, Scott JP, Hall AR, Tilling L, editors: *The correspondence of Isaac Newton* (5 vols, continuing), Cambridge, UK, 1959, Royal Society at the University Press, vol I, pp 362–389.
9. Newton I: *Opticks: or, a treatise of the reflexions, refractions, inflexions and colours of light. Also two treatises of the species and magnitude of curvilinear figures*, London, 1704, Smith and Walford, Printers to the Royal Society.
10. Mehra J, Rechenberg H: *The historical development of quantum theory*, vol 5, Erwin Schrödinger and the rise of wave mechanics: Part 1. Schrodinger in Vienna and Zurich 1887–1925, New York, 1987, Springer-Verlag.
11. Descartes R: Discours de la méthode pour bien conduir sa raison et chercher la vérité dans les sciences plus la dioptrique, les meteores, et la geometrie, qui sont des essais de cete methode [Discourse on the method for properly conducting reason and searching for truth in the sciences, as well as the dioptrics, the meteors, and the geometry, which are essays in this method], 1637. In Cottingham J, Stoothoff R, Murdoch D, translators-editors: *The philosophical writings of Descartes*, vol 1, Cambridge, UK, 1985, Cambridge University Press.
12. Hooke R: *Micrographia; or, some physiological descriptions of minute bodies made by magnifying glasses with observations and inquiries thereupon*, London, 1665, Martyn & Allestry.
13. Maxwell JC: A dynamical theory of the electromagnetic field, *Philos Trans R Soc Lond* 155:459–512, 1865.
14. Planck M: Zur theorie des gesetzes der energieverteilung im normalspektrum, *Verh Dtsch Phys Ges* 2:237–245, 1900.
15. Van der Waerden BL, editor: *Sources of quantum mechanics*, Amsterdam, 1967, North-Holland Publishing.
16. Torretti R: *The philosophy of physics*, Cambridge, UK, 1999, Cambridge University Press.
17. Rutherford E: The scattering of α and β particles by matter and the structure of the atom, *Philos Mag*, Series 6 21:669–688, 1911.
18. Bohr N: On the constitution of atoms and molecules. Parts I–III, *Lond Edinb Dublin Philos Mag J Sci, Sixth Series* 26(151):1–25, (153):476–501, (155):857–875, 1913.
19. Billings CW: *Lasers: the new technology of light*, New York, 1992, Facts on File.
20. Einstein A: Über einen die erzeugnung und verwandlung des lichtes betreffenden heuristichen geischtpunkt [On a heuristic point of view concerning the generalization and transformation of light], *Ann Phys* 17:132–148, 1905.
21. Singh V: Einstein and the quantum. In Wadia SR, editor: *The legacy of Albert Einstein: a collection of essays in celebration of the year of physics*, Singapore, 2007, World Scientific Publishing.
22. Hallmark CL, Horn DT: *Lasers: the light fantastic*, ed 2, Blue Ridge Summit, Pa, 1987, TAB Books.
23. Einstein A: Über die Entwickelung unserer Anschauungen über das Wesen und die Konstitution der Strahlung [On the evolution of our vision on the nature and constitution of radiation], *Phys Z* 10(22):817–826, 1909.
24. Hoffmann B: *The strange story of the quantum*, ed 2, New York, 1959, Dover Publications, p 42.
25. Einstein A: Strahlungs-emission und -absorption nach der quantentheorie, *Verh Dtsch Phys Ges* 18(13–14):318–323, 1916.
26. Einstein A: Zur quantentheorie der strahlung [On the quantum theory of radiation], *Mitt Phys Ges Zurich* 18:47–62, 1916.
27. Einstein A: Zur quantentheorie der strahlung [On the quantum theory of radiation], *Phys Z* 18:121–128, 1917. (identical to 1916 paper of the same name, with a minor correction).
28. Schilling BW: Lasers. In Driggers RG, editor: *Encyclopedia of optical engineering*, vol 2, New York, 2003, Marcel Dekker.
29. Institute for Advanced Dental Technologies: *The laser course. Laser dentistry: a clinical training seminar*, Southfield, Mich, 1999, The Institute, III.6.
30. *The photonics dictionary, int'l ed 46, Pittsfield, Mass, 2000, Laurin Publishing, D-111*.
31. Carruth JA, McKenzie AL: *Medical lasers: science and clinical practice*, Bristol, UK, 1986, Adam Hilger.
32. Hey AJ, Hey T, Walters P: Quantum co-operation and superfluids. In *The new quantum universe*, Cambridge, UK, 2003, Cambridge University Press.
33. Lewis GN: The conservation of photons, *Nature* 118(2): 874–875, 1926.
34. *American Heritage dictionary of the English language*, ed 5, Boston, 2012, Houghton Mifflin.
35. Hecht J: *Beam: the race to make the laser*, New York, 2005, Oxford University Press.
36. Hecht J: *Laser pioneers*, rev ed, Boston, 1992, Academic Press.
37. Ladenburg R: Untersuchungen über die anomale Dispersion angeregter Gase. I. Teil. Zur Prüfung der quantentheoretischen Dispersionsformel [Research on the anomalous dispersion of gases], *Z Phys A* 48(1–2):15–25, 1928.
38. Bertolotti M: *Masers and lasers: an historical approach*, Bristol, UK, 1983, Adam Hilger.
39. *Laser pioneer interviews with an introduction to laser history by Jeff Hecht*, Torrance Calif, 1985, High Tech Publications.

40. Townes CH: The laser's roots: Townes recalls the early days, *Laser Focus* 14(8):52, 1978.
41. Gordon JP, Zeiger HJ, Townes CH: Molecular microwave oscillator and new hyperfine structure in the microwave spectrum of NH_3, *Phys Rev* 95(1):282–284, 1954.
42. Schawlow AL, Townes CH: Infrared and optical masers, *Phys Rev* 112(6):1940–1949, 1958.
43. Bromberg JL: Amazing light, *Invent Technol Mag* 7(4)[~118 pp], 1992 [online serial] http://www.americanheritage.com/articles/magazine/it/1992/4/1992_4_18.shtmlinnovationgateway.org/content/amazing-light-1. Accessed March 2014.
44. Friedman G: Inventing the light fantastic: Ted Maiman and the world's first laser, *OE Rep* (200):5–6, August 2000. Also available as: *Lasers & sources. Inventing … laser*, Greg Friedman [website]. DOI: 10.1117/2.6200705.0001. SPIE. c200914. [~45 pp]; http://spie.org/x13999.xml. Accessed March 2014.
45. Maiman TH: Stimulated optical radiation in ruby, *Nature* 187(4736):493–494, 1960.
46. Townes CH: *How the laser happened: adventures of a scientist*, New York, 1999, Oxford University Press.
47. Sorokin PP, Stevenson MJ: Stimulated infrared emission from trivalent uranium, *Phys Rev Lett* 5(12):557–559, 1960.
48. Javan A, Bennett Jr WR, Herriott DR: Population inversion and continuous optical maser oscillation in a gas discharge containing a He-Ne mixture, *Phys Rev Lett* 6(3):106–110, 1961.
49. Johnson LF, Nassau K: Infrared fluorescence and stimulated emission of Nd3+ in CaWO, *Proc Inst Radio Eng* 49(12):1704, 1961.
50. Snitzer E: Optical maser action of Nd3+ in a barium crown glass, *Phys Rev Lett* 7(12):444–446, 1961.
51. White AD, Rigden JD: Continuous gas maser operation in the visible, *Proc Inst Radio Eng* 50(7):1697, 1962.
52. Rabinowitz P, Jacobs S, Gould G: Continuous optically pumped Cs laser, *Appl Opt* 1(4):513–516, 1962.
53. Hall RN, Fenner GE, Kingsley JD, et al.: Coherent light emission from GaAs junctions, *Phys Rev Lett* 9(9):366–368, 1962.
54. Geusic JE, Marcos HM, Van Uitert LG: Laser oscillations in Nd-doped yttrium aluminum, yttrium gallium, and gadolinium garnets, *Appl Phys Lett* 4(10):182–184, 1954.
55. Patel CKN: Continuous-wave laser action on vibrational-rotational transitions of CO_2, *Phys Rev A* 136(5):1187–1193, 1964.
56. Bridges WB: Laser oscillation in singly ionized argon in the visible spectrum, *Appl Phys Lett* 4(7):128–130, 1964, erratum 5(2):39.
57. Silfvast WT, Fowles GR, Hopkins BD: Laser action in singly ionized Ge, Sn, Pb, In, Cd and Zn, *Appl Phys Lett* 8(12):318–319, 1966.
58. Sorokin PP, Lankard JR: Stimulated emission observed from an organic dye, chloro-aluminum phthalocyanine, *IBM J Res Dev* 10(2):162–163, 1966.
59. Sorokin PP, Lankard JR: Flashlamp excitation of organic dye lasers: a short communication, *IBM J Res Dev* 11(2):148, 1967.
60. Ewing JJ, Brau CA: Laser action on the $^2\Sigma^+_{1/2} \rightarrow {}^2\Sigma^+_{1/2}$ bands of KrF and XeCl, *Appl Phys Lett* 27(6):350–352, 1975.
61. Madey JM: Stimulated emission of bremsstrahlung in a periodic magnetic field, *J Appl Phys* 42(5):1906–1913, 1971.
62. Maiman comments on his precocious five-year-old [editorial], *Laser Focus* 1(9):2–4, 1965.
63. Maiman TH: A look at things to come: biomedical lasers evolve toward clinical applications, *Hosp Manage* 101(4):39–41, 1966.
64. Stern RH, Sognnaes RF: Laser beam effect on dental hard tissues, *J Dent Res* 43(5):873, 1964. [abstract 307].
65. Kinersly T, Jarabak JP, Phatak NM, Dement J: Laser effects on tissue and materials related to dentistry, *J Am Dent Assoc* 70(3):593–600, 1965.
66. Goldman L, Gray J, Goldman J, et al.: Effect of the laser beam impacts on teeth, *J Am Dent Assoc* 70(3):601–606, 1965.
67. Goldman L, Hornby P, Meyer R, Goldman B: Impact of the laser on dental caries, *Nature* 203(4943):417, 1964.
68. Gordon Jr TE: Laser interactions with extracted human teeth: a preliminary report, *Dent Digest* 72(4):154–158, 1966.
69. Gordon TE: Some effects of laser impacts on extracted teeth, *J Dent Res* 45(2):372–375, 1966.
70. Lobene RR, Fine S: Interaction of laser radiation with oral hard tissues, *J Prosthet Dent* 16(3):589–597, 1966.
71. Taylor R, Shklar G, Roeber F: The effects of laser radiation on teeth, dental pulp, and oral mucosa of experimental animals, *Oral Surg Oral Med Oral Pathol* 19(6):786–795, 1965.
72. Adrian JC, Bernier JL, Sprague WG: Laser and the dental pulp, *J Am Dent Assoc* 83(1):113–117, 1971.
73. Paghdiwala AF: Application of the erbium:YAG laser on hard dental tissues: measurement of the temperature changes and depths of cut. In Profio AE, editor: *Laser research in medicine, dentistry and surgery* vol 64, 1988. ICALEO Santa Clara, Calif, Proceedings, Toledo, Ohio, 1988, Laser Institute of America, pp 192–201.
74. Dostálová T, Jelínková H, Kucerová H, et al.: Clinical evaluation of Er-YAG laser caries treatment. In Wigdor HA, Featherstone JD, Rechman P, editors: *Lasers in dentistry III*, 1997. San Jose, Calif Proc SPIE 2973, Bellingham, Wash, 1997, International Society for Optical Engineering, pp 85–91.
75. Matsumoto K, Nakamura Y, Mazeki K, Kimura Y: Clinical dental application of Er:YAG laser class V cavity preparation, *J Clin Laser Med Surg* 14(3):123–127, 1996.
76. Sonntag KD, Klitzman B, Burkes EJ, et al.: Pulpal response to cavity preparation with the Er:YAG and Mark III free electron lasers, *Oral Surg Oral Med Oral Pathol Oral Radiol Endod* 81(6):695–702, 1996.
77. Eversole LR, Rizoiu I, Kimmel AI: Pulpal response to cavity preparation by an erbium, chromium:YSGG laser-powered hydrokinetic system, *J Am Dent Assoc* 128(8):1099–1106, 1997.
78. Pellagalli J, Gimbel CB, Hansen RT, et al.: Investigational study of the use of Er:YAG laser versus dental drill for caries removal and cavity preparation—phase I, *J Clin Laser Med Surg* 15(3):109–115, 1997.
79. Wigdor HA, Walsh Jr JT, Featherstone JD, et al.: Lasers in dentistry, *Lasers Surg Med* 16(2):103–133, 1995.
80. Fried D, Seka W, Glena RE, et al.: Thermal response of hard dental tissues to 9- through 11-µm CO_2 laser irradiation, *Opt Eng* 35(7):1976–1984, 1996.
81. Featherstone JDB, Fried D: Fundamental interactions of lasers with dental hard tissues, *Med Laser Appl* 16(3):181–194, 2001.
82. Fan K, Bell P, Fried D: Rapid and conservative ablation and modification of enamel, dentin, and alveolar bone using a high repetition rate transverse excited atmospheric pressure CO_2 laser operating at $\lambda = 9.3$ µm, *J Biomed Opt* 11(6), 2006. 064008-1–064008-11.
83. Staninec M, Darling CL, Goodis HE, et al.: Pulpal effects of enamel ablation with a microsecond pulsed $\lambda = 9.3$-µm CO_2 laser, *Lasers Surg Med* 41(4):256–263, 2009.
84. Nguyen D, Chang K, Hedayatollahnajafi S, et al.: High-speed scanning ablation of dental hard tissues with a $\lambda = 9.3$ µm CO_2 laser: adhesion, mechanical strength, heat accumulation, and peripheral thermal damage, *J Biomed Opt* 16(7), 2011. 071410-1–071410-9.

85. Yamamoto H, Okabe H, Ooya K, et al.: Laser effect on vital oral tissues: a preliminary investigation, *J Oral Pathol* 1(5):256–264, 1972.
86. Tanaka H: Effect of ruby-laser irradiation on gingiva, *Shigaku [Odontol]* 63(4):355–364, 1975.
87. Schafir R, Slutzki S, Bornstein LA: Excision of buccal hemangioma by carbon dioxide laser beam, *Oral Surg Oral Med Oral Pathol* 44(3):347–350, 1977.
88. Adrian JC: Effects of carbon dioxide laser radiation on oral soft tissues: an initial report, *Mil Med* 144(2):83–89, 1979.
89. Strong MS, Vaughan CW, Jako GJ, Polanyi T: Transoral resection of cancer of the oral cavity: the role of the CO_2 laser, *Otolaryngol Clin North Am* 12(1):207–218, 1979.
90. Tuffin JR, Carruth JA: The carbon dioxide surgical laser, *Br Dent J* 149(9):255–258, 1980.
91. Horch HH, Gerlach KL: CO_2 laser treatment of oral dysplastic precancerous lesions: a preliminary report, *Lasers Surg Med* 2(2):179–185, 1982.
92. Horch HH, Gerlach KL, Schaefer HE: CO_2 laser surgery of oral premalignant lesions, *Int J Oral Maxillofac Surg* 15(1):19–24, 1986.
93. Frame JW: Carbon dioxide laser surgery for benign oral lesions, *Br Dent J* 158(4):125–128, 1985.
94. Frame JW: Removal of oral soft tissue pathology with the CO_2 laser, *J Oral Maxillofac Surg* 43(11):850–855, 1985.
95. Frame JW, Das Gupta AR, Dalton GA: Rhys Evans PH: Use of the carbon dioxide laser in the management of premalignant lesions of the oral mucosa, *J Laryngol Otol* 98(12):1251–1260, 1984.
96. Kamami YV: Outpatient treatment of sleep apnea syndrome with CO_2 laser, LAUP: laser-assisted UPPP results on 46 patients, *J Clin Laser Med Surg* 12(4):215–219, 1994.
97. Wilder-Smith P, Arrastia A-MA, Liaw L-H, et al.: Incision properties and thermal effects of three CO_2 lasers in soft tissue, *Oral Surg Oral Med Oral Pathol Oral Radiol Endod* 79(6):685–691, 1995.
98. Wilder-Smith P, Dang J, Kurosaki T: Investigating the range of surgical effects on soft tissue produced by a carbon dioxide laser, *J Am Dent Assoc* 128(5):583–588, 1997.
99. Payne BP, Nishioka NS, Mikic BB, et al.: Comparison of pulsed CO_2 laser ablation at 10.6 μm and 9.5 μm, *Lasers Surg Med* 23(1):1–6, 1998.
100. Myers TD, Myers WD, Stone RM: First soft tissue study utilizing a pulsed Nd:YAG dental laser, *Northwest Dent* 68(2):14–17, 1989.
101. White JM, Goodis HE, Rose CL: Use of the pulsed Nd:YAG laser for intraoral soft tissue surgery, *Lasers Surg Med* 11(5):455–461, 1991.
102. Neill ME, Mellonig JT: Clinical efficacy of the Nd:YAG laser for combination periodontitis therapy, *Pract Periodont Aesthet Dent* 9(Suppl 6):1–5, 1997.
103. Yukna RA, Carr RL, Evans GH: Histologic evaluation of an Nd:YAG laser-assisted new attachment procedure in humans, *Int J Periodont Restorative Dent* 27(6):577–587, 2007.
104. Benedicenti A, Daneo M, Verrando M, et al.: Valutazione dell'assorbimento d'acqua di un composito, il Durafill, polimerizzato in luce laser argon rispetto alla normale polimeriizzazione [Evaluation of water absorption by a composite, Durafill, polymerized with argon laser light, in relation to normal polymerization], *Parodontol Stomatol (Nuova)* 23(3):27–29, 1984.
105. Séverin C: Apport du rayonnement laser-argon à la polymerization des photocomposites: collage des verrous orthodontiques [The effect of argon laser radiation on the polymerization of photocomposites: bonding of orthodontic brackets], *J Biomater Dent* 1(2):111–112, 1985. 161–165.
106. Séverin C, Maquin M: Argon ion laser beam as composite resin light curing agent. In Yamamoto H, Atsumi K, Kusakari H, editors: *Lasers in dentistry: proceedings of the International Congress of Laser in Dentistry, Tokyo, 1988*, Amsterdam, 1989, Excerpta Medica, pp 241–246.
107. Gordon TE, Smith DL: Laser welding of prostheses: an initial report, *J Prosthet Dent* 24(4):472–476, 1970.
108. Smith DL, Burnett AP, Gordon Jr TE: Laser welding of gold alloys, *J Dent Res* 51(1):161–167, 1972.
109. Huling JS, Clark RE: Comparative distortion in three-unit fixed prostheses joined by laser welding, conventional soldering, or casting in one piece, *J Dent Res* 56(2):128–134, 1977.
110. Apotheker H, Nishimura I, Seerattan C: Laser-welded vs soldered nonprecious alloy dental bridges: a comparative study, *Lasers Surg Med* 4(2):207–213, 1984.
111. Weichman JA, Johnson FM: Laser use in endodontics: a preliminary investigation, *Oral Surg Oral Med Oral Pathol* 31(3):416–420, 1971.
112. Dederich DN, Zakariasen KL, Tulip J: Scanning electron microscopic analysis of canal wall dentin following neodymium-aluminum-garnet laser irradiation, *J Endod* 10(9):428–431, 1984.
113. Yamazaki R, Goya C, Yu DG, et al.: Effects of erbium, chromium:YSGG laser irradiation on root canal walls: a scanning electron microscopic and thermographic study, *J Endod* 27(1):9–12, 2001.
114. Sulewski JG: Historical survey of laser dentistry, *Dent Clin North Am* 44(4):717–752, 2000.
115. Myers TD: The future of lasers in dentistry, *Dent Clin North Am* 44(4):971–980, 2000.
116. Goldman L: Dental applications of the laser. In Goldman L, editor: *Biomedical aspects of the laser: the introduction of laser applications into biology and medicine*, New York, 1967, Springer-Verlag.
117. Ball KA: *Lasers: the perioperative challenge*, ed 3, Denver, 2004, AORN.
118. Catone GA, Alling III CC: *Laser applications in oral and maxillofacial surgery*, Philadelphia, 1997, Saunders.
119. Clayman L: *Oral Maxillofac Surg Clin North Am* 9(1):1–131, 1997.
120. Joffe SN: Lasers in medicine. In Driggers RG, editor: *Encyclopedia of optical engineering*, vol 2, New York, 2003, Marcel Dekker.
121. Sulewski JG: *Selected US FDA marketing clearances*, San Diego, 2014, Academy of Laser Dentistry 21st Annual Conference and Exhibition. 08.
122. Klein MJ: The first phase of the Bohr-Einstein dialogue. In McCormmach R, editor: *Historical studies in the physical sciences,* vol 2, Philadelphia, 1970, University of Pennsylvania Press, pp 1–39.

2

Laser Fundamentals

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The word *laser* is an acronym for *l*ight *a*mplification by *s*timulated *e*mission of *r*adiation. In this chapter, brief descriptions of these five terms, within the context of the unique qualities of a laser instrument, are presented as background for a subsequent overview of the uses of lasers in dentistry.

Light

Light is a form of electromagnetic energy that exists as a particle and that travels in waves at a constant velocity. The basic unit of this radiant energy is called a *photon.*[1] The waves of photons travel at the speed of light and can be defined by two basic properties: amplitude and wavelength (Figure 2-1). *Amplitude* is defined as the vertical height of the wave from the zero axis to its peak as it moves around that axis. This correlates with the amount of intensity in the wave: The larger the amplitude, the greater the amount of potential work that could be performed. For a sound wave, amplitude correlates with *loudness.* For a wave emitting light, amplitude correlates with *brightness.* A joule (J) is a unit of energy; a useful quantity in laser dentistry is a *millijoule* (mJ), or one thousandth (10^{-3}) of a joule (0.001 J).

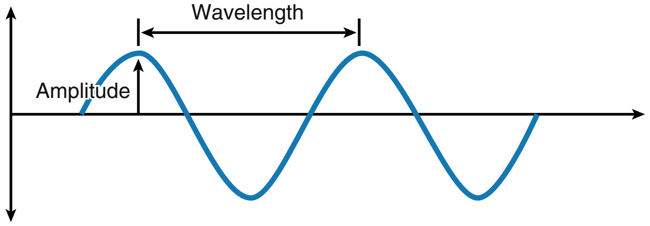
The second property of a wave is *wavelength* (λ), the horizontal distance between any two corresponding points on the wave. This measurement is important to both how the laser light is delivered to the surgical site and how it reacts with tissue. Wavelength is measured in meters (m). Dental lasers have wavelengths on the order of much smaller units, using terminology of either *nanometer* (nm), equal to one billionth (10^{-9}) of a meter, or *micrometer* (µm), one millionth (10^{-6}) of a meter (replaces the micron [µ] unit, still occasionally seen in laser science).

As waves travel, they rise and fall about the zero axis a certain number of times per second; this is called *oscillation.* The number of oscillations per unit time is defined as *frequency.* Frequency is measured in hertz (Hz); 1 Hz equals one oscillation per second. Frequency is inversely proportional to wavelength: The shorter the wavelength, the higher the frequency, and vice versa. Although the hertz as just defined is a basic unit in physics, it also is used more specifically to describe the number of pulses per second of emitted laser energy.

Ordinary light, such as that produced by a table lamp, usually is a warm, white color. “White” as seen by the human eye is really the sum of the many colors of the visible spectrum: red, orange, yellow, green, blue, and violet. The light usually is diffuse—that is, not focused. Laser light is distinguished from ordinary light by two properties. Laser light is *monochromatic*: It is generated as a beam of a single color, which is invisible if its wavelength is outside of the visible part of the spectrum. In addition, the waves of laser light are *coherent*, or identical in physical size and shape. Thus the amplitude and frequency of all of the waves of photons are identical. This coherence results in the production of a specific form of focused electromagnetic energy.

The beams emitted from laser instruments are *collimated* (produced with all waves parallel to each other) over a long distance, but once the laser beam enters certain delivery systems such as optical fibers or tips (e.g., in neodymium-doped yttrium-aluminum-garnet [Nd:YAG], erbium, and diode lasers), it diverges at the fiber tip. This monochromatic, coherent beam of light energy can be used to accomplish the treatment objective.

Using a household fixture as an example, a 100-watt (W) lamp will produce a moderate amount of light for a room area, with some heat. On the other hand, 2 W of laser light can be used for precise excision of a fibroma while providing adequate hemostasis at the surgical site, without disturbing the surrounding tissue.[2] The difference between the 100 W of an ordinary light bulb able to light up a room and the 2 W of a laser able to perform a surgical procedure lies in the property of coherence. As an apt analogy, imagine a crew race on a river. The boat that comes in first is the boat in which all of the members of the crew team are working together. At any given moment, they are all at the same stage of the stroke cycle, so that all of their energies are working together to propel the boat. All of the members of the crew team place their oars in the water at the same instant. They all remove their oars from the water at the same instant. They are working together in perfect unison. In similar fashion, all of the light waves in a laser work together in a beam of coherent energy. By contrast, in the boat that comes in last, the crew members may be seen to be at different stages of the stroke cycle. Some have their oars going



• Figure 2-1 Properties of electromagnetic waves. Amplitude is the height of the wave from the zero axis to the peak. Wavelength is the horizontal distance between two adjacent parts of a wave.

into the water, and some have their oars coming out of the water; some are at the top of the stroke cycle, and some are at the bottom of the stroke cycle. The team members are not working together as one. The work expended by this disorganized crew, which cannot propel their boat forward with any effective speed, would be analogous to the energy from an ordinary light bulb, which is insufficient for excision of soft tissue.

Amplification

Amplification is the part of this process that occurs inside the laser. In this section, the components of a laser instrument are identified to show how laser light is produced.

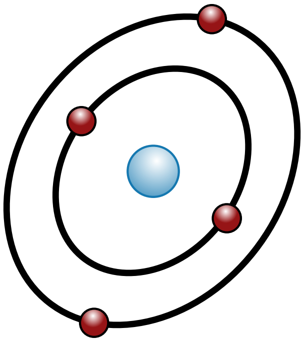
The center of the laser is called the *laser cavity.* The following three components make up the laser cavity:

- Active medium
- Pumping mechanism
- Optical resonator

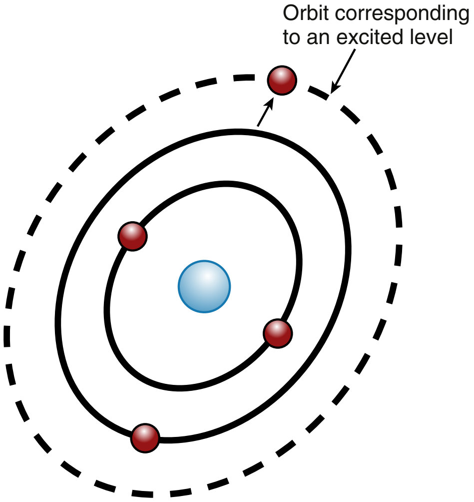
The *active medium* is composed of chemical elements, molecules, or compounds. Lasers are generically named for the material of the active medium, which can be (1) a container of gas, such as a canister of carbon dioxide (CO_2) gas in a CO_2 laser; (2) a solid crystal, such as that in an erbium-doped YAG (Er:YAG) laser; (3) a solid-state semiconductor, such as the semiconductors found in diode lasers; or (4) a liquid, such as that used in some medical laser devices.

Surrounding this active medium is an excitation source, such as a flash lamp strobe device, electrical circuit, electrical coil, or similar source of energy that pumps energy into the active medium. When this *pumping mechanism* drives energy into the active medium, the electrons in the outermost shell of the active medium's atoms absorb the energy. These electrons have absorbed a specific amount of energy to reach the next shell farther from the nucleus, which is at a higher energy level. A "population inversion" occurs when more of the electrons from the active medium are in the higher energy level shell farther from the nucleus than are in the ground state (Figure 2-2). The electrons in this excited state then return to their resting state and emit that energy in a form known as a photon (Figure 2-3). This is called *spontaneous (not stimulated) emission* (Figure 2-4).

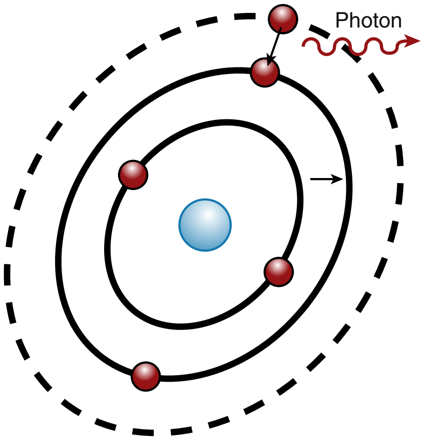
Completing the laser cavity are two mirrors, one at each end of the optical cavity, placed parallel to each other; or in the case of a semiconductor diode laser, two polished surfaces at each end. These mirrors or polished surfaces act as *optical resonators,* reflecting the waves back and forth, and help to collimate and amplify the developing beam. A cooling system, focusing lenses, and other controlling mechanisms complete the mechanical components. Figure 2-5 shows a schematic of a gas or solid active-medium laser (e.g., CO_2, Nd:YAG). Figure 2-6 shows a schematic of a semiconductor diode device.



• Figure 2-2 An atom of an active medium in ground state.



• Figure 2-3 An atom of an active medium in excited state.



• Figure 2-4 An atom of an active medium spontaneously emits a photon and returns to a stable orbit, giving off the energy that it had just absorbed, according to the principle of conservation of energy.