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edited by Ronald G. Driggers.

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edited by

Ronald G. Driggers
Electro-Optics and Photonics Division Chief
U.S. Army Research Laboratory
Adelphi, Maryland, U.S.A.

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Ronald G. Driggers, Editor
Electro-Optics and Photonics Division Chief
U.S. Army Research Laboratory
Adelphi, Maryland, U.S.A.

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Brief Contents

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Lasers

Bradley W. Schilling
U.S. Army Night Vision and Electronic Sensors Directorate,
Fort Belvoir, Virginia, U.S.A.

INTRODUCTION

Laser, an acronym for ''light amplification by stimulated emission of radiation,'' is a device that generates or amplifies coherent electromagnetic radiation that is very nearly single wavelength, is highly directional, and has high intensity. The operating principle behind the laser is an extension of a general principle called maser action that was originally demonstrated at microwave frequencies and is an acronym for ''microwave amplification by stimulated emission of radiation.'' C.H. Townes of the United States first demonstrated the maser in 1945.[1] In a laser, the atoms (or molecules) of a gain medium are placed in an excited state by an influx of energy. When stimulated by a photon of a specific energy, these excited atoms are induced to return to a lower energy state, in the process giving off a second photon having the same wavelength and phase as the stimulating photon. This second photon is now likely to stimulate other excited atoms, and so on, resulting in an amplification of radiation in the laser gain medium. These photons build up in the laser resonator until a threshold is reached and coherent laser light is emitted. Lasers are typically associated with wavelengths that span the infrared (IR), visible, ultraviolet (UV), and X-ray regions of the electromagnetic spectrum.

The first device to employ such stimulated emission operated at microwave frequencies and was called a maser. In 1958, Townes and Schawlow outlined the theoretical constructs to extend the maser concept to optical frequencies.[2] Just two years later, in 1960, Theodore Maiman of Hughes Research Laboratories constructed and demonstrated the first laser. The gain medium of this laser was a ruby crystal and a helical flashlamp was used as the optical pumping mechanism to excite the atoms of the laser rod. Application of coating to the flattened ends of the ruby rod with a highly reflective (HR) material formed the resonator cavity.[3] The following three factors, as shown in Fig. 1, are the minimum physical components necessary to have a functional laser: 1) a laser gain medium, 2) a pump mechanism, and 3) a specific structure called a resonant cavity.[4] There are other electrooptical components that are present in some lasers resonators, including Q-switches for generating very high peak-power laser pulses, nonlinear devices such as optical parametric oscillators for frequency shifting, polarizing elements, optical components for beam shaping or beam steering, and others.

There are many different types of lasers, roughly classified by the type of gain medium they employ, or by their optical output characteristics. For instance, a common laser classification is ''gas lasers,'' which achieved a population inversion in a mixture of pressurized gases. Similarly, solid-state lasers employ a solid material such as a crystal or doped glass in the resonator, and semiconductor lasers are fabricated from semiconductor materials. Alternately, ''visible lasers'' is another common laser classification, based on the region of the electromagnetic spectrum in which the emitted wavelength falls. The ruby laser (a solid-state laser) and the He–Ne laser (a gas laser) are both visible lasers because they both emit radiation in the visible wavelength region. Similarly, there are UV lasers and IR lasers; short-pulsed lasers and high-power lasers. In any case, the output generated by the laser resonator leads to a beam of light with very special properties when compared with standard optical sources, such as a flashlight or light bulb. In comparison, a laser can be designed to have a very narrow frequency distribution, to be very bright, to be very directional with a small beam divergence, and/or to have very short duration pulses. These beam characteristics make lasers an indispensable tool in many fields of science and engineering including medical science, biotechnology, communications, manufacturing, industrial engineering, and military systems.

ABSORPTION AND STIMULATED EMISSION

The three fundamental radiation processes associated with the interaction of light and matter that have particular relevance to laser physics are: 1) stimulated absorption 2) spontaneous emission, or decay, and 3) stimulated emission.[4] These concepts are based on quantum theory, which requires that matter exists only in certain specifically allowed energy levels or states. The probability that an atom will occupy a certain energy state is proportional to $e^{-E/kT}$, where E is the energy, T is the temperature and k is Boltzmann's constant. In the absence

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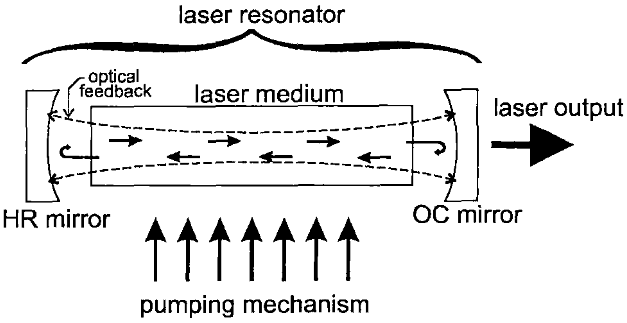


Fig. 1 Elements of a typical laser oscillator.

of any type of excitation, the atom will exist at a level of low overall energy, called the ground state. This situation is depicted graphically in Fig. 2 where energy levels are plotted against the probability of population. The various energy levels are depicted as bold lines while additional levels, depicted by narrower lines, represent the molecule's vibrational energy levels. These vibrational levels are related to the vibration of the atomic nuclei. As shown in Fig. 2, for a collection of atoms in the ground state, lower energy states have a higher probability of population than higher energy states. In order for lasing to occur, the atoms of the gain medium must have the ability to sustain a population inversion, a key property of all laser gain materials. A population inversion is achieved through a pumping process, which acts directly on the gain medium, injecting energy into the system. The atoms of the gain medium achieve a population inversion when there is a higher probability that atoms exist in a high quantum energy level, also shown in Fig. 2.

An atom can transition between energy levels, having an energy difference ΔE, through a number of mechanisms. The mechanisms involving radiative processes are of particular importance to us. An atom can be excited into a higher energy state, a process called absorption, through heating, photon interaction, particle interaction, or other means. If an atom exists in an excited state, it can decay to a lower energy state spontaneously, emitting a photon. A photon is a quantum, or wave packet, of electromagnetic radiation. This energy transition is known as spontaneous emission, and is shown graphically in Fig. 3. The emitted photon will have frequency $\nu = \Delta E/h$, where ΔE is the energy difference between the two energy levels, and h is Planck's constant. Additionally, if a photon of frequency ν impinges on the matter, a transition can occur between a lower energy state and an upper energy state (about ΔE higher), as the matter absorbs the photon. This process is known as stimulated absorption, and is also depicted in Fig. 3. A transition from an upper energy state to a lower energy state can also be induced by an impinging photon, emitting a second photon which has the same frequency and is in phase (i.e., is coherent) with the stimulating radiation wave. This is known as stimulated emission, shown in Fig. 3. Stimulated emission is the reverse of the stimulated absorption process. If the matter in question, such as the gain material of a laser, is forced out of thermal equilibrium by some pumping process that results in a higher population in the upper energy state than the lower energy state, then the material is in a state of population inversion. When a state of population inversion is achieved, it is more likely that an impinging photon will result in stimulated emission than in absorption. This leads to a coherent gain, or amplification, of the electromagnetic radiation in the cavity at the transition frequency, ν, or light amplification by stimulated emission of radiation.

THE BUILDING BLOCKS OF A LASER

Although there are many different types of lasers, there are three basic components that are common to all standard lasers. Lasers require some gain medium, capable of sustaining a population inversion, a pumping mechanism to induce a population inversion, and a

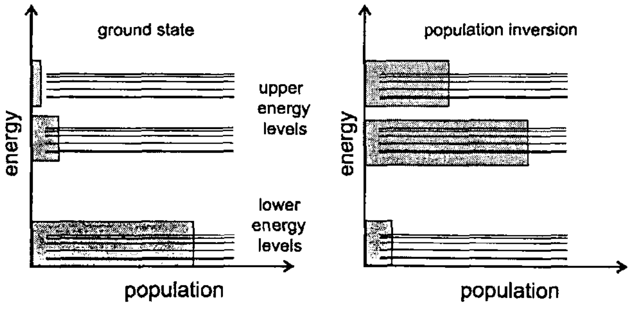


Fig. 2 Example to illustrate population for a collection of atoms at ground state and under the population inversion condition.

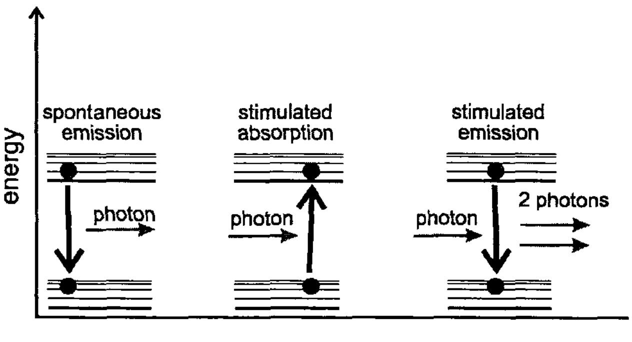


Fig. 3 Illustrations of spontaneous emission, stimulated absorption, and stimulated emission.

resonant cavity structure to store energy and offer optical feedback. This section will introduce these components, shown in Fig. 1, in more detail.

Gain Medium and Pumping

In light of the physical constraints associated with the fundamental radiative processes of lasing action, it is apparent that the gain medium and the pumping mechanism of a laser are closely linked. These components will be treated together in this section. The laser gain medium can be a crystal, glass, gas, or something else. The most important attribute of the gain medium is the availability of specific energy levels that can sustain a population inversion upon pumping. There are two main categories of pumping: 1) particle pumping, which usually involves electrical gas discharge or electron collisions in the gain medium, and 2) optical pumping, which generally employs either flashlamps or other lasers. Pumping techniques are essentially gain media-dependent. Because of the physical nature of the laser system, solid-state lasers are optically pumped while gas lasers employ particle pumping. These concepts are introduced here through an example of each major combination of gain medium and pump mechanism.

Helium–neon gas laser and particle pumping by gas discharge

It is typical for a gas laser, such as the common helium–neon (He–Ne) laser, to obtain a population inversion through particle pumping.[3,6] In a He–Ne laser, the gain medium is a gas mixture consisting of a few Torrs of He combined with approximately one-tenth that of the pressure of Ne. This gas mixture is contained inside a quartz plasma discharge tube equipped with electrodes to supply electrical power. Each time the laser is turned on, an initial spike of high voltage is applied across the electrodes to ionize the gas and break down the gas discharge. During lasing, a dc voltage on the order of 1000–1500 V produces a current of around 15 mA through the laser tube. Electrons within the gas discharge are accelerated by the applied voltage, and populate metastable (long-lived) energy levels of He, as shown in Fig. 4. Some of this energy is transferred via atom collision to a Ne atomic energy levels having nearly the same excitation energy as those present in the He atom, a process called resonant transfer. A key characteristic of the He–Ne gas mixture is the presence of these nearly coincident energy levels, making the resonant transfer process possible. The excited Ne atoms radiatively decay to lower Ne energy states, resulting in laser emission. Lasing is possible in the He–Ne laser at several different wavelengths, the 633-nm line being one of the most dominant. The He–Ne system is an example of indirect pumping, because the excitation path first populates an intermediate state before energy is transferred to the upper lasing state. When a laser system pumps the upper lasing state directly from the ground state, the system is said to have a direct pumping path.[2]

Semiconductor diode lasers and direct electron pumping

Semiconductor lasers are discussed in a subsequent section as one of the primary optical pump mechanism

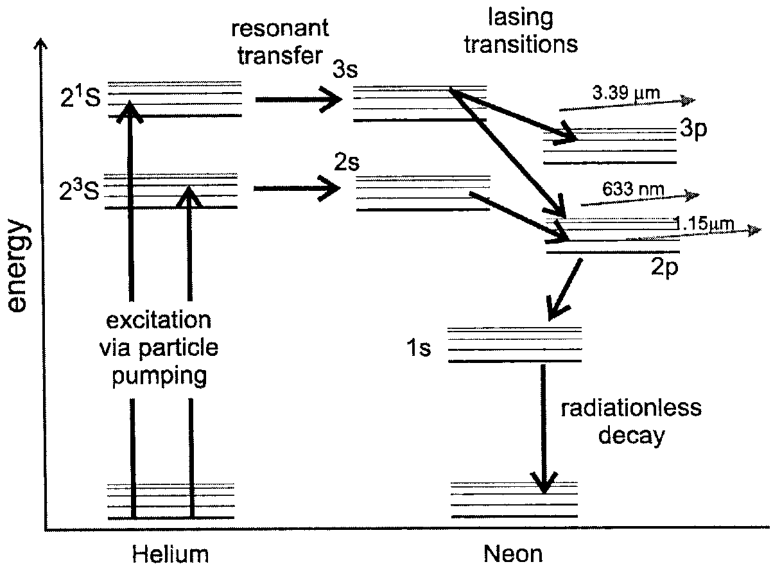


Fig. 4 Simplified energy level diagram for the He–Ne laser.

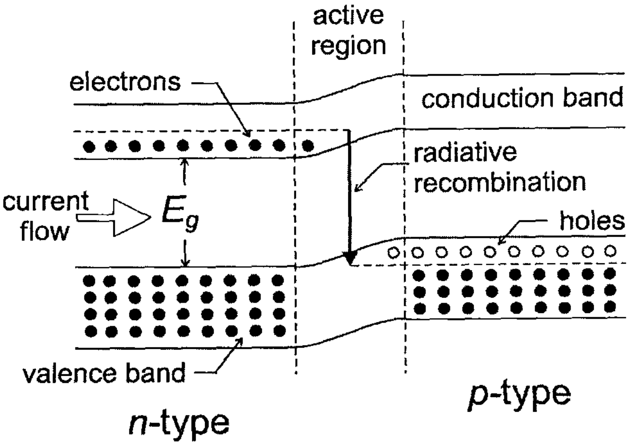


Fig. 5 Semiconductor $p-n$ junction.

for many laser systems.[4,6] However, these devices are themselves lasers, requiring a different mechanism to achieve a population inversion, namely a direct injection current. These devices are quite different then other laser systems, which rely on optically active ions for radiative energy transfer. As suggested by their name, the gain media for these devices are semiconductor materials, periodic crystals having bands of allowed energy levels separated by forbidden regions. For an unexcited semiconductor, the uppermost, populated energy band is called the valence band (lying just below the energy band gap), and the lowermost, empty energy band is called the conduction band (lying just above the energy band gap). A semiconductor material is characterized by its energy band gap, or the energy difference between the valence and conduction bands, $\Delta E = E_g$. The operating principle of a semiconductor laser is based on the $p-n$ junction, or an interface between a p-type and an n-type semiconductor. P- and n-type semiconductors are created by adding a small amount of an impurity atom to the material. If the impurity atoms contain extra electrons, an n-type semiconductor is created; for a p-type semiconductor the impurity atoms must have fewer electrons. The valence band of a p-type material is said to contain holes, the name assigned to the absence of an electron, while the extra electrons present in a n-type semiconductor are forced into the conduction band.

The $p-n$ junction, illustrated in Fig. 5, is created by fabricating a device with these two different types of materials in direct contact with each other. At the interface, electrons in the conduction band of the n-type material may recombine with holes in the valence band of the p-type material. If conditions are such that a photon is emitted during the process, it is referred to as radiative recombination. The frequency of the radiation corresponds to the band gap energy, or $\nu = E_g/h$. When a voltage is applied across the junction, more electron-hole pairs are forced into radiative recombination. The $p-n$ interface is said to receive an injection current, and the area where radiative recombination occurs, called the active region, widens. With the cleaved faces of the semiconductor materials acting as resonator mirrors, the system has all the components of a laser. As the injection current increases beyond a certain threshold, a population inversion exits in the junction and the device lases in a direction parallel to the material interface.

Solid-state lasers and optical pumping

Optical pumping is often employed in solid-state lasers, or lasers with a solid material as the active medium. For these laser systems, a separate optical source floods the gain material with photons, some of which are absorbed creating the desired population inversion. The two primary optical pumping techniques are flashlamp and diode pumping. Consider one of the workhorses of the solid-state class of lasers, the neodymium-doped yttrium aluminum garnate, or Nd:YAG, laser. The Nd:YAG laser is a four-level laser system, as depicted in the simplified energy diagram, shown in Fig. 6. In the four-level system, the pump power threshold is reduced because the lasing transition does not terminate at the ground level. The laser initially absorbs light from the optical pump source, and then quickly relaxes to the upper lasing state. The Nd:YAG laser has a strong lasing transition emitting near-IR radiation of 1.06 μm. The lower-lasing level for Nd:YAG has a relatively short lifespan, and therefore remains only very sparsely populated making a population inversion easier to achieve.

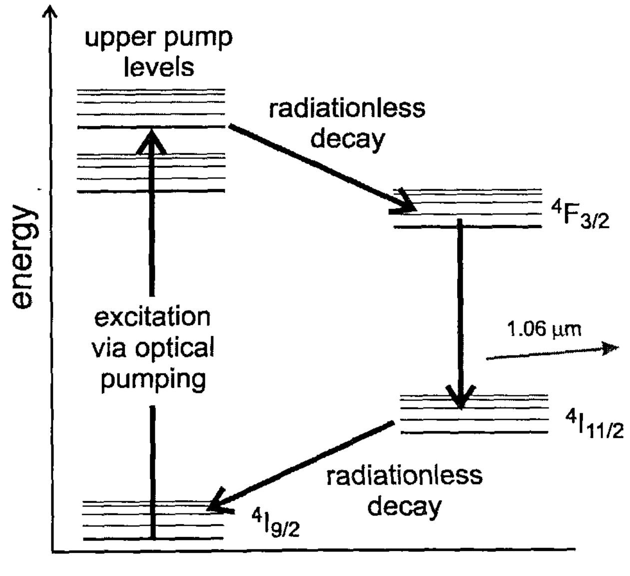


Fig. 6 Simplified energy level diagram for the Nd:YAG laser.

Flashlamp pumping

The cheapest and most common optical pump source is the flashlamp, in many ways similar to flashlamps used in flash photography. Essentially, a flashlamp consists of a sealed quartz tube filled with a gas, such as xenon, and two electrodes, which penetrate into the sealed tube. A high voltage spike applied across the electrodes creates a plasma discharge within the tube, emitting photons in all directions. The two most important factors affecting the efficiency of optical pumping are the spectral characteristics of the pump, and the geometrical arrangement between the pump and gain medium. Interestingly, flashlamps offer relatively poor performance in both areas. Because of the characteristics of the plasma discharge that generates the pump photons, flashlamps emit radiation in a very broad spectral band, including the UV, visible, and IR spectral regions. Because the radiative transition bands associated with stimulated absorption in solid-state laser materials are comparatively narrow, a high percentage of the impinging photons do not contribute to the desired population inversion. This results in a low optical-to-optical efficiency, and the generation of excess heat in the pump cavity. Additionally, because flashlamps radiate energy in all directions, it is not trivial to couple light from the flashlamp into the gain medium. Usually, a reflective, semielliptical pump cavity surrounds the flashlamp and gain medium to focus a maximum amount of pump radiation into the laser rod. In some designs, however, optical coupling is achieved by simply placing the laser gain medium and flashlamp in the closest possible proximity to each other. In either case, the pumping geometry is said to be transversely pumped, meaning the pump light enters the gain medium perpendicular to the optical axis. Unless special care is taken to design the pump cavity, transverse pumping can lead to nonuniformity in the laser output beam. Although these factors cause the flashlamp-pumped laser to be optically inefficient, flashlamps are capable of generating so much optical radiation that it is still practical to use them as pump sources. In fact, flashlamp pumps are used in some of the highest powered solid-state lasers, such as those used for military and industrial applications.

Diode-pumping

The second common approach to optical pumping employs one or more lasers, usually either light-emitting diodes (LEDs), single laser diodes, or laser diode arrays, as the pumps themselves. As sources of optical radiation the diode laser and the flashlamp are close to opposites, it is therefore interesting to note that they have both become commonly used as optical pumps for solid-state lasers. As could be expected, the use of a diode laser as an optical pump rectifies the primary shortfalls associated with flashlamp pumping. Where a flashlamp has broadband emission, a laser is nearly monochromatic and can be tuned to (or selected for) the appropriate absorption band of the laser medium. Secondly, while a flashlamp emits radiation in all directions, a laser is highly directional. These two factors make diode pumping very optically efficient, a characteristic that manifests itself favorable in many laser parameters, all the way through to the system level. For instance, a highly efficient pumping mechanism leads to a laser resonator with more desirable thermal characteristics. The greater the ratio of absorbed photons to unabsorbed photons, the fewer photons contribute to the generation of heat in the laser pump cavity, which is beneficial for several reasons. Chief among these is the reduction of thermooptic effects in laser resonator components, which can distort the beam and corrupt beam quality.[5] From the system perspective, a cooler laser will require less aggressive cooling techniques. Often, high-powered lasers generate so much heat that during operation water is continually forced through the laser mounting apparatus to cool the laser. The necessity for the equipment associated with water cooling is undesirable for some laser applications because of its expense, power usage, and cumbersome qualities. From another system-level perspective, a more efficient, and therefore cooler, laser can be operated at a higher quiescent level, such as a higher pulse-repetition rate or higher output power. Or, the laser could run at the same operating point but will consume less power, a point that is especially important for portable laser devices where battery life is important.

As previously mentioned, transversely pumped lasers often have nonuniform output profiles in the transverse direction. The typical diode emits optical pump radiation in a well-defined cone usually spanning angles of tens of degrees. The small size and directionality of diode lasers have led to an effective alternate pumping geometry, called end-pumping. As shown in Fig. 7, in the typical end-pumping configuration the pump source is positioned

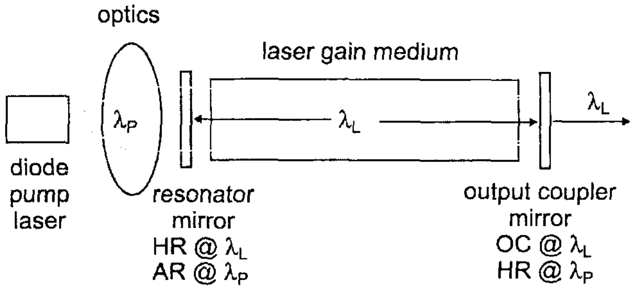


Fig. 7 Pumping geometry for typical end-pumping with a diode laser.

at one end of the resonator. The pump radiation enters the gain medium longitudinally, or along the optical axis. The resonator mirrors may have dual wavelength coatings to enhance the coupling of the pump light, and the power stored in the resonator. For instance, the first mirror might have an optical coating that is antireflective (AR) at the pump wavelength, λ_P, and HR at the lasing wavelength, λ_L. Using this pump geometry, the pump radiation is able to penetrate deep into the laser rod, maximizing the absorption length and further improving pumping efficiency. It is possible, through focusing optics and component placement, to physically control the pump volume in the laser gain material. Taking advantage of this capability, the laser medium can be pumped with a pattern closely overlapping that of the transverse electric and magnetic $TEM_{0,0}$ laser mode. The laser pumped in this manner is encouraged to oscillate naturally in the $TEM_{0,0}$ mode, enhancing beam quality without additional intracavity mode-shaping devices. The main drawback to diode-pumping is the expense associated with the diodes themselves. These prices are sure to come down as manufacturing quantities increase for these devices.

Laser Resonator

The final component necessary for a functioning laser is a physical structure called a resonator cavity. A basic laser resonator consists of two mirrors, with at least one being partially transmissive to allow a percentage of the laser radiation to escape the resonator. This partially transmissive mirror is referred to as the output coupler (OC). Depending on the laser design, the second resonator mirror can be highly reflective (HR) at the laser wavelength. The laser gain medium lies between the resonator mirrors and can be a crystal, glass, gas, or something else. The most important attribute of the gain medium is the availability of specific energy levels that can sustain a population inversion. The resonator serves to store the radiation resulting from stimulated emission and provide optical feedback, thus maintaining the coherence of the electromagnetic field. In the initial stages of the lasing process, both spontaneously emitted photons and those resulting from stimulated emission are emitted in all directions. Photons that propagate parallel to the optical axis of the resonator, or very nearly so, are reflected back and forth between the mirrors. As these photons propagate between the resonator mirrors, additional photon emissions are stimulated, amplifying the electromagnetic field in the process. Photons which are not traveling parallel to the optical axis of the resonator either pass outside of the gain medium or are absorbed at the edges, contributing little or nothing to laser amplification. Sometimes a laser resonator design incorporates waveguiding mechanisms at the edges, such as reflective walls or graded-index materials, redirecting the stray photons back into the gain medium where they contribute to the amplification process. Because waveguiding techniques cause a greater number of photons to contribute to the amplifications process, the overall efficiency of a laser resonator is improved. In a continuous wave (CW) laser, radiation will build in the resonant cavity until the cavity and gain medium losses are balanced by the stimulated emission process, at which time the system is said to be lasing, and radiation is emitted through the OC.

Longitudinal laser modes

The electromagnetic field that oscillates in the laser resonator has well-defined modes or spatial patterns both longitudinally (along the optical axis) and transversely (perpendicular to the optical axis). The radiation propagating within the laser cavity behaves as a standing wave and is defined by the separation (L) of the mirrors. Standing waves can only exist between the mirrors when their separation corresponds to an integer number, m, of half wavelengths, or $L = m\lambda/2$. Assuming a constant index of refraction, η, in the resonator, longitudinal laser mode frequencies are expressed as $\nu = mc/2\eta L$, where c is the speed of light. The frequency spacing between longitudinal modes is the inverse of the round-trip time for radiation in the cavity, or $\Delta\nu = c/2\eta L$. A typical example of the relationship between longitudinal modes and the frequency bandwidth of the active medium is shown in Fig. 8. Often, many longitudinal modes meet the standing wave criteria, each having a much narrower frequency bandwidth than that of an energy transition of the active medium. In general, the radiative transition will allow for a large number of modes to exist in narrow frequency bands determined by the cavity design. One way to keep only a single longitudinal mode oscillating is to design the resonator in such a way that the mode separation, $\Delta\nu$, exceeds the radiative transition bandwidth.

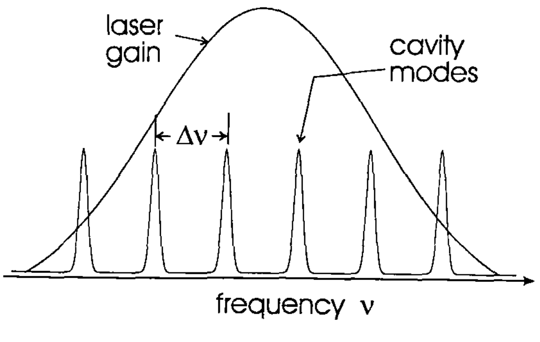


Fig. 8 Longitudinal modes in a typical laser resonator.

Transverse laser modes

In addition to longitudinal modes, the cavity will support certain specific transverse modes as well, designated TEM$_{m,n}$ modes. The subscripts m and n correspond to the number of horizontal and vertical nodes present in the laser beam. A node is a physical location where the amplitude of the electric field is zero, corresponding to zero intensity in the laser beam profile. The laser beam's transverse mode structure is largely determined by the resonator cavity characteristics. Common resonator cavity types that incorporate both curved and flat mirrors are shown in Fig. 9. The simplest design uses two planar or flat mirrors, carefully aligned parallel to each other, as shown in Fig. 9a). A plane-parallel resonator design has the advantage of being simple and therefore inexpensive, and lends itself well to monolithic devices in which the mirrors are applied directly to a solid gain material, usually in the form of a dielectric coating. Recall that the resonator mirrors of semiconductor lasers are typically fabricated by cleaved faces along the crystalline structure of the material, and therefore fall in the plane-parallel resonator category. A resonator cavity may be designed with one or two concave mirrors, as shown in Fig. 9b) and c). As well as shaping the transverse mode pattern of the laser beam, the use of curved mirrors reduces cavity losses resulting from diffraction. Stable resonator designs, such as that of Fig. 9c), exhibit transverse modes which are closely described by the Hermite–Gaussian function, $G_l(r)$, where $l = 0, 1, 2, \ldots$, the first few orders of which are shown in Fig. 10. When a stable resonator is designed to operate in the lowest order mode, the TEM$_{0,0}$ mode, the output most closely approximates a gaussian beam profile, having the form $G_0(r) = \exp(-r^2/2)$, shown in Fig. 10a). Fig. 11 shows the corresponding intensity distributions for stable laser resonators with (x,y) symmetry. This lowest order transverse mode is desirable for many applications because no nodes are present in the beam. A TEM$_{0,0}$ laser beam offers a beam of maximum brightness, of smallest angular beam divergence, and with the capability to be focused down to the smallest sized spot. One disadvantage of the stable resonator design is that higher-order modes are often relatively narrow, failing to efficiently fill the volume of the laser gain material. Finally, a laser resonator can be designed with diverging optics, as shown in Fig. 9d), called an unstable resonator design. Unstable resonators have the highest diffraction losses, but have transverse mode patterns that readily fill the laser gain media volume, while maintaining low-order transverse modes. The transverse field variation in the

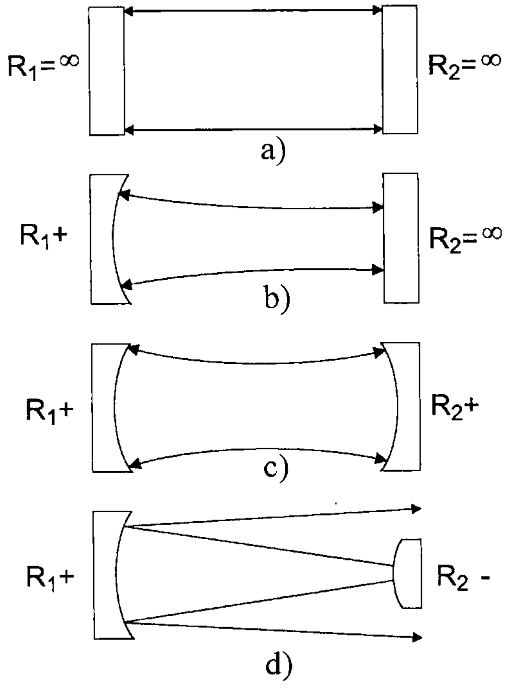


Fig. 9 Common laser resonator cavity designs.

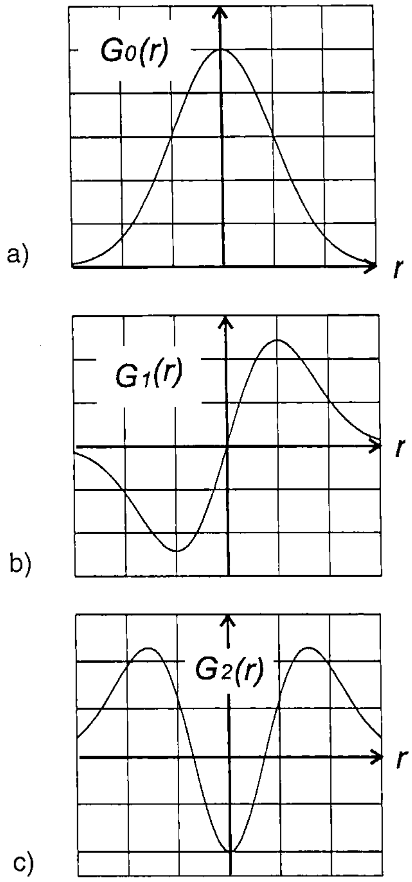
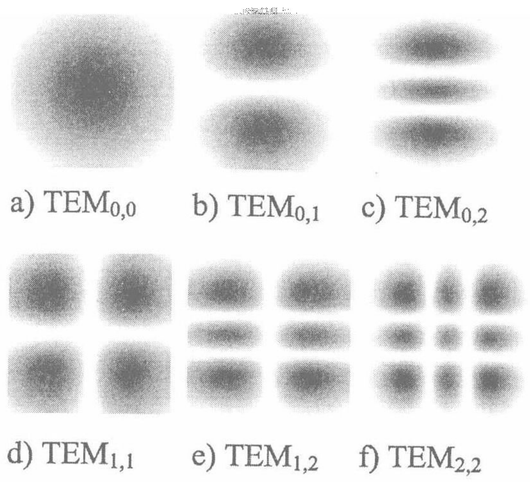


Fig. 10 Hermite–Gaussian transverse-mode pattern in a stable laser resonator cavity.



a) $TEM_{0,0}$ b) $TEM_{0,1}$ c) $TEM_{0,2}$

d) $TEM_{1,1}$ e) $TEM_{1,2}$ f) $TEM_{2,2}$

Fig. 11 Intensity distributions of lower order Hermite–Gaussian transverse modes for a stable laser resonator.

laser cavity also determines the spatial coherence of the laser beam. A laser beam which has the same instantaneous phase at points which are located a large distance from each other (within the confines of the laser beam) is said to have a high degree of spatial coherence. Lasers operating in the lowest order modes possess the highest degree of spatial coherence.

KEY LASER BEAM OUTPUT CHARACTERISTICS

It is the unique optical characteristics of the output of a laser that makes it such a useful tool when compared with typical incoherent sources of light. These important differences stem from the way laser radiation is generated, namely by the properties of the resonant cavity, and are in general related to the temporal and spatial coherence of the laser. When compared with standard incoherent light sources, such as an incandescent light bulb or a flashlight, the coherent radiation from a laser has a more narrow frequency distribution, is more intense, has higher brightness, has a smaller beam divergence, is more directional, and is therefore easier to collimate, and is capable of very short duration pulses. In this section, a few of these important characteristics are discussed in the context of common laser applications.

Laser Beam Divergence

All light beams diverge, or spread out, as they propagate. A laser can be designed to produce a beam approaching the diffraction limit, or the minimum possible beam divergence. This capability makes the laser an indispensable tool for applications requiring light propagation over long distances, such as remote sensing, laser range finding, laser radar, machine vision, active imaging, free-space laser communications, and vibration sensing. Consider laser range finding, a straightforward laser sensing application. A laser range finder measures the range to a distant object by measuring the amount of time it takes a laser pulse to travel to the target and return to a photoreceiver, which is part of the range finder system.[7] The distance to the target, R, is calculated using the round trip time τ, as $R = c\tau/2$, where c is the speed of light.[8] A small beam divergence is important to maximize the amount of laser energy intercepted by a finite sized target a long distance away.

The far-field full-angle diffraction-limited beam divergence for a gaussian beam is given by $\Delta\theta = 4\lambda/\pi D = 1.27\lambda/D$, where D is the diameter of the gaussian beam at its waist, and $\Delta\theta$ is measured at the $1/e^2$ point, in radians.[9] The output from a laser operating in the $TEM_{0,0}$ mode is a close approximation to a diffraction-limited gaussian beam. A second expression commonly found in the literature relating to beam divergence is the far-field divergence of the diffraction pattern resulting from a plane wave passing through a circular aperture. The resulting far-field pattern consists of a series of concentric circles and is called an Airy disk pattern. The full-angle beam divergence subtended by the central lobe of the Airy disk pattern is $\Delta\theta = 2.44\lambda/D$, in radians where D in this case is the diameter of the circular aperture.[9] For some applications it is desirable to decrease the laser beam's divergence using optics. If a simple telescope arrangement having magnification power M is used to expand the beam, the beam divergence is reduced by a factor of M, or $\Delta\theta_e = \Delta\theta/M$ where the subscript "e" indicates the expanded beam characteristics. An application closely related to laser range finding is laser radar, sometimes called lidar for light radar, in which laser ranging is used in a three-dimensional (3-D) imaging application. There are many different forms of laser radar, however, one of the simplest involves incorporating a direct-detect laser ranging system, like that described above, with a scanning apparatus to obtain a 3-D range map of an object or scene of interest. Example laser radar images are shown in Fig. 12.[10] Each image shown in Fig. 12 consists of 256×256 pixels of data. The beam divergence of the 1.06-μm laser used for the laser radar data acquisition was 100 μrad. In the laser radar case, beam divergence is not only related to overall range capability, but to the lateral resolution possible in the results. Fig. 12a) shows an intensity image in which for each (θ, φ) scan position, the intensity of the return signal is displayed. Fig. 12b) shows a range mapping of the same image, in which the pixel color displayed corresponds to the range to the target for that (θ, φ) scan position. These

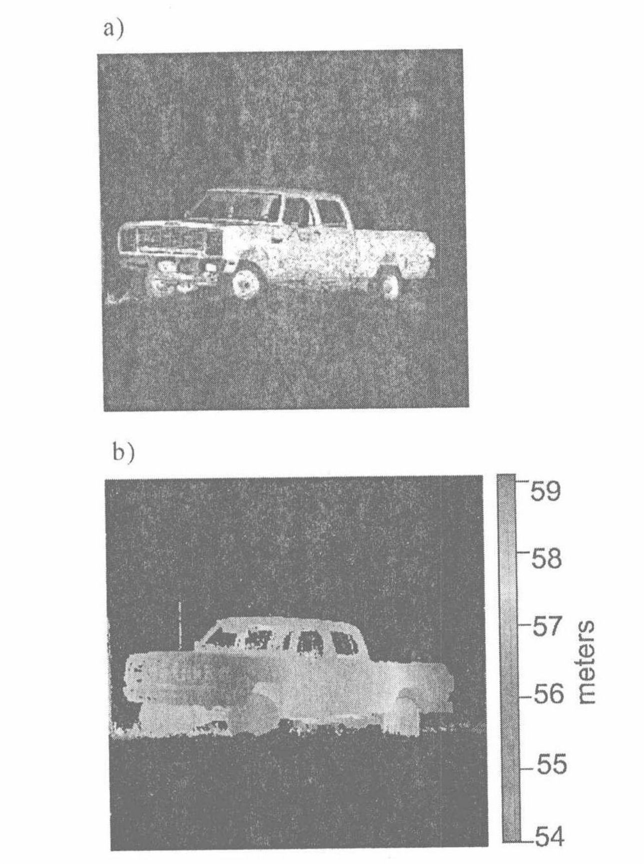


Fig. 12 a) Laser radar data showing intensity mapping. Ranges shown are from ≈ 54 to 59 m. b) Laser radar data showing range mapping. Ranges shown are from ≈ 54 to 59 m.

images were taken of a pickup truck at a range of approximately 50 m from the laser radar transceiver.

High Peak-Power Lasers

There are many applications which make use of the high peak-power possible with some lasers, including laser range finding and other laser sensing applications. Additionally, many industrial applications require very high peak-power lasers, including metal processing such as hole piercing, cutting, welding, and marking. A special mode of operation called quality factor-switching, or Q-switching, has been developed to increase the peak power of certain lasers by several orders of magnitude compared with the average power capability of the same laser. The quality factor of a laser resonator is defined as the ratio of the energy stored to the energy dissipated in the gain medium.[5] In Q-switching, initially the resonator is maintained in a lossy state (low Q) while the gain medium is pumped. Because the low-Q resonator inhibits lasing, the population inversion in the gain medium reaches a level far greater than the threshold for normal lasing. With the population inversion at a heightened level, the resonator is suddenly switched to a high-Q state, using some sort of intracavity optical switch. Upon switching to a high Q, stimulated emission occurs very rapidly in the laser cavity and radiation is emitted in a very powerful short pulse. Q-switched pulses having durations corresponding to a few cavity lengths are possible. Devices commonly used for Q-switching include electrooptic shutters, rotating mirrors or prisms, an acoustooptic shutters, and saturable absorbers.

Coherence

Recording an optical hologram requires a source of coherent light, so it is rather amazing that optical holography was invented in 1947, about 13 years before the first laser was demonstrated.[1] It is not an exaggeration, however, to say that the true capabilities of holographic recordings could not be fully demonstrated or explored without the laser. There are two types of coherence associated with laser light: spatial coherence, and temporal or frequency coherence. Holography represents an application requiring a high degree of both types of coherence. A hologram is a record of the interference pattern formed by the combination of two single wavelength waves, usually originating from the same laser source. The first wave pattern is called the object wave and illuminates the object or scene of interest. The second wave set is called the reference wave, and is usually very simple in nature, such as a plane wave. A recording is made of the light reflected from the object or scene as it interferes coherently with the reference wave, and a hologram is created. By recording not only the light emanating from the object, but the reference beam as well, both intensity and phase information are stored in the hologram. A 3-D image of the original object or scene is reconstructed by illuminating the hologram with a reference wave having the same optical characteristics as that used for recording. Gas lasers, such as He–Ne and argon-ion lasers, are commonly used in holography for their coherence (i.e., single temporal and spatial mode) characteristics.

CONCLUSION

For more then four decades, scientists and engineers have advanced the field of lasers by not only incorporating these tools into useful systems, but by developing a myriad assortment of new laser sources. Lasers can be found operating at power levels ranging from nanowatts to terawatts, at wavelengths from the microwave to the X-ray spectral region, and with pulse durations ranging from femtoseconds to CW. The spe-