The Laser

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One of the greatest inventions of the twentieth century, if not of all times, the laser is regarded as humankind's most versatile light source, a truly new kind of light with remarkable properties unlike anything that existed before—a light fantastic! Since it was first used to generate light in 1960 by Theodore Maiman at Hughes Research Laboratories with the help of a ruby crystal, the laser has been at the core of most light-based technologies and has garnered applications in all facets of life. It is a marvelous tool that has enabled many scientific discoveries. Numerous books, textbooks, and articles have been written about laser physics and engineering. This article is a brief tutorial introducing some of the basic principles underlying the development of the laser and highlighting some of its remarkable characteristics.

4.1 Introduction: A Laser in the Hands of Ibn al-Haytham

As the millennium-old contributions of al-Hasan ibn al-Haytham (ca. 965–ca. 1040) to light and vision are being celebrated in this *International Year of Light*, one might wonder if the laser could have been invented in al-Hasan's time. It is even tempting to imagine him being handed a red light beam from a laser, shining through the smoke created by incense somewhere in Fatimid Cairo, and to speculate on his possible reaction. As the reigning expert of optics and vision of his time, would he have found laser light to be truly remarkable? Would he have used it to corroborate his original observations pertaining to reflection, refraction, and the focusing of light?

Seeing the laser beam, al-Hasan would probably have surmised that it could be sunlight shaped into a thin beam by the use of some ingenious contraption of mirrors, a tiny version of the mirror systems said to have been used by Archimedes to destroy the Roman fleet in 212 BC. What about the red color of the laser beam? Simple: it's sunlight transmitted through a piece of red glass, much like those made and traded by the Phoenician glassmakers. Puzzled about the unusual thinness of the beam, its very limited divergence, and its exceptional brightness, al-Hasan would have waited for the Sun to set; seeing that the light beam still shined brilliantly through the smoke, he might then have concluded that the contraption uses a miniaturized version of a red lantern, similar to those he saw as a child in Basra. He would then have again contemplated the exceptional brightness of the light. And as to the narrowness of the beam, he might have speculated that it is collimated light passed through tiny holes much like those used in the then-known camera obscura.

al-Hasan Ibn al-Haytham
(Alhazen) ca. 965 – ca. 1040

Known for his methodical reliance on experimentation and controlled testing, al-Hasan would have conducted an experiment using the brightest red lantern available, along with mirrors, magnifying lenses, and pinholes, to produce a similar beam of light. He probably would have succeeded in creating a dim red beam of light, a miniaturized version of the beam produced at the Pharos (lighthouse) of Alexandria, which used a mirror to reflect sunlight during the day and a fire lit at night. But no matter what he might have done with the oil-based light sources of the day, it would not have been possible for him to come close to the brightness and narrowness of the laser beam.

Frustrated with his failure, al-Hasan would probably have engaged in a set of experiments benefitting from the available "magic" light source to confirm his findings about reflection and refraction from his stock of mirrors and lenses. He would not have known that it took centuries to discover the wave nature of light (propagation, diffraction, interference, and coherence), its electromagnetic nature (polarization and propagation through anisotropic media), its quantum nature (photons and light–matter interaction), and to develop concepts such as thermal equilibrium, oscillation, modes, spectral analysis, and transient dynamics—all of which are necessary to truly understand, design, and use lasers.

4.2 The Laser: An Optical Oscillator

The laser is simply an oscillator of light, and the phenomenon of *oscillation* is one of its underlying foundational principles.

4.2.1 Oscillators

An oscillator is a device, system, or structure that produces oscillation at some frequency, with little or no excitation at that frequency. An example of a mechanical oscillator producing sound is the familiar tuning fork. When struck, it vibrates, or oscillates, creating sound at its characteristic (resonance) frequency (Fig. 4.1). The oscillation eventually decays since there is no energy source to sustain it. A musical instrument is made of mechanical structures (chords or pipes) that oscillate at distinct frequencies, which may be altered by changing their dimensions or shapes, as the instrument is played. Another example is the undesirable acousto-electrical oscillation often encountered when a microphone is connected to an audio amplifier feeding a close-by loudspeaker (Fig. 4.2). A small disturbance sensed by the microphone is amplified, and if the sound produced by the loudspeaker reaches the microphone, it gets amplified once more, and the cycle is repeated. Circulation through this feedback loop results in

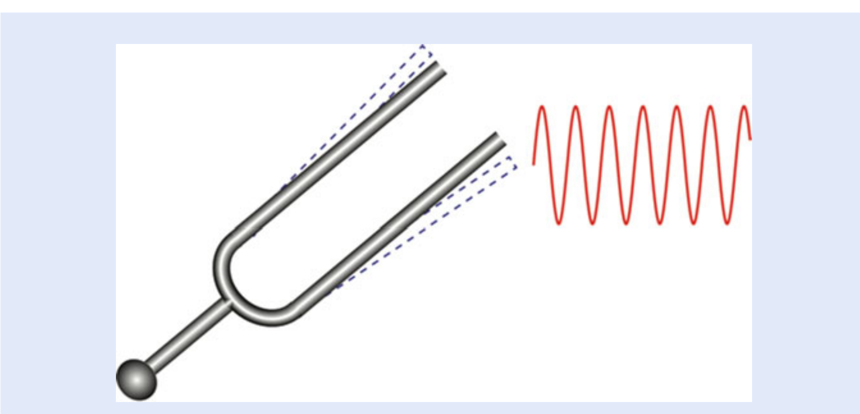

Fig. 4.1 When struck, a tuning fork vibrates at its characteristic resonance frequency

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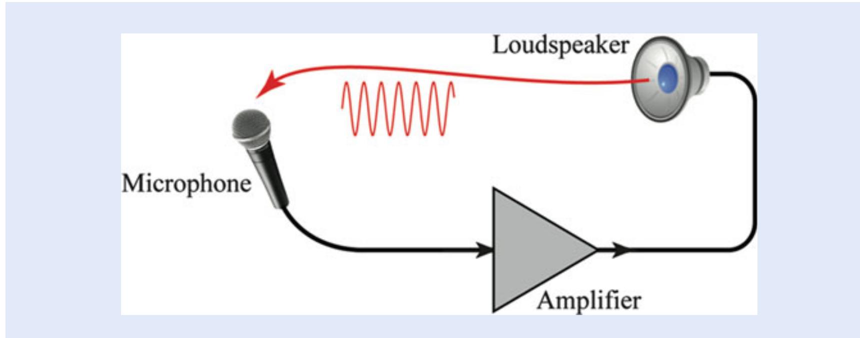


Fig. 4.2 Undesirable oscillation is created when the loudspeaker sound reaches the microphone

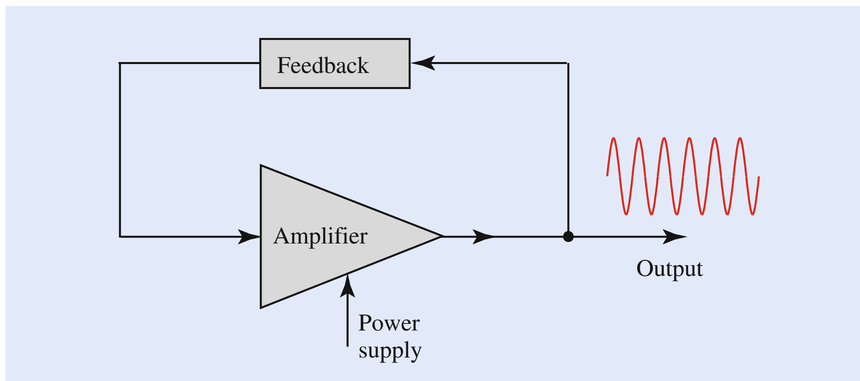


Fig. 4.3 An electronic oscillator using an amplifier and a feedback loop

oscillation—the familiar whistle sound. The frequency of oscillation is characteristic of the overall system.

The oscillator is a basic building block of virtually all electronic systems, analog or digital. An electronic oscillator comprises a resonant electronic amplifier along with a feedback system that directs the output of the amplifier back to its input, in the form of a feedback loop, as illustrated in Fig. 4.3. It is essential that the feedback be positive, i.e., the feedback signal re-entering the amplifier must be in phase with the original signal. Oscillation is initiated by noise, which contains a broad spectrum of all frequencies. The resonant amplifier amplifies a selected frequency component, and the feedback circuit brings the output back to the input for further amplification. For example, with gain of 2, a tiny input traveling 20 times through the feedback loop is amplified by a factor of $2^{20} \approx 10^6$. Of course, the output of the device cannot grow without bound, since the amplifier eventually saturates, i.e., its gain is reduced when its input becomes too large. As illustrated in Fig. 4.4, when the reduced gain eventually becomes equal to the loss encountered in the loop, growth of the circulating signal ceases, and the oscillator output stabilizes. The ultimate result is the generation of energy at a specific resonance frequency, with little initial excitation at that frequency. Energy is of course provided by the amplifier power supply, e.g., a battery. Resonant amplification is achieved by means of a resonant element, usually in the form of a capacitor connected to an inductor in the domain of electronics, whose values determine the resonance frequency.

High-frequency electronic oscillators were developed as electronics technology advanced. Electronics emerged in the first half of the twentieth century and has advanced steadily with efforts to achieve miniaturization and greater switching

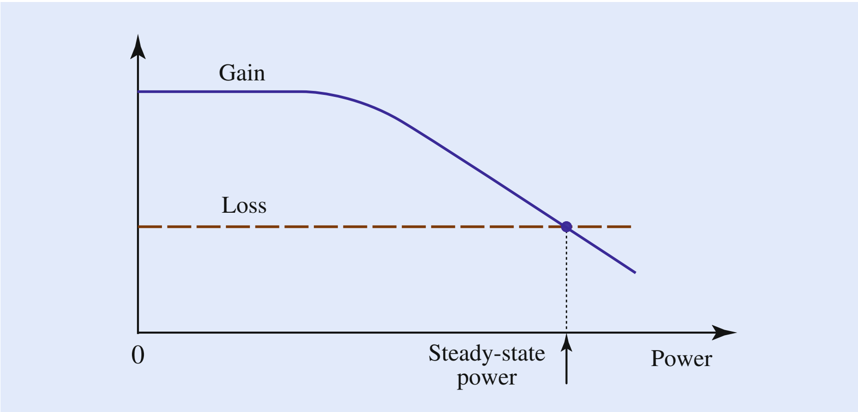


Fig. 4.4 Buildup of oscillation. As the power increases, the amplifier gain is reduced; when it equals the loss in the feedback loop, a steady-state power is reached

speeds—and this continues to this day. The quest to build electronic oscillators that operate at higher and higher frequencies was fueled by the desire to make use of wider and wider bands of the electromagnetic spectrum. The earliest electronic oscillators operated at audio frequencies (AF) and radio frequencies (RF), in the kHz and MHz ranges. They used transistor-based amplifiers and inductor–capacitor resonant circuits. Early microwave (MW) oscillators in the GHz range employed special vacuum-tube amplifiers, such as magnetrons and klystrons, which were based on ingenious mechanisms for forging interactions of the microwave field with electron beams, along with microwave cavity resonators that provided the prerequisite feedback. These oscillators were used for decades following their introduction in the 1940s, but were ultimately replaced by solid-state devices such as Gunn and IMPATT diodes.

The development of AF, RF, and MW oscillators was motivated by the needs of the electronics and telecommunications industries, and the development of oscillators at frequencies in the GHz range was fueled by the need for radar systems during the Second World War. This evolutionary process was bound to lead naturally to the development of oscillators in the THz frequency range and beyond, including optical frequencies (the frequency of visible light lies in the 400–770 THz range, and ultraviolet light and X-rays have even greater frequencies), but this natural evolution took several decades. This may be because the need for a new kind of light source was not pressing since many conventional light sources already existed. Gas-discharge lamps emitting over a narrow band of frequencies, filtered both temporally and spatially, met the needs of most scientific applications envisioned at the time.

Perhaps it was the development of the maser, the microwave predecessor of the laser, that stimulated the extrapolation to optical frequencies; both the laser and the maser are based on the same amplification principle: *stimulated emission*. In fact, after the laser was invented, it was known as an *optical maser* in the early technical literature. The term “maser” is an acronym for Microwave Amplification by Stimulated Emission of Radiation.

4.2.2 The Optical Oscillator

As mentioned earlier, two basic mechanisms are necessary to build an oscillator: resonant amplification and positive feedback. The frequency of oscillation is dictated not only by the resonant amplifier, but also by the feedback system, because of the requirement that the phase of the feedback signal arrives in phase with the initial input. An energy source is of course necessary to support the amplification process. In essence, the device converts the power supply energy to energy at the oscillation frequency. How might these basic mechanisms be implemented in the optical regime in order to build an optical oscillator?

Before we go further, it is important to note that optical oscillators exist naturally and need not be invented! Every single excited atom emitting light is itself an optical oscillator. When the atom undergoes a transition between two energy levels with energy difference ΔE it produces a photon at frequency $\nu = \Delta E/h$, where h is Planck's constant. The transition may be regarded as an oscillator with resonance frequency ν. The problem is that these identical atoms emit photons independently, in random directions and with no common phase, although they do have the same resonance frequency. The acoustic analog of such an incoherent source is a large set of independently struck tuning forks, or a large orchestra playing without a conductor. The outcome, which is a superposition of light emitted by say 10^{23} independent atoms, is an optical field that oscillates randomly in both time and space. This is light that lacks temporal and spatial coherence, i.e., it is basically optical noise. What is needed instead is a *single* optical oscillator producing a coherent optical field, rather than an extensive set of independent oscillators, each with miniscule power. The laser does just that!

The laser is an optical oscillator that employs a *coherent* optical amplifier—a medium, which when illuminated by incoming light, produces more light in the same direction and with the same properties as the incoming light. Gordon Gould, one of the early pioneers of the laser, is credited with calling this mechanism Light Amplification by Stimulated Emission of Radiation, thereby introducing the acronym LASER. Since the laser is an oscillator, rather than an amplifier, a more appropriate name would perhaps be Light Oscillation by Stimulated Emission of Radiation, but the associated acronym would have been imprudent.

To construct a system that acts as a single oscillator, i.e., a coherent light source, feedback is necessary. With adequate feedback, the stimulated emission mechanism synchronizes the individual independent atomic oscillators to act collectively as a single optical oscillator. Feedback can be readily implemented by means of an arrangement of mirrors or reflective surfaces that form an optical resonator within which light is repeatedly passed through the amplifying (or gain) medium. The simplest optical resonator takes the form of two parallel planar or spherical mirrors between which the light circulates back and forth, as illustrated in Fig. 4.5. This structure, known in the optics community as a Fabry–Pérot interferometer, was not readily recognized as a resonator until the laser was invented. Amplification occurs at each passage since the gain medium amplifies in both directions. Useful light is extracted by making one of the mirrors partially transmitting.

Every oscillator has a built-in mechanism for stabilization that governs the steady output power (see Fig. 4.4). In lasers, if the pump power is sufficiently high such that the gain in the medium is greater than the resonator loss, then

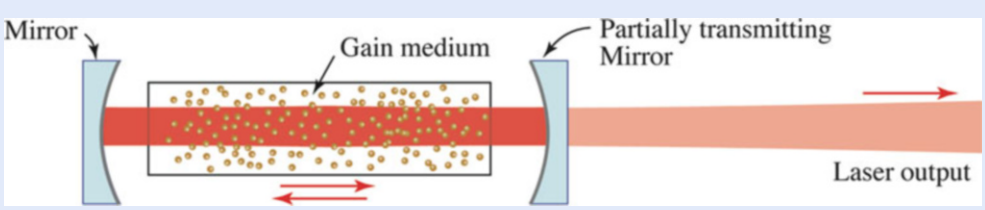


Fig. 4.5 The laser is an optical oscillator that makes use of an amplifying (gain) medium placed inside a resonator

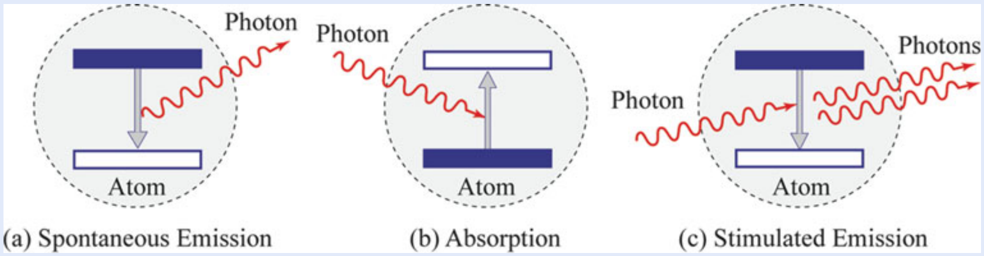


Fig. 4.6 Interaction of light with matter by transitions between two energy levels. (**a**) Spontaneous emission of a photon by an excited atom. (**b**) Absorption of a photon by an unexcited atom. (**c**) A photon stimulates an excited atom to emit a second photon

lasing is initiated and the optical power increases exponentially. However, since atoms undergoing stimulated emission become de-excited in the process, the population inversion is thereby reduced so that further growth of the optical power is suppressed. When the decreased gain eventually equals the loss, the system reaches equilibrium and a steady laser power is delivered.

4.2.3 Optical Amplification by Stimulated Emission

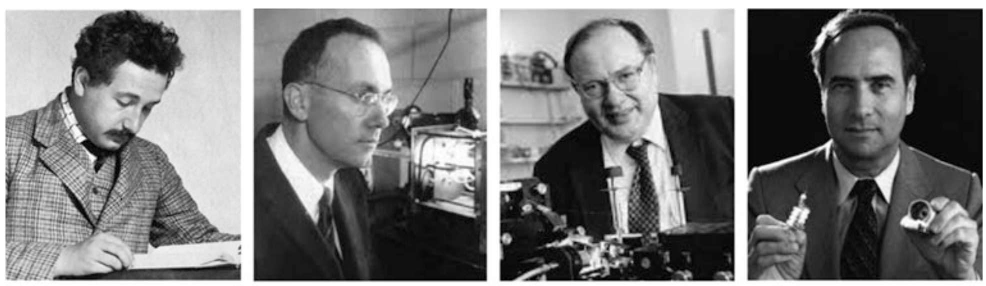
There are three processes inherent in the interaction between photons and atoms (see Fig. 4.6). The first is *spontaneous emission*, which does not generate coherent light. The second is *absorption*, which causes the medium to become an attenuator rather than an amplifier. When unexcited atoms absorb light, they are excited to the higher energy level and subsequently decay back spontaneously, either by emitting light or via some other non-radiative means. *Stimulated emission* is the third component of the interaction. The relation among these processes was set forth by Albert Einstein in 1917 when he revisited Max Planck's law of radiation (the spectral distribution of blackbody radiation in thermal equilibrium).

Einstein showed that while an atom in an unexcited state (lower energy level) might absorb a photon at a rate proportional to the incoming photon flux density, an atom in an excited state (higher energy level) is just as likely to be stimulated by the incoming photons and to emit a photon, so that the flux of photons increases. An important recognition was that the photon emitted via stimulated emission is in the same direction and has the same properties as the stimulating photon. These three mechanisms—absorption, and stimulated and spontaneous emission—govern the interaction of photons with atoms and underlie the law of radiation in thermal equilibrium as well as the generation of laser light.

For a medium with an excess of unexcited atoms, absorption exceeds stimulated emission and the medium provides net attenuation. This is the situation when the medium is in thermal equilibrium. If this equilibrium is somehow disturbed to create an excess of excited atoms, stimulated emission dominates absorption and the medium provides net gain. The medium then serves as a coherent optical amplifier. This non-equilibrium state, called *population inversion*, may be achieved via a process known as *pumping*. In fact, the pumping process supplies the medium with the energy needed to realize the desired gain. Since transitions occur only when the optical frequency matches the resonance frequency of the atomic transition (i.e., the energy of the photon $h\nu$ matches that of the atomic transition energy ΔE), the amplifier is a resonant amplifier. It provides gain only within a narrow spectral band dictated by the atomic transition.

Following Einstein's conception in 1917, the fact that stimulated emission could provide optical gain was confirmed in 1928 by Rudolf W. Ladenburg.

Its use for amplification (also called *negative absorption*) was predicted by Valentin A. Fabrikant in 1939. Optical pumping, i.e., achieving population inversion by the use of another light source, was proposed in 1950 by Alfred Kastler (Nobel Prize for Physics in 1966) as a mechanism for introducing gain. Despite these early discoveries of the basic ingredients of this coherent optical amplifier, it was not until 1960 that a laser was constructed and successfully operated by Maiman. The first maser had been built in 1953 by Charles H. Townes, James P. Gordon, and Herbert J. Zeiger. Townes, Nikolai G. Basov, and Aleksandr M. Prokhorov were awarded the 1964 Nobel Prize for Physics for theoretical work leading to the maser. Masers are now used as low-noise microwave amplifiers for applications such as radio telescopes. In 1958 Arthur L. Schawlow (Nobel Prize for Physics in 1981), together with Townes, suggested a method for extending the stimulated-emission principle of the maser to the optical region of the spectrum.



Albert Einstein (1879--1955) | Charles Townes (1915--2015) | Arthur Schawlow (1921--1999) | Theodore Maiman (1927--2007)

4.2.4 Laser Materials and Pumping Methods

An enormous variety of materials are used as gain media in lasers and laser amplifiers; these include solids, gases, liquids, and plasmas. The wavelengths of these devices span extended bands of the electromagnetic spectrum, all the way from the microwave to the X-ray region. They make use of a wide variety of resonator configurations and pumping schemes (Fig. 4.7). Pumping may be implemented optically by means of light at a wavelength other than the resonance wavelength, e.g., by a flash lamp or another laser; or it may be implemented by use of an electric current, as is the case in semiconductor laser diodes.

4.3 Optical Resonators and Their Modes

Optical feedback is commonly provided by use of a resonator, which serves as a "container" within which the generated laser light circulates and is built up, and can be stored. Optical resonators take a variety of configurations, as illustrated by the examples in Fig. 4.7. The most common configuration is two planar or spherical mirrors. Ring lasers use an arrangement of mirrors in a ring configuration or use a closed-loop optical fiber or integrated-optic waveguide. Dielectric waveguides with two cleaved end surfaces are used in semiconductor lasers. In microdisks and microspheres, light circulates inside the rim of the material by total internal reflection at near-grazing incidence, in what are known as whispering-gallery modes. Periodic dielectric structures such as distributed Bragg reflectors

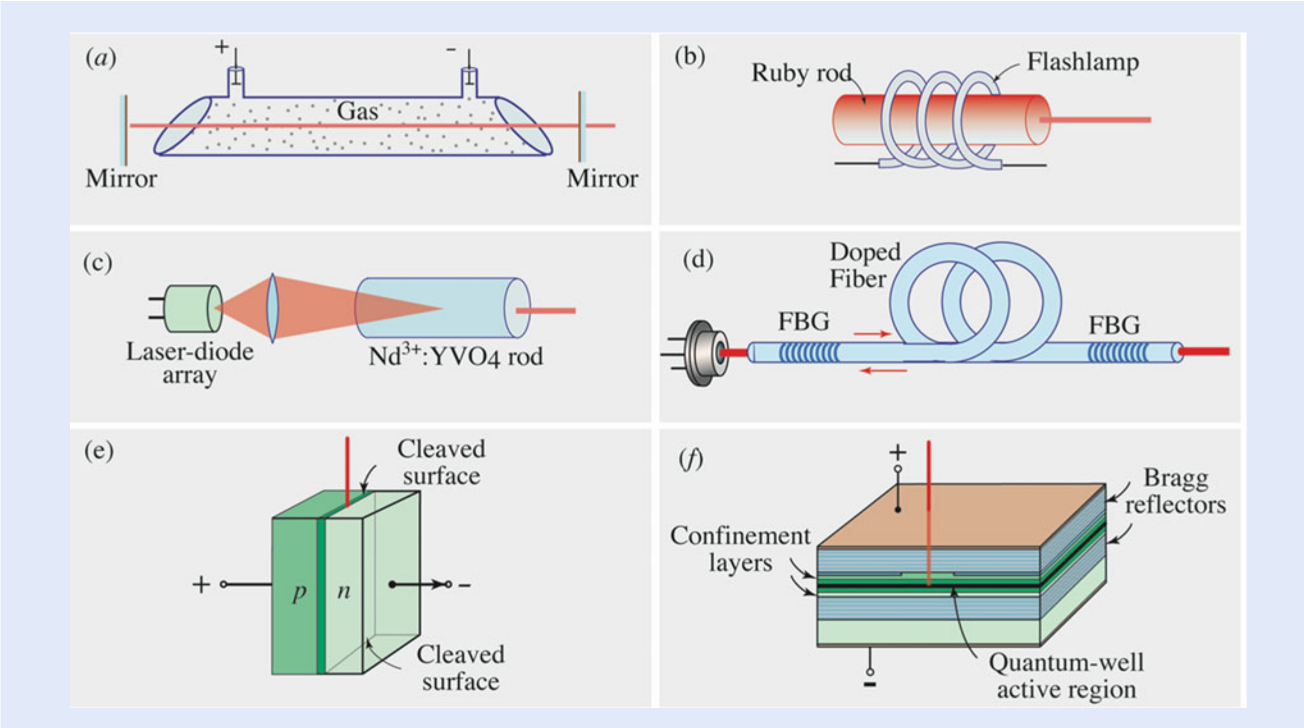


Fig. 4.7 Examples of lasers. (**a**) Gas laser pumped by direct current (DC). (**b**) Solid-state laser, e.g., ruby, optically pumped with a flashlamp. (**c**) Nd:YVO4 solid-state laser optically pumped by a laser diode array. (**d**) Fiber laser (e.g., erbium-doped silica fiber) with fiber Bragg grating (FBG) reflectors, pumped with a laser diode. (**e**) Laser diode (forward-biased *p*–*n* junction) with cleaved surfaces acting as mirrors, pumped by electric-current injection. (**f**) Quantum-well semiconductor laser, pumped electrically. Charge carriers are restricted to the active region by the confinement layers and Bragg reflectors serve as mirrors

(DBRs) are used as mirrors for trapping the light inside a fiber or in small structures, as in the micropillar resonator. Light can also be trapped in defects within dielectric photonic-bandgap structures, forming photonic-crystal resonators. In microresonators, which are used in microlasers, the size of the resonator can be of the same order of magnitude as its resonance wavelength. Nanoresonators, which can be far smaller than the resonance wavelength have come to the fore in recent years.

The optical resonators are characterized by their quality factor Q, which is the ratio of the resonance frequency to the line width. A low-loss resonator has a large Q, corresponding to sharp resonance and long storage time (in units of optical period). Resonators may have Q as high as 10^8, corresponding to a narrow spectral width of 3 MHz and a storage time of approximately 0.3 μs, for resonance at a wavelength of 1 μm.

4.3.1 Modes

Another foundational principle underlying the laser is that of *modes*. A resonator supports light in specific spatial and longitudinal modes. Modes are fields that self-reproduce as they circulate through the resonator. Spatial modes are spatial distributions that maintain their shape after one round trip. Longitudinal (or spectral) modes are fields with frequencies for which the circulating light arrives in the same phase (or shifted by multiples of 2π) after one round trip.

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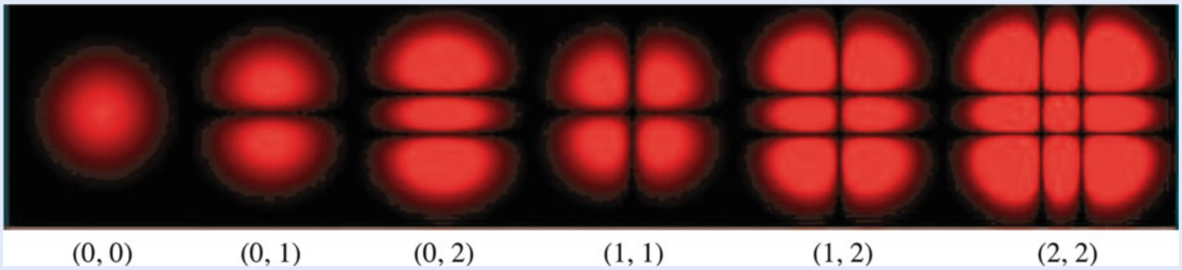

Fig. 4.8 Spatial distributions of the Hermite–Gauss modes of spherical-mirror resonators. The Gaussian mode, which is the lowest-order mode (0, 0), is the most confined around the resonator axis

As mentioned earlier, this ensures positive feedback, which is a necessary condition for oscillation. Each spatial mode may support multiple longitudinal modes.

Laser oscillations occur in those spatial and longitudinal modes for which the round-trip gain is greater than the loss. Since the gain is available within the spectral range defined by the atoms, only those modes whose frequencies lie in this range may oscillate. Moreover, since the spatial modes have different spatial profiles, and therefore undergo different losses, only a finite number of spatial modes oscillate, with the more confined modes favored. And each of these spatial or spectral modes has two polarization degrees of freedom, constituting polarization modes (horizontal/vertical linear polarization or right/left circular polarization).

Ideally, the laser is designed to operate in a single spatial mode with a single longitudinal mode. Such a single-frequency laser is a single optical oscillator with the highest spatial and temporal coherence. However, lasers are also often designed for operation in a single spatial mode with many longitudinal modes. Since these modes oscillate independently, their sum undergoes interference (beating) resulting in amplitude variation and a broader spectrum with reduced temporal coherence. However, such variations are usually on a short time scale, e.g., nanoseconds, so that the average power remains steady when averaged over a longer time, which serves well for certain applications. Operation in multiple spatial modes, each with its own longitudinal modes, can be useful for applications requiring greater power, although such multimode lasers exhibit reduced temporal and spatial coherence.

The spatial modes of the spherical-mirror resonator are the Hermite–Gauss modes illustrated in Fig. 4.8. The widths of these modes and their divergence angles are determined by the curvatures of the mirrors and their separation.

4.3.2 The Gaussian Beam

The Hermite–Gauss mode with the smallest width is the Gaussian mode. This is responsible for generating the Gaussian beam (Fig. 4.9), which has the smallest angle of divergence for a given width. Its diffraction-limited divergence angle is inversely proportional to the beam radius at its waist W_o, namely $\theta_o = \lambda/\pi W_o$. For example, for $\lambda = 1$ μm and $W_o = 1$ cm, $\theta_o = 3.18 \times 10^{-5}$ radians. At a distance $d = 3.8 \times 10^8$ m (the distance to the moon), this corresponds to a spot diameter $2d\theta_o \approx 24$ km. If the beam radius were increased from 1 cm to 1 m, the spot size at the moon would be only 240 m. The Gaussian laser beam is highly collimated near its waist so that it may be regarded as a planar wave and used for applications requiring plane waves.

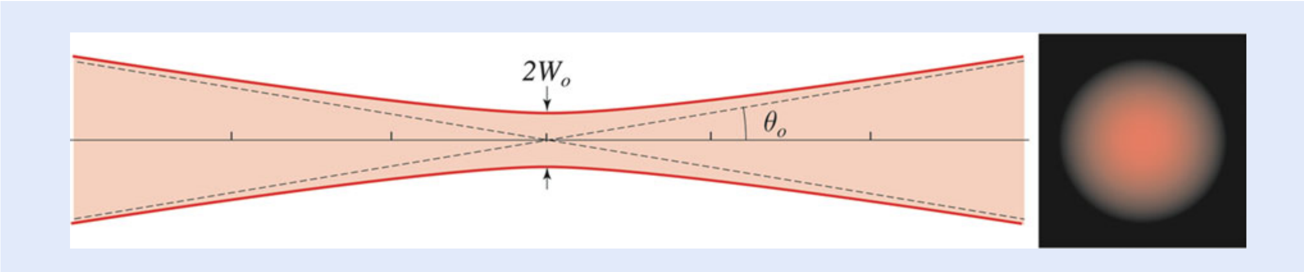

Fig. 4.9 The Gaussian beam

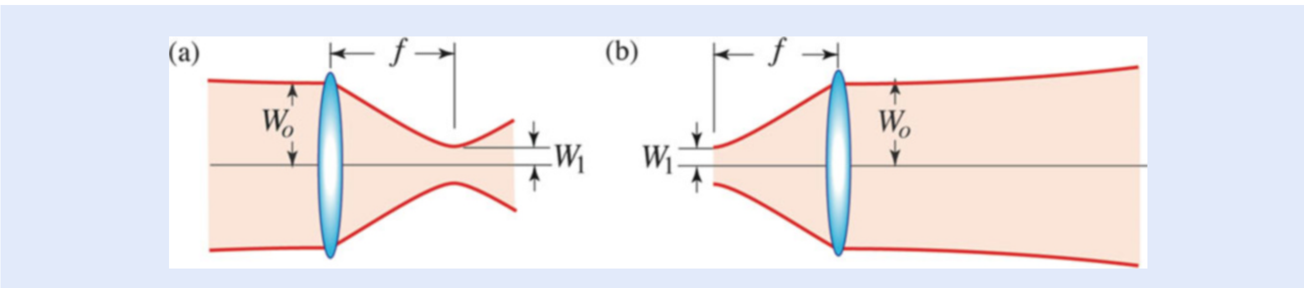

Fig. 4.10 Manipulation of a Gaussian beam by use of a lens of focal length *f*. (**a**) Reduction of the beam waist (focusing). (**b**) Reduction of the divergence angle (collimation)

The angle of divergence, and the associated waist, of the Gaussian beam may be manipulated by the use of lenses. For example, a beam with large waist W_o (and small divergence angle) may be used to generate a beam of smaller waist (and large divergence angle) W_1 by use of a lens of short focal length *f*. This is important for applications in lithography and laser scanning microscopy or for industrial applications such as cutting and welding. Conversely, a beam of small width and large divergence angle, such as that generated by a laser diode, may be converted into a beam with small divergence angle by use of a lens, as shown in Fig. 4.10. This is used in laser pointers.

4.4 Coherence of Laser Light

The most unique property of the laser is its temporal and spatial coherence. Laser light has a long coherence time (narrow spectrum) and a large coherence area. Conventional light sources have short coherence times (broad spectra) and small coherence area; they are incoherent.

The *coherence time* τ_c is the time duration over which the wave maintains its phase. This quantity is inversely proportional to the spectral width of the light. Laser light has a very narrow spectral distribution, ideally single frequency (a single wavelength), i.e., it is monochromatic or single color. Temporal coherence is also called longitudinal coherence. The *coherence length* $\ell_c = c\tau_c$, where *c* the speed of light. Long coherence length signifies that the phase of the wave is correlated over a long distance along its direction of propagation. Temporal coherence allows the production of ultrashort pulses of light, as short as a femtosecond or even in the attosecond regime.

Spatial (or transverse) coherence describes the correlation of light fluctuations in the transverse plane. The coherence area is the area within which the wave is correlated. Because of its spatial coherence, laser light in the Gaussian spatial mode undergoes minimal spread as it travels, so that the beam has the least divergence (diffraction-limited), i.e., is highly directional, and the smallest spot size at great distances. This feature is important for various applications including free-space communication. Also, the laser beam can be focused to a spot of minimal width, so that it provides maximal irradiance, an important feature for various applications such as lithography and other industrial applications.

It is essential to note that the coherence properties of light from a conventional incoherent source can be improved by means of spectral and spatial filters. A spectral filter with narrow spectral width can enhance the temporal coherence by filtering out frequencies outside a narrow spectral band. A spatial filter, which may be constructed by sending the light through a pinhole, enhances spatial coherence. Light originating from a point is radiated as a spherical wave, which may be converted into a planar wave with full spatial coherence. Such enhancement of the coherence was in fact practiced before the invention of the laser, when coherent light was generated and used to demonstrate wave properties of light such as interference and diffraction, and to form thin optical beams. The difficulty with such enhancements is that much of the power of the original light was lost by the filtering process. An abiding advantage of laser light is that it combines excellent coherence properties with high power. This explains al-Hasan's frustration in the fictitious story about his attempt to convert light from a lantern into a beam resembling that from the laser. His effort to create order out of chaos ended up with discarding most of the light itself.

Can coherent laser light be distinguished from light generated by a thermal source that is filtered temporally and spatially to have the same coherence time and coherence area as the laser light? The answer is yes! Measurements of other statistical properties of the light intensity and the photons do reveal a difference. One measure is the intensity correlation, introduced by Robert Hanbury Brown and Richard Q. Twiss, fueled major advances in classical and quantum coherence theory. Light from a thermal source exhibits intensity fluctuations whose variance is equal to the squared mean, so that $g^{(2)} = \langle I^2 \rangle / \langle I \rangle^2 = 2$, where I is the intensity, whereas for laser light this variance is zero, which leads to $g^{(2)} = 1$. Photon counts obey Bose–Einstein statistics for thermal light, and Poisson statistics for coherent light from a laser. These counting probability distributions are distinctly different. For a mean number of photons $\langle n \rangle$ detected in a fixed time interval, the count variance is $\langle n \rangle + \langle n \rangle^2$ for thermal light, while it is only $\langle n \rangle$ for coherent laser light.

4.5 Pulsed Lasers

With steady pumping exceeding the threshold required for lasing, the laser output power remains constant over time and the laser is said to be *continuous wave* (CW). Pulsed lasers produce optical power in the form of pulses of certain duration and repetition rate. The creation of short pulses is the temporal equivalent of *focusing* of power in space. Key features of the pulsed laser are the pulse energy, the peak power, and the average power. Higher peak powers may be obtained for shorter pulses with the same pulse energy. Certain applications require high peak power, while others call for high pulse energy. Pulsed operation at a low repetition rate provides adequate time between pulses for the pump to build up a population inversion, thereby allowing the generation of pulses with high energy for the same average power.

Laser pulse durations may be as short as femtoseconds and can be compressed to attoseconds. Pulse-repetition rates extend from hours to more than 10^{11} pulses per second, while peak powers can reach 10 MW. Some gain media are suitable only for use in pulsed lasers since CW operation would require pumping at a steady power so high that it could be impractical or result in excessive heat.

There are two principal schemes for pulsed-laser operation. The first exploits the transient dynamics of the laser system and the energy storage capability of the resonator by on–off switching of the gain, the loss, or the fraction of light extracted from the resonator. These are, respectively, called *gain switching*, *Q-switching*, and *cavity dumping*. The energy is stored during the off-time and released during the on-time. In the second scheme, called *mode locking*, the set of independently oscillating longitudinal modes of the laser are locked together to produce a single periodically pulsed oscillator. Both of these schemes may be used to generate short laser pulses with peak powers far greater than the constant power deliverable by CW lasers.

Gain switching is based on pulsing the pumping source. This is feasible if the pulsing time scale is much slower than time scales governing the lasing process. Examples of gain switching include lasers using electronically charged flashlamps, and semiconductor laser diodes in which the electric current used for pumping is itself pulsed.

Q-switching is loss switching. During the off-time the resonator loss is increased (by spoiling the resonator quality factor *Q*) using a modulated absorber inside the resonator. Because the pump continues to deliver constant power at all times, energy is stored in the atoms in the form of an accumulated population difference. When the losses are reduced during the on-times, the large accumulated population difference is released, generating an intense short optical pulse.

Cavity dumping is based on storing light in the resonator during the off-times, and releasing it during the on-times. During the off-time, the pump is operated at a constant rate and the generated light is stored in the resonator, which is not allowed to transmit and has negligible losses. The light is subsequently released, or "dumped," as a useful pulse by suddenly removing one of the mirrors altogether (e.g., by rotating it out of alignment), increasing its transmittance to 100 %. As the accumulated light leaves the resonator, the sudden increase in the loss arrests the oscillation, and the process is repeated, resulting in strong pulses of laser light.

Mode-locking. Mode locking is the most important of the various techniques for generating ultrashort laser pulses, from tens of picosecond to less than 10 fs. This is attained by locking the phases of the longitudinal modes together. Since the frequencies of these modes are equally separated, they behave like the Fourier components of a periodic function, and therefore form a periodic pulse train with period equal to the round-trip time between the resonator mirrors (Fig. 4.11). The coupling of the modes is achieved by periodically modulating the losses inside the resonator. The pulse width is determined by the number and profile of the

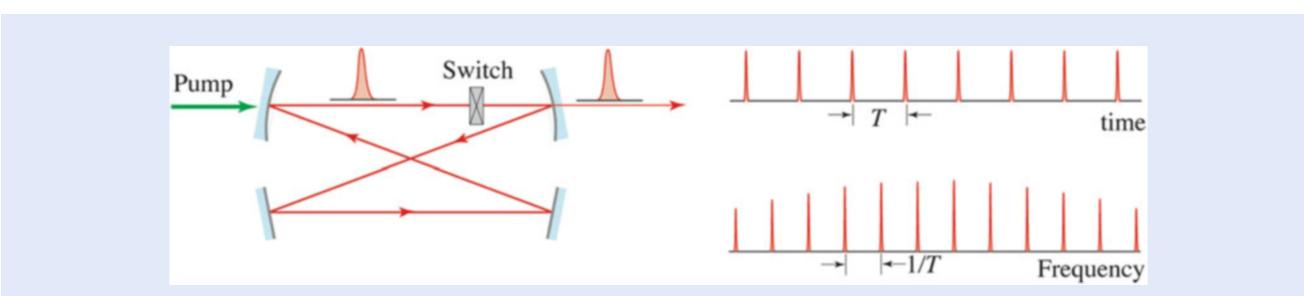

Fig. 4.11 The mode-locked laser. A pulse circulating inside a ring resonator periodically hits the exit mirror and is partially transmitted. The result is a pulse train with period equal to the round-trip time *T*. The spectrum of the emitted light, which is also periodic with period 1/*T*, represents the now-locked longitudinal modes of the resonator. Locking is implemented by modulating the losses inside the resonator using a loss mechanism acting as a switch that lets a pulse out each time period *T*

spectral components (the modes). In accordance with Fourier theory, the wider the overall spectral width (i.e., the larger the number of modes), the shorter the pulse duration. For example, because of their wide spectral width, Ti:sapphire lasers generate pulses of only a few femtoseconds duration.

4.6 Conclusion

The history of the laser has been both an evolution and a revolution. As described earlier in this article, the development of the laser was an *evolutionary* process that drew together concepts formulated over a period of more than four decades (1917–1960). It also benefitted from the evolution of electromagnetic oscillators with increasing frequency, culminating in the maser. This evolution continues today, with new lasers of ever higher frequencies (wavelengths as short as tens of nanometers for X-ray lasers), pulses of durations shorter than 100 as, and greater optical powers: more than 100 kW for CW operation and peak powers in the GW regime (and as high as PW for laser fusion applications). Focused intensities can be as high as 10^{23} W/m^2.

There is no doubt, however, that within a few years of its invention the laser started a *revolution* in optics and optics-based technologies and applications, which created an abundance of opportunities in the early 1960s for major new scientific discoveries and a proliferation of novel technologies with far reaching applications.

Examples of the new sciences are: nonlinear optics, optoelectronics, laser spectroscopy, femtosecond physics and chemistry, attosecond atomic physics, and quantum optics. Laser applications have expanded to cover all aspects of modern technology:

Applications requiring high power and precision focusing include drilling, cutting, welding, ablation, material deposition, additive manufacturing, directed energy, and fusion.

Applications using the directional precision and focusing capability of the laser include optical disk drives, printers and scanners, barcode scanners, metrology and surveying, lithography, scanning microscopy, and adaptive optics imaging.

Applications utilizing high-speed modulation and switching include fiber-optic and free-space optical communications, optical cables, and interconnects.

Applications to medicine and health care include laser surgery, skin treatments, ophthalmic and cardiovascular diagnostics, laser vision correction (Lasik), and other diagnostic and therapeutic procedures.

The laser is truly a light fantastic!

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