Light Amplification by Stimulated Emission of Radiation, LASER

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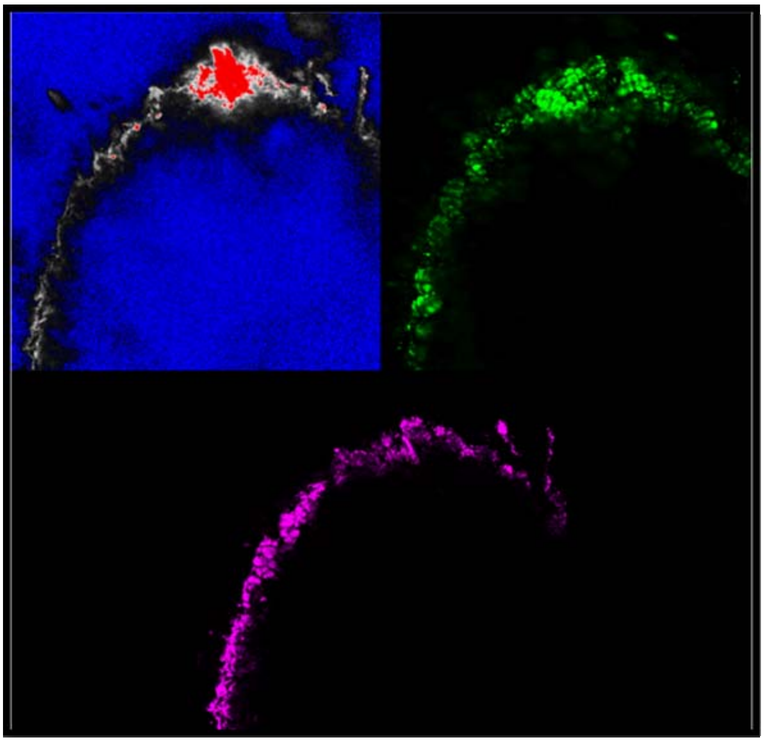

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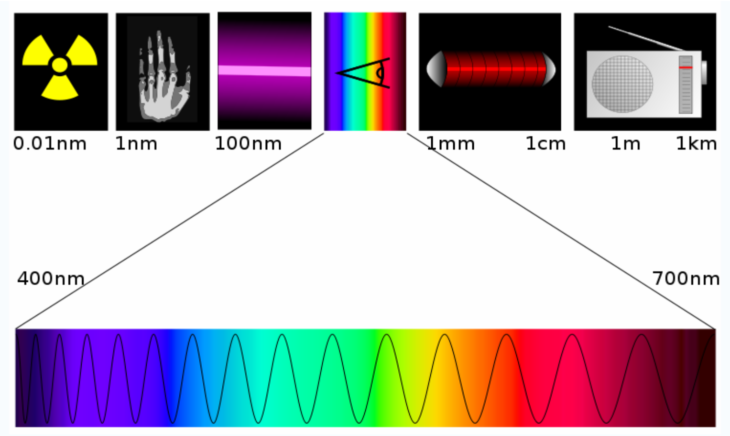
Light Amplification by Stimulated Emission of Radiation, **LASER** (**laser**), is a mechanism for emitting light within the electromagnetic radiation region of the spectrum, via the process of stimulated emission. The emitted laser light is (usually) a spatially coherent, narrow beam that can be manipulated with lenses. In laser technology, "coherent light" denotes a light source that produces (emits) light of in-step waves of identical frequency and phase. The laser's beam of coherent light differentiates it from light sources that emit *incoherent* light beams, of random phase varying with time and position; whereas the laser light is a narrow-wavelength electromagnetic spectrum monochromatic light; yet, there are lasers that emit a broad spectrum light, or simultaneously, at different wavelengths.

Terminology

The word laser originally was the upper-case LASER, the acronym from *Light Amplification by Stimulated Emission of Radiation*, wherein *light* broadly denotes electromagnetic radiation of any frequency, not only the visible spectrum; hence infrared laser, ultraviolet laser, X-ray laser, et cetera. Because the microwave predecessor of the laser, the maser, was developed first, devices that emit microwave and radio frequencies are denoted "masers". In the early technical literature, especially in that of the Bell Telephone Laboratories researchers, the laser was also called optical maser, a currently uncommon term, moreover, since 1998, Bell Laboratories adopted the *laser* usage. Linguistically, the back-formation verb *to lase* means "to produce laser light" and "to apply laser light to". The word *laser* sometimes is inaccurately used to describe a non-laser-light technology, e.g. a coherent-state atom source is an atom laser.



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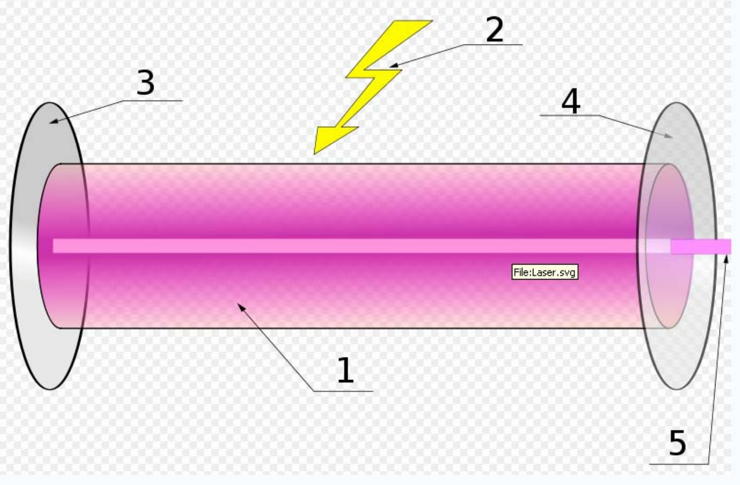
A laser consists of a gain medium inside a highly reflective optical cavity, as well as a means to supply energy to the gain medium. The gain medium is a material with properties that allow it to amplify light by stimulated emission. In its simplest form, a cavity consists of two mirrors arranged such that light bounces back and forth, each time passing through the gain medium. Typically one of the two mirrors, the output coupler, is partially transparent. The output laser beam is emitted through this mirror.

Light of a specific wavelength that passes through the gain medium is amplified (increases in power); the surrounding mirrors ensure that most of the light makes many passes through the gain medium, being amplified repeatedly. Part of the light that is between the mirrors (that is, within the cavity) passes through the partially transparent mirror and escapes as a beam of light.

The process of supplying the energy required for the amplification is called pumping. The energy is typically supplied as an electrical current or as light at a different wavelength. Such light may be provided by a flash lamp or perhaps another laser. Most practical lasers contain additional elements that affect properties such as the wavelength of the emitted light and the shape of the beam.



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Laser physics

The gain medium of a laser is a material of controlled purity, size, concentration, and shape, which amplifies the beam by the process of stimulated emission. It can be of any state: gas, liquid, solid or plasma. The gain medium absorbs pump energy, which raises some electrons into higher-energy ("excited") quantum states. Particles can interact with light both by absorbing photons and by emitting photons. Emission can be spontaneous or stimulated. In the latter case, the photon is emitted in the same direction as the light that is passing by. When the number of particles in one excited state exceeds the number of particles in some lower-energy state, population inversion is achieved and the amount of stimulated emission due to light that passes through is larger than the amount of absorption. Hence, the light is amplified. By itself, this makes an optical amplifier. When an optical amplifier is placed inside a resonant optical cavity, one obtains a laser.

The light generated by stimulated emission is very similar to the input signal in terms of wavelength, phase, and polarization. This gives laser light its characteristic coherence, and allows it to maintain the uniform polarization and often monochromaticity established by the optical cavity design.

The optical cavity, a type of cavity resonator, contains a coherent beam of light between reflective surfaces so that the light passes through the gain medium more than once before it is emitted from the output aperture or lost to diffraction or absorption. As light circulates through the cavity, passing through the gain medium, if the gain (amplification) in the medium is stronger than the resonator losses, the power of the circulating light can rise exponentially. But each stimulated emission event returns a particle from its excited state to the ground state, reducing the capacity of the gain medium for further amplification. When this effect becomes strong, the gain is said to be *saturated*. The balance of pump power against gain saturation and cavity losses produces an equilibrium value of the laser power inside the cavity; this equilibrium determines the operating point of the laser. If the chosen pump power is too small, the gain is not sufficient to overcome the resonator losses, and the laser will emit only very small light powers. The minimum pump power needed to begin laser action is called the *lasing threshold*. The gain medium will amplify any photons passing through it, regardless of direction; but only the photons aligned with the cavity manage to pass more than once through the medium and so have significant amplification.

The beam in the cavity and the output beam of the laser, if they occur in free space rather than waveguides (as in an optical fiber laser), are, at best, low order Gaussian beams. However this is rarely the case with powerful lasers. If the beam is not a low-order Gaussian shape, the transverse modes of the beam can be described as a superposition of Hermite-Gaussian or Laguerre-Gaussian beams (for stable-cavity lasers). Unstable laser resonators on the other hand, have been shown to produce fractal shaped beams. The beam may be highly *collimated*, that is being parallel without diverging. However, a perfectly collimated beam cannot be created, due to diffraction. The beam remains collimated over a distance which varies with the square of the beam diameter, and eventually diverges at an angle which varies inversely with the beam diameter. Thus, a beam generated by a small laboratory laser such as a helium-neon laser spreads to about 1.6 kilometers (1 mile) diameter if shone from the Earth to the Moon. By comparison, the output of a typical semiconductor laser, due to its small diameter, diverges almost as soon as it leaves the aperture, at an angle of anything up to 50°. However, such a divergent beam can be transformed into a collimated beam by means of a lens. In contrast, the light from non-laser light sources cannot be collimated by optics as well.

Although the laser phenomenon was discovered with the help of quantum physics, it is not essentially more quantum mechanical than other light sources. The operation of a free electron laser can be explained without reference to quantum mechanics.

Modes of operation

The output of a laser may be a continuous constant-amplitude output (known as *CW* or *continuous wave*); or pulsed, by using the techniques of Q-switching, mode locking, or gain-switching. In pulsed operation, much higher peak powers can be achieved. Some types of lasers, such as dye lasers and vibronic solid-state lasers can produce light over a broad range of wavelengths; this property makes them suitable for generating extremely short pulses of light, on the order of a few femtoseconds (10^{-15} s).

Continuous wave operation

In the continuous wave (CW) mode of operation, the output of a laser is relatively constant with respect to time. The population inversion required for lasing is continually maintained by a steady pump source.

Pulsed operation

In the pulsed mode of operation, the output of a laser varies with respect to time, typically taking the form of alternating 'on' and 'off' periods. In many applications one aims to deposit as much energy as possible at a given place in as short time as possible. In laser ablation for example, a small volume of material at the surface of a work piece might evaporate if it gets the energy required to heat it up far enough in very short time. If, however, the same energy is spread over a longer time, the heat may have time to disperse into the bulk of the piece, and less material evaporates. There are a number of methods to achieve this.

Q-switching

In a Q-switched laser, the population inversion (usually produced in the same way as CW operation) is allowed to build up by making the cavity conditions (the 'Q') unfavorable for lasing. Then, when the pump energy stored in the laser medium is at the desired level, the 'Q' is adjusted (electro- or acousto-optically) to favourable conditions, releasing the pulse. This results in high peak powers as the average power of the laser (where it running in CW mode) is packed into a shorter time frame.

Modelocking

A mode locked laser emits extremely short pulses on the order of tens of picoseconds down to less than 10 femtoseconds. These pulses are typically separated by the time that a pulse takes to complete one round trip in the resonator cavity. Due to the Fourier limit (also known as energy-time uncertainty); a pulse of such short temporal length has a spectrum which contains a wide range of wavelengths. Because of this, the laser medium must have a broad enough gain profile to amplify them all. An example of a suitable material is titanium-doped, artificially grown sapphire (Ti: sapphire).

The mode locked laser is a most versatile tool for researching processes happening at extremely fast time scales also known as femtoseconds physics, femtoseconds chemistry and ultrafast science, for maximizing the effect of nonlinearity in optical materials (e.g. in second-harmonic generation, parametric down-conversion, optical parametric oscillators and the like), and in ablation applications. Again, because of the short timescales involved, these lasers can achieve extremely high powers.

Pulsed pumping

Another method of achieving pulsed laser operation is to pump the laser material with a source that is itself pulsed, either through electronic charging in the case of flash lamps, or another laser which is already pulsed. Pulsed pumping was historically used with dye lasers where the inverted population lifetime of a dye molecule was so short that a high energy, fast pump was needed. The way to overcome this problem was to charge up large capacitors which are then switched to discharge through flash lamps, producing a broad spectrum pump flash. Pulsed pumping is also required for lasers which disrupt the gain medium so much during the laser process that lasing has to cease for a short period. These lasers, such as the excimer laser and the copper vapour laser, can never be operated in CW mode.

Foundations

In 1917, Albert Einstein established the theoretic foundations for the LASER and the MASER in the paper *Zur Quantentheorie der Strahlung* (On the Quantum Theory of Radiation); via a re-derivation of Max Planck’s law of radiation, conceptually based upon probability coefficients (Einstein coefficients) for the absorption, spontaneous emission, and stimulated emission of electromagnetic radiation; in 1928, Rudolf W. Ladenburg confirmed the existences of the phenomena of stimulated emission and negative absorption; in 1939, Valentin A. Fabrikant predicted the use of stimulated emission to amplify “short” waves; in 1947, Willis E. Lamb and R. C. Retherford found apparent stimulated emission in hydrogen spectra and effected the first demonstration of stimulated emission; in 1950, Alfred Kastler (Nobel Prize for Physics 1966) proposed the method of optical pumping, experimentally confirmed, two years later, by Brossel, Kastler, and Winter. On 16 May 1960, Theodore Maiman demonstrated the first functional laser at the Hughes Research Laboratories, introducing a technology applied mostly used for data storage, via optical storage devices, such as the compact disk player and the DVD player, wherein a semiconductor laser, less than a millimeter wide, scans the disc’s surface; the second-most application is fiber-optic communication, and related devices, e.g. bar code reader, laser printer, laser pointer

Maser

In 1953, Charles H. Townes and graduate students James P. Gordon and Herbert J. Zeiger produced the first microwave amplifier, a device operating on similar principles to the laser — but amplifying microwave radiation, rather than infrared or visible radiations; yet, Townes's maser was incapable of continuous output. Meantime, in the Soviet Union, Nikolay Basov and Aleksandr Prokhorov were independently working on the quantum oscillator, and produced the first MASER when they solved the problem of continuous-output systems, by using more than two energy levels. These MASER systems could release stimulated emissions without falling to the ground state, thus maintaining a population inversion. In 1955, Prokhorov and Basov suggested an optical pumping of a multi-level system, as a method for obtaining the population inversion, later a main method of laser pumping.

Townes reports that he was opposed by several academically eminent colleagues — among them Niels Bohr, John von Neumann, Isidor Rabi, Polykarp Kusch, and Llewellyn H. Thomas — arguing that the MASER was theoretically impossible. In 1964, Charles H. Townes, Nikolay Basov, and Aleksandr Prokhorov shared the Nobel Prize in Physics, “for fundamental work in the field of quantum electronics, which has led to the construction of oscillators and amplifiers based on the maser–laser principle”.

Laser

In 1957, Charles Hard Townes and Arthur Leonard Schawlow, then at Bell Labs, began a serious study of the infrared laser. As ideas developed, they abandoned infrared radiation to instead concentrate upon visible light. The concept originally was called an optical “maser”. In 1958, Bell Labs filed a patent application for their proposed optical maser; and Schawlow and Townes submitted a manuscript of their theoretical calculations to the *Physical Review*, published that year in Volume 112, Issue No. 6.

LASER notebook: First page of the notebook wherein Gordon Gould coined the LASER acronym, and described the technologic elements for constructing the device.

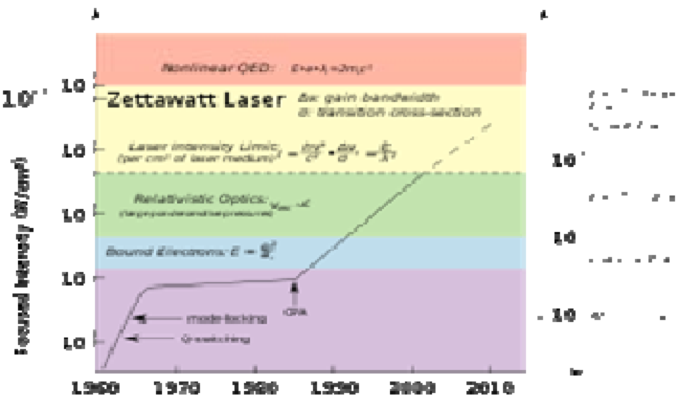
Simultaneously, at Columbia University, graduate student Gordon Gould was working on a doctoral thesis about the energy levels of excited thallium. When Gould and Townes met, the spoke of radiation emission, as a general subject; afterwards, in November 1957, Gould noted his ideas for a “laser”, including using an open resonator (later an essential laser-device component). Moreover, in 1958, Prokhorov independently proposed using an open resonator, the first published appearance (the USSR) of this idea. Elsewhere, in the US, Schawlow and Townes had agreed to an open-resonator laser design — apparently unaware of Prokhorov’s publications and Gould’s unpublished laser work.

At a conference in 1959, Gordon Gould published the term LASER in the paper *The LASER, Light Amplification by Stimulated Emission of Radiation*. Gould’s linguistic intention was using the “-aser” word particle as a suffix — to accurately denote the spectrum of the light emitted by the LASER device; thus x-rays: *xaser*, ultraviolet: *uvaser*, et cetera; none established itself as a discrete term, although “raser” was briefly popular for denoting radio-frequency-emitting devices.

Gould’s notes included possible applications for a laser, such as spectrometry, interferometry, radar, and nuclear fusion. He continued developing the idea, and filed a patent application in April 1959. The U.S. Patent Office denied his application, and awarded a patent to Bell Labs, in 1960. That provoked a twenty-eight-year lawsuit, featuring scientific prestige and money as the stakes. Gould won his first, minor patent in 1977, yet it was not until 1987 that he won the first, significant patent lawsuit victory, when a Federal judge ordered the US Patent Office to issue patents to Gould for the optically-pumped and the gas discharge laser devices.

In 1960, Theodore H. Maiman constructed the first functioning LASER, at Hughes Research Laboratories, Malibu, California, ahead of several research teams, including those of Townes, at Columbia University, Arthur Schawlow, at Bell Labs, and Gould, at the TRG (Technical Research Group) company. Maiman’s functional LASER used a solid-state flash lamp-pumped synthetic ruby crystal to produce red laser light, at 694 nanometers wavelength; however, the device only was capable of pulsed operation, because of its three-level pumping design scheme. Later in 1960, the Iranian physicist Ali Javan, and William R. Bennett, and Donald Herriot, constructed the first gas laser, using helium and neon; later, Javan received the Albert Einstein Award in 1993. Basov and Javan proposed the semiconductor laser diode concept. In 1962, Robert N. Hall demonstrated the first *laser diode* device, made of gallium arsenide and emitted at 850 nm the near-infrared band of the spectrum. Later, in 1962, Nick Holon yak, Jr. demonstrated the first semiconductor laser with a visible emission; like the early gas laser device, the early semiconductor laser could only be used in pulsed-beam operation, and when cooled to liquid nitrogen temperatures (77˚K). In 1970, Zhores Alferov, in the USSR, and Izuo Hayashi and Morton Panish of Bell Telephone Laboratories also independently developed room-temperature, continual-operation diode lasers, using the heterojunction structure.

Recent innovations



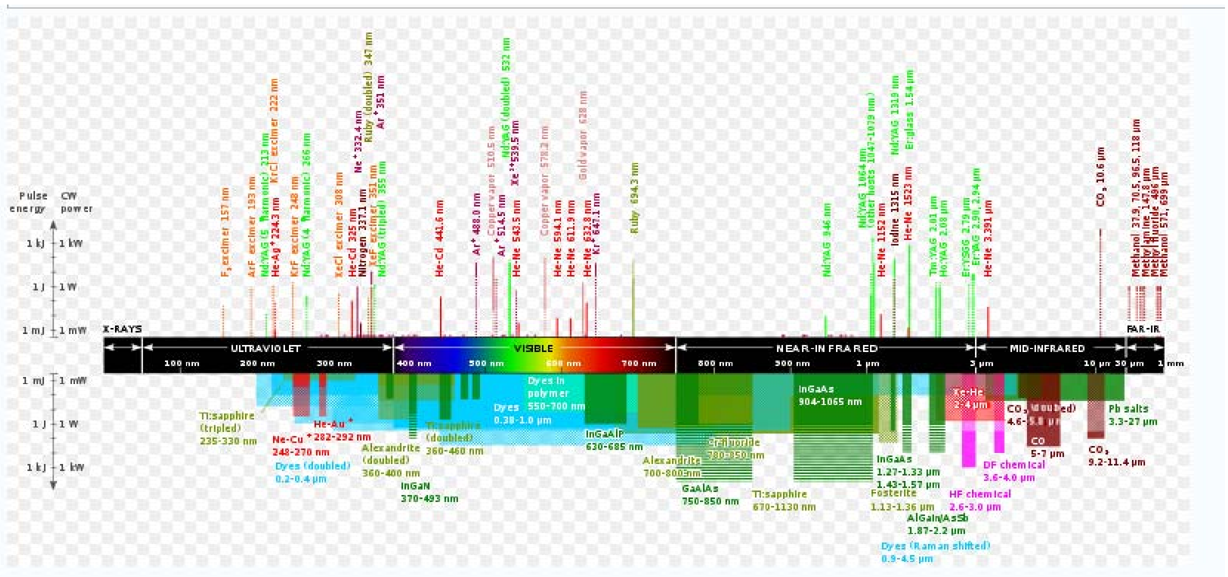
Graph showing the history of maximum laser pulse intensity throughout the past 40 years. Since the early period of laser history, laser research has produced a variety of improved and specialized laser types, optimized for different performance goals, including: and this research continues to this day.

- new wavelength bands
- maximum average output power
- maximum peak output power
- minimum output pulse duration
- maximum power efficiency
- maximum charging
- maximum firing
- minimum cost

Lasing without maintaining the medium excited into a population inversion was discovered in 1992 in sodium gas and again in 1995 in rubidium gas by various international teams. This was accomplished by using an external maser to induce "optical transparency" in the medium by introducing and destructively interfering the ground electron transitions between two paths, so that the likelihood for the ground electrons to absorb any energy has been cancelled.

Types and operating principles

For a more complete list of laser types see this list of laser types.



Wave lengths of commercially available lasers. Laser types with distinct laser lines are shown above the wavelength bar, while below are shown lasers that can emit in a wavelength range. The color codifies the type of laser material (see the figure description for more details).

Gas lasers

Gas lasers using many gases have been built and used for many purposes. The helium-neon laser (HeNe) emits at a variety of wavelengths and units operating at 633 nm are very common in education because of its low cost. Carbon dioxide lasers can emit hundreds of kilowatts at 9.6 µm and 10.6 µm, and are often used in industry for cutting and welding. The efficiency of a CO_2 laser is over 10%. Argon-ion lasers emit light in the range 351-528.7 nm. Depending on the optics and the laser tube a different number of lines are usable but the most commonly used lines are 458 nm, 488 nm and 514.5 nm. A nitrogen transverse electrical discharge in gas at atmospheric pressure (TEA) laser is an inexpensive gas laser producing UV light at 337.1 nm. Metal ion lasers are gas lasers that generate deep ultraviolet wavelengths. Helium-silver (HeAg) 224 nm and neon-copper (NeCu) 248 nm are two examples. These lasers have particularly narrow oscillation linewidths of less than 3 GHz (0.5 picometers), making them candidates for use in fluorescence suppressed Raman spectroscopy.

Chemical lasers

Chemical lasers are powered by a chemical reaction, and can achieve high powers in continuous operation. For example, in the Hydrogen fluoride laser (2700-2900 nm) and the Deuterium fluoride laser (3800 nm) the reaction is the combination of hydrogen or deuterium gas with combustion products of ethylene in nitrogen trifluoride. They were invented by George C. Pimentel.

Excimer lasers

Excimer lasers are powered by a chemical reaction involving an *excited dimer*, or *excimer,* which is a short-lived dimeric or heterodimeric molecule formed from two species (atoms), at least one of which is in an excited electronic state. They typically produce ultraviolet light, and are used in semiconductor photolithography and in LASIK eye surgery. Commonly used excimer molecules include F_2 (fluorine, emitting at 157 nm), and noble gas compounds (ArF [193 nm], KrCl [222 nm], KrF [248 nm], XeCl [308 nm], and XeF [351 nm]).

Solid-state lasers

Solid-state laser materials are commonly made by "doping" a crystalline solid host with ions that provide the required energy states. For example, the first working laser was a ruby laser, made from ruby (chromium-doped corundum). The population inversion is actually maintained in the "dopant", such as chromium or neodymium. Formally, the class of solid-state lasers includes also fiber laser, as the active medium (fiber) is in the solid state. Practically, in the scientific literature, solid-state laser usually means a laser with bulk active medium, while wave-guide lasers are caller fiber lasers.

"Semiconductor lasers" are also solid-state lasers, but in the customary laser terminology, "solid-state laser" excludes semiconductor lasers, which have their own name.

Neodymium is a common "dopant" in various solid-state laser crystals, including yttrium orthovanadate (Nd:YVO_4), yttrium lithium fluoride (Nd:YLF) and yttrium aluminium garnet (Nd:YAG). All these lasers can produce high powers in the infrared spectrum at 1064 nm. They are used for cutting, welding and marking of metals and other materials, and also in spectroscopy and for pumping dye lasers. These lasers are also commonly frequency doubled, tripled or quadrupled to produce 532 nm (green, visible), 355 nm (UV) and 266 nm (UV) light when those wavelengths are needed.

Ytterbium, holmium, thulium, and erbium are other common "dopants" in solid-state lasers. Ytterbium is used in crystals such as Yb: YAG, Yb: KGW, Yb: KYW, Yb: SYS, Yb: BOYS, Yb: CaF2, typically operating around 1020-1050 nm. They are potentially very efficient and high powered due to a small quantum defect. Extremely high powers in ultra short pulses can be achieved with Yb: YAG. Holmium-doped YAG crystals emit at 2097 nm and form an efficient laser operating at infrared wavelengths strongly absorbed by water-bearing tissues. The Ho-YAG is usually operated in a pulsed mode, and passed through optical fiber surgical devices to resurface joints, remove rot from teeth, vaporize cancers, and pulverize kidney and gall stones.

Titanium-doped sapphire (Ti:sapphire) produces a highly tunable infrared laser, commonly used for spectroscopy as well as the most common ultra short pulse laser.

Thermal limitations in solid-state lasers arise from unconverted pump power that manifests itself as heat and phonon energy. This heat, when coupled with a high thermo-optic coefficient (dn/dT) can give rise to thermal lensing as well as reduced quantum efficiency. These types of issues can be overcome by another novel diode-pumped solid-state laser, the diode-pumped thin disk laser. The thermal limitations in this laser type are mitigated by using a laser medium geometry in which the thickness is much smaller than the diameter of the pump beam. This allows for a more even thermal gradient in the material. Thin disk lasers have been shown to produce up to kilowatt levels of power.

Fiber-hosted lasers

Solid-state lasers where the light is guided due to the total internal reflection in an optical fiber are called fiber lasers. Guiding of light allows extremely long gain regions providing good cooling conditions; fibers have high surface area to volume ratio which allows efficient cooling. In addition, the fiber's wave guiding properties tend to reduce thermal distortion of the beam. Erbium and ytterbium ions are common active species in such lasers.

Quite often, the fiber laser is designed as a double-clad fiber. This type of fiber consists of a fiber core, an inner cladding and an outer cladding. The index of the three concentric layers is chosen so that the fiber core acts as a single-mode fiber for the laser emission while the outer cladding acts as a highly multimode core for the pump laser. This lets the pump propagate a large amount of power into and through the active inner core region, while still having a high numerical aperture (NA) to have easy launching conditions.

Pump light can be used more efficiently by creating a fiber disk laser, or a stack of such lasers.

Fiber lasers have a fundamental limit in that the intensity of the light in the fiber cannot be so high that optical nonlinearities induced by the local electric field strength can become dominant and prevent laser operation and/or lead to the material destruction of the fiber. This effect is called photo darkening. In bulk laser materials, the cooling is not so efficient, and it is difficult to separate the effects of photo darkening from the thermal effects, but the experiments in fibers show that the photo darkening can be attributed to the formation of long-living color centers.

Photonic crystal lasers

Photonic crystal lasers are lasers based on nano-structures that provide the mode confinement and the density of optical states (DOS) structure required for the feedback to take place. They are typical micrometre-sized and tunable on the bands of the photonic crystals.

Semiconductor lasers

Semiconductor lasers are also solid-state lasers but have a different mode of laser operation.

Commercial laser diodes emit at wavelengths from 375 nm to 1800 nm, and wavelengths of over 3 μm have been demonstrated. Low power laser diodes are used in laser printers and CD/DVD players. More powerful laser diodes are frequently used to optically pump other lasers with high efficiency. The highest power industrial laser diodes, with power up to 10 kW (70dBm), are used in industry for cutting and welding. External-cavity semiconductor lasers have a semiconductor active medium in a larger cavity. These devices can generate high power outputs with good beam quality, wavelength-tunable narrow line width radiation, or ultra short laser pulses.

Vertical cavity surface-emitting lasers (VCSELs) are semiconductor lasers whose emission direction is perpendicular to the surface of the wafer. VCSEL devices typically have a more circular output beam than conventional laser diodes, and potentially could be much cheaper to manufacture. As of 2005, only 850 nm VCSELs are widely available, with 1300 nm VCSELs beginning to be commercialized and 1550 nm devices an area of research. VECSELs are external-cavity VCSELs. Quantum cascade lasers are semiconductor lasers that have an active transition between energy *sub-bands* of an electron in a structure containing several quantum wells.

The development of a silicon laser is important in the field of optical computing. Silicon is the material of choice for integrated circuits and so electronic and silicon photonic components (such as optical interconnects) could be fabricated on the same chip. Unfortunately, silicon is a difficult lasing material to deal with, since it has certain properties which block lasing. However, recently teams have produced silicon lasers through methods such as fabricating the lasing material from silicon and other semiconductor materials, such as indium (III) phosphide or gallium (III) arsenide, materials which allow coherent light to be produced from silicon. These are called hybrid silicon laser. Another type is a Raman laser, which takes advantage of Raman scattering to produce a laser from materials such as silicon.

Dye lasers

Dye lasers use an organic dye as the gain medium. The wide gain spectrum of available dyes allows these lasers to be highly tunable, or to produce very short-duration pulses (on the order of a few femtoseconds).

Free electron lasers

Free electron lasers, or FELs, generate coherent, high power radiation that is widely tunable, currently ranging in wavelength from microwaves, through terahertz radiation and infrared, to the visible spectrum, to soft X-rays. They have the widest frequency range of any laser type. While FEL beams share the same optical traits as other lasers, such as coherent radiation, FEL operation is quite different. Unlike gas, liquid, or solid-state lasers, which rely on bound atomic or molecular states, FELs use a relativistic electron beam as the lasing medium, hence the term free electron.

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