LASER

A laser (from the acronym Light Amplification by Stimulated Emission of Radiation) is an optical source that emits photons in a coherent beam. The verb to lase means "to produce coherent light" or possibly "to cut or otherwise treat with coherent light", and is a back-formation of the term laser.

Laser light is typically near-monochromatic, i.e. consisting of a single wavelength or color, and emitted in a narrow beam. This is in contrast to common light sources, such as the incandescent light bulb, which emit incoherent photons in almost all directions, usually over a wide spectrum of wavelengths.

Laser action is explained by the theories of quantum mechanics and thermodynamics. Many materials have been found to have the required characteristics to form the laser gain medium needed to power a laser, and these have led to the invention of many types of lasers with different characteristics suitable for different applications.

The laser was proposed as a variation of the maser principle in the late 1950's, and the first laser was demonstrated in 1960. Since that time, laser manufacturing has become a multi-billion dollar industry, and the laser has found applications in fields including science, industry, medicine, and consumer electronics.

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Physics

See also: Laser science

Principal components:
1. Active laser medium
2. Laser pumping energy
3. Mirror

4. Partial mirror
5. Laser beam

A laser is composed of an active laser medium, or gain medium, and a resonant optical cavity.

The gain medium transfers external energy into the laser beam. It is a material of controlled purity, size and shape, which amplifies the beam by the quantum mechanical process of stimulated emission, discovered by Albert Einstein while researching the photoelectric effect. The gain medium is energized, or pumped, by an external energy source. Examples of pump sources include electricity and light, for example from a flash lamp or from another laser. The pump energy is absorbed by the laser medium, putting some of its particles into high-energy, or excited, quantum states. When the number of particles in one excited state exceeds the number of particles in some lower-energy state, population inversion is achieved. In this condition, an optical beam passing through the medium produces more stimulated emission than the stimulated absorption so the beam is amplified. An excited laser medium can also function as an optical amplifier.

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 monochromaticity established by the optical cavity design.

The optical cavity, an example of a type of cavity resonator, contains a coherent beam of light between reflective surfaces so that each photon passes through the gain medium multiple times before being 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. However, 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 intracavity laser power which determines the operating point of the laser. If the pump power is chosen 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 required to begin laser action is called the lasing threshold. Note that the gain medium will amplify any photons passing through it, regardless of direction, however it is only the ones that happen to be aligned with the cavity that manage to make multiple passes through the medium and so have significant amplification.

Experiment using a (likely argon) laser. (US military)

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 often Gaussian beams. If the beam is not a pure Gaussian shape, the transverse modes of the beam may be analyzed as a superposition of Hermite-Gaussian or Laguerre-Gaussian beams. The beam may be highly collimated, that is, having a very small divergence, but a perfectly collimated beam cannot be created, due to the effect of diffraction. Nonetheless, a laser beam will spread much less than a beam of incoherent light. The distance over which the beam remains collimated increases with the square of the beam diameter, and the angle at which the beam eventually diverges varies inversely with the diameter. Thus, a beam generated by a small laboratory laser such as a helium-neon (HeNe) laser spreads to approximately 1.6 kilometres (1 mile) in diameter if shone from the Earth's surface to the Moon. By comparison, the output of a typical semiconductor laser, due to its small diameter, diverges almost immediately on exiting the aperture, at an angle that may be as high as 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 or much.

A HeNe laser demonstration at the Kastler-Brossel Laboratory at Univ. Paris 6. The glowing ray in the middle is an electric discharge producing light in much the same way as a neon light; though it is the gain medium through which the laser passes, it is not the laser beam itself which is visible there. The laser beam crosses the air and marks a red point on the screen to the right.

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, modelocking, 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 the generation of extremely short pulses of light, on the order of a femtosecond (10-15 s).

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

It should be understood that the word light in the acronym Light Amplification by Stimulated Emission of Radiation is typically used in the expansive sense, as photons of any energy; it is not limited to photons in the visible spectrum. Hence there are X-ray lasers, infrared lasers, ultraviolet lasers, etc. Because the microwave equivalent of the laser, the maser, was developed first, devices that emit microwave and radio frequencies are usually called masers. In early literature, particularly from researchers at Bell Telephone Laboratories, the laser was often called the optical maser. This usage has since become uncommon, and as of 1998 even Bell Labs uses the term laser[1]. One sometimes also encounters other prefixes, based on the portion of the spectrum in which a device emits, for example raser for a radio-frequency laser (or maser), and graser for a gamma-ray laser[2]. This usage is also now uncommon.
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History

In 1916, Albert Einstein laid the foundation for the invention of the laser and its predecessor, the maser, in a ground-breaking rederivation of Max Planck's law of radiation based on the concepts of spontaneous and induced emission. The theory was forgotten until after World War II.

In 1953, Charles H. Townes and graduate students James P. Gordon and Herbert J. Zeiger produced the first maser, a device operating on similar principles to the laser, but producing microwave rather than optical radiation. Townes' maser was incapable of continuous output. Nikolay Basov and Aleksandr Prokhorov of the Soviet Union worked independently on the quantum oscillator and solved the problem of continuous output systems by using more than two energy levels. These systems could release stimulated emission without falling to the ground state, thus maintaining a population inversion. Townes, Basov and Prokhorov shared the Nobel Prize in Physics in 1964 "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."

In 1957 Charles Hard Townes and Arthur Leonard Schawlow, then at Bell Labs, began a serious study of the infrared maser. As ideas were developed, infrared frequencies were abandoned with focus on visible light instead. The concept was originally known as an "optical maser". Bell Labs filed a patent application for their proposed optical maser a year later. Schawlow and Townes sent a manuscript of their theoretical calculations to Physical Review, which published their paper that year (Volume 112, Issue 6).

Simultaneously, Gordon Gould, a graduate student at Columbia University, was working on a doctoral thesis on the energy levels of excited thallium. Gould and Townes met and had conversations on the general subject of radiation emission. After that meeting, Gould made notes about his ideas for a "laser" in November 1957. In 1958, Prokhorov proposed an open resonator which became an important ingredient of future lasers. The first introduction of the term "laser" to the public was in Gould's 1959 paper "The LASER, Light Amplification by Stimulated Emission of Radiation". Gould intended "aser" to be a suffix, to be used with an appropriate prefix for the spectra of light emitted by the device (e.g. X-ray laser = xaser, UltraViolet laser = uvaser). None of the other terms became popular, although "raser" is sometimes used for radio-frequency emitting devices.

Gould's notes included possible applications for a laser, such as spectrometry, interferometry, radar, and nuclear fusion. He continued working on his idea and filed a patent application in April 1959. The U.S. Patent Office denied his application and awarded it to Bell Labs in 1960. This sparked a legal battle that spanned three decades, with scientific prestige and much money at stake. Gould won his first minor patent in 1977, but it was not until 1987 that he could claim his first significant patent victory when a federal judge ordered the government to issue a patent to him for each of the optically pumped and the gas discharge laser.

The first working laser was made by Theodore H. Maiman in 1960[3] at Hughes Research Laboratories in Malibu, California, beating several research teams including those of Townes at Columbia University, and Arthur L. Schawlow at Bell Labs[4]. Maiman used a solid-state flashlamp-pumped synthetic ruby crystal to produce red laser light at 694 nanometres wavelength. Maiman's laser, however, was only capable of pulsed operation due to its three energy level transitions. Later in the same year the Iranian physicist Ali Javan, together with William Bennet and Donald Herriot, made the first gas laser using helium and neon. Javan later received the Albert Einstein Award in 1993.

The concept of the semiconductor laser diode was proposed by Basov and Javan; and the first laser diode was demonstrated by Robert N. Hall in 1962. Hall's device was constructed of gallium arsenide and produced emission at 850 nm, in the near-infrared region of the spectrum. The first semiconductor laser with visible emission was demonstrated later the same year by Nick Holonyak, Jr. As with the first gas lasers, these early semiconductor lasers could be used only in pulsed operation, and indeed only when cooled to liquid nitrogen temperatures (77 K).

In 1970, Zhores Alferov in the Soviet Union and Izuo Hayashi and Morton Panish of Bell Telephone Laboratories independently developed continuously operating laser diodes at room temperature, using the heterojunction structure.

The first application of lasers visible in the daily lives of the general population was the supermarket barcode scanner, introduced in 1974. The laserdisc player, introduced in 1978, was the first successful consumer product to include a laser, but the compact disc player was the first laser-equipped device to become truly common in consumers' homes, beginning in 1982.
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Recent innovations
This section is a stub. You can help by adding to it.

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
new wavelength bands
maximum average output power
maximum peak output power
minimum output pulse duration
maximum power efficiency

and this research continues to this day.

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.

In 1985 at the University of Rochester's Laboratory for Laser Energetics a breakthrough in creating ultrashort-pulse, very high-intensity (terawatts) laser pulses became available using a technique called chirped pulse amplification, or CPA, discovered by Gérard Mourou. These high intensity pulses can produce filament propagation in the atmosphere.

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Uses
Main article: Laser applications

At the time of their invention in 1960, lasers were called "a solution looking for a problem". Since then, they have become ubiquitous, finding utility in thousands of highly varied applications in every section of modern society, including consumer electronics, information technology, science, medicine, industry, law enforcement and the military.

In 2004, excluding diode lasers, approximately 131,000 lasers were sold world-wide, with a value of US$2.19 billion [5]. In the same year, approximately 733 million diode lasers, valued at $3.20 billion, were sold [6].

A laser harp.

The benefits of lasers in various applications stems from their properties such as coherency, high monochromaticity, and capability for reaching extremely high powers. For instance, a highly coherent laser beam can be focused down to its diffraction limit, which at visible wavelengths corresponds to only a few hundred nanometers. This property allows a laser to record gigabytes of information in the microscopic pits of a DVD. It also allows a laser of modest power to be focused to very high intensities and used for cutting, burning or even vaporizing materials. For example, a frequency doubled neodymium yttrium aluminum garnet (Nd:YAG) laser emitting 532 nanometer (green) light at 10 watts output power is theoretically capable of achieving a focused intensity of megawatts per square centimeter. In reality however, perfect focusing of a beam to its diffraction limit is somewhat difficult.

Lasers used for visual effects during a musical performance. (A laser light show.)

Consumer electronics and communication In consumer electronics, telecommunications, and data communications, lasers are used as the transmitters in optical communications over optical fiber and free space. They are used to store and retrieve data from compact discs and DVDs, as well as magneto-optical discs. Laser lighting displays (pictured) accompany many music concerts.

Science In science, lasers are employed in a wide variety of interferometric techniques, and for Raman spectroscopy and laser induced breakdown spectroscopy. Other uses include atmospheric remote sensing, and investigation of nonlinear optics phenomena. Holographic techniques employing lasers also contribute to a number of measurement techniques. Laser (LIDAR) technology has application in geology, seismology, remote sensing and atmospheric physics. Lasers have also been used aboard spacecraft such as in the Cassini-Huygens mission. In astronomy, lasers have been used to create artificial laser guide stars, used as reference objects for adaptive optics telescopes.

Medicine In medicine, the laser scalpel is used for laser vision correction and other surgical techniques. Lasers are also used for dermatological procedures including removal of tattoos, birthmarks, and hair; laser types used in dermatology include ruby (694 nm), alexandrite (755 nm), pulsed diode array (810 nm), Nd:YAG (1064 nm), Ho:YAG (2090 nm), and Er:YAG (2940 nm). Lasers are also used in photobiomodulation (laser therapy) and in acupuncture.

Industry In industry, laser cutting is used to cut metals and other materials. Laser line levels are used in surveying and construction. Lasers are also used for guidance for aircraft. Lasers are used in certain types of thermonuclear fusion reactors. Lasers are also used extensively in both consumer and industrial imaging equipment. The name laser printer speaks for itself but both gas and diode lasers play a key role in manufacturing high resolution printing plates and in image scanning equipment.

Law enforcement and road safety In law enforcement the most widely known use of lasers is for lidar, to detect the speed of vehicles.

The surface of a test target is instantly vaporized and bursts into flame upon irradiation by a high power continuous wave carbon dioxide laser emitting tens of kilowatts of far infrared light. Note the operator is standing behind sheets of plexiglass which is naturally opaque in the far infrared.

Military Military uses of lasers include use as target designators for other weapons; their use as directed-energy weapons is currently under research. Laser weapon systems under development include the airborne laser, the advanced tactical laser, the Tactical High Energy Laser, the High Energy Liquid Laser Area Defense System, and the MIRACL, or Mid-Infrared Advanced Chemical Laser.
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Popular misconceptions

The representation of lasers in popular culture, especially in science fiction and action movies, is generally very misleading. Contrary to their portrayal in many science fiction movies, a laser beam is never visible in the vacuum of space, and even in air, beams or rays of laser light are not necessarily any more visible than rays from any other light source. In air the beam can hit dust and other particles in its path and scatter producing a glowing "ray", in much the same way that a sunbeam glows in dusty air, an effect which can be used to make the beam more visible by increasing the number of particles suspended in the air using, for instance, a theatrical fog machine.

Moderate intensity (greater than ~10 milliwatts) laser beams of shorter green and blue wavelengths and high intensity beams of longer orange and red wavelengths can be visible in air due to Rayleigh scattering or at very high intensities possibly Raman scattering. With even higher intensity pulsed beams, the air can be heated to the point where it becomes a plasma, which would also be visible. This would also cause a rapid heating and explosive expansion of the surrounding air which would produce a popping noise analogous to the thunder which acompanies lightning. This phenomenon is also capable of causing a retroreflection of the laser beam back into the laser source possibly damaging its optics. When this phenomenon occurs in certain scientific experiments it is variously referred to as a "plasma mirror" or "plasma shutter".

Science fiction films special effects often depict laser beams propagating at only a few metres per second—i.e., slowly enough to see their progress, in a manner reminiscent of conventional tracer ammunition—whereas in reality a laser beam travels at the speed of light, and would seem to appear instantly to the naked eye from start to end.

Some action movies depict security systems using lasers of visible light (and their foiling by the hero, typically using mirrors); the hero may see the path of the beam by sprinkling some dust in the air. It is actually far easier and cheaper to build infrared laser diodes rather than visible light laser diodes and such systems almost never use visible light lasers.

In action movies laser weaponry is commonly portrayed as generating a 'zapping' sound when fired. The only sounds emitted by real-world lasers are the sounds of the equipment used to generate them, which is typically a low-pitched hum.

Several of these misconceptions can be found in the James Bond film Goldfinger, the first film to feature a laser. In one of the most famous scenes in the Bond films, Bond, played by Sean Connery faces a laser beam approaching his groin while melting the solid gold table to which he is strapped. The director Guy Hamilton found that a real laser beam would not show

up on camera so it was added as an optical effect. The melting effect on the table was achieved by a man underneath the table holding an oxyacetylene torch, while a real laser would have produced a fairly heat-free and silent cut.
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"LASER"

Even though the word laser comes from an initialism (Light Amplification by the Stimulated Emission of Radiation), it has been incorporated into the language as a separate word—an acronym—and as such it is written in lower case letters. By back-formation, the verb "to lase" has also been created, meaning "to produce coherent light through stimulated emission".

A dye laser used at the Starfire Optical Range for LIDAR and laser guide star experiments is tuned to the sodium D line and used to excite sodium atoms in the upper atmosphere.
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Scientific misconceptions

Besides in movies and popular culture, laser misconceptions are present in many science texts. For example, laser light is not inherently parallel light as is usually claimed. All laser beams spread out as they propagate, due to diffraction. For a good quality "singlemode" beam, the divergence (cone angle) of the beam is inversely proportional to the width of the beam at its narrowest point, so a beam can be made more parallel by increasing its minimum diameter. All beams eventually spread out, however, since the beam cannot be infinitely wide at its narrowest point. Note that poor-quality laser beams spread much faster with distance than singlemode beams do.
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Laser safety

Main article: laser safety

Even the first laser was recognized as being potentially dangerous. Theodore Maiman characterized the first laser as one Gillette; as it could burn through one Gillette razor blade. Today, it is accepted that even low-power lasers with only a few milliwatts of output power can be hazardous to a person's eyesight.

At wavelengths which the cornea and the lens can focus well, the coherence and low divergence of laser light means that it can be focused by the eye into an extremely small spot on the retina, resulting in localized burning and permanent damage in seconds or even faster. Lasers are classified into safety classes numbered I (inherently safe) to IV (even scattered light can cause eye and/or skin damage). Laser products available for consumers, such as CD players and laser pointers are usually in class I, II, or III. Certain infrared lasers with wavelengths beyond about 1.4 micrometres are often referred to as being "eye-safe". This is due to the fact that the intrinsic molecular vibrations of water molecules very strongly absorb light in this part of the spectrum and thus a laser beam at these wavelengths is attenuated so completely upon its passage through the eye's cornea that no light remains to be focused by the lens onto the retina. The label eye-safe can be misleading however, as it only applies to relatively low power continuous wave beams and any high power or q-switched laser at these long wavelengths will still obviously burn the cornea, causing severe eye damage.
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Categories
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By type
For a more complete list of laser types see this list of laser types.

Spectral output of several types of lasers.
Gas lasers
The Helium-neon laser (HeNe) emits 543 nm and 633 nm and is very common in education because of its low cost. Carbon dioxide lasers emit up to 100 kW at 9.6 µm and 10.6 µm, and are used in industry for cutting and welding. Argon-Ion lasers emit 458 nm, 488 nm or 514.5 nm. Carbon monoxide lasers must be cooled but can produce up to 500 kW. The 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),[7] 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.
Excimer lasers
Excimer lasers produce ultraviolet light, and are used in semiconductor manufacturing and in LASIK eye surgery. Commonly used excimer molecules include F2 (emitting at 157 nm), 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 made from ruby, or chromium-doped sapphire. Another common type is made from Neodymium-doped yttrium aluminium garnet (YAG), known as Nd:YAG. Nd:YAG 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. Nd:YAG lasers are also commonly frequency doubled to produce 532 nm when a visible (green) coherent source is required.
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 ultrashort 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, used for spectroscopy.
Solid state lasers also include glass or optical fiber hosted lasers, for example, with erbium or ytterbium ions as the active species. These allow extremely long gain regions, and can support

very high output powers because the fiber's high surface area to volume ratio allows efficient cooling, and its waveguiding properties reduce thermal distortion of the beam.

Semiconductor lasers

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 pointers, 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, 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-linewidth radiation, or ultrashort 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,[8] 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.

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).

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By output power

Note that the significance of these figures varies; they represent peak power output. Many lasers are designed for a high peak output with an extremely short pulse, and this is technically very different from the technology behind a steady beam such as a communication, data, or cutting laser. Also note that usually, output power is a small fraction of the input power needed to generate the laser.

5 mW - laser in a CD-ROM drive

5-10 mW - laser in a DVD player

100 mW - laser in a CD-R drive

250 mW - output power of Sony SLD253VL red laser diode, used in consumer 48-52 speed CD-R burner.[9]

1 W - output power of green laser in current Holographic Versatile Disc prototype development.

100 to 500 Watt (peak output 1.5 kW) - typical sealed CO_2 lasers used in industrial Beam Laser Machines (cutting lasers). These are usually compact, extremely reliable, inexpensive to run and can provide over 20,000 hours of cutting before requiring service.[10]

As of 2005 the National Ignition Facility is working on a system that, when complete, will contain a 192-beam, 1.8-megajoule, 700-terawatt laser system adjoining a 10-meter-diameter target chamber.[11]

As of 2006, manufacturers have expressed confidence that "no fundamental barriers stand in the way of squeezing 1 kW out of a single 1 cm diode laser bar" [12]

1.25 PW - world's most powerful laser (claimed on 23 May 1996 by Lawrence Livermore Laboratory).