CO_2 gas lasers

Owing to their reliability and durability as beam sources, CO_2 lasers have earned a permanent place in materials processing. Tens of thousands of beams sources are in use worldwide. Most of them are used for cutting and welding. The wavelength of a CO_2 laser beam is 10.6 micrometers, putting it in the far-infrared spectrum.

Characteristics of CO_2 lasers at a glance:

- Wide power range, from less than 10 watts to more than 20,000 watts
- High beam quality, M² from 1.1 to 5.0 (inverse M² factor (K-number) from 0.9 to 0.2; beam parameter product from 4 to 17 millimeter-milliradians)
- Choice of operating mode: CW mode or pulsed

History | The first CO_2 lasers appeared in the U.S. in the 1970s. They had an output of 500 watts and M² beam qualities on the order of 5 (inverse M² factor (K) of 0.2). These early laser units, however, were not very reliable: their power decreased when operated for long periods. In addition, lasers used in production took up a great deal of space. It is not surprising that these types of CO_2 lasers aroused little interest and were limited to certain niche areas. This changed in the early 1980s, as machine tool builders in Germany began developing their own lasers. Working closely with research institutes, they produced the first industrially viable CO_2 lasers with a power of more than 1 kilowatt. Since then, the CO_2 laser has continued its steady advance, as evidenced by both rising sales figures and increased power.

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GLOWING GAS MOLECULES

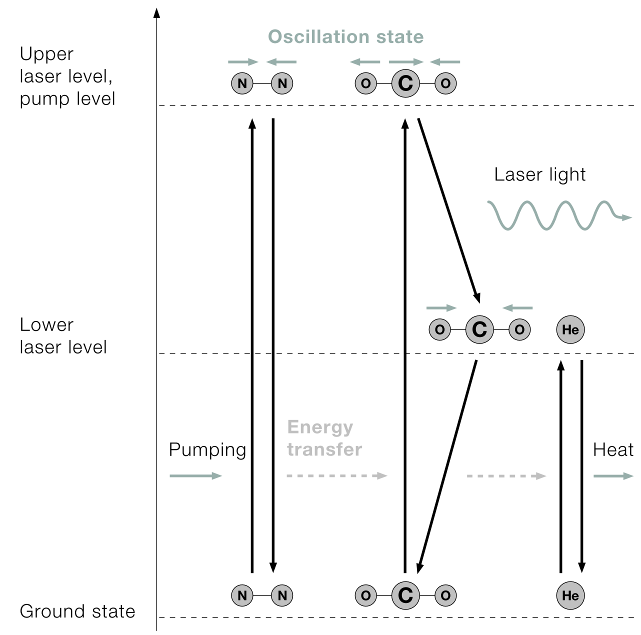
Its name is an instant giveaway: in CO_2 lasers, the laser light is emitted by CO_2 molecules. A CO_2 molecule contains one carbon atom and two oxygen atoms. They form a chain, with the carbon atom nestled between the oxygen atoms. When excited, the molecule begins to oscillate. The various states of oscillation correspond to different energy levels. In a CO_2 laser, four energy levels are involved in the laser process. The pump level and upper laser level are very close together.

The laser-active medium, however, is not only composed of CO_2. It is a mixture of helium (He), nitrogen (N_2), and carbon dioxide (CO_2). Helium and nitrogen are assist gases. They assist the actual laser process in the CO_2 molecule.

The laser process in detail | In the gas mixture, a high-voltage direct current or high-frequency alternating current initiates a gas discharge, producing free electrons that strike the nitrogen molecules and excite them. The nitrogen molecules begin to oscillate. Colliding with the CO_2 molecule, the nitrogen molecules transfer their energy to the CO_2 molecule, causing it to jump from the ground state to the upper laser level. In this state of oscillation, all three atoms of the molecule are in motion. As it makes the transition to the lower laser level, the CO_2 molecule emits laser light with a wavelength of 10.6 micrometers.

1 Flashback: a CO_2 laser from the 1980s

The mysterious purple glow The wavelength of a CO_2 laser beam is in the far infrared, which is why we can't see it. Yet when a CO_2 laser is in operation, the gas mixture glows purple. Where's the light coming from? The purple glow is merely a secondary effect. It comes from gas atoms and molecules that are excited to very high energy levels and then drop back to the ground state.



Interplay of molecules and atoms: the laser process in a CO_2 laser

From there, it returns to the ground state, releasing heat in the process. This is where the atoms of the inert gas helium come into play: they accelerate depopulation of the lower laser level by colliding with the CO_2 molecules, while absorbing and dissipating heat.

HOW TO DESIGN A LASER

Not all CO_2 lasers are created equal. Within the marketplace, many different laser design concepts abound. Physicists and engineers develop these concepts by designing the fundamental components of the beam source and tailoring them to specific beam characteristics such as power, beam quality, mode, and operating mode. The most important influencing factors are as follows:

- **Laser gas mixture |** The amount of carbon dioxide, helium, and nitrogen in the mixture has an effect on the laser process. The following composition has proved effective: 5.5 % CO_2, 29.0 % N_2, and 65.5 % He.
- **Shape and length of the resonator |** The resonator is a cavity such as a tube that contains the laser gas. The greater the resonator's volume is, the higher the laser power that can be generated. The shape of the resonator and the mirrors determine the possible modes.
- **Type of pump source |** Direct current or high-frequency alternating current can be used to energize the laser gas.
- **Cooling |** The laser gas has to be cooled effectively. This is because the laser gas becomes very warm during operation, and laser activity comes to a halt at temperatures between 200 to 300 degrees Celsius. The gas is either continuously circulated and cooled outside the discharge cavity, or cooled by diffusion.

Developing a laser concept requires a great deal of time and money. For the investment to pay off, the concept has to be scalable. In other words, the concept should enable creation of higher laser output levels using the same physical principles and the same design. Looked at in this way, the approach taken by laser manufacturers is not unlike that of a carmaker that offers a wide range of models based on only a few different designs.

In the following, we will take a look at two concepts for CO_2 lasers. Although both lasers are pumped using a high-frequency alternating current, the cooling system and resonator shape are different.

FLOWING GAS CO_2 LASERS

Among the different types of flowing gas CO_2 lasers, the one with the square design is a familiar face. It is compact, robust, and reliable. Depending on the configuration, it can produce a laser beam with up to 20 kilowatts of power.

It first appeared in 1989. At that time, this laser was able to cut steel plate with a thickness of up to 12 millimeters. Sixteen years later, it could already handle thicknesses over 30 millimeters. Meanwhile, power and beam quality have increased considerably, while weight, gas consumption, and operating costs have decreased steadily. In materials processing, it is used in cutting and welding systems or, more rarely, in combination with robots.

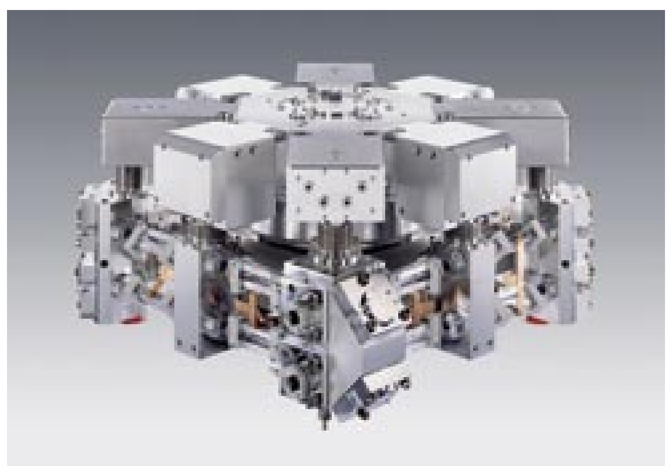
Design | The laser gas is contained in quartz glass tubes forming the discharge path. Electrodes on the outside of the tubes energize the laser gas without contact. A discharge path several meters long is required to produce two or more kilowatts of laser power. To keep the design as compact as possible, the discharge paths are laid out, for instance, in the shape of a square. Bending mirrors reflect the laser beam at the corners of the square, connecting the discharge paths optically. Rear mirrors and output mirrors complete the resonator design.

At the center of the beam source, a radial turbine blower on magnetic bearings continuously circulates the laser gas. The gas flows into the discharge tubes at the corners of the square and is extracted at the center of each side. Inside the inlet and outlet housings, the gas passes water-cooled heat exchangers and cools down. A gas mixer blends carbon dioxide, helium, and nitrogen to make the laser gas. A vacuum pump ensures the correct operating pressure, maintaining a gas pressure of about 100 hectopascals.

Beam properties | When the laser beam exits the device, it has a circular cross-section and a high beam quality. The mode depends on the diameter of the quartz tubes in the resonator and on the shape of the mirrors. Fundamental mode (Gaussian mode), doughnut mode, or multimodes are all possible with this concept.

Tried and true | The square-folded resonator design has proven to be very effective in industrial applications. Advantages of the concept include:

- Short gas travel between cooling and resonator
- No misalignment due to heating
- Durability: smooth operation unaffected by shocks or vibrations
- Non-wearing, maintenance-free radial turbine blower with non-contact magnetic bearing
- Non-wearing electrodes and high pump efficiency



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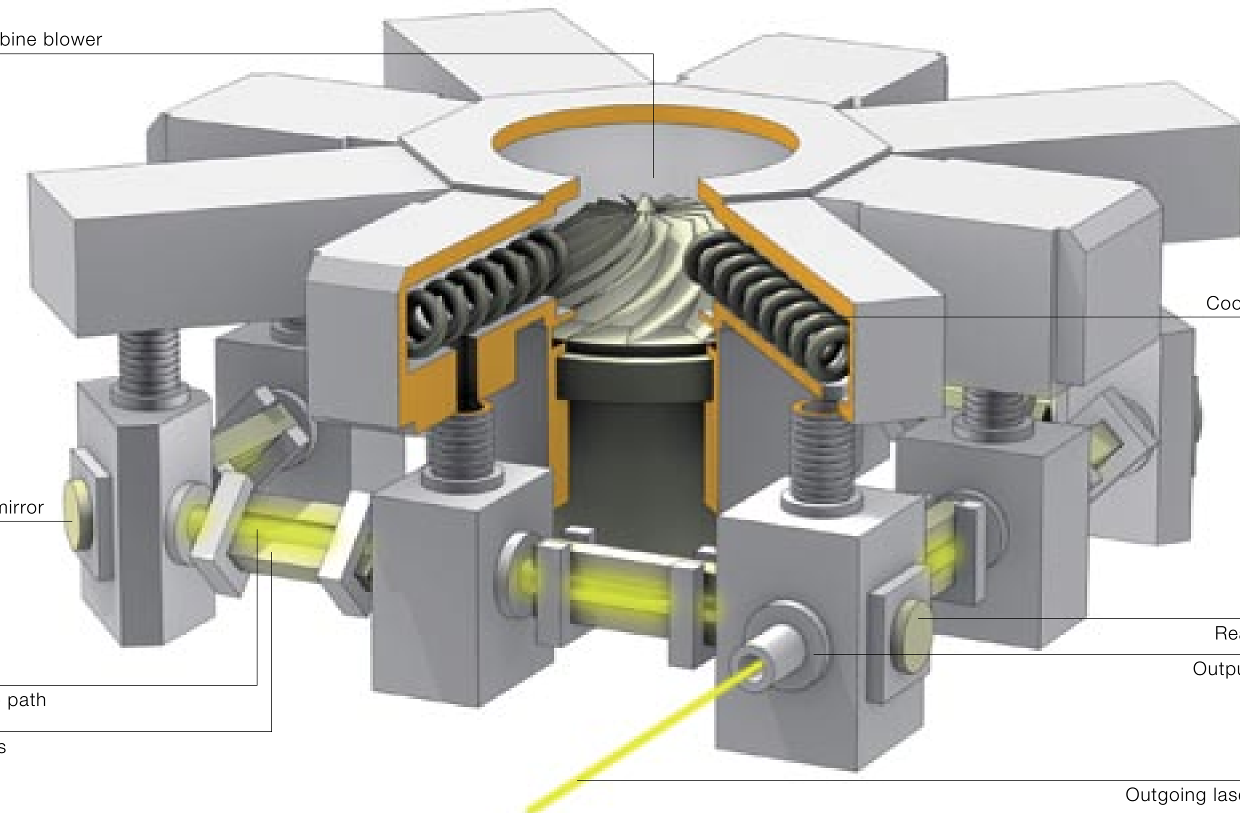
1 A flowing gas CO_2 laser with 16 discharge paths

Traveling at the speed of sound In high-power CO_2 lasers, heat output in the kilowatt range must be dissipated for each discharge tube. For this to work, the gas has to be replaced quickly; consequently, it is introduced into the discharge tubes at 200 meters per second. Once there, it heats up and is further accelerated, reaching speeds approaching the speed of sound. Each gas molecule passes through the discharge tubes 30 times a second, and the time it takes to run the entire length of the discharge path is less than 1 millisecond.



Compact, powerful, and reliable: a glimpse inside a flowing gas CO_2 laser with square design

Variants | Laser units of this series are suitable for many applications, ranging from high-speed cutting to surface processing. For greater laser power, the length and diameter of the discharge paths are varied. A 20-kilowatt CO_2 laser with a square design, for instance, has 16 discharge paths. The discharge paths are designed as squares that are arranged one on top of the other.

The mode is obtained by limiting the beam delivery. One way of doing this is to use an aperture whose diameter is smaller than that of the discharge tubes.

1 Diffusion-cooled CO_2 laser: the laser light is generated in the tube; amazing, but the small gas cylinder contains enough laser gas for up to two years of operation.

DIFFUSION-COOLED CO_2 LASERS

Unlike flowing gas CO_2 lasers, diffusion-cooled CO_2 lasers do not rely on gas circulation for cooling. Instead, they use a system in which the laser gas releases heat through the resonator walls (diffusion cooling). For effective cooling of the laser gas, the space between the resonator walls must be as small as possible, while the wall area must be as large as possible. At the same time, you also need a certain gas volume in order to achieve high laser power.

So how can you achieve a power output of a few kilowatts and still maintain a compact design? The answer is the coaxial laser, another beam source in the family of CO_2 lasers.

Design | The resonator consists of two metal tubes that are arranged coaxially one inside the other. These metal tubes are water cooled. The discharge path is formed by the space between the two tubes. This is where the laser gas is contained. The tube walls function both as RF electrodes and as cooling elements.

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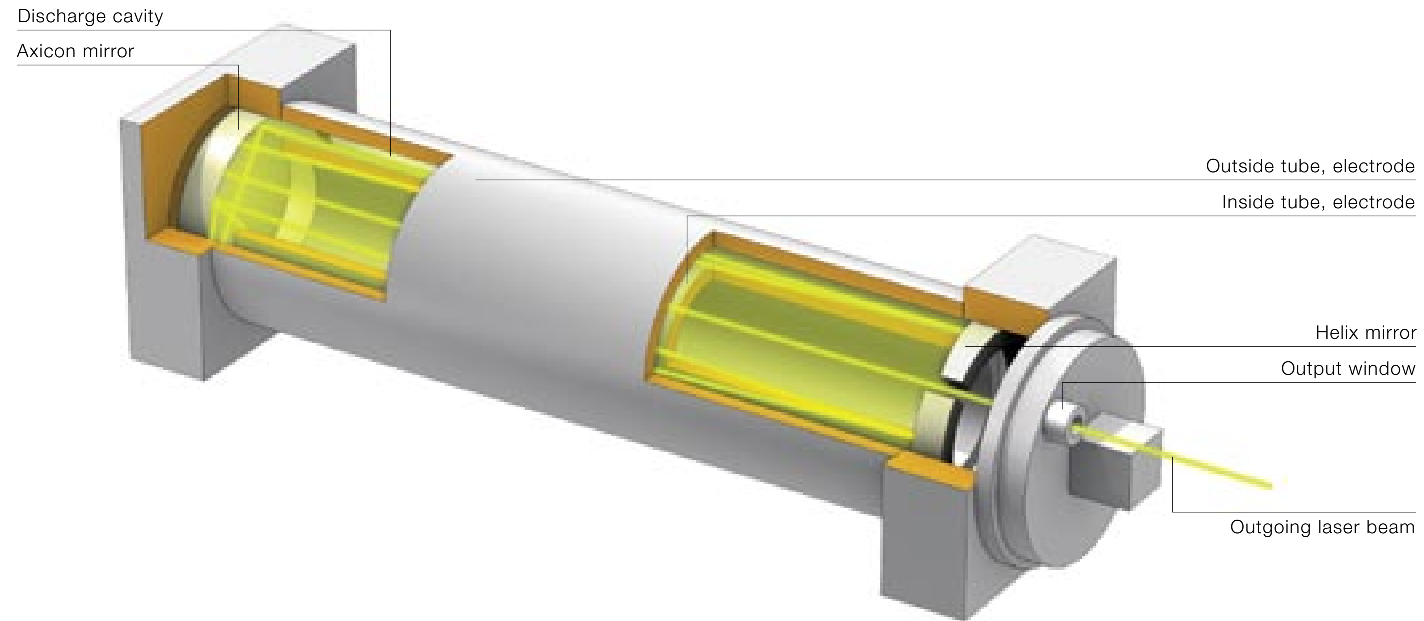
The rear mirror is located at one end of the resonator. It is an axicon mirror that has a ring-shaped reflecting surface around its edge forming a 45-degree angle to the plane. The reflecting surfaces on the opposite side of the axicon are at a 90-degree angle. Here's how it works: an assumed light beam strikes the axicon mirror on one side of the discharge path. It is then reflected onto the opposite side of the ring and, from there, directed back into the space between the two tubes. The incident and reflected beam are parallel.

At the other end of the resonator, the beam strikes a helix mirror, which is also in the shape of a ring. Since the reflecting surface is sloped, the mirror reflects the beam at a greater angle. This, in turn, causes the beam to zigzag as it is reflected back and forth, creating a steady radiation field within the resonator. The helix mirror has an opening through which a portion of the radiation field exits as a laser beam. The inside of the resonator is separated from the outside environment by a diamond window in front of the opening.

The beam | When the laser beam leaves the resonator, it has the cross-section of the segment of a circle. This raw beam cannot be controlled and focused in a way that is suitable for processing materials. Therefore, it is shaped into a round beam while still inside the beam source with the help of several cylindrically curved mirrors. When the laser beam exits the beam source, it is symmetrical and has a high M^2 beam quality of 1.1 (inverse M^2 factor (K) of 0.9). To get a complete picture of the beam mode, you must look at the two directions of the resonator: the stable direction and the unstable direction. In the stable direction between the tube walls, a Gaussian mode forms. In the unstable direction around the axis, however, the mode does not have a clear form. A mode shot of the unshaped beam reveals an irregular structure, or a mountain, as the developers say.

A case for the "decucumberer" When the laser beam leaves the resonator of a coaxial laser, it has the cross-section of a segment of a circle, or a cucumber, as developers like to say. So what are the mirrors called that are used to make the beam round? Take three guesses. Give up? "Decucumberers," of course.



The medium power specialist: a glimpse inside a diffusion-cooled CO_2 laser

A concept with great promise | Diffusion-cooled CO_2 lasers have been used in this form since 2003. They excel in applications requiring compact design, moderate power, and high beam quality. One such application is combination punching and laser cutting machines. On these machines, the coaxial laser is located on the machine frame. Another advantage of this laser: the laser gas is already mixed and contained in a small gas cylinder. The laser gas in the resonator is replaced automatically after 72 operating hours. The quantity involved is so small that the gas in the cylinder can last from one and a half to two years.

The design of the coaxial laser ensures its reliability in continuous operation. During operation, the resonator tubes heat up. The axicon mirror is able to compensate for the cold-warm behavior, because it always reflects the incident rays parallel to the other side. The beam is reflected even when striking the axicon at a slight angle, allowing the laser to continue operation without interruption.

Laser manufacturers expect the coaxial laser to establish itself in the low to medium power segment and prove to be especially popular with newcomers to laser processing.

Solid-state lasers

As early as the beginning of the 1970s, solid-state lasers were being used on a relatively large scale for industrial production. They delivered short laser pulses with a power of a kilowatt or more, making them suitable for use as tools in precision mechanics. They were first used for applications such as welding the delicate springs of mechanical watches or drilling the jewels – usually small synthetic rubies – used as seats for the watch mechanism.

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Versatility through diversity | Today, there are many different types of solid-state lasers. Their diversity is what makes them so versatile: solid-state lasers can be used for cutting, welding, soldering, drilling, hardening, and marking. Their properties and features at a glance:

- Short fundamental wavelength of about 1 micrometer
- The fundamental wavelength can be changed: green and ultraviolet lasers are also possible.
- There are pulsed solid-state lasers and CW lasers that are able to work in CW mode and pulsed mode.
- Solid-state lasers have a wide power range. CW lasers deliver outputs of several kilowatts. Pulsed lasers generate pulses of up to several hundred kilowatts.
- The beam quality varies greatly depending on the laser type. It ranges from medium to very high: M^2 from 1.2 to 74 (inverse M^2 factor (K-number) of 0.8 to 0.01; beam parameter product of 0.4 to 25 millimeter-milliradians).

The fiber optic advantage | The beams of solid-state lasers with fundamental wavelengths of about 1 micrometer can be coupled into fiber optic laser cables and transported without any appreciable loss of quality or power. The advantage of these cables: laser and workstation are separate and can be located in different places. With beam splitters and deflectors, the laser beam of one beam source can be sent to multiple workstations through different fiber optic cables.

1 A rod laser from the 1970s used for spot welding

2 Gain media in solid-state lasers: a rod, fiber, and disk

Synthetic crystals The crystals that glow inside solid-state lasers are manufactured synthetically. This is the only way to create the perfectly regular crystal lattice needed for the laser. The technical term for these perfect crystals is "single crystal."

LIGHT FROM CRYSTALS AND GLASS

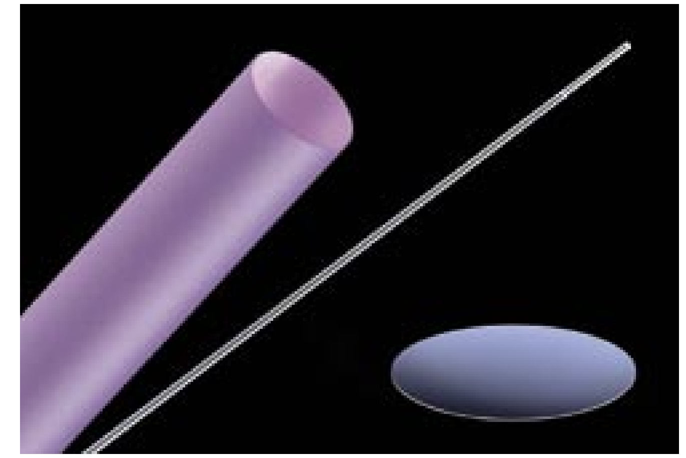
The laser light in the solid is created by fluorescing foreign ions, which are introduced in small amounts into a glass or crystalline host material. The process of introducing these elements is called doping. Neodymium (Nd) and ytterbium (Yb) are the primary dopants used in beam sources for industrial materials processing. The wavelengths of their laser light are nearly identical: about 1.06 micrometers for neodymium and 1.03 micrometers for ytterbium.

Nd:YAG | The neodymium concentration in the crystal of a Nd:YAG laser is typically around one percent. The neodymium ions turn the transparent yttrium aluminum garnet (YAG) into a reddish crystal.

Four energy levels are involved in the laser process. Light from arc lamps or diode lasers is used to promote the electrons of neodymium ions to a highly excited state. From there, they quickly make the transition to the upper laser level, releasing energy into the crystalline host in the form of heat. This is followed by a transition back to the lower laser level, where laser light with a wavelength of 1.06 micrometers is produced. Once in the lower laser level, the electrons quickly decay to the ground state and give off heat.

In a neodymium ion, the lower laser level is considerably higher than the ground state. As a result, the lower laser level is not populated when the crystal is in the ground state, making it easy to create a population inversion.

Yb:YAG and Yb:glass | Used as Yb:YAG in disk lasers and as Yb:glass in fiber lasers, ytterbium is gaining in importance. The concentration of ytterbium in the YAG is typically around ten percent. The higher doping concentration enables higher laser outputs per volume of gain medium.



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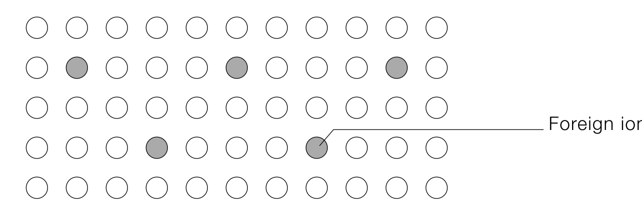
The laser process of the ytterbium ion also involves four energy levels. However, since the lower laser level and the ground state are very close together, this laser system is referred to as a quasi-three-level laser system. For this same reason, even a small temperature increase is enough to populate the lower laser level. Thus, adequate cooling of the gain medium is necessary in order to achieve population inversion and maintain constant laser power.

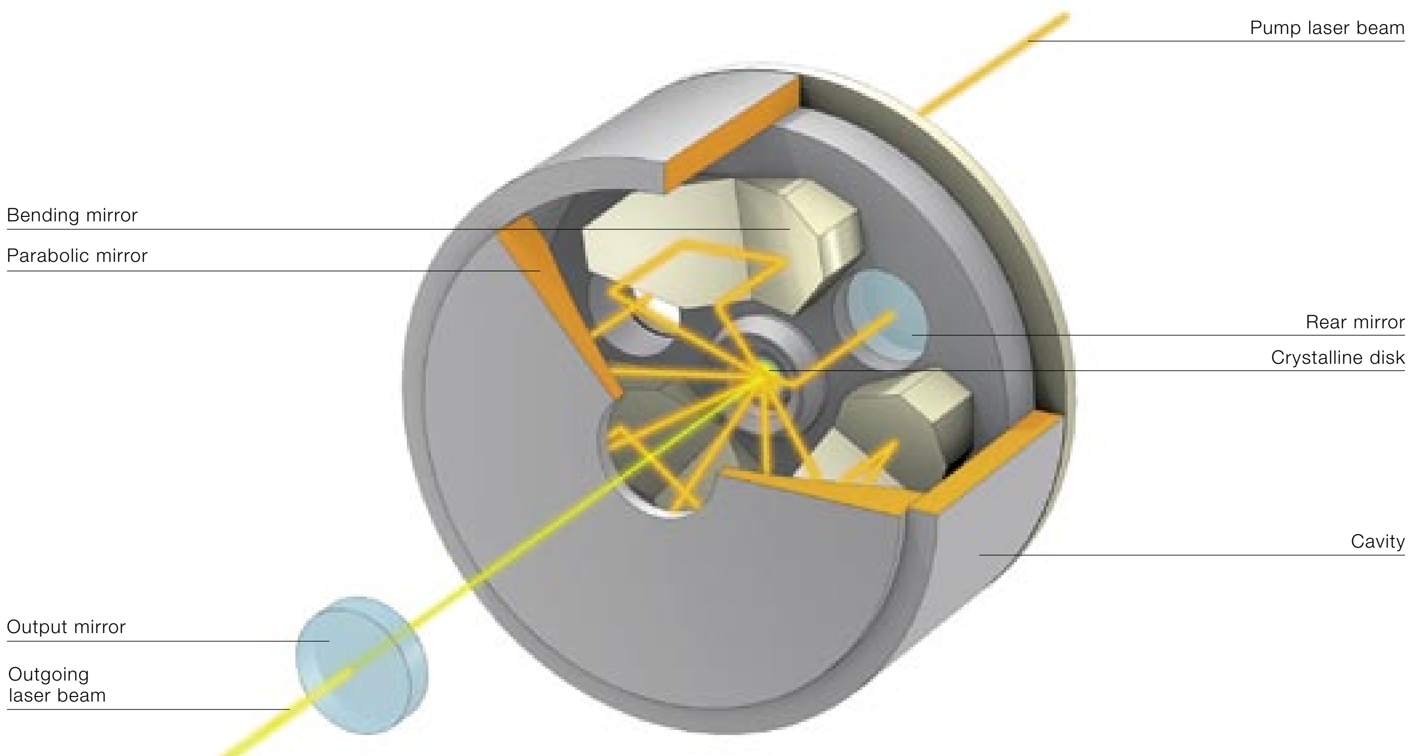


Doped crystal: ions of another element, or "foreign" ions, are incorporated into the crystal lattice, which is called the host lattice.

The green glow The crystal of an Yb:YAG disk laser glows green during operation, even though the wavelength of the laser beam is in the infrared, and the laser beam is invisible. So where's the green light coming from? It is caused by doubly excited impurities in the crystal. When making the transition to the ground state, they emit a green light. The green glow is a by-product with a useful side effect: because the pump spot on the disk glows green, it is possible to align the laser without the help of optical instruments. All that has to be done is to ensure that the green spot appears as sharp as possible. When this is done, you know that the pump beam has been set optimally.

WAFER-THIN: THE DISK LASER

In creating the disk laser, developers went in a direction opposite to the one taken with the fiber laser: instead of replacing the rod with a fine, long fiber, they used a thin, round disk. The first high-power disk lasers appeared on the market in 2003. Within a short time, their power has doubled. Experts have great hopes for this beam source, which is able to attain the high beam qualities of a CO_2 laser with greater efficiency, while offering the benefits of fiber optic laser cables. In the laboratory, laser manufacturers can already generate several kilowatts with one disk. The disks of standard devices are able to deliver 2 kilowatts and more.



Transforming a low-quality pump laser beam into a high-quality beam: a glimpse inside a disk laser

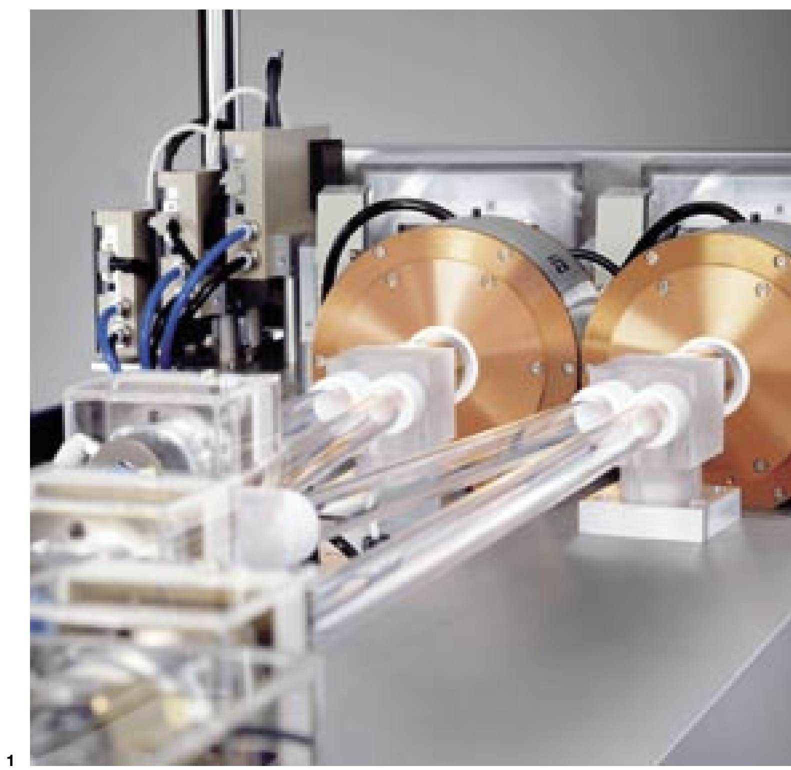
Design and mode of operation | The laser-active heart of a disk laser is a small, wafer-thin crystalline disk made of Yb:YAG. It measures just under 15 millimeters in diameter and is only two tenths of a millimeter thick. The disk rests on a heat sink, which dissipates heat and cools the disk. The cooled rear side of the disk has a reflective surface, which reflects the laser beam and pump light.

The laser light from diode lasers is used as the pump light. It is focused to a diameter of a few millimeters and then aimed at the disk. The disk is so thin that it absorbs only a fraction of the pump radiation that passes through. Therefore, to increase the absorption length, the pump beam is sent through the disk a total of 16 times, using several pairs of bending mirrors, a rear mirror, and a parabolic mirror.

On its journey, the pump beam first strikes the parabolic mirror, which focuses it on the disk. The portion of the disk illuminated by the pump beam is called the pump spot. The pump beam passes through the disk and is reflected by the reflective rear side. Then, it passes through the disk a second time and exits the disk. It strikes the parabolic mirror once more. The parabolic mirror focuses the beam and directs it to a pair of bending mirrors. This pair of bending mirrors sends the pump beam back to the parabolic mirror – this time, at a slightly different angle. From there, the pump beam returns to the disk, is reflected back to the parabolic mirror, and so on. After two further pairs of bending mirrors and eight more times through the disk, the pump beam reaches the rear mirror, which sends the beam back the same way it came. By now, the pump radiation is almost completely absorbed.

The laser beam is propagated perpendicular to the surface of the disk and exits the cavity through a hole in the center of the parabolic mirror. The output mirror of the resonator is located outside the cavity.

Beam properties | What sets the laser beam produced by a disk laser apart is its high beam quality. The beam quality is much greater than that of a rod laser and is independent of the power. The reason for this is that, unlike rods, disks induce almost no thermal lensing, which deforms the laser beam. While there is a difference in temperature between the top and bottom of the disk, the temperature profile runs axially in the direction of the laser beam, and not radially as is the case in a rod. As a result, the optical path is the same for all photons, and the beam is not deformed. With regard



1 Disk laser with two cavities: the laser beam travels through the tubes.