Extract of the book:
The Fascinating World of Sheet Metal

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The laser – a tool for processing flexible materials

As early as 1917 Albert Einstein described the theoretical foundations of stimulated emission. However, it was not until 1960 that the first laser appeared – a ruby laser constructed by Theodor H. Maiman. Today, lasers are an integral part of our highly technical world. They are used in the medical field, in advertising, as measuring instruments or as a tool for cutting, welding or marking.

When the first laser was introduced in 1960, it was derided as an "invention in search of an application". Today, lasers have become so widespread and their fields of application so diverse, that this assessment seems virtually grotesque. In supermarkets, lasers read the prices of the purchased goods. In hospitals and clinics lasers are used for corrective eye surgery. Laser spectroscopy has become an indispensible method for analyzing atoms and molecules. It would also be hard to imagine consumer electronics without lasers – CD-ROM players or laser shows are just two examples.

But lasers have also long become a mainstay in day-to-day industrial life, CO_2 and Nd:YAG lasers are particularly important. Today, they replace conventional production procedures in many fields; for example, in welding metals or marking signs and workpieces. Furthermore, lasers are used in almost all areas of material processing: drilling, stripping, bending, hardening, recasting, coating, alloying, and dispersing.

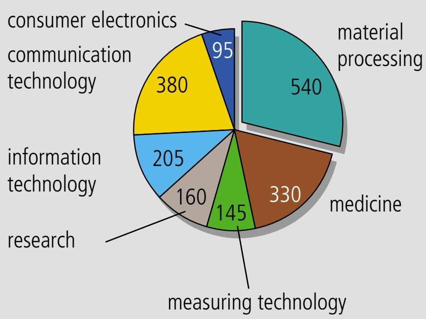
What is a laser?

The term "laser" basically describes in abbreviated form the way the device operates: "Light Amplification by Stimulated Emission of Radiation". Practically speaking, a laser is the source of radiation which emits a narrowly focused beam. The type of beam has a particular wavelength, characteristic for each type of laser. Its uniform waves run almost parallel and in phase. In physics, these characteristics are called "monochromatic" and "coherent".

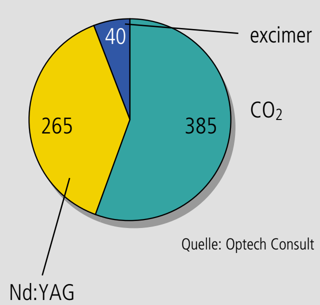
Although not all lasers emit a beam visible to the naked eye (wavelength = 400 to 750 nm), the laser is usually referred to as a source of light and the radiation as a laser light.

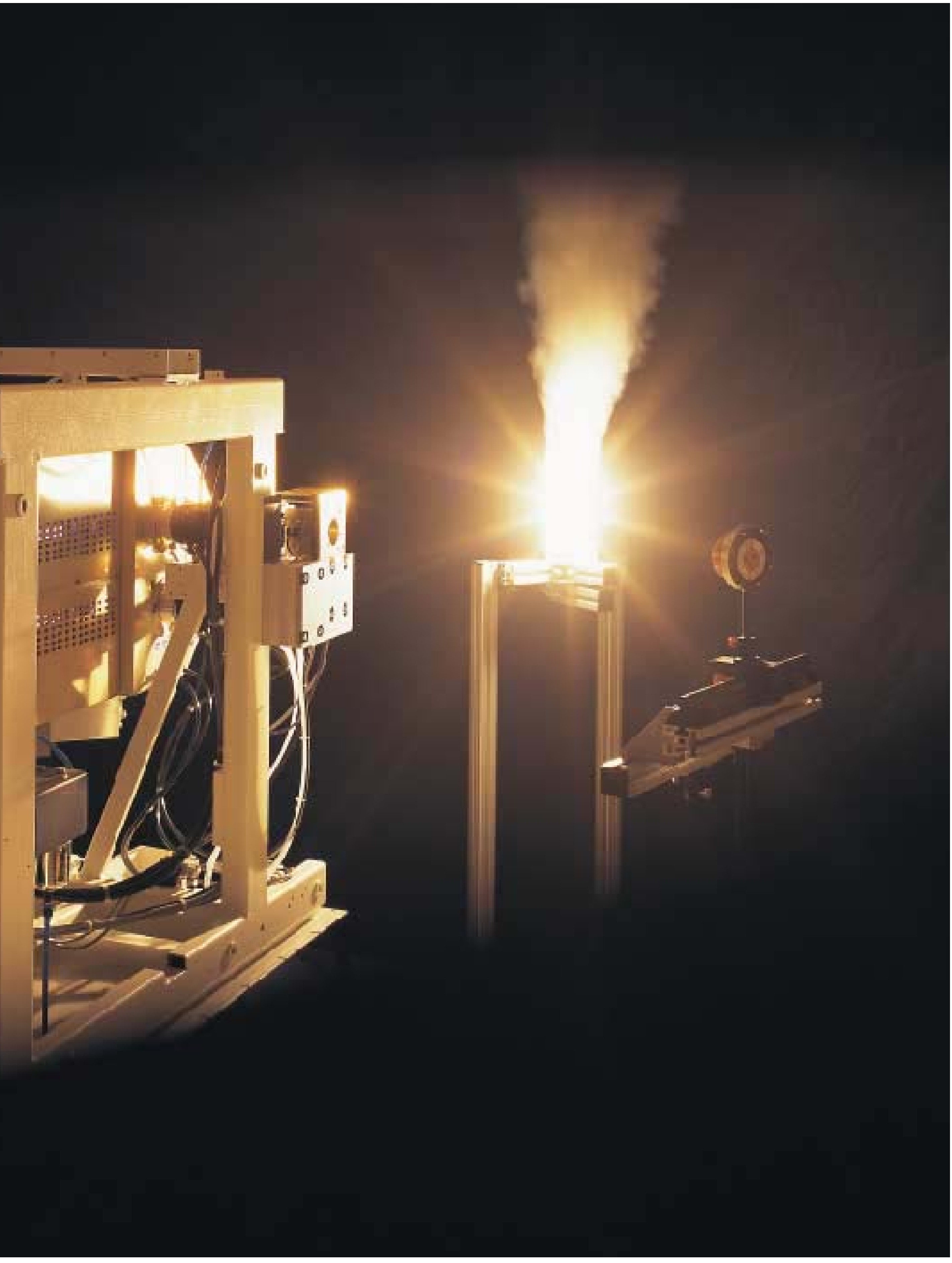
World market for laser systems

World market for laser beam sources 1994 in millions

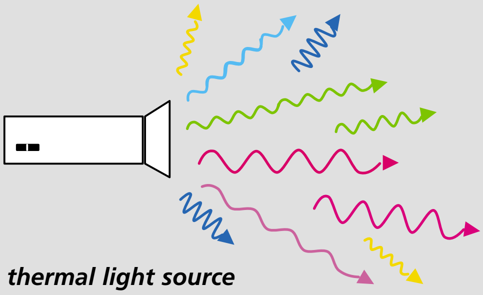


Laser systems for material processing 1995 in millions

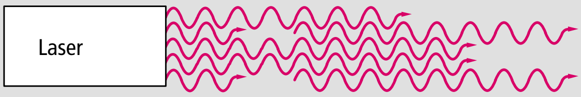




Laser light



Light from a thermal light source



Laser: coherent, monochromatic, and nearly parallel light

The difference between the light of a flashlight and a laser: the flashlight emits a mixture of different wavelengths which are neither in phase nor parallel. A laser beam has equally long waves; they run nearly parallel and in phase.

How a laser beam is created

All lasers operate according to the same principle: energy is coupled into laser-active material. The atoms or molecules of the laser-active material are stimulated to a higher level - the upper laser level. The coupling of energy is known as "pumping", and the energy source as the "pump source". In order for the laser effect to take place, more atoms or molecules must be on the upper level than on the lower one. This is known as occupation inversion. When inversion has been reached, the laser-active material can release the energy in the form of light with a specific wavelength and propagation direction.

This happens in the so-called resonator. In its most simple form, a resonator consists of two parallel mirrors between which the laser-active material is located. The mirrors ensure that only light waves in a particular direction – parallel to the axis – are retained in the resonator. The waves are amplified in the laser-active material and laser light is produced.

In order for the laser light to leave the resonator, one of the mirrors must be semi-transparent. A certain percentage

Large and small high-powered lasers: CO_2 laser (30 kW) and diode laser (200 W)

Laser media and pump sources

Type of laser	Laser-active material	Pump mechanism and pump sources	Important examples with wavelengths and preferred fields of application
Gas laser	gas or vapor	electrically stimulated gas discharge	CO_2 laser: 10.6 µm (far infrared), material processing; HeNe laser: 633 nm (red), measurment technology; excimer laser: 175–483 nm (ultraviolet), measurment technology, photochemistry
Solid-state laser	crystals or lenses which have been doped with optically active ions	optical, with stimulating lamp or diode laser	Ruby laser: 694 nm, first laser invented; Nd:YAG laser and Nd:glass laser: 1.06 µm (near infrared, material processing)
Dye laser	organic dyes in a highly diluted solution	optical, with photo-flash lamp or laser	Tunable from approx. 300 nm to 1.2 µm, spectroscope
Semi-conductor laser	semi-conductor	electric	GaInP (670–680 nm), GaAlAs (780–880 nm), very small dimensions, light source in CD players, optical disk storage systems and laser printers, telecommunication devices

of laser light leaves the mirror and is then made available for a variety of applications, for example, material processing.

Laser active material: The laser light is generated in the laser-active material. This can be gas (for example CO_2), a solid body (for example, a Nd:YAG-crystal), or a liquid (for example a colored solution). The number of possible laser-active materials is quite extensive. Even today, new materials are being discovered which can produce laser light.

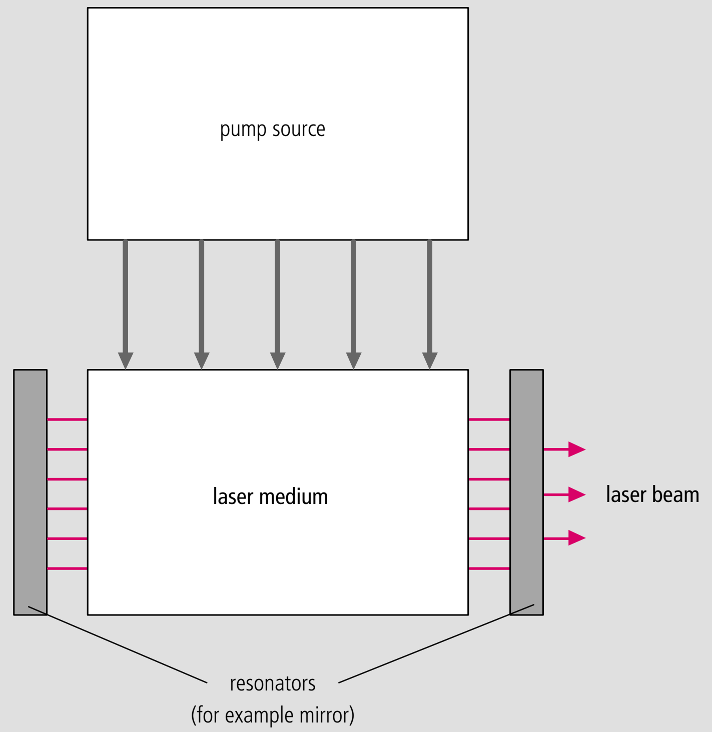
Pump sources: Energy can be coupled into the laser-active material in a number of ways. Two pumping mechanisms are important for processing materials:

- electrical pumping: the laser-active material is stimulated by an electrical source of energy. For example, direct current or high frequencies can stimulate CO_2 lasers.
- optical pumping: the laser-active material is radiated by intense light, for example, a lamp or a semi-conductor diode. A stimulating lamp radiates the crystal of an Nd:YAG laser.

The properties of a laser

Laser light possesses a number of characteristics which distinguish it from the light of a thermal light source – a light bulb, for example.

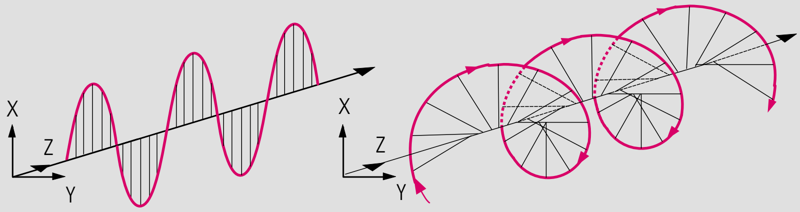
Wavelength: A laser emits a beam of a precisely defined wavelength specific for its type. We say that the laser light is monochromatic. An HeNe laser, for example, creates a red light with a wavelength of 633 nm; CO_2 lasers create an infrared light with a wavelength of 10.6 µm and Nd:YAG lasers, infrared light with 1.06 µm.



Components of a laser

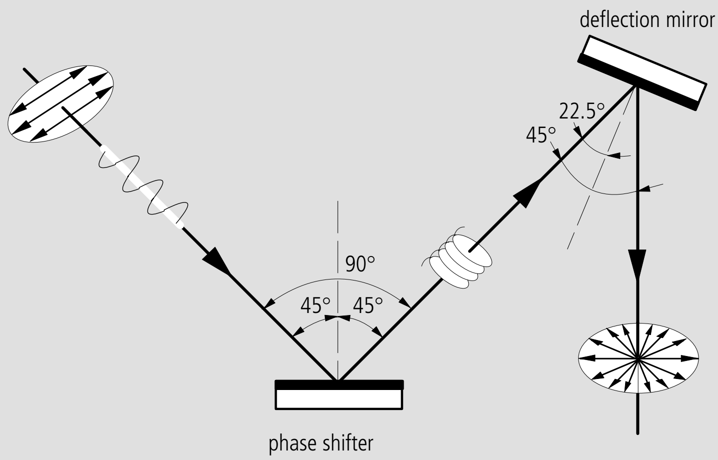
Polarization

The electrical field of a light source normally oscillates randomly way on a plane perpendicular to the direction of propagation. This type of beam is known as "unpolarized".



In a linear polarized beam, the electrical field of the electromagnetic waves oscillates only on a single plane (left). In circular polarized light (right) the electric field strength oscillates so that the point of the field vector forms a spiral around the direction of propagation.

Circular polarized light can be created from linear polarized light using a specially coated mirror (a phase shifter, also known as ECQ for "Enhanced Cutting Quality").



Phase shifter: the principle is shown above. Below the circular polarizer of a CO_2 laser.

Coherence: The electromagnetic waves of the laser light oscillate in phase. The laser light is said to be coherent in time and space.

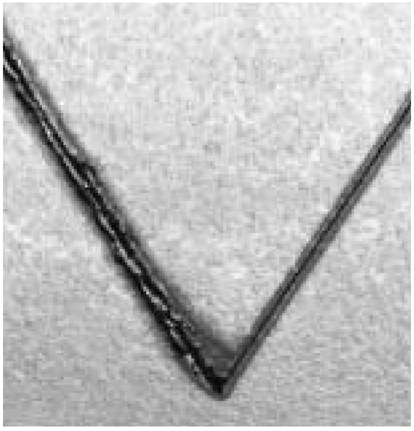
Low divergence: Laser light has a low divergence. This means that laser light is nearly parallel. The degree to which it deviates from the parallel is referred to as divergence. The amount of divergence is expressed by the angle of aperture.

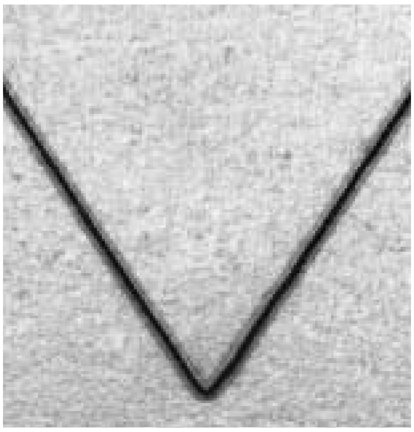
Good focusability: Laser radiation can be focused well. Good focusability means that the entire energy of a laser beam can be focused onto a very small spot. Taking a CO_2 laser as an example, a beam producing 2.6 kW of energy can be focused onto a focal point with a diameter of 0.15 mm. The average intensity in this case is 15 MW/cm². In comparison, a stove hot plate with a heating power of 1 kW and 15 cm diameter has an intensity of 5.6 W/cm². As one can see, the intensity of the laser is nearly 3 million times higher.

Polarization: Laser light can be easily polarized. The laser effect itself does not have any influence on the polarization direction of the laser light. Some laser designs only amplify waves of a particular direction of polarization. These lasers generate linear polarized light. An example of a laser which generates polarized light is the CO_2 lasers with folded resonators such as those used in material processing.

If linear polarized light is used for laser cutting or laser welding, the processing result is dependent on the direction. As a rule, however, processing results independent of the processing direction are desired. For this reason, unpolarized or circular polarized light is preferable for material processing.

Intensity distribution in the beam cross section – modes: The cross section of laser light reveals a characteristic intensity distribution. This is known as "mode". In the cross section of the basic mode (TEM_{00} = transversal electromagnetic mode) the beam intensity is strongest in the middle and diminishes symetrically on all sides to form a normal Gaussian distribution curve. The mode form TEM_{01} is characterized by two intensity peaks left and right of the center; the center itself has 0 intensity. The intensity distribution of the laser radiation is determined by the structure of the laser and the type of laser-active material.

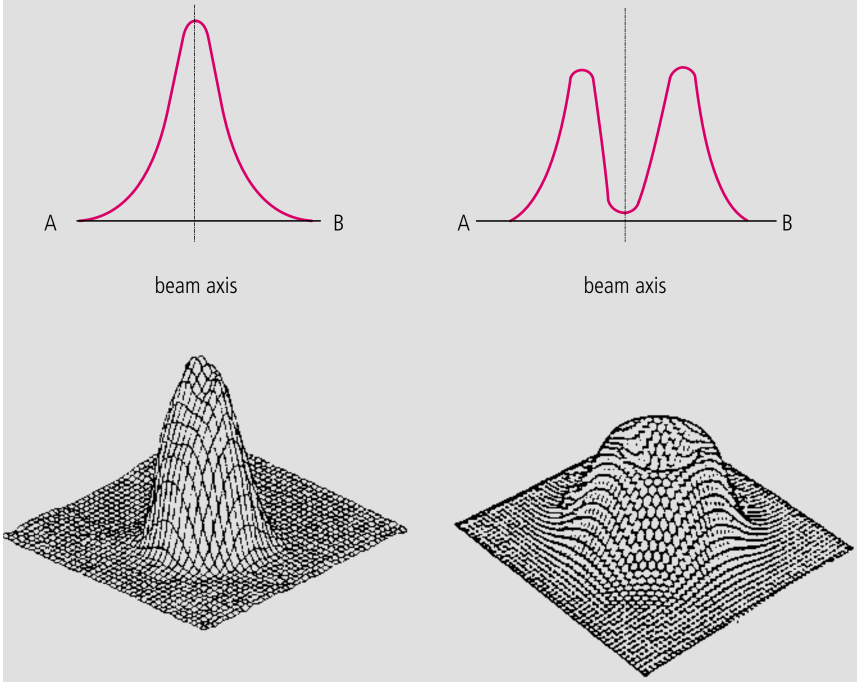




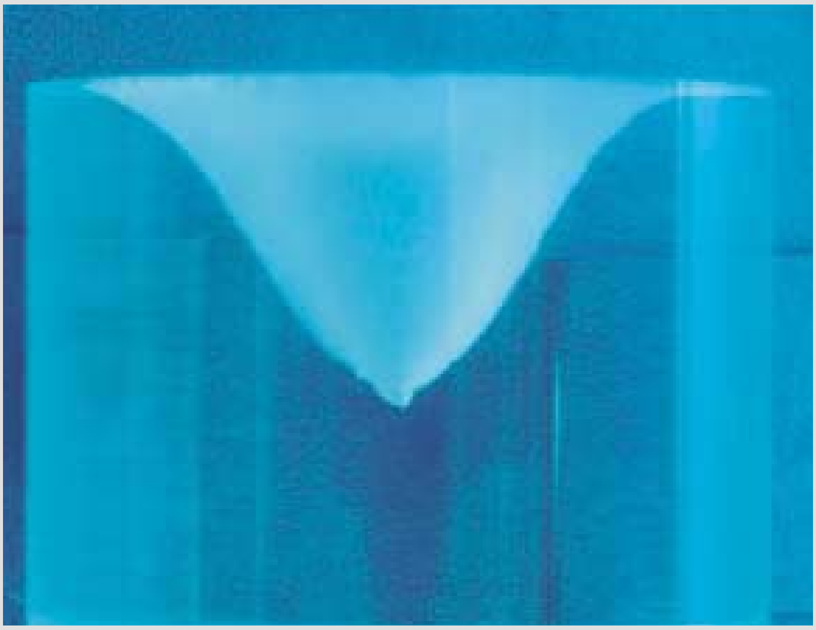
Laser-cut edge with polarization plane perpendicular (top) and parallel to the processing direction (bottom).

If, when cutting with a laser, the processing direction is parallel to the polarization direction, the cuts are made quickly and cleanly. If on the other hand the processing direction is perpendicular to the polarization plane, the cut may, in extreme cases, not go completely through the material.

Modes



Intensity distribution (modes) in the cross section of a laser beam: left TEM_{00}, right TEM_{01}
The laser beam is focused to the smallest possible point for welding, cutting or drilling. For hardening, on the other hand, the laser light is projected as a flat surface.



The intensity distribution in the cross section of a laser beam becomes apparent in the so-called mode shot. The unfocused beam is directed onto the surface of a plexiglas cylinder. This results in the characteristic cavity which has the same shape as the distribution of intensity in the cross section of the laser beam.

Lasers in material processing

A two types of lasers in particular have proven themselves in industrial practice: the CO_2 gas laser and the Nd:YAG solid-state laser. Both systems possess a series of characteristics which are important for their use in everyday industrial application:

- very high laser output (CO_2 laser: 40 kW in CW mode, Nd:YAG laser: pulses of several hundred kilowatts)
- high beam quality
- high operating safety
- adjustable power and adjustable power flow
- good controllability
- compact design allows good integration into existing machine concepts
- high quantum optical efficiency

The structure of CO_2 lasers

A gas mixer prepares the laser gas – a mixture of CO_2, N_2 and He – in an ideal mixing ratio (approx. 0.5:2:5). A vacuum pump provides the necessary operating pressure of 100 mbar – about one tenth of the atmospheric pressure. The gas mixture is then delivered to a discharge tube.

Stimulation: Electrodes (direct or alternating current) are located in or at the discharge tube. They produce the gas discharge in the laser gas while the CO_2 molecules are stimulated to the upper laser level. The gases N_2 and He have only a supporting function: nitrogen makes the stimulation more effective, and helium cools the laser gas.

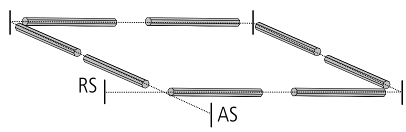
Resonator: The resonator is composed of two mirrors. The laser light is generated between the mirrors in the laser-active material. One of the mirrors – the output coupler – is semi-transparent. A part of the laser light leaves the resonator through this mirror.

Cooling: During the gas discharge, the laser gas becomes very hot. To properly maintain the laser process, the temperature must not exceed 200–300 °C. For this reason, the laser gas must be cooled during operation. The heat either dissipates on the walls of the discharging tube – by means of diffusion cooling – or it is carried away by quickly replacing the gas, i.e. by convective cooling. In this case the laser gas is circulated by a pump and thereby cooled. Thus, the laser gas is continuously replaced in the discharge chamber.

Compact design: CO_2 lasers for industrial use excel because of their compact design and the facility with which they can be integrated. Three steps were very important on the way to realizing more compact lasers:

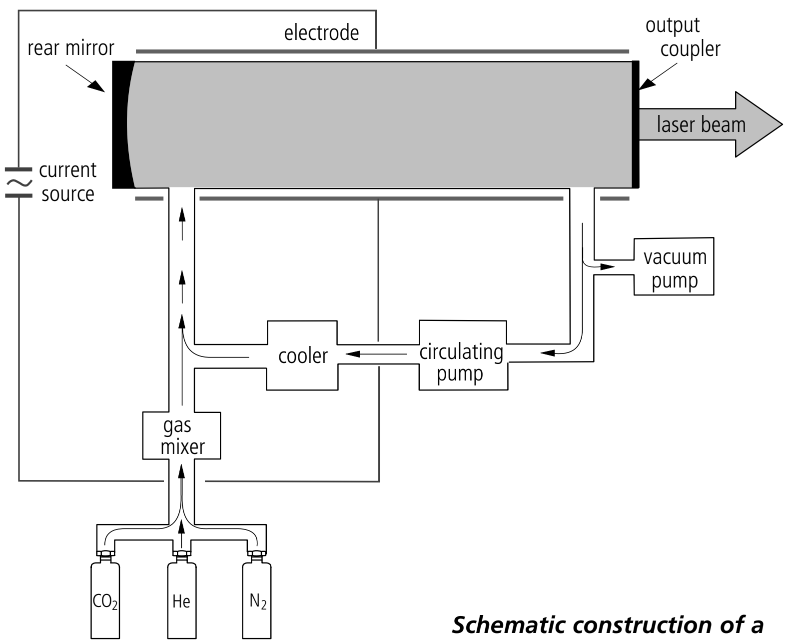
1. Folding the resonator: The longer the discharge path in the resonator, the higher the attainable laser power. A discharge path of one meter produces an ouput of approx. 1 kW. When using CO_2 lasers for material processing – which require several kWs – the discharge path in the resonator must be several meters in length.

To facilitate construction of the CO_2 lasers, the beam is deflected several times. The resonator is designed accordingly. Deflecting the beam is known as "folding" and the corresponding resonator is called a "folded resonator".

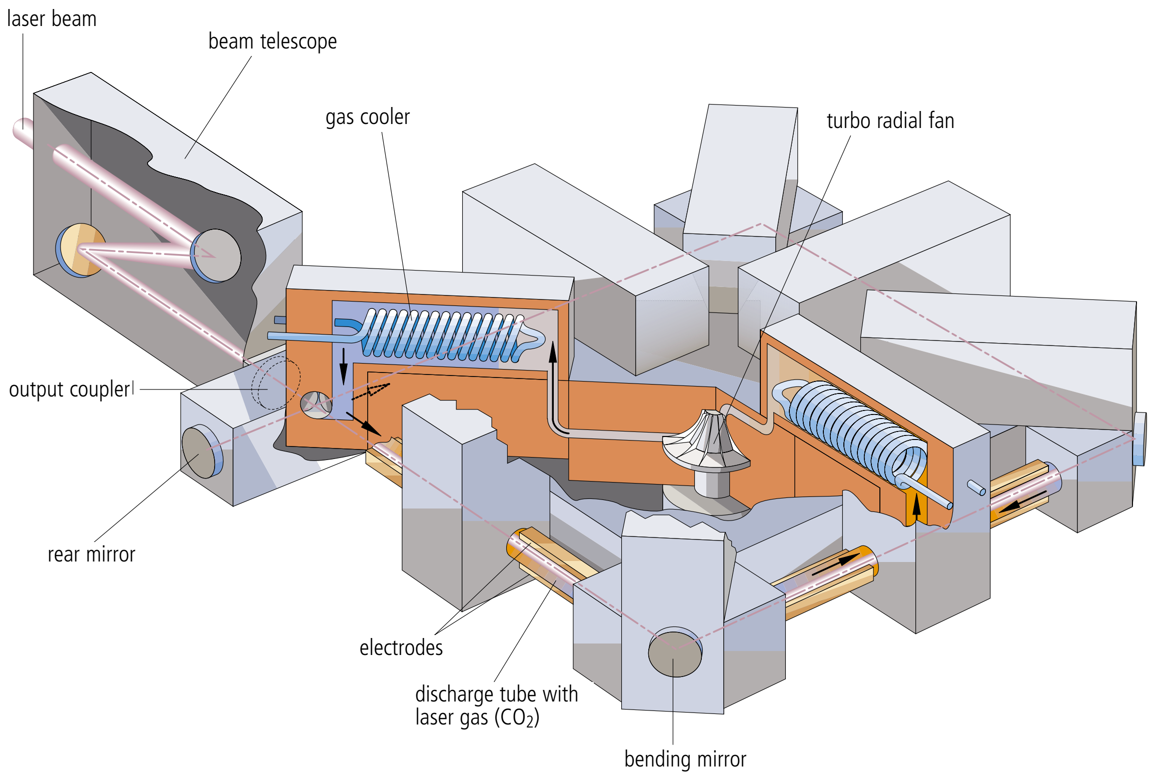


Square-folded resonator

2. Integrating the circulation: As a rule, the blower which continuously circulates the laser gas mixture is integrated into the laser. For example, in square-folded resonators the blower can be positioned directly under the center of the square. Radial turbine blowers are ideal for this purpose. These are particularly quiet in operation and have relatively small dimensions. They circulate the laser gas at the necessary velocity without significant pressure variations.



Schematic construction of a CO_2 laser



Structure of an axial flowing, frequency-stimulated CO_2 laser: The resonator is square-folded so that the light path can remain long despite the compact form of construction. In each route section of the square, a separate gas discharge is produced. The discharge tubes are located around the outside of the square. Gas is delivered halfway along each side and returned from the corners to the center of the square. A radial tubine blower is located at the center of the resonator for circulating the laser gas. The gas cooler is integrated into the circulation, because the blower and all gas lines are cooled. The telescope located at the end of the beam delivery widens the beam so that it can be guided over longer distances.

3. Integrating the laser gas cooling system: By directly cooling the pump and the gas lines to and from the pump, the laser gas cooling system is made particularly compact.

Beam quality: The beam quality number K specified by the manufacturers of laser systems serves to characterize the focusability of a CO_2 laser beam. K can take on a value between 0 and 1, whereby 1 indicates the best beam quality.

CO_2 lasers for material processing reach K values of up to 0.7 with a power output of 1 kW and more than 0.2 with an output of approx. 25 kW.

Power control by pulse operation: The power of CO_2 cw lasers stimulated by high frequencies is regulated using pulse operation. A series of pulses are generated with the maximum power. The average laser power output is regulated by the ratio between the pulse duration and the pause lengths.

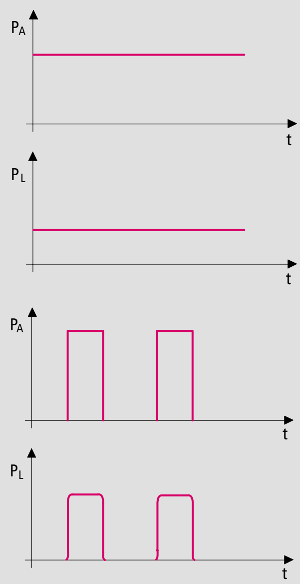
An example: the laser generates 1000 pulses, each lasting 0.0005 seconds with a power output of 2600 W. Between each pulse there is a pause of 0.0005 seconds in which the laser does not emit any light.

Laser operating modes

cw mode (continuous wave operation): In cw mode (cw = continuous wave) the laser beam is generated continuously while being constantly fed with energy. The laser emits a constant intense laser light.

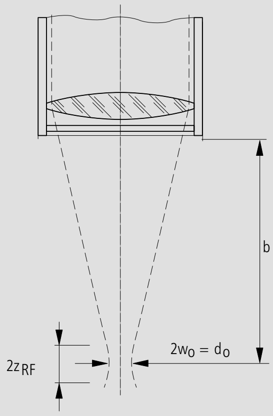
P_A = stimulation energy
P_L = laser output power
t = time

Pulse mode: Pulses in lasers used for material processing are normally created by a pulsating stimulation: They are stimulated in intervals rather than continuously (pumped). The pulsating stimulation energy leads to a pulsating laser output power. In pulse operation very high laser power can be generated which is limited, however, to the duration of the pulse.



Beam quality

When processing materials with a laser, the ability to focus the laser precisely is absolutely critical, because good focusability means a smaller spot size and better depth of field. When focusability is good, focusing optics with a longer focal length can be used which in turn leads to a large work clearance. The focusability of a laser beam is often referred to as beam quality.



Different variables are used to describe the beam quality. The beam quality of a CO_2 laser is usually indicated by the beam propagation factor K; for an Nd:YAG laser the beam parameter product q. At times M^2 is given. The parameters are defined as follows:

- beam parameter product:
  $q = w_0 \cdot 1/2\ \Theta$
- beam propagation factor:
  $K = \lambda/\pi \cdot 4/(d_0 \cdot \Theta) = \lambda/\pi \cdot 1/q$
  w_0 = radius of the beam waist
  d_0 = diameter of the beam waist
  Θ = divergence angle
  λ = laser wavelength
  $M^2=1/K$

The values are mathematically related and can be compared to each other. All three variables are suitable for comparing lasers of the same wavelength. The beam parameter product q is particularly suited for comparing the laser beams focusability since the the influence of the wavelength on the focusing diameter is already accounted for in q.

Hence, the average power amounts to 1300 W.

Laser power output and the power flow can be be regulated particularly well in this way. Especially at a very low power output the advantages become apparent: a gating frequency of approx. 10 Hz is presently able to cut very small contours with diameters and web widths which are considerably smaller than the sheet thickness.

The structure of Nd:YAG lasers

Nd:YAG lasers can also be constructed in a compact manner. A single enclosure can accommodate the electrical power supply, the control and the laser itself. The laser light cable from the device leads to the processing area.

Cavity: The three most important components of a laser (laser rod, stimulating or flash lamp, and mirror) are located in a highly reflecting or

CO_2 gas laser: variants

Gas flow velocity

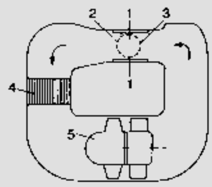
Slow flow gas laser
- no pump for circulating gas
- the flow velocity is determined by the set gas pressure and the replacement of consumed gas.

Fast flow gas laser
- pump for circulating gas
- The flow velocity depends on the delivery capacity of the pump.

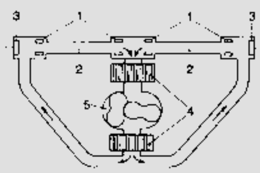
Advantages:
- The higher gas flow rate allows for more laser power if all other factors are equal.
- The higher gas flow velocity reduces the dwell time of the gas in the discharge path. The gas does not heat up as much, making it easier to cool.

Gas flow direction

Transverse flow gas laser
- Gas flows transverse to the beam axis.



Axial flow gas laser
- Gas flow is guided parallel to the beam axis.



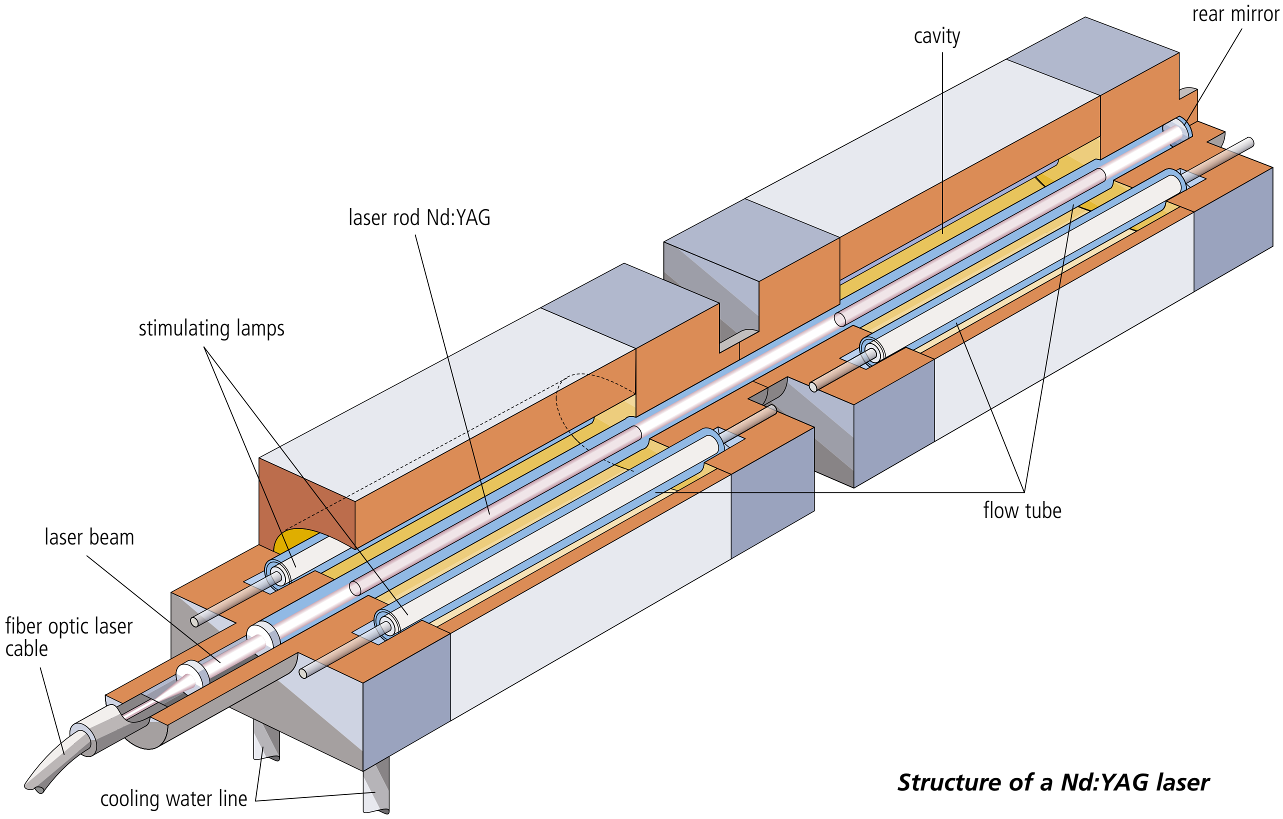
1 electrodes
2 resonator
3 resonator mirror
4 cooler
5 gas circulator

Type of stimulation

Direct current
- The electrodes are charged with high DC voltage.
- The electrodes are located within the resonator.

Radio-frequency
- The electrodes are charged with radio-frequency alternating current (for example 13.56 MHz).
- The electrodes are not in contact with the gas.

Advantages:
- The resulting homogeneous gas discharge provides for consistent laser power.
- Less voltage is required to stimulate the gas mixture than when coupling energy using a source of DC voltage. The result is lower gas consumption. At the same time, the potential danger of electric shocks is reduced.
- As the electrodes do not touch the laser medium and thus are not exposed to a gas discharge, there is no wear on the electrodes. In addition, electrode material cannot contaminate the resonator (mirror, glass tubes). Maintenance and gas consumption are reduced.



Structure of a Nd:YAG laser

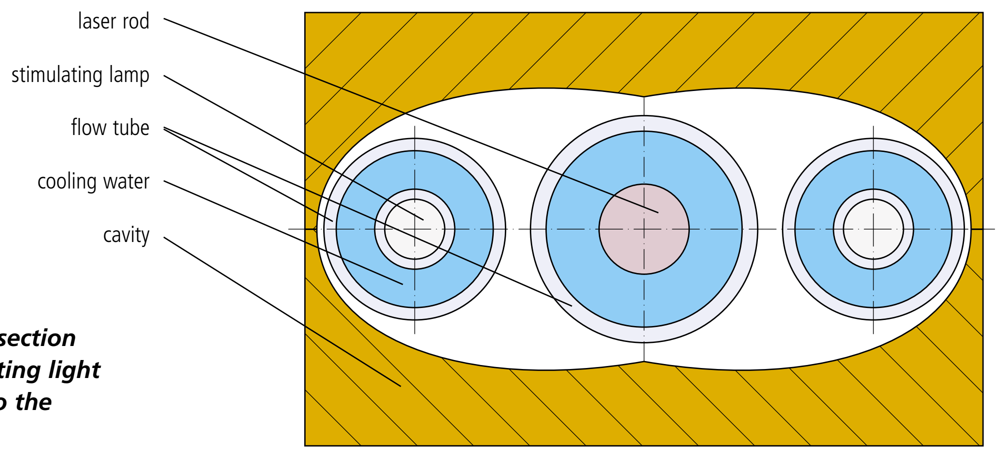
diffusely reflecting case known as the cavity. The cavity has a double elliptical cross section. Both stimulating lamps are mounted in the focal lines of the ellipses. The laser rod itself is located in the center.

Laser rod: The laser rod consists of a single artificially grown crystal made of yttrium aluminum garnet (YAG), in which a small part of the yttrium ions are replaced by neodymium ions (Nd).

Cooling: Aside from the laser effect, further processes take place in the laser rod which release a great deal of heat. The rod becomes hot and expands. There is a danger of the crystal exploding. For this reason, the laser rod must be cooled. The laser rod is thus surrounded by a glass tube – the "flow tube" – through which cooling water flows or else the entire cavity is flooded with cooling water. As a result, the Nd:Yag rod is constantly cooled on the surface.

Optical stimulation: Nd:YAG lasers are pumped optically, for example, with krypton arc lamps. The stimulating lamps of the laser are supplied with the control's set electrical power from the laser's power supply. A change in the stimulating power results in a direct change of laser power. Various pulse forms in the stimulating light can be obtained using the control.

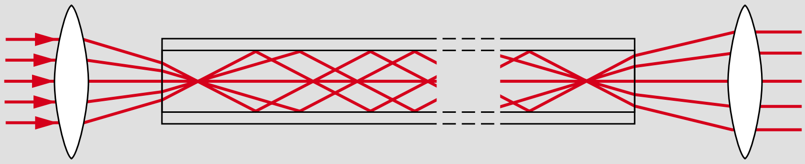
Recently, diode pumped solid-state lasers have become a much discussed topic. In these systems, the laser-active material is stimulated with the help of semi-conductor lasers, also known as diode lasers. Diode pumped solid-state



A double elliptical cross section ensures that the stimulating light is efficiently coupled into the laser rod.

Fiber optic laser cables

Fiber optic laser cables consist of a core (optical fiber), a sheath, and a protective covering. The core material has a higher refractive index than the sheath material.



Structure of a fiber optic cable

The light beams which strike the boundary between the core and the sheath are reflected in the core. As long as the fibers are not sharply bent, the light beams can be reflected from one side to the another.
The laser beam must be focused onto the polished end of the optical fiber for transmitting with fiber optic laser cables. After emerging from the optical laser cable, the laser light is aligned in a parallel direction and focused onto the processing point.

lasers are highly efficient, have a long service life, and a small volume – characteristics which make them ideal for material processing. Advances in semi-conductor laser technology in the future will also lead to innovations in solid-state laser technology.

Power regulation: The stimulating or flash lamps deteriorate with time. This means that the intensity of the stimulating light and thus the laser power are dependent on the age of the lamp. Industrial users of Nd:YAG lasers, however, must be able to regulate the power precisely. Only this guarantees good, reproducible processing results. Nd:YAG lasers used in industrial applications, should provide a form of power control.

Beam quality: The beam parameter product q is usually used for characterizing the focusability of a Nd:YAG laser beam. It is calculated from the optical divergence and the beam diameter at the beam waist and remains constant during the entire beam propagation, even when the beam is guided through lenses or reflected by mirrors.

The smaller the beam parameter product of a laser beam, the better the beam quality and the better the beam focusability.

Nd:YAG lasers for material processing attain beam qualities of q ~ 4 mmmrad at power levels up to 100 W. At higher power levels, thermal effects have a greater influence and hence reduce the beam quality.

Beam delivery: The wavelength of the Nd:YAG laser in the near infrared zone makes it possible to use components made of glass for the beam delivery. Among the components used are mirrors, deflectors, beam splitters, observation optics, energy and performance meters as well as fiber optic laser cables.

Fiber optic laser cables turn Nd:YAG lasers into highly flexible tools. In industrial use, fiber optic laser cables are particularly interesting for the following reasons:

- The laser beam can be guided over very long distances without any significant energy loss. Only at the point of beam entry or exit are there small losses (max. 8 %).
- Fiber optic laser cables with a protective sheath are approx. 10 mm thick, and can be bent to a minimum radius of a few centimeters. They can be installed easily.
- Fiber optic laser cables can be adapted to the spatial conditions. The laser can be set up at a remote site away from the processing area. It can be quickly modified. Areas which are difficult to access can be processed. 3D processing is simple.
- Deflectors and beam splitters can divert the laser light to various processing stations.
- Input and output optics are attached by screws. They do not require adjustment.

Nd:YAG laser rod

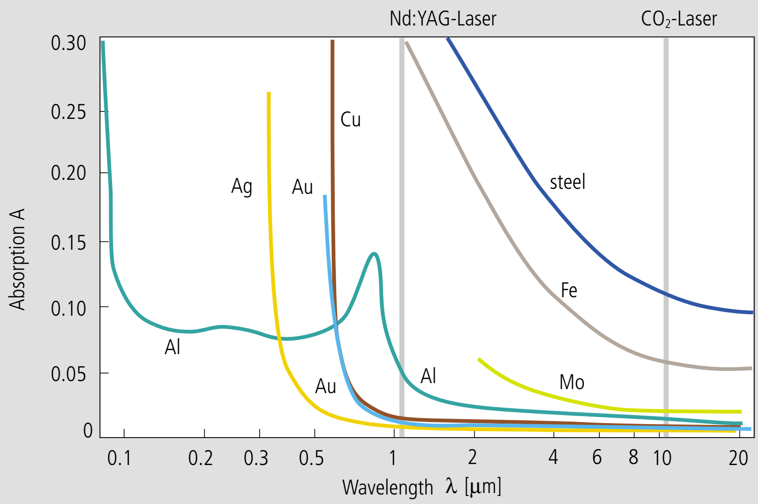
Outlook

The history of laser technology is and will remain a history of breakthroughs and fast-paced developments. A few trends in material processing for the next years are already emerging:

- The maximum power output of CO_2 industrial lasers as well as Nd:YAG industrial lasers will continue to increase (CO_2 lasers: up to 40 kW and more; Nd:YAG lasers: 5–6 kW in cw mode).
- Advances in semiconductor lasers will have a profound effect on the market. Semi-conductor lasers – often referred to as diode lasers – can be used as a pump source in solid-state lasers which will lead to innovations in solid-state laser technology. Furthermore, the direct use of high-performance diode lasers is conceivable in material processing.
- The increase in Nd:YAG laser performance will pose an even greater challenge to CO_2 lasers in a growing number of areas. The ability to deliver the beam using fiber optic cables makes Nd:YAG lasers particularly interesting for three-dimensional applications.
- The most important laser applications (cutting, welding, and marking) will continue to play a leading role. Lasers will be used as a tool in more and more areas. Particularly laser bending and laser forming will become common.

Nd:YAG laser with 4 cavities and 2 kW power

Absorption coefficients of metal



When the laser light strikes the material, only a part of the beam is absorbed. On the one hand, the degree to which the light is absorbed depends on the material itself. On the other hand, it is also dependent on the wavelength of the laser light. The beam of Nd:YAG lasers is absorbed more efficiently than that of CO_2 lasers. This is an important fact to consider when processing precious metals, copper, and aluminum.