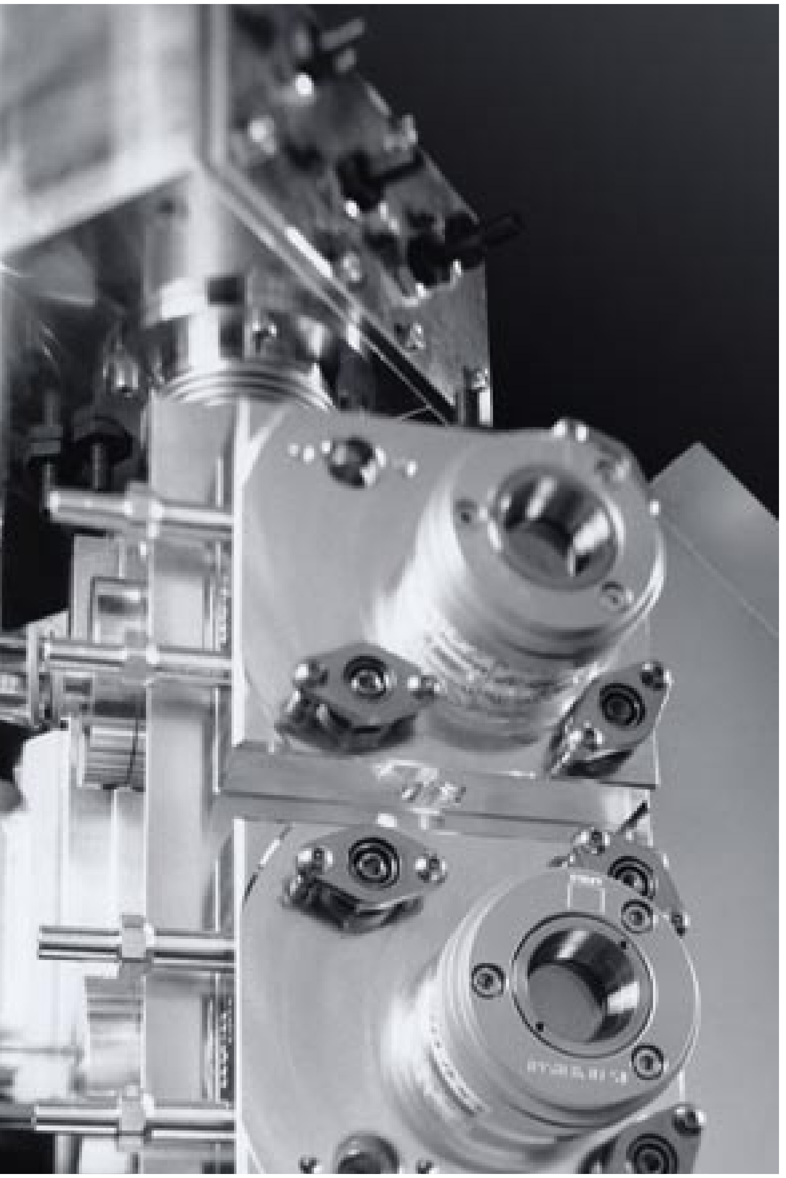
From the beam source to the workpiece

1 Close-up of a CO_2 laser: on the lower right, you can see the output mirror through which the laser beam exits the beam source.

"I wish we had detectors that could measure the beam and detect its position without altering the beam. As it is, however, we literally have to work blind, without seeing what we are shaping and guiding. It's not until the end that we can see the effect of the focused laser beam on the workpiece and tell whether everything's been done right. Before that, the beam is invisible." *Jürgen-Michael Weick, Development and Design*



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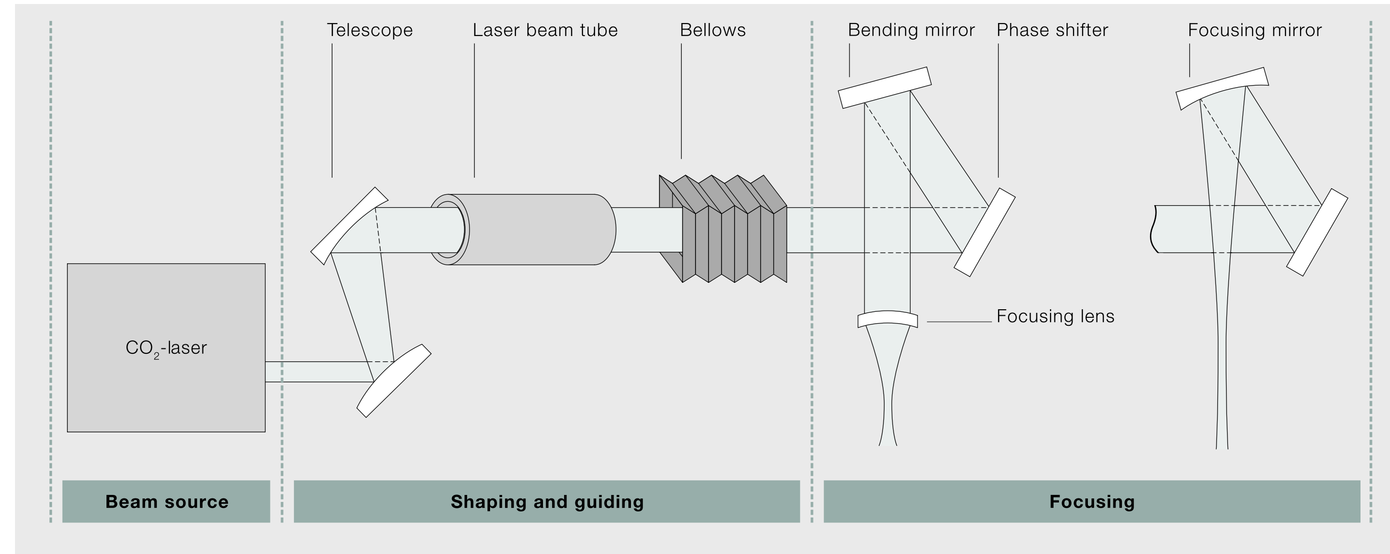
Light flashes, metal hisses, and sparks begin to fly. Cuts are made. Joints are sealed. Marks become visible. The moment the focused laser beam strikes a precise point on the workpiece, it has all the properties needed to perform a particular task. Yet, how does the beam get from point A to point B? And what allows it to be used as a tool?

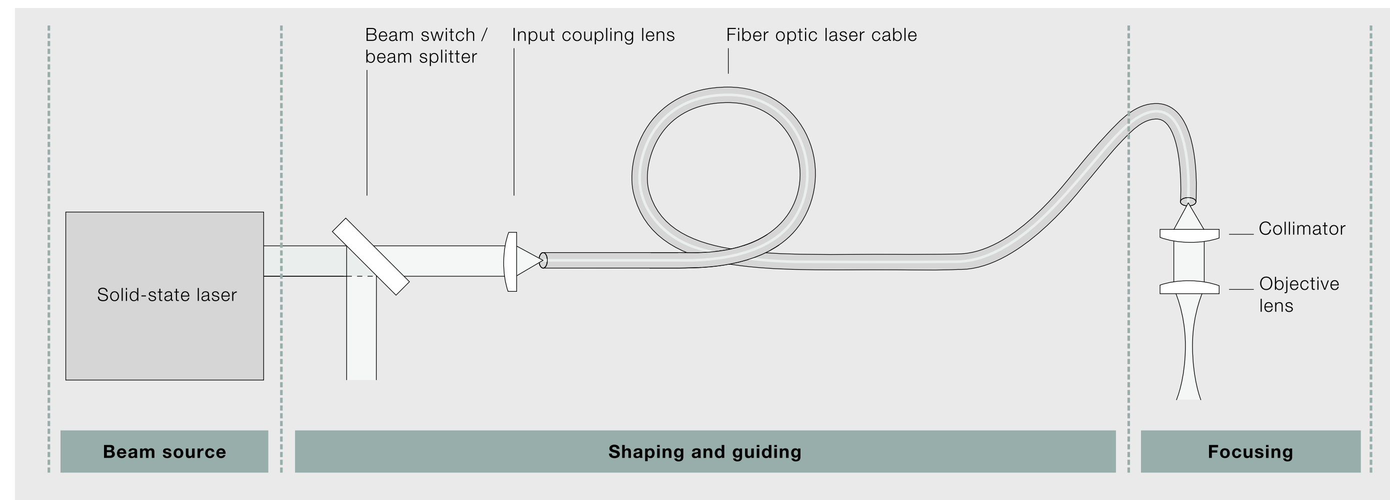
On its way from the beam source to the workpiece, the laser beam is shaped, guided, and finally focused. It passes through a series of different components, depending on the laser type and processing task involved:

- Laser beam tubes and bellows, which encase and shield the laser beam off
- Fiber optic laser cables that are capable of guiding the beam of a solid-state laser flexibly to any point within an entire production facility
- Flat mirrors for bending the laser beam or directing the beam to several workstations
- Partially reflecting mirrors for splitting the laser beam
- Curved mirrors for shaping and focusing
- Lenses for shaping and focusing
- A frequency doubler, if needed, to change the wavelength of the solid-state laser
- A phase shifter, if needed, to change the direction of oscillation of the CO_2 laser light

The right physical model | Laser engineers rely on physical and mathematical models to calculate the beam delivery and processing optics. One such model is geometric optics.

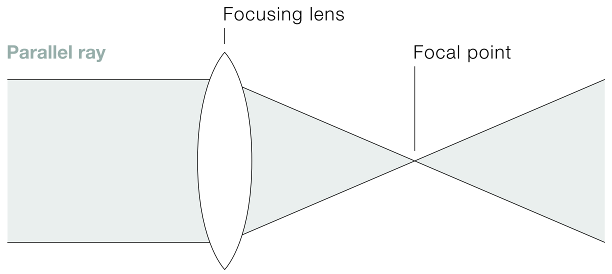


The laser beam of a CO_2 laser is usually expanded, routed through tubes or bellows, and finally focused with mirrors or lenses.

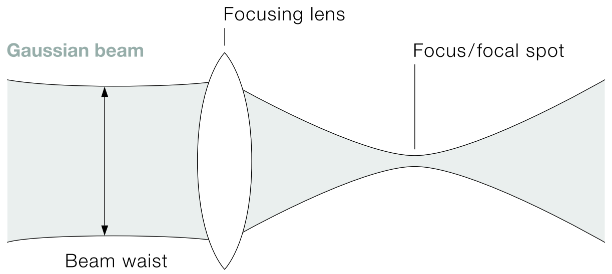


The laser beam of a solid-state laser is usually routed to the workstation in a fiber optic laser cable and focused using lens systems.

„Sometimes people ask me why a focused laser beam has a focal spot and not a focal point and whether the difference is really all that significant. That's when I give them a very pragmatic answer: a focal point is a mathematical term. By definition, it is infinitely small and dimensionless. However, kilowatts of laser power cannot flow through an infinitely small point. The laser beam, therefore, has a finitely small focal spot."
Peter Schäfer, Process Development



Geometric optics: in this case, an ideal parallel ray can be focused to an infinitely small focal point.



Gaussian optics: a real laser beam has a beam waist and can only be focused to a finitely small focal spot.

The formulas of geometric optics are used in calculating such things as the necessary lens, image size, and the zoom factor in a camera. A fundamental concept is that of "parallel rays." In geometric optics, the rays in a beam of light are considered to be perfectly parallel. When focused, all light rays intersect at a single focal point, which is dimensionless and infinitely small.

For laser technology, geometric optics is only a simple approximation that is usually unable to describe reality with sufficient accuracy. That's why laser physicists and engineers use Gaussian optics to calculate the components used in the beam delivery and processing optics.

Gaussian optics describes the laser beam as a Gaussian beam. The laser beam converges, becoming progressively narrower until it reaches its smallest diameter, called the beam waist. Here, the light waves are parallel. Farther on, in the near field, the laser beam begins to spread out again. It diverges until it attains a constant divergence angle in the far field. The divergence angle depends on the beam quality and diameter of the beam waist. The divergence decreases as the beam quality and beam waist increase. Focusing involves concentrating the laser beam. The part with the smallest beam diameter is the focus, or focal spot.

A question of wavelength | Materials respond differently to certain wavelengths. As a result, the wavelength of the laser beam determines which components and materials can be used in the beam delivery and in the focusing optics. Here's an example: quartz glass, also called fused silica, is transparent to the wavelength of solid-state lasers, but not to the wavelength of CO_2 lasers. This is the reason why the light of solid-state lasers can be guided through glass fibers, while that of CO_2 lasers cannot.

A selection | In the following, we'll take a look at the typical components required for beam delivery and control as well as the processing optics for focusing, as employed in CO_2 and solid-state lasers. Besides these parts, you can find a great deal of other components whose design can vary from manufacturer to manufacturer.

KILOWATTS OF POWER IN FINE FIBERS

Laser with beam splitter, fiber optic laser cable, and optics from 1985

Fiber optic laser cables connect solid-state lasers to the workstations. Today, the bright yellow cables are an everyday sight. Back in 1985, though, they were black and still a sensation. Paul Seiler, former president of TRUMPF Laser GmbH + Co. KG in Schramberg, Germany, recalls: "Before fiber optic laser cables appeared, the laser unit and workstation were connected via a fixed, rigid beam guideway and located right next to each other. When we came out with the first generation of fiber optic laser cables in 1985, it was an enormous step forward with far-reaching consequences."

Physicists and engineers worked for several years to develop the first fiber optic laser cables. Transporting laser light in glass fibers was already known from telecommunications. Nevertheless, with a diameter of 20 micrometers, these fibers were much too thin to transport laser beams with a pulse power of several kilowatts. Paul Seiler: "We needed thicker fibers with a diameter of several hundred micrometers. That's why we never speak of "optical fibers," but rather "fiber optic laser cables." Many other components were needed in order to transform the fibers into industrially viable cables. Fibers were first enclosed in durable outer sheaths to protect them from damage. Components were developed for coupling and extracting the laser light. Connectors joined the laser device and optics: it was a simple, elegant, and highly precise solution.

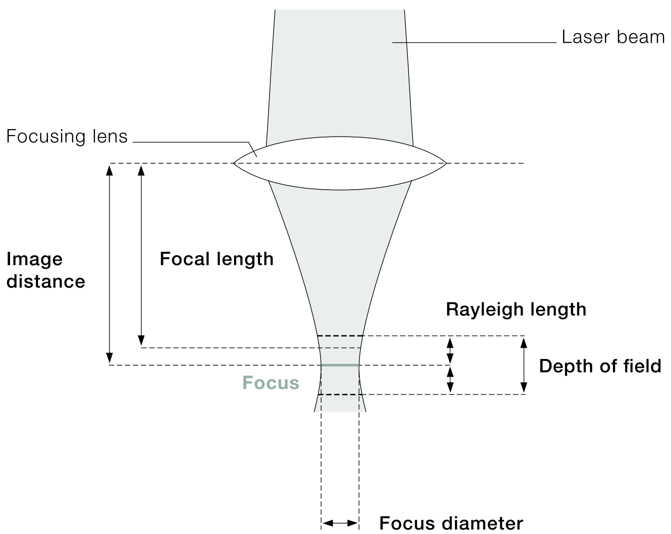
The production of the first fiber optic laser cable gave a jolt to the laser market. Laser light could now be transported flexibly over several meters. The laser beam of one beam source could be split and directed via fiber optic laser cables to multiple optics for tasks such as producing several weld points simultaneously. Beam switches made it possible to couple the laser light into different fiber optic laser cables. Paul Seiler remembers: "Switching between multiple workstations made solid-state lasers more economical. Also, the flexible fiber optic laser cables could be combined with robots. As a result, solid-state lasers were able to compete with CO_2 lasers, and the construction of large, high-power laser devices began."

The success story continues: standardized connectors make it possible to connect lasers and workstations from different manufacturers worldwide. The standard is the fruit of collaboration between laser users and laser manufacturers. "One thing is certain," says Paul Seiler, "Fiber optic laser cables will continue to be a vital part of solid-state laser technology into the future."

Getting to the point: focusing

At the end of the beam delivery, the laser beam enters the processing optics. They transform the beam into a tool for use in different processes by adapting the beam properties. The focus diameter, depth of field, image distance, and power density are precisely tailored to each process. For this reason, materials processing involves the use of different processing optics. While they all rely on lenses or mirrors to focus the laser beam, their individual characteristics depend on the process and machine for which they will be used.

In the following, we'll examine the physical fundamentals that apply to all processing optics and then look at examples of some of the these optics.



Transforming a laser beam into a tool: the focusing principle and the most important laser beam parameters

PHYSICAL FUNDAMENTALS

When focused, the laser beam is concentrated on a tiny focal spot. At the focus, the power density is several orders of magnitude higher than that of the raw beam. The laser beam is now able to process material.

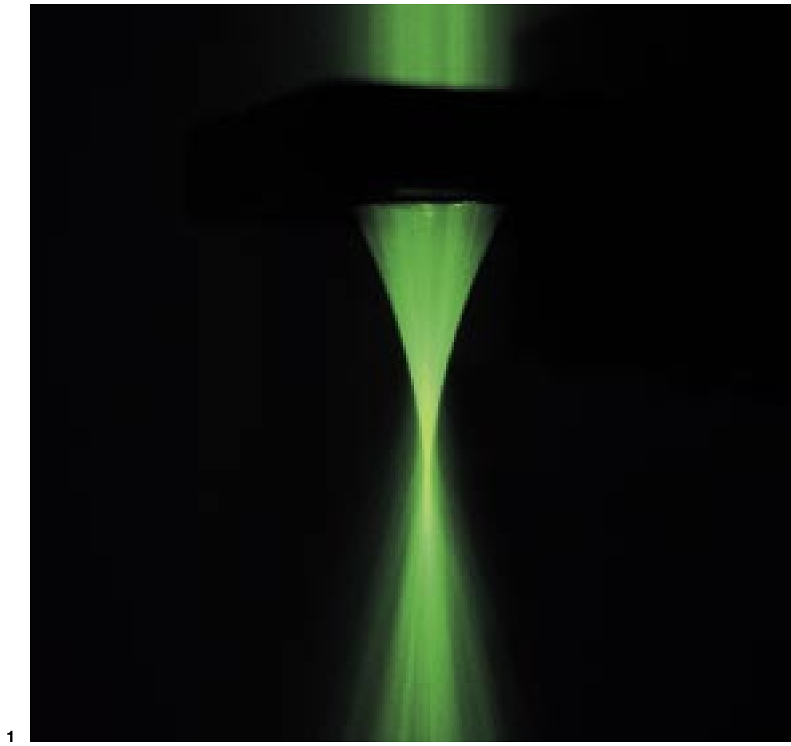
Mirrors or lenses focus the laser beam by deflecting and concentrating it by reflection or refraction. Certain parameters are used to describe the focused beam. The following parameters are crucial for materials processing.

- **Focus diameter |** The smaller the focus diameter is – that is, the greater the beam is focused – the higher the power density at the focus is. The power density has to be tailored to the process. Another important aspect of this parameter: a smaller focus diameter allows finer processing of the material.
- **Rayleigh length |** After the focus, the beam begins to spread out. The Rayleigh length indicates the distance from the focus at which the cross-sectional area of the beam is doubled. A longer Rayleigh length means a smaller degree of divergence. Two times the Rayleigh length is frequently referred to as "depth of field." Long Rayleigh lengths are needed for applications, for instance, that involve cutting thick sheets.
- **Image distance |** The image distance is the distance from the lens center to the focus. It corresponds approximately to the focal length. As the image distance increases, so does the standoff, i.e. the distance between the lens and workpiece. Some processes such as welding with scanning optics require a large standoff.

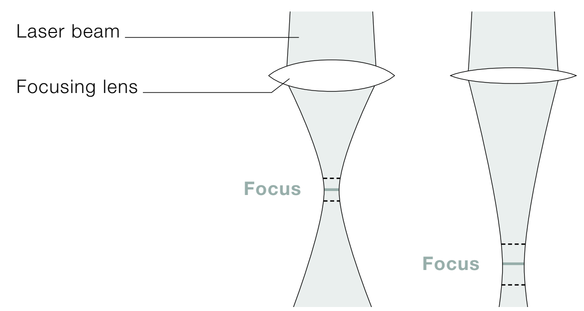
Many influencing factors determine the values of these parameters. The following are especially important:

Putting sunlight to work Remember using a magnifying glass to focus sunlight onto a piece of paper when you were a kid? The principle is simple: the magnifying glass concentrates the light on a small focal spot. At the focal spot, the power density is so high that the paper begins to burn. The only reason this works is because the sun is so far away from the earth: the light rays concentrated by the magnifying glass are nearly parallel and, thus, easy to focus.

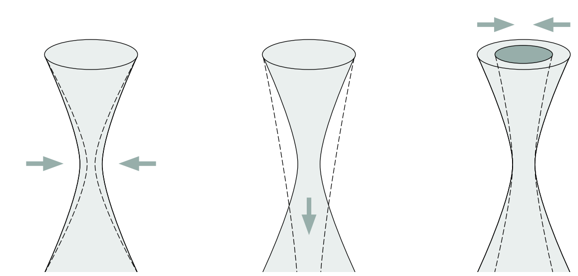
- **Focal length |** The focal length of the lens or focusing mirror refers to the distance from the lens center or the mirror to the focal point of an ideal parallel ray. The smaller the focal length is, the greater the beam is focused and the smaller the focus diameter, Rayleigh length, and image distance are.
- **Beam quality |** The beam quality has an effect on the smallest possible focus diameter and the Rayleigh length. A higher beam quality makes it possible to produce smaller focus diameters. In addition, the Rayleigh length is longer while the focus diameter remains the same.
- **Divergence |** The divergence angle of the laser beam affects the image distance. As the divergence angle increases, the image distance becomes greater with respect to the focal length. When the divergence angle is negative (convergence), the image distance is smaller than the focal length.
- **Beam diameter |** The diameter of the beam waist before the lens influences the focus diameter. A larger beam diameter means a smaller focus diameter.



1 Light beam: this green, focused laser beam clearly demonstrates the divergence characteristic of laser light.



A shorter focal length (left) produces a smaller focus diameter with shorter image distance, shorter Rayleigh length, and less depth of field.



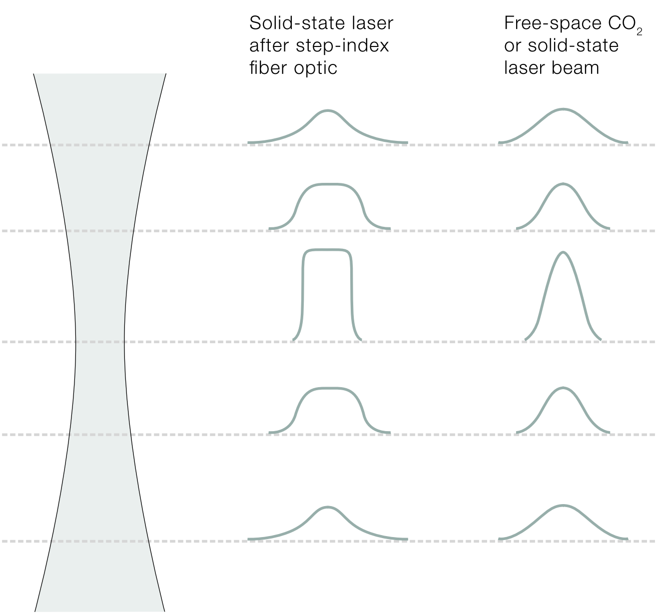
Higher beam quality enables a smaller focus diameter with the same focal length (left), a greater standoff with the same focus diameter (center), and a smaller beam diameter on the lens (right).

Depth of field versus depth of focus Depth of field is a familiar concept in photography. Some photographers, however, also use the older term "depth of focus" to mean the same thing. In laser technology, too, both terms are often used as synonyms, even though they have slightly different meanings. Depth of field is the degree to which the laser beam diverges after the focus; depth of focus is the distance over which the focused laser spot has a constant diameter. The Rayleigh length or two times the Rayleigh length is often used as a measure of beam divergence after the focus. However, no standard definition exists.

For materials processing, the processing optics must produce the right focus diameter with the required Rayleigh length and appropriate standoff. To design a set of processing optics, you first have to determine the quality of the laser beam. Once you know this, you can specify the properties of the optical components in the processing optics.

Focusing on the focus | The laser beam of solid-state lasers is usually guided through fiber optic laser cables. When this is done, the mode of the beam source is lost, and the laser beam exits the fiber with a homogeneous power density. Focusing produces an image of the fiber end that is as sharp as possible. At the focus, the power density is also homogeneous. Owing to its shape, the power density profile is called a "top hat." The laser beam loses its focus before and after the focal point.

In free-space laser beams, the mode of the beam source is maintained throughout the beam delivery. CO_2 laser machines are examples of such systems. At the focus, the power density profile also corresponds to the mode of the beam source.



Focusing on the focus: comparison of different power density distributions

OPTICS: MORE THAN MIRRORS AND LENSES

Lenses or mirrors shape the laser beam, this being the most important task of the processing optics. In addition to focusing, however, the optics perform a variety of other jobs:

- They supply the auxiliary materials that are needed for the process; for example, gas for cutting or welding or filler materials for welding.
- They include sensors for process control; for example, standoff control during laser cutting or process monitoring during laser welding.
- They provide interfaces to the machine and the machine control; for example, power connections, cooling water connections, and data interfaces.
- They include devices that prevent dirt and dust from settling on sensitive lenses or mirrors; for example, protective glass or crossjets (streams of air that deflect spatter).
- They can also include power meters and a pilot light, which aids in setting up the machining process and is often referred to as a "teaching aid".

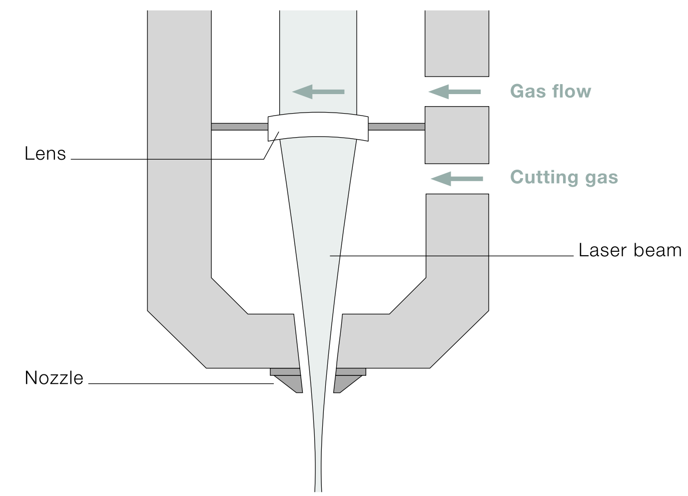
The design of processing optics is equally extensive and varies from manufacturer to manufacturer.

FOCUSING WITH LENSES

Lens optics are used for CO_2 lasers and solid-state lasers. They contain one or more lenses that focus the beam. The material of which the lenses are made must be transparent to the wavelength of the specific laser beam. Otherwise, the lenses will absorb the laser light and become warm, producing aberrations. At worst, this can cause damage to the lenses and processing optics. Therefore, CO_2 laser light is focused using lenses made of zinc selenide (ZnSe) or gallium arsenide (GaAs). In solid-state lasers, fused silica lenses are used. In the following, we'll look at different design variants of lens optics for cutting or welding.

With one lens | The simplest processing optics design involves the use of only one lens for focusing the laser beam. The cutting optics of a CO_2 flatbed laser cutting machine are a good example of such a design. The unfocused laser beam has a diameter of between 12 and 25 millimeters when it strikes the lens. The lens then focuses the beam, and the beam exits the nozzle together with the cutting gas. But the lens has yet another function to fulfill: it acts as a pressure seal, separating the area before the nozzle, in which there is a pressure of several bar, from the beam guideway in which the pressure is only 1 millibar over the atmospheric pressure. A stream of gas is blown over the lens to prevent particles from settling on its surface.

Compared to fused silica lenses, lenses made of zinc selenide and gallium arsenide have certain drawbacks: when they heat up, their refraction index changes to a greater degree than that of fused silica lenses. If they overheat, they can catch fire, releasing noxious particles, gases, or aerosols. Plus, they are expensive. That is why mirror optics are used for welding with high CO_2 laser outputs.



The lens optics of a CO_2 flatbed laser cutting machine

1 The cutting optics of a CO_2 flatbed laser cutting machine in action

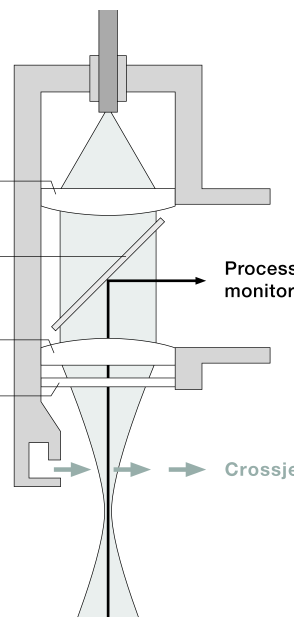
1 These lens cutting optics for solid-state lasers are equipped with automatic standoff control.

2 Lens welding optics for solid-state lasers

Plug and play Connecting the fiber optic laser cable to the beam source and machine is incredibly easy: all the user has to do is plug it in. The components are designed so that they are automatically centered when plugged in. Simply connect the cable, and the job is done.

Two lenses | Processing optics for solid-state lasers are very compact and typically include two lenses. After emerging from the fiber optic laser cable, the laser beam passes directly into the optics. The first lens, called a collimator, makes the beam parallel. The second lens, called the objective lens, is used to focus the beam.

A bending mirror or partially transmitting mirror can be placed in the collimated beam between the two lenses, enabling an angular optics design. In addition, sensors can be set up so that they use the mirror to “look” into the beam delivery of the laser. This allows direct viewing of the machining point for purposes such as monitoring the welding process.



Working with two lenses: welding optics for solid-state lasers

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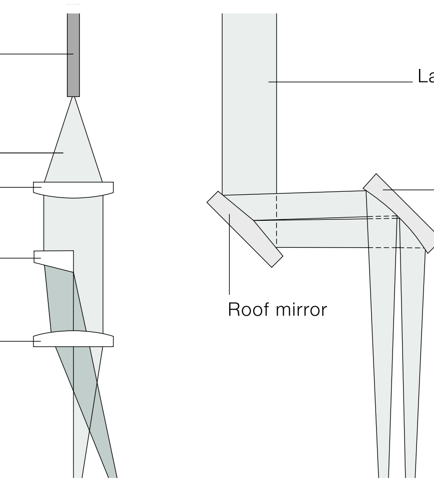
Protective glass shields the lens from any spatter that may arise during processing. A stream of air called a crossjet also keeps spatter off the protective glass.

Cutting optics have a pointed nozzle from which the cutting gas and laser beam exit together. During cutting, the distance between the nozzle and workpiece must remain constant. For this reason, some cutting optics are equipped with an active sensor system. The sensor continuously measures the distance between the nozzle and workpiece, making adjustments as necessary. This is done either by raising or lowering all of the cutting optics or by moving only the front section with the objective lens and nozzle.

Foci or focuses? “Focus” has two acceptable plural forms in English: the English plural “focuses” and the Latin plural “foci.” The same is true of words like “cactus” (cactuses, cacti), “fungus” (funguses, fungi), “nucleus” (nucleuses, nuclei), “radius” (radiuses, radii), and even “hippopotamus” (hippopotamuses, hippopotami). Like “fungi, ”the plural “foci” also has two acceptable pronunciations: “fō’kī” and “fō’sī.” The choice of plurals tends to create uncertainty about which form to use and when. In some contexts, the English plural may sound uneducated; in others – like talking to your buddy at the bar – a Latin plural may come across as being overly pedantic, unnatural, or pretentious.

Multiple foci | Some applications such as double seam welding require two or more foci.

The foci can be created in different ways using lens optics. One way is to split the beam in the optics and then focus it. This is done by introducing a fused silica wedge in front of the collimator or in between the collimator and the objective lens. The wedge refracts a part of the beam, thus resulting in two partial beams. The objective lens focuses both of them. Two foci with circular cross sections are produced on the workpiece, each of them an image of the fiber end. The slope of the wedge is used to control the distance between the focal center points. Multiple foci can also be produced by focusing the laser beams from two or more fiber optic laser cables in one set of optics. This method enables higher outputs at the machining point.



A double focus can be created in different ways: using a fused silica wedge in lens optics (left) or using a roof mirror in mirror optics (right).

More than one focus can also be produced with mirror optics: the laser beam is split using a bending mirror with two sloping surfaces called a roof mirror. After that, the focusing mirror focuses the two partial beams.

Diffractive optics represent a different approach. They function similar to a hologram and are able to produce any number of foci of any desired shape by diffracting the laser beam. Up to now, diffractive optics have found little application in industrial processing. The reasons: the farther the focus pattern is from the optical axis, the greater the degree of aberration. Moreover, a greater amount of energy loss results when high laser outputs are involved.

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