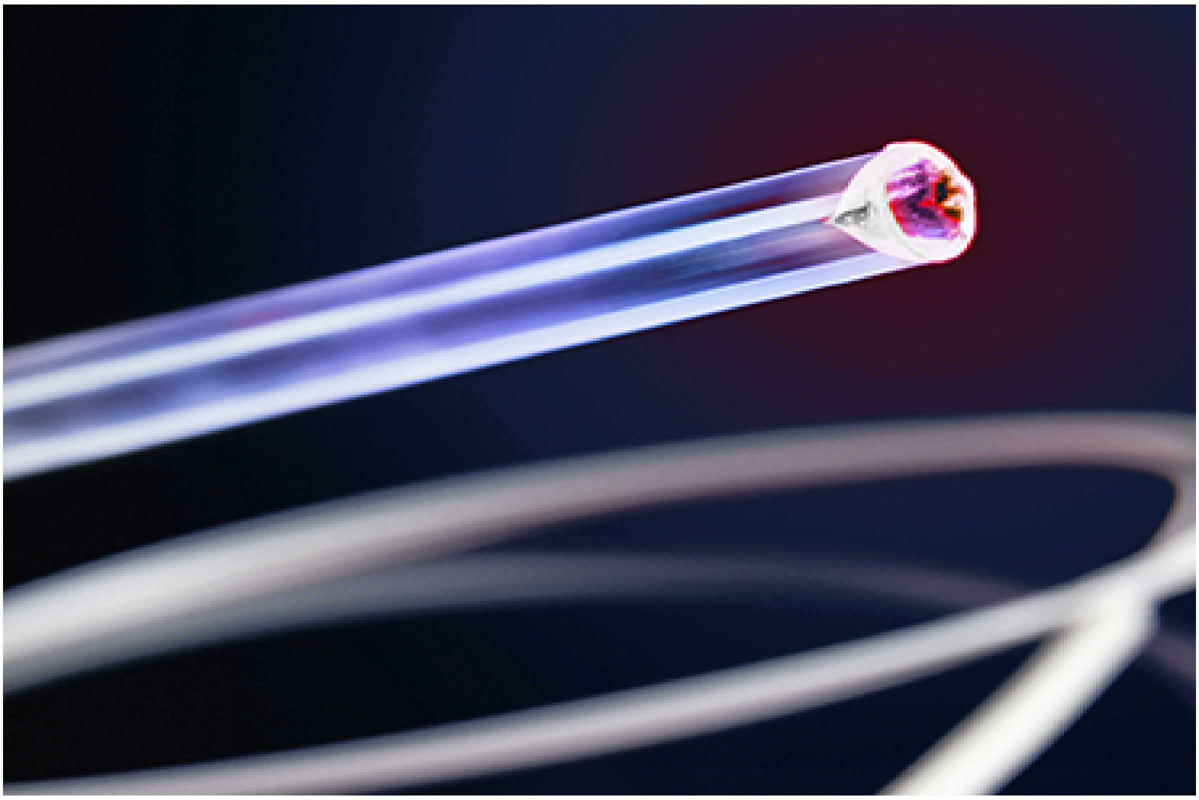

Pure fiber Lasers and Its Applications

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CONTENTS

A] STRUCTURE OF FIBER LASERS

A.1] The Optical fiber

The basic building block of fiber laser technology is the optical fiber. An optical fiber is a long cylindrical piece of highly transparent glass. Typical fiber core diameters range from a few microns to hundreds of microns, while lengths range from meters to many kilometers. The huge aspect ratio of the fiber length versus diameter is responsible for many of the unique properties of fiber lasers. The glass fiber is an optical waveguide able to contain and propagate light with negligible loss. When the total internal reflection condition is satisfied, light propagates inside the fiber with negligible radiative losses through the wall of the fiber. Optical fibers are classified as :

1) Passive fibers transport light
2) Active fibers introduce amplification by mixing the propagating light with pump laser light in the presence of rare earth metal ions embedded in the fiber core.

The fiber laser is a variation on the standard solid-state laser, with the medium being clad fiber rather than a rod, slab, or a disk. Laser light is emitted by a dopant in the central core of the fiber, and the core structure can range from simple to fairly complex. A key factor for fiber lasers is that the fiber has a large surface-to-volume ratio so that heat can be dissipated relatively easily.

Fiber lasers are optically pumped, most commonly with laser diodes but in a few cases with other fiber lasers. The optics used in these systems are usually fiber components, with most or all of the components fiber-coupled to one another. In some cases, bulk optics are used, and sometimes an internal fiber-coupling system is combined with external bulk optics.

A.2] The Diode Pump

Th Diode pump technology leverages the vast telecommunication industry experience. The single emitter diodes are manufactured using telecom-proven technology and processes, and each wafer is qualified to rigorous telecommunication industry standards, which sets apart from alternative industrial pump products using short-lived diode bars and bar-stack technologies. As a result, single emitter diodes offer an order of magnitude higher pumping brightness and up to double the power efficiency of bar-stack pumps. Single emitter pumps are able to use simple water or even forced air cooling, as opposed to bars-stacks which require expensive, unreliable and complex microchannel coolers using high pressure deionized water.

A diode pump source can be a single diode, an array, or many separate pump diodes, each with a fiber going into a coupler. The doped fiber has a cavity mirror on each end; in practice, these are fiber Bragg gratings, which can be fabricated within the fiber (see Fig. 1). There are no bulk optics on the end, unless the output beam goes into something other than a fiber. The fiber can be coiled, so the laser cavity can be many meters long if desired.

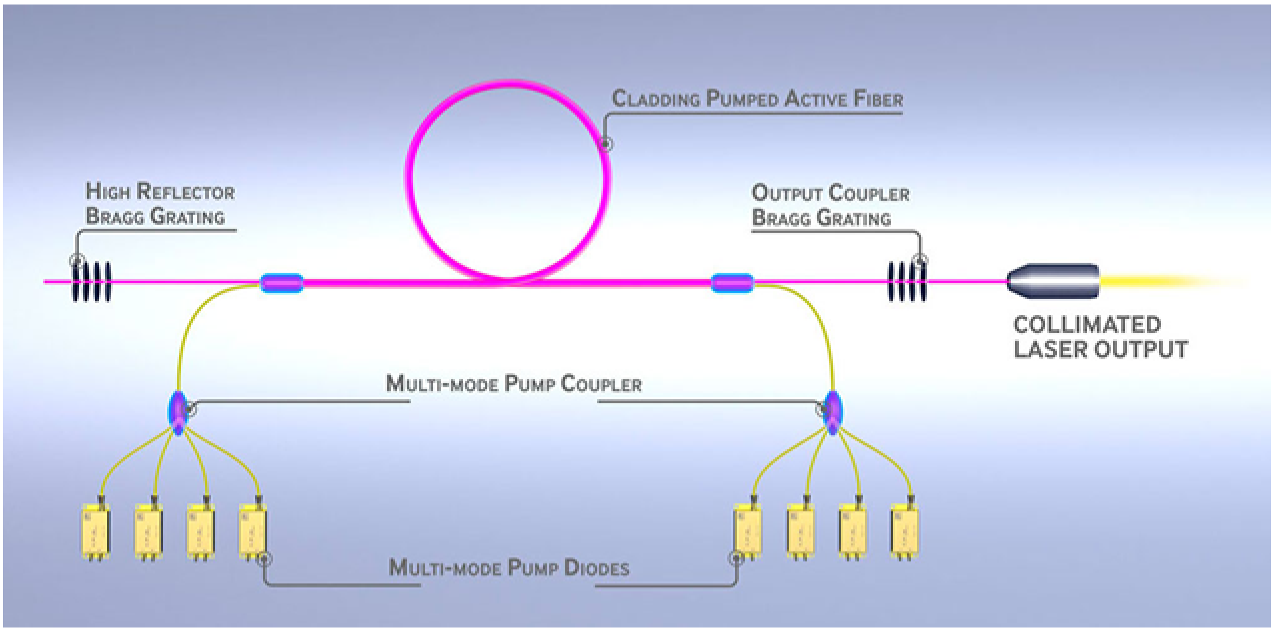


Figure 1: Fiber Laser-The State of the Art

A.3] Dual-core structure

The structure of the fiber used in fiber lasers is important. The most common geometry is a dual-core structure (see Fig. 2 & 3). An undoped outer core (sometimes called an inner cladding) collects the pump light and guides it along the fiber. Stimulated emission generated in the fiber passes through the inner core, which often is singlemode. The inner core contains the dopant (ytterbium or erbium) that is stimulated to emit radiation by the pump light. Numerous noncircular variations exist on the shape of the outer core; these shapes, which include hexagonal, D-shaped, and rectangular, decrease the chances of the pump light missing the central core.

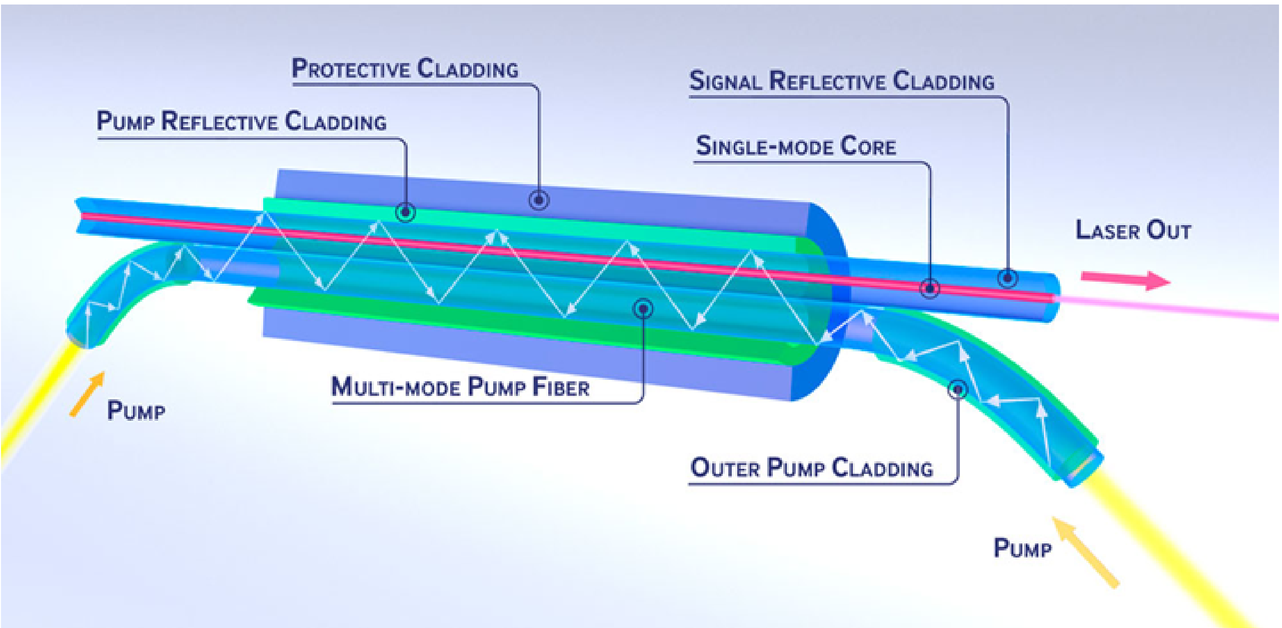


Figure 2: Structure of a fiber laser

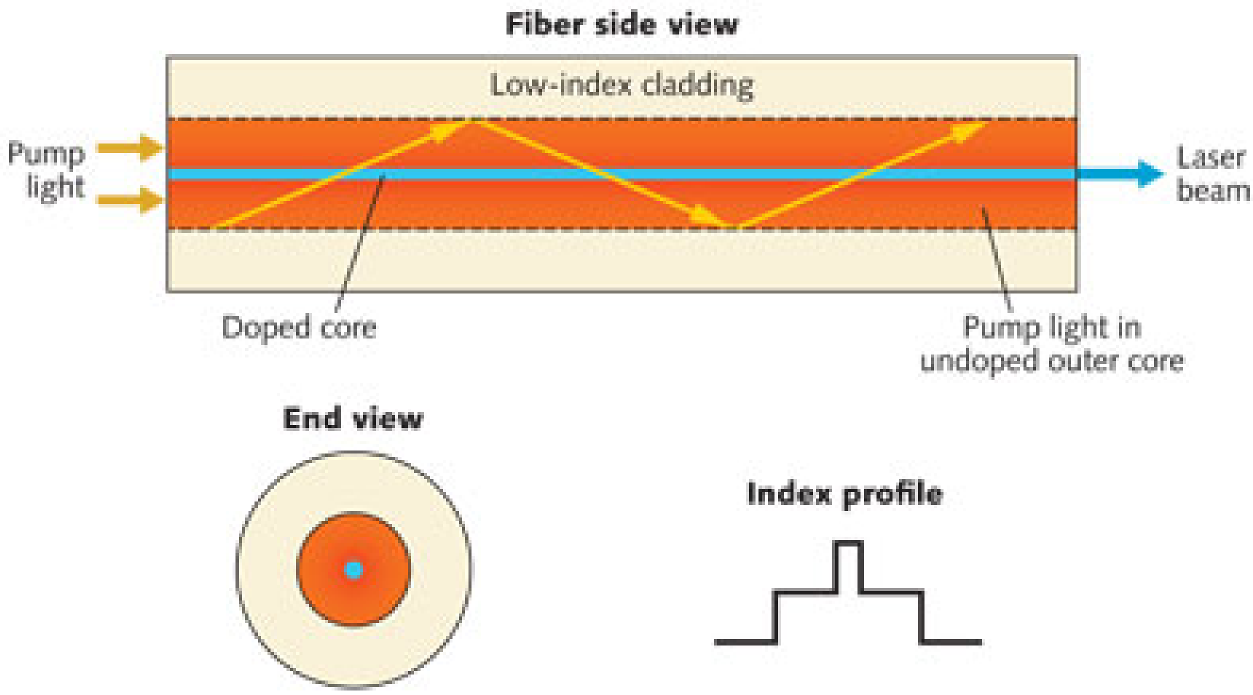


Figure 3: The structure of a fiber laser includes a doped inner core, which is the laser itself; an undoped outer core (also called an inner cladding) through which the pump light is channeled; and an outer cladding.

The fiber's unique properties make it an ideal active gain medium and laser resonator material. It is flexible and easy to handle. Fibers of different types, compositions and core diameters can be spliced to construct complex optical systems combining the pump sources, optical amplification and beam delivery fiber without the need for free space optics and their inherent risks of contamination, damage and or misalignment. The fiber is a hugely flexible medium which enables a vast variety of design options and functions. Examples of specialty optical fiber types are single-mode and multi-mode fibers, photonic crystal fibers, and fibers composed of diverse materials whose optical properties vary in both the axial and radial dimensions. Of particular importance to fibers used for cladding pumping, consist of a single-mode core, used as active gain medium, surrounded by a larger diameter optical waveguide for propagating multi-mode diode pump light.

A.4] Cladding Pumped Technology

A fiber laser can be end- or side-pumped (see Fig. 4). In end-pumping, the light from one or many pump lasers is fired into the end of the fiber. In side-pumping, pump light is coupled into the side of the fiber; actually, it is fed into a coupler that couples it into the outer core. This is different from side-pumping a laser rod, where the light comes in orthogonally to the axis.

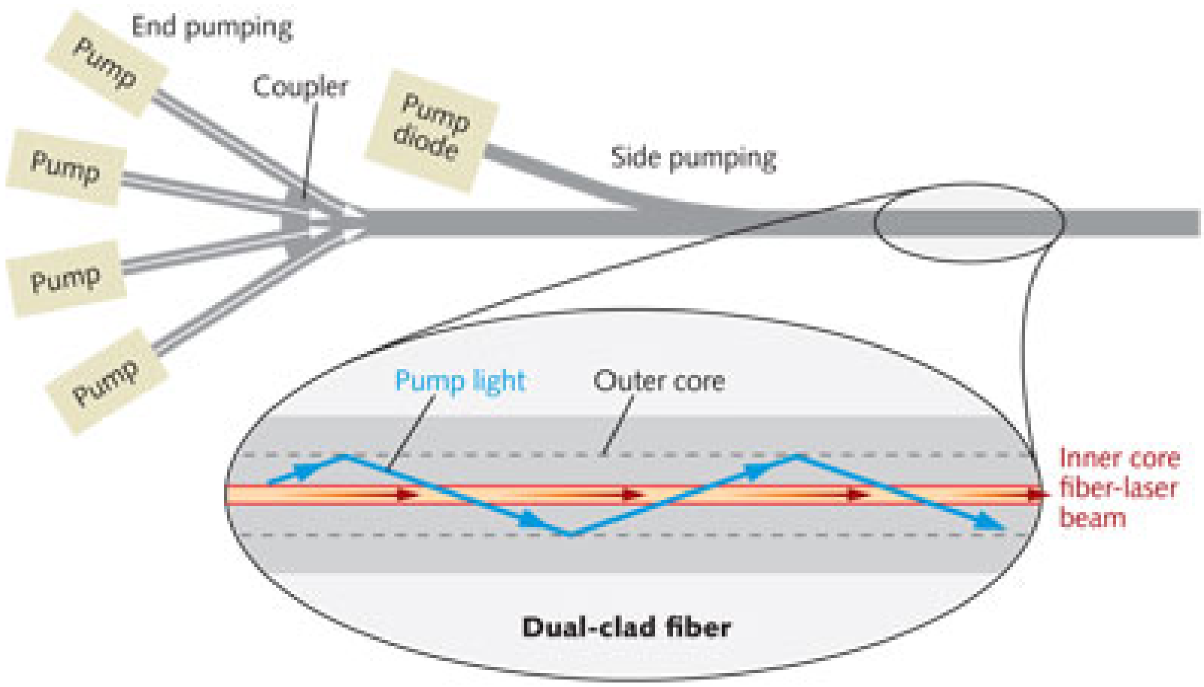


Figure 4 : A fiber laser can be end-pumped with one or many lasers, or side-pumped (usually with many lasers) by side-coupling pump light into the outer core.

The multi-mode output of broad-area single emitter diodes is collected into fibers with core diameters as small as 100 microns. Using the side-pumping technique developed by Dr. Valentin Gapontsev and Dr. Igor Samartsev, the light from many pump diodes is efficiently coupled into the cladding of an active gain fiber. The pump light undergoes multiple reflections within the cladding while frequently intersecting the single-mode core, where the pump is absorbed and re-emitted by rare-earth ions (see Fig 5). This elegant mechanism brightness converts multi-mode diode light into single-mode fiber laser light with exceptional efficiency.

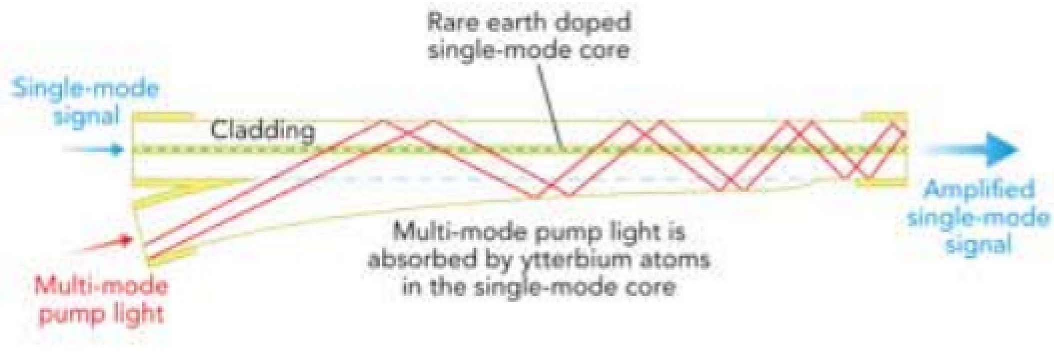


Figure 5 : Basic construction of an active fiber in the fiber laser

The title "rare earths" came about because at the time of their discovery they were indeed thought to be rare. Recent discoveries have shown that the ores of these elements do occur in many places worldwide, although there are some concerns over supply as much of the current reserves occur in Chinese territory in Inner Mongolia. These rare earth elements make up the upper of the two lines at the base of the periodic table of elements. These 15 elements belong to the group known as the lanthanides because of their chemical similarity to the element lanthanum. The rare earth active element in most widely used fiber lasers is ytterbium, named for the small Swedish village of Ytterby close to where large deposits of this and a number of other rare earth ores were first found. The complex electronic structure of ytterbium allows efficient generation of coherent photons when this element is carefully distributed within the core of the laser, the active fiber.

The difference between a fiber laser and other free-space laser marking with fiber lasers technologies are widely misunderstood and sometimes misrepresented. In a fiber laser the beam is actually generated within the fiber. In other technologies, the beam is generated in free space and is then squeezed into a fiber-optic cable to be delivered to the workpiece.

A.5] Single Emitter Pump Advantages

Single emitter diode lifetimes exceed 100,000 hours, about an order of magnitude longer than the measured lifetimes of bar-stack alternatives.

Unlike traditional alternatives, frequent on/off modulation of diodes does not affect anticipated lifetime. Pumps are hermetically sealed to telecom standards, so are unaffected by the most aggressive industrial environments including humidity, dust and vibration. The exceptionally high reliability of single emitter pumps is proven in laboratories and substantiated by excellent field reliability.

Table 1: Comparative advantages of Single Emitter Pumping (SEP) architecture against Bar Pumping (BP)

Distributed Single-Emitter Pumping	Bar Pumping
Distributed single-emitter pump architecture that is free of the drawbacks of bar pumping.	Laser diode bars, also known as monolithic laser diode arrays, combine multiple emitters along a large area chip.
Single emitter pumps form an ensemble of independent individual elements.	Emitter count on a single bar varies from 10 to 100.
Contrary to bars, the failure of any number of single emitter pumps does not affect the performance and reliability of the remaining pump ensemble.	The bar architecture forces all emitters to share a common electrical current source and thermal management system. Thermal and electrical cross-talks seriously limit bar lifetimes and place severe constraints on their performance.
Distributed pumping's advantages include scalability, their modular design and flexibility, simple thermal management, virtually unlimited pump redundancy and ease of diode replacement.	The lifetime of a bar or a bar-stack is generally limited by its weakest emitter or an unreliable microchannel water cooling system.
Distributed pumping is alignment-free and is thus only truly service-free pump solution – a convenience only found in fiber lasers.	The inferiority of bar-based pumping schemes for lasers is a significant driver behind the rapid adoption of fiber laser technology over disk or rod-based solid-state lasers.

Table 2: Parametric Comparison of SEP v/s. BP

	Bar / Bar Stack (BP)	Single Emitter Pump (SEP)
Individual Emitter Output Power, W	1-2	6-10+
Coupling Efficiency, %	75 / 50	90-95
CW MTBF, hrs	5,000 - 10,000	> 200,000
QCW MTBF, hrs	2,000- 5,000	> 200,000
Wall-plug Efficiency. % (in fiber)	25-35	50-60

B] FEATURES OF FIBER LASERS

Using a fiber as a laser medium gives a long interaction length, which works well for diode-pumping. This geometry results in high photon conversion efficiency, as well as a rugged and compact design. When fiber components are spliced together, there are no discrete optics to adjust or to get out of alignment.

The fiber-based laser design is highly adaptable. It can be adapted to do anything from welding heavy sheets of metal to producing femtosecond pulses. Many variations exist on the fiber-laser theme, as well as some configurations that are not, strictly speaking, fiber lasers. Fiber amplifiers provide single-pass amplification; they are used in telecommunications because they can amplify many wavelengths simultaneously. Fiber amplification is also used in the master-oscillator power-amplifier (MOPA) configuration, where the intent is to generate a higher output from a fiber laser. In some circumstances, an amplifier is used even with a continuous-wave (CW) laser.
Another example is fiber-amplified spontaneous-emission sources, in which the stimulated emission is suppressed. Yet another example is the Raman fiber laser, which relies on Raman gain that essentially Raman-shifts the wavelength. This is an application that is not in wide use, although it is

certainly being used in research. In fact, some new research is going on into using fluoride glass fibers for Raman lasing and amplification rather than the standard silica fibers.

However, the fiber host is usually silica glass with a rare earth dopant in the core. The primary dopants are ytterbium and erbium. Ytterbium has center wavelengths ranging from about 1030 to 1080 nm and can emit in a broader range of wavelengths if pushed. Using pump diodes emitting in the 940 nm range can make the photon deficit very small. Ytterbium has none of the self-quenching effects that occur in neodymium at high densities, which is why neodymium is used in bulk lasers and ytterbium is used in fiber lasers (they both provide roughly the same wavelength).

Erbium fiber lasers emit at 1530 to 1620 nm, which is an eye-safe wavelength range. This can be frequency-doubled to generate light at 780 nm—a wavelength that's not available from fiber lasers in other ways. And finally, ytterbium can be added to erbium so that the ytterbium absorbs pump light and transfers that energy to erbium. Thulium is another dopant that emits even deeper into the near-infrared (NIR; 1750 to 2100 nm), and is thus another eye-safe material.

B.1] High efficiency

Fiber lasers are quasi-three-level systems. A pump photon excites a transition from a ground state to an upper level; the laser transition is a drop from the lowest part of the upper level down into some of the split ground states. This is very efficient: For example, ytterbium with a pump photon at 940 nm produces an emitted photon at 1030 nm-a quantum defect (lost energy) of only about 9% (see table 3).

In contrast, neodymium pumped on its standard 808 nm pump line has a quantum defect of about 24%. So ytterbium has an inherently higher efficiency, although not all that efficiency can be realized because some photons are lost. Ytterbium can be pumped in a number of bands. Erbium can be pumped at either 1480 or 980 nm; the latter is not as efficient from a photon defect point of view, but is useful even so because better pump sources are available at 980 nm.

Table 3: Photon Conversion Efficiencies

Active elements	Output	Pump bands	Photon conversion
Neodymium (solid-state)	1064 to 1088 nm	808 nm	76%
Ytterbium	1030 to 1100 nm	910, 940, 975 nm	>90% at 940/1030
Erbium	1550 nm	980, 1480 nm	95%, 63%
Yb-Er	Erbium	Ytterbium	
Thulium	1750 to 2100 nm	793 nm	2 out/ 1 in

Overall fiber-laser efficiency is the result of a two-stage process. First is the efficiency of the pump diode. Semiconductor lasers are very efficient, with on the order of 50% electrical-to-optical efficiency. Laboratory results are even better, with 70% or even more of the electrical pump energy being converted into light. When this output is matched carefully to the fiber laser's absorption line, the result is the pump efficiency.

The second is the optical-to-optical conversion efficiency. With a small photon defect, high excitation and extraction efficiency can be achieved, producing an optical-to-optical conversion efficiency on the order of 60% to 70%. The result is a wall-plug efficiency in the 25% to 35% range.

B.2] Configurations for many purposes

Continuous-wave fiber lasers can be either single- or multimode (in terms of transverse modes). A single mode produces a high-quality beam for materials working or sending a beam through the atmosphere, while multimode industrial lasers can generate higher raw power. If an application does not require the extremely high intensities resulting from single mode operation, the higher total power from multimode operation is often an advantage, for example, for some kinds of cutting and welding, and particularly for heat-treating, where a large area is illuminated.
Long-pulse fiber lasers are essentially quasi-CW lasers, typically producing millisecond-type pulses. Typically they have a 10% duty cycle (resulting from the pump diode modulation). This results in higher peak powers than in CW operation—typically on the order of ten times higher. This can be an advantage for some kinds of materials working such as pulse drilling. The repetition rate can range up to 500 Hz, depending on the pulse duration.

Q-switching is possible in fiber lasers, with the principle being the same as for bulk *Q*-switched lasers. Typical pulse lengths range from low nanosecond up to the microsecond range; the longer the fiber, the more time is needed to *Q*-switch the output, producing a longer pulse.

Fiber properties impose some limitations on *Q*-switching. Nonlinearities are more severe in a fiber laser due to the core's small cross-sectional area, so the peak power has to be somewhat limited. One can either use bulk *Q*-switches, giving higher performance, or a fiber *Q*-switch, which is spliced to the ends of the active part of the fiber laser.

The *Q*-switched pulses can be amplified in fiber or in bulk. An example of the latter is found at the National Ignition Facility (NIF; Livermore, CA), where a fiber laser is the master oscillator for the 192 beams of the NIF laser. Small pulses from the fiber laser are amplified up to megajoule size in large slabs of doped glass.

In mode locked fiber lasers, the repetition rate depends on the length of the gain material, as in any kind of mode locking scheme, while pulse duration depends on the gain bandwidth. The shortest achievable oscillator pulses are in the 50 fs range, with more typical durations in the 100 fs range. Shorter pulses can be generated in oscillator-amplifier systems with external chirped-pulse amplification and subsequent pulse compression.

An important difference exists between erbium- and ytterbium-doped fibers, resulting from the fact that the two are operating in different dispersion modes. Erbium-doped fibers emit at 1550 nm, which is in the anomalous-dispersion region; this allows the production of solitons. Ytterbium-doped fibers are in the positive or normal dispersion realm; as a result, they generate strongly chirped pulses. As a result, a chirped fiber Bragg grating may be needed to dechirp the pulses to compress the pulse length.
There are a number of ways to modify fiber-laser pulses, particularly for things like picosecond ultrafast research. Photonic-crystal fibers can be made with extremely small cores to produce strong nonlinear effects for applications such as supercontinuum generation. In contrast, photonic crystals also can be made with very large single-mode cores to avoid nonlinear effects at high power.

Bendable large-core photonic-crystal fibers are being created for high-power applications; one of the tricks being looked at is intentionally bending such a fiber enough that any undesired higher-order modes will go away, leaving only the fundamental transverse mode. Nonlinearities allow harmonics to be generated; sum and difference frequency mixing can create higher frequencies and shorter wavelengths. Nonlinear effects can also produce pulse compression, leading the way to the production of frequency combs.

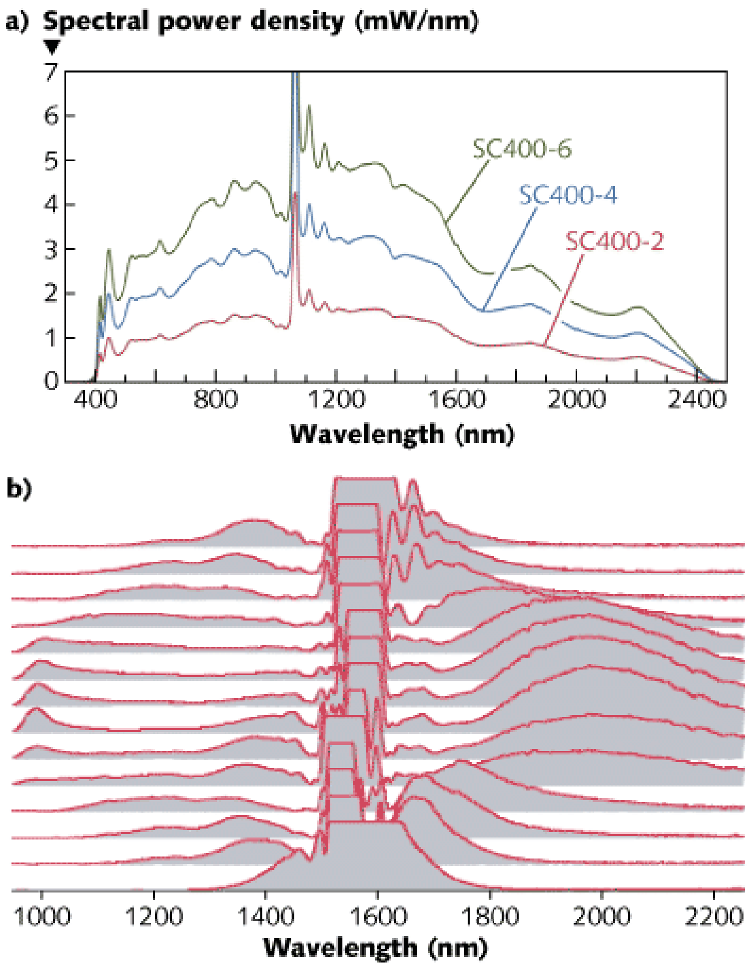


Figure 6 : A fiber supercontinuum produces a broadband spectral output from narrowband pulses via nonlinear optical effects (a; *Courtesy of Fianium*). Supercontinuum outputs in the watt range are achievable. The spectral output of an IR supercontinuum fiber can be changed by varying the pulse width (b; *Courtesy of Toptica*).

In a supercontinuum source, very short pulses produce a broad continuous spectrum via self-phase modulation. In one example, initial 6 ps pulses at 1050 nm (from a ytterbium fiber laser) produces a spectrum ranging from the ultraviolet to beyond 1600 nm, with some irregularity across the spectrum (see Fig. 6). Another supercontinuum source, this one working in the IR, is pumped with an erbium fiber laser at 1550 nm. In this case, the spectrum of the supercontinuum source varies with pulse width. This design achieves a range of more than an octave, ranging out past 2200 nm.

C] APPLICATIONS OF FIBER LASERS

C.1] Applications of High Power Lasers

The industrial market is now the largest market for fiber lasers; much of the action right now is at the kilowatt-class power level. Particularly interesting is their use in automotive work. The automotive industry is moving to high-strength steel to produce cars that meet durability requirements but are relatively light for better fuel economy; the problem is how to cut the high-strength steel. And that's where they turn to fiber lasers. It's very difficult, for example, for conventional machine tools to punch holes in this kind of steel; however, fiber lasers (and other types of lasers as well) can easily cut these holes.

Fiber lasers have some advantages over other lasers for materials processing. For example, the near-IR wavelengths of fiber lasers are absorbed well by metals. The beam can also be delivered by fiber, which allows a robot to easily move the beam focus around for cutting and drilling.

Fiber lasers can satisfy extreme power requirements. The U.S. Navy's Laser Weapon System (LaWS), tested last year by the Naval Sea System Command, has six fiber lasers, each emitting 5.5 kW, incoherently combined into one beam and fired through a beam director (see Fig. 7). The 33 kW system was used to shoot down an unmanned aerial vehicle (UAV). Although the beam was not single-transverse-mode, the system is of interest because it can be constructed of standard, easily-available components.

FIGURE 7 : The US Navy's Laser Weapon System (LaWS) contains six individual fiber lasers with their beams incoherently combined into a single 33 kW output. (*Courtesy of US Navy*)

The highest single-mode power available from a fiber laser is 10 kW, from IPG Photonics. In the system, a master oscillator produces a kilowatt of optical power that is fed into an amplifier stage pumped at 1018 nm with light from other fiber lasers. The entire laser system is about the size of two refrigerators.

The highest multimode power reached is 50 kW, also by IPG Photonics. The system relies on incoherent beam combination, so it's not a super high-quality beam (beam parameter product of 10, M^2 of 33). This laser has been shipped around the country and has operated at 50 kilowatts in five states. This is the kind of durability that makes fiber lasers attractive for industry.

Other applications exist for fiber lasers in high-power cutting and welding—for example, replacing resistance welding for high-speed sheet steel, solving the problem of material distortion caused by resistance welding. Power and other feedback controls allow fiber lasers to cut a very precise curve, especially going around corners.

C.2] Drilling Concrete and Other Specialised Applications

A 4 kW multimode fiber laser has been used to cut and drill concrete. Why would one want to cut concrete with a laser? When engineers are attempting to earthquake-proof existing buildings, they want to be very careful with the concrete. However, they need to put things like rebar in it to bolster its strength so it won't just crumble if an earthquake hits. Conventional percussion drilling can crack and weaken concrete, but fiber lasers cut it without fracturing.

Q-switched fiber lasers are used, for example, in pulsed materials working, such as laser marking or working semiconductor electronics. They are also used for lidar; a module green module about the size of one's hand, contains an eye-safe erbium fiber laser with a 4 kW peak power, a 50 kHz repetition rate, and a 5-to-15-ns pulse duration.

There is a lot of interest in smaller fiber lasers for micro-and nanoscale machining. For surface ablation, if the pulse duration is made shorter than about 35 ps, then there is no material splatter, just ablation, eliminating the formation of kerfs and other unwanted artifacts on the metal being cut. Pulses down in the femtosecond regime and produce nonlinear effects that are insensitive to wavelength and don't heat the surrounding area, allowing material work without damaging or weakening the surrounding area. In addition, holes can be cut with high aspect ratios—for example, rapidly (within a few milliseconds) drilling small holes through 1-mm-thick stainless steel using 800-fs pulses at a 1 MHz repetition rate.

C.3] In The Biomedical Field And Agricultural Systems

One can also do surface machining of transparent materials—for example, the human eye. To cut flaps for LASIK surgery, femtosecond pulses are tightly focused with a high-numerical-aperture lens onto a spot below the eye's surface, causing no damage at the surface, but breakdown of the eye material at a controlled depth (see Fig. 8). The surface of the cornea, the smooth surface of which is important for vision, escapes unharmed. The flap, separated from underneath, can then be pulled up for ablative excimer-laser lens shaping. Other medical applications for picosecond and femtosecond fiber lasers include shallow-penetration surgery in dermatology, and use in certain kinds of optical coherence tomography (OCT).

Scientific applications of femtosecond fiber lasers include laser-induced breakdown spectroscopy, time-resolved fluorescence spectroscopy, and general materials research. And fiber lasers are used to produce femtosecond frequency combs, valuable in metrology as well as general research. One realistic near-term application for easily generated frequency combs will be atomic clocks for future-generation GPS satellites, resulting in much finer position resolution on the ground—a boon not just for knowing exactly where you are on the street, but also for automated equipment such as robot tractors that need to know they're tilling between, not on, rows of corn based on GPS measurements.

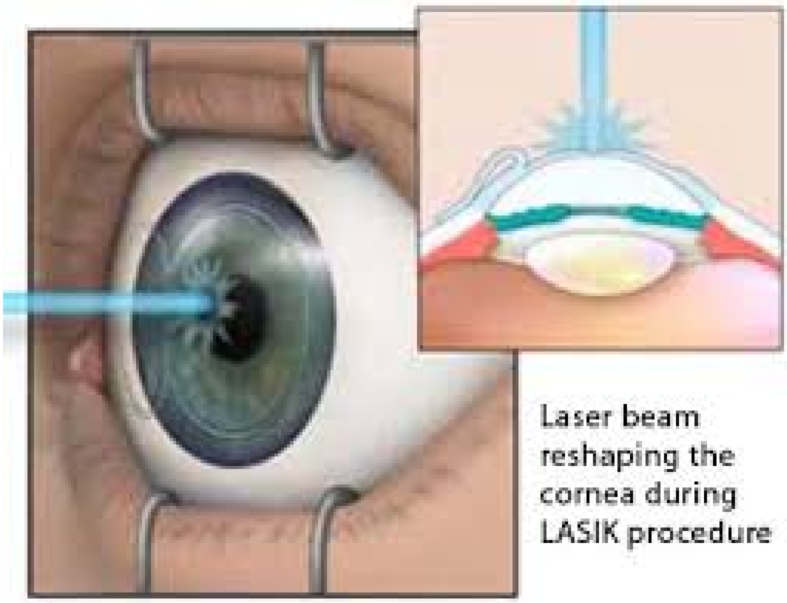


Figure 8 : Application of fiber Lasers in eye surgeries

C.4] In Communication

A single-frequency fiber laser is available with a linewidth of less than 1 kHz (see Fig. 9). This is an impressively small device with an optical output of 10 mW to 1 W in the erbium fiber band. It is useful in communications, metrology (for example, in fiber gyroscopes), and spectroscopy.

Figure 9 : A single-frequency fiber laser has a linewidth of less than 1 kHz. (*Courtesy of PolarOnyx*)

C.5] In Manufacturing And Laser Marking

Wavelengths for laser marking It has been well known for many years that at near-infrared wavelengths, metal reflectivity is significantly lower than at the longer emission wavelengths of carbon dioxide gas lasers at 10.6 µm. A second benefit of using shorter wavelengths is that the divergence of a laser beam is proportional to its wavelength and inversely proportional to the diameter of the beam, summarized in the equation below:

$$\Theta = \lambda \div (\pi \omega)$$

where Θ = beam divergence, λ = laser wavelength, and ω = beam waist.
So, shorter wavelengths allow smaller focused spots and hence smaller surface features. Despite these focusability limitations, longer-wavelength far-infrared gas lasers still retain a strong position within the marking industry, because many widely marked materials such as paper and thin-film optically transparent polymers simply do not absorb enough of the laser beam. This absorption is required to generate localized features on the surface that are visible to the unaided human eye. Lasers producing

near-infrared wavelengths, such as fiber lasers, are used for marking a very wide range of materials, both metals and nonmetals. In these cases, marks that must be visible by the unaided eye are created either by ablating material or by creating oxide layers on the surface, or by a combination of both of these. An ablative mark might appear very precise to the unaided eye, but examined under higher magnification one can usually see evidence of the small-scale but very dynamic and energetic heating and vaporization processes that are occurring. Although most of these features cannot be resolved by the unaided eye and are so shallow as to not affect the functionality of the component in most circumstances, the slightly roughened edges are probably responsible for light scattering and hence making the mark visible. Many polymers can also be laser-marked by inducing a range of surface effects such as foaming, carbonization, and ablation. For marking lighter-colored polymers, thin polymer films, or semiconductor materials such as silicon when small features are required, even better absorption may be necessary - although the reasons for this are beyond the scope of this article, in some cases shorter wavelength lasers in the visible spectrum are used.

C.5.1] What can laser marking systems do?

Laser marking system manufacturers all use very sophisticated commercially available laser marking software to control the galvanometer scanners that produce relative motion between the laser spot and the workpiece. It is the laser and the optics at the heart of the machine, however, that control the marking mechanisms the system can produce. These marks can be almost infinite combinations of characters and graphics, logos, unique serialized alphanumerics, or one of a number of different barcode designs. There are many justifications for this: traceability, anti-counterfeiting, material, batch or manufacturer identification. The primary function of all marks is they must be readable, either by machine or by the unaided eye. Other secondary requirements may be: a)The functionality of the part must not be compromised throughout its lifetime in any way - for example, it should not mechanically weaken or cause corrosion of the part; b)The mark must endure for the lifetime of the part; and c)The mark must be aesthetically pleasing. The sophistication of laser marking systems make the marking process look very simple, but laser marking software allows many different approaches to producing an optimized mark on a particular surface. A range of scan speeds, scan line overlaps, scan patterns, and laser delays are available, and different operators may use very different approaches to achieve a similar mark. This tells us that laser marking is still something of a “black art” - although some general rules can be applied, a great deal of laser marking is still experientially based (see Fig. 10).

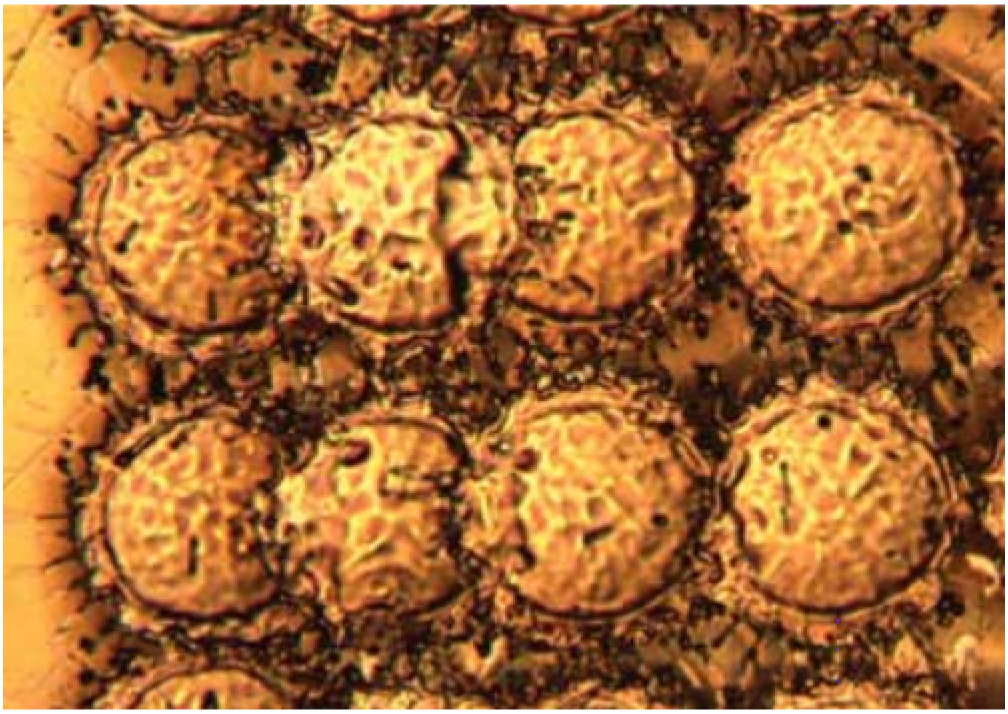


Figure 10 : Laser-marked 304 stainless steel, 20 kHz, 0.5 mJ, 2 m/s. Melt spots are 70 μm diameter

C.5.2]Technical benefits of fiber lasers

One major benefit of ytterbium-doped fiber lasers is that the near-infrared 1070 nm wavelength emitted is close enough to the 1064 nm wavelength of neodymium-doped Yttrium aluminum garnet (Nd:YAG) lasers as to make no difference during the actual process of laser marking. This made for a relatively easy replacement of continuous wave Nd:YAG lasers by fiber lasers for most marking applications. This early success exposed the marking industry to fiber lasers and their many additional benefits became better understood. This led, in turn, to more advanced applications where fiber lasers were able to challenge the still relatively new diode-pumped solid-state laser technology.

Another often unappreciated aspect of fiber lasers is that the whole optical path of the laser is fully maintained and hermetically sealed within zero-loss fully coated optical fibers - it must be made this way when the optical fibers are produced. The continuous optical path is achieved by combining all of the fiber based optical components using advanced optical fiber splicing techniques. This approach has enormous benefits and is unlike any other laser technology, in that no optical misalignment is possible until the laser beam exits into the focusing optics. Another related aspect is that in principle it is very simple to generate higher average power; one simply uses longer active fibers or additional fiber amplifier stages with more pump diodes. Of course, this scaling simply cannot be achieved without an in-depth understanding of the science and technology of fiber lasers, which in turn leads to an understanding of precisely where damaging optical effects such as Raman scattering will occur and can be avoided.

C.5.3] Fixed or variable pulse length nanosecond fiber lasers

Both fixed and variable pulse length nanosecond lasers have been used extensively for laser marking, and the simplicity, ruggedness, and cost effectiveness of fixed pulse length fiber lasers has, as we have seen, allowed significant market penetration. There are, however, a limited number of circumstances where the added flexibility of a shorter laser pulse can provide benefits. One good example of this in the field of laser marking is marking clear polycarbonate components. The mechanism is rather different from most other materials in that small micron-sized bubbles are generated beneath the surface of the material and these bubbles appear black to the unaided eye. Reducing the pulse length to 30 ns along with careful control of other marking parameters such as speed, pulse energy, and the distance between fill lines allows these bubbles to be generated beneath the surface without agglomerating into features that disrupt the surface of the component (Fig 11).

Figure 11: Subsurface mark in polycarbonate. Letters are 2 mm tall.

This approach is highly desirable for marking medical devices as unwanted debris entrapment can be eliminated. There are benefits for some highly specialized marking processes in using even shorter pulses, as low as 1.5 ns. Once again, fiber lasers have a significant advantage because these short pulses and high pulse repetition rates can be achieved without compromising average power to any great extent. For example, one particular model available from the leading supplier delivers 18 W average power at 300 kHz with 1.5 ns pulses (60 μJ), an M2 of 1.3, and a peak power >40 kW. Although pulse duration is an important laser processing variable, it is only one of (a number of Fig. 11 laser marking with fiber lasers) the factors that contribute to producing a particular feature size. This parameter combination allows off-the-shelf infrared fiber lasers to produce feature sizes with conventional optics that have only previously been obtainable using more complex and costly shorter wavelength diode-pumped solid-state lasers.

C.5.4] What does higher average power do for laser marking?

Because of the complex nature of the phenomena involved in laser marking, it is difficult to predict whether marking speed or marking depth will double by doubling the power of the laser. In most cases, however, a higher average power laser will allow users to mark either faster or deeper, or a combination of both. For applications where a significant depth to the mark is required, 30 W or even 50 W lasers have been developed without any increase in footprint and without any compromise in the focusability (or brightness) of the laser.

Table 4: Ablation rates using 50 W nanosecond fiber laser for percussion drilling 0.6 mm thick 304 stainless steel

Frequency (kHz)	Pulses/hole	Drill time (mS)	Avg Hole Vol (mm^3)	Removal rate (mm^3/s)	Removal Eff. (mm^3/l)	Removal Rate (mm^3/min)
50	250	5	0.029	6.37	0.12	382.4
100	2000	40	0.034	0.86	0.03	51.8

The results shown in the table above were gathered during percussion drilling experiments with a 50 W fiber laser. Although this is the best possible case for material removal (the mechanism that is observed when deep engraving metals), removal rates as high as 5 mm3 /s have been measured. It should be noted that using a higher average power laser translates directly into a higher heat input to the part, and distortion on thinner components may well limit the average power that can be used. When mark depth is >100 μm, these marks retain their readability even after serious abuse of metal surfaces; this may be deemed “tamper evident” in that a significant amount of adjacent material needs to be removed to render the mark illegible.

C.5.5] Mid infrared-wavelength fiber lasers

There are a number of other rare earth elements from the same Lanthanides group in which ytterbium resides that have been used as active media in solid state lasers to generate alternative wavelengths. Holmium (Ho,) erbium (Er,) and thulium (Tm) are all adjacent to each other in the periodic table, and all of these have been used for some years in fiber lasers for various non-industrial laser applications such as laser surgery, largely due to the high absorption of this wavelength by H_2O. Thulium fiber lasers emitting longer wavelength beams (in the spectral region of 1900-2010 nm) have now been developed to very high power levels (>100 W) for melting processes such as polymer welding due to their higher volumetric absorption in unfilled polymers. These lasers are not yet available at power levels in the pulsed nanosecond regime to be of interest to the laser marking industry, but they will be available in the not-too-distant future.

C.6] In Material Welding

C.6.1] Introduction

The telecom crash in the late 1990s can be seen in hindsight as a pivotal event in the history of industrial lasers; from it emerged industrial fiber laser technology. The existence at that time of in- depth scientific and engineering expertise in active fibers and fiber amplifiers, combined with the availability of an extensive toolkit of components, enabled a brisk scaling-up of laser power into the multi-kilowatt regime. The industry’s shift to fiber laser technology is now challenging well-established lasers in many sectors of the industry. CO2 and Nd:YAG laser technologies are now almost 50 years old, but the huge success of this new technology comes as no surprise to those who have worked with both the old and the new. The major impacts have been in multi-kilowatt metal processing and in low-power general purpose laser marking, but there is also rapid progress in other areas. The following presents the emergence of a new process for a new class of mid infrared longer wavelength fiber lasers.

While the differences between a CO_2 gas laser and a fiber laser are obvious and these two technologies cannot be confused, the difference between a fiber laser and a fiber-delivered laser is not always immediately apparent. The technology change comes from generating the beam within the fiber itself, and the inclusion of other optical fiber components within the same continuous hermetically sealed fiber-optic beam path. This contrasts with fiber-delivered lasers, where the beam is generated by an array of solid-state optical crystals and discrete optical components and is delivered to the workpiece via fiber for only the final part of its journey. The fiber laser is produced by constructing continuous beam paths Fiber laser technology broadens out within fibers; these are very familiar techniques for those in the fiber optics industry. This fit-and-forget process is at the heart of the success of the fiber laser, as it removes the need for maintenance issues associated with other types of industrial lasers.

C.6.2] Fiber Lasers In The Mid Infrared

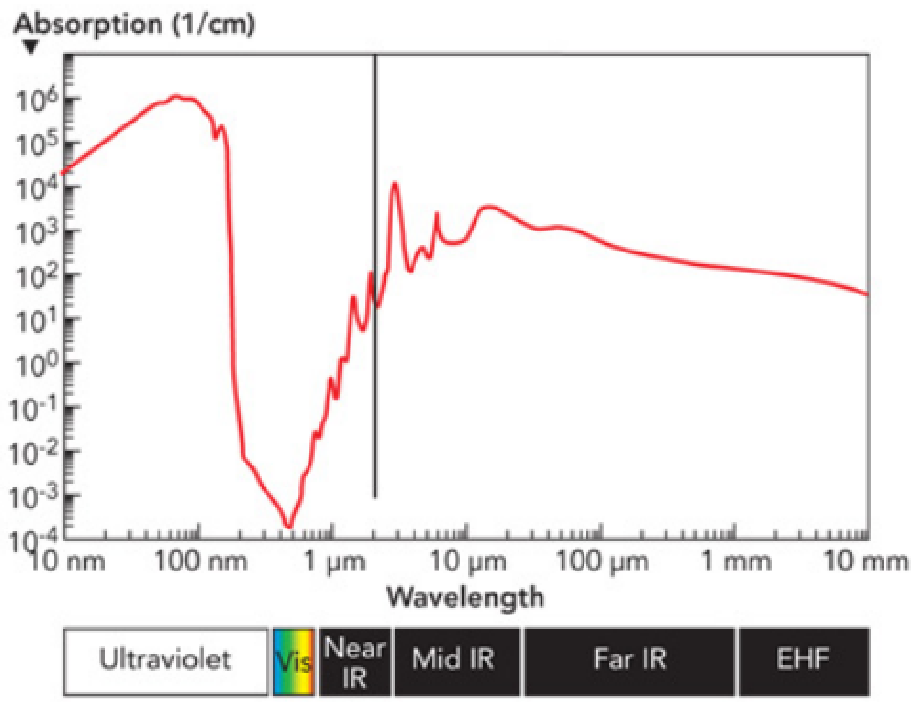


Figure 12 : IR wavelength ranges and water absorption peak vs. wavelength.

The infrared portion of the electromagnetic spectrum is usually divided into three regions; the near- , mid-, and far-infrared (Fig. 12). Our concern here is with the higher-energy near-IR regime, approximately 0.8–2.5 µm wavelength. Laser scientists are familiar with CO2 lasers where electromagnetic bonds between atoms are seen as quantum mechanical springs — for example, the asymmetric vibrational state of the CO_2 molecule is close to the stretching state of the N_2

molecule, so energy exchange between the two molecules occurs and lasing in the far IR occurs.

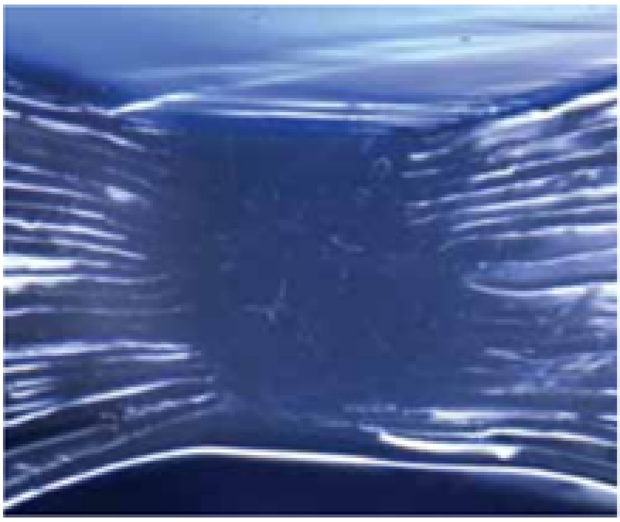
Mid-IR wavelengths are part of the fiber laser story, and thulium was seen very early on as a candidate rare-earth ion dopant for fiber lasers, because the many Tm 3+ transitions allow a wide range of useful wavelengths to be generated using silica-based fibers in the 2 µm spectral region. Strong absorbance by water occurring around this wavelength led to an early interest in thulium fiber lasers for superficial tissue ablation with minimum coagulation depth, a form of "bloodless surgery." Many other non-materials-processing applications have led to the availability of a range of optics for these wavelengths.

It has been known from previous work and from spectroscopic data that many polymer matrices absorb more efficiently at this wavelength, but the reason why Fiber laser technology broadens out is not immediately clear. In this mid-IR range, the spectra from even the simplest polymer materials are complicated by numerous vibrational modes and are not simple symmetrical peaks. The wavelength equivalent for a C-H bond absorption peak is typically 3225 nm, well away from the range of the thulium laser. The energy transitions in the stretch vibrational states of these C-H molecular bonds in high-density polyethylene (HDPE), for example, are therefore small compared to the binding energy of electrons in a carbon atom. It appears, however, that the prominent absorption closest to 1940 nm is the first overtone of the prominent fundamental C-H stretching absorption at 1724 nm. Having said that, mid-IR developments are underway and 3225 nm laser wavelengths are now becoming available. This will be an interesting area for future work. With the availability of much higher average power at these wavelengths and the high water absorption, please ensure relevant safety standards are followed for guidance.

C.6.3] Thulium fiber lasers for polymer welding

Although 50 W average power thulium fiber lasers have been commercially available for several years, recent developments have pushed average power to >100 W while still maintaining a high-brightness single-mode beam, with a power level and $/W cost appropriate for high-volume manufacturing processes. The existing through-transmission laser welding (TTLW) technique gaining acceptance within industry only allows lap joints with one absorbing and one transmitting component to be welded. Also, as it employs a near-IR laser, it is unable to weld clear-to-clear polymers unless an additive is used, such as Clearweld infrared dye, and this can make the laser process unacceptable.

C.6.4] Preliminary Trials



Fgur 13 : Outline of weld volume, 22 layers of 0.1 mm thick virgin LDPE.

Table 5: Absorption of Makrolon polycarbonate at 1940 nm

Thickness (mm)	0.5	0.8	1.4	2.0	2.5	5.7
% Loss	10	14	18	18	25	44

Trials were conducted to confirm the improved absorption levels of a 1940 nm thulium fiber laser beam on many thermoplastics; results on polycarbonate (PC) are reported above. Using a 4.2 mm diameter collimated beam, power was maintained below 5 W to ensure no significant heating or melting. This data shows that 10%–45% absorption occurs volumetrically in this clear sheet material depending on sample thickness. These results can be compared with those from a commercially available transmission tester that uses a 0.8 mW diode laser source at 850 nm, which showed >92% transmission on all samples.

As heat input to the sample is increased incrementally and by exercising careful control over the temporal and spatial characteristics of the beam, melting occurs in a highly controllable manner in materials up to 6 mm thick. A simple lap joint with very basic clamping was all that was then required to produce optically clear spot welds between two facing surfaces of like thermoplastics. Relative motion between the laser beam and the melt zone produced linear welds, controlling relative speed and power (line energy) penetration in a manner analogous to welding of metals.

The cross section of the multilayered joint in low- density polyethylene (LDPE, Fig 13) was prepared as a simple way of delineating the melt zone.

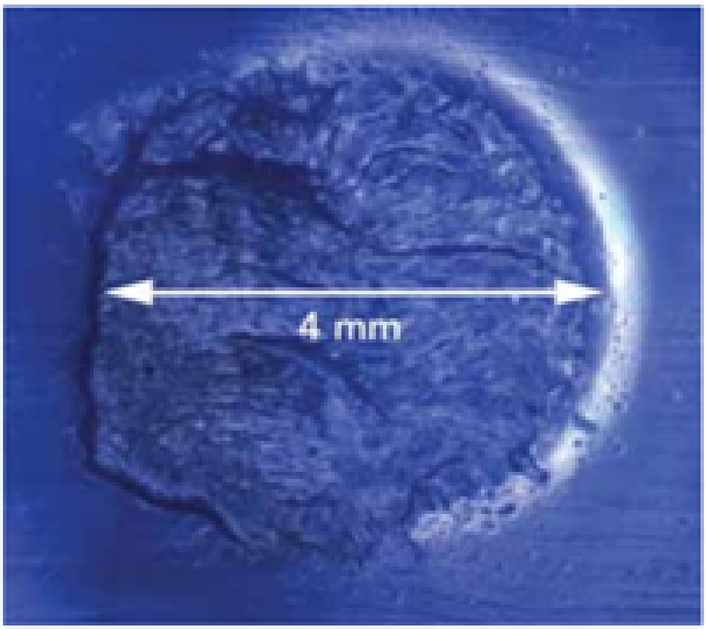


Figure 14 : Material failure surface at interface of 3 mm diameter PC spot weld.

In polymers this is more difficult than for metals, where conventional metallography can be employed. As with all welds, strength depends largely on the weld area at the interface, and mechanical testing has shown that joint strengths greater than the strength of the parent material can be readily produced. Fig 14 shows a spot weld fracture surface in polycarbonate where cohesive material failure has occurred.

C.6.5] Discussion

Fig 13 clearly shows the volumetric absorption of the laser beam in multiple thicknesses of LDPE, which serves two purposes: it shows layers of polyethylene joined together by a high-quality weld, and clearly outlines the melt zone confirming volumetric absorption, as expected from a consideration of Beer's Law. The classic derivation of this law divides the absorbing sample into thin slices perpendicular to the beam, and tells us that light from each subsequent slice is slightly less intense. For a parallel beam of a specific wavelength of monochromatic radiation passing through a homogeneous solid material, the loss of radiant intensity (ΔI) is proportional to the product of the path length through the material Δx and the initial radiant intensity

$$\Delta I = It\Delta x$$

where t is the absorption coefficient and represents the relative loss of radiant intensity per unit path length in the material.

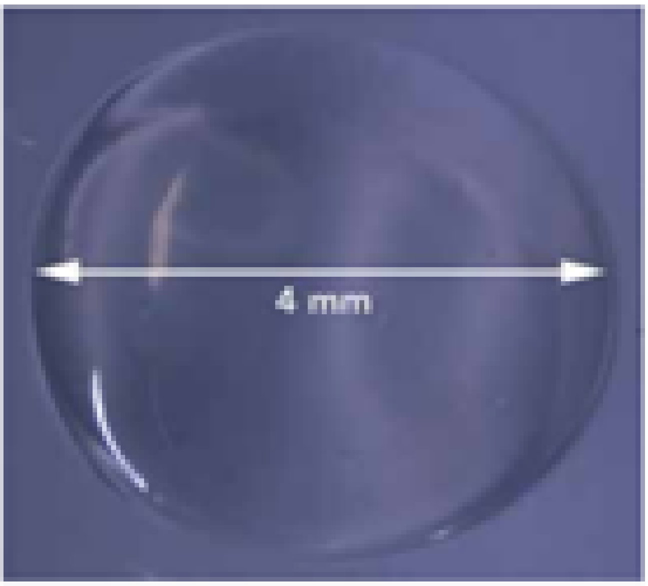


Figure 15 : 4 mm diameter optically clear spot weld through 2 mm thick unmodified polypropylene.

An important contrast exists with 4 mm: the longer-wavelength far-infrared regime is where almost 100% absorption occurs, and the polymer welding process is limited to thin films due to the relatively slow conduction processes involved.

With fine-tuning of the welding process, spot or seam welds with no visible charring or degradation were readily achieved. This simple welding technique has since been applied successfully to a wide range of thicknesses of many polymer materials (Fig 15 & 16).

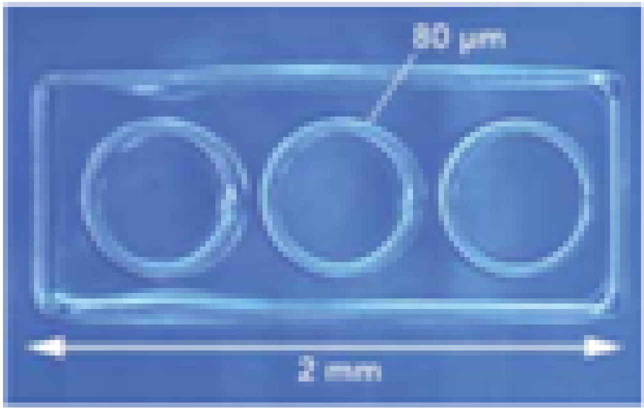


Figure 16 : < 0.1 mm weld lines in Zeonor cyclic olefin polymer, 2 mm long simulated microfluidic device.

For materials ranging from 0.1–3.0 mm thickness, this absorption appears well-suited at this wavelength for welding many optically clear thermoplastics. The use of high-brightness fiber lasers allows long focal length low f-number lenses or even collimated beams to be employed, as large spots and low power density (typically < 500 W/cm2) only are required for polymer welding. As many thermoplastic polymers are well-known for their tendency to distort when welding, this enlarges the operating envelope of the process considerably, and removes the need to focus on a particular plane at the joint interface as has been necessary when lower-brightness lasers are used, so access for tooling is also much improved. Although the Gaussian nature of a single mode beam may at first glance be considered detrimental, optical techniques for producing top-hat beam shapes are now available for this wavelength and may in some circumstances be required. Optically transmissive clamping devices can be used to produce smooth weld surfaces on rigid polymers.

There are many benefits to this process:

1) Butt and lap joints are possible
2) Light clamping pressure only is required
3) Transmissive clamping plate is not always required
4) No extra absorbers are required
5) Optically clear defect-free welds are readily obtained
6) Low-heat-input, sub-0.1 mm wide weld features are achieved
7) Long focal length lenses or collimated beams rule out access issues.

C.7] Drilling With Fiber Lasers In Industries

C.7.1] An Introduction

Companies that use laser sources for drilling have three requirements: cost efficiency, high productivity, and high quality. Cost efficiency is affected by productivity and quality, but is also determined by the operating and maintenance costs of the laser source. Quality is the compliance with specifications such as geometrical tolerances or metallurgical results, e.g., recast layer thickness. Productivity is the number of holes that are drilled per time.

The type of laser source used for drilling is not important as long as all three main objectives are achieved. Therefore, companies will use new laser sources if they have benefits in cost efficiency, productivity, or quality compared to state-of-the-art flashlamp-pumped Nd:YAG lasers.

New diode-pumped lasers such as fiber lasers seem to have benefits considering their specifications; costs of the laser sources with a mean power of less than 1 kW, and operating costs are smaller.

Smaller operating costs also result from a higher electrical efficiency, a greater lifetime of diodes compared to flashlamps, and the omission of adjustment.
When using a flashlamp-pumped laser source, the beam is guided by mirrors that need to be adjusted and have a small loss of power (0.2 to 5% per mirror). Using a fiber laser, the beam delivery system does not need to be adjusted as the beam is guided by a flexible fiber. The loss of power of the beam delivery system is rather small as no mirrors are used. Fibers as a beam delivery system are more flexible as the beam can be delivered to different work stations by beam switches or fiber replugging.

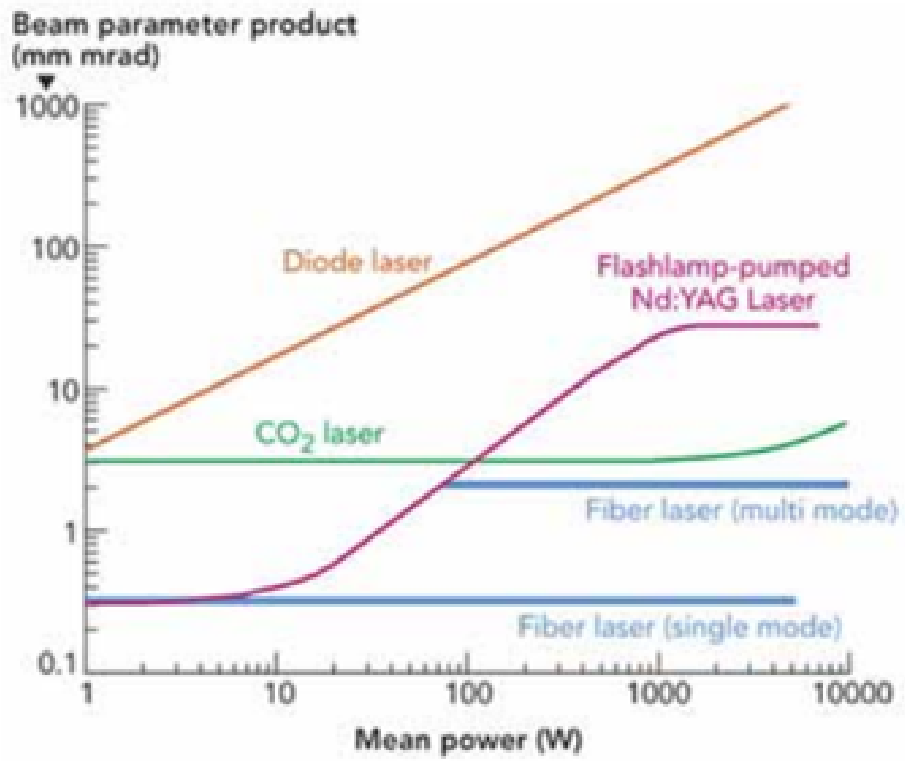


Figure 17 : A beam parameter product as a function of the mean power of different laser sources

Fiber lasers can provide a smaller beam parameter product at high mean powers compared to flashlamp-pumped Nd:YAG lasers (Fig 17) as fiber lasers have a smaller beam parameter product in the range above 100 W. Below 100 W, single mode fiber lasers have a comparable beam parameter product of ~0.35.

Thus, drilling with fiber lasers is applicable when quality and productivity is comparable to flashlamp-pumped Nd:YAG lasers as fiber lasers offer more cost-savings.

C.7.2] Experimental setup

The suitability of the two different laser types for drilling – flash lamp and diode pumped laser – is analyzed by comparing drilling results. Therefore, geometrical specifications of holes to be drilled are defined. The geometry is based on typical venting holes that are drilled in tool forms. The exit diameters of through holes are supposed to be 120 µm with a depth of 5 mm in stainless steel 1.4301. In some cases, tool forms can have several thousands of holes. Therefore, high productivity is needed to reduce manufacturing time. The hole quality, such as recast layer thickness or taper, is not specified but is considered to be as high as possible.

In the experiments, a flashlamp-pumped Nd:YAG laser LASAG FLS 652N and a pulsed fiber laser IPG YLS-600/6000-QCW with a 50 µm fiber are used. The focal length of both optics is 100 mm. With these drilling optics, the focal diameter of the Nd:YAG laser is 232 µm, while that of the fiber laser is 74 µm (Fig 18). The times-diffraction-limit-factor M2 is 15.7 for the Nd:YAG and 10 for the fiber laser. The reason for choosing a flashlamp-pumped laser source with a high average power and a small beam quality is the demand for high productivity.

Oxygen with a pressure of 8 bar is used as the process gas. The distance from the nozzle to the workpiece is 1 mm. The laser beam is focused onto the surface of the workpiece. As drilling completes, the productivity, hole exit diameters, and recast layers are measured and compared.

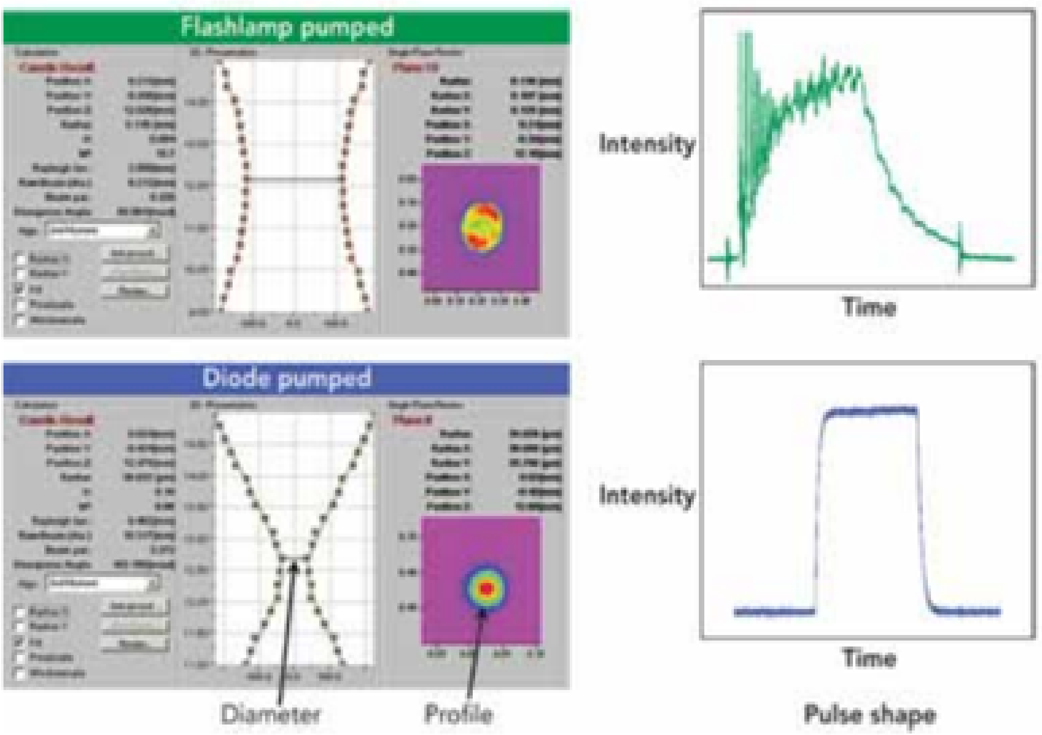


Figure 18: Beam profile of the flashlamp (top) and diode-pumped (bottom) laser radiation.

C.7.3] Results

The specified hole geometry can be achieved by drilling with more than one set of parameters. Every set of parameters can have advantages such as higher productivity, but can also have disadvantages such as higher tolerances of the exit diameter or higher taper. When choosing one set of parameters, a compromise between productivity and quality has to be made. For example, choosing a higher repetition rate leads to higher productivity, but also leads to a higher taper when drilling with the flashlamp-pumped laser source (Fig 19). The repetition rate of the flashlamp-pumped laser source is fixed to 40 Hz as the entrance diameter of the hole becomes very large at higher repetition rates.

In the case of drilling with the diode-pumped laser source, the influence of the repetition rate on taper is small (Fig 20). When drilling with a repetition rate higher than 100 Hz, the taper is almost constant, but the holes are enlarged in the middle (barreling). The standard deviation of hole diameters also increases at repetition rates higher than 100 Hz. Thus, the repetition rate when drilling with the fiber laser is fixed to 100 Hz. Both repetition rates are maximized in order to have a high productivity with a reasonable geometric quality such as taper.

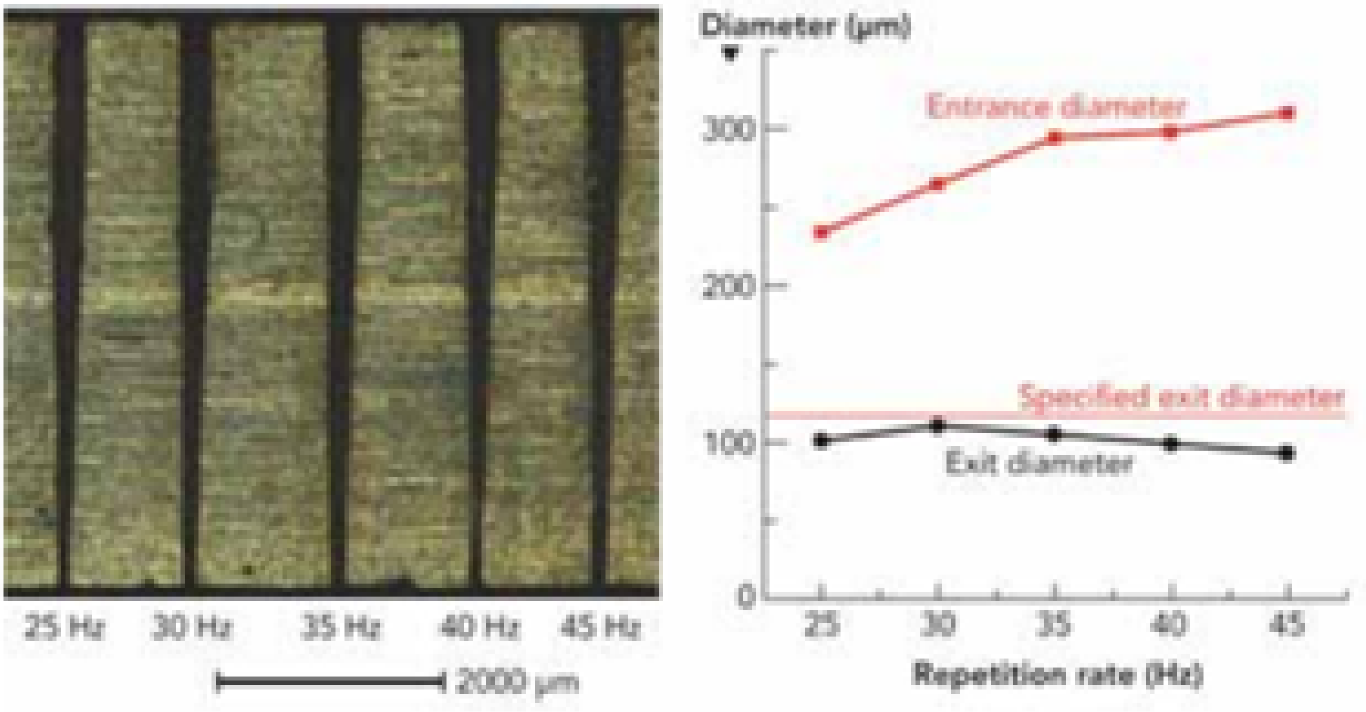


Figure 19 : Longitudinal sections of holes drilled with the flashlamp-pumped laser varying the repetition rate (left) and entrance and exit diameters as a function of the repetition rate (right).

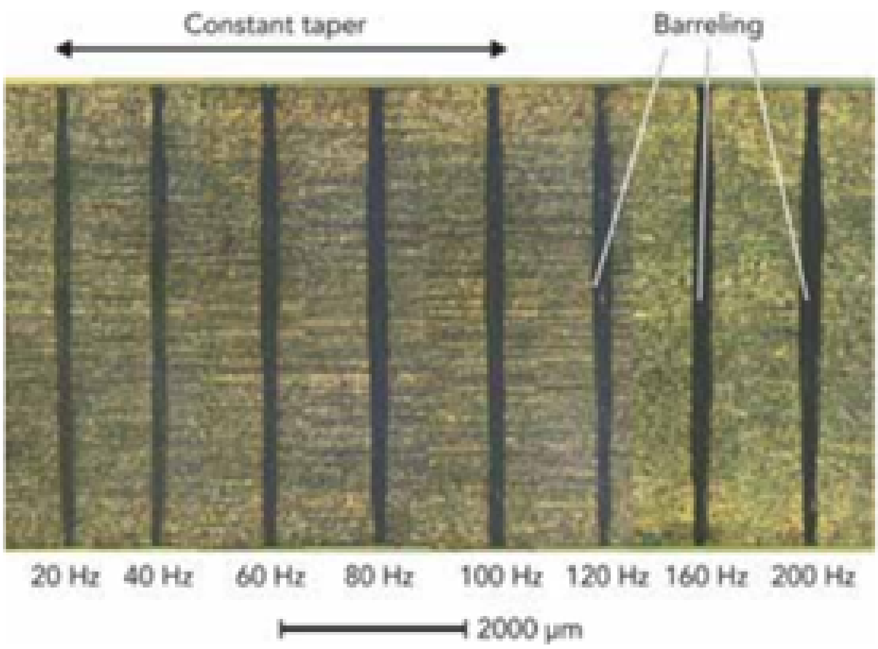
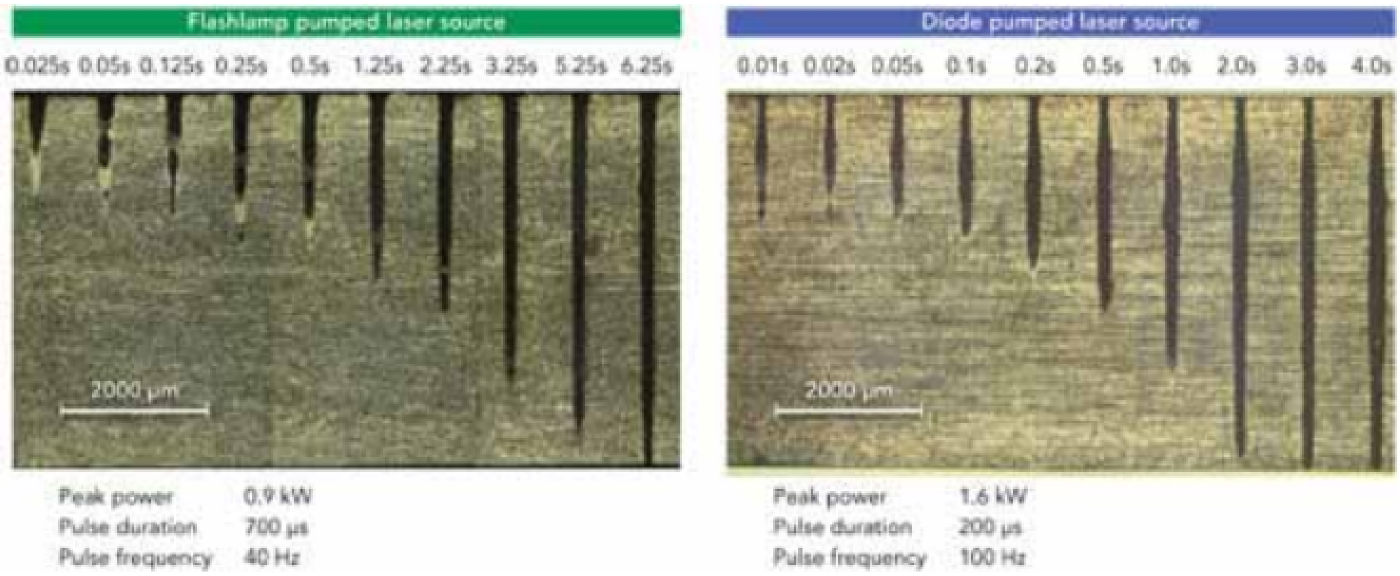


Figure 20 : Hole geometries as a function of the repetition rate using the diode-pumped laser.

The parameters are set up by a systematic variation considering drilling productivity and quality. To compare the productivity of holes drilled by the Nd:YAG and fiber laser, the hole depth is measured after a defined number of laser pulses in longitudinal sections (Fig 21). The drilling depth is plotted as a function of the pulse number, which is converted into time (Fig 22). The drill through time of the 5 mm workpiece is 3 s using the diode-pumped and 6.25 s using the flashlamp-pumped

Figure 21 : Longitudinal section of holes drilled with the flashlamp-pumped (left) and diode-pumped (right) laser source with increasing pulse count.



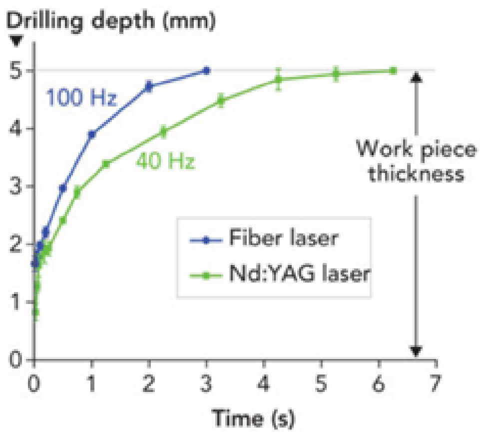


Figure 22 : Hole depth as a function of time using the Nd:YAG flashlamp and diode-pumped fiber laser.

laser source. The difference in the drill through time is a result of the two repetition rates. To analyze the reproducibility of the exit diameter, several hole exits are measured. The number of holes are plotted as a function of the tolerance of the hole exit and a Gauss distribution is calculated (Fig 23). The Gauss distribution of hole exits using the diode-pumped is smaller compared to the flashlamp-pumped laser source. This can be a result of the intensity profile as the times-diffraction-limit-factor of the fiber laser is smaller by a factor of 1.6.

Also, the pulse-to-pulse stability of the flashlamp-pumped laser source is smaller as pulses can spike and the pulse energy can vary. The thickness of recast layers is measured with an image processing software in longitudinal sections. Recast layers of holes drilled with the Nd:YAG laser as well as the fiber laser are comparable. The thickness of recast layers for both laser sources is approximately 20 µm.

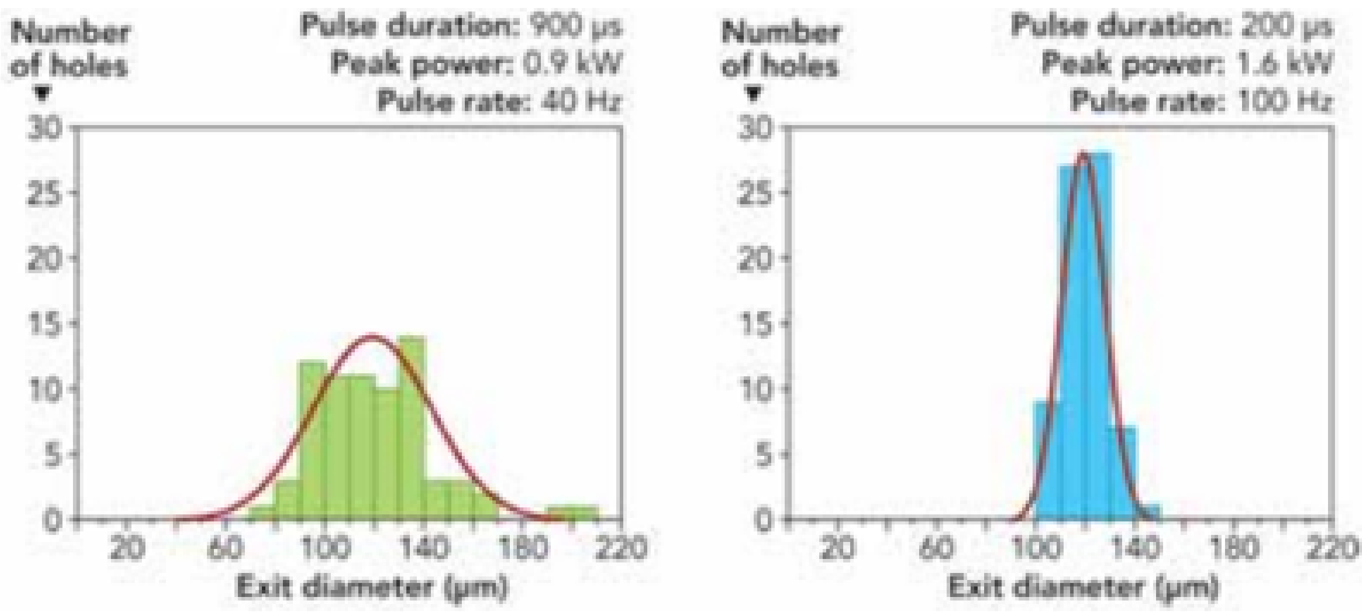


Figure 23 : Distribution of exit diameters of holes drilled with the (left) flashlamp pumped and (right) diode-pumped laser source.

C.7.4] Conclusion

Pulsed fiber lasers can provide a smaller beam parameter product at high mean powers compared to flashlamp-pumped Nd:YAG laser sources and are more economical as acquisition costs and operating costs are less. The specified hole geometry with a diameter of 120 µm and a depth of 5 mm in stainless steel 1.4301 can be achieved with a flashlamp as well as a diode-pumped laser source. When drilling with both laser systems, compromises between productivity and geometrical quality such as taper must be made. Parameters, which consider productivity as well as quality, are determined.

The productivity using a fiber laser is higher in the experiments compared to the Nd:YAG laser as the repetition rate of the Nd:YAG laser is smaller. The repetition rate cannot be raised because this increases taper and the standard deviation of hole diameters.

The tolerance of hole exit diameters is smaller when drilling with the fiber laser. This can be a result of the smaller times-diffraction-limit-factor M2 as well as a better pulse-to-pulse stability of fiber lasers compared to flashlamp-pumped Nd:YAG lasers.

Drilling with flashlamp-pumped Nd:YAG lasers is still state-of-the-art. Nd:YAG lasers are commonly used for industrial applications such as drilling, cooling holes in turbine blades, or manufacturing holes in tool forms. There will be economic and technical benefits using a diode-pumped laser source for drilling if companies will change their laser sources from flashlamp-pumped Nd:YAG lasers to diode-pumped lasers such as fiber lasers in the future.

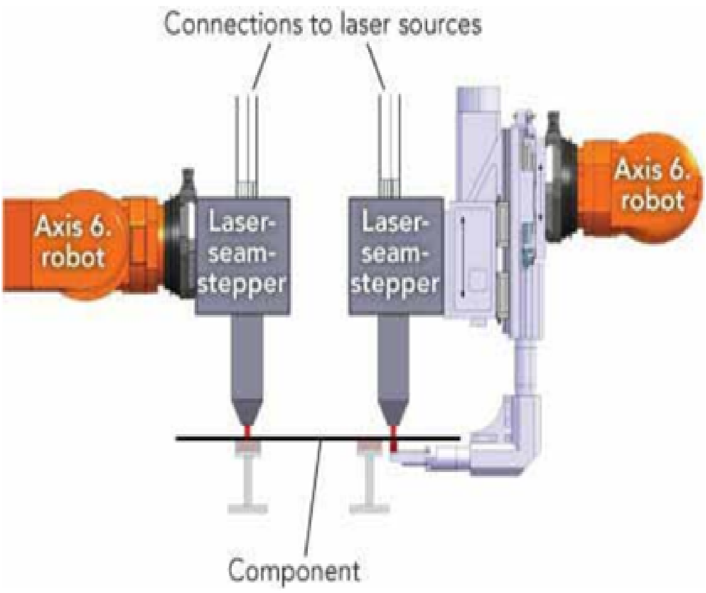
C.8] Fiber Laser Spot Welding

For today's high volume production in the automotive industry, resistance spot welding and laser remote welding, while well established, present advantages and disadvantages. For laser remote welding the main advantage is the significant cycle time reduction due to almost complete elimination of idle times and the mechanical advantages of laser welded seams. For resistance spot welding an advantage is the integrated clamping technology, which comes nearly for free. IPG Laser GmbH has combined these advantages in a new technology, COSY, offering the resistance spot welding process, featuring the simplicity of clamping tools and production facilities, used in combination with the advantages of laser welding.
A problem for some types of solid-state laser welding is operator safety, which requires a protective housing for lasers with power up to 6 kW. When used for welding sheet metal in the automotive industry, safety equipment with fast reaction safety devices is necessary. This complicates their use in an open production facility, for example in automotive body and assembly plants.

Laser welding for the production of sheet metal components in body plants offers the following advantages:

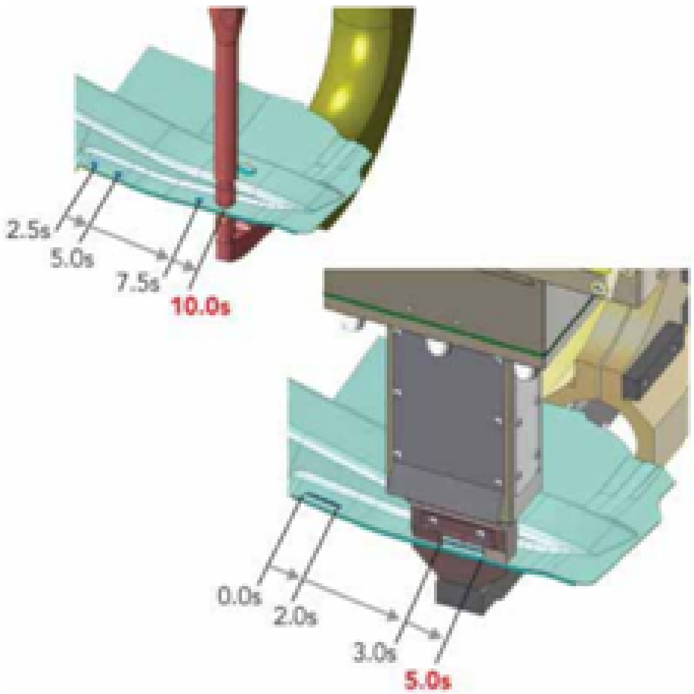
1) Higher process speed (shorter cycle times)
2) Increased component strength by longer seams with higher torsional stiffness
3) Efforts and costs comparable to today's modern resistance welding systems
4) Realization of high job safety requirements with reduced costs

Fiber laser welding with a suitable welding tool provides the opportunity to accomplish all these objectives. As shown in Figure 24, a Laser-Seam-Stepper (LSS1) module deflects the preset laser beam via a processing fiber into X-Y coordinates. For safety the laser beam is directed via funnel-shaped small angle housing. To release laser power, the housing has to contact the component to be welded.
Laser welding with or without a weaving function (±1 mm) can be produced within the range determined by the housing (standard = 40 mm). The easiest application is a module mounted for example on the 6th axis of an industrial robot (30 kg



handling capacity). The robot moves the module to the required welding position. In this position it is placed onto the component only by robot force. Below the component, within the range of the welding seams, a fixed lower tooling is used as counter force or support (as shown in Fig 24 left).

Figure 24: Laser-Seam- Stepper (left without C-Gun; right with C-Gun)



During a typical stepping operation (30 mm welding seam, 30 mm free space, 30 mm welding seam, etc.), a laser welding seam can be placed with a welding velocity of approximately 30 mm/s every 1.3 –1.5 seconds (see Fig 25).

Figure 25 : Resistance spot welding vs. laser welding with COSY LSS1-C-Gun

The Laser-Seam-Stepper with C-Gun (LSS1C) is mounted on a servo motor driven traversing unit. This is similar to a resistance welding gun with compensating module (see Fig 24 right). This version allows an industrial robot (80 kg handling capacity) to move the LSS1C into a welding position and to close with a freely programmable force. The lower tool belonging to the C-gun is used as a counter force and additional safety equipment against unintended back reflected laser radiation.

The force-controlled closing of the laser welding system (0.5 – 3 kN) results in a fitting accuracy (gap < 0.2 mm) which is absolutely necessary for laser welding.

A module of the system compensates for tolerances regarding the position and geometry of the components. All joining forces (0.5 – 3 kN) applied in the system are performed within the laser welding tool only, the robot is not required for these joining forces. During a typical stepping operation a laser seam can be placed every 1.7 – 2 seconds.

Features of the laser welding tools, COSY LSS1/LLS1C, with a compact fiber laser are:

1) The mechanically compact design of the basic unit COSY-LSS1 can be moved by an industrial robot with a handling capacity of 30 kg.
2) The basic version enables the system to weld linear seams with a maximum length of 40 mm.
3) Optionally a weaving function (3 – 30 Hz) can be switched on in order to spread the welding seam (2 mm).
4) Laser sources are very compact fiber laser systems with power between 500 W and 3 kW and a total efficiency of more than 30 %.
5) The fiber laser and the welding head are maintenance free.
6) The system is laser safe and can be used without complex laser protection housings. (Protective equipment as used in robot spot and arc welding cells is sufficient.)
7) The LLS1C can join the sheet metal plates to be welded with a defined force in the area of the welding seam. This process reduces the normally high clamping effort during laser welding.
8) The system is controlled via hardware interlock or buss systems. In the easiest case preconfigured seams of 10 mm – 40 mm seam length, including welding speed and laser power can be selected and started.

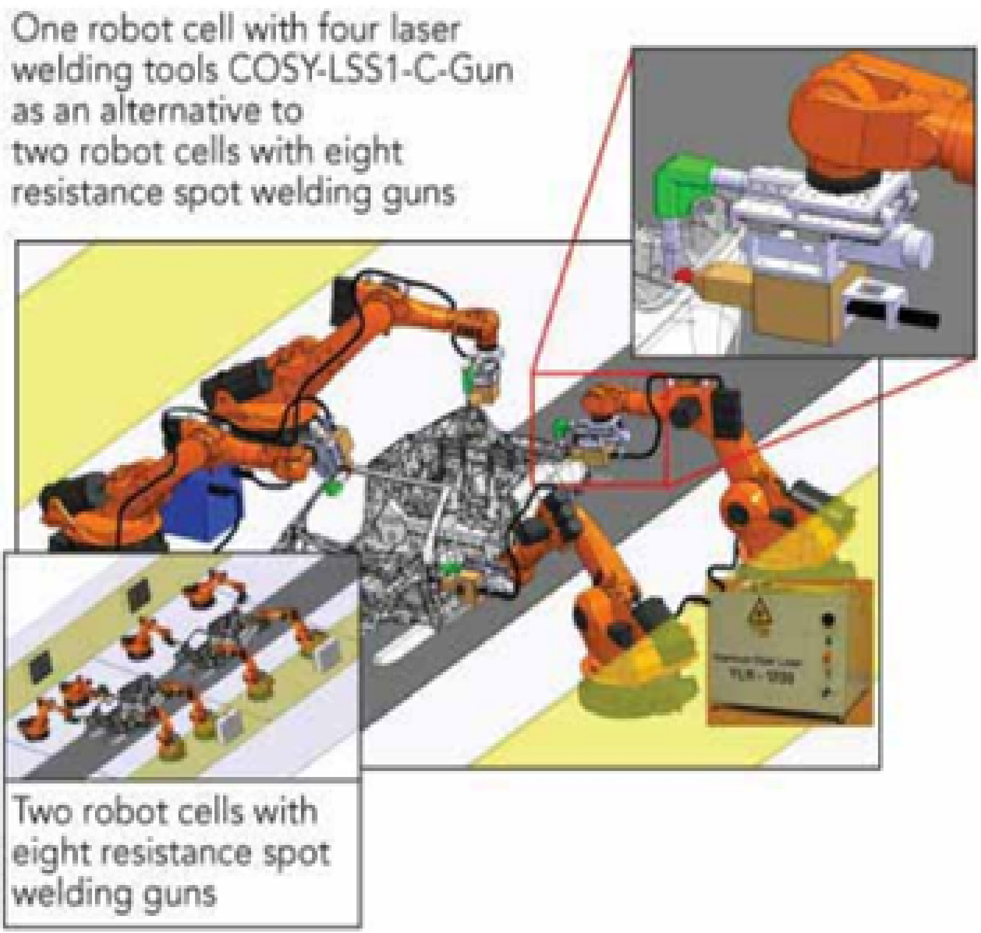


Figure 26 : COSY LSS1-C-Gun with IPG fiber laser vs. resistance spot welding

Typical applications for this system are sheet metal assemblies in the body-inwhite production lines (see Fig 26), which up to now have been joined with many resistance welding spots. The intention of the COSY-LSS1 and COSY-LSS1-CGun is to replace two welding spots with a typical distance of approximately 30 mm by one laser step seam of approximately 30 mm.

For example in the case of 30 resistance spot welds the cycle time is approximately 75 seconds. If spot welding is replaced by laser welding in the manner described, only 15 laser weld seams are required. The cycle time can be reduced down to only 37 seconds in total, as well as the required floor space.

D] The Fiber Laser Revolution

The amazing success of fiber laser technology and its revolutionary impact on laser-based manufacturing bear the hallmarks of more widely publicized technology game changers, such as the displacement of vacuum tubes by the transistor. The analogy is apt when we consider that legacy lasers are bulky, inefficient and short lived devices which are difficult to assemble and require frequent service. Fiber lasers, on the other hand, are compact, highly efficient and robust devices which offer service-free operation through the entire application lifetime.

The simplicity and elegance of the fiber laser account for its efficiency, compactness, robustness and low cost which drive its enormous success in the marketplace.

D.1] The True Industrial Laser

The fabulous success over the first 50 years of industrial lasers owes itself to the laser's ability to convert common sources of energy into highly directed beams. To accomplish this task, every laser is comprised of its energy source, a method of coupling that energy into the laser cavity, and a method of delivering the resultant laser beam to the workpiece. The technical advantages of fiber are apparent in each stage of the architecture.

D.2] Energy Source

Legacy lasers utilize numerous energy sources ranging from lamps, RF plasmas and even chemical reactions. Common drawbacks of these energy sources include poor energy conversion efficiency, frequent service requirements and environmentally unfriendly consumables. Fiber lasers utilize long-lived semiconductor diode lasers to efficiently convert electricity into light, and thus require no service or consumables.

D.3] Energy Coupling

Conventional laser optical cavities convert input energy within bulky air or gas-filled spaces. Large cavities are necessary due to the inefficiency of gas lasing or the need to insert bulk optical elements within the cavity. Fiber lasers are incredibly compact because they convert semiconductor diode energy into useful laser beams within a fiber no thicker than a human hair.

D.4] Laser Beam Delivery

Legacy lasers utilize complex optics to extract the laser beam and deliver it to the workpiece. For example, a sealed window may be needed to isolate exotic or noxious chemicals inside the laser. External steering optics are often needed to deflect the laser output onto its target. In contrast, flexible optical fiber provides an elegant built-in, ideal beam delivery system.

Both key fiber laser elements, semiconductor diodes and optical fiber, lend themselves to mass production with outstanding process control and repeatability, while the key fiber laser assembly step is fusion splicing of optical fibers. Compare this with the bulky hermetic laser cavities, precision optical alignments and ultra-flat optical surface requirements typical of legacy lasers, and it's apparent that the simplicity and elegance of the fiber laser accounts for its efficiency, compactness, robustness and low cost which drive its enormous success in the marketplace.

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