

DOI: <https://doi.org/10.26628/simp.wtr.v97.1194.199-206>

Review Article

## Comparison of selected functional properties of laser energy sources using for welding processes

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Received: 28.10.2025; Accepted: 10.12.2025; Published: 15.12.2025

**Abstract:** This article discusses the basic types of laser energy sources using in welding and related processes, such as surface modification and cutting. It presents the fundamentals of photon beam generation in various types of welding lasers. A general comparison of their selected technological and operational properties, including energy efficiency, wavelength, beam quality, photon beam transport method, operational durability, investment cost, operating cost, and service complexity, is provided. Recommendations for selecting laser welding methods for industrial applications are provided based on economic and technical considerations.

**Keywords:** laser process; beam welding; welding sources; similitude and differences in lasers

### Introduction

A laser is a device that emits electromagnetic radiation from the light spectrum, utilizing the phenomenon of stimulated emission. The name LASER is an acronym for *Light Amplification by Stimulated Emission of Radiation*. The laser light beam is coherent, usually polarized, and characterized by slight divergence. The basic elements of a laser are an active medium, a resonator, a pumping system that supplies energy to the active medium. Under appropriate conditions, lasing occurs in the active medium, i.e., quantum amplification of photons. The optical system enables the selection of appropriate photons. The most important properties of laser light include:

- beam divergence, defined as the increase in the cross-sectional area of the beam with distance, is determined by the divergence angle  $\theta$ , thanks to the low beam divergence, almost 100% of the radiation energy can be directed to a specific place,

$$\theta = \frac{1,22\lambda}{D}$$

where:

$\lambda$ - wavelength,

$D$ - beam width at the laser output.

- coherence is the spatial and temporal, phase and frequency dependence of electromagnetic vibrations,
- radiation power and energy density,
- propagation of laser radiation in the environment.

Lasers radiate nearly all their energy in narrow beams, unlike other light sources that radiate in all directions and whose energy cannot be concentrated to achieve a spot power density greater than the source's. Laser radiation energy can be concentrated, allowing for parallel beam alignment. High power density facilitates high photon concentration. This allows for simultaneous interaction of several photons with a single atom.

The described peculiarities of the laser beam determine its growing role in welding and related techniques [1] focused on metalworking, surface modification [2], thermal cutting or ablation [3].

Laser welding is widely used in various industrial sectors, such as automotive and other vehicle manufacturing, shipbuilding, and aerospace, but is also increasingly being adopted by small and medium-sized companies that produce simple, lightweight, and specialized construction products. This is due to the numerous advantages of lasers, including: high-quality welding processes [4], high precision of heat input energy control [5] and process flexibility [6]. The much higher speed of laser welding than other welding methods based on arc energy sources, including MIG and MAG, is also significant. [7], TIG or MMA [8], This fact significantly affects the welding efficiency due to the intense and deep melting of the base material, but is also related to the increase in the melting efficiency of the filler material (if any)[9]. Laser welding is characterized by relatively low deformation of welded joints and has the effect of reducing the Heat Affected Zone compared to conventional methods. [10]. This article presents and systematizes the main types of laser welding energy sources and the differences between them in terms of technological suitability and main areas of application.

## The main types of industrial lasers used for processing engineering materials

Lasers are usually classified based on their active medium: gas (He-Ne, CO<sub>2</sub>, N<sub>2</sub>), semiconductor (usually diode), solid-state (e.g., ruby, Nd:YAG), dye, metal vapor (e.g., copper vapor); by operating mode (continuous and discrete); power level; wavelength, e.g., infrared (IR invisible, absorbed by metals and water); visible (e.g., He-Ne, CO<sub>2</sub>); ultraviolet (UV short wave); and safety classes: class 1 - safe under normal conditions; class 2/2M - low power, visible; class 3R/3B - dangerous when viewed directly (3B is more dangerous); class 4 - the highest class, hazardous to eyes, skin, and fire (e.g., industrial and medical lasers). There are four main types of lasers used in the industrial field, as shown in Table 1. The different types are further divided based on excitation type, operating mode (continuous, pulsed), and other parameters. Each type has different applications and advantages, making it suitable for welding or cutting specific materials.

**Tab. I** A basic overview of the different types of lasers used in the metal joining industry

Parameter	CO <sub>2</sub> laser	Nd:YAG laser	Fiber laser	Disk laser	Diode laser
Energy efficiency (%)	10-25	3-10	25-50	15-30	40-60
Wave length (nm)	10600	1064	~1070	~1030	450-1064
Beam quality	High	Good	Very high	Very high	Medium-high
Transport of beam	Solid mirror	Flexible optical fibre	Flexible optical fibre	Flexible optical fibre	Direct from diode
Durability (h)	~20 000	1000-10 000	>100 000	10 000-100 000	10 000-50 000
Investment cost	High	High	Medium	Medium	Medium
Operating cost	High	High	Medium	Medium	Medium
Complexity of maintenance	High	High	Medium	Medium	Medium

## Solid-state lasers

### *Fiber optic laser*

Currently, the most used type of laser in welding. The fiber laser is the most technologically advanced type of semiconductor laser. Its active medium is long optical fibers doped with rare-earth metals (Nd, Yb, or Er). Laser diodes excite the source, and the energy is conducted through an optical coupler into the active fiber (instead of mirrors that guided the concentrated light to the work area, as was the case in older lasers). Fiber lasers and diode lasers are two different types of lasers, although they are often confused because modern fiber lasers are pumped by semiconductor diodes, which deliver energy to the active fiber, where the laser light is generated. The main difference is that in a diode laser, the beam comes directly from the

diode, while in a fiber laser, the beam is generated in an optical fiber doped with rare-earth metals, providing flexibility and high efficiency.

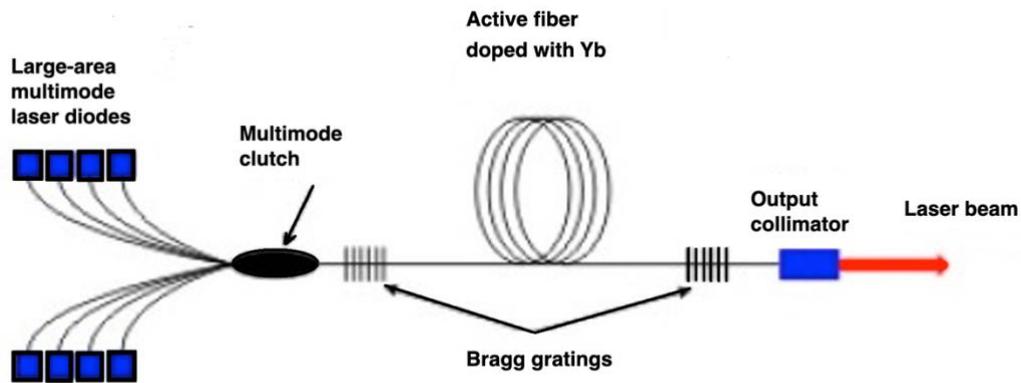


Fig. 1. Schematic diagram of the fiber laser operation [11]

Fiber lasers come in several varieties, categorized by their operating mode. They can operate continuously (CW), pulsed, or quasi-pulsed (QCW). The pump light in the fiber creates a high-power density, which is then delivered to the operating point. The correct addition of a positive feedback loop (creating a resonant cavity) allows for laser oscillation. A major advantage of a fiber laser is its simplicity (the entire laser is essentially an optical fiber), robustness, and modularity, unique to these lasers. The laser consists of so-called laser modules, the power of which can be gradually increased by combining them (currently up to 80 kW). Other advantages include high efficiency (25-50%), long durability of the energy source (~100,000 h), small space requirement for installing the welding system, high quality of the laser beam, the lowest operating costs of all the mentioned types and low maintenance requirements, which further make this type of solution more attractive.

### Disk Laser - „Thin Disk”

The first lasers that could be called disk lasers were developed in the 1990s. The active medium is a thin crystalline disk, cooled from below. Like fiber lasers, the disk laser operates at a wavelength of ~1030 nm and is characterized by very high beam quality. This provides a large surface-to-volume ratio, thus ensuring very efficient thermal management. Currently, the thin disk concept is used in a variety of commercial lasers – from compact, efficient low-power systems to multi-kW lasers, including continuously operating CW lasers, as well as pulsed (femtosecond to nanosecond) oscillators and amplifiers. [12].

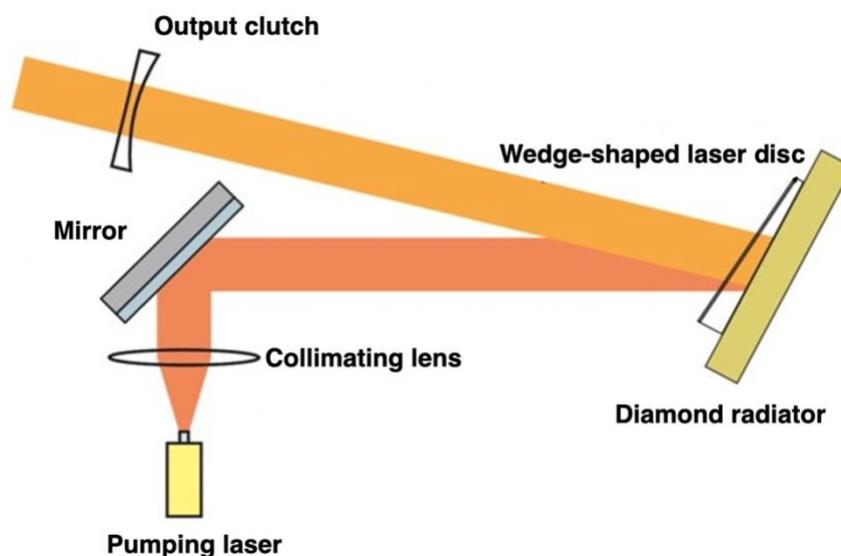


Fig. 2. Optical configuration of the monolithic pump geometry placed in the I-resonator [14]

Thin-disk lasers are used in welding [13], but are also essential in photonics research and many industrial applications. They constitute a unique class of laser and amplifier architecture that provides output power with excellent properties related to beam quality, continuous stability, thermal management, and power scalability. For many applications, reduced laser complexity and size would be very beneficial. Below, Fig. 2 shows one solution schematically illustrating the operation of a disk laser. [14].

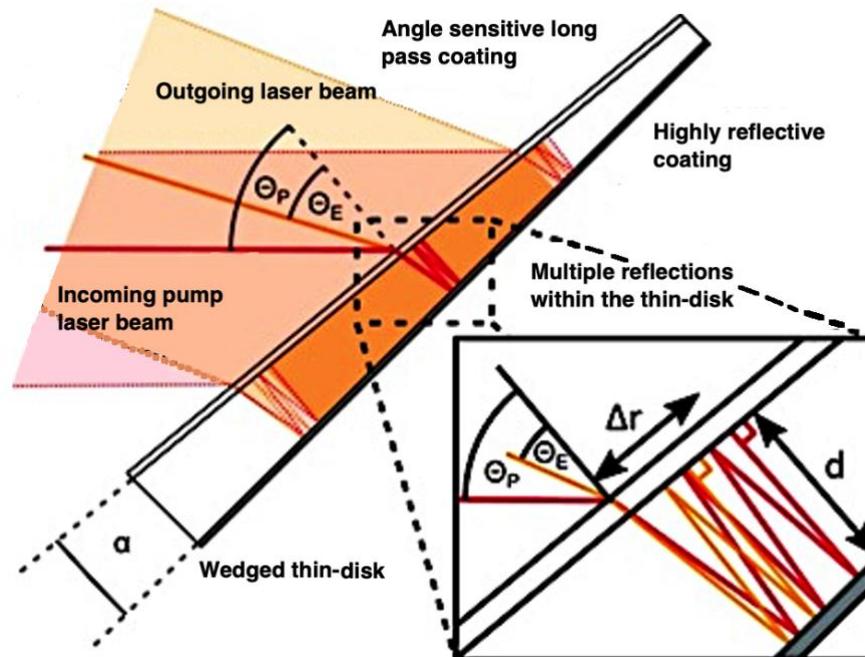


Fig. 3. Sketch of curved thin-disk geometry [14]

The rear side of the disk is covered with a highly reflective mirror for both the pump laser beam and the laser wavelengths and integrated with a suitable heat sink (usually a diamond one in the latest solutions) as shown in Fig. 3. The front side is anti-reflective (highly absorbent surface) efficiently cooled from the rear by a liquid and used in a resonance or wave reflection amplifier [15].

### ***Nd:YAG Lasers***

Solid-state (neodymium crystal) Nd:YAG lasers generate radiation with a wavelength of 1064 nm, which is characterized by good absorption by the solid surface for joining and other types of processing of various metals. The beam can be transported via flexible optical fibers, providing considerable flexibility in the use of this type of energy source, for example, in manipulation devices such as welding robots. Industrially used Nd:YAG lasers are lamp-pumped lasers, lithium-plate lasers (LPSS), or diode-pumped lasers (DPSS), the operating diagram of which is shown in Fig. 4. The active medium is a matrix of an artificial YAG crystal (triangular aluminium) doped with neodymium (Nd) or ytterbium (Yb) ions. LPSS Nd:YAG lasers have low efficiency in converting electrical energy to output energy because a large portion of the tube's energy is not converted into the laser beam but is instead transformed into heat (which requires relatively intensive liquid cooling). DPSS Nd:YAG lasers have relatively higher efficiency and better beam quality. However, the use of Nd:YAG lasers has been steadily declining for several years, which may be due primarily to the relatively short tube lifespan, which ranges from 1,000 to 10,000 hours, and the relatively frequent and costly maintenance of these sources.

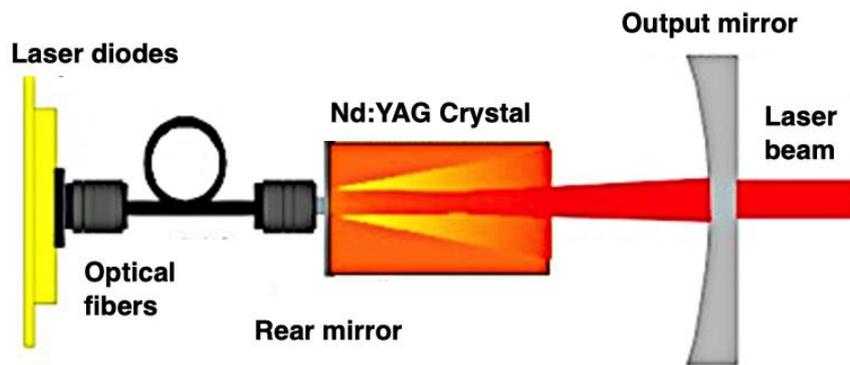


Fig. 4. Schematic diagram of the Nd:YAG DPSS laser [11]

## Gas lasers

CO<sub>2</sub> lasers: One of the oldest forms of laser welding and cutting used in welding. The active medium is a gas mixture (CO<sub>2</sub>, N<sub>2</sub>, He). They generate far-infrared radiation (wavelength 10.6 μm).

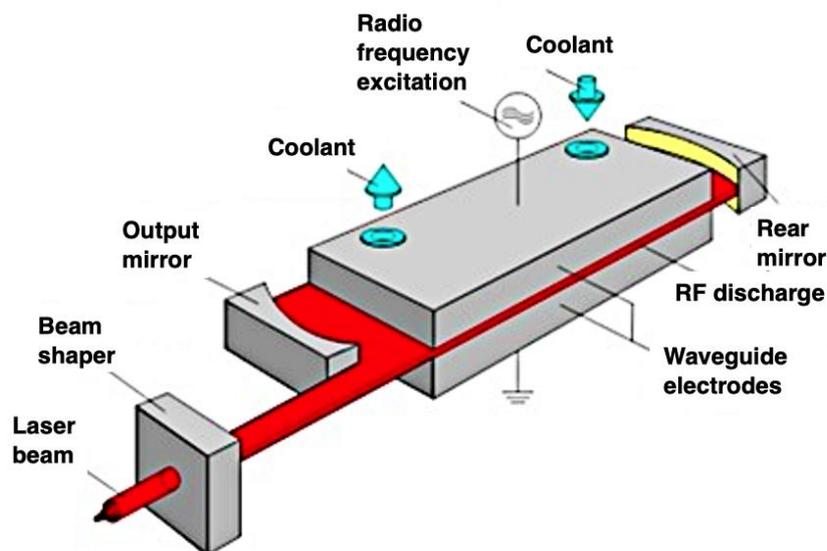


Fig. 5. Schematic diagram of the CO<sub>2</sub> laser [11]

They require beam transport via a rigid optical path built around a mirror system, which limits their flexibility in technological operations. In terms of design, they are divided into closed lasers with a hermetically sealed resonator and flow lasers, where the gas flows continuously through the resonator (which is necessary for high power applications of approximately 10 kW). Excitation of the active gas is achieved using radiofrequency waves passing between two electrodes, which, due to their large surface area, simultaneously ensure gas diffusion within the resonator. Figure 5 schematically illustrates the structure of a CO<sub>2</sub> laser. These lasers are distinguished by high reliability with proper maintenance, a long service life of around 20,000 hours, and moderate investment and maintenance costs.

## Hybrid solid-state lasers (e.g. Fiber-Disk)

Hybrid lasers are modern solutions that have recently entered the industry. They combine the advantages of various laser beam generation methods, such as those combining multiple fiber laser modules with solutions known from disk lasers. This design concept of a dual source of multiple laser energy beams combined into a single output beam is still being developed. This solution allows for relatively flexible power scaling compared to single laser beam energy sources. [16]

## Comparison of selected technological properties of welding lasers

### *Energy efficiency*

CO<sub>2</sub> lasers have relatively low energy efficiency. Approximately 5-25% of the electrical energy consumed is converted into laser beam energy. The rest is mainly thermal losses, requiring intensive cooling. Fiber lasers are unrivalled in this respect. Their 25-40% efficiency translates into significantly lower process costs and lower cooling requirements than CO<sub>2</sub> lasers. The relatively high energy efficiency of fiber lasers not only translates directly into lower operating costs but also significantly impacts workspace organization and the space occupied by the device.

### *Energy absorption and process quality*

Laser energy absorption by metal is the process of converting electromagnetic radiation into heat, driven by the oscillations of free electrons in the metal's crystal lattice under the influence of a photon beam. The efficiency of energy absorption depends primarily on the laser wavelength, the type of metal, and its surface condition. Higher absorption occurs at shorter wavelengths. A wavelength of 1 μm (fiber, disk, Nd:YAG) is much better absorbed by metals (especially non-ferrous metals such as copper) [17] or aluminium [18]) than the 10.6 μm wavelength of a CO<sub>2</sub> laser. Solid-state laser welding allows for higher speed, lower power and efficient processing of highly reflective materials. [19].

Beam quality (parameter BPP – *Beam Parameter Product*) determines the ability to focus the beam on a very small area. Fiber and disk lasers have high beam quality, enabling welding with deep liquid phase penetration or even with a vapor channel effect [20], colloquially "keyhole" and welding of thin sheets with high precision. Some publication [19] clearly indicates the difference in the width of the weld and the HAZ (Heat Affected Zone) between disk and fiber lasers, indicating that the width of both characteristic geometric features of the weld made under comparable conditions in the case of fiber laser welding is greater.

### *Operability and susceptibility to process automation*

Laser welding, in comparison, is about 5 times faster than TIG [21] (*ang. Tungsten Inert Gas*) welding for this reason alone, in order to fully utilize the maximum welding efficiency and achieve a constant level of quality and repeatability, the beam should be guided in at least an automated manner [22]. While much depends on operating conditions when it comes to durability and operating costs, CO<sub>2</sub> lasers objectively have a limited lifespan of approximately 20,000 hours and require regular gas replacement, optics conditioning, and the optical path delivering the beam to the operating space.

Nd:YAG lasers with pump tubes have a tube lifespan of 1,000-10,000 hours, which generates additional costs for maintenance, spare parts, and downtime.

Fiber lasers pumped with semiconductor diodes have a lifespan of over 100,000 hours. They do not have consumables requiring periodic replacement (such as tubes or gases), and their maintenance is mainly limited to cleaning and replacing the optical tips and their mirrors. This significantly impacts the total cost of ownership (TCO), which is difficult to precisely and absolutely determine because it is so closely linked to individual operating conditions.

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## Summary

So, which source is better? There is no clear answer to the question "which laser is better?". Choosing the right type of laser welding should be based on knowledge of the technological features of a specific method, its availability in the analyzed production conditions, and economic considerations. Each type of laser welding has its own unique characteristics, which, depending on the application conditions, may be perceived as limitations and eliminate the method from use, or may be its advantage. Choosing the right welding method should be preceded by an analysis of numerous factors. For most industrial applications (sheet metal welding, cutting, cladding), fiber lasers seem to be the best choice. Their high efficiency, low TCO, high beam quality, and flexibility of integration with other devices make them currently the dominant and most versatile type of laser welding. Disk lasers are very similar in parameters to fiber lasers and have competed with them for many years. Currently, the market clearly favors fiber technology, primarily due to its slightly higher efficiency and simpler design, but disk lasers remain a recognized, high-quality welding power source, especially in applications requiring the highest beam quality at very high-power levels.

Nd:YAG lasers in their conventional form (with lamps) are a declining form of welding and can still be found in older installations or niche applications.

CO<sub>2</sub> lasers still find their place in applications requiring welding over very long distances (several meters) or in specific processes (e.g., thermal cutting of thick steel sheets), where their relatively long wavelength is advantageous.

It should be emphasized that lasers based on the same photon beam generation technique offered by different competing manufacturers will exhibit significant differences in performance characteristics, to the extent that independent qualification of the welding technology may be required not only for the laser welding variant, but also for the specific type of device.

## Conclusions

Over the past 15 years, fiber laser technology has revolutionized the welding market, driven by the increased availability of these devices due to supply from Asian markets, competition among manufacturers, and numerous other factors, including manufacturers' desire to automate production processes. For new investments in precision welding, fiber lasers are the optimal choice in over 90% of cases, especially for welding thin components, offering the best ratio of investment cost to efficiency, quality, and reliability. Other types of welding lasers are used in specific, niche processes and applications, or are the domain of older machinery.

**Conflicts of Interest:** The authors declare no conflict of interest.

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