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Fibre Laser as an Energy-Saving Tool
Overview of Industrial Applications

Abstract: Fibre lasers [sometimes mistakenly referred to as fibre optic lasers] have established their position in a variety of industrial applications. The advantages of these lasers such as excellent beam quality, solid (compact) design and possibility of power adjustment within a wide range have supplanted conventional laser sources in a number of applications or made laser technologies applicable in some areas for the first time ever. Their electric efficiency (up to approximately 45%) make fibre lasers energy-saving tools, minimising outlays and costs related to power consumption and cooling. The article describes fibre laser technologies and overviews micro- and macro-processing applications using pulsed-mode lasers or lasers emitting a continuous single (basic mode) beam or a multi-mode beam.

Keywords: laser welding, fibre laser, industrial applications,

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Principle of Operation

A fibre laser is a radiation converter which converts a multimode pumping laser beam having a wavelength of 970 nm into an output laser beam having a wavelength of 1070 nm and quality corresponding to a basic mode beam. Unlike in a conventional solid-state laser, a fibre laser radiation beam is generated in a doped active optical fibre pumped optically via an active fibre optic coupler with a pumping optical fibre (Fig. 1).

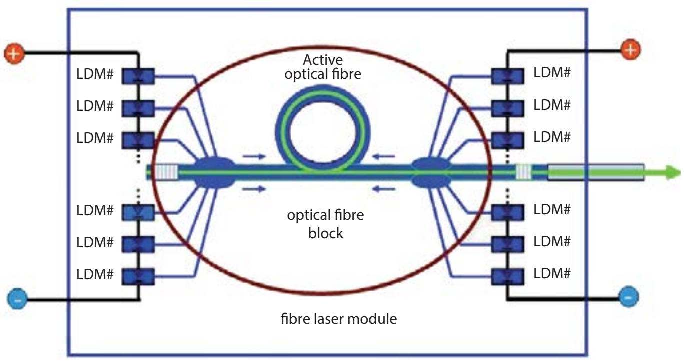

Fig. 1. Pictorial diagram of a fibre laser module [resonator]

A laser beam leaving the active resonator fibre enters a transporting optical fibre leading the beam to the processing head of a working station laser.

In IPG-manufactured fibre lasers, single emitters emitting radiation having a wavelength of 970 nm are used as pumping diodes. The emitters are available on the telecommunications market and used only in industrial applications. Single diodes are cooled directly, not by means of microducts.

The use of laser radiation in cutting or welding using a scanning beam requires high switch-on/

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switch-off frequency (in a kHz range) in order to reduce a process time or limit a heat input to a material. Fibre lasers can be switched over in a kHz range. The power of diodes can be modulated in a 0-100% range, without compromising their active life. Individual emitters operate thermally, independent of one another; heat can be carried off in a simple manner. Presently, such emitters are mass-produced and they have power ranges of 10, 20, and 30-70 W. An optical fibre block is provided with Bragg mesh applied on an active fibre. The mesh adopts the function of a mirror, both fully reflecting and semi-permeable [output mirror]. An optical fibre block is cooled passively and never needs to be re-aligned or calibrated as in this form it does not contain separate optical components. All resonator components are coupled with an optical fibre, making laser resistant to thermal and mechanical effects or contamination. By joining laser modules it is possible to increase the power of a device to many kilowatts without compromising the good quality of a radiation beam.

The module design concept enables users to continuously increase output power, making a fibre laser a unique instrument. Fibre laser features are the following:
- lack of output power limitations,
- high beam quality,
- very high total efficiency,
- long life of pumping diodes,
- small installation area,
- mobility,
- low investment and operating costs.

Pulsed Fibre Laser

Pulsed fibre lasers have the configuration of an oscillator or an amplifier based on a fibre laser. By means of a Q-switch, the oscillator ensures short impulses (in a nanosecond range). The amplifier is a fibre laser module amplifying impulses in a range of many kilowatts. Depending on an optical fibre used, the power of one impulse may reach 1 MW, whereas its energy can achieve 50 mJ.

Pulsed Fibre Laser in a Solar Technique (1)

By reproducing small notches (deformations) on the upper surface of a silicon plate [photovoltaic module] the frontal and rear part [of stacked silicon plates] are insulated from each other [necessary insulation of silicon plate edges for proper operation of p and n type semiconductor layers]. The size of such deformations, i.e. a width of approximately 40 μm and a depth of approximately 20 μm, is responsible for a low level of shading effect [the reduction of an active area]. Figure 2 presents a trace of this type (40 μm in width) made 200 μm away from the edge of a plate.

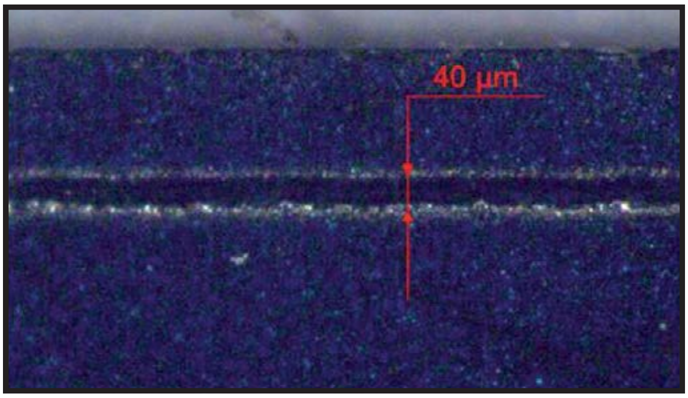

Fig. 2. Magnified insulation of photovoltaic cell edges. The electric insulation of the frontal and rear sides required their separation by means of notches (surface deformations) made using a fibre laser

Due to a very good radiation beam quality, pulsed lasers equipped with scanning working heads can also be used if operating distances are large, i.e. up to 300 mm. Depending on frequency (and average laser power), mirrors of a scanning head move a laser radiation beam at a rate restricted within a 0.5-2 m/s range. Therefore, silicon plates can be processed in a second-long pace.

Pulsed Fibre Optic Laser in a Solar Technique (2)

If a pulsed fibre optic laser of good radiation beam quality, relatively low impulse energy (1 mJ) and medium power is used for marking and ablation, for fast surface ablation it is

Fig. 3. Trace after removing a layer in the near-edge zone of a thin-layer photovoltaic cell plate

Fig. 4. Single-mode fibre laser of a power restricted within a 400-1000 W range. Main applications of this machine include precise and highly precise cutting as well as spot and continuous welding

Fig. 5. Fibre laser of many kilowatt power used for welding and cutting thick elements made of alloy steels

necessary that impulses should have a peak power of up to 1 MW and an average power of up to 500 W. In order to achieve a typical power density restricted within a 5×10^7-1×10^8 W/cm^2 range while cleaning a surface, it is possible to use a beam having a peak power of up to 1 MW and a focusing area diameter of approximately 1 mm. In addition, it is possible to obtain high ablation rates, in a range exceeding 40 cm^2/s. An important application is the removal of a surface in the near-edge zone of thin-layer photovoltaic modules (Fig. 3).

The scanning head of a pulsed fibre laser is used for removing a 15 mm wide path in the module near-edge area. While doing so it is possible to close up the surface tight. In order to prevent humidity penetration during many years of operation, only three several-micrometre thick functional layers are removed from the edge of a photovoltaic module

As the cycle of making thin-layer photovoltaic modules (1300 × 1100 mm) should not exceed 30 s, the removal of layers in the near-edge area using a laser requires a material removal rate exceeding 40 cm^2/s.

Applications of Fibre Lasers Emitting a Basic-Mode Continuous Beam

Presently, IPG Photonics-manufactured fibre lasers emitting a basic-mode continuous beam ($M^2 < 1{,}1$) have a power of up to 10 000 W (Fig. 4 and 5). Figure 6 presents the correlation between the size of a radiation beam focusing area on a workpiece and a working distance and unprocessed [unfocused] beam divergence.

A basic-mode laser beam emitted by a fibre laser provided with focusing optics having a focal length of 200 mm can be focused on an area having a diameter of, e.g. 30 µm, whereas an unprocessed beam is widened only up to 10 mm ($1/e^2$). As a result, it is possible to use a small and slender process optics and dynamic scanning heads equipped with small mirrors.

The main applications for this type of continuous beam emitting lasers include high precision and very high precision cutting as well as spot and linear welding. Precise cutting of sheets in a submillimetre range requires a power of 100 W, i.e. enabling the obtainment of power density necessary for cutting,

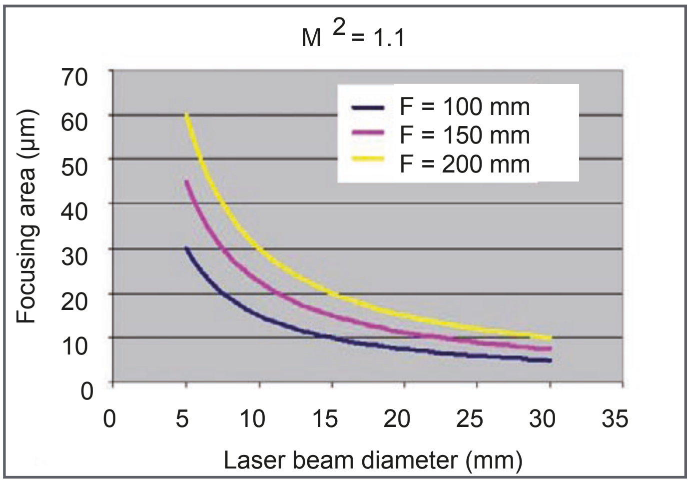

Fig. 6. Size of single-mode fibre laser radiation beam reproduction area on a workpiece depending on a working distance (100, 150 and 200 mm)

i.e. restricted within a 10^7-10^8 W/cm² range. As regards precise cutting, depending on laser application and power, lasers can be externally modulated by means of frequency in kHz so that, in addition to continuous operation, a beam can also operate in a pulsed mode, generating impulses in a microsecond range.

Basic-mode fibre laser welding has found numerous applications, from welding stainless steel foil overlap joints (while making fuel cells) to joining copper plugs and copper frames with external leads, in the case of which penetration must reach up to 2 mm.

Figure 7 presents the metallographic specimen of a joint, in which a copper plug was connected with a massive copper conductor rail.

An advantage of basic mode continuous beam fibre laser welding is, depending on a good beam quality, high power density, required when joining copper alloys. Unlike lamp-pumped resonators emitting impulses of a time limited to approximately 100 ms, fibre laser resonators emitting a continuous beam are not limited in this respect. As a result, on one hand, it is possible to obtain a required penetration depth and, on the other, it is possible to avoid cracks, as due to extinction characteristics of any length, weld deposit cooling conditions are optimised intentionally. As a result of high focusing ability, even for a low continuous beam power (below 100 W), it is possible to obtain power density enabling metal cutting and welding. The quality of a beam, of the order of $M^2<1.1$, limited by diffraction, leads to slender radiation beam narrowing, reducing the amount of heat in a workpiece. Further examples of basic mode fibre laser welding are presented in Figures 8 and 9.

Applications of Fibre Lasers Emitting a Multi-Mode Continuous Beam

If a required penetration depth or the thickness of a material to be cut exceeds 2 mm, it would be useful to dispose of a "switch" between a basic mode fibre laser beam and a multi-mode beam. A multi-mode fibre laser is composed of many single-mode lasers. Depending on a number of connected single-mode laser modules, it is possible to transmit up to 5 kW via a multi-mode optical fibre having a diameter of 50 μm and up to 20 kW via a multi-mode optical fibre having a diameter of 100 μm.

The beam quality of a fibre laser provided with an optical fibre having a diameter of 50 μm (BPP=2) and an optical fibre having a diameter of 100 μm (BPP=4) enables numerous welding and cutting applications, examples of which are presented below.

Cutting

A fibre laser provided with an optical fibre having a diameter of 50 μm or that of 100 μm,

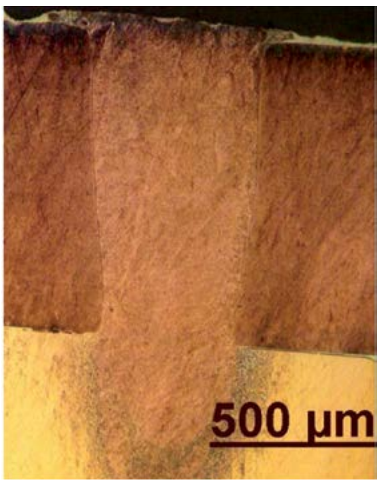

Fig. 7. Metallographic specimen of an overlap joint of a copper contact pin

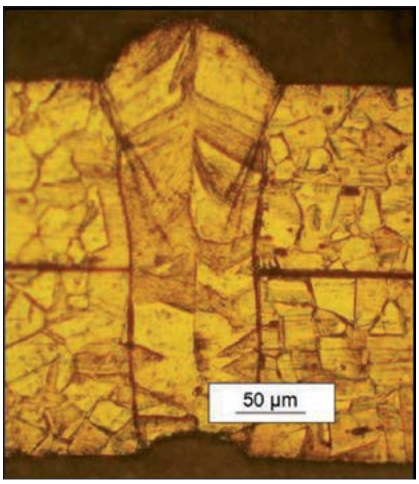

Fig. 8. Overlap joint 2 x 0.1 mm made of alloy steel

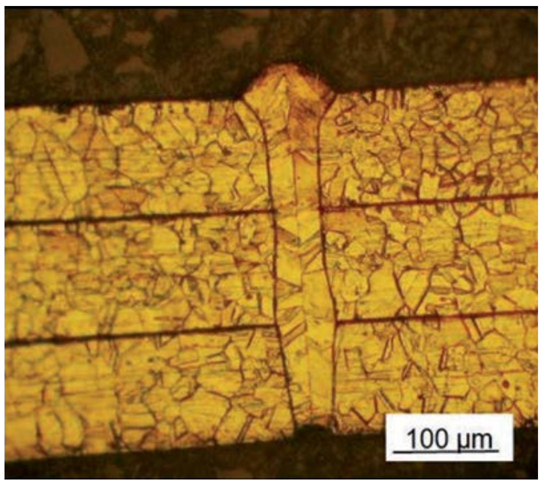

Fig. 9. Overlap joint 3 x 0.1 mm made of alloy steel

emitting a continuous beam of a power up to 8kW, has already been used by many producers of flat cutting machines and supplanted conventional lasers. A lower-power fibre laser cuts faster than a CO_2 laser, thus reducing energy consumption. The power consumption of a 2 kW beam fibre laser amounts to 5 kW, whereas the power consumption of a 4 kW beam CO_2 laser amounts to 44 kW. Figure 10 presents cutting rates obtained by both machines.

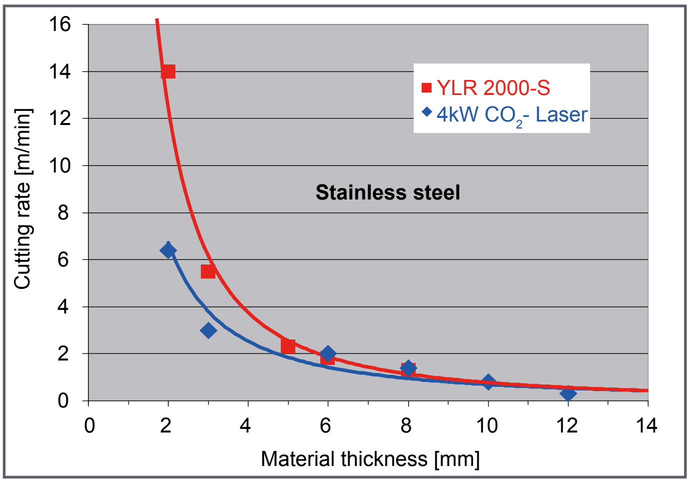

Fig. 10. Comparison of a cutting rate offered by a fibre laser (beam power of 2 kW) with that obtained using a CO_2 laser (beam power of 4 kW)

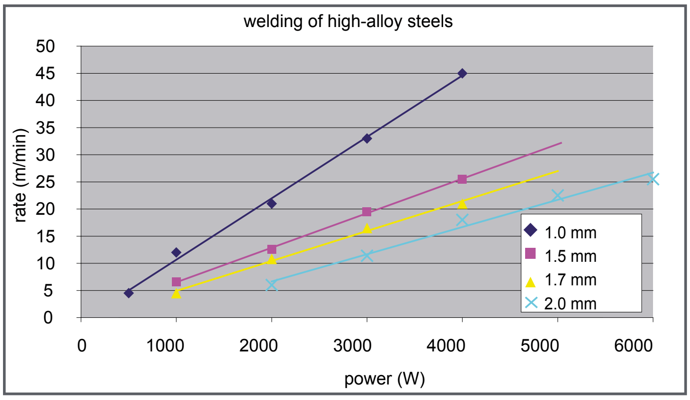

Fig. 11. Cutting rate of a fibre laser (1-5 kW)

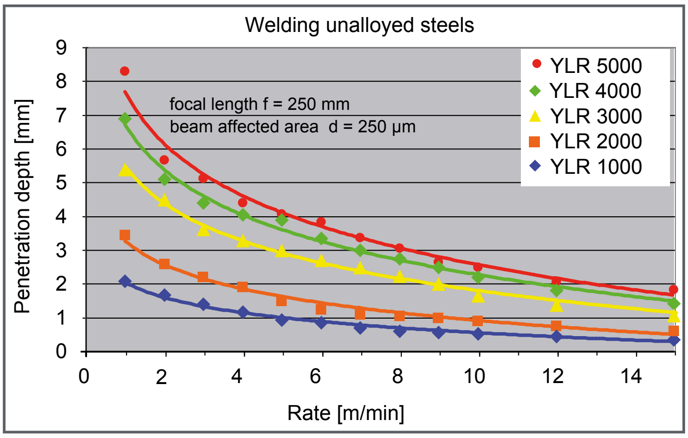

Fig. 12. Welding rates and laser beam penetration depths obtained by 1-5 kW fibre lasers

An advantage of fibre lasers is simple beam transmission via optical fibres, translating to higher efficiency and energy saving. Leading a beam in CO_2 lasers in a free manner [transmission system referred to as flying optics] is significantly more expensive.

In the past, great progression was made in relation to the optimisation of process parameters concerned with optics, gas supply and nozzle geometry as well as in terms of determining proper laser parameters (i.e. power and modulation) in order to guarantee cutting quality expected by users of co2 laser cutters. Many years of research spent on optimising fibre laser cutting process parameters have led to the obtainment of impressive process efficiency as well as to excellent cutting quality within a vast range of thicknesses and materials. An example of multi-mode fibre laser cutting is spatial cutting (3D) of type B car body pillars made of high-strength steels. Figure 11 presents processing rates obtainable in cutting 1-2 mm thick sheets using a 1-5 kW laser.

Welding

In welding, the possibility of adjusting power within a wide range, related to the welding device module design, proves very advantageous. Depending on a required welding rate and a penetration depth reached by a laser beam, a required laser power is obtained by joining an appropriate number of laser modules. Figure 12 presents a welding rate and a laser beam penetration depth obtained by 1-5 kW fibre lasers.

In the manufacture of furnace chambers used in power plants or while producing heavy machinery, it is necessary to obtain a penetration depth of up to 30 mm during a production process. Figure 13 presents a butt joint made of 32 mm thick alloy steel plate I. A fibre laser enables welding thick-walled elements which previously were welded only in multi-run arc welding processes or, in cases of larger batches, welded in a vacuum chamber using an electron beam.

Summary

Due to their unique design, fibre lasers have replaced conventional lasers, enabling new applications to be invented. IPG Photonics is the manufacturer of state-of-the-art fibre lasers used in contour band saws, welding machines and other systems for material laser processing.

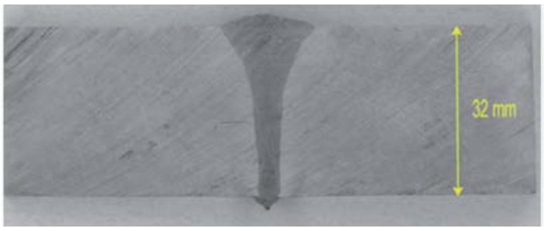

Fig. 13. Type I butt joint made of 32 mm thick alloy steel (t=32 mm) ; laser power of 30 kW; even thick elements can be welded successfully