Basics and Features of High-Power Fiber Laser

Kuniharu Himeno[1]

The high-power fiber laser is superior to other high-power lasers with a gain medium of solid crystal or gas in all aspects such as beam quality, energy efficiency, space efficiency, stability and reliability, and is getting the major position in laser processing field. Fujikura has grown up high-power fiber laser technologies on the basis of its proprietary optical fiber related technologies, and one of the milestones is described in "special issue on fiber laser" of this Fujikura Technical Review. As an introdction of the issue, this report reviews structural features of high-power fiber lasers and their advantages together with parameters characterizing the advantages.

1. Introduction

Since the laser, originally Light Amplification by Stimulated Emission and Radiation, was invented more than half a century ago, it has given rise to major innovations in a variety of fields including fiber optic communications, optical storage, material processing, healthcare, analysis, and instrumentation. The field of laser processing, one of the large application areas of the laser comparable with optical communications and storage, has traditionally been dominated by carbon dioxide (CO_2) gas and yttrium aluminum garnet (YAG) solid ones. Recently, however, as output power of laser diodes (LDs) has increased, a high-power fiber laser consisting of high-power LDs and double-clad active fibers with Yb-doped core is expected to take a leading position. In fact, the sales of fiber lasers are now approaching those of CO_2 lasers, and are forecast to surpass the latter in 2015[1)].

Fujikura started research and development of optical fibers 40 years ago, and since then has been promoting related technologies for optical fiber communications. Over time, the company has established an entire range of fundamental technologies needed for fiber lasers, including specialty fibers (e.g. active fibers), optical components such as fiber Bragg gratings (FBGs) or pump combiners, fiber and component connection, and control of optical communication devices.

Based on these optical-fiber-related technologies, Fujikura started R&D projects on high-power fiber lasers in 2005[2)]. It has thus mastered elemental optical technologies for power improvement of fiber lasers such as high-power LDs and optical isolators for high power, which, in combination with heat dissipation technology used in the electric/electronic devices, have resulted in the current product lines, including high-power pulse fiber lasers, high-power continuous wave (CW) fiber lasers, and linearly polarized CW fiber lasers. Some of these new technologies and products are presented in this issue.

This article explains the basics and features of high-power fiber lasers as an introduction to the other articles in this issue. The described items are as follows : the configuration and features of the high-power fiber lasers which have enhanced the output power, technical points realizing the high-power such as operation of individual laser modes, and the characteristic indices featuring the advantages of the high-power fiber lasers.

2. Configuration of fiber lasers

2.1 Basic configuration of fiber lasers

The fiber laser is a laser that uses an optical fiber as the active medium, which usually has a rare-earth-doped core. Figure 1 shows the basic configuration of the optical circuit of a high-power fiber laser with a rare-earth-doped core fiber. Light from pumping LDs passes through a pump combiner into the active fiber to pump the active element in the core. The electrons are pumped to an energy level corresponding to the wavelength of the pump light, and then transit to a lower longer-life metastable state. If the intensity of the pump light is sufficiently high, the number of electrons in the metastable state exceeds that in the ground state—a situation known as population inversion. The spontaneous emission, or the transition of electrons to the ground state causing emission of light (luminescence) with a wavelength corresponding to the energy difference, occurs irrespective of population inversion.

The major active element used in the fiber lasers for material processing is Yb. This element provides light absorption (available for pumping) at wavelengths of 900-1000 nm, and fluorescence that causes laser oscillation lies at 1000-1100 nm[3)]. Since most metallic mate-

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[1] Fiber Laser Business Development Division, New Business Development Center

Panel 1. Abbreviations, Acronyms, and Terms.

YAG—Yttrium Aluminum Garnet	NA—Numerical Aperture
LD—Laser Diode	MOPA—Master Oscillator-Power Amplifier
FBG—Fiber Bragg Grating	BPP—Beam Parameter Product
CW—Continuous Wave	WPE—Wall Plug Efficiency
DCF—Double Cladding Fiber	

rials show relatively high light absorption in this wavelength range, Yb-doped core fiber lasers are suitable for material processing as Nd-doped YAG lasers.

On both sides of the active fiber, FBGs (gratings formed on optical fiber cores) are provided, which act as mirrors reflecting light of a specific wavelength. The mirrors of high and low reflection constitute a laser resonator. The light with a specific wavelength reflected selectively by the FBGs among the spontaneous emission causes induced emission in the resonator. The light thus produced by induced emission propagates in the resonator to be reflected by the both FBGs and stimulates further induced emission. The repetition of induced emission results in laser oscillation to emit laser light from the output port of low reflection FBG.

In addition to the optical circuit shown in Fig. 1, the fiber laser contains a driver for the pumping LDs and its power source, a controller circuit to regulate the output power through the LD driver, a heat dissipation section which cools the pumping LDs, active fiber and fiber splices, and a housing containing these components and circuits.

2.2 *Structure of active fiber*

Figure 2 shows the structure of the active fiber using double-clad fiber (DCF) structure, an important feature of the high-power fiber laser, as well as a waveguide of the pump and laser lights. The pump light, which is the power source of the laser, enters the first cladding, is confined and propagates within the second cladding. The Yb ions in the core are pumped by the light passing across it, which produce laser light by resonance occurring between the FBGs as described earlier. The laser light is confined in the core by the first cladding and propagates in the core.

Owing to its large cross section, the first clad of the DCF can accept a large amount of pump light from a number of high-power multimode LDs as gathered by the pump combiner as shown in Fig. 1. On the other hand, the core diameter should be small enough to permit single-mode oscillation of the fiber laser as shown in Fig. 1. The DCF can thus be regarded as a mode converter that makes a highly convergent single-mode laser light from a number of less convergent multimode light beams from the LDs. The DCF is thus an essential component of the high-power fiber laser.

2.3 *Enhancing power of fiber lasers*

The waveforms of laser light in different operation modes are shown in Fig. 3. Fiber lasers configured as shown in Fig. 1 are usually operated either in the CW mode where the laser beam of constant power is emitted or in the quasi-CW mode where the output light is modulated with a frequency of several tens kHz. The CW laser is used for macroscopic material processing

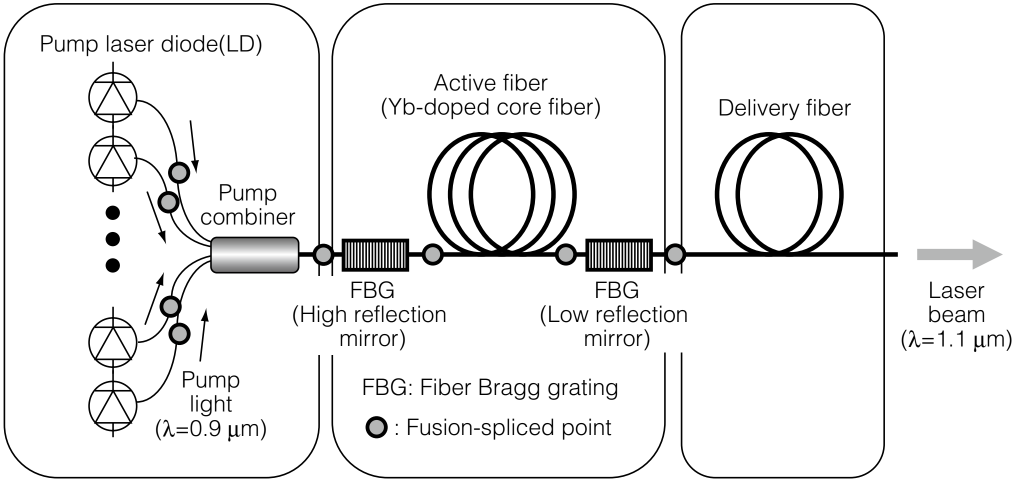


Fig. 1. Basic configuration of optical part in high power fiber laser.

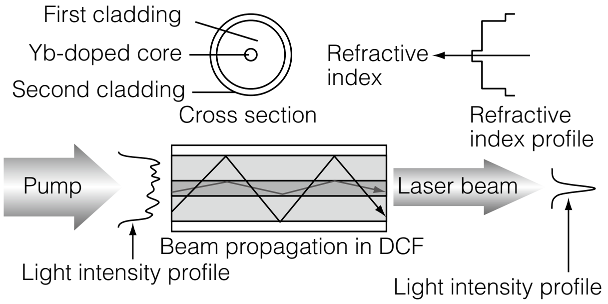
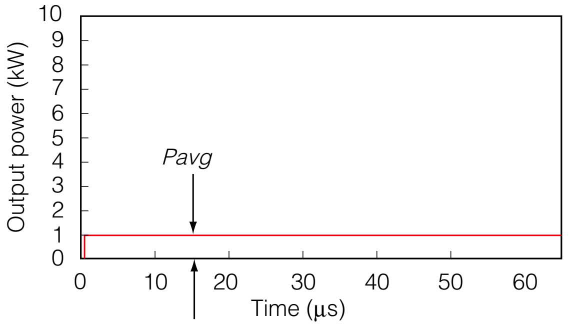
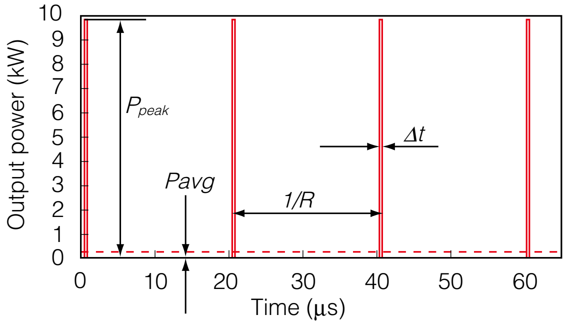


Fig. 2. Structure of double-clad fiber(DCF) and propagation of light beam.



(a) CW operation



(b) Pulse operation

Fig. 3. Waveform of laser light for respective operation modes.

such as cutting and welding.

Principal means for enhancing the output of a CW laser shown in Fig. 1 are (1) using pump LDs with higher luminance, higher output and low numerical aperture (NA), and (2) increasing the number of the input ports of the combiner and using a DCF with a greater cladding diameter. In addition, combination of the output beams from more than one single-resonator fiber lasers is a common practice. The combination is performed in a fiber-type component rather than in space, in order to utilize features of the fiber laser, which will be described in the later section. The combined light is multimodal even if the output of the single-resonator lasers is in the single-mode.

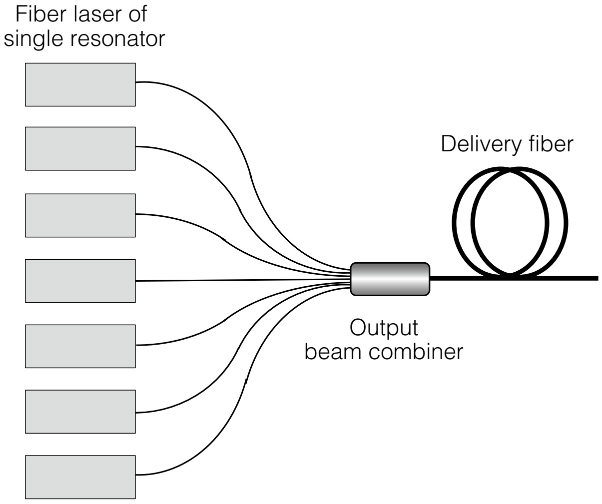


Fig. 4. Power enhancement by output beam from single-oscillator fiber laser.

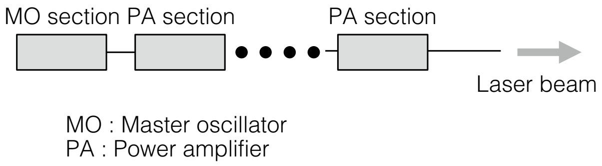


Fig. 5. Master oscillator power amplifier(MOPA) configuration.

Lasers for surface processing and micro processing, such as marking and patterning, are operated in the pulse mode with a high peak power (Fig. 3(b)) in order to evaporate the material by instantaneous heating of the surface. The pulse laser is characterized by the energy E of a single pulse or the peak power P_{peak}, which are related to the average power P_{avg}, pulse repetition frequency R, and effective pulse width Δt as follows:

$$E = \frac{P_{avg}}{R} \tag{1}$$

$$P_{peak} = \frac{E}{\Delta t} \tag{2}$$

Since the operation speed of the LDs limits the speed of pulse operation of lasers with the basic configuration of Fig. 1, a master oscillator power amplifier (MOPA) configuration as shown in Fig. 5 is generally used in pulsed fiber lasers. Pulsed laser light generated by the master oscillator (MO) is amplified by the power amplifier (PA) to give a high power pulsed laser light.

The MO usually uses an LD which can be directly modulated at a high modulation speed or a fiber laser. The fiber laser used as the MO has an optical switch based on acousto-optics or nonlinear optical effect for

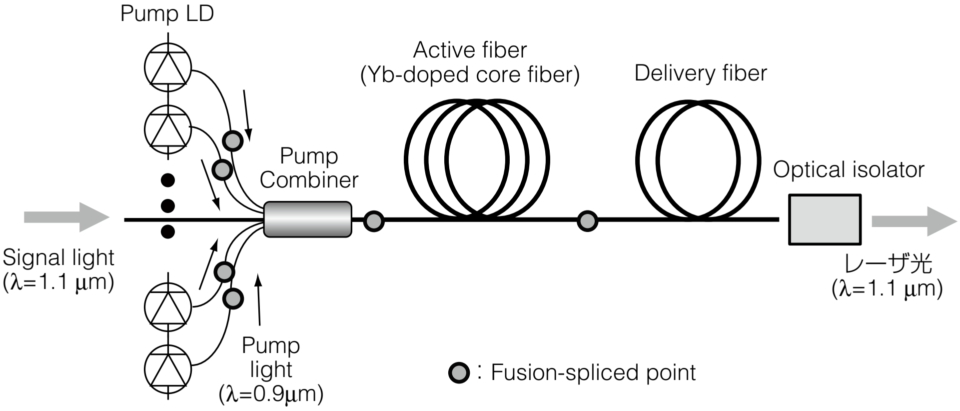


Fig. 6. Basic configuration of power amplifier(PA).

modulation, which is integrated in the resonator shown in Fig. 1.

The configuration of the PA, shown in Fig. 6, is similar to that of Fig. 1, but it lacks the FBGs and the pump combiner has a mechanism to introduce the pulse signal into the Yb-doped core fiber. The optical isolator provided to the emission port of the PA is an essential component in the MOPA configuration: it prevents light reflected by the work from re-entering the PA. Without this, the reflected light would be amplified in the PA and possibly return to the MO, and, if the power exceeds a threshold, would destroy components and fibers even made of quartz glass.

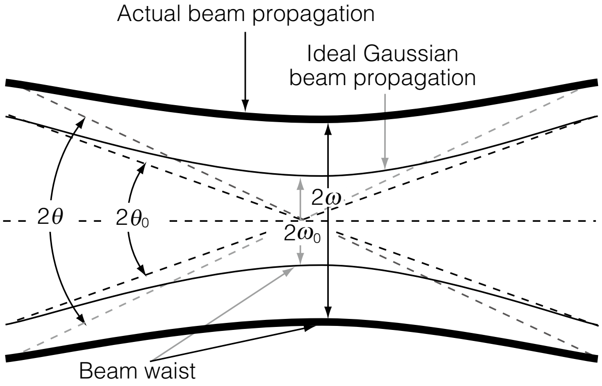


Fig. 7. Laser beam propagation at beam waist.

3. Features and characteristic indices of fiber lasers

Yb-doped fiber lasers are superior to traditional lasers using solids or gases as the active medium in many aspects including power, beam convergence, power efficiency, space efficiency, stability of power and beam, and reliability. This section explains the characteristic indices that indicate the performance of high-power fiber lasers along with their features and advantages.

3.1 High beam quality

The quality of the laser beam emitted from a fiber laser chiefly depends on the transverse mode of the light from the Yb-doped core. Appropriate choice of the core diameter and difference of relative refractive indices can reduce the number of transverse modes to ensure the high quality of fiber lasers.

A characteristic index of laser beam quality is M^2, which measures the limit of constriction of the beam with respect to the diffraction limit. Fig. 7 shows the waist of a beam constricted by a lens. M^2 is given by

$$M^2 = \frac{w\theta}{w_0\theta_0} = w\theta\frac{\pi}{\lambda} \tag{3}$$

where w_0 and w are the spot sizes of the ideal Gaussian beam and the actual beam, respectively, at the waist, and θ_0 and θ the spread angles of the ideal Gaussian beam and the actual beam, respectively. The spot size of the ideal Gaussian beam is defined as the beam radius at which the light intensity is $1/e^2$ times the peak intensity, while that of a general beam is defined as the secondary moment of the light intensity.

A single-transverse-mode beam from a fiber laser has $M^2 = 1.1$, indicating that the beam can be constricted approximately down to the diffraction limit. This is an advantageous feature when the beam is used for micro processing such as marking or patterning. It also means a higher power density of the beam on the surface of the work, which facilitates processing of aluminum, copper, or other materials that are difficult to process by conventional lasers. From a different viewpoint, this feature indicates that the fiber laser beam can have a smaller divergence angle than other types of lasers for a given spot diameter, namely, a longer focal length. Therefore, fiber lasers are useful for remote processing in which the work is processed by the beam from a distant laser-emitting end via a galvano mirror.

An index describing the possibility of convergence of the beam or extension of the focal length is the beam parameter product (BPP), which is related to M^2 as follows:

$$BPP = w\theta = M^2 \frac{\lambda}{\pi} \quad (4)$$

The CO_2 laser also provides a beam of very good quality and can attain $M^2 = 1$. However, its wavelength as long as 10.6 μm limits the *BPP* to 3.4 mm·mrad even at $M^2 = 1$. In contrast, single-mode fiber lasers attain a *BPP* of 0.34 mm.rad and multimode fiber lasers even with combined beam according to Fig. 3 attain about 2.5 mm·mrad. The fiber laser thus provides a better solution than the CO_2 laser in terms of the beam diameter actually obtained.

3.2 High power and brilliance

While the beam quality of high-power solid lasers, including YAG lasers, deteriorates at powers higher than 100 W due to the thermal lens effect, fiber lasers based on a thin optical fiber with a diameter of several hundred micrometers as the active medium can easily be cooled and therefor attains high power output while maintaining the laser beam quality.

The brilliance *B*, defined[4] by equation (5), is a characteristic index for the entire light source, including the beam quality:

$$B = \frac{P}{\pi\omega^2 \times \pi\theta^2} = \frac{P}{\pi^2 BPP^2} = \frac{P}{M^4\lambda^2} \quad (5)$$

As mentioned in the previous section, the power of fiber lasers can be enhanced in more ways than other types of lasers. The brilliance *B*, when we consider light from the pump LDs as the starting point in Figs. 1 and 3, is not enhanced in light combiners such as the pump combiner and the output combiner, but only in the resonator where the DCF is used. For example, the brilliances of high-power fiber lasers are more than 5000 times that of the pumping LDs[5]. The DCF acts not only as a mode converter but also as an effective brilliance intensifier.

3.3 High energy conversion efficiency

Fiber lasers have very low loss of the pump and laser lights, because they are both confined and guided in the low-loss fiber core. The pumping LDs have an electricity-light conversion rate as high as 40 to 50%. Furthermore, the high quantum efficiency of ytterbium serving as the active element leads to 60-75% efficiency in energy conversion from pump light to laser light. Owing to these factors, fiber lasers achieve a high output power with a high energy conversion efficiency while maintaining a high beam quality.

A characteristic index for the overall efficiency of a laser is wall plug efficiency (WPE), defined as the ratio of the output power Po to the power Pi supplied to the laser device from a commercial power source. For an electron-electron conversion efficiency η_{EE} of the power source and the LD driving circuit, an electron-photon conversion efficiency η_{EP} of the pumping LD, and a photon-photon conversion efficiency η_{PP} of the resonator (including loss in the pump and laser lights), *WPE* is represented by the following equation:

$$WPE = \frac{P_O}{P_i} = \eta_{EE} \times \eta_{EP} \times \eta_{PP} \quad (8)$$

For a typical high-power fiber laser, η_{EE}, η_{EP}, and η^{PP} are around 0.8, 0.5, and 0.7, respectively, resulting in a *WPE* of 28%, clearly showing the superiority of the fiber lasers in efficiency, as compared to *WPE*s of about 10% for CO_2 and YAG lasers. Incidentally, since any energy loss is converted to heat, fiber lasers need heat dissipation mechanisms as do other types of lasers.

3.4 Small dimensions and reduced weight

Owing to the very high energy conversion efficiency and a resonator consisting of fine fiber and small optical components, the high-power fiber laser has a far smaller heat dissipation mechanism and power supply, and thus far smaller overall dimensions and weight, than conventional high-power lasers.

For example, while a typical 300-W YAG laser has a volume of 0.4 m^3 and a weight of 300 kg, the volume and weight of a fiber laser with the same output power are 0.08 m^3 and 50 kg, respectively. In addition, forced air cooling is enough to remove heat from a fiber laser of this class, which eliminates an external chiller and the space for it. Similarly, a 4-kW fiber laser with a volume of 1.2 m^3 and a weight of 650 kg compares favorably with a CO_2 laser with 2.5 m^3 and 1500 kg for the same output power.

3.5 High stability and reliability

Conventional lasers need lenses and mirrors for constructing the resonator and conducting the beam to the working point. Since these optical components are fastened mechanically to housings and/or base plates and are susceptible to displacement due to vibration, shock, or temperature changes, they require adjustment after installation as well as periodical adjustments. The components may also be stained or damaged during prolonged usage and must be cleaned or replaced periodically. In contrast, fiber lasers constructed by fusion-splicing optical fibers are not influenced by vibration, shock, or temperature changes, and therefore have stable output power and beam quality. They are also practically maintenance-free since the paths of the beam are not exposed to the atmosphere.

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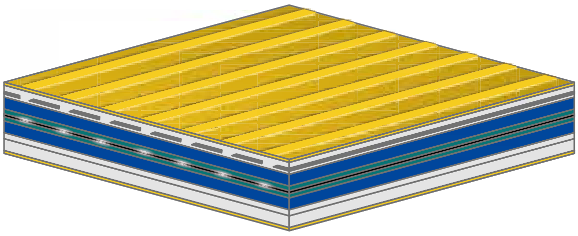
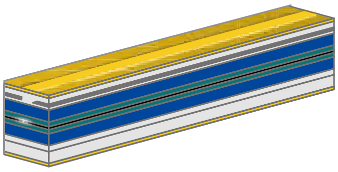


(a) LD bar chip



(b) Single-emitter LD chip

Fig. 8. Structures of LD chips.

the pumping system also contribute to the high reliability of the high-power fiber laser. LDs can pump YAG lasers, and in fact, high-power YAG lasers pumped by LDs had been regarded as potential mainstream tools for material processing. The LD-pumped YAG laser generally uses a multi-emitter LD bar consisting of a chip containing several light-emitting units (Fig. 8(a)). Since the emitters in the chip have to be connected in parallel, failure of a single unit leads to total loss of light from the chip.

In contrast, the high-power fiber laser uses single-emitter LD chips consisting of a chip containing only one light emitter (Fig. 8(b)) for its high-power pumping LDs. This means that defective units are effectively rejected in one-by-one screening, which contributes to ensuring the reliability of the high-power pumping LDs. In addition, heat from an emitter does not affect other emitters, which allows separation of chip and thermal designs. This also ensures high reliability of the high-power pumping LDs. Furthermore, since the single-emitter LD chips are connected in series when several pumping LDs or LD chips are used, even in the case where an LD chip is failed (e.g. short-circuited), it does not affect others. Thus, the high reliability of the high-power fiber laser owes also to the LDs and LD systems used.

4. Conclusion

This report describes the basics and features of the high-power fiber laser. The author hopes that the contents help my readers understand the following articles in this issue better.

Reference

1) A. Nogee: The Worldwide Market for Lasers-Market Review and Forecast 2014, Strategies Unlimited, pp.32, 2014.

2) K. Himeno: “Fiber lasers and their advanced optical technologies of Fujikura”, Fujikura Technical Review no. 42, pp. 33-37, 2013.

4) T. Arai: Fundamental engineering of laser processing (in Japanese), Maruzen Co., Ltd., pp. 129-130, 2007.

5) K. Sumimura and M. Nishiura: Fiber lasers (in Japanese), The Optronics Co., Ltd., p. 133, 2013.