10-W Fiber Laser for Laser Marking Application

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Fiber lasers are promising candidates for next-generation laser sources for laser machining systems as they are superior to Nd-YAG solid-state lasers in most characteristics such as space and energy-efficiency and beam finesse required for micro-machining. In particular, there exists an obvious demand for fine marking, so that laser marking is a befitting application for fiber lasers in making effective use of the characteristics of fiber lasers.

In this paper, a newly developed fiber laser for laser marking application is reported. The fiber laser employs a master oscillator power amplifier (MOPA) configuration with a Q-switch and a unique pump combiner consisting of a multi-hole silica capillary and achieves an average output power of 14.4 W and a fine beam quality of M^2 = 1.1. The fiber laser also employs a direct analog control of pumping LDs and various fail-safe functions. Consequently, the developed fiber laser is proved to be a useful laser source for laser marking application, from a practical standpoint.

1. Introduction

The fiber lasers that employ ytterbium (Yb) doped fibers (YbDFs) as amplifying media are among the highest power lasers. In addition, the laser emission wavelength of an YbDF laser, around 1.06 μm, is nearly the same as that of Nd-YAG solid-state lasers which are the most presently available solid-state laser sources in material processing and machining industry. The YbDF lasers are superior to Nd-YAG lasers in most characteristics such as dimensions, energy-efficiency, and resolution for micro-machining. As a result, the YbDF lasers are promising candidates for next-generation laser sources for laser material processing and machining systems.

Laser marking is one of the applications in laser material machining or processing. By exposing the surface of the marking object material, called “work,” to the laser beam, the surface of a work at its exposed area is heated and consequently oxidized, melted, or sublimated. These material modifications cause visual changes such as ditching, foaming, and coloring. As a result, drawings such as characters and logos can be printed on the work. The laser marking is applicable to various materials such as metals, semiconductors, and polymers.

Downsizing of equipment in many industries is desired, so that components and devices in the equipment are getting more and more miniaturized. A clear demand for precise marking exists in marking applications because many of the objects are tiny components or devices such as IC packages, IC chips, resistances, and capacitors.

Fiber lasers are among the best solutions for such a demand because the beam from a well-designed fiber laser can be focused on an extremely small spot size in the order of micrometers. This small spot size comes from the intrinsic property of the fiber lasers, which can emit a diffraction-limited beam. This property also realizes high power-density at a focal point. Thus, it is thought that laser marking is a befitting application in making effective use of the characteristics of fiber lasers.

In this paper, a newly developed fiber laser for laser marking application is reported. First, the principles and features of fiber lasers, especially of an YbDF laser, are introduced. Next, the configuration of the developed fiber laser and applied components and technologies such as a double-clad YbDF, a pump combiner, and a controlling circuit are described. Finally, the performance of the fiber laser is reported.

2. Principles and features of fiber lasers

In fiber lasers, rare earth doped fibers are employed as light amplifying media. A rare earth doped fiber is a fiber with a core in which rare earth ions are dispersed and signal (or seed) light can be amplified by stimulated emission from the photo-excited rare earth ions. As for YbDFs, trivalent ytterbium ions (Yb^{3+}) are allowed to have an interband

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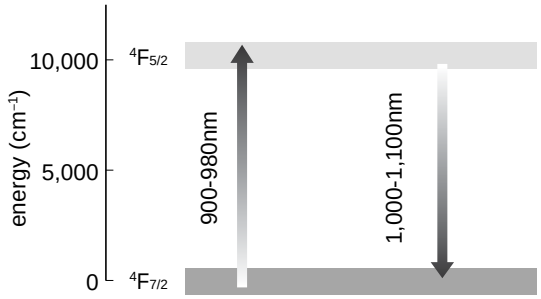


Fig.1. Energy level diagram of Yb^{3+}.

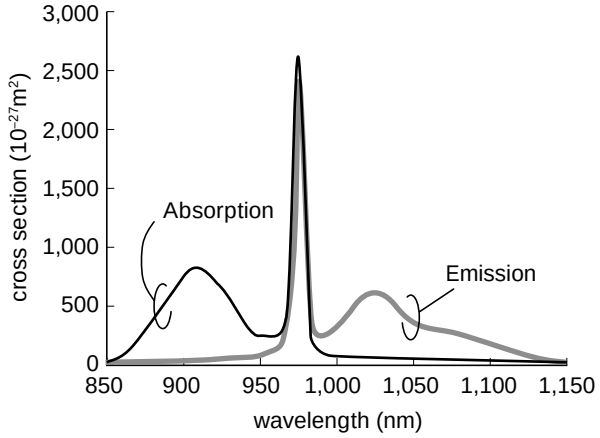


Fig.2. Absorption and emission cross section spectrum of YbDF.

transition between $^4F_{5/2}$ and $^4F_{7/2}$, and its transition energy corresponds to the photon energy at a wavelength of around 1.0 μm as shown in Fig.1. Thus, YbDFs can irradiate the laser light of nearly 1.0 μm wavelength. Figure 2 shows the absorption and emission cross sectional spectrum of a typical YbDF. The pump wavelength in an YbDF amplifier or laser is chosen out of the range from 900 nm to 980 nm where YbDFs have large absorption cross sections. Similarly, an amplifying or laser oscillation wavelength is selected out of the wavelength range from 1,000 nm to 1,100 nm where YbDFs have large emission cross sections in the range. By these pumping and amplifying or oscillation wavelength selections, high energy-efficient amplification or laser oscillation can be achieved.

The YbDF lasers are among the highest output power rare earth doped fiber lasers as a result of the following two natures of YbDFs. The first advantageous nature is YbDF's light emitting scheme. Only three electron levels in an Yb ion, two fundamental levels of $^4F_{5/2}$ and one excited level of $^4F_{7/2}$ relate to the emission. This electron level diagram results in less nonradiative transition processes such as up-conversion that deteriorates the efficiency of light emission. The other advantageous nature is that Yb^{3+} ions can be relatively heavily-doped into silica glass. As a result, we can obtain a large absorption cross section

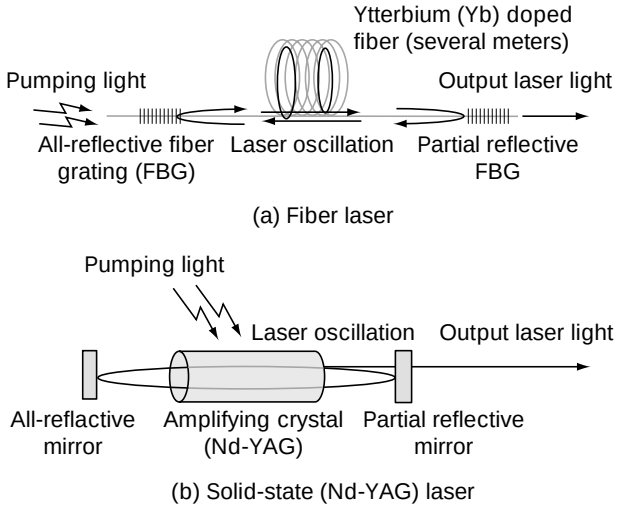


Fig.3. Schematics of (a) fiber laser and (b) solid-state laser.

of YbDFs by the high concentration doping of Yb.

As YbDF lasers can irradiate high-power beams, they are optimal laser sources for material processing or machining such as cutting, welding, drilling, soldering, and marking, all of which need to expose the work point or area of a work to high-density energy.

Additionally, YbDF lasers have an advantage that their emission wavelengths can be equal or near to that of Nd-YAG lasers. As Nd-YAG lasers are among the most available laser sources for material processing and machining, YbDF laser systems can employ technical resources obtained for Nd-YAG lasers, such as optical components, technical knowledge, and especially, existing facilities.

Figure 3 shows the schematic illustrations of a fiber laser and a solid-state laser typified by an Nd-YAG laser. Typically, a conventional solid-state laser consists of two facing reflective mirrors forming an optical resonance cavity for lasing and a solid-state amplifying medium such as an Nd-YAG crystal allocated between these mirrors (see Fig.3 (b)). Meanwhile, a fiber laser has schematically the same configuration, except that it consists of only fibers and fiber-based optical components (see Fig.3 (a)). As the fiber laser does not have free-space optical paths and its laser light is guided by only fiber-based (solid-state) paths, the fiber laser shows high robustness against environmental conditions such as dust, humidity, temperature, and their changes. Moreover, the fiber laser does not require annoying alignment of optical paths, which is required when we utilize free-space optical paths in the laser. This robustness is a great advantage of the fiber laser over other solid-state lasers.

One of the constraint factors to obtain higher output power by solid-state lasers comes from the difficulty in exhausting the heat from the amplifying medium. Solid-state amplifying media used in conven-

tional solid-state lasers typically have mechanical dimensions of several millimeters in diameter and several centimeters in length. On the contrary, the rare earth doped fiber is an amplifying medium with its diameter in the range of submillimeters and its length around several meters for an output power of which more than 1 W is required. Owing to these dimensions, the rare earth doped fiber can have larger specific surface area than the conventional solid-state amplifying media. As a result, the cooling efficiency of the fiber lasers is superior to that of the conventional solid-state lasers. Consequently, the cooling system for the fiber laser can be simplified, for example, cooling fans are effective enough to cool the YbDF. This contributes to the downsizing of the laser systems. In addition, this excellent cool-efficiency can also reduce the thermal lens effect [1)] of the amplifying media, which is the limiting factor of output laser power. As a result, the fiber laser can generate high power and high power-density laser beam.

As mentioned above, fiber lasers are composed of only fiber-based paths. Thus, by employing single-mode optical components in the optical paths, a definite single-transverse-mode cavity and resultant single-mode laser operation can be easily obtained in the laser. The number of optical modes included in an output beam is closely related to the beam quality represented by M^2 factor. The M^2 factor is defined as the beam size parameter divided by the beam size for a diffraction-limited Gaussian beam with the same wavelength, and it represents how small spot size can be obtained by the beam. The best possible beam quality is $M^2 = 1$, which corresponds to a diffraction-limited Gaussian beam. The $M^2 = 1$ beam quality is theoretically available by using a definite single-mode beam. The fiber laser, which can easily realize the single-transverse-mode output beam by the single-mode cavity, is currently one of the ultimate light sources with a beam that is focusable to a diffraction-limited spot size.

Table 1. Comparison of fiber laser with solid-state (Nd-YAG) laser.

Item	Fiber laser	Solid-state laser
Amplifying media	Rare earth doped fiber	Crystal
Cooling method	Air cooling	Water cooling
Dimensions	Small	Large
Portability	Good No need to optical alignment	Bad
Robustness for environment	High Consist of only solid path	Low Include airy path
Beam quality (M^2)	Fine (~1)	Low (3~7)
Cross sectional area of cavity	Small	Large
Optical power density	High	Low
Robustness for optical damage	Low	High
Energy usage efficiency	High (~ 60 %)	Low (~ 10 %)
Maintenance	Easy Basically maintenance free	Needed for water cooling systems and optical realignment

From these viewpoints, the fiber laser is an appropriate light source for micro-material processing or micro-machining such as laser marking that needs a high power and a fine beam.

Additionally, the fiber laser is superior in the coupling efficiency between the pump laser diodes (LDs) and the amplifying medium. Consequently, it has high energy usage efficiency. In contrast to the efficiency, it is difficult for the fiber laser to raise its output power to a level of several kilowatts as the light power density becomes extremely high because of the small cross section of light propagating area. In some cases of a kilowatt fiber laser, the density reaches up to 100 GW/cm^3. As a result, the laser cavity (fiber) might break because of optical damage.

A qualitative comparison of fiber lasers with Nd-YAG solid-state lasers of several tens of watt output is summarized in Table 1.

3. Configurations and applied technologies

3.1. Overview of configurations

We have employed a master oscillator power amplifier (MOPA) configuration as a principal design of our new fiber laser. The schematic illustration of the fiber laser is shown in Fig.4. It consists of a master oscillator (MO), a power amplifier (PA), a pump combiner, pump LDs, an isolator, and controlling circuits.

Seed laser light is generated in the MO, which is composed in the similar configuration as shown in Fig. 3, except for adding a Q-switch in the cavity to generate pulsed light. For material processing, the peak power of the laser beam is as important as the average power as some materials have their specific power-density threshold to be processed by laser beam. A Q-switched laser can produce a pulsed laser beam with a high peak power. That is the reason why we adopt the Q-switch operation.

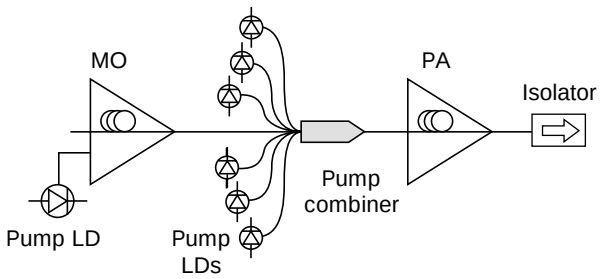


Fig.4. Schematic diagram of designed 10W fiber laser.

The pulsed seed light from the MO is amplified in the PA to obtain a high-power laser beam. The PA mainly consists of a double-clad YbDF (DC-YbDF). The pumping light from pump LDs is delivered into the inner cladding of the YbDF through the pump combiner. By absorbing the pumping light energy in the core of the YbDF, the seed light is amplified from subwatts to around 10 watts in average power. The average power of 10W corresponds to a few hundred watts to several kilowatts in peak power.

The isolator is installed at the output end to prevent the reflected light intruding back from marking objects. The controlling circuit drives and monitors the laser (it is not indicated in Fig.4).

3.2. Double-clad ytterbium doped fiber (DC-YbDF)

The fiber used in the PA is made of silica glass. The silica glass, which has a damage threshold of about 100 GW/cm^2, is one of the toughest materials against optical damage. Therefore, the silica glass is a suitable material for such a high-optical-power-handling system like a fiber laser.

Even though such robust material as silica glass is used for the PA region, careful designing for the PA structure is needed to prevent optical damage. In our 10W fiber laser, several tens of watt pumping light and more than a kilowatt pulsed signal light are propagated in the PA. Because the fiber has a very small propagating area, the optical power density in the fiber can be very high up to 100 GW/cm^2 if no provision for the optical damage is adopted.

For that purpose, we have employed a double-clad YbDF (DC-YbDF) in the PA region. The DC-YbDF has a core region and two clad layers, whose refractive indices are different from each other. The core propagates signal light. The inner clad that surrounds the core propagates pumping light. The outer clad surrounding the inner clad is for caging pumping light. UV-curable resin is coated around the outer clad in order to protect the fiber from outward injury. The schematics of cross sectional structure and reflective index profile of the DC-YbDF are shown in Fig.5. The diameter of inner clad is several hundred micrometers, which enables to lower the optical power density of pumping light and consequently to prevent optical damage of the fiber. Optical power density for signal light is also reduced by expanding the core diameter up to around 20 μm. Moreover, the YbDF is designed to suppress the effects of photo-darkening [2] and skew modes [3].

With these deliberate designs, the pulsed fiber laser of an average output power of tens of watts class can be developed.

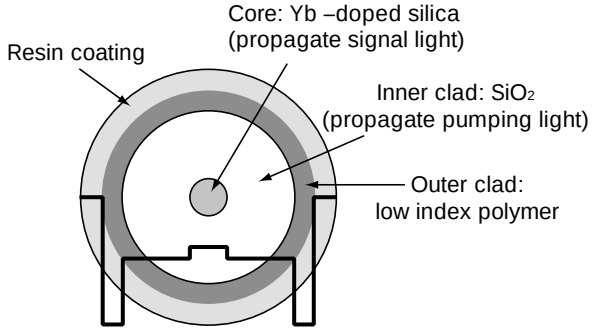


Fig.5. Cross sectional structure and reflective index profile of DC-YbDF.

3.3. Pump combiner

Combining pumping light to DC-YbDF is very important from the viewpoint of energy usage efficiency. Thus, the pump combiner is one of the key devices for fiber lasers.

We have developed and employed our unique pump combiner consisting of multi-hole silica capillary [4] for the developed fiber laser. The schematic structure of the combiner is shown in Fig.6. The multi-hole silica capillary has ten holes, a center hole and its surrounding nine holes. A single-mode fiber for propagating seed light is inserted in the center hole in the capillary and nine multimode fibers for pumping light propagation are inserted in the surrounding holes. By heating the silica capillary together with the inserted fibers, the capillary is softened and the holes of the capillary are compressed by surface tension. Finally, fibers and capillary are fusion-bonded by the heat and solidified to a multi-core silica rod. Subsequently, the multi-core silica rod is spliced to a bridge fiber by a fusion splicer. The bridge fiber is a fiber that is tapered from one end to another and is designed to convert the beam spot size of both seed and pumping light from one end to another. The spot size of the signal light at the output end becomes larger than the one at the incident end. This spot size conversion contributes to the reduction of insertion loss of signal light in the combiner as the core diameter of the DC-YbDF is larger than that of the output fiber of the MO. In contrast to the spot sizes for the signal light, the spot size of pumping light at the output end of the bridge fiber becomes smaller than the one at its incident end. This design also adjusts the mismatch of spot sizes of light between the fiber from pump LDs and the DC-YbDF.

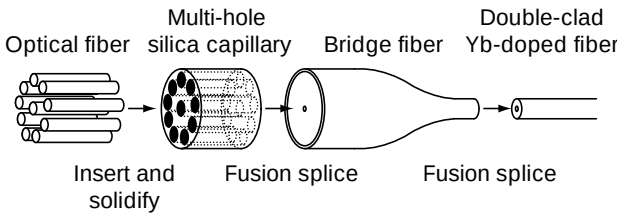


Fig.6. Schematics of pump combiner.

As a result, the insertion loss for pumping light is also reduced.

Deformation such as the ovalization of the core of inserted fibers, that is, the light propagation area of the multi core fiber, can be eliminated by using the multi-hole capillary. This also led to the reduction of insertion loss.

We have obtained the low-loss combiner of an insertion loss of 2.1 dB for signal light and 0.18 dB for pumping light by the structure and employed it to our developed fiber laser.

3.4. Controlling circuit

In addition to the marking resolution characteristics, marking speed is one of the important characteristics of laser marking systems.

Our developed fiber laser directly embraces external analog control on pump LDs from an external marking system, which is equipped by a marker system manufacturer, so as to enable high-speed printing up to a few thousand characters per minute.

Moreover, the fiber laser has various fail-safe functions. Conceivable failure modes of fiber lasers are a failure at pump LDs caused by temperature increase, undesired parasitic laser oscillation in DC-YbDF, and reflected light from works (marking object) or broken fiber end. In the worst case, these might cause irreversible damage to the components of the laser. In order to prevent these troubles, status and parameters such as internal temperature, electric current for cooling fans, reflected optical power intensity, seed light intensity, trigger signal for the Q-switch are monitored regularly, and the fiber laser can automatically shut down the output if any undesired anomalies are detected by the monitor. These parameters and statuses can be monitored by marking system using RS-232C if required. These are unique functions of our developed fiber laser.

4. Characteristics of the developed fiber laser

Table 2 shows the list of obtained characteristics of the developed fiber laser. Figure 7 also shows the exterior view of the fiber laser. The weight of the fiber laser is approximately 9 kg, and its dimensions including cooling fans are D 345 mm × W 260 mm × H 140 mm. It is considerably miniaturized as compared to conventional Nd-YAG lasers.

The pulse repetition rate of the output light from the laser is tunable in the range from 5 kHz to 100 kHz. The maximum average power of 14.4 W can be obtained in the operation at a repetition rate of 100 kHz. Figure 8 shows a pulse waveform at an average output power of 10 W and a repetition rate of 20 kHz. The peak power of the pulse is 5.6 kW and the pulse width in FWHM is 57 ns. The pulse energy calculated from these values is 0.33 mJ/pulse. These performance parameters are nearly equal to those of the designed fiber laser.

Wall-plug efficiency, which represents the energy usage efficiency from electric input to optical output, is 6.8 % when the average output is 14 W. This includes power consumption at the control circuit, the Q-switch, and the cooling fans, and it is consider-

Table 2. Characteristics of the developed fiber laser.

Characteristics	Values/Attributes
Power supply	AC 100V (50/60 Hz)
Dimensions	W 260 mm × D 345 mm × H 140 mm
Weight	~ 9 kg
Cooling method	Cooling fan
Oscillation wavelength	1,065 nm
Spectrum width (FWHM)	3.9 nm
Pulse repetition rate	Tunable, 5 kHz – 100 kHz
Pulse width (FWHM)	57 ns @20 kHz operation
Pulse energy	0.33 mJ/pulse @20 kHz operation
Max. of averaged output power	14.4 W @100 kHz operation
Max. of pulsed power peak	5.6 kW @20 kHz operation
Beam quality (M^2)	≦ 1.1
Beam noncircularity	1.2 %
Wall plug efficiency	6.8 % @14W output (Including consumption of control circuit, Q-switch, cooling fans and so on)

Fig.7. Exterior view of developed fiber laser.

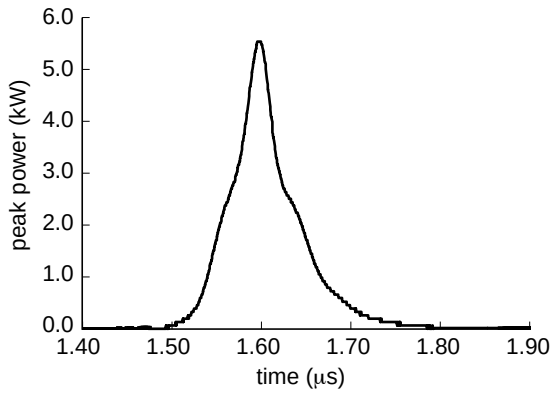
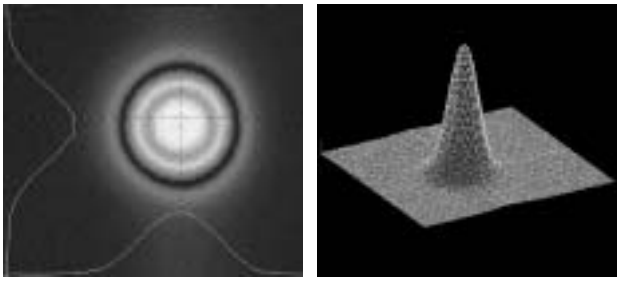


Fig.8. Pulse waveform of the output light of the fiber laser.



(a) 2-D (b) 3-D

Fig.9. Output beam profile of the fiber laser: (a) 2-D image, (b) 3-D image.

ably efficient as compared to conventional Nd-YAG lasers.

Figure 9 shows an obtained beam profile of output light of the laser. As can be seen from the figure, the beam is close to a Gaussian beam and M^2 of the beam estimated from the beam profile data is 1.1. From a practical viewpoint, it is discernible that the output beam is a definite single-transverse-mode beam. The theoretical focal diameter of the output beam is approximately 15 μm, which is calculated from the value of M^2 achieved in the laser and the core diameter of the employed DC-YbDF. In addition, the non-circularity of the output beam is 1.2 %, which can be dealt as a perfectly circled beam. Thus, the developed laser has potential to write fine lines down to 15 μm on the work, though the actual limit for the fine marking would depend on the focal optics of the marker system. This line width is less than one fourth of the line width obtainable using commercially available Nd-YAG laser markers. In terms of drawing resolution, the developed fiber laser can print several tens smaller than the commercially available Nd-YAG laser markers.

To summarize the section, both the pulsed output of average power of more than 10 W and fine beam quality focusable with less than 20 μm have been achieved simultaneously in the fiber laser, and the power and beam quality make the fiber laser a useful laser source for laser marking application.

5. Conclusion

A new fiber laser for laser marking application has been developed. The fiber laser employs an MOPA configuration with a Q-switch and a unique pump combiner consisting of a multi-hole silica capillary.

The fiber laser can irradiate a single-transverse-mode beam with an average output power of 14.4 W and a high peak-power of 5.6 kW at a pulse width of 57 ns. The beam quality of the laser is excellent as M^2 = 1.1. The estimated focal spot size is approximately 15 μm, and the fiber laser can print characters or drawings with a line width several tens smaller than that of the commercially available Nd-YAG laser markers. The fiber laser also employs direct analog control of pump LDs, and it has various fail-safe functions.

The developed fiber laser is expected to be a useful laser source for laser marking application.

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