A Preventive Measure against Fiber Damage of a Femtosecond 1.55-µm Er-doped Fiber Laser System using Multimode Optical Fiber

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A system of passively-mode-locked figure-of-eight erbium-doped fiber laser oscillator-amplifier system was studied. Cooling the erbium-doped fiber down to 0 ℃ increased the output power of the oscillator to 1.8 times that of the room temperature. To avoid the optical damage of the fiber end, a graded-index multimode fiber of 8 mm in length was connected by fusion splice. The output power increased from 29 to 41 kW for direct amplification and from 72 to 93 kW for pulse extraction and amplification without any damage of the fiber end. The mechanisms of the temperature effect and the optical damage are discussed. Damage prevention by a factor of up to 25 is expected.

1. Introduction

Passively-mode-locked fiber lasers [1,2] can generate femtosecond optical pulses. They have merits of compactness and of lower cost compared with Ti:sapphire lasers. In particular, Yb-doped fiber lasers with a wavelength of 1.05 µm have been extensively developed [3-7] and widely used for micromachining [8-10]. Various mode-locking techniques have been developed for Yb-doped fiber lasers including nonlinear polarization rotation [3], a semiconductor saturable absorber [6], or semiconductor saturable mirror [7]. On the other hand, Er-doped fiber lasers with a wavelength of 1.55 µm can also generate femtosecond pulses [11-16]. The output power is much lower than that of Yb-doped fiber lasers. However, they can be assembled with low-cost components for optical communication. To compensate for the low power, amplification of the output pulse is expected. Er-doped fiber amplifiers (EDFAs) [17-19] have been studied extensively for telecom applications, and are presently available as compact low-cost modules. As the gain bandwidth of Er-doped fibers (EDFs) is sufficiently wide, the femtosecond pulses can be efficiently amplified with oscillator-amplifier systems [20,21]. The present authors developed a system of a passively-mode-locked Er-doped fiber-laser oscillator and an amplifier [22], obtained 240-fs pulses with a peak power of 25 kW, and performed micromachining by ablation with a line width down to 4 µm on opaque materials [23,24]. However, optical damage at an output fiber end limited the output power, and thus processing of transparent materials, such as those performed with Ti:sapphire lasers [25,26], have not yet been successful. To avoid optical damage, it has been known to be effective to expand the radius or the spot size of the beam using a tapered-core fiber [27] or a short length of silica fiber without a core (an end cap). For high average-power lasers, all the fiber is composed of multimode fiber.

In this paper, we connected a short length of graded-index multimode fiber with a large core diameter to avoid damage. By using fusion splice, it is expected that the two fibers are connected continuously without any gap. Increase in the output power was investigated. Also, temperature control of the EDF in the oscillator was studied.

2. Experimental procedures

The experimental set-up of the Er-doped fiber laser system [24] and damage prevention is depicted in Fig. 1. Generation of femtosecond pulses were performed by passive mode-locking using a nonlinear-amplifying loop mirror (NALM) using an EDF. The principle of the NALM is described in Discussion. An autocorrelation measurement was performed to measure the pulse widths.

To study the temperature dependence of the femtosecond-pulse generation, the temperature of the Er-doped fiber was controlled with a cold plate As One FTP-28190 with a temperature range of 0-40 °C. The output pulses were amplified with a commercially available EDFA module, Furukawa ErFA21003. The current of the pump laser diode can be varied up to 390 mA. The output power in the specification is more than +15 dBm (32 mW) for an input power of -10 dBm (0.1 mW). Pulse extraction was performed for increasing the peak power and a reduced number of pulses were amplified. Also, direct amplification without pulse extraction was performed and compared. We varied the gain of the EDFA by the current of the pump laser.

Next, a graded-index multimode optical fiber with a core diameter of 50 µm was connected to the output single-mode fiber end by fusion splice. A Furukawa S182K fusion splicer was used. The connected multimode fiber was cut to be 8 mm in length. Possible damage generation was studied with both the measurement of the output power and the observation using a microscope with a CCD camera (Prior Scientific G-130).

3. Experimental Results

3.1 Temperature Effect

Figure 2 shows the measured average power of the fiber-laser oscillator for variation in the temperature of the EDF. A stepwise increase in the average output power was observed for cooling down below 20 °C. The increase in the average power was from 2.9 to 4.5 mW. The average power was highest for the lowest temperature of 0 °C, and the power was 5.2 mW. The pulse repetition rate was 12 MHz. The following experiments were performed at the temperature of 0 °C.

3.2 Damage Prevention

In the previous experiments, the optical damage was observed at the end face of the output fiber of the amplifier as shown in Fig. 3, where the current of the pump laser diode was 300 mA, and the exposure time was 15 min. The detailed damage characteristics were described in [24]. The pump current was limited to be less than 290 mA to avoid damage. After connecting the multimode fiber, the output average power for direct amplification was measured and the result is shown in Fig. 4. When the pump current was increased to 390 mA, the average output power increased from 73 to 98 mW without damage. The measured results for both direct amplification and pulse extraction and amplification are summarized in Table 1. For direct amplification, the measured pulse width was 181 fs and the calculated peak power was 29 kW. After connecting the multimode fiber, although the pulse width increased to 203 fs, the peak power increased to 41 kW. For pulse extraction and amplification, the measured pulse width without multimode fiber was 131 fs and the calculated peak power was 72 kW. The pulse repetition rate was 6 MHz. After connecting the multimode fiber, the pulse width increased to 143 fs, while the peak power increased to 93 kW.

After these experiments, the end facet of the multimode fiber was observed with a microscope. As shown in Fig. 5, no damage was observed.

4. Discussion

It has been known that the gain of an EDFA increases with the decrease in the temperature. The temperature dependence for 1.48-μm pumping has been reported to be -0.07 dB/°C [28]. This is mainly due to thermal excitation within the upper laser level of Er^{3+} ions for a higher temperature, and the population inversion decreases for a higher temperature through stimulated emission at the pumping wavelength. It has also been reported that the noise figure decreases with the temperature [29]. It is noted that for 0.98-μm pumping these temperature dependence and the noise figure are much smaller.

The measured stepwise change is considered to be due to switching conditions of the NALM [16] are discrete. In the NALM, two optical pulses propagating in the clockwise and the counterclockwise directions suffer a different phase shift induced by the nonlinear Kerr effect as,

$$\delta\phi_c - \delta\phi_{cc} = \frac{\pi I_{in} n_2 L(G-1)}{\lambda} \quad , \qquad (1)$$

where I_{in} is the intensity of the input of the NALM, G is the gain of the EDF, and n_2 is the nonlinear refractive index of the fiber, and L is the fiber length. The output intensity of the NALM is given by
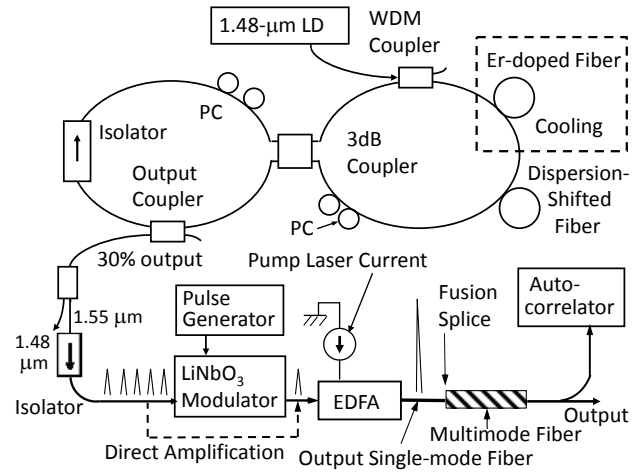

Fig. 1 Experimental set-up of a femtosecond fiber-laser oscillator, an amplifier, and a multimode fiber.
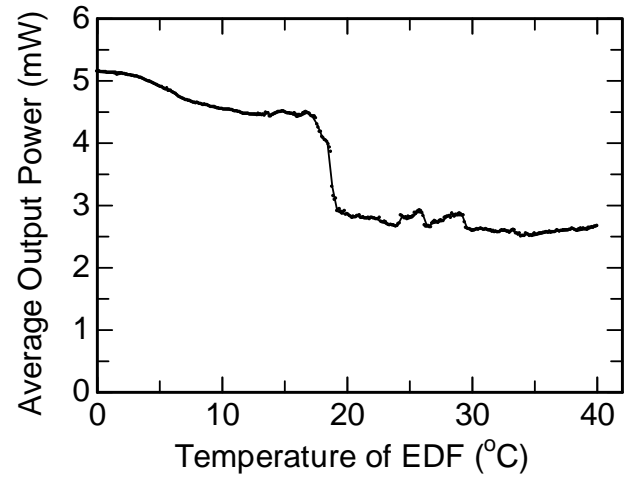

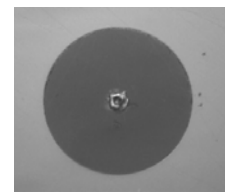**Fig. 2** Dependence on the temperature of an Er-doped fiber on the output power of the oscillator.

Fig. 3 A typical damage at the end facet of the single-mode fiber of the output of an erbium-doped fiber amplifier.

$$I_{out} = I_{in}G\sin^2\left[(\delta\phi_c - \delta\phi_{cc})/2\right]. \qquad (2)$$

This value shows maxima for the phase differences of $(2m+1)\pi$, where m is an integer. These discrete transmission characteristics are considered to induce the stepwise output change.

Next, we discuss the optical damages. It has been reported on silica glasses or fibers that the damage threshold for laser-pulse irradiation depends on the wavelength [30], pulse width [30-32], single or multiple shots [33], surface

roughness [34], spot size [35], and dopant concentration [36]. The mechanisms of optical damages have been considered as generation of initial electrons by multiphoton ionization or tunneling ionization [37] and the following increase by such as avalanche ionization. It has been known that for pulses longer than 10 ps the damage threshold in J/cm^2 is proportional to the square of the pulse width τ. This is considered to be due to the diffusion of the electron energy to the glass network or lattice during the laser pulse. However, the measured damage threshold for shorter pulses of 1 ps-100 fs are higher than that predicted by this $\tau^{1/2}$ dependence [30,32]. This is considered to be because avalanche ionization takes a time and thus is negligible in such a short time [30].

The multiphoton ionization, one of the origins of the initial electrons, is induced by multiphoton absorption. The multiphoton ionization should be strongly wavelength dependent, because a number of photons should exist at the same time, and thus the probability should drastically decrease for the increase in the number. Four-photon absorption has been considered for the wavelength of 0.526 μm and eight-photon absorption of the wavelength of 1.053 μm. However, the measured damage threshold in J/cm^2 at 1.053 μm was only 2 times that of 0.526 μm [30]. This is considered to be because initial electrons can be supplied also by tunneling ionization under a high electric field [32,37] that is less wavelength-dependent. Although the wavelength of 1.55 μm corresponds to eleven-photon absorption, the damage threshold for the present experiment is estimated to be only 1.5 times that at 1 μm.

The damage threshold in the previous experiment using no multimode fiber was 0.057 J/cm^2 for repetition rate of 100 kHz [24]. This value is rather low compared with a typical value of ~2 J/cm^2 for fused silica for a single pulse [30].

For single-mode fibers, considering the intensity distribution in the core, the intensity at the center of the core is the highest, and thus the optical damage is considered to be determined by this highest intensity. When the Gaussian distribution is assumed, the intensity at the center of the core I_0 for the power P is given by $I_0=2P/(\pi\omega_0^2)$, where ω_0 is the spot size and $2\omega_0$ is the mode-field diameter.

On the other hand, for a graded-index multimode fiber with the refractive-index distribution

$$n(r) = n_0\left(1 - \frac{A}{2}r^2\right), \tag{3}$$

assuming the ray-optics approximation, the transmission characteristics is given by the matrix as

$$\begin{pmatrix} r_{out} \\ r'_{out} \end{pmatrix} = \begin{pmatrix} \cos\sqrt{A}z & \frac{1}{\sqrt{A}}\sin\sqrt{A}z \\ -\frac{1}{\sqrt{A}}\sin\sqrt{A}z & \cos\sqrt{A}z \end{pmatrix} \begin{pmatrix} r_{in} \\ r'_{in} \end{pmatrix}, \tag{4}$$

where z is the length of the fiber. The input image is reproduced after the length
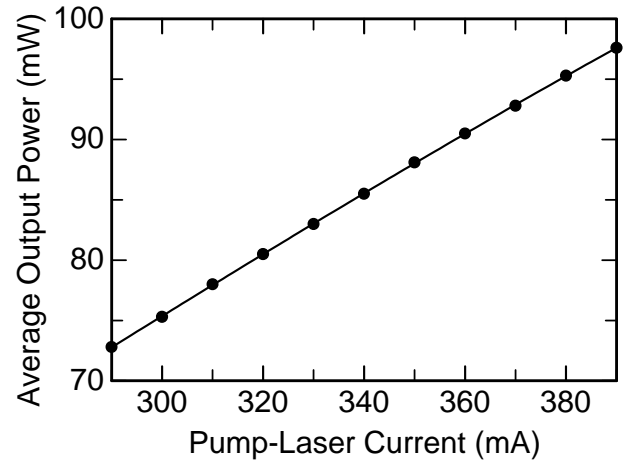
$$L = \frac{2m\pi}{\sqrt{A}}, \tag{5}$$

Fig. 4 Variation in the average output power of direct amplification using a multimode fiber with the current of the pump diode laser of an EDFA.

Table 1 Results of the pulse widths and the output peak powers with and without a multimode fiber.

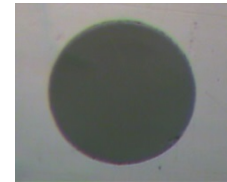| Amplification	MMF	Pulse width (fs)	Peak power (kW)
Direct amplification	without MMF	181	29
	with MMF	203	41
Pulse extraction and amplification	without MMF	131	72
	with MMF	143	93

Fig. 5 Photograph of the end facet of the multimode fiber after the experiment.

where m is an integer. In the present experiment, $2\pi/A^{-1/2}$ was 0.9 mm, and the fiber length of 8 mm was much larger than this value. If the fiber is highly multimode and equally excited with incoherent light, the profile of the power distribution in the core agrees with the profile of the refractive-index distribution [38]. Assuming a square type refractive-index distribution, the intensity in the center of the core I_0 for the power P is given by $I_0=2P/(\pi a^2)$, where a is the core radius. Thus the reduction ratio in I_0 by connection of a multimode fiber to a single-mode fiber is $(\omega_0/a)^2$. In the present experiment, this value is 1/25 for a mode field diameter of 10 μm and a core diameter of 50 μm. The damage threshold is considered to be increased by a factor of 25 by connection with the multimode fiber.

5. Conclusion

Improvement in the output of a system of a passively-mode-locked figure-of-eight Er-doped fiber laser and an amplifier was studied. Cooling the Er-doped fiber down to 0 ℃ increased the output power of the oscillator to 1.8 times. Optical damage was avoided by fusion splice with a multimode fiber, and the average and the peak powers increased. The broadening of pulse widths by using a multimode fiber was up to 12 %. Damage prevention up to 25 times is expected using a multimode fiber. Focusing characteristics in micromachining are to be investigated.

Acknowledgment

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