The Development of a High Quality and a High Peak Power Pulsed Fiber Laser With a Flexible Tunability of the Pulse Width

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ABSTRACT In the laser processing field, the pulsed laser which can temporally control its laser beam entering into a processed object, is becoming popular in applications of marking and of micro processing. In such applications, it is necessary to increase the output power with maintaining of the beam quality and to have the tunability of the pulse width and the repetition rate for an optimization of the processing conditions, an improving of the processing speed and an expansion of the processing area. In order to meet such requirement, we have developed the pulsed fiber laser with the configuration of a Master Oscillator Power Amplifier (MOPA) which has a direct modulated seed light source and an optical fiber amplifier which amplifies the output from the seed light source. This pulsed fiber laser uses a specialty fiber manufactured by OFS as a gain fiber of the optical amplifier, in order to achieve a high peak power optical pulse output with an inhibition of a non-linear effect in an optical fiber, and over 100kW of a high peak power amplification and a high beam quality output are achieved in a time domain where the pulse width is in sub-nanosecond to several nanoseconds.

1. INTRODUCTION

For the laser processing, a high speed and a high quality processing are required. Many of the laser processing utilize a heat energy which is generated by a laser light being absorbed into a material. However, when heat energy input to a processing object is increased, depending on the properties of the material to be processed, the heat remains on the processing surface and a heat affected layer named Heat Affection Zone (HAZ) is formed, and it becomes a factor to cause degradation of the processing quality. In order to suppress this, the high precision control of the heat energy input to the processing object is effective. Then, the pulsed laser which can temporally control the light energy is utilized.

The pulsed fiber laser with an optical fiber, which has a pulse width of sub-microsecond (hundreds nanosecond) with a Q switch method, is used mainly in marking applications. The pulsed fiber laser which has a pulse width of several nanoseconds to tens of nanoseconds is being promoted in the applications of micro processing. In such a laser processing by pulsed fiber laser, a shorter pulse width and a variability of the repetition rate are required for an optimization of the processing condition and an expansion of the processing area.

With that background in mind, we have been developing the pulsed fiber laser with a variable pulse width and a repetition rate in the nanosecond range1). By using an optical pulse from the direct modulated semiconductor laser and a pulse amplification with a specialty fiber together, we have also achieved the optical pulse output with a high beam quality and a high peak power in a time domain of the sub-nanosecond to several nanoseconds, which were difficult to obtain before. In this article, we will report an introduction of the technologies of this seed light source and the high power optical pulse amplification, and their characteristics.

2. THE PULSED FIBER LASER

Figure 1 shows the basic configuration of the pulsed fiber laser. This is the MOPA configuration where an optical pulse output from a seed light source is amplified by optical fiber amplifiers. The major features of this configuration are that the output characteristics of the pulsed laser such as a pulse width and a repetition rate can be freely adjusted by controlling the seed light source’s drive, and a high power output becoming available by connecting optical fiber amplifiers in multiple stages (double-stage configuration in Figure 1). In addition, we use a Cascaded Resonator Raman Laser (CRRL) where the high power output is available in a fundamental mode as a pump light source of a booster amplifier to achieve the optical amplification with a high beam quality2).

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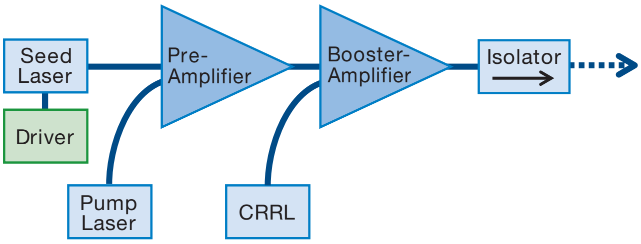

Figure 1 **Configuration of pulsed fiber laser.**

Since the peak power of the optical pulse increases according to the higher power output, a deterioration of the pulse shape and an energy spread occur due to a non-linear effect in the optical fiber. To inhibit these occurrences, there are measures such as expanding an effective core area of the optical gain fiber, however, there will be the issue that a trade-off situation occurs between peak power and beam quality.

Therefore, we have developed a seed light source which has a high flexibility of output characteristic and a generation of stable optical pulse, and an optical fiber amplifier which can achieve a high gain and a high output by the inhibition of the non-linear effect.

3. THE DEVELOPMENT OF THE SEED LIGHT SOURCE WITH A FLEXIBLE TUNABLILITY OF THE PULSE WIDTH

3.1 Pulse Generation Method

For the seed light source of a pulsed fiber laser in the MOPA configuration, as the generation method of an optical pulse that can control the characteristics such as a pulse width and a repetition rate, we have the following methods available: (a) a Q-switch method where an optical shutter such as an optical modulator is placed in the optical resonator and the optical pulse is oscillating by temporally changing the Q-factor of the resonator, (b) an external modulation method where an optical pulse is cut out from the output of a CW laser by an optical intensity modulator such as an Acousto-Optic Modulator (AOM) or an Electro-Optic Modulator (EOM), and (c) a direct modulation method where an oscillation is temporally controlled by a directly modulating driving current of the seed light source.

The pulse generation method of the pulsed fiber laser and its features are shown in Table 1.

Table 1 **Pulse generation method of pulsed fiber laser.**

Method	Q-switch	External modulation		Direct modulation
		AOM	EOM	
Pulse width	Tens to hundreds of nanoseconds	Tens of nanoseconds or more	Tens of picoseconds or more	Hundreds of picoseconds or more
Repetition rate	Tens to 50 kHz	Order of kHz to 10 MHz		
Advantages	High pulse energy	Pulse width, repetition rate, variability in a wide range		
Demerits	Narrow variable range	A high-speed response is difficult.	A high extinction ratio is difficult.	A high output is slightly difficult.

The Q-switch method can generate an optical pulse which has a comparatively high energy, however its variable range is limited because the pulse width and the repetition rate depend on the characteristics of the resonator.

The external modulation method using the AOM or the EOM can achieve a wide range variability of pulse output characteristics such as a pulse width and a repetition rate by controlling a drive pulse input to the modulator. However, in the external modulation with the AOM, it is difficult to generate an optical pulse with a pulse width of tens of nanoseconds because a response speed of the AOM becomes a limitation. The external modulation with the EOM can generate an optical pulse with a pulse width of tens of picoseconds, however, it will be an issue that the ON/OFF extinction ratio of the optical pulse is low.

On the other hand, since the direct modulation method modulates a drive current of the semiconductor laser, it is possible to generate optical pulse with a pulse width of tens of nanoseconds, while having the same characteristics as the external modulation. The energy of the optical pulse output is smaller than the Q-switch method, however, it can obtain the pulse energy which is required for the laser processing with the amplification of the optical pulse by the post-stage optical amplifier of the MOPA configuration.

3.2 The Direct Modulated Seed Light Source

The basic configuration of a direct modulated seed light source is shown in Figure 2. The seed light source consists of a semiconductor laser which generates an optical pulse, a driver IC which drives the semiconductor laser and the controller which controls those components. The wavelength of the semiconductor laser which is used for this development is in the 1550 nm range. In the controller, a digital circuit generates an electric pulse signal for driving, and it is the configuration where the control of the pulse width and the repetition rate is available from the command of a host device. The center wavelength of the optical pulse can be adjusted by setting the control temperature of the laser from the controller.

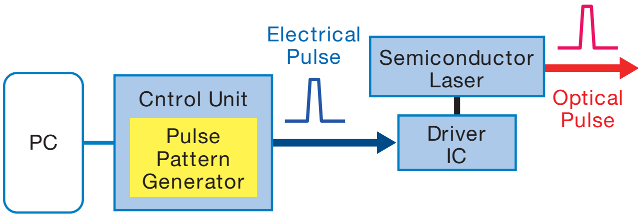

Figure 2 Configuration of direct modulated seed laser.

The temporal optical pulse shapes from the direct modulated seed light source are shown in Figure 3. It can be confirmed that the optical pulse output is stable when the pulse width is in the range of 1.6 – 200 ns. The peak power of the optical pulse at this time is 20 mW approx..

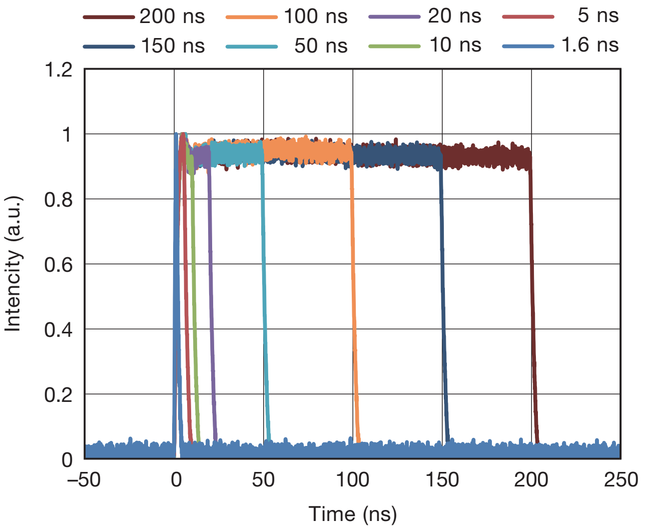

Figure 3 Optical pulse shapes from direct modulated seed laser. (Pulse width: 1.6-200 ns, Repetition rate: 100 kHz)

4. THE DEVELOPMENT OF THE HIGH POWER OPTICAL PULSE AMPLIFIER

4.1 The High-power Optical Gain Fiber

As shown in Figure 1, the optical amplifier which amplifies the optical pulse generated in the seed light source has a double-stage configuration with a pre-amplifier and a booster-amplifier. A normal Single Mode Fiber (SMF) is used for the pre-amplifier, and in order to inhibit the non-linear effect associated with the higher power output, a specialty fiber for high power optical amplification is used for the booster- amplifier where the optical power increases.

A comparison of an effective core cross-sectional area (A_{eff}) of each fiber is shown in Figure 4. The normal SMF has tens of micro-square meter (μm^2) of effective core cross-sectional area and propagates only single mode of the fundamental mode (LP_{01}). On the other hand, the specialty fiber for high power optical amplification has a design which avoids the increase of the optical energy density in the optical fiber by expanding its effective core cross-sectional area larger than the SMF, and therefore a non-linear effect is inhibited.

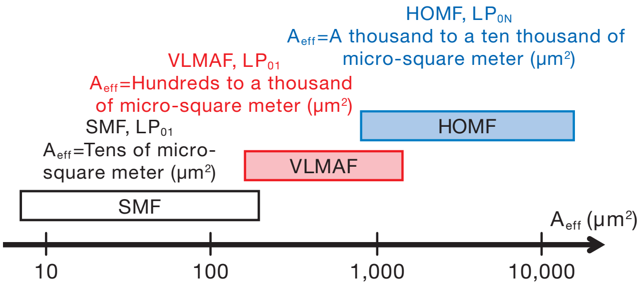

Figure 4 Comparison of A_{eff} of optical fibers at wavelength of 1550 nm.

A Very-Large Mode Area Fiber (VLMAF), one of the specialty fibers for high power optical amplification, is the optical fiber which expands its effective core cross-sectional area up to hundreds to a thousand of micro-square meter (μm^2)3), 4). The single mode stability in the optical fiber deteriorates because of the expansion of the effective core cross-sectional area, however, an inhibition of the gain in the higher-order mode in the gain fiber and a high efficiency output in the fundamental mode become possible by an optimization of the optical fiber configuration and a core pumping with a CRRL, as the pump light source, whose output is in the fundamental mode.

On the other hand, a Higher Order Mode Fiber (HOMF), another specialty fiber for high power optical amplification, is the optical fiber which inhibits a non-linear effect more than a VLMAF by using the propagation of a higher-order mode in the optical fiber with the effective core cross-sectional area of 1,000 – 10,000μm^2.5), 6) Its feature is that the propagation in the fiber is in a higher-order mode which is a singular selection by optimizing the optical fiber configuration.

The basic configuration of the high power optical amplifier using a HOMF is shown in Figure 5. A signal light in the fundamental mode and a pump light which are input and converted to a higher-order mode by a Long Period Grating (LPG) at the input side, and then the signal light in higher-order mode is amplified while it is propagating in the HOMF. This amplified signal light in the higher-order mode is converted again to the fundamental mode by the LPG at the output side.

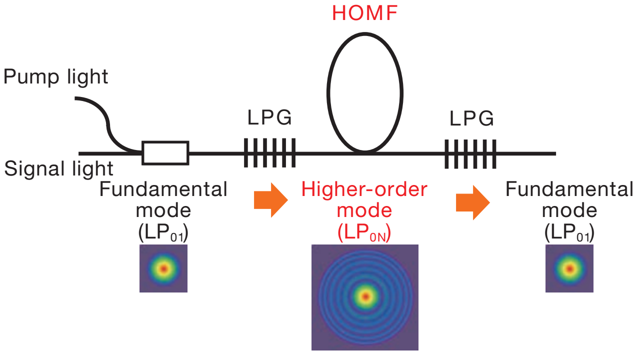

Figure 5 Configuration of high power optical amplifier using HOMF.

4.2 The Pulse Amplification With a Higher Order Mode-Erbium Doped Fiber Amplifier (HOM-EDFA)

Using an erbium doped HOMF as a gain fiber of a booster amplifier and using a CRRL in 1480 nm as a pump light source, we did amplification experiments of an optical pulse. The input condition to the booster amplifier (HOM-EDFA) is 1.5 ns of a pulse width, 50 mW of an average power and 71.4 kHz of a repetition rate.

The output power from the HOM-EDFA with respect to the pump power, is shown in Figure 6. The average output power of more than 10 W after pulse amplification is achieved.

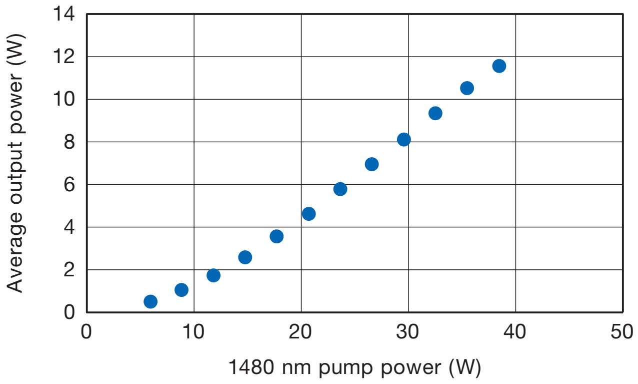

Figure 6 Output power from HOM-EDFA.

An optical pulse waveform of the HOM-EDFA output with an average output power of 10 W is shown in Figure 7. The pulse width of the optical pulse, Full Width Half Maximum (FWHM), becomes 1.4 ns. At this time, the conversion value of the peak power is 100 kW.

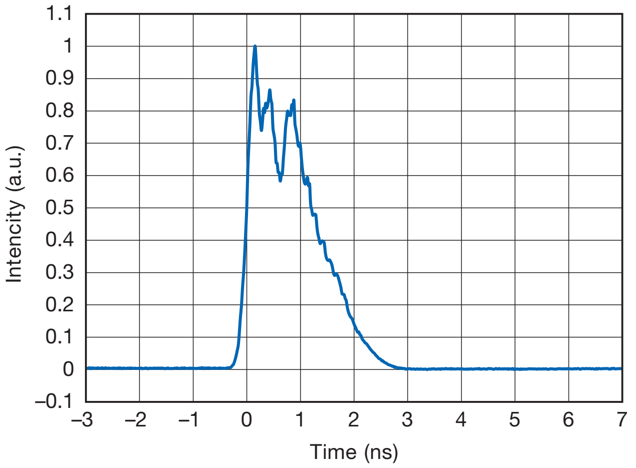

Figure 7 Optical pulse waveform of HOM-EDFA output. (Repetition rate: 71.4 kHz, Average output power: 10 W)

The optical spectrum of the HOM-EDFA output with an average output power of 10 W is shown in Figure 8. The signal level to the noise level on the spectrum achieves a good Signal-to-Noise Ratio (SNR) of over 25 dB.

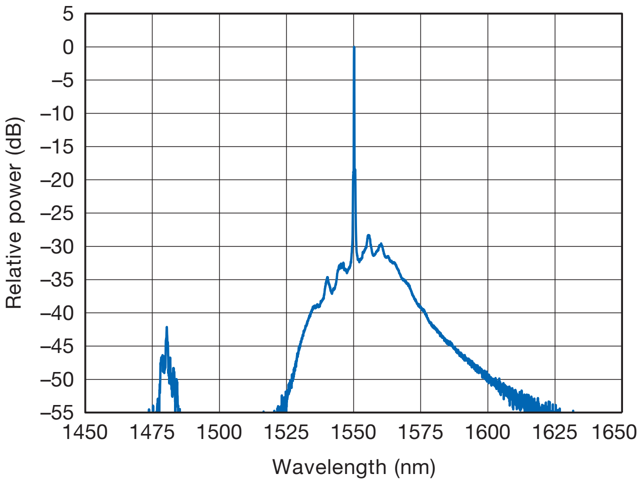

Figure 8 Optical spectrum of HOM-EDFA output. (Repetition rate: 71.4 kHz, Average output power: 10 W)

The measurement results of M^2-value as the characteristic index which shows a beam quality of the output optical pulse is shown in Figure 9. The horizontal axis shows the position in the direction of the beam propagation, and the vertical axis shows each beam radius in x-direction and y-directon.

The each beam radius is fitted to a curve and the M^2-value is derived from that fitted curve7). As the result, the M^2-value is less than 1.2 in both x- and y-direction. This indicates that the beam shape is near ideal Gaussian shape and a high beam quality is maintained.

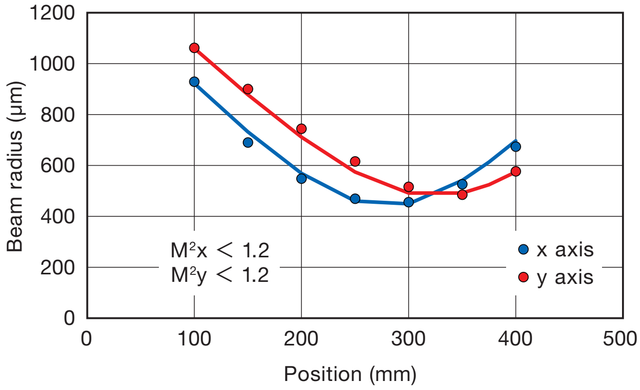

Figure 9 M^2 measurement results of HOM-EDFA output. (Repetition rate: 71.4 kHz, Average output power: 10 W)

4.3 The Pulse Amplification With a Very Large Mode Area-Erbium Doped Fiber Amplifier (VLMA-EDFA)

The experiment results of the optical pulse amplification which has an erbium doped VLMAF as a gain fiber of a booster amplifier are shown in the followings. A CRRL in 1480 nm is used as a pump light source. The input condition to the booster amplifier, a Very Large Mode Area-Erbium Doped Finer Amplifier (VLMA-EDFA), is 1.2 ns of a pulse width, 32 mW of an average power and 71.4 kHz of a repetition rate.

The optical output power characteristic to the pump power of the VLMA-EDFA is shown in Figure 10. The average output power after the pulse amplification becomes 12.7 W at maximum.

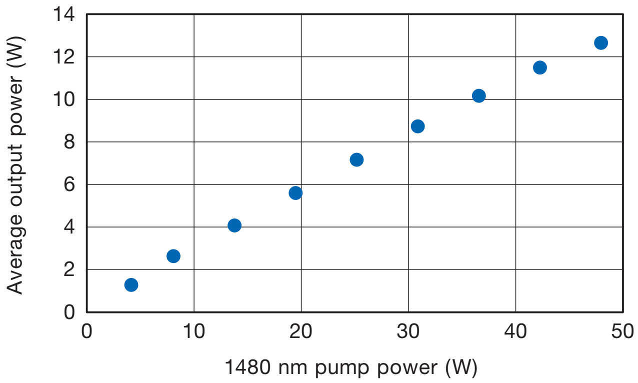

Figure 10 Output power from VLMA-EDFA.

The optical pulse waveform of the VLMA-EDFA output at the maximum average output power is shown in Figure 11. The pulse width of the optical pulse (FWHM) becomes 0.8 ns. At this time, the conversion value of the peak power achieves a high peak power output of 220 kW approx.

The optical spectrum of the VLMA-EDFA output with the maximum average output power is shown in Figure 12. The signal level to the noise level on the spectrum achieves a good SNR of over 30 dB.

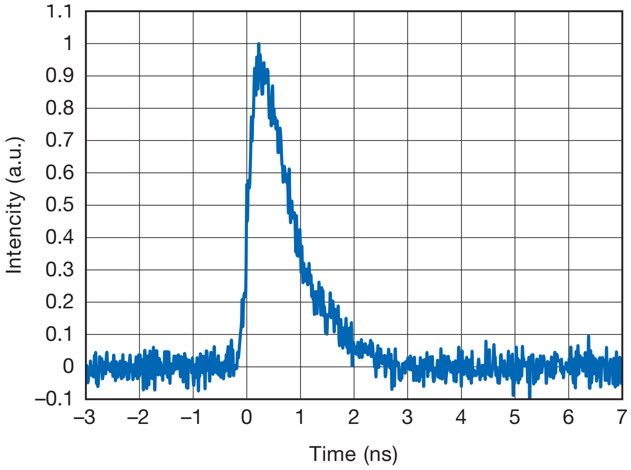

Figure 11 Optical pulse waveform of VLMA-EDFA output. (Repetition rate: 71.4kHz, Average output power: 12.7W)

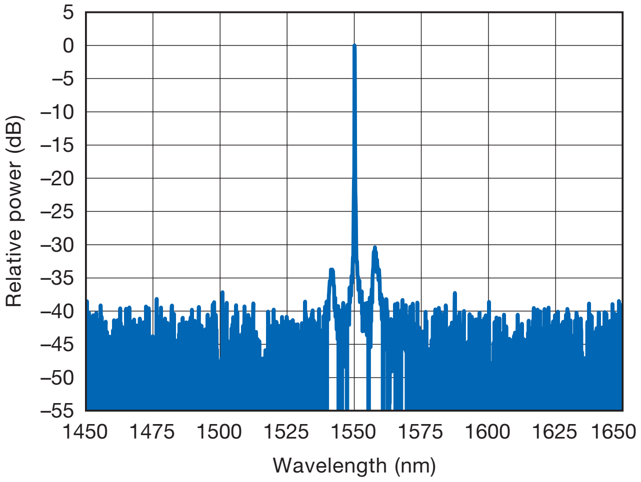

Figure 12 Optical spectrum of VLMA-EDFA output. (Repetition rate: 71.4 kHz, Average output power: 12.7 W)

The measurement results of M^2-value are shown in Figure 13. As the result, the M^2-value is less than 1.2 in both x- and y-direction and a high beam quality is confirmed.

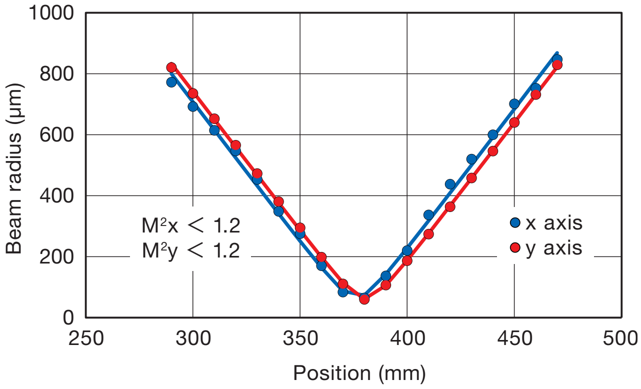

Figure 13 M^2 measurement results of VLMA-EDFA output. (Repetition rate: 71.4 kHz, Average output power: 12.7 W)

5. CONCLUSION

Using short pulse generation technology by direct modulation of a laser and specialty fiber technologies such as a VLMAF and a HOMF, we have developed a High peak power pulsed fiber laser of the best in the world, which has a variable pulse width and a repetition rate. The generation of an optical pulse in the time domain with the pulse width from sub-nanosecond to several nanoseconds, a high peak power amplification over 100 kW and a high beam quality output are achieved, which were difficult to obtain previously.

With those technologies, it becomes possible to design an optimum processing condition for the well-balanced processing with a high quality and a high speed, therefore, new applications of the laser processing, such as the high-speed micro-boring on ceramics and others, the surface modification of metals and the high-precision processing of resin materials, are becoming very promising.

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