Improvement of Output Characteristics of a Large-Mode-Area Er-Doped Fiber Amplifier Pulse Pumped by a Cascaded Raman Fiber Laser With a Low Repetition Frequency

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***Abstract*—We improve the output of a MOPA system that emits single-frequency high-energy optical pulses using a large mode area Er-doped fiber amplifier pumped by a cascaded Raman fiber laser with a low 150 Hz repetition frequency. It is found that the unwanted light generated in the cascaded Raman fiber laser at the same time as the pump light saps the gain of the amplifier and degrades its output characteristics. By combining the removal of unwanted light with a pulse pump technique, the pulse energy is improved from less than 1.0 mJ to 1.2 mJ with at the same time a SNR of 30 dB compared to 19 dB before the improvement. The percentage of power in the signal also improves from 61.0% to over 90.7%.**

***Index Terms*—Doped fiber amplifiers, Er-doped fibers, high power amplifiers, lidar, pulsed lasers, pump lasers.**

I. Introduction

HIGH power fiber amplifiers at 1.5 μm have been shown to be indispensable tools, not only for fundamental science such as precision frequency metrology [1] and gravitational wave detection [2], but also for industrial applications including Light Detection and Ranging (lidar) [3], [4], atmospheric sensing [5], [6], optical time domain reflectometers [7], and optical communications [8]. In particular, pulses with a single frequency, a high energy (>1 mJ) and a long pulse duration (>100 ns) are required in the field of coherent doppler wind lidars (CDWLs). Laser systems emitting single-frequency, high-energy pulses using fiber amplifiers have been developed for a wavelength of 1.5 μm for CDWLs [9], [10], [11], [12], [13], [14], [15], [16], [17], [18], [19], [20], [21], [22], [23], [24]. In particular, several groups have reported a high-energy master oscillator power amplifier (MOPA) system using an Er-Yb co-doped fiber amplifier (EYDFA) [12], [14], [15], [19], [20] or an Er-doped fiber amplifier (EDFA) [13], [16], [17], [18], [21], [22], [24] with a large mode area (LMA) to avoid the stimulated Brillouin scattering (SBS) due to nonlinearities in the fiber which is induced with a small mode field diameter. Most work on all-fiber MOPA systems using an LMA EDFA or an LMA EYDFA as a main amplifier have to date been demonstrated with pulse energies of 1 millijoule level with a high repetition frequency (f_{rep}) of over 1 kHz. In recent years, a MOPA system which emits single-frequency 1.8-mJ pulses with a f_{rep} of 2.5 kHz has been reported using a silicate glass LMA EYDFA and an amplified spontaneous emission (ASE) absorber to suppress an out-of-band ASE [19]. An LMA EDFA or an LMA EYDFA could be useful not only as a main amplifier, but also as a pre-amplifier. In fact, by employing an LMA EDFA as a pre-amplifier, we have recently developed a MOPA system with an output energy of 45.2 mJ at an f_{rep} of 150 Hz [24]. The maximum measurable distance ($L_{\max}$) of a typical CDWL is calculated to be $L_{\max} = c/(2f_{\mathrm{rep}})$ (c being the speed of light), so a transmitter laser system with a high energy and a low f_{rep} (<1 kHz) would be useful for long distance measurements with a CDWL.

Increasing the output energy while minimizing the degradation of a signal to noise ratio (SNR) and ratio of a power in a signal to a total power (a percentage of power in the signal) is an important issue in long distance measurements with a CDWL, especially when using an LMA EDFA or LMA an EYDFA as a preamplifier in a MOPA system, since ASE from the preamplifier saps the gain of the main amplifier and degrades the output. Few studies of an LMA EDFA or an LMA EYDFA with a low pulse repetition rate below 1 kHz and a good SNR have achieved high energy pulse trains due to ASE and the gain dynamics during off periods [14], [16], [20], [24]. The generation of 200 ns pulses with a pulse energy of 0.24 mJ at 100 Hz was demonstrated using a pulsed pumping technique to mitigate the generation of ASE in the LMA EYDFA [14]. Although a maximum pulse energy of 1.5 mJ with an f_{rep} of 0.3–1 kHz is obtained from an in-band pumped LMA EDFA, a SNR is seeming to be 15-dB level and a beam quality factor M^2 of 1.6 [16]. A peak power of 23–27 W at an f_{rep} of 50–500 Hz and a pulse duration in the region of 20 μs were obtained, along with a SNR of 45 dB, by using sacrificial seed light which prevents the growth of ASE in an LMA EYDFA [20].

Other issues in long distance outdoor measurements with a CDWL [25], [26] are the limited amount of electric power

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available and limited ease of thermal management. In this case, it is preferable to use 1480 nm lasers as the pump light sources rather than the conventional 980 nm laser diodes (LDs), since the low level of quantum defects produces a low thermal load. Recently commercially available, a cascaded Raman fiber laser (CRFL) which emits a high-power 1480 nm beam with a single mode fiber is a good candidate for a pump source to obtain high efficiency due to the realization of core pumping [26]. Although several groups have demonstrated the amplification of single-frequency pulses using an LMA EDFA pumped by the light from a CRFL [18], [21], [22], [24], only one group showed an output pulse exceeding 1 mJ [21]. A phosphate-glass based LMA EDF which could absorb 1480 nm pump light better than a typical silica based LMA EDF was used in this study.

High-energy MOPA systems with good SNR and percentage of power in the signal at low f_{rep} employing LMA EDFAs pumped by a CRFL have not been demonstrated. It should be noted that we generated 0.64 mJ pulses with a SNR of 50 dB and f_{rep} of 150 Hz from a CW pumped LMA EDFA using a CRFL in our previous study [24]. However, its output energy immediately after the output of the LMA EDFA had an upper limit of <1 mJ due to unknown causes other than SBS. Furthermore, the SNR was poor (<20 dB), so it was necessary to reduce the ASE by using two narrow-bandwidth bandpass filters, which reduced the signal energy due to their losses.

In this work, we demonstrate improvement of the output characteristics of an all-fiber MOPA system with an LMA EDFA pumped by a CRFL as the main amplifier at a low f_{rep}. We observe degradation of the output signal energy, the SNR and the percentage of power in the signal due to the amplification of light in the 1.5–1.6 um band generated in the CRFL, which enters the LMA EDFA at the same time as the 1480 nm pump light, sapping the gain of the LMA EDFA. In addition, pulse operation of the CRFL is performed to compare the output characteristics of the LMA EDFA with a conventional CW pump. For the same pump energy, the signal energy is higher for shorter pump pulses, and the SNR is also better for shorter pump pulses for the same output energy. Combining the rejection of the unwanted light generated in the CRFL with pulsed pump operation improves the signal pulse energy from under 1.0 mJ to more than 1.2 mJ, and simultaneously improves the SNR by more than 11 dB. The percentage of power in the signal also improves from 61.0% to over 90.7%. In addition, numerical analysis using a Frantz-Nodvik equation is performed to obtain the characteristics of the LMA EDFA.

II. Experimental Setup

Fig. 1 shows the setup for pulsed laser amplification. A seed laser emits single-frequency light with a linewidth of 1 MHz. A transform-limited signal pulse with a pulse energy of 31 nJ and an f_{rep} of 150 Hz is generated by a pulse modulator. The SNR is 55 dB at a resolution bandwidth (RBW) of 0.1 nm and a video bandwidth (VBW) of 10 Hz. The signal pulses are amplified by an EDFA, which is pumped with a pump pulse duration of 1.3 ms. ASE in the output beam of the EDFA occurring just before the signal pulse is removed by another pulse modulator. The output pulses are sent to a commercial LMA EDFA module (OFS: 7000438) and amplified by it. This module consists of a mode field converter, a wavelength division multiplexing (WDM) coupler to combine a pump beam and a signal beam, and an LMA EDF with a core diameter of 50 μm (not shown in Fig. 1). The LMA EDFA is pumped by a commercial CRFL module (OFS: 7008003-1480-10) with a maximum output power of 10 W which performs wavelength conversion of the output of an Ytterbium doped fiber laser over several Stokes shift by using cascaded Raman fibers [27]. As detailed later, two cases are tested for a CRFL and an LMA EDFA: (i) insertion of another WDM coupler that separates light near 1480 nm from the 1.5–1.6 μm band light and (ii) direct fiber connection. We confirm that the 1.5-μm light passing from the common port to the 1480-nm output port is less than 30 dB or more relative to the input power. To measure the light beam with wavelength longer than 1500 nm, a high-pass filter (HPF) is inserted after the WDM coupler in the case of (1). The signal light and the pump light are mixed by the WDM coupler in the LMA EDFA module (not shown in Fig. 1). The amplified signal pulses from the LMA EDFA are collimated by a collimator lens and another HPF is used to remove the pump beam. The pulse energy of the collimated beam is measured by a pyroelectric energy sensor with a maximum measurable pulse width of 17 μs (Coherent: J-25MB-HE). The pulse shapes of the LMA EDFA are observed by using a photodetector and oscilloscope, and the spectra are measured by an optical spectrum analyzer connected via a single mode fiber (SMF) which is placed into the center of the output beam as in previous study [28]. An optical isolator is used to prevent the unwanted return light. The beam quality is measured using a charge coupled device (CCD) camera with a plano-convex lens.

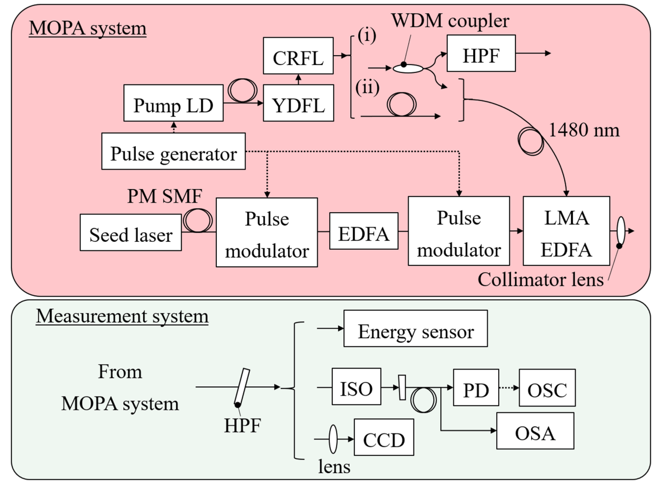

Fig. 1. Schematic diagram of the experimental setup. EDFA: Er-doped fiber amplifier; PM SMF: Polarization-maintained single mode fiber; LMA EDFA: Large mode area Er-doped fiber amplifier; HPF: High-pass filter; ISO: Optical isolator; Pump LD: Laser diode for pumping the YDFL; YDFL: Ytterbium-doped fiber laser; CRFL: Cascaded Raman fiber laser; WDM coupler: Wavelength Division Multiplex coupler; PD: Photodetector; OSC: Oscilloscope; OSA: Optical spectrum analyzer; CCD camera: Charge coupled device camera. The optical and electrical paths are shown as solid and dashed lines, respectively.

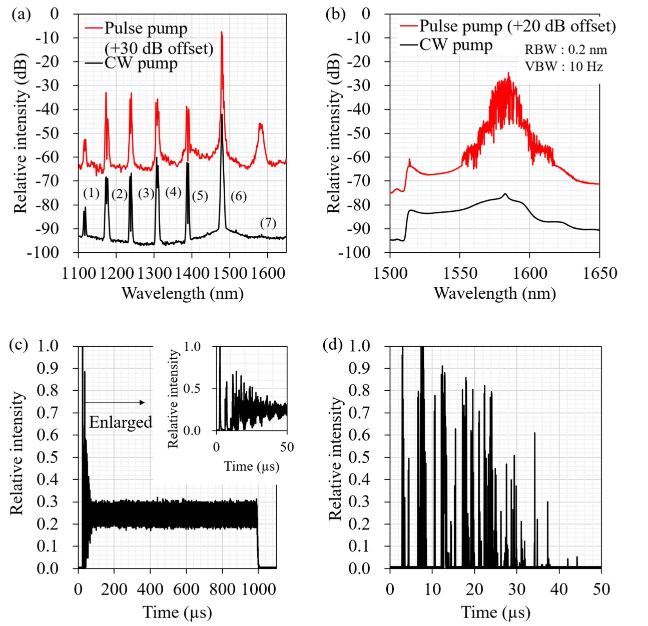

Fig. 2. (a) Measured output spectra from the CRFL. The black curve shows the spectrum when the YDFL is CW pumped. The red curve shows the spectrum when the YDFL is pulse pumped with a pulse duration of 1 ms. The RBW is 1.0 nm and the VBW is 10 Hz. (b) Measured output spectra of the light around 1582 nm extracted by the WDM and the HPF. The RBW is 0.2 nm, and the VBW is 10 Hz. (c) Measured pulse shape of the output from the CRFL. Inset figure is an enlarged view of the relaxation oscillations in the output pulse from the CRFL. (d) The measured time waveform of the 1.5–1.6 μm band output from the CRFL.

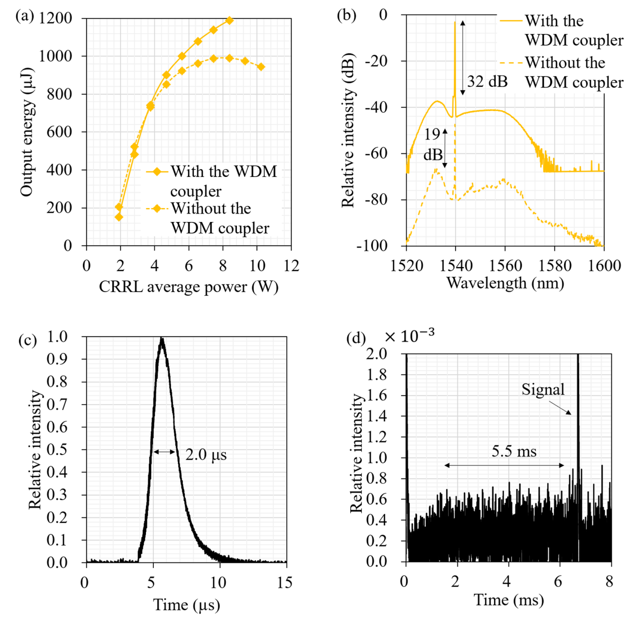

Fig. 3. (a) Measured output pulse energy from the LMA EDFA. The two curves show the output energy with (solid curve) and without (dashed curve) the WDM coupler between the CRFL and LMA EDFA. (b) Spectra of the signal pulses in 5.6 W CW pump operation with (solid curve) and without (dashed curve) the WDM coupler. The RBW is 0.1 nm, and the VBW is 10 Hz. (c) Measured pulse shape of the output beam from the LMA EDFA without the WDM coupler. (d) Enlarged view of the base of the output pulse shape.

III. Experimental Results

A. Output Characteristic of the CRFL

Fig. 2(a) shows the measured output spectra of the CRFL with a output peak power of 9 W. The RBW is 1.0 nm and the VBW is 10 Hz. The black and red curves show the cases of CW pumping and pulse pumping with a pulse duration of 1 ms, respectively. The main peak wavelength is at 1480 nm indicated as (6), and the other peak wavelengths are (1) 1117 nm, (2) 1175 nm, (3) 1240 nm, (4) 1310 nm, (5) 1390 nm, and (7) 1582 nm, which are consistent with the Raman scattering wavelengths of the CRFL [27]. The generation of the next Stokes wavelength at 1582 nm by scattering of the 1480 nm light in the CRFL is suppressed, and the power of the 1582 nm light is over 50 dB lower than that of the 1480 nm for CW pumping. It is noted that unlike in the case of CW pumping, when pulsed pumping is used, a large 1582 nm spectral peak is observed. Fig. 2(b) shows the measured output spectra of the CRFL around 1582 nm, extracted using the WDM coupler and the HPF. The RBW is 0.2 nm, and the VBW is 10 Hz. A small amount of light from 1.5 μm to 1.6 μm is generated in the CRFL as well as the 1480 nm pump light. The average power of the light at 1.5–1.6 μm band measured by the power meter is about 0.03% of the total output power of the CRFL. Fig. 2(c) shows the measured time waveform of the output beam from the CRFL with the pulse duration of 1 ms. Relaxation oscillations which last about 50 μs are observed. The inset shows an enlarged view of the relaxation oscillations measured at different times. Fig. 2(d) shows the measured time waveform of the 1.5–1.6 μm band output from the CRFL extracted using the WDM coupler and the HPF. Since relaxation oscillations always occur at the rising edge during pumping and all of them are integrated, the large optical signal at 1582 nm is considered to be observed only for pulse operation when measuring the optical spectrum. No significant differences in spectra and time waveforms are observed when the pulse duration is changed from 1 ms to 3 ms.

B. Output Characteristic of the LMA EDFA

There are significant differences in the output energy and spectrum of the LMA EDFA with and without the WDM coupler inserted between the CRFL and the LMA EDFA, regardless of whether a CW pump or a pulse pump is used. Fig. 3(a) compares the output energy of the CW pump with and without the WDM coupler. The solid and dashed curves show the signal energy of the LMA EDFA with and without the WDM coupler, respectively. Without the WDM coupler, the output energy has reached its limit, but with the coupler inserted, the signal energy continues to increase as the pump power increases. Fig. 3(b) shows the output spectra of the 5.6-W CW pump with and without the WDM coupler. The solid and dashed curves show the signal energy of the LMA EDFA with and without the WDM coupler, respectively. The SNRs are 32 dB for configuration (i) and 19 dB for (ii). Although the higher energy is obtained, the SNR improves 13 dB by inserting WDM coupler for removing unwanted light from the CRFL. In case of (ii), the SNR is limited by the ASE generated in the LMA EDFA with the peak wavelength of 1534 nm. The SNR in (i) is limited by the pedestal near the signal wavelength with the spectral width of 2 nm due to the bandpass filter built in the back end of the EDFA module (not shown in Fig. 1). Calculated from the spectra in Fig. 3(b), the percentage of power in the signal improves from 61.0% to 94.9%. There is a common ASE peak around 1534 nm, but without the WDM coupler, additional peaks are seen in the 1560 nm and 1582 nm bands. These spectral peaks in the non-signal wavelength region are generally consistent with a previous study by another group using a CRFL as the pump light source [18]. We think that without the WDM coupler inserted, the 1.5–1.6 um band light generated simultaneously with the 1480 nm excitation light in the CRFL would enter the LMA EDFA, sap its gain, be amplified, and emitted. Since a typical EDFA has high gain in the 1530 nm and 1560 nm regions, the light generated by the CRFL is seen to be strongly amplified. Although typical EDFA has little gain in the 1582 nm band, a small peak in the wavelength range corresponding to the 1582 nm peak in the output from the CRFL is also observed. Although a typical WDM coupler for combining pump and signal beam is also function as a short-pass filter, the removal of this unwanted light is not sufficient and further attenuation is needed.

Fig. 3(c) shows the pulse shape of the output beam without the WDM coupler removing the unwanted light. The pulse duration is 2.0 μs. An enlarged view of the base of the pulse is shown in Fig. 3(d). The ASE signal is observed to be generated 5.5 ms before the signal pulse. When the signal pulse and ASE are integrated in time domain, the area ratio is 3:2, which is in general agreement with the ratio obtained from the results of measurements in spectral domain shown in Fig. 3(b).

All the experiments described below are performed with case (i) in Section II, i.e., with WDM couplers inserted between the CRFL and the LMA EDFA.

Fig. 4(a) shows the measured output pulse energy of the LMA EDFA. Each plot shows the measurement results with pump pulse durations of 1 ms (green triangles), 2 ms (blue squares) and 3 ms (red circles). For comparison, the result when a CW pump is used is also shown as yellow diamonds in Fig. 4(a) with a pulse duration of $1/f_{\mathrm{rep}}$. The signal energy is measured directly by a pyroelectric energy sensor. The maximum signal pulse energy reaches 1.2 mJ at a pump energy of 30.6 mJ and with a pump pulse duration of 3 ms in pulse pump operation. It should be noted that the upper limit of the energy measurement is limited by the maximum power output of the CRFL module and the maximum input power to the WDM coupler used in this experiment. This figure shows that the signal energy is higher when the pulse duration is shorter, even though the pump energy is the same. This is because the longer the interval between the pumping and the signal pulse input, the more excited electrons in the Er ions return to the lower states ($^4I_{11/2}$) with a spontaneous decay lifetime (τ_f) of 10 ms, and these contribute to the ASE generation.

The effective pump energy of the LMA EDFA is determined by the total input pump energy and energy store efficiency (η_{st}) described as

$$\eta_{st} = \frac{1 - \exp\left(-t_p/\tau_f\right)}{t_p/\tau_f}\,, \tag{1}$$

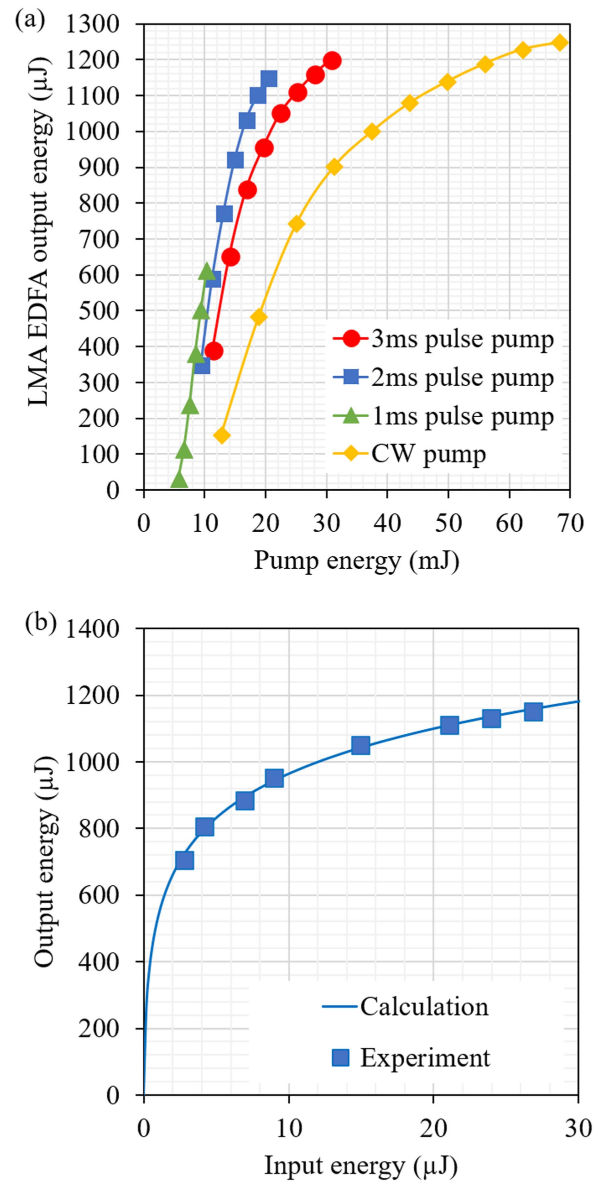

Fig. 4. Measured output pulse energy from the LMA EDFA. (a) Each plot shows the change in output energy versus average pump light power when the pump conditions are CW pump (yellow diamonds), pulsed pump with a pulse duration of 1 ms (green triangles), 2 ms (blue squares), and 3 ms (red circles), respectively. (b) Experimental and calculated dependences of the output pulse energy on the input pulse energy in the case of pulsed pumping with a pulse duration of 2 ms.

where t_p is the pump duration [29]. A comparison of the pump energy required to obtain the same output energy for each pump duration roughly follows the ratio of η_{st} in the low-energy region. In the high-energy region, the pump energy ratio does not necessarily follow the ratio of η_{st} since a part of the input pump energy is converted to ASE [29].

The degradation of the output from the LMA EDFA due to relaxation oscillations which include unwanted 1.5–1.6 um band light has not been observed, since the population inversion is not created in the LMA EDFA when this unwanted light generated only at the rising edge of pulse pumping enters the LMA EDFA in the low f_{rep} operation as shown in Fig. 2(c) and (d).

TABLE I
LIST OF PARAMETERS

Parameter	Value
Saturation fluence (J/cm^2)	17
Small signal logarithmic gain	8.0
Effective area of the LMA EDFA (μm^2)	1100

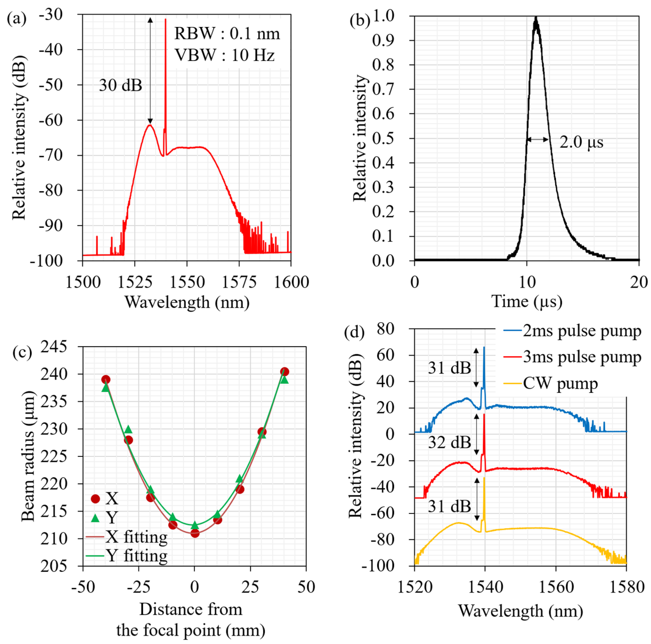

Fig. 5. (a) Measured output spectra from the LMA EDFA with an output energy of 1.2 mJ. (b) Measured time waveform of output pulse from the LMA EDFA. (c) Measured beam quality. The circles and triangles indicate beam radius vs. distance from the focal point for the X and Y directions, and the solid curves show the fitted curves for each direction, respectively. (d) Measured output spectra from the LMA EDFA with an output energy of 1.0 mJ. The yellow, red, and blue lines show CW operation, 3 ms pulse operation (+50 dB offset), and 2 ms pulse operation (+100 dB offset), respectively.

Fig. 4(b) shows numerical analysis for pulse pumping with the pulse duration of 2 ms using a Frantz-Nodvik equation described as

$$P_{out} = A_{eff} E_{sat} \ln \left(1 + \left(\exp\left(\frac{P_{in}}{A_{eff} E_{sat}}\right) - 1\right) \exp\left(g_0 L\right)\right), \quad (2)$$

where P_{out} is an output energy, A_{eff} is an effective area of the LMA EDFA, E_{sat} is a saturation fluence, P_{in} is an input energy, and g_0L is a small signal logarithmic gain [29], [30]. This approach to the calculation is in good agreement with the experimental data if E_{sat} and the g_0L are 17 J/cm^2 and 8.0, respectively. In this calculation, A_{eff} is assumed to be 1100 μm^2 [18]. Table I lists the parameters used in the calculations.

Fig. 5(a) shows the measured output spectra of the LMA EDFA with a pump pulse duration of 3 ms and a pulse energy of 1.2 mJ. The RBW and VBW are 0.1 nm and 10 Hz, respectively. The SNR of the spectrum is 30 dB and is limited by the ASE generated in the LMA EDFA with a peak wavelength of 1534 nm. The calculated percentage of power in the signal is 90.7%.

Fig. 5(b) shows the measured pulse shape of the output beam from the LMA EDFA. The pulse duration is about 2.0 μs, which corresponds to approximately 625 W peak power. No signs of SBS are observed in the spectra or time waveforms in this experiment. In the previous study, a 700 W peak power with the pulse duration of 1 μs was observed when using the same type of fiber used in our experiments and it was concluded that the output power was limited by SBS effect due to 3-m long fiber [18]. Unlike the result without WDM coupler shown in Fig. 3(d), the ASE signal generated immediately before the signal pulse is not observed. It is estimated that the ASE signal was below the detection limit of our measurement system.

Fig. 5(c) shows the beam radius (1/e^2) versus distance from the focal point. X and Y correspond to the horizontal direction (parallel to the layers) and the vertical direction (perpendicular to the layers), respectively. The beam quality factor M^2 is calculated to be 1.21 ($= \sqrt{1.22 \times 1.19}$).

To investigate the difference in the SNR and the percentage of power in the signal with different pump durations, the spectra at an output energy of 1.0 mJ are compared. Fig. 5(d) shows the respective spectra for pump pulse durations of 2 ms (blue, +100 dB offset), 3 ms (red, +50 dB offset), and a CW pump (yellow). Shortening the pump pulse duration improves the percentage of power in the signal from 94.9% with CW pump operation to 98.7% with 2-ms pulse pump. These results are because the longer the pump duration, the longer the ASE lasing time before the signal inputs. This is consistent with the results shown in Fig. 4(a). In all cases, SNRs are about 31 dB, and are limited by the SNR of the output beam in the EDFA module including BPF used as a preamplifier.

IV. DISCUSSIONS AND CONCLUSION

Laser spiking in the CRFL due to relaxation oscillations could cause damage to fiber components, since the peak power is 4 times larger than the light generated in any other time domain as shown in Fig. 2(c). Although the rise time of the electrical pulse signals was varied from 30 μs to 200 μs by changing the time constant of the electrical circuit, no improvement was seen. Adding a loss modulator driven by an external control signal inside or outside the CRFL could solve this problem.

It is desirable to pump the LMA EDFA with high power and short pump duration taking into account the results shown in Figs. 4(a) and 5(d) and their discussions. Recently, CRFLs with 50 W-class output power have been available, so the pump duration could be further shortened [18], [27]. In this case, the technique presented in this article could also be applied to high f_{rep} operations. However, increasing the power of the CRFL output also raises not only the peak power of the spiking due to relaxation oscillations which can damage fiber components, but also the beam power in the 1.5–1.6 μm band produced over the entire pump pulse duration, which degrades the output energy, the SNR and the percentage of power in the signal. Highly durable WDM couplers or HPFs that separate light at 1480 nm from light above 1.5 μm would be needed.

Compared to previous study with the highest output pulse energy at low f_{rep} operation below 1 kHz [16], the maximum pulse energy is slightly lower due to the limitation of the output power of the CRFL and the damage threshold of the WDM coupler used in our experiment, but the SNR is more than 15 dB higher. In addition, another 1.5-um light source as a pump laser is not required, and separation of pump light and signal light is easier.

In conclusion, we have improved the output of an LMA EDFA that emits a single-frequency, high-energy pulse by combining the elimination of unwanted light in the 1.5–1.6 μm band generated in the CRFL with pulsed pump operation. A pulse energy of 1.2 mJ is achieved at the $f_{\rm rep}$ of 150 Hz, and the SNR improves to more than 30 dB compared to 19 dB before the improvement. The percentage of power in the signal also improves from 61.0% to over 90.7%. The peak power is 625 W and no SBS is observed in this experiment. The beam quality factor M^2 of the output beam is 1.21. In addition, the output energy is measured relative to the input energy and fitted with the Frantz-Nodvik equation to identify the characteristics of the LMA EDFA. The improvement techniques shown in this article could be useful for high $f_{\rm rep}$, short duration pulse operation.

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