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Demonstration of a high-energy, narrow-bandwidth, and temporally shaped fiber regenerative amplifier

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We report a high-energy and high-gain fiber regenerative amplifier for narrow-bandwidth nanosecond laser pulses that uses a Yb-doped photonic crystal fiber. The input pulse energy is 270 pJ for a 3.5 ns laser pulse with 0.3 nm (FWHM) bandwidth. At a pump laser power of 8.6 W at 974 nm, pulse energies up to 746 μJ with 1.2% (rms) energy stability are generated. To the best of our knowledge, this is the highest energy obtained in a fiber-based regenerative amplifier. A high-energy, nearly diffraction-limited, single-mode beam with a high gain of 64 dB shows promise for future application in the front ends of high-power laser facilities.

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Nanosecond laser sources with high gain and energy on the order of millijoules have attracted widespread attention in the sciences and in industrial applications. A striking example is the large-scale laser facility dedicated to inertial confinement fusion using lasers, such as the National Ignition Facility (NIF), Laser Mégajoule (LMJ), SGII series, and Inertial Fusion Energy (IFE). Normally, the nanosecond laser amplifier consists of several stages to provide high gain and energy amplification ability. The master-oscillator power amplifier (MOPA) structure provides flexibility in power, energy, and temporal shape adjustment, as well as environmental stability. However, since the structure needs several stages to achieve high gain and high pulse energy, MOPA is too complex for the front end of laser facilities such as NIF and LMJ [1–3]. One alternative is the regenerative amplifier, which is quite compact and can provide high-gain, high-optical signal-to-noise ratio (OSNR), and excellent stability. Compared with the MOPA structure, the regenerative amplifier can obtain better OSNR and temporal stability because of the pseudo cavity. The bulk regenerative amplifier has been utilized in the front end of NIF and LMJ as part of the pre-amplification module (PAM). Nevertheless, better beam quality, higher gain and compactness, and better suppression of FM-to-AM, which are challenges for the bulk regenerative amplifier, will be required in future front ends of large-scale laser facilities. Fiber lasers have attracted more interest than bulk solid-state lasers because of their flexibility, compactness, laser-confined structure, and long-term stability. Additionally, the fiber regenerative amplifier could maintain a smaller B-integration than a MOPA-based fiber amplifier because the mode area of fiber in regenerative amplifier is much larger than the first or second stages in a MOPA amplifier. Fiber regenerative amplifiers have achieved gain greater than 40 dB and output energy of 30 nJ [4]. However, the output energy of fiber regenerative amplifiers has always been limited to below approximately 200 μJ because of fiber damage [5,6]. Recently, large-mode-area, double-cladding, or photonic crystal fibers with single-mode operation ability have become commercially available; we believe that such fibers will be a solution to developing fiber regenerative amplifiers for high-energy, narrow-bandwidth, and temporally shaped front ends [7].

With photonic crystal fiber as the gain medium, output energies as high as 1.5 mJ have been obtained in an amplifier with the MOPA structure [8]. The output pulse energy is commonly limited by end-face damage in the fiber, which is directly proportional to $\tau^{1/2}$ (where τ is FWHM pulse width) [9]. Large core diameter fibers are essential to exceeding this limitation for high pulse energy amplification, and a rod fiber with 100 μm core diameter has recently been used [10]. The front end of a large-scale facility for ignition confinement fusion (ICF) is different from that of a normal facility. The requirements for high performance in a single-mode beam, i.e., high-gain, high-OSNR, millijoule-level energy polarization extinction ratio (PER), and energy stability are particularly strict in the front end [11]. The polarizing photonic crystal fiber is quite suitable for the front end because of its single-mode guidance, large-mode field diameter, single polarizing ability, and coiling ability, which are excellent properties to obtain a good amplification quality.

In this Letter, we demonstrate a fiber regenerative amplifier with high-gain, high-energy, and long-term stability for narrow-bandwidth and temporally shaped nanosecond laser pulses that can be utilized in the front end of large-scale laser facilities in the future. This fiber regenerative amplifier can replace several stages of a direct amplifier in the front end, and will be more compact and stable. With the photonic crystal fiber, nanosecond laser pulses of 700 μJ are obtained, which, to the best of our knowledge, is the highest energy for fiber regenerative amplifiers.

Figure 1 shows the schematic of the experimental setup, which consists of two parts: the all-fiber front-end seeder and the fiber regenerative amplifier. A distributed feedback (DFB) laser with a bandwidth less than 100 kHz at 1053 nm is used as the oscillator for the entire system. The repetition rate and temporal pulse shape can be arbitrarily controlled with an acousto-optic modulator (AOM) and electro-optic modulator driven by an arbitrary waveform generator (AWG). Considering the process of inertial confinement fusion using lasers, the suppression of stimulated Brillouin scattering (SBS) and smoothing by spectral dispersion (SSD) are quite important [11]. Here, we use the phase modulator driven by a single-tone signal to broaden the laser pulse spectrum to 0.3 nm. The threshold of SBS is related to the bandwidth of the pump laser [12]; therefore, it is improved by nearly 100 times compared to the original laser. Before the pulse enters the regenerative amplifier, an AOM is used to improve the OSNR further. Finally, a 3.5 ns temporally shaped signal pulse of energy 270 pJ at 1 Hz repetition rate is collimated by an aspherical lens into the fiber regenerative amplifier. The repetition rate of regenerative amplifier is 1 Hz because the front-end system in large facilities such as NIF, LMJ, or SGII series are all worked at low repetition rate. A 2.5 m polarizing photonic crystal fiber with a core diameter of 40 μm is pumped by a continuous diode at 974 nm and used as the gain fiber in the regenerative cavity. The amplifier is controlled by a large-aperture Pockels cell, and the backward laser is eliminated by the Faraday isolator in the cavity. By adjusting the fiber polarization controller (PC), the signal laser can be reflected by a polarization beam splitter (PBS) and then coupled into the gain fiber. The gain of signal laser in the gain fiber can be maximized by turning the half-wave plate before the gain fiber to align the signal laser at the slow axis of the polarizing fiber. The adjustment of the half-wave plates can maximize the fiber gain, as well as align the polarization of a laser in cavity to the slow axis of fiber. The half-wave voltage is added to the Pockels cell to convert the s-polarized light to p-polarized light or vice versa. The Pockels cell is opened immediately before the signal laser is coupled out of the fiber. After a certain number of round-trips, the amplified laser pulse transmits outside the regenerative amplifier as the Pockels cell is closed. A 25 nm bandpass filter is inserted into the cavity to suppress stimulated Raman scattering (SRS). A high-speed photodiode with bandwidth of 10 GHz and a 12 GHz oscilloscope are used to detect the waveform.

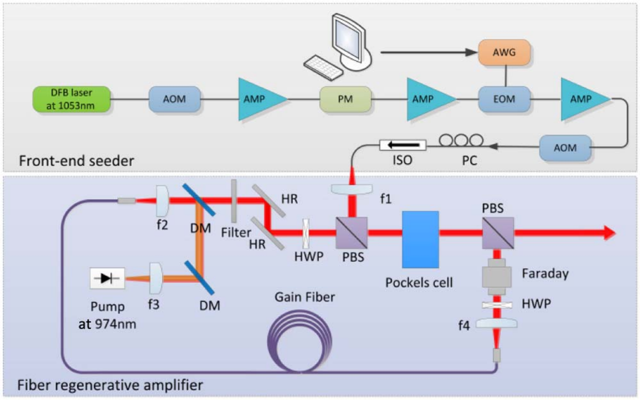

Fig. 1. Experimental schematic of the narrow-bandwidth and temporally shaped fiber regenerative amplifier system. DFB, distributed feedback laser; AOM, acousto-optic modulator; AMP, single mode fiber amplifier; PM, phase modulator; EOM, electro-optic modulator; AWG, arbitrary waveform generator; PC, polarization controller; ISO, high power isolator; PBS, polarizing beam splitter; HWP, half-wave plate; DM, dichroic mirror; f1, f2, f3, f4, aspherical lens.

In the front end of a large-scale facility, a narrow-bandwidth laser pulse is desired, but the spectrum is broadened to 0.3 nm to suppress SBS, as mentioned above. The gain fiber was coiled in a 38 cm diameter plane to maintain good polarizing ability. The fiber polarization controller is necessary because the front-end seeder system is based on a normal single-mode fiber. When the laser spectrum is broadened, FM-to-AM modulation induced by the group-velocity dispersion (GVD) and polarization mode dispersion would seriously affect temporal pulse shape after the laser transmits polarization dependent element. In a large facility, the laser of front end often needs to be transmitted for 100 m of SM fiber or PM fiber which will induce obvious temporal modulation because of FM-to-AM conversion.

In the experiment, the gain fiber was cleaved at an 8° angle to avoid parasitic lasing. A section of coreless fiber with 700 μm length and 400 μm diameter was fused to the fiber to lower the intensity at the facets. Figure 2 shows the maximum total gain with different pump powers for pulse contrast ratio 6:1 (red line) and 8:1 (black line). The contrast ratio is defined as the proportion of the amplitude of the trailing edge and the front edge. The maximum total gain is approximately 64 dB at 8.6 W pump power (total diode power) for pulse. The growth of total gain slows at higher pump power, indicating that gain saturation has occurred. The maximum output pulse energy and round-trips under different pump powers are shown in Fig. 3. Upon increasing the pump power, the pulse energy increases proportionally. The output energy is measured using a pyroelectric joulemeter (Coherent EnergyMax). At the highest pump power, 8.6 W, the output pulse energy is 746 μJ at 1 Hz, which is the highest output energy obtained with a fiber-based

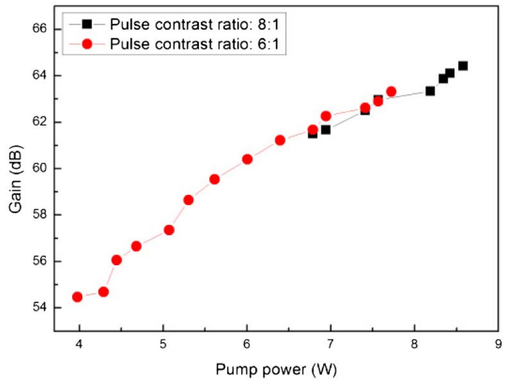

Fig. 2. Maximum total gain versus pump power (W) for pulses with different contrast ratio.

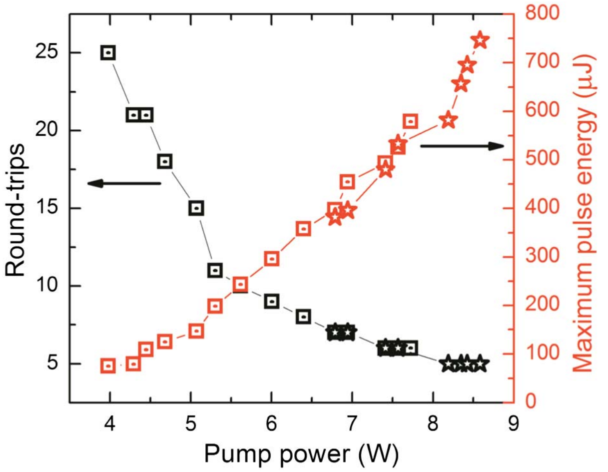

Fig. 3. Maximum output pulse energy (red line) and number of round-trips (black line) needed to reach the highest output energy versus pump power for pulse contrast ratio 6 : 1 (square) and 8 : 1 (star).

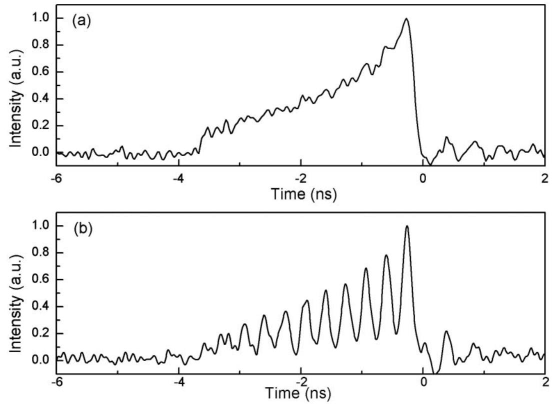

Fig. 4. FM-to-AM of pulse after amplification. (a) Aligned laser polarization to the slow axis of fiber and (b) misalignment.

regenerative amplifier. The output energy for pulse contrast ratio 6 is consistent with the pulse with contrast ratio 8. The energy stability is 1.2% rms (short term) and 1.6% rms (3 h) at 746 μJ pulse energy. The number of round-trips decreases with pump power, and the energy stability (rms) increases simultaneously, which we believe is the result of gain saturation. It should be noticed that the number of round-trips at maximum output energy is only five. Decreasing round-trips would cause the output energy to dramatically reduce, which is the result of high single-pass gain in the regenerative amplifier. The output energy would also decrease quickly after exceeding the maximum round-trips at a certain pump power because the cavity loss is larger than the gain.

For a narrow-bandwidth nanosecond front end, the FM-to-AM modulation is a significant factor affecting the output temporal quality. Generally, it is most significantly related with the dispersion in the fiber, and, in the regenerative amplifier, polarization-mode dispersion dominates the shape of the output pulse. The photonic crystal fiber is the key to suppressing the FM-to-AM modulation because of the excellent polarizing quality whose measured polarization extinction ratio (PER) is more than 20 dB. In our fiber regenerative amplifier, two half-wave plates (HWP) are used to control the polarization of laser pulses in a cavity to the slow axis of the gain fiber. If the pulse polarization is far from the slow axis, heavy amplitude modulation generated by the FM-to-AM modulation is observed. The pulse shape will contain several peaks, and the modulation depth can even be greater than 80%, as shown in Fig. 4(b). If the polarization of the laser is adjusted to the slow axis of the fiber, no obvious modulation is observed, which is shown in Fig. 4(a). Owing to the polarizing quality of the fiber, as mentioned above, a pulse need not strictly be polarized in the slow axis before entering the gain fiber. Upon adjusting the polarization controller in the cavity, no significant modulation is observed, as shown in Fig. 5. The measured PER of the output pulse is above 20 dB in experiment.

The injected signal is a 3.5 ns laser pulse (base width) with 270 pJ energy and 0.3 nm bandwidth. To pre-compensate for the gain saturation in the regenerative amplifier, the pulse is shaped by the electro-optic modulator and AWG to a temporal profile with a low front edge and high end edge. The shaped pulse is the black line shown in Fig. 5. A square pulse is observed at 580 μJ, and the temporal profile continues to change with larger pulse energy because of the large square pulse distortion (SPD). The final waveform with the highest energy of 764 μJ is the red line in Fig. 5(b). This regenerative amplifier can maintain a good temporal fidelity than the MOPA structure as shown in [6]. After amplification, the pulse approaches a deep saturated state, and it is reasonable that the gain saturation seriously influences the temporal profile. A shorter fiber with lower gain can be used to decrease the SPD which will be demonstrated in the following work.

It should be mentioned that a short pulse with a pulse width of approximately 100 ps (FWHM) is observed when the Faraday isolator does not exist in the cavity at the beginning of our experiment. This type of pulse appears randomly, and an obvious threshold effect is exhibited. The output spectrum is examined, and a spectral peak appears shifted by approximately 0.12 nm with respect to the pulse spectrum. All these characteristics indicate that the short pulse is generated by SBS. Because the 0.12 nm spectral drift is coincident with the 0.06 nm Stokes-spectral drift in the fiber, we believe that the short pulse is a second-order Stokes light induced by the feedback of the backscattered SBS laser. Because the injected pulse would transmit several times in the cavity, the valid fiber length is

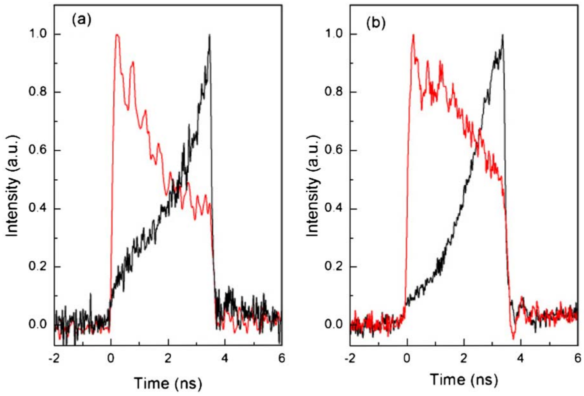

Fig. 5. Pulse shape of the injected signal (black line) and the output pulse (red line). (a) Pulse contrast ratio 6:1 and (b) pulse contrast ratio 8:1.

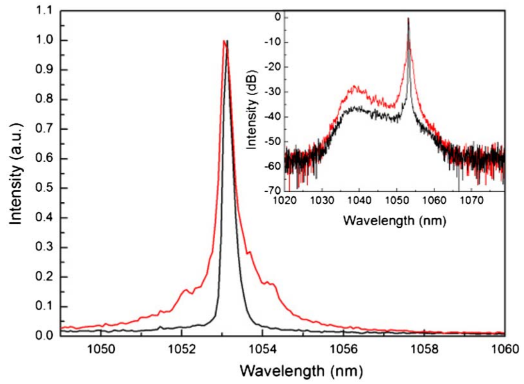

Fig. 6. Spectra of the injected pulse (black line) and output pulse at 746 μJ (red line).

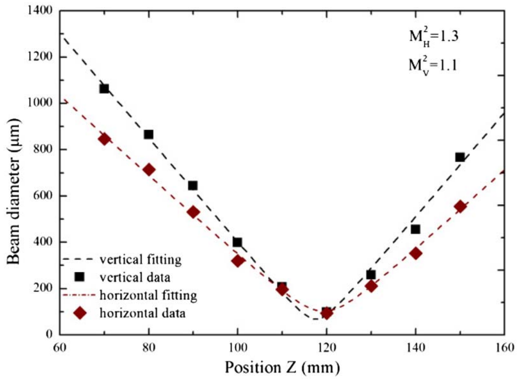

Fig. 7. Beam characteristics at 746-μJ output energy.

enough for SBS. The pulse disappears after the Faraday isolator is added into the cavity. The explanation for this phenomenon is out of the scope of this Letter, and further study will be conducted in the future to understand this phenomenon.

The output spectrum is measured using an optical spectrum analyzer (Ocean Optics HR2000+) with 0.1 nm resolution, as shown in Fig. 6. The black line is the injected pulse, and the red line is the spectrum of the output pulse at 746 μJ. The output spectrum is only slightly different from the input pulse because of the self-phase modulation in the fiber when the peak power of the output pulse is almost 210 kW. For application in a front end, the spectrum width should be between ~0.3 nm, which is seen as narrow linewidth in a large laser facility. The narrow linewidth laser is needed because the efficiency of nonlinear conversion stages at last can be higher. The slightly broadened spectrum (0.37 nm, FWHM) is not of consequence to be applied in a front-end system.

The OSNR measured temporally by a photodiode, and an attenuator is above 30 dB when a 25 nm bandpass filter is added into the cavity. The filter is mainly inserted to suppress the stimulated Raman scattering that can occur in the regenerative cavity. Figure 7 shows the focal spot diameter, along with the propagating position near the focal plane. A lens with a focal length of 120 mm is used to measure the M^2 value of the output beam.

The M2 beam quality values measured along the horizontal and vertical directions are 1.3 and 1.1, respectively, indicating that the beam is nearly single mode. The excellent beam quality is a key factor for application in the front end of a large-scale facility. The nearly single-mode beam will improve the performance of the main amplifier in the facility.

In conclusion, we demonstrated a temporally shaped and narrow-bandwidth fiber regenerative amplifier. A photonic crystal fiber with a 40 μm core diameter is chosen as the gain medium. In the experiment, a 3.5 ns pulse with a narrow bandwidth of 0.3 nm and 270 pJ energy is amplified to 746 μJ at a pump power of 8.6 W, which, to the best of our knowledge, is the highest energy achieved thus far. The energy stability is approximately 1.2% (rms) at the highest energy. Nearly a 64 dB gain is achieved, and no significant SBS or SRS is observed. The OSNR is above 30 dB, and the PER is 20 dB, which is sufficient for application in the front end of a large-scale facility. The beam quality was measured, and the M^2 values were 1.3 and 1.1 in the horizontal and vertical directions, respectively. By carefully adjusting the polarization state, the amplitude modulation generated through FM-to-AM modulation is eliminated almost completely. Further pulse energy scaling can be realized using a shorter fiber with a larger mode area. The fiber regenerative amplifier designed for application in a temporally shaped and narrow-bandwidth front end can replace several stages of an amplifier and simultaneously improve beam quality, energy stability, and temporal profile stability and fidelity. The fiber regenerative amplifier has advantages in beam quality, flat gain over a large bandwidth, and heat dissipating performance which can be ignored nearly without active cooling, compared with a regular Nd: glass regenerative amplifier. However, the regenerative amplifier is not all-fiber because the technique to fabricate fiber components such as large-aperture Pockels cells, WDMs, or couplers for large-mode field photonic crystal fiber is not mature at present. Further work will be done to build an all-fiber high-energy regenerative amplifier. The fiber regenerative amplifier shows an alternative method for PAM in large-scale laser facility.

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