

High-gain all-fiber regenerative amplifier

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Received April 5, 2012; accepted July 23, 2012; posted online December 20, 2012

An all-fiber regenerative amplifier at 1053 nm is demonstrated. The input signal pulse energy is 75 pJ in a 3.5-ns pulse at a 1-Hz repetition rate. At a low level of input pump power of 110 mW, the saturated output energy is 120 nJ with fluctuation less than 2% root mean square (RMS) even the fluctuation of the input pulse be about 15% (RMS). And the signal-to-noise ratio (SNR) is 66 dB. Maximum output energy of 780 nJ with a total gain of more than 40 dB is obtained at pump power of 130 mW. Scaling to higher pulse energy is constrained by stimulated Raman scattering.

OCIS codes: 060.2320, 140.3280.

doi: 10.3788/COL201210.S20610.

As one of the most important components of a high-power laser system, the front end system seeds the subsequent laser system with pulses that have high stability, high beam quality, proper bandwidth, and high signal-to-noise ratio (SNR). The output quality of front end determines the output quality of the whole laser system to a large extent. So developing a high-gain and high output stability amplifier with superior beam quality is attractive and important.

Fiber optical amplifiers based on rare-earth-doped fibers have been investigated for decades^[1–3] because of their inherent compactness, superior beam quality, and stability. Optical pulses with high repetition rate are routinely amplified by one or more staged single-pass rare-earth-doped fiber amplifiers. However, the front end of high-power laser system runs in the state of extremely low repetition rate. The low-duty-cycle pulses leave large population inversion in the gain fiber for long durations between pulses, which can lead to serious broadband amplified spontaneous emission (ASE). The ASE competed for the unsaturated gain restricts the gain and degrades the SNR^[4].

All-fiber regenerative amplifiers circulate the optical pulses in a fiber cavity for amplifying, which greatly improve the energy gain and SNR. In addition, all-fiber regenerative amplifiers can easily operate at saturation which can enhance the output stability a lot. In 2006, Yang^[5] reported a ring cavity, Q-switched fiber regenerative amplifier that achieved 40-dB gain and 30-nJ output pulse energy at 1530 nm. Recently Xin *et al.*^[6] demonstrated a Yb-doped all-fiber regenerative amplifier operating at 1053 nm amplified 10-ns, 15-pJ square pulses to 240 nJ. In this letter, we report an all-fiber regenerative amplifier with Yb-doped fiber as the gain medium for amplifying 3.5-ns optical pulses with an extremely low repetition rate of 1 Hz from 75 to 120 nJ at 1053 nm. Operating at saturation, the output stability and SNR is being improved greatly.

The experimental setup of the all-fiber regenerative amplifier is schematically shown in Fig. 1. The seed signal is 3.5-ns square pulses from a chopping laser system of front end^[7] and has a repetition rate of 1 Hz at 1053 nm which is 23 nm off the gain peak of Yb-doped fiber used in the experiment. The input-pulse energy is 75 pJ.

A 2×2 acousto-optic modulator (AOM) switch which is used to control whether the pulses are coupled into the cavity or into the output port has been built. The AOM is controlled by a digital delay generator which is synchronized to the seed pulses. When the AOM is turned off, the amplifier is equivalent to a single-pass amplifier. The pulses are amplified once in the cavity then to the output port. As the AOM is in the open state, the pulses circulate in the cavity until the AOM is turned off. The duration of the AOM opened can be exactly controlled by the digital delay generator. A section of 3.2 m Yb-doped single-clad fiber with a mode field diameter of 3.6 μm acts as the gain medium. The gain medium is counter-pumped by a 980-nm laser diode (LD) through a 980/1053 nm wavelength division multiplexer (WDM). The 980-nm band-pass filter (BPF) protects the LD from the damage caused by optical feedback. A 1053-nm BPF with 1-nm bandwidth is used to suppress the ASE.

Figure 2 shows the amplifier output energy at different roundtrips at the pump power of 110 mW. Because of the low pump power level, the gain is comparatively low at first few roundtrips due to a high amount of ASE competing with the signal^[8]. Then as the number of roundtrip increases, the output energy grows exponentially to the maximum then declines because of gain saturation. At the 14th roundtrip we obtain the maximum saturated output energy of 120 nJ with high SNR of 66 dB. Operating at saturated regime, the output stability can be improved greatly. As it is shown in Fig. 3, even the input power has a fluctuation of 15% root mean square (RMS), the RMS of output energy can be less than 2%.

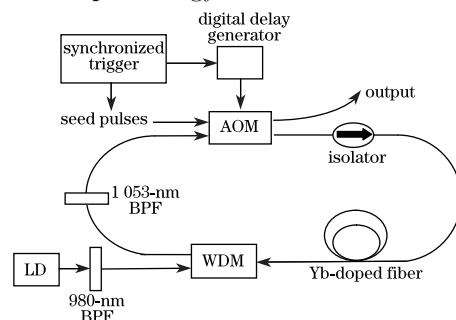


Fig. 1. Schematic of the experimental setup of regenerative amplifier.

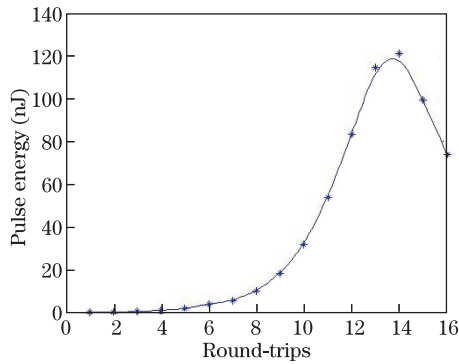


Fig. 2. Measured pulse energy as roundtrip is increased. The pump power is 110 mW.

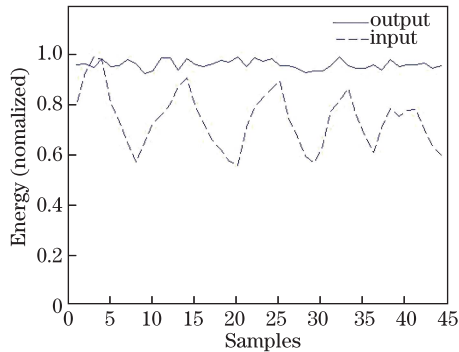


Fig. 3. Variations of input and output energy.

Changing the pumping power and roundtrips, the maximum output energy we have got is 780 nJ, yielding a gain of more than 40 dB. The relationship between output energy and roundtrips is shown in Fig. 4. In the 7th roundtrip the gain of single pass begins to decline and leads to severe square pulse distortion, which means the amplifier is operating at a state close to the saturated regime. The pulses are deformed and the energy declines if we add one more roundtrip. For the fiber regenerative amplifier, raising the pump power and decreasing the roundtrips, we can obtain higher output energy. However, the maximum output energy is restricted by the stimulated Raman scattering (SRS), which is proved in the experiment. As the pump power enhances, the output energy grows rapidly, and reaches the threshold of SRS within a few roundtrips. Adding roundtrips will raise the output energy but also increase the total length of fiber which will decline the threshold of SRS.

In this regenerative amplifier SRS is the dominant

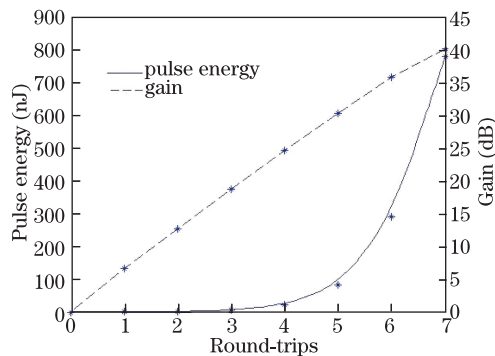


Fig. 4. Measured pulse energy and total gain as roundtrip is increased. The pump power is 130 mW.

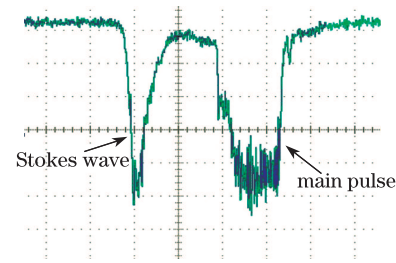


Fig. 5. Separation of Stokes wave and main pulse.

nonlinear scattering process. The maximum output energy is constrained by the SRS. Because of the low repetition of 1 Hz, the spectrum output is difficult to be detected. Using the dispersion of long single mode fiber, the Stokes wave and the main pulses can be separated revealing the SRS effect^[9]. Removing the BPF in the cavity and adding 3-km fiber to the output port, the Stokes wave and the main pulses are split, as shown in Fig. 5. The delay time between Stokes wave and main pulse we measure from the oscillograph is 4.8 ns. Frequency shift calculated is about 13 THz, which is consistent with the Raman shift of fused silica^[10]. The results show that as the pulses energy exceeds the threshold value of the SRS, the energy of the main pulses transfer to the Stokes wave rapidly, and the temporal structure becomes complex and eventually irregular.

In conclusion, we discuss the design and testing of an all-fiber regenerative amplifier at 1053 nm. The input signal pulse energy is 75 pJ in a 3.5-ns pulse at a 1-Hz repetition rate. At 110-mW of pump power, the maximum saturated output energy is 120 nJ after 14 roundtrips with good output stability and SNR. And at 130 mW of pump power, we obtain the maximum output energy of 780 nJ after 7 roundtrips. The total gain is more than 40 dB. Further scaling is constrained by the SRS. So the major work in the future are optimizing the structure of cavity and diminishing the rise-time of the AOM to shorten the cavity length in order to increase the threshold of nonlinearity.

This work was supported by the National Natural Science Foundation of China under Grant No. 61205103.

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