Millijoule pulse energy picosecond fiber chirped-pulse amplification system

Zhi Yang (杨 直)[1,2*], Xiaohong Hu (胡晓鸿)[1], Yishan Wang (王屹山)[1], Wei Zhang (张 伟)[1], and Wei Zhao (赵 卫)[1]

[1]*State Key Laboratory of Transient Optics and Photonics, Xi'an Institute of Optics and Precision Mechanics, Chinese Academy of Sciences, Xi'an 710119, China*

[2]*Graduate University of the Chinese Academy of Sciences, Beijing 100049, China*

[*]*Corresponding author: yz2422@163.com*

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The efficient generation of a 1.17-mJ laser pulse with 360 ps duration using an ytterbium (Yb)-doped fiber amplifier chain seeded by a homemade mode-locked fiber laser is demonstrated experimentally. A specially designed figure-of-eight fiber laser acts as the seed source of a chirped-pulse amplification (CPA) system and generates mode-locked pulses with hundreds of picosecond widths. Two kinds of large-mode-area (LMA) double-clad Yb-doped fibers are employed to construct the pre-amplifier and main amplifier. All of the adopted instruments help avoid severe nonlinearity in fibers to raise sub-nanosecond pulse energy with acceptable signal-to-noise ratio (SNR). The output spectrum of this fiber-based CPA system shows that amplified spontaneous emission (ASE) is suppressed to better than 30 dB, and the onset of stimulated Raman scattering is excluded.

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Over the years rare-earth doped double-clad fiber amplification technology has been combined with chirped-pulse amplification (CPA) techniques to amplify relatively weak ultrashort laser pulses in gain fibers to realize high per-pulse energy[1−5]. Rare-earth doped fibers have numerous practical virtues, such as the fiber core-determined robustness of the laser modal properties, high efficient gain, and weaker thermal lensing effects[6]. All of these characteristics present fiber amplifiers access to the growing number of high-precision material processing applications. The minimization of processing traces in materials is the primary reason for using short-pulse lasers as shorter pulses are typically able to minimize the heat-affected zone at the work piece and consequent potential damage to nearby components. The high energy fiber laser amplifiers reportedly reach millijoule levels mainly in nanosecond regimes[7−11], still a relatively long pulse for fine processing applications considering heat dispersion requirement. Few reports on the more ideal short pulse fiber laser source of picosecond duration exceeding 1 mJ for such applications have published because the extremely high peak power of picosecond pulses in fibers induce damage to the fibers, and the onset of nonlinear effects stemming from the tiny fiber core is difficult to eliminate[12]. In Ref. [3], a 1-mJ laser pulse at sub-picosecond was produced from the compression of a 2-ns amplified laser pulse in a fiber CPA system. This is the highest pulse energy ever extracted from femtosecond fiber amplifiers. However, femtosecond CPA systems unavoidably adopt dispersion compensation devices, thereby complicating the entire system. Conversely, a high energy picosecond fiber CPA system without a compression instrument, as the one recounted, features a simpler structure compared with a femtosecond CPA system, and can still effectively perform in many applications. Technically, in the production of high energy laser pulses, relatively low repetition rates are naturally required to ensure high per-pulse energy for a realistic average output power[13]. Nevertheless, laser pulses with low repetition rates encounter low amplification efficiency because of the limited uplevel life-time of inverted populations. As the period of signal pulse array becomes longer, amplified spontaneous emission (ASE) consumes more active populations in gain fibers and therefore diminishes signal-to-noise ratio (SNR) as well as amplification efficiency. Thus, many procedures, such as the optimization of gain fiber length, noise component filtering, etc., are necessary in the construction of high energy amplifiers and worthy of careful consideration.

In this letter, we report a Yb-doped fiber-based CPA system generating a 1.17-mJ pulse energy with a pulsewidth of 360 ps at a repetition rate of 10 kHz. The seed laser chain of this CPA system comes from our homemade mode-locked fiber laser, followed by single mode fiber amplifiers and large-mode-area (LMA) Yb-doped fiber amplifiers. Numerous laborious tasks were undertaken in the experiment to minimize nonlinear effects while guaranteeing efficient amplification and acceptable SNR for the generation of millijoule laser pulses of hundreds of picoseconds.

The experimental setup of the millijoule level fiber CPA system is shown in Fig. 1. It mainly comprises a passively mode-locked Yb-doped fiber laser, which provides a pulse seed for the CPA system, a fiber-structured acousto-optic pulse picker, which down-counts the pulse array's repetition rate, a Yb-doped single mode fiber (SMF) amplifier, and two stages of Yb-doped LMA fiber amplifiers.

In CPA technology, extremely short laser pulses are difficult to perfectly amplify, which is why stretching the pulse width through dispersion devices is necessary before amplification. Grating pairs and chirped fiber-gratings are diffractive implements able to provide large

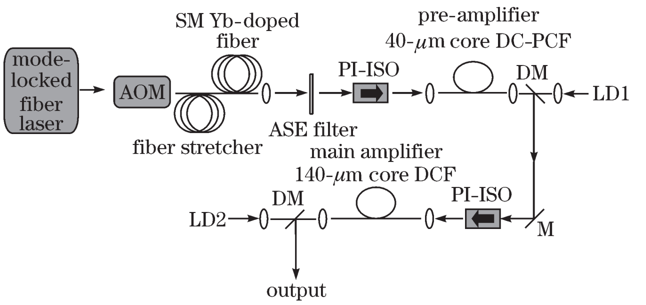

Fig. 1. Experimental setup of the millijoule level fiber CPA system. AOM: acousto-optic modulator; SM: single mode; PI-ISO: polarization independent isolator; DC-PCF: double-clad photonic crystal fiber; DM: dichroic mirror; LD: laser diode; M: mirror; DCF: double-clad fiber.

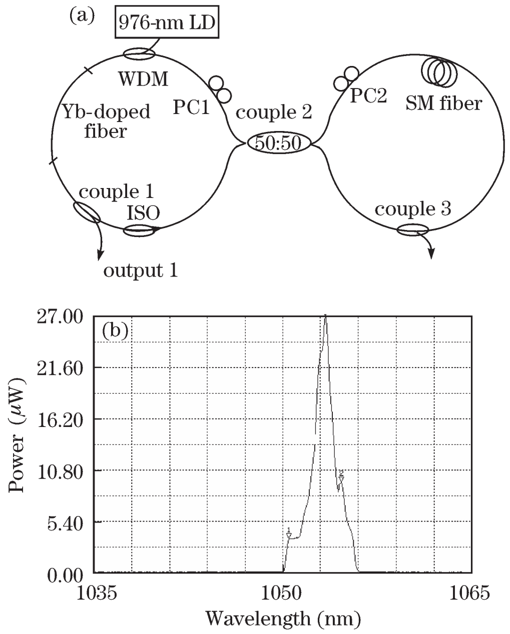

Fig. 2. (a) Schematic of figure-of-eight cavity mode-locked fiber laser and (b) mode-locked seed laser spectrum.

amounts of dispersion to laser pulses, but using these are complicated and they are highly sensitive to vibration. In our self-made mode-locked seed laser, we built a figure-of-eight fiber laser (Fig. 2(a)), in which one of its loops is more than 40-m long to provide large normal dispersion from silica fiber material dispersion[14,15]. A long fiber loop in a laser cavity not only helps stretch pulse duration, but also decreases the repetition frequency of the mode-locked pulse array. For pulse picking in AOM, a relatively low repetition rate of fundamental frequency makes it easier to pick out only one laser pulse at every acousto-optic interaction in acousto-optic modulator (AOM). This self-made all-fiber structure passively mode-locked laser operates in the all-normal-dispersion region and directly generates 336-ps width pulses at a repetition of 3.9 MHz at 1053-nm center wavelength (Fig. 2(b)).

The average output power of the mode-locked seed source was first amplified to 80 mW by single mode Yb-doped fiber amplifier before being fed to fiber-coupled AOM, which was used to lower the pulse repetition rate from 3.9 MHz to 10 kHz. The average optical power was reduced correspondingly to 8 μW. This large attenuation arises from the large insertion loss of fiber-coupled AOM and the intrinsic discharge of 389 pulses of each 390 pulse at down-counting operation. The selected 10 kHz pulsed laser was so weak that it must be amplified even in single mode Yb-doped fiber amplifiers before being used in an LMA fiber amplifier. However, nonlinear effects such as self-phase modulation (SPM), stimulated Raman scattering (SRS), etc. arise at a certain level where amplified pulse energy reaches in SMFs. Thus, we shortened fiber length as much as we could in SMF amplifier chains to avoid nonlinearity. Meanwhile, adding a roll of SM28 fiber between the AOM and the subsequent SMF amplifiers to extend pulse width and therefore reduces peak power before amplification. Furthermore, two band-pass filters of 10-nm width pass band were incorporated into the amplifier chains, and the accumulated SRS component was removed[16]. About 440-m SM28 fiber functions as a pulse stretcher and the output amplified energy from single mode fiber amplifier chains reached tens of microjoules without any additional spectral component except for SPM-induced spectrum broadening.

The filtered laser from SMF amplifiers was coupled into the pre-amplifier, which consists of a 1.2-m long double-clad photonic crystal fiber (PCF) with a 40-μm (NA = 0.03) Yb-doped core and a 170-μm (NA = 0.62) inner cladding pumped by a fiber coupled laser diode emitting at a 915-nm wavelength. The counter-propagation pump scheme was adopted, making the signal and pump light propagate in opposite directions, which helps lower the outgrowth of ASE. At a launched pump power of 5.7 W, a 2.3-W amplified average power was obtained corresponding to a pulse energy of 230 μJ, with an amplification slope efficiency

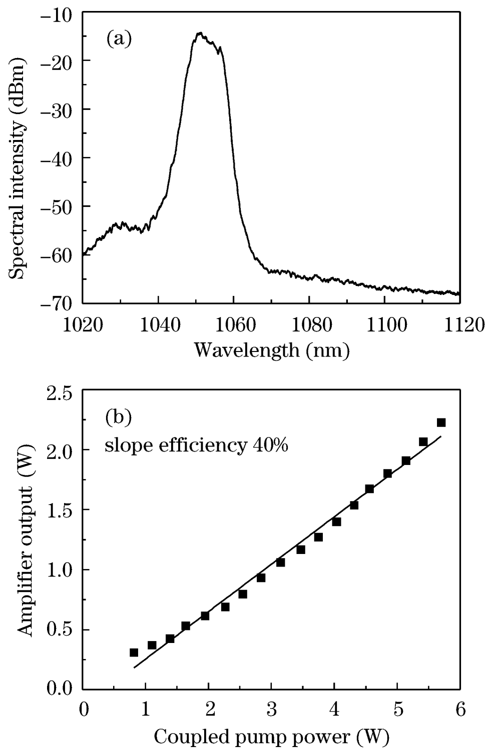

Fig. 3. Spectral characteristic of the pre-amplifier stage (a) and amplified output power as a function of coupled pump power (b) for 40-μm core Yb-doped double-clad PCF.

of 40%. The output characteristic of the pre-amplifier stage is shown in Fig. 3. Figure 3(a) shows the spectrum of the amplified laser from the pre-amplifier, indicating that the ASE is suppressed to better than 40 dB and no spectral component induced by SRS effect is observed. However, the spectrum full-width at half-maximum (FWHM) is broadened to 6.2 nm, much broader than that of the seed laser (Fig. 2(b)), basically because of the SPM effect imposed on laser pulses in fibers. The corresponding amplification dynamic curve is plotted in Fig. 3(b), which shows the amplified power scaling ability at different pump power levels in the pre-amplifier.

For higher energy scaling at sub-nanosecond pulse widths, larger core gain fiber is employed. In this letter, a 1.5-m long double-clad LMA Yb-doped fiber with a core diameter of 140 μm (NA = 0.07) and a 400-μm (NA = 0.47) D-shaped inner cladding were adopted in the final and main amplification stage of the experiment. The fiber features a pump light absorption coefficient as high as 17 dB/m at 975 nm; therefore, a relatively short fiber length is feasible in amplification. Both ends of the fiber were cleaved to an angle of no less than 5° to avoid self-oscillation. We observe laser oscillation once the pump light exceeded a certain power level in this LMA Yb-doped fiber at a wavelength of 1037 nm when any end has no angle. This continuous wave self-oscillation laser consumes some inverted populations and competes with signal lasers at 1053 nm, thereby worsening amplification efficiency.

Seeding the main amplifier with average power of 1.02 W from the pre-amplifier, an amplified average power of 11.7 W corresponding to 1.17-mJ pulse energy is achieved when 27-W 975-nm pump laser is backward launched into the inner cladding of the gain fiber. The output amplified laser spectrum is shown in Fig. 4(a), in which ASE is suppressed to better than 30 dB below a signal wave, and the onset of SRS is also excluded. The inset of Fig. 4(a) shows the autocorrelation trace of the amplified 1.17-mJ pulses, whose duration is 360 ps as a Gaussian pulse shape is assumed. Autocorrelation trace stems from the autocorrelation calculation of the intensity of two pulses; the calculated trace is always symmetric no matter what shape the pulse might takes. Thus, as the measurement range of our autocorrelator is no more than 1.6 ns, the measured autocorrelation trace displays only half when the pulse's width reaches hundreds of picoseconds. Another half of the autocorrelation trace must be identical to the displayed half according to its symmetry characteristic, and the measured pulse width will be accurately read from the half trace.

The slope efficiency in the main amplifier stage is effectively improved because of the higher pump absorption coefficient of Yb^{3+} at 975 nm. Figure 4(b) shows that the slope efficiency in the main amplifier is 48%.

The output beam profile of the main amplifier imaged on a charge-coupled device camera (Fig. 5) shows jumbled intensity distribution of the laser field, normally the multi-transverse mode profile, and indicates that the optical wave operates in a multi-transverse mode regime because of the large core diameter of the main amplifier gain fiber. To clarify this, normalized frequency V is introduced to predict the propagation mode character in fibers[17] as

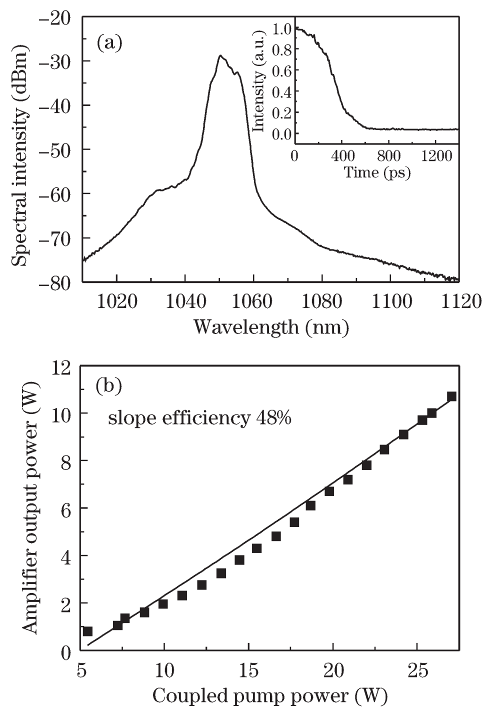

Fig. 4. Spectrum and autocorrelation trace (inset) of the amplified pulse (a) and amplified output power as a function of coupled pump power (b) for 140-μm core Yb-doped double-clad fiber.

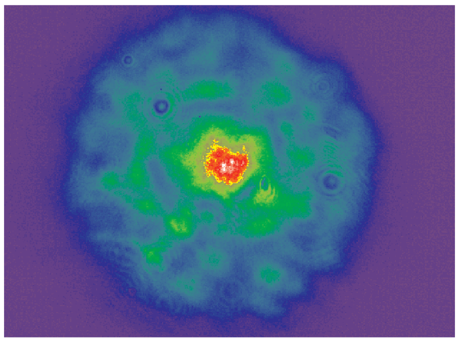

Fig. 5. Output beam profile of the final amplifier stage.

$V = \frac{2\pi}{\lambda} \cdot \alpha \cdot$ NA, where λ is the operating wavelength, α is the fiber radius, and NA is the numerical aperture of the fiber. In our final stage amplifier, the adopted gain fiber has a core diameter of 140 μm, NA = 0.07. For the operating laser wavelength of 1053 nm, the calculated V equals 29.2, much larger than 2.4048, the single mode V parameter. Also from V parameter, we can estimate propagation mode number N in this fiber as follows: $N = \frac{1}{2}V^2 \approx 426$. Thus, a numerous modes propagate in the fiber core and diminish the spatial quality of the output laser. In the experiment, the bending loss was introduced to suppress the higher-order transverse modes to a certain extent by coiling the 140-μm core diameter LMA fiber; however, little improvement was obtained. Low nonlinearity air-cladding rod-type PCFs with large core diameters (e.g., 80 μm) have been used as main power amplifiers[3,18] and nearly diffraction-limited beam quality was obtained. However, as pointed in Ref. [3], the fiber has no polymer coating and has to be embedded in a water-cooled aluminum body. This adds to the complexity of the system. Further experimental study aiming to obtain single or low-level transverse mode laser output from 140-μm core diameter LMA fiber is currently ongoing.

In conclusion, a fiber-based CPA system that can directly generate millijoule-level per-pulse energy for laser pulses of several hundreds of picosecond durations is demonstrated experimentally. In pre-amplifier and main amplifier stages, two kinds of LMA double-clad Yb-doped fibers offer largely stored energy to enhance amplification and help avoid unwanted nonlinear effects. Moreover, an extremely large core diameter keeps the fiber away from the optical damage threshold as amplified pulse energy increases. After careful coupling of seed laser and pump light at every amplification stage, a 1.17-mJ laser pulse at a repetition rate of 10 kHz is achieved and no unwanted spectral component arises from nonlinear effects. The corresponding peak power of 3.25 MW is the highest level obtained to date from a fiber CPA system at a picosecond regime in China. Results indicate that a fiber-based CPA system has the potential to extract much higher energy levels and will play an important role in the areas of micromachining, material processing, and other applications.

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