Optimization of spectral distortion in a ytterbium-doped mode-locked fiber laser system

Fuqiang Lian,[1] Zhongwei Fan,[1,]* Zhenao Bai,[2] Xiaohui Li,[3] and Qi Jie Wang[3]

[1]*Academy of Opto-Electronics, Chinese Academy of Sciences, University of Chinese Academy of Sciences, Beijing 100094, China*
[2]*Beijing GK Laser Technology Co., Ltd., Beijing 100192, China*
[3]*School of Electrical and Electronic Engineering, Nanyang Technological University, 50 Nanyang Ave. 639798, Singapore*
*Corresponding author: aoefiberlaser@126.com

A method for optimizing the spectral distortion of an ultrafast pulse in a polarization-maintaining picosecond linear-cavity fiber laser with a one-stage fiber amplifier is proposed and demonstrated. The mechanism of control of the spectral distortion in the fiber system has been investigated. The experimental and theoretical results illustrate that the filtering effect of a fiber Bragg grating can effectively decrease the spectral oscillatory distortion accumulated by self-phase modulation. Injected into a Nd:YAG regenerative amplifier, the ultrafast pulse could produce high pulse energy of 1.2 mJ at a repetition rate of 1 kHz.   © 2015 Chinese Laser Press

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1. INTRODUCTION

Ultrafast fiber lasers have rapidly attracted significant attention in the past decade with the development of optical fiber devices [1–3]. Yb-doped ultrafast fiber lasers have been widely used in industrial applications. For most material processing, the output power is a very critical factor [4,5]. Chen *et al.* designed a 100 W all-fiber picosecond master oscillator power amplifier (MOPA) laser in 2009, the seed source of which is a Yb-doped single-mode fiber laser passively mode locked by a semiconductor saturable absorber mirror (SESAM) [4]. In the subsequent year, a dispersion-compensation single polarization fiber laser seeded by a gain-switched laser diode (LD) with 21 ps pulse width, 908 MHz repetition rates, and average power up of to 100 W was achieved [5].

In some delicate applications, such as laser ranging or frequency doubling, another important feature is the shape of the spectrum. It is our main concern to achieve smooth spectra with reduction of spectral distortion, especially for a multi-longitudinal-mode Yb-doped ultrafast fiber laser with a linear all-fiber cavity. In order to generate a smooth spectrum, the mechanisms of output spectrum broadening should be analyzed and understood. These questions have been explored in only a few papers [6–9]. In the above references, spectral features of rare-earth-ion-doped continuous fiber lasers have been discussed in theory and experiments. Stolen and Lin discovered spectral distortion through coupling nearly Gaussian pulses ($T = 90$ ps), obtained from an argon-ion laser, into a 99-m-long fiber with 3.55 μm core diameter [10]. Tomlinson *et al.* simulated the sidelobes on the pulse spectrum that they described as optical wave breaking [11]. The spectrum induced by self-phase modulation (SPM) showed an oscillatory fringe covering the entire frequency range. In general, the spectrum consists of more than one peak, and the outermost peaks are the most intense.

The traditional method of improving spectral oscillatory fringes is to sacrifice the output power or increase the diameter of the fiber. In comparison with previous work, we came up with a novel method, i.e., using the filtering effect of a fiber Bragg grating (FBG) to effectively reduce frequency chirp induced by SPM effects and to optimize the spectral distortion.

2. EXPERIMENTAL SETUP

The schematic diagram of the fiber laser is shown in Fig. 1. The system is based on a passively mode-locked all-fiber oscillator. A SESAM is used for generation of stable passive mode-locked operation. The output pulse is amplified by a one-stage Yb-doped fiber MOPA.

The oscillator is based on a linear cavity, in which the mode field diameter of the Yb-doped fiber is 6 μm with Yb-doped absorption (at 976 nm) of 219 dB/m. The Yb-doped fiber length is 0.4 m. The gain fiber is core-pumped by a LD via a polarization-maintaining (PM) fiber wavelength division multiplexer (WDM). The back mirror is a homemade fiber-coupled SESAM, which is glued to a fiber optic connector (FC/PC). The front mirror of the oscillator is a high reflectivity (60%) FBG of 0.22 nm bandwidth, which supplies the filtering effect for a mode-locked pulse. The total fiber length of the laser cavity is 2.6 m, radiating a pulse train with repetition rate of 38 MHz. The linear polarization mode-locking pulse propagates along the fast axis of the fiber. The oscillator output fiber is connected to a one-stage PM fiber amplifier. The backward pump is introduced into the fiber amplifier, the purpose of which is to reduce the nonlinear effects.
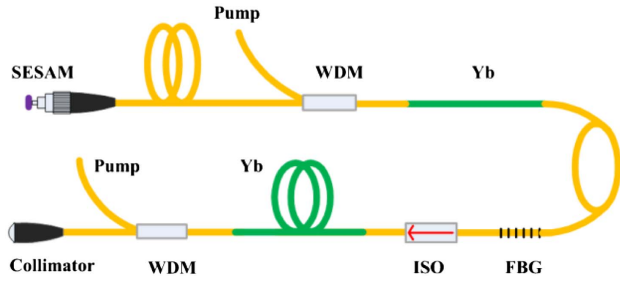
Fig. 1.   Picosecond pulse Yb-doped fiber laser source based on a MOPA configuration. ISO, optical isolator.

Fig. 3.   (a) Output spectra versus different output power. All the curves are measured by an optical spectrum analyzer with 0.02 nm resolution. (b) Intensity autocorrelation trace of an amplified mode-locked pulse.

3. RESULTS AND DISCUSSION

Stable mode-locked self-starting is obtained at a threshold pump power of 80 mW, as shown in Fig. 2(a). Typically, mode-locked multiple pulses circulating in the cavity can be obtained at a pump power of 115 mW. The MOPA output power characteristics measured at discrete pump power levels is shown in Fig. 2(b). For all measurements of amplified power, the oscillator average output power was 12 mW, and the maximum amplifier output power of 170 mW is achieved at a total pump power of 400 mW. The slope efficiency is proportional to the pump power, because the pump wavelength we used is 975 nm. The temperature of the pump will increase with the pump power, which results in the center wavelength of the pump moving to 976 nm. The absorption efficiency of the gain fiber at 976 nm is higher than that at 975 nm, resulting in a slope efficiency that is proportional to the pump power; see Fig. 2.

The corresponding change in spectrum of the oscillator is shown in Fig. 3(a). Figure 3(b) shows the measured autocorrelation of the pulse, which is considered to be of Gaussian shape, and the pulse width of the mode-locked pulse is 14.5 ps. Along with the power increasing, the output spectrum starts to slightly broaden and is accompanied by the spectral distortion, namely, the peak of the pulse is moving toward the long wavelength. The main reason for spectral broadening is that population inversion well above the mode-locked threshold excites much larger numbers of oscillating longitudinal modes. The spectral distortion derives mainly from the SPM effect. The dispersion length L_D and the nonlinear length L_{NL} provide the length scales over which dispersive or nonlinear effects become important for pulse evolution. The dispersion length L_D of the fiber oscillator is about $L_D = T_0^2/|\beta_2| = 12$ km, and the nonlinear length is about $L_{NL} = 1/\gamma P_0 = 20.8$ m. The length of oscillator is 2.6 m, $L \ll L_D$ but $L \approx L_{NL}$, the dispersion is negligible compared to the nonlinear effect.

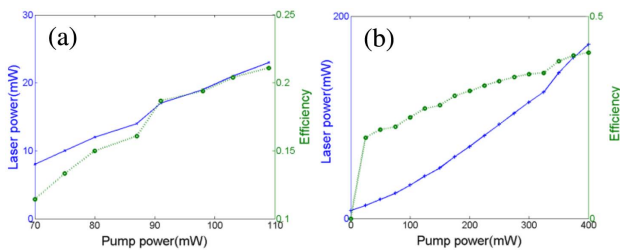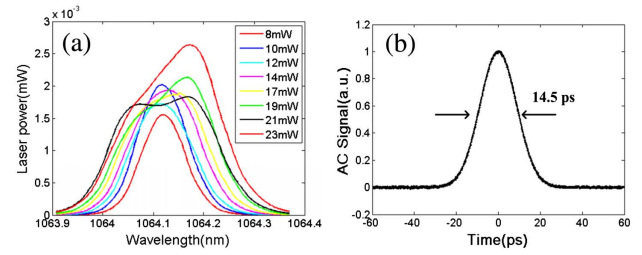The spectra of the amplifier are shown in Fig. 4(a), the most notable feature of which is that the spectra amplified by the one-stage fiber amplifier possess considerable spectral broadening (the maximum bandwidth of 0.46 nm) and are accompanied by an oscillatory structure of three peaks covering the entire frequency range. The resolution of the optical spectrum analyzer is 0.02 nm.

The disadvantage of considerable spectral broadening is that it is not conducive to amplification by a laser crystal. This is because the pulse spectrum is much broader than the bandwidth of the laser crystal, so that only a fraction of the pulse energy will be amplified. To solve this problem, we should know the mechanism of the spectral broadening, which indicates that the origin of the spectral structure can be understood by referring to a time dependence of the SPM-induced frequency chirp. The spectra, shown in Fig. 4, have the characteristic modulation associated with SPM. The pulses are frequency chirped by a nonlinear spectral phase accumulated in the optical fiber, which is induced by SPM increases in magnitude with the propagated distance. In other words, new frequency components are generated continuously as the pulse propagates down the fiber. These SPM-generated frequency components broaden the spectrum over its initial width. In Fig. 4(b), the spectrum at the pump power of 172 mW consists of three peaks and the outermost peaks are the most intense. The majority of the pulse energy is shifted to the spectral leading edge and the trailing edge.

The pulse evolutions in Fig. 5 are obtained by pulse spectral evolution [12]:

$$S(\omega) = \left| \int_{-\infty}^{\infty} U(0, T) \exp[i\phi_{NL}(L, T) + i(\omega - \omega_0)T]dT \right|^2. \quad (1)$$

The results of spectral evolution in the fiber of Fig. 5 possess two kinds of incident spectral bandwidth. The mode-locked pulse is assumed to be Gaussian in shape, and the average power of both Figs. 5(a) and 5(b) is 170 mW, with peak

Fig. 2.   (a) Typical output power and slope efficiency of an oscillator, and (b) amplified output power and slope efficiency.
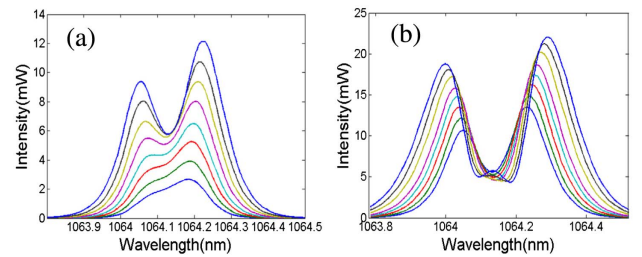

Fig. 4.   (a) Spectra versus laser power from 8 to 71 mW. (b) Spectra versus laser power from 82 to 172 mW. The bandwidth of the FBG in the fiber oscillator is 0.22 nm.
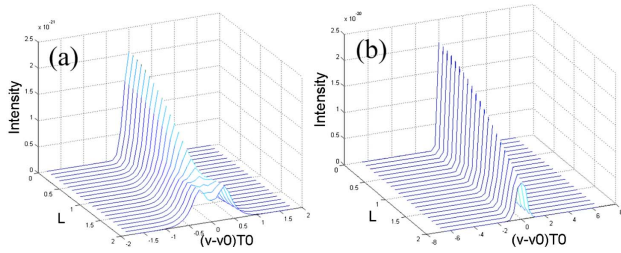
Fig. 5. Spectral evolution of the incident spectra introduced by SPM with a nonlinear Schrödinger equation fast Fourier transform algorithm: (a) Spectral bandwidth of 0.18 nm, (b) Spectral bandwidth of 0.12 nm.

Fig. 7. Intensity autocorrelation of amplified mode-locked pulse.

power of 310 W and 268 W, respectively. The amplified pulses are coupled in 2 m of fiber with nonlinear-index coefficient of 2.73×10^{-20} m^2/W, which approximately corresponds to an effective mode area of 28 μm × 28 μm. By contrast, we can observe that Fig. 5(a) possesses considerable spectral broadening, which is accompanied by an oscillatory structure covering the entire frequency range and accords with the experimental spectra of Fig. 4. The main parameters related to achieving the spectral filtering effect in a fiber laser with a linear cavity are the Yb-doped fiber gain bandwidth and the reflection spectral bandwidths of the SESAM and the FBG, while the gain bandwidth and the reflectance spectral bandwidth of the SESAM are too wide (>40 nm) to limit the spectral bandwidth of the mode-locked pulse. Therefore, the crucial parameter affecting spectral bandwidth of a linear cavity is the bandwidth of the FBG. Through optimizing the spectral bandwidth parameter, the simulation results in Fig. 5(b) significantly demonstrate that the spectral structure maintains the original Gaussian shape and suppresses spectral broadening and distortion.

To solve the above-mentioned spectral distortion for the linear cavity, we decided to adopt the more narrow FBG spectral width of 0.15 nm to decrease the frequency chirp induced by SPM. The reflection spectra of two types of FBG have the same Gaussian shape, which ensures that the unique difference between them is caused by the spectral bandwidth. The spectra of mode-locked trains amplified by the one-stage fiber amplifier are shown in Fig. 6. It shows that the spectra of laser power from 8 to 71 mW have no significant spectrum dips, as in Fig. 4(a). Also, the spectra of Fig. 6(b) illustrate that the oscillation spectra are reduced from three peaks to two peaks, which makes the pulse energy concentrated at the spectral center wavelength rather than the leading edge and trailing edge, as in Fig. 4(b). This is because the narrower spectral bandwidth of a mode-locked pulse accumulates less frequency chirp during the power amplification process. Therefore, the

measured spectra of Fig. 6 show that the distortion of the spectrum has been effectively suppressed with the use of the narrower FBG spectral width of 0.15 nm. Figure 7 shows the autocorrelation optical pulse duration is 787.2 μs. The pulse is considered to be Gaussian in shape, the pulse width of which is 16.7 ps. In the case of the pulse width possessing unapparent broadening, the above method could effectively improve spectral distortion caused by SPM.

To demonstrate the significance of optimizing spectral distortion, we injected the pulses generated in Fig. 4 and Fig. 6 into the Nd:YAG regenerative amplifier. Experimental results showed that only the pulses in Fig. 6, which are optimized, could extract substantial energy from the regenerative amplifier and generate high pulse energy of 1.2 mJ at a repetition rate of 1 kHz. The spectral distortion diverting the main energy from the center wavelength to the wings becomes the reason for the pulses in Fig. 4, which are unable to extract energy, i.e., the gain bandwidth of the Nd:YAG crystal is mismatched.

4. CONCLUSION

We have investigated the mechanism of spectral distortion in a picosecond fiber system. Through numerical simulations and experiments, it is shown that the spectral broadening and oscillatory profile with increasing power in the mode-locked fiber laser is attributed to frequency chirp induced by the SPM effect. The use of the filtering effect of a FBG is an effective solution to optimize spectral distortion. By adopting the above method, an ultrafast fiber laser system could be used as the oscillator of a solid regenerative amplifier, and has largely transcended the conventional solid mode-locked laser. The amplified pulse could produce high pulse energy of 1.2 mJ with a repetition rate of 1 kHz by injecting into the Nd:YAG regenerative amplifier.
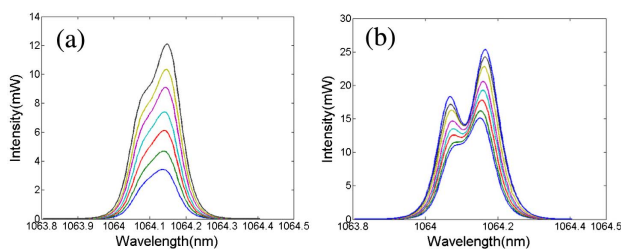
Fig. 6. (a) Spectra versus laser power from 8 to 71 mW. (b) Spectra versus laser power from 82 to 172 mW. The bandwidth of the FBG in the fiber oscillator is 0.15 nm.
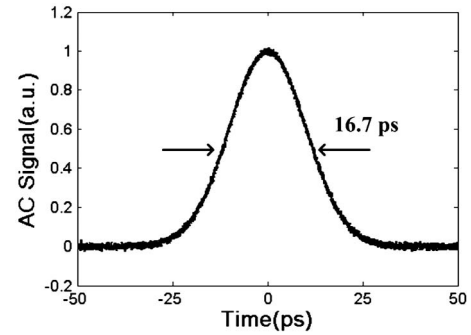
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