Low Threshold Stretched-pulses Mode-locked Er^{3+}-doped Fiber Laser with Ring Cavity

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Abstract: A low threshold stretched-pulses mode-locked Erbium-doped fiber ring cavity femtosecond laser with small positive-dispersion Er^{3+}-doped fiber was demonstrated. By introducing the small positive-dispersion fiber, the pulse energy and spectrum width were improved, the sideband of the spectrum was effectively restrained, and the self-starting pump power threshold was only 90 mW. The passive mode-locked continued to a pump power level as low as 29 mW. Self-starting mode-locked pulses with time duration of 175 fs, spectral width of 40 nm and repetition rate of 33 MHz were achieved by using this stretched-pulse configuration.

Key words: Low threshold; Stretched-pulse; Nonlinear polarization evolution; Mode-locked; Ring cavity

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0 Introduction

Single-mode rare-earth-doped fiber lasers have been the subject in the last year of intensive investigations, because of their advantages in terms of compactness, robustness, and reliability compared to conventional solid-state lasers [1-5]. In particular, passively mode-locked Erbium-doped fiber lasers (EDFL) are an attractive alternative to solid-state lasers for generating femtosecond pulses at near-infrared wavelengths for a broad range of applications. EDFLs offer a practical structure to get ultra-short pulses. The 270 fs-long soliton pulses have been obtained [6]. Unfortunately, when operating in the soliton regime, the single-pulse energy is constrained to be close to that of a fundamental soliton[7-10]. The spectrum width is also limited (typically, below 10nm) and has the soliton sideband problem. Stretched-pulse mode-locked lasers have been proposed to solve these problems[11]. In these systems, the effective nonlinearity is reduced by stretching and compressing the pulses within the cavity. This approach can increase the pulse energy and broaden the spectrum width in order to support shorter pulse duration than that achieved in soliton systems. To characterize the stretching and compressing effect of pulse duration, a stretched factor $F_{\text{stretching}}$ is introduced, which can be defined as a ratio of the maximum and minimum pulse duration within the cavity.

Usually, the buildup of pulses from noise and subsequent stabilization requires the using of a fast saturable absorber (SA) element[12], such as nonlinear polarization evolution (NPE)[13], a nonlinear optical loop mirror, and a nonlinear amplifying loop mirror[8]. The best performance in mode-locked fiber lasers is currently provided by stretched-pulse lasers with NPE for amplitude modulation. With this technique, 77-fs-long, 56nm-width pulses were previously reported[11]. However, this kind of structure usually needs a high pump power of larger than 250 mW to initiate mode-locking[14]. When the pump power is raised beyond the threshold about only 30 or 40 mW, the multiple-pulse will appear. Therefore, the working range of those fiber lasers is very small.

In this paper, it is shown that the configuration not only improves the energy and spectrum width of the pulse, but also decreases the threshold value and increases the stability by introducing a small positive-dispersion Er^{3+}-doped fiber into ring cavity. The small dispersion fiber can avoid large magnitude change of pulses width and increase the self-phase-modulation (SPM) effect. Thus, the threshold value will lower. Meanwhile, the range of pump power become broader and the laser works more stable. In addition, the fiber-in-line type polarization controllers are adopted to solve the inexact pigtail

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length problem in conventional wave plate style controller. The high energy and wide spectrum ultra-short pulse laser has widely application on the generation of super-continuum spectra and frequency-doubling with periodically poled lithium niobate. The stretched-pulse mode-locking is an important technique to improve the property of ultra-short pulse fiber laser for researching on nonlinearity phenomenon. In experiment, self-starting mode-locked pulses with pump threshold power of only 90 mW, spectral width of 40 nm, pulse duration of about 175 fs at a 33 MHz repetition rate were obtained. Moreover, this configuration has a wide working range over the conventional pulse fiber laser.

1 Experimental setup

The schematic of experimental setup is illustrated in Fig. 1, which consists of a 980nm diode-pump laser source, a polarization-sensitive isolator, two polarization controller (PC), a 980/1 550 nm wavelength division multiplexer coupler (WDM), an 95/5 output coupler, and a 2.4 m-long section of single mode Erbium-doped fiber. This fiber has an un-pumped loss of 25 dB/m near 1530nm, a core diameter of 5.5 μm, an effective n_2 of 2.11e-16, and absorption of pump light of ≥7 dB/m near 980 nm. The dispersion per meter of the Erbium fiber was $+0.024\ ps^2$ at 1550 nm. All the pigtails of the implements in the cavity are consisted of 3.7 m-long Corning single mode fiber (SMF) with dispersion per meter of $-0.020 ps^2$ at 1 550 nm. In order to obtain a low threshold pump power and a clean spectrum, the total cavity dispersion is designed to be small and anomalous. The polarization-sensitive isolator is introduced to ensure unidirectional operation in the cavity, facilitate self-starting, and provide the fast SA action. The 980 nm pump laser has the Bragg grating structure, which can improve the stability and restrain the wavelength excursion caused by temperature. Pump light is coupled into the optical ring cavity through the 980 nm/1 550 nm WDM. The output couple ratio is chosen to be 95/5 for enhancing the optical power inside the cavity. By properly adjusting the polarization controllers, the stable mode-locked pulses can be obtained. Meanwhile, another 90/10 coupler is introduced for observing the pulse shape in time domain and pulse spectrum simultaneously.

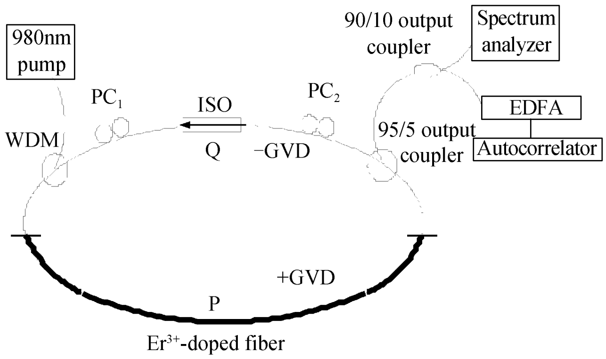

Fig. 1 Schematic of the experimental setup

2 Experimental results and discussions

By adjusting the two PC properly, self-starting mode-locking to a single pulse per round trip (at fundamental frequency) is observed at a launched pump power of approximately 90 mW. As usual in these systems, hysteresis was observed[11], and the mode-locked pulse could be maintained when the launched pump power was decreased to a level as low as 29 mW. When the pump power was increased above 180 mW, multiple-pulse operation and Q-switching were observed. The laser has a wide pump power range (~150 mW) compared with the previous stretched-pulse fiber lasers. When the pump power is between 40 mW and 150 mW, the good mode-locked state could be achieved by slightly adjusting the polarization controllers PC_1 and PC_2. Fig. 2 shows the output pulse train signal in the time domain from the oscilloscope. The peak to peak jitter is 7.017% from the digital oscilloscope. With the pump power being set to 150 mW, the laser generated an average output power of 2.35 mW. To measure the repetition rate of pulses, the pulse stream of this laser output is fed into a 50 GHz photo-detector (XPDV2020R) of U2T company. A high-speed Agilent 86100C oscilloscope of 70 GHz electronic bandwidth is connected with the photo-detector in order to display the pulse waveform. The oscilloscope

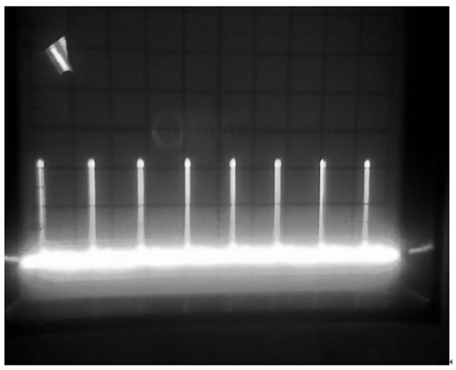

Fig. 2 Output pulse train signal in the time domain

shows the repetition of the pulse is 33 MHz. The single pulse energy is 71 pJ according to the repetition.

Fig. 3 shows the spectrum of the fiber laser from the output coupler at 40 mW of the pump power. The center wavelength is 1 567 nm and the spectrum width (FWHM) is 40 nm. The periodic stretching and compressing cavity structure can effectively reduce the nonlinearity in the total cavity and avoid saturation of the additive-pulse mode-locked mechanism. In fact, the pulse transits around the cavity, spreading in the positive-dispersion fiber and compressing to shortest width at a certain point in the SMF fiber. The SPM is very large at the point which the pulses width is the shortest. Thus high-bandwidth pulses can then be produced. Because of the larger spectrum width compared with the soliton fiber laser (6～10 nm), the shorter pulse duration can be obtained according to the Fourier transform limited theory. Meanwhile, the clean spectrum without any sideband was observed, which can be attributed to a fact that dispersive wave, the main reason of producing spectrum sideband[15-17], is not needed to adapt to the periodic perturbation in the our structure, and thus the sideband of the spectrum can be avoided.

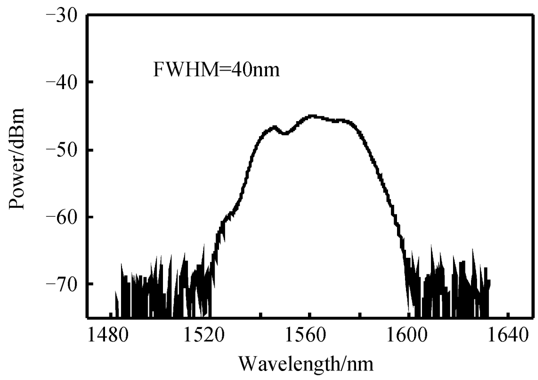

Fig. 3　Spectrum of the output mode-locked pulses

The autocorrelation trace of the output pulse is shown in Fig. 4. Since the efficiency of the frequency-doubling crystal in the autocorrelator was low, we used an Erbium-doped fiber amplifier (EDFA) to raise the pulses energy up to the required value. Nevertheless, the EDFA with opposite dispersion spans of doped fibers was designed to provide net dispersion near to zero. The EDFA is consisted of 3 m-long Erbium fiber which has the dispersion of $+0.013\ ps^2/m$ and 2 m-long SMF fiber. The net dispersion is calculated by this $\beta_{net}=0.013\times3-0.02\times2=-0.001\ ps^2$. Thus, the linear chirp impact of the EDFA was little and the linear chirp in the cavity could be compensated by selecting an appropriate length of standard mode fiber at the output end. The output coupling fiber for the shortest pulse duration was tried with different length, finally the optimal length is found to be 2 m. The FWHM of the 302 fs corresponds to a 175 fs pulse, assuming a Lorentz profile. However, the nonlinear chirp derived from the EDFA had some impact on the pulse compression. With a higher efficient crystal being used in the autocorrelator, the pulse duration can be directly measured and thereby the shorter value can be obtained.

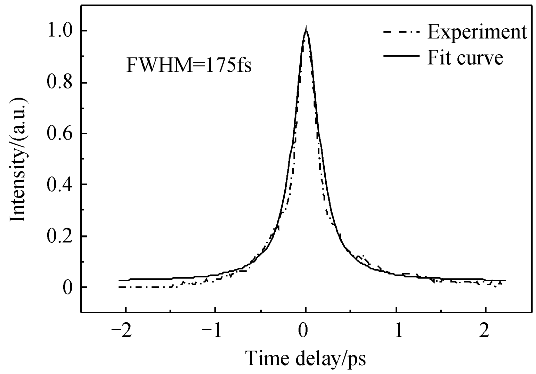

Fig. 4　Autocorrelation trace of the pulses

3　Conclusion

In conclusion, a low threshold stretched-pulses mode-locked fiber laser is demonstrated with small positive-dispersion Er^{3+}-doped fiber. The self-starting pump power threshold is only 90 mW, and mode-locked operation could be maintained at a pump level of only 29 mW. Mode-locked pulses with 40 nm spectral width, 175 fs pulse duration and 33 MHz repetition rate were achieved. The spectrum width of 40 nm indicates that even shorter pulses may potentially be generated.

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低阈值展宽脉冲锁模掺 Er^{3+} 光纤环形激光器的实验研究

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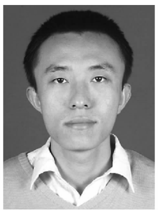
摘　要:将正色散值较小的掺铒光纤引入传统的环形腔构成了低阈值的展宽脉冲锁模激光器.通过使用这种掺铒光纤,激光器的锁模阈值大大降低,激光器的自起振泵浦功率仅为 90 mW,而且在 29 mW 的低泵浦功率时仍然可维持稳定的锁模状态.实验中获得了脉冲宽度为 175 fs,光谱半高宽为 40 nm,重复频率为 33 MHz 的锁模脉冲输出.激光器工作稳定,光谱干净光滑.

关键词:低阈值;展宽脉冲;非线性偏振旋转;锁模;环形腔



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