10GHz regeneratively mode-locked erbium-doped fiber laser combined with nonlinear amplifying loop mirror

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Abstract: Mode-locked fiber lasers can generate short pulses with a high repetition rate. It can be used in nonlinear optical imaging, photo-communication and other fields. Obtaining narrow pulses with high repetition frequency has become a hot research topic. In this article, we demonstrate a hybrid mode-locked fiber laser, which is a regeneratively mode-locked erbium fiber laser operating at 10 GHz, incorporating a nonlinear amplifying loop mirror to generate a 1.9 ps pulse sequence. This all-fiber laser with a high-repetition-rate and short pulses has the advantages of high stability and self-starting, which has a wide range of applications.

1. Introduction

In the field of fiber lasers, high repetition frequency and narrow pulses have extremely high application value in many areas, such as microfabrication, biomedicine, lidar, and spectral detection\cite{1}. It is also an attractive pulse source for long-distance fiber-optic communication systems. Because of their long-term stability and high efficiency, mode-locked fiber lasers have attracted much attention.

Passively mode-locked technique refers to a technology that performs mode-locked without any external RF signal injection. For example, real saturable absorber mirror (SAM)\cite{2,3}, nonlinear polarization rotation (NPR)\cite{4,5}, nonlinear optical loop mirror (NOLM)\cite{6}, or nonlinear amplifying loop mirror (NALM)\cite{6,7}. A Hybrid mode-locked laser is a combination of active mode-locked laser and passive mode-locked laser. Active mode-locked fiber lasers can generate GHz pulse sequences, but the pulse width is from picosecond to sub-picosecond\cite{9}, while passive mode-locked fiber lasers can generate femtosecond pulses, but the repetition frequency is limited by the length of the laser cavity. To take advantage of these two mode-locked schemes, a hybrid mode-locked fiber laser is proposed\cite{10}, which can generate ultrashort pulses with high repetition frequency. It can generate very short pulses using passive mode-locked while maintaining a high repetition rate through active mode-locked. For instance, C. X. Yu et al. reported a hybrid mode-locked laser by combining a phase modulator and nonlinear polarization rotation in the laser cavity, and a 480fs pulse at 1 GHz was obtained\cite{10}. Furthermore, Toshihiko et al. reported a regeneratively FM mode-locked erbium fiber laser operating at 9.2 GHz, in which a SESAM saturable absorber was combined to generate a 440fs pulse train\cite{11}.

In this article, we propose and experimentally demonstrate a novel hybrid mode-locked fiber laser. The laser structure is a regeneratively mode-locked erbium fiber laser with a nonlinear amplifying loop mirror. Experimentally, the pulse with repetition rate of 10GHz is realized in the fiber laser, and the laser has polarization-maintaining and self-starting functions. The pulses can be compressed down to 1.9 ps, which is shorter than the pulses without nonlinear amplifying loop mirror.
2. Experiment setup and principle

The experimental setup of the proposed hybrid mode-locked fiber laser is illustrated in Figure 1. The laser loop includes a pump source with a maximum output power of 600mW. A LiNbO₃ intensity modulator (EOSpace) with a bandwidth 40GHz. An erbium-doped gain fiber with a length of approximately 1m. An optical filter, its central wavelength is 1550nm, bandwidth is 3nm, and an optical coupler with a ratio of 30: 70. The output pulses are divided into two channels by couplers, 70% of which enter the modulator to form a ring cavity laser, and only 30% of which are sent to the photodetector. The length of the laser cavity is approximately 11.9 m, which corresponds to a fundamental repetition frequency of about 17.31MHz.

In the electric loop, there is a photodetector with a bandwidth of 30 GHz, an electric band-pass filter with a center frequency of 10GHz, a bandwidth of 10MHz, an RF amplifier with a gain of 29dB, and a phase shifter. The function of the phase shifter is to adjust the phase of the RF signal to meet the condition of mode-locking. The NALM loop is composed of a 0.5m EDF pumped by a laser diode through a WDM, which is the same as EDF and WDM used in the main loop. A 2×2 coupler connects the two loops mentioned above with a splitting ratio of 50:50.

For the NALM configuration, a gain medium with gain coefficient, G, is added to increase the asymmetric nonlinearity within the loop. the NALM has the following power transmission curve:

\[ T = 1 - 2\alpha(1 - \alpha) \left( 1 + \cos \left( \frac{2\pi n_z IL}{\lambda} \right) \right) \]  

(1)

Where \( \alpha \) is the coupling ratio of the coupler and \( I \) is the intensity of light. Equation (1) shows the characteristics of saturated absorption, which means that the loss on both sides of the pulse is greater than the loss near the peak. The pulse will be compressed after passing through the nonlinear loop mirror, and finally an ultrashort pulse will be output.

The system is numerically simulated to explain the generation mechanism of pulses in the ring cavity, as shown in Figure 2. The output of the self-regenerative mode-locked laser is shown in Figure 2(a), and the output of the hybrid mode-locked laser is shown in Figure 2(b). It can be seen from the figure that the stability of the active mode-locked fiber laser is still not high, and the amplitude fluctuation is caused by noise, which is the biggest disadvantage of the active mode-locked laser. In the self-regenerative active mode-locked laser, a nonlinear amplifying ring mirror is added to form a hybrid mode-locked laser. It can be clearly observed that the pulse width is not broadened in the hybrid mode-locked laser,
and the pulse width is significantly shorter than that in the active mode-locked laser, and the peak power of the pulse is more stable. The results show that the hybrid mode-locked laser based on a nonlinear amplifying ring mirror still has good self-starting characteristics and can get high repetition rate ultrashort pulses. Furthermore, the effect of nonlinear amplifying ring mirror is similar to that of the saturable absorber, and the stability of laser pulse is improved by the effect of saturable absorber.

3. Results and Discussion

In our experiment, we gradually increase the pump laser diodes' output power and adjust the bias voltage of the MZM to make it at the quadrature bias point. A stable mode-locked is achieved with a pump power of 23dBm.

We use an optical spectrum analyzer (OSA, YOKOGAWA AQ6370C) to measure the spectrum of the mode-locked pulses, as shown in Figure 3(a). It can be obtained from figure 3(a) that the spectrum of the pulse sequence has a mode interval of 0.08 nm, which confirms that the laser works in the mode-locking state of 10GHz. The spectrum center is 1550 nm, and the spectral bandwidth is about 2 nm. We calculate that the time-bandwidth product (TBP) is about 0.482, which is close to the compression limitation of the pulse. The mode-locked pulse train is detected by a mixed-signal oscilloscope (MSO 72004C, shown in Figure 3(b)). The output pulse interval is stable and the pulse interval is 100ps. The pulse shape indicates that the laser is in a stable mode-locked state.

Further, the RF spectrum of output pulse is measured by an electrical signal analyzer (N9030A PXA Signal Analyzer, shown in Figure 4(a). It can be obtained that the mode-locked laser works in a harmonic mode-locked state, and the frequency is 10.0097 GHz, which is 578 times the fundamental frequency. In addition, there is no supermode noise, and the supermode noise suppression ratio is more than 75dB. Furthermore, extending the measurement range of the electrical spectrometer to 25 GHz, the results are shown in Figure 4(b). Two frequency components of only 10GHz and 20 GHz can be observed at this
point, further demonstrating that the laser operates at 10GHz.

![Figure 4. RF spectrum of the hybrid mode-locked laser: (a) RF spectrum of the center frequency range of 10 GHz; (b) The characteristics of the electric spectrum in the frequency range of 25 GHz](image)

The pulse duration of the output pulse from the proposed hybrid mode-locked lasers is measured by an autocorrelation instrument (FR-103XL). The autocorrelation trace is shown in Figure 5. The black curve is that there is no nonlinear amplifying loop mirror. According to the pulse width calculation formula in the autocorrelator, the actual pulse width is 11.93 ps. Furthermore, we measure the pulse duration of our proposed hybrid mode-locked laser (the blue curve in Figure 5). We get the actual pulse width of the proposed structure is 1.93 ps, which is compressed compared with the one without NALM. This indicates that the pulse of a transform-limited pulse is obtained successfully.

![Figure 5. Autocorrelation trace of the oscillator output. Black curve: Mode-locked fiber laser without NALM; blue curve: Mode-locked fiber laser with NALM.](image)

4. Conclusions
In conclusion, we demonstrated a new type of hybrid mode-locked laser, in which a nonlinear amplifying loop mirror (NALM) was installed in a regeneratively mode-locked erbium fiber laser. The repetition frequency of the output pulse can finally reach 10.0097 GHz. At the same time, the output pulse can be compressed from 11.93ps to 1.9ps. This stable mode-locked fiber laser has the advantage of self-starting and is suitable for all-fiber amplifiers, which has led to critical scientific and industrial applications. In addition, benefiting from the development of high-speed opto-electronic devices (e.g. modulators, photodetectors) will enable the proposed hybrid mode-locked laser with the repetition rate up to 40 GHz or more.

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