Rational harmonic figure-eight actively-passively mode-locked erbium-doped fiber laser

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The nonlinear optical loop mirror (NOLM) is used as a saturable absorbed to reshape pulses. Experimentally, an actively mode-locked erbium-doped fiber ring laser with figure-eight structure is set up. $2-4$ order harmonic pulse train with stable amplitude has been obtained when the RF modulation frequency is about 2.5 GHz.

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There has been considerable interest in the study of ultrashort pulses with high repetition rate in order to develop high-bit-rate optical communication system. Although actively mode-locked fiber laser represents a potential source of such pulses, its repetition rate and pulse width are usually limited by the bandwidth of the intracavity modulator. On the other hand, passively mode-locked fiber laser can produce stable and even shorter pulse train, however, its repetition rate is limited due to the low cavity fundamental frequency. Recently, a new technique called rational harmonic (RH) mode-locking has attracted great interests. Several researchers have reported results on the RH mode-locked fiber laser. Armed demonstrated the generation of 14 and 20 GHz repetition rate optical pulses when the RF driving frequency of the modulator was about 7 GHz[1]. In 1998, Shenping Li reported RH active and passive mode-locking in a figure-eight fiber laser and optical pulses at repetition rates up to the 19th harmonic of the RF modulation frequency were generated[2]. Yoshida has obtained RH mode-locked pulses with a repetition rate of $80-200$ GHz[3].

In the RH mode-locking technique, the repetition rate of the output pulses is the lowest common multiple of the laser cavity resonance frequency and RF modulation frequency. When the modulation frequency f_m is set at $f_m=(m+1/n)f_0$, where f_0 is the cavity fundamental frequency, n (integer) is the harmonic order of the RF modulation frequency, and m (integer) is the harmonic order of the laser cavity, an optical pulse train with a repetition rate of $f_p=(|n|m+1)f_0$ can be generated[4].

In RH mode-locking, when the repetition rate is larger than twice the RF frequency, the pulse amplitude becomes severely uneven, which limits the application of these pulses. The amplitude fluctuation is caused by the existence of the unmatched lower RHs. According to the RH mode-locking theory, amplitude noise in the cavity will increase with the increase of harmonic order n. Therefore, it is difficult to suppress the noise by adjusting the polarization controller (PC) or the modulation frequency.

In this work, the nonlinear optical loop mirror (NOLM) is placed in an actively harmonic mode-locked erbium-doped fiber laser to form an actively and passively mode-locked laser. This hybrid structure has the advantages of both actively mode-locking and passively mode-locking. By using the nonlinear modulation characteristic of NOLM, the output pulse is significantly compressed and reshaped. Output pulse trains with stable amplitude at 5, 7.5, and 10 GHz (the second, third and fourth RHs)are obtained, and the noise is successfully eliminated.

NOLM is essentially a Sagnac interferometer. It uses the asymmetry created by an unbalanced central coupler to generate the relative nonlinear phase shift between the counterpropagating pulses within the interferometer, as shown in Fig. 1. If dispersion is ignored, the transmission T of a NOLM is given by[5]

$$T=1-R=1-2\alpha(1-\alpha)$$
$$\times\{1+\cos[(1-2\alpha)|E_{\text{in}}|^2 2\pi n_2 L/\lambda]\},$$

where α is the splitting ratio of the NOLM, n_2 is the nonlinear index, L is the length of the loop, λ is the operating wavelength, E_{in} is the input field. R is the reflectivity. The transmission characteristic of NOLM output power versus input power P_{in} is shown in Fig. 2. It is shown that the increase of transmission with intensity is similar to the action of a fast saturable absorber. For pulse injected into the NOLM with peak intensity less than the first maximum of transmission, the peak of the pulse will transmit more readily than its wings.

According to above analysis, it is known that NOLM can provide an intensity-dependent nonlinear modulation.

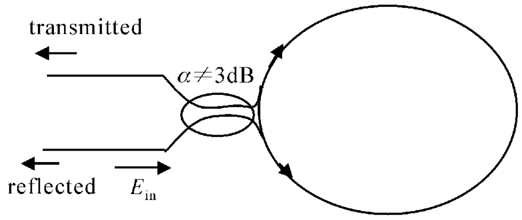

Fig. 1. Structure of a NOLM.

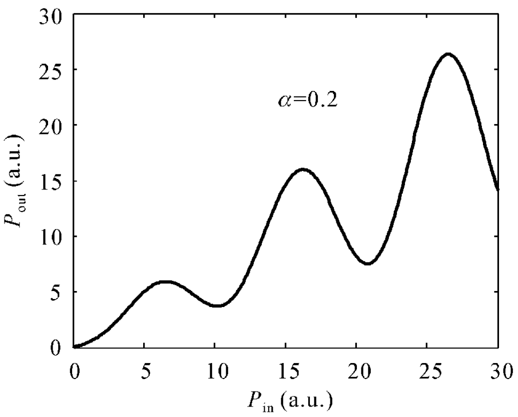

Fig. 2. Transmission characteristic of NOLM.

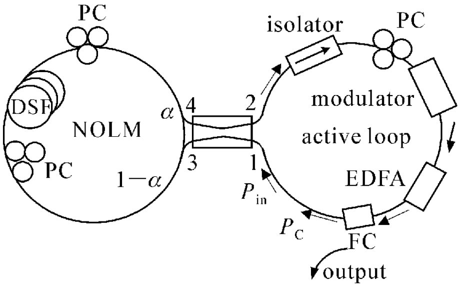

Fig. 3. Experimental setup of figure-eight rational harmonic actively-passively mode-locked Er^{3+} doped fiber laser.

In our experiment, the NOLM is placed in the figure-eight structure as a passive modelocker as shown in Fig. 3. The operation of this laser is that as a pulse propagates around the NOLM loop, it is shortened and amplified each time of transmitting through the active loop. The high-intensity portions of the pulse are transmitted and amplified, while the low-intensity portions are reflected back from port 1 to the active loop and rejected by the isolator. As a result, the amplitude fluctuation caused by unmatched lower RHs is effectively suppressed and the noise having lower intensity is eliminated.

The experimental setup is shown in Fig. 3. The splitting ratio of the central coupler is 20 : 80. The dispersion shifted fiber(DSF) is 100 m long. The modulator is IOC's 2.5 GHz M-Z $\mathrm{LiNbO_3}$ modulator. Gain is produced by IRE-POLUS's Er-doped fiber amplifier (EDFA). The RF modulation signal source is HP's 83752 synthesized sweeper. The output signal is provided by a 90/10 coupler and is analyzed by HP's 83480A digital communication analyzer and Ansitru's MS9001A optical spectrum analyzer respectively.

Simultaneous passive and active mode-locking at the nth RH order requires a precise PC adjustment and a fine adjustment of the modulation frequency as well. When the PCs have been correctly adjusted, various orders of RH mode-locking can be obtained by only tuning the modulation frequency. The fundamental cavity frequency is $f_0 = 1.378188$ MHz, corresponding to a cavity length of 150 m.

When modulated at $f_m = 2.499343938$ GHz, i.e. $f_m \approx (1813+1/2)f_0$, the second ($n = 2$) RH mode-locked pulse train with stable amplitude is obtained. The output pulse train and the optical spectral profile are shown in Fig. 4. The pulsewidth judged by oscilloscope is 21.8 ps, however, considering the oscilloscope's response time, its actual pulsewidth is 13 ps. The spectral width is 0.2 nm. The pulse is nearly transform-limited, having a time-bandwidth product of 0.33.

Figure 5 shows the third ($n = 3$) RH mode-locked pulse train and its spectral profile at $f_m = 2.499113700$ GHz, i.e. $f_m \approx (1813 + 1/3)f_0$. The pulsewidth judged by oscilloscope is 27 ps. The actual pulsewidth is 18 ps. The spectral width is 0.18 nm, having a time-bandwidth

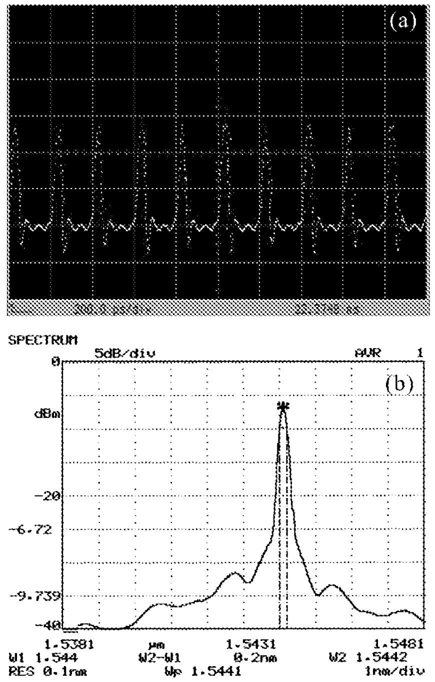

Fig. 4. Output pulse train (a) and spectral profile (b) of RH actively and passively modelocked fiber laser as $n = 2$.

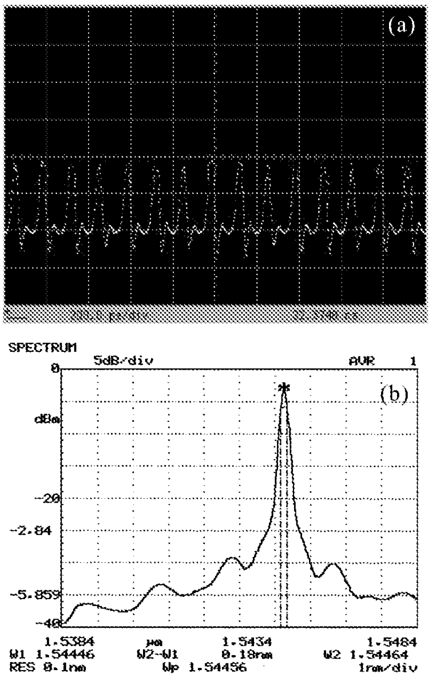

Fig. 5. Output pulse train (a) and spectral profile (b) of RH actively and passively modelocked fiber laser as $n = 3$.

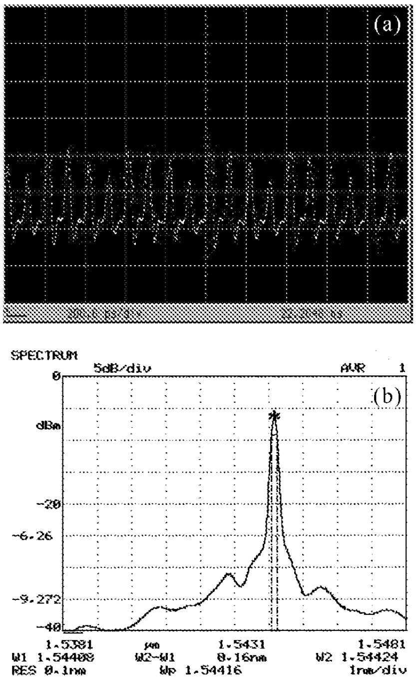

Fig. 6. Output pulse train (a) and spectral profile (b) of RH actively and passively modelocked fiber laser as $n = 4$.

product of 0.407.

Figure 6 shows the fourth ($n = 4$) RH mode-locked pulse train and its spectral profile at $f_m = 2.498999391$ GHz, i.e. $f_m \approx (1813 + 1/4)f_0$. The pulsewidth judged by oscilloscope is 29.6 ps. The actual pulsewidth is 21 ps. The spectral width is 0.16 nm, having a time-bandwidth product of 0.423.

From the experimental results we conclude that the amplitude stability of the mode-locked pulses is improved considerably when a NOLM is incorporated into the active mode-locking fiber laser. RH modelocking from $n = 2$ to 4 is achieved and the experimental RH frequencies are very close to the theoretical values. Compared with previous experimental results[6,7], the resulting pulses are more stable and much shorter. Once modelocking pulses are formed, they can last more than one hour keeping stable amplitude. This technology may be useful for ultra-high-bit-rate optical communication systems. However, there are still some other factors affecting the stability of the pulse train, such as the polarization fluctuations in the long fiber cavity due to mechanical vibrations and the cavity length drift due to the temperature fluctuation of the Er-doped fiber.

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