Figure-eight actively-passively mode-locked erbium-doped fiber laser

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The advantages of using nonlinear optical loop mirror (NOLM) to compress pulse with slight amplitude fluctuation and reflected energy loss are analyzed in theory. Experimentally the NOLM is placed in an actively mode-locked erbium-doped fiber ring laser to form a figure-eight actively and passively mode-locked fiber laser. 12 ps mode-locked pulses centered at 1.543 μm were obtained with the modulation frequency of 2.498748700 GHz. 3.715 mW output power is achieved with 50 mW pump power.

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The generation of ultra-short pulses with high repetition rates is very important for high bit rate optical communications. Mode-locked fiber lasers represent a potential source of such lasers. According to its operation scheme, mode-locked fiber laser (MLFL) mainly includes actively mode-locking, passively mode-locking and hybrid mode-locking[1]. Up to now, the highest repetition rate obtained from actively mode-locked fiber laser (AMLFL) is 40 GHz, with 3.5 ps pulse-width[2]. The shortest pulse-width of 269 fs with repetition of 21.37 MHz has been obtained in our country[3] using the method of nonlinear polarization rotation first brought forward in 1992[4]. AMLFLs have the ability to generate stable pulse train in a high repetition rate with small chirp; however its relative wide pulse-width will not fit for long-haul communications well. Meanwhile, it has been shown that passively MLFLs could, in general, produce even shorter pulses with simple structure. Its major shortcomings are limited repetition rates due to the low cavity fundamental frequency, and the poor stability of the mode-locked pulses[5], although these can be overcome in actively mode-locked lasers. Hence, hybrid passively and actively MLFLs have the advantages of both of them and can overcome their drawbacks effectively. Here, we combined actively and passively mode-locking in a figure-eight Er^{3+}-doped fiber laser incorporating a nonlinear optical loop mirror (NOLM). 12 ps mode-locked pulses centered at 1.543μm were obtained with the modulation frequency of 2.498748700GHz, corresponding spectral width is 0.22 nm. This laser combines the merits of actively and passively mode-locking.

Nonlinear loop mirrors are essentially a Sagnac interferometer and their operation is based on interference between two counterpropagating beams, which acquire different amounts of phase shift upon rotating the loop, due to the nonlinear index of the fiber[6]. If no phase bias arising from the loop birefringence is present, the transmission of the nonlinear loop mirror increase with the incident intensity. When a π phase shift is attained, the normally reflecting loop mirror will become totally transmissive. There are two general types of nonlinear loop mirrors shown in Fig. 1, the nonlinear amplifying loop mirror (NALM) in Fig. 1(a) and the NOLM in Fig. 1(b).

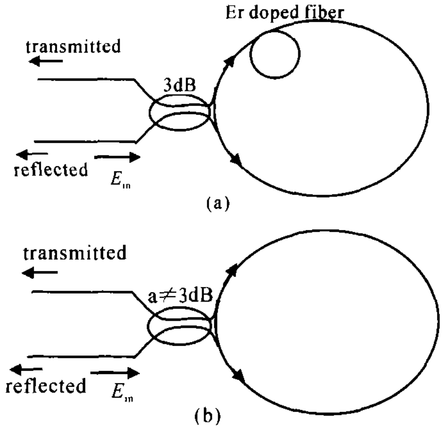

Fig. 1. Two types of nonlinear loop mirror. (a) NALM; (b) NOLM.

Figure-eight lasers have been constructed almost exclusively with NALM[7,8]. These interferometers are constructed with a 50 : 50 coupler and an asymmetrically located amplifier that induces a relative nonlinear phase shift between the counterpropagating pulses. NALMs have the advantages of possessing exceedingly large extinction ratios. However, in the steady state of operation, NALMs typically retroreflected tens of percent of the incident light and, because of the 50 : 50 coupler, they force the pulses within the laser to undergo very large amplitude changes[9]. To minimize these perturbations and decrease the loss, NOLM might be used.

NOLM uses the asymmetry created by an unbalanced central coupler to generate the relative nonlinear phase shift between the pulses within the interferometer. If dispersion is ignored, the transmission of a NOLM is given by[1]

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

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

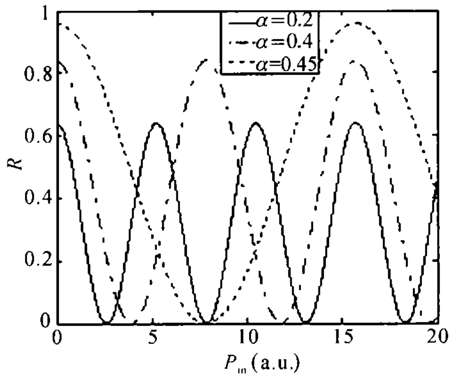

Fig. 2. Reflectivity characteristic of NOLM.

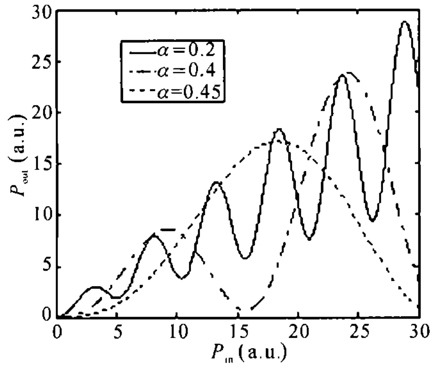

Fig. 3. Transmission characteristic of NOLM.

operating wavelength, E_{in} is the input field. R is the reflectivity. The reflectivity R and transmission characteristic P_{out} of NOLM with input power P_{in} is shown in Figs. 2 and 3. Different curve corresponds to different splitting ratio α. It has been shown that if α is closer to 0.5, the peak reflectivity is larger; in contrast, if α is far off 0.5, most energy is transmitted and only a small part is reflected.

In addition, unpredictable amount of birefringence from bending and twisting is inevitably introduced in forming the loop and changes the relative phase between the counterpropagating beams in a complicated way.

The experimental setup is shown in Fig. 4. The splitting ratio of central coupler (coupler 1) is 20 : 80. The use of 100 m dispersion shifted fiber (DSF) prevents significant temporal spreading of the less energetic pulse as it propagates through the loop mirror. This improves the temporal overlap of the two pulses when they meet at the central coupler and therefore increase the maximum transmission of the loop mirror. The modulator is IOC's 2.5 GHz M-Z LiNbO$_3$ modulator. The gain is produced by IRE-POLUS's EDFA, which has a bandwidth of 1530 – 1570 nm and 18 dBm saturated power. The splitting ratio of output coupler (coupler 2) is 10 : 90. The RF modulation signal source is HP's 83752 synthesized sweeper and the oscillograph is HP's 83480A digital communication analyzer. In addition, the spectrum is measured by Ansitru's MS9001A optical spectrum analyzer.

The hybrid mode-locked pulses under 2.498748700 GHz are shown in Fig. 5(a). The pulsewidth judged from oscilloscope is 20 ps, however, if its response time is considered, its actual pulsewidth is 12 ps. Figure 5(b) shows the optical spectral profile, where the central wavelength is 1.543 μm and the spectral width is 0.22 nm. The pulse is nearly transform-limited, having a time-bandwidth product of 0.33.

The measured output power of fiber laser versus the pump power of EDFA is shown in Fig. 6. 3.715 mW output was attained with 50 mW EDFA pump power. The threshold for CW operation is only 1 mW. Once mode-locked pulses were formed, they could be remained

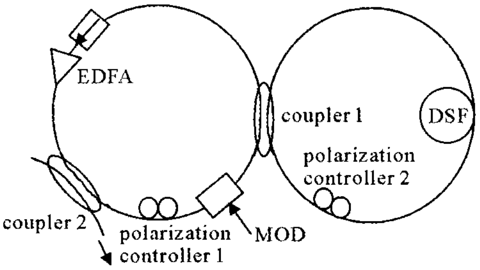

Fig. 4. Experimental setup of figure-eight actively-passively mode-locked Er^{3+}-doped fiber laser.

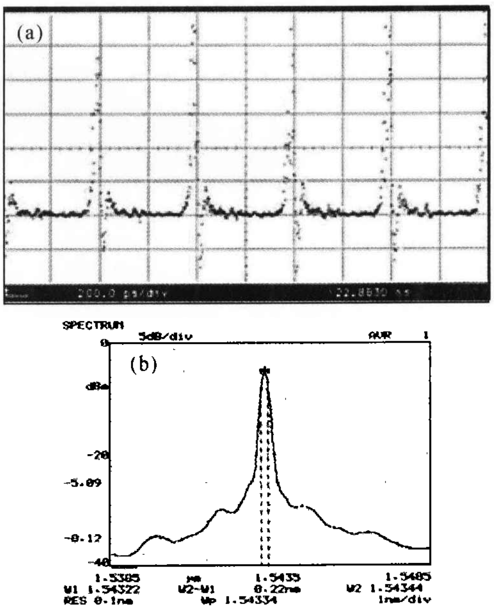

Fig. 5. Output mode-locked pulses train (a) and spectral profile (b).

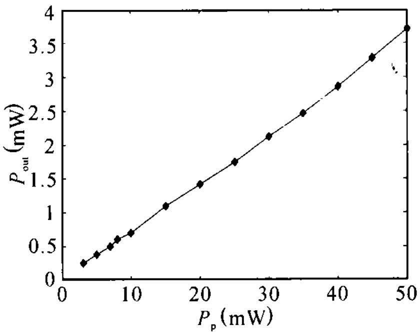

Fig. 6. Output power of fiber laser versus pump power of EDFA.

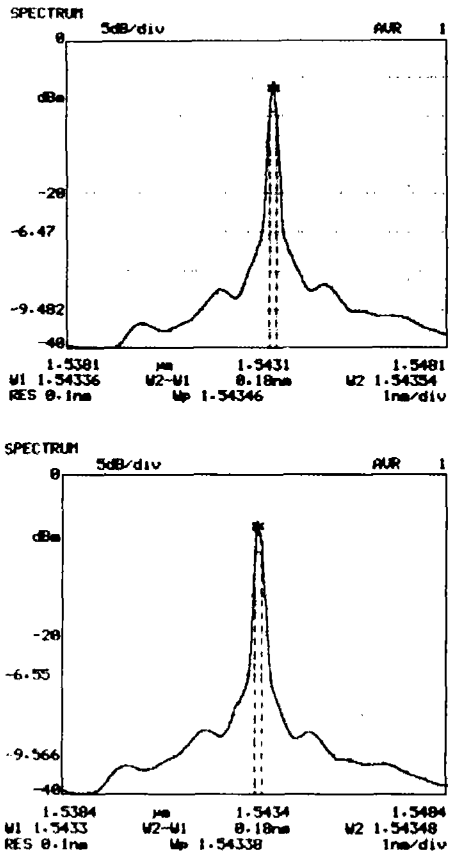

Fig. 7. Drift of output central wavelength.

even the pump power of EDFA was reduced to 3 mW, which demonstrated that the laser efficiency is improved using unbalanced coupler.

In our experiment, the stability is mainly affected by the change of cavity length, which changes with temperature and outside strain. In addition, the random type of uncertainty associated with the loop birefringence is another reason causes the instability. As the fiber laser operating in mode-locked state, there is a tiny drift of its output central wavelength, as shown in Fig. 7. This is because the RF modulation frequency is given by

$$f_{\text{mod}} = \frac{mc}{n(\lambda)L}, \tag{2}$$

where m is an integer, c is the velocity of light in vacuum, λ is the operating wavelength, L is the cavity length and n is the refractive index of fiber. When RF modulation frequency is fixed, tiny drift of wavelength will emerge to automatically adapt the changes caused by cavity length L.

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References

1. G. P. Agrawal, *Applications of Nonlinear Fiber Optics* (Academic Press, University of Rochester, Rochester, 2001) p. 201.
2. T. Pfeiffer and G. Veith, Electron. Lett. **29,** 1849 (1993).
3. D. F. Liu, G. F. Chen, and X. H. Wang, Science in China (Series A) **29,** 656 (1999).
4. V. J. Matsas, T. P. Newson, D. J. Richardson, and D. N. Payne, Electron. Lett. **28,** 1391 (1992).
5. X. Y. Wu and S. C. Li, Optoelectronics · Laser (in Chinese) **8,** 36 (1997).
6. I. N. Duling III, C. J. Chen, P. K. A. Wai, and C. R. Menyuk, Quantum. Electron. **30,** 194 (1994).
7. G. Town, J. Chow, and M. Romagnoli, Electron. Lett. **31,** 1452 (1995)
8. D. J. Richardson, A. B. Grudinin, and D. N. Payne, Electron. Lett. **28,** 778 (1992).
9. A. J. Stentz and R. W. Boyd, Electron. Lett. **30,** 1302 (1992).