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Research Article

NOLM-based Mode-locked Yb-doped Fiber Laser with Wide-spectrum

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Abstract: In this paper, a mode-locked Ytterbium-doped fiber laser based on nonlinear optical loop mirror (NOLM) is proposed. The laser generates a wide-spectrum dissipative soliton resonance mode-locked pulse with strong stimulated Raman scattering. The fiber laser is pumped forward, and the fiber ring cavity contains double-cladding Yb-doped fiber, output coupler, polarization controller, polarization independent isolator and other elements. NOLM is connected with the ring cavity by through a 3dB beam splitter and 25m single-mode fiber. The total length of the eight-shape cavity laser is about 60meters. By adjusting the intra-cavity polarization controller, a stable dissipative soliton resonance mode-locked spike pulse can be achieved. The repetition frequency of the pulse train is 3.44MHz, which is consistent with the cavity length. The 3dB bandwidth of the spectrum reaches 70.6nm, and the 10dB bandwidth is close to 147.11nm. In this experiment, dissipative soliton resonance mode-locked pulses with wide spectrum and high pulse energy are realized by a traditional mode-locking method, which has wide application in many fields such as laser spectral detection and terahertz wave generation.

Keywords: Mode-locked fiber laser, Wide spectrum, Dissipative soliton, Stimulated Raman scattering

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1 Introduction

Compared with traditional rare earth ion-doped fiber lasers, Raman fiber lasers have more flexible output wavelength, ultrafast gain dynamics process and wider gain spectrum. With these advantages, Raman fiber lasers have attracted wide attention in industry [1,2], remote sensing[3,4], medicine[5,6] and other fields in recent years. At present, the commonly used mode-locking technologies in Raman fiber lasers include: NPR[7,8], NOLM[9,10], SESAM[11], nanomaterial saturable absorber[12,13]. In 2019, Feng Y. et al used NOLM technology to generate stable rectangular pulses with 733kHz fundamental repetition rate, and they used the pumped laser source operating at 1064nm[14]. The maximum pulse energy was 64.1nJ. There are two peaks in the output spectrum, the central wavelength of the main peak is 1120.2 nm with the bandwidth of about 2.1 nm, and the second peak is about 1132.0 nm. The intensity of the second peak is 20dB lower than the main peak. Sometimes, however, the bandwidth of about 2.1 nm of the output of this simple Raman laser cannot reach the requirement of some technologies. Therefore, it is further considered to generate a 1μm-band laser pulse by the Yb-doped fiber, utilizing the nonlinear effect of optical fibers, and producing the first or second order Raman spectrum at the same time to maintain a stable output of laser mode-locked pulses. In 2017, Li et al.[15] demonstrated an all-normal dispersion mode-locked Yb-doped fibers laser, which is based on nonlinear polarization evolution (NPE).The pulse duration is 3.8 ps and the 3dB bandwidth of the output spectrum is up to 13.8 nm at a repetitive frequency of 28.1MHz, the output power is more than 130 mW at the pump power of 500 mW. As we known, the broad-spectrum mode-locked pulse is at the forefront of research. In 2018, Zhao et al.[16] also obtained a wide bandwidth mode-locked laser pulse. The mode-locking mechanism they used is nonlinear polarization rotation (NPR). The average output power is 17 mW and the signal-to-noise ratio is up to 77dB when the pump power was 356 mW. There are two peaks in the wide spectrum, the main peak at 1040.16 nm and the Raman peak at 1086.31 nm. The 20dB bandwidth of the output spectrum is 64.04 nm. This is despite a comparative wide spectrum of mode-locked laser pulse, a depression with the height of about 20dB exists in the whole spectrum.

In this paper, a mode-locked double cladding Yb-doped fiber ring laser was constructed by using nonlinear optical loop mirror (NOLM).The wide-spectrum dissipative soliton resonance mode-locked pulse had been demonstrated. The repetition frequency of the stable pulse is 3.44MHz. When the pump power is 2.3W, the maximum pulse energy is 7.3nJ and the pulse width of 4.0ns. The laser pulse spectra are accompanied by strong Stokes Raman peaks and other results from the light wave interaction. The 3dB bandwidth of the spectrum reaches 70.6 nm, and the 10dB bandwidth approaches 147.1 nm.

2 Experimental setups and working principle

The experimental setup of NOLM mode-locked fiber laser is shown in Figure 1. The fiber ring cavity is mainly composed of double cladding Yb-doped fiber, output coupler, polarization controller and polarization independent isolator. Among them, the model of Yb3+ doped double cladding fiber is Nufern YDF-5/130, the main parameters are: 0.55 dB/m@915 nm, length is 20 m, which can provide greater gain. NOLM is composed of a 3dB beam splitter, which is connected to the ring cavity, a 25 mm single mode optical fiber (C1060) is inserted into the NOLM to adjust the nonlinear phase shift in the ring. The pumping source of the laser is a multimode fiber-coupled semiconductor laser with a central output wavelength of 915 nm. Pumped light is coupled into Yb-doped fiber via pump combiner to achieve gain amplification of weak signal pulse, and the optical pulse is periodically modulated by NOLM to achieve stable mode locking. The laser pulse exports through 20% of the output coupler with a 20:80 ratio. The total length of the laser ring cavity is about 60m. The laser works in the positive dispersion regime, therefore, an all-positive dispersion mode-locked fiber laser has been established in this experiment. In order to synchronously observe the laser pulses characteristics, the output optical signals are divided into two beams by a 2x1 coupler with a beam splitting ratio of 50:50, and the time-domain waveform, average power, spectrum of the pulses are tested by different testing devices. The test instruments used in the experiment are: high-speed photoelectric detector (bandwidth is 3 GHz, rise time is 130ps) and digital oscilloscope (LeCroy, wavepro 7300A, bandwidth is 3 GHz, sampling rate is 20 GS/s) connected to achieve mode-locked pulse measurement, using spectrometer (Ocean Optics HR4000, Ando AQ6310B) to achieve pulse spectrum measurement. The radio frequency (RF) characteristics of mode-locked pulses were analyzed by spectrum analyzer (GWINSTEK GSP-9330). In addition, the average output power was measured by optical power meter (JW3216).

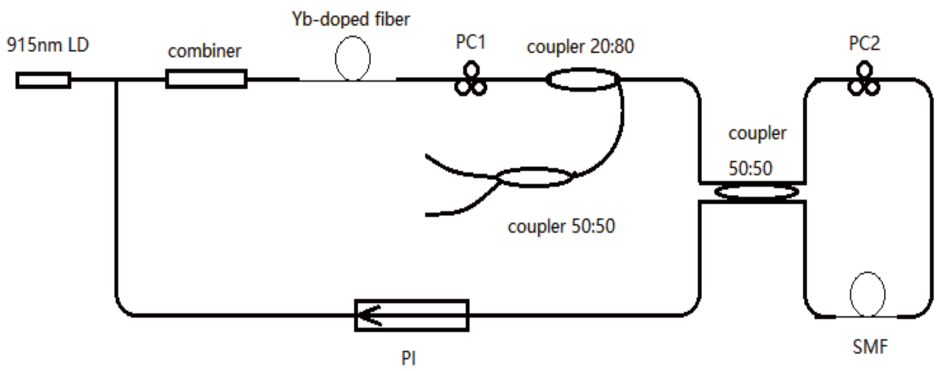


Figure 1. Experimental setup of NOLM mode-locked fiber laser

3 Results and discussions

By adjusting the polarization controller and the pump power, the output of the laser was observed synchronously. When the pump power reached 1.4W, a stable mode-locked pulse could be obtained. Figure 2 is a sequence diagram of mode-locked pulses, which the repetition period is about 0.29 and the pulse width is 2.7 ns.

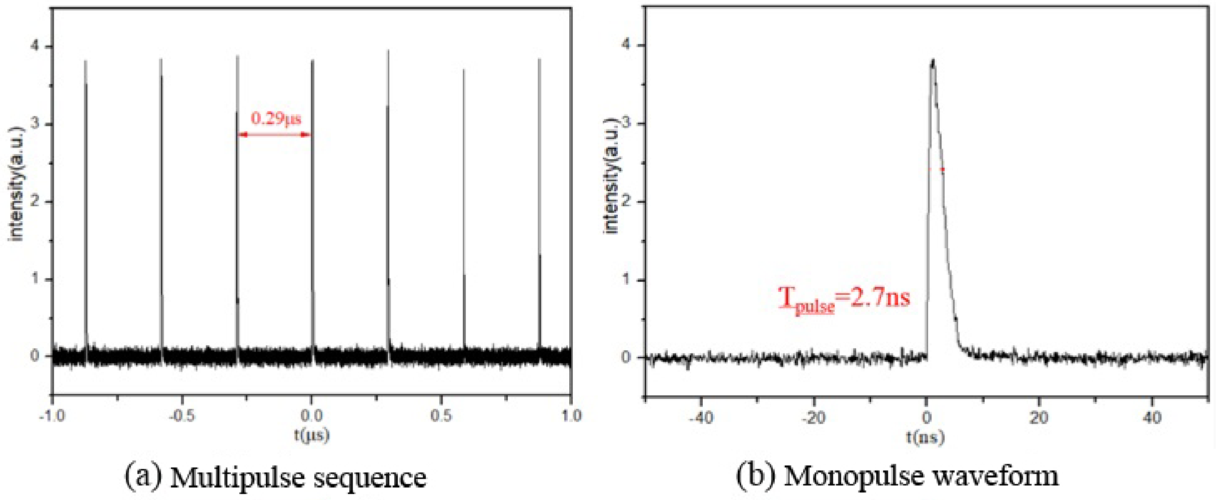


Figure 2. Stable mode-locked pulse sequence diagram

Figure 3 is the RF spectrum diagram of the mode-locked laser pulse train. Figure 3(a) has a scanning range of 20 MHz and a resolution bandwidth of 100 Hz. It can be seen from the figure that higher harmonics appear, which indicates that the stability of the pulse is higher. Figure 3(b) has a scanning range of 6.5 MHz and a resolution bandwidth of 30 Hz. A single signal is shown in the figure. The repetition frequency of the laser output pulse is about 3.44Hz, and the signal-to-noise ratio of the mode-locked pulse is about 49dB, which does not reach the value in reference[16]. During the experiment, it was found that the peak value slightly fluctuated up and down in the multi-pulse state, which may be due to the instability of the nonlinear phase shift in NOLM, mainly due to the large pump power not fully absorbed, which affected the evolution of the pulse stability.

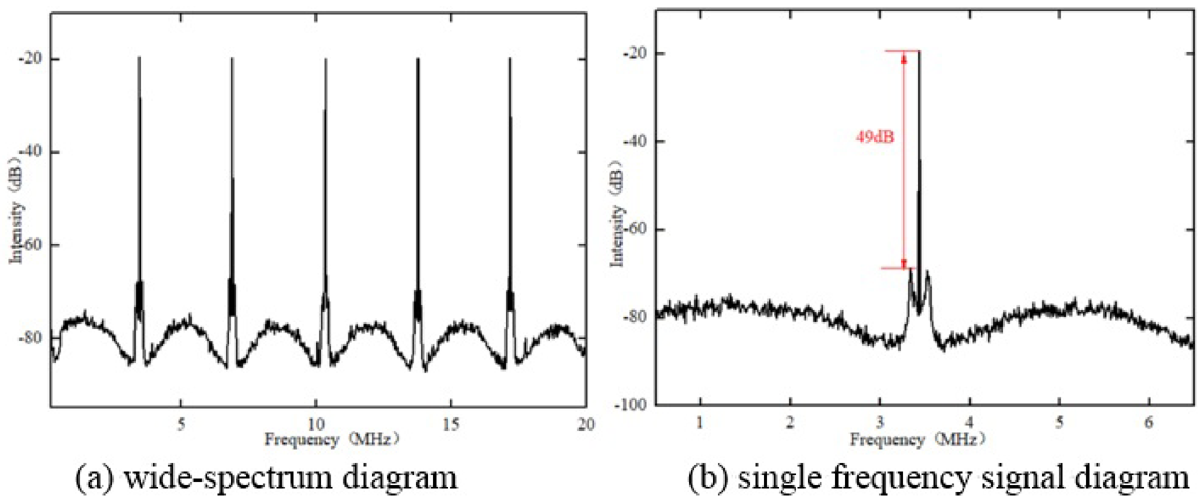


Figure 3. Stable mode-locked pulse sequence diagram

The evolution of NOLM mode-locked pulse with pump power was measured in the experiment, as shown in Figure 4(a). When the pump power is increased from 1.5W to 2.3W, the width of the pulse is increased from 2.1ns to 4.0ns. It can be seen from Figure 4(a) that the peak power of the pulse basically remains unchanged, which shows a similar phenomenon to the dissipative soliton resonance, but the shape of the pulse is spike. When the pump power is increased exceed to 2.3W, the stable pulse is destroyed, the pulse shape cannot be maintained, and the pulse peak jitter is serious, which may be caused by the excessive nonlinear effect in the ring cavity. The synchronous spectra of the mode-locked pulses are shown in Figure

4(b). It can be seen that the main peak of the spectrum is near 1086 nm when the pump power is 1.5 W, which conforms to the position of the fluorescence peak of ytterbium ion in double-clad fiber. The bandwidth of 3dB reaches 32.5nm. With the increase of pump power, the spectral width of the pulse increases continuously, and the peak at 1086 nm remains unchanged, while the first Raman Stokes peak near 1140 nm increases gradually, which broadens the spectrum from 1086 nm main peak to the first Raman peak. At 1.7W pump power, the Raman peak at 1140nm has reached the fundamental peak of 1086nm. When the pump power is further increased, the first Stokes peak gradually increases beyond the fundamental frequency peak. The whole spectrum curve is relatively smooth, and the peak of the spectrum becomes the Raman peak of 1140 nm. When the pump power increases to 2.3W, the 3dB bandwidth of the spectrum reaches 70.6nm, the curve line has not significant depression between the fundamental fluorescence peak and first-order Stokes peak. The 10dB bandwidth is further measured to be about 147.1nm.

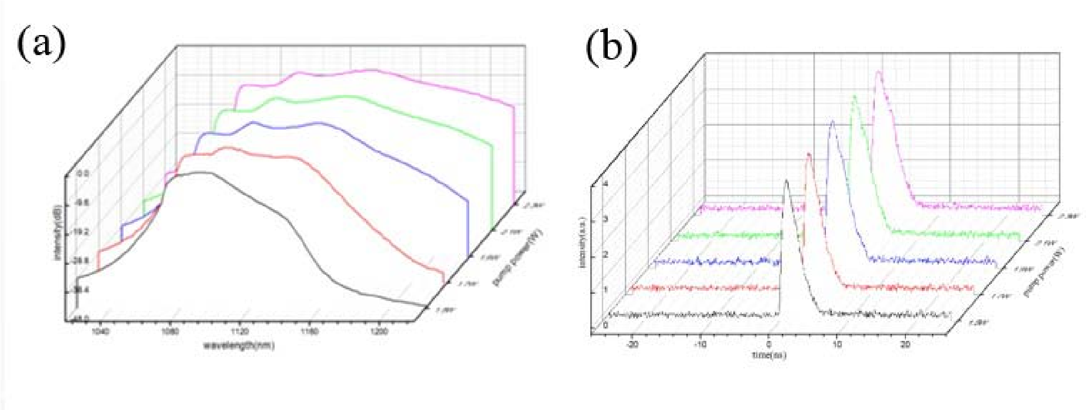
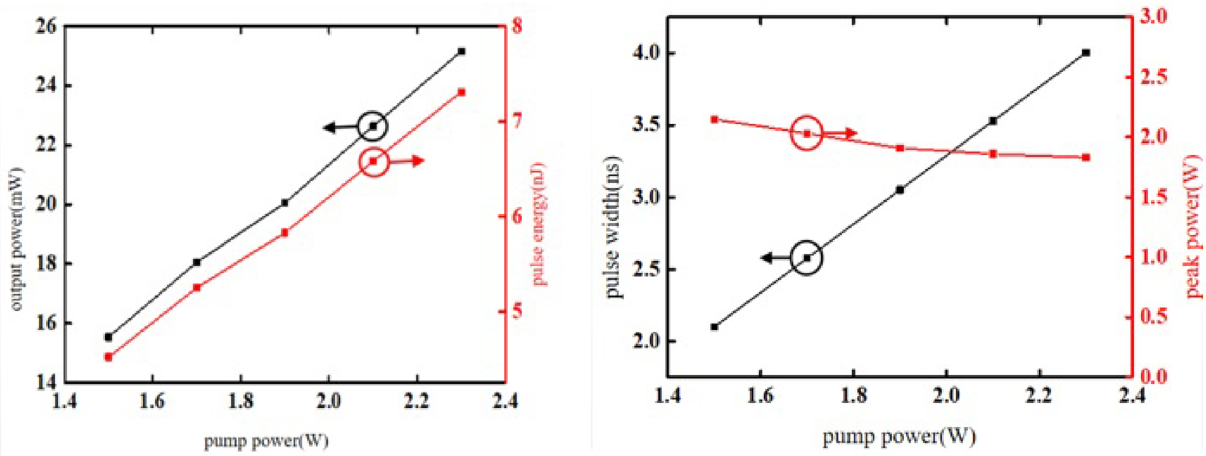


Figure 4. Pulse time-domain waveform (a) and spectrogram versus pump power (b)

Figure 5(a) shows the relationship between the average power, pulse energy, pulse width peak power of the output pulse and the pump power. The experimental results show that the threshold pump power of mode-locked laser is 1.4 W. When the pump power increases from 1.5 W to 2.3 W, the output power and pulse energy increase linearly. The average output power increases from 15.54 mW to 26.76 mW. According to the pulse repetition frequency, the energy of mode-locked pulse increases from 4.52 nJ to 7.31 nJ. Figure 5(b) shows that the pulse width increases linearly with the increase of pump power from 2.1 ns to 4.0 ns, indicating good pulse output characteristics, while the estimated peak power of the pulse decreases slightly, but basically maintains at about 2 W.



(a) Pulse output power and pulse energy

(b) Pulse width and peak power

Figure 5. Relation between pulse output characteristic parameters and pump power

4 Conclusion

A wide spectrum mode-locked Yb-doped fiber laser based on NOLM has been studied. By controlling the polarization controller, a broadband spectrum stable mode-locked dissipative soliton pulse was achieved. The repetition frequency of the pulse is 3.44MHz. When the pump power is 2.3W, the pulse energy reaches 7.3nJ, corresponding to the pulse width of 4.0ns. Under the influence of strong stimulated Raman scattering, the first-order Raman peaks with the same intensity as the fundamental frequency peaks appear. Due to some kind of light wave interaction in the fiber ring cavity, the whole spectrum curve is relatively smooth, the 3dB bandwidth of the spectrum reaches 70.6 nm, and the 10dB bandwidth approaches 147.1 nm. It is shown that a stable broadband mode-locked pulse is realized in the mode-locked fiber laser designed in this paper. It is a mode-locked pulse with the same characteristics as a fundamental-Raman composite soliton. This kind of dissipative soliton mode-locked pulse with wide spectrum and high pulse energy has great significance and value in both theory and application.

Acknowledgements

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