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Raman-Assisted Passively Mode-Locked Fiber Laser *

Lei Zhao(赵磊), Pei-Jun Yao(姚培军), Chun Gu(顾春)**, Li-Xin Xu(许立新)

Department of Optics and Optical Engineering, University of Science and Technology of China, Hefei 230026

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We propose and demonstrate a Raman-assisted passively mode-locked Yb-doped fiber laser in a normal dispersion regime. A section of highly nonlinear fiber is adopted to enhance the nonlinearity to extend the bandwidth of the gain spectrum by the stimulated Raman effect. The mode-locked fiber laser emits a broad spectral bandwidth of 64 nm at the −20 dB level and a highly stable pulse operation with a signal-to-noise ratio of 77 dB.

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In the past two decades, passively mode-locked fiber lasers have experienced rapid development due to their growing demand in applications such as optical coherence tomography, gyroscopes, optical sensing, optical metrology and optical coherence radar.[1–6] Ytterbium-doped fiber (YDF) mode-locked lasers working at 1.0 μm have been well developed with all-normal dispersion (ANDi) fibers. Compared with the fiber lasers working in the conventional soliton and dispersion soliton regime, ANDi lasers have been proved to have high tolerance for strong nonlinear evolution in the cavity but keep their single pulse operation. As a result, higher energy pulses can be generated with such laser cavity designs.[7,8]

Low repetition rate lasers with long cavity have shown their capacity to deliver high energy pulses. However, increasing the fiber cavity length does not guarantee higher pulse energy due to some effects, such as pulse split caused by excessively driven self-phase modulation (SPM) and cross-phase modulation (XPM),[9,10] and wavelength shift induced by stimulated Raman scattering (SRS).[11–17] In earlier studies, SRS could have an effect on the stability of laser operation.[11–15] Cundiff *et al.* found that the intracavity pulses switch the states between abrupt collapse and recovery because of SRS.[14] Aguergaray *et al.* found that in the noise-like operation regime, the destabilization was related to the appearance of Stokes pulses generated from the Raman effect.[12] Meanwhile, other studies also showed that a passively mode-locked fiber laser could stably operate even in the presence of SRS.[16,17] Kharenko *et al.* found that the passively mode-locked fiber laser combined with non-polarization-maintaining (non-PM) fiber and polarization-maintaining (PM) fiber could generate stable pulses in the presence of SRS.[16] Bednyakova *et al.* showed that the formation of a bound Raman-soliton complex allowed the laser to operate stably.[17] However, in the last two works, SRS effect was considered as noise, and the usage of the PM fiber makes the cavity more complicated.

In this Letter, we report a stable passively mode-locked Yb-doped fiber laser with SRS contribution. Apart from conventional cavity designs, a section of highly nonlinear fiber (HNLF) is introduced to provide sufficient nonlinear phase shift for enabling nonlinear polarization rotation (NPR) based mode locking. Moreover, it is found to be able to stimulate the Raman effect to extend the spectral bandwidth in such a short cavity. The fiber laser delivered a broad spectrum of 64.04 nm and a very stable pulse train with a signal-to-noise ratio (SNR) as high as 77 dB.

Figure 1 shows the experimental setup of our mode-locked laser based on the nonlinear polarization rotation (NPR) mechanism. The laser cavity consists of a 974 nm laser diode (LD) pump, a wavelength division multiplexing (WDM), a 70 cm section of ytterbium-doped fiber (CorActive Yb 164, with 470 dB/m absorption at 976 nm), a 7.5 m section of HNLF (with γ about 15 $W^{-1}\cdot km^{-1}$), a polarization-dependent isolator (PD-ISO), two polarization controllers (PCs), an 80:20 output coupler with a 20% output, and a polarization-independent isolator (PI-ISO). The 974 nm LD is used to pump the Yb-doped fiber through WDM. The PD-ISO is used to ensure the unidirectional operation of the laser cavity and the NPR mode-locked unit is cooperating with two PCs (as seen in Fig. 1). The PI-ISO, which is placed directly after the output port, is used to prevent light from returning into the cavity. The optical spectrum is measured by an optical spectrum analyzer (OSA, ANDO AQ6317B), and the temporal properties are measured by a 4 GHz digital oscilloscope (LeCroy Wave Runner 640Zi) and a 10 GHz photodetector.

In our fiber laser, stable self-starting mode-locked pulses appear when the pump power reaches 240 mW. At the maximum achievable pump power of 356 mW, the average output power is increased to 17 mW. The output spectrum of the laser is shown in Fig. 2. As a result of SRS, there are two peaks in the spectrum: a main peak centered at 1040.16 nm and a Raman peak centered at 1086.31 nm. The 20 dB bandwidth of the

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**Corresponding author. Email: guchun@ustc.edu.cn

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spectrum is larger than 64 nm.

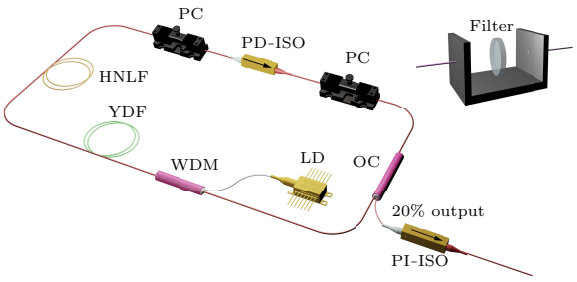

Fig. 1. Schematic diagram of the proposed mode locked fiber laser (inset: filtering schematic). LD, laser diode; WDM, wavelength division multiplexer; YDF, ytterbium-doped fiber; HNLF, highly nonlinear fiber; PC, polarization controller; PD-ISO, polarization dependent isolator; OC, optical coupler; and PI-ISO, polarization independent isolator.

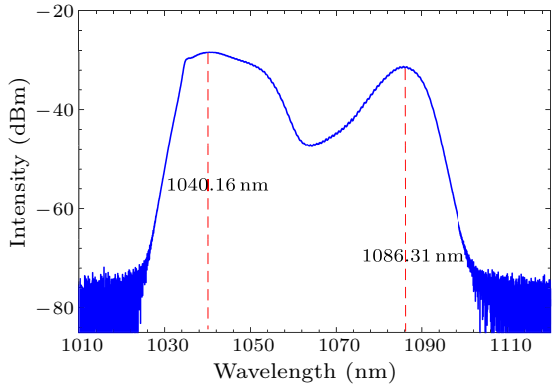

Fig. 2. The output spectrum of the mode-locked fiber laser.

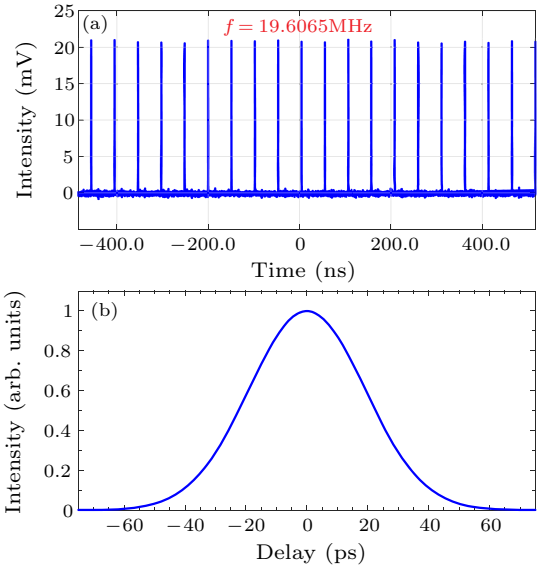

Fig. 3. (a) Oscilloscope trace of the laser pulses in the time domain. (b) Autocorrelation trace of the laser pulse.

A 4 GHz digital oscilloscope with a 10 GHz photodetector and an autocorrelator (APE SM-250, measuring range from 1.5 ps to 250 ps) were used to measure the mode-locked pulse. The results are shown in Fig. 3. Figure 3(a) shows the passively mode-locked pulse train with a repetition rate of 19.61 MHz. Figure 3(b) shows the autocorrelation trace of the single pulse, which is fitted with a Gaussian shape and indicates that the input pulse duration is 31.76 ps. The single pulse energy and the peak power are 0.87 nJ and 41.6 W, respectively.

The radio-frequency (RF) spectrum of the mode-locked pulse train was measured by an RF spectrum analyzer (AV4021). The results indicate the high stability of the mode-locked pulses, as shown in Figs. 4(a) and 4(b). Figure 4(a) shows the fundamental frequency repetition rate of 19.6065 MHz corresponding to the cavity length of approximately 10.5 m. The SNR, as high as 77 dB, was measured with a scan range of 50 kHz and with a resolution bandwidth (RBW) of 1 Hz. Figure 4(b) shows the frequency range from 0 to 25 MHz without any sidebands generation, which also indicates the high stability of the mode-locked pulses.

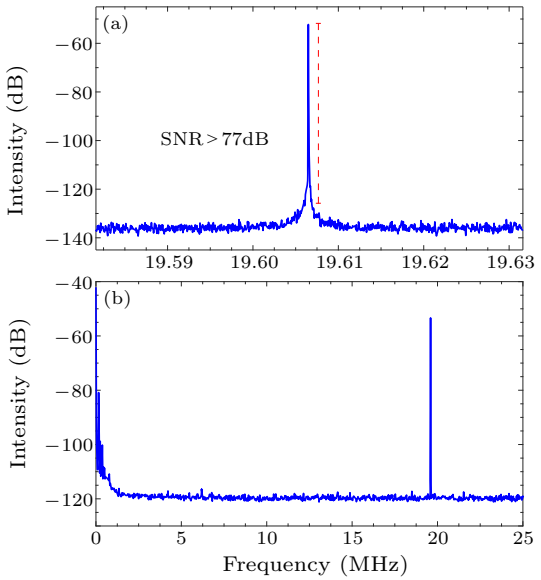

Fig. 4. The RF spectrum of the output mode-locked pulses. (a) Spectrum with a fundamental frequency repetition rate of 19.6065 MHz, span of 50 kHz, and resolution bandwidth of 1 Hz. (b) Spectrum in the range of 0–25 MHz with resolution bandwidth of 1 kHz.

To verify the performance of SRS in the mode-locked process, two bandpass filters (filters A and B) are used to split the output spectrum. The central wavelength of the filter A is 1041 nm and the bandwidth is 15 nm. The spectrum of the filter A is in the range of the Yb gain. The central wavelength of the filter B is 1080 nm and the bandwidth is 16 nm. The spectrum of the filter B is in the range of the Raman gain. The measured transmitted spectra and the corresponding pulse train are shown in Fig. 5. The spectrum curves in Figs. 5(a) and 5(b) are aligned with Yb gain peak and Raman component, respectively. The two spectral components inherit the original pulse state with the same repetition rate of 19.61 MHz. Therefore, it can be obtained that the Raman part participates in the NPR mode-locked op-

eration as a 'signal' instead of 'noise'.

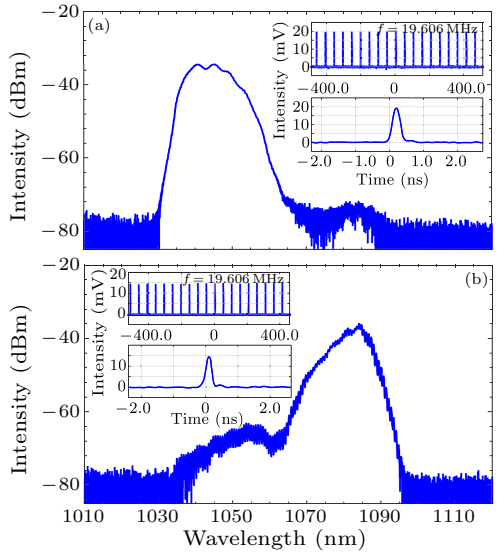

Fig. 5. (a) The spectrum filtered by filter A (inset: corresponding pulse train and single pulse oscilloscope trace). (b) The spectrum filtered by filter B (inset: corresponding pulse train and single pulse oscilloscope trace).

In summary, we have demonstrated a stable Raman-assisted passively mode-locked Yb-doped fiber laser with a broad spectrum. At the maximum pump power of 356 mW, the SNR of the pulses is 77 dB while the 20 dB bandwidth of the output spectrum is 64.04 nm. The NPR evolution combining with SRS is the key to achieving these results. The stable pulse train output is demonstrated by an oscilloscope, an RF spectrum analyzer and an autocorrelator. Furthermore, two band-pass filters are used to split the spectrum into the Yb gain component and the Raman gain component. A consistent pulse train and repetition rate are measured to confirm SRS's participation in the NPR evolution.

This type of mode-locked fiber laser can greatly improve the output spectrum width and stability of rare earth doped fiber lasers, which may find extensive applications such as spectrum measurement, nonlinear research, and ultrashort pulse generation.

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