Subnanosecond and picosecond generation regimes of all-PM Yb-doped fiber laser mode-locked by NOLM

A A Borodkin, D V Khudyakov and S K Vartapetov
Physics Instrumentation Center of Prokhorov General Physics Institute, Russian Academy of Sciences, Troitsk, Moscow, 142190, Russia
E-mail: borodkin_andrey@mail.ru

Abstract. We demonstrated two stable pulsed operation regimes of all-polarization maintaining (PM) Yb-doped fiber laser oscillator with pulse duration of 640 and 85 ps. Nonlinear optical loop mirror (NOLM) was used for laser mode-locking. The first operation regime delivered high energy pulses of 5 nJ, and second regime delivered pulses of 0.7 nJ at a common repetition rate 5 MHz. The dynamics of the temporal and spectral parameters of laser pulses was studied using mathematical simulation based on numerical solution of the nonlinear Schrödinger equation. The simulation results showed that in stable regime with pulse duration of 85 ps the pulse could be compressed to 2 ps.

1. Introduction
Nowadays ultrashort pulse fiber lasers are widely used in various fields of science, technology and medicine. Due to the easy fabrication, low cost and high repetition rate, fiber lasers are often applied for various technical tasks, such as precision processing of materials, marking, surface treatment, metal cutting. For these tasks lasers with pulse duration in the range of 1 ps - 10 ns are typically used [1,2]. For reaching such a wide range of pulse duration, various stretchers are applied [2,3]. However, stretchers degrade the characteristics of the output pulse and significantly increase the size and cost of the fiber laser. Development of a fiber laser with the possibility of changing the pulse duration by transition from one stable pulse generation regime to another is the important task. The output pulse with duration from 10 ps to a few ns can be obtained in the fiber oscillator with NOLM [4,5]. But none of them are capable of changing the pulse duration significantly. As the additional advantage, fiber lasers with NOLM can be performed on the polarization maintaining fiber. Such fiber allows avoiding instability resulting from the polarization state drift in the fiber due to external influences. Thus such lasers offer the temperature and polarization stability.

In this paper we demonstrate a NOLM mode-locked fiber oscillator with two stable pulsed operation regimes with pulse durations of 640 ps and 85 ps with 5 MHz repetition rate. The transition between modes is performed by means of pump power changing. All elements of the ring fiber laser have normal group velocity dispersion, and fibers are polarization maintaining to achieve polarization and temperature stability of radiation.

2. Scheme of the pulsed fiber laser
The scheme of a fiber laser with two stable pulsed operation regimes consisting of elements with normal group velocity dispersion is shown in figure 1. The ring laser is made of PM fibers with a core...
diameter of 6 μm and a cladding diameter of 125 μm. The total ring cavity dispersion is 1 ps². As an active medium we used an ytterbium-doped PM single mode fiber with a core diameter of 6 μm and absorption of 250 dB·m⁻¹ at a wavelength of 976 nm. The active fiber was pumped by a single mode laser diode with a maximum average power of 460 mW at a wavelength of 976 nm. The diode radiation was coupled into the cavity using a PM WDM 980/1030 fiber multiplexor based on a PM fiber. Two output channels (through 20% and 50% couplers) were used to couple out radiation from the cavity and to diagnose the laser radiation, respectively. The linear polarization in the cavity was oriented along the slow axis of the PM fiber using a fiber isolator–polarizer. As a mode-locking element we used a NOLM made of a 30 m long ring PM fiber segment. Stable generation of pulses was achieved using a 90/10 coupler (3) in the NOLM loop. Since the resonator scheme consisted only of PM fiber elements, pulsed lasing was stable and did not depend on the temperature variations and on the optical fibers bends. There was no spectral filter in the laser, which is typically included in the picosecond fiber lasers with NOLM.

Figure 1. Scheme of the fiber laser with two operation regimes: (1) PM WDM 980/1030 multiplexor; (2) 20/80 output coupler; (3) 10/90 coupler; (4) 30 m long fiber loop; (5) isolator–polarizer; (6) 50/50 output coupler; (7) active Yb fiber.

3. Experiment
The threshold of self mode-locking was reached at a pump power of 400 mW. At this pumping level laser operated in a regime of stochastic pulses with pulse-to-pulse instability ~ 15%. After initiation of pulsed lasing, it was possible to decrease the pump diode power to a lower level of 300 mW with stable pulsed operation. The pulse repetition rate at the chosen cavity length was 5 MHz.

Figure 2. Experimentally measured and calculated parameters of the subnanosecond operation regime: (a) spectra; (b) autocorrelation functions of a pulse.

The average laser output power was 25 mW, which corresponds to pulse energy of 5 nJ. The optical output spectrun the regime of pulsed operation was measured with a Yokogawa AQ6370C spectrometer with a resolution of 0.02 nm (figure 2a). The center wavelength and the FWHM of the
spectrum were 1032 nm and 0.04 nm, respectively. The pulse duration was measured by the method of noncollinear second harmonic generation in a nonlinear crystal, which was used to determine the pulse autocorrelation function (figure 2b). The FWHM of the autocorrelation function was 650 ps and the function shape was triangular, which testifies that the pulse shape is rectangular.

After decreasing the pump power in the laser below 300 mW, the pulse generation became unstable. With further decrease of the pump power to 80 mW, another stable regime of generation occurs with a lower power radiation output and a shorter pulse duration.

The average laser output power in such stable regime was 3.5 mW, which corresponds to a pulse energy of 0.7 nJ, that is 7 times less than in the subnanosecond regime. The optical output spectrum of pulsed operation was measured with a resolution of 0.5 nm (figure 3a). The center wavelength and the FWHM of the spectrum were 1033 nm and 4 nm, respectively. The autocorrelation function of the pulse was measured as in the previous case (figure 3b). The FWHM of the autocorrelation function was 66 ps, and the function shape was close to triangular, which testifies that the pulse shape deviated from Gaussian to rectangular.

Figure 3. Experimental and calculated parameters of picosecond operation regime: (a) spectra; (b) autocorrelation functions of a pulse.

4. Numerical simulation
The mathematical simulation of the dynamics of temporal and spectral pulse’s parameters, obtained in a fiber laser with NOLM, was performed using the nonlinear Schrödinger equation as described in [5]. In simulation, firstly we intentionally chose a longer pulse than in the experiment with a zero chirp. The calculations were continued until the radiation parameters became unchanged during a number of cavity round-trips. After several round-trips, the combined action of the amplifying medium, self-phase modulation, dispersion, and NOLM led to the formation of a stable output spectrum (figure 2a) and pulse (figure 4) with corresponding autocorrelation function (figure 2b). The calculated duration of the output pulse was 640 ps (figure 4). The pulse autocorrelation function obtained in simulation is in good agreement with the autocorrelation function measured by the method of noncollinear second harmonic generation (figure 2b). The pulse shape is rectangular, which agrees with the results of another work on pulsed fiber lasers with NOLM [1].
To calculate the parameters of laser radiation in picosecond regime, we used the results obtained in the simulation of subnanosecond fiber laser as initial conditions. With pump power decreasing, a stable generation of subnanosecond pulses is transferred to the stable picosecond regime. The pulse autocorrelation and output spectrum obtained in simulation are in good agreement with the experimental data (figure 2). In the picosecond regime, the output pulse has linear chirp and could be compressed. Calculated duration of the compressed pulse is 2 ps (figure 5).

5. Conclusions
A passively mode-locked ytterbium fiber laser with two stable pulsed operation regimes is presented. For the laser mode-locking a NOLM is used. The durations of the output pulses are 640 ps and 85 ps, and they can be tuned by pump power changing. Subnanosecond regime delivers high energy pulses of 5 nJ, and picosecond regime delivers pulses of 0.7 nJ at repetition rate of 5 MHz. The ring cavity is designed using PM fibers only, which ensures low sensitivity of the laser to the environmental conditions and a stable polarization at the output. Numerical simulation of the laser shows a good agreement of experimental and theoretical output characteristics. In the picosecond regime pulses are linearly chirped and can be compressed by an external compressor to duration of 2 ps.

References
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