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# Femtosecond Ring All-Fiber Yb Laser with Combined Wavelength-Division Multiplexer–Isolator

**A. V. Ivanenko, S. M. Kobtsev, and S. V. Kukarin**

*Novosibirsk State University, ul. Pirogova 2, Novosibirsk, 630090 Russia*

e-mail: kobtsev@lab.nsu.ru

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**Abstract**—An original scheme of an all-fiber all-normal-dispersion ring mode-locked Yb laser is proposed and experimentally studied. A single fiber element serves as a wavelength-division multiplexer for the pumping radiation, an optical isolator, and a spectrally selective element for the radiation of the Yb laser. The output pulse duration is 900 fs, and the intracavity compression yields the pulses with a duration of 200 fs. The maximum laser power is 35 mW at a wavelength of 1070 nm.

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## INTRODUCTION

Femtosecond fiber lasers with a wavelength of about 1 μm are widely used in various applications [1–3]. One of the methods for the passive mode-locking in such lasers employs the nonlinear polarization evolution in the optical fiber that serves as the laser cavity [4–6]. Recent works [7–11] show that the ytterbium-doped fiber lasers with the normal dispersion of the cavity medium can be used to generate short pulses with relatively high energies. Normally (see [10, 12, etc.] for exceptions), a spectrally selective element provides stable mode-locking in such lasers. The element does not allow the all-fiber configuration, which is often demanded by users owing to the simplicity of the all-fiber laser. Most of all-normal-dispersion mode-locked fiber lasers are based on ring cavities, which makes it possible to get rid of end reflectors but necessitates the application of an optical diode inside the laser cavity for the generation of a unidirectional wave. In addition, the activation of the mode-locking based on the nonlinear polarization evolution necessitates the presence of several polarization controllers inside the cavity. Thus, a conventional all-normal-dispersion mode-locked fiber laser contains many elements in the cavity and such a laser must be designed in the fiber/bulk configuration with open air spaces between discrete (non-fiber) elements [4, 5, 12].

A conventional cavity of the all-normal-dispersion mode-locked fiber laser contains a fiber spectral multiplexer for the delivery of the pump energy to the cavity, a segment of an active fiber, an isolator that provides the unidirectional traveling wave inside the cavity, a beam splitter for the partial outcoupling of the radiation, a saturable absorber or a polarization-sensitive element with two polarization controllers for the mode-locking, and a spectral filter that serves as an additional element for the stabilization of the mode-locked lasing. Normally, a polarizer or a polarization-maintaining beam splitter that provides the outcoupling of the polarized radiation from the cavity serves as a polarization-sensitive element.

In contrast to the conventional scheme, which contains the active medium and four fiber elements (multiplexer, filter, isolator, and beam splitter) and the scheme from [13], which employs a specific filter (beam splitter), the proposed scheme contains only two fiber elements: a combined multiplexer–isolator–filter and a beam splitter. To the best of our knowledge, such a laser scheme is the simplest scheme of the femtosecond fiber laser with respect to the number of fiber elements.

## EXPERIMENT

Figure 1 demonstrates the laser scheme. An ytterbium-doped fiber that does not maintain the polarization and has a core diameter of 7 μm and a length of 0.5 m serves as the active element. The active fiber is core-pumped by the radiation of a diode laser with a wavelength of 980 nm through the multiplexer–isola-

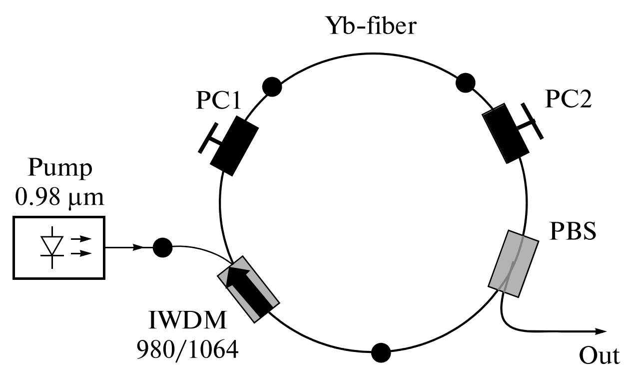


**Fig. 1.** Scheme of the femtosecond all-fiber ring ytterbium laser: IWDM wavelength-division multiplexer and isolator, PC1 and PC2 polarization controllers, and PBS polarization beam splitter.

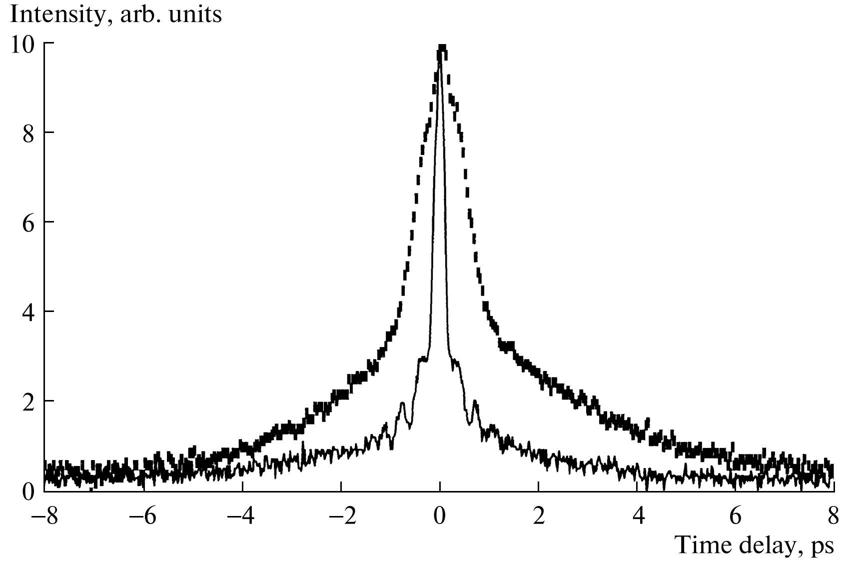


**Fig. 2.** Noncollinear autocorrelation functions of the femtosecond all-fiber ring ytterbium laser: (dashed line) output pulse and (solid line) compressed pulse.

tor whose transmission band centered at 980 nm is supplemented with a transmission band with a width of 10 nm centered at 1064 nm. The radiation is outcoupled from the cavity with the aid of a polarization beam splitter. The mode-locking is implemented owing to the nonlinear polarization rotation, and the tuning to the mode-locking regime is performed with two fiber polarization controllers. The first controller is placed in front of the active medium, and the second controller is placed in front of the polarization beam splitter. The first tuning of the laser to the mode-locking regime involves the tuning of the two polarization controllers. In the subsequent working sessions, the mode-locking is activated automatically. At a maximum pump power of 300 mW, the power of the polarized output radiation amounts to 35 mW at a wavelength of 1070 nm.

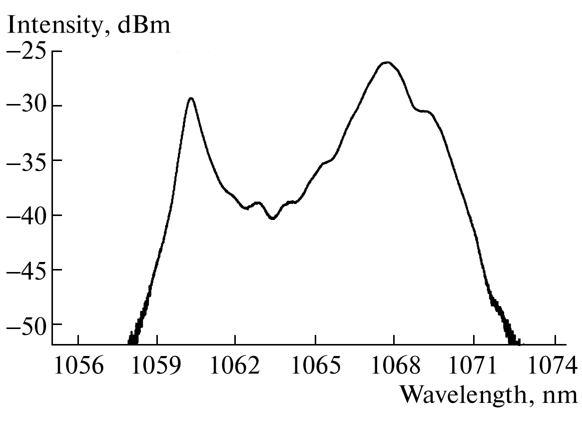


**Fig. 3.** Spectrum of the radiation of the femtosecond all-fiber ring ytterbium laser.

The duration of the output laser pulses is 900 fs at a repetition rate of 97 MHz. The extracavity pulse compression with two diffraction gratings leads to a pulse duration of 200 fs. Figure 2 shows the autocorrelation functions of the output and compressed pulses. The peak power of the output laser pulses is up to 0.4 kW, and the peak power of the compressed pulses increases to 1.7 kW. The pulse energy is 0.4 nJ.

The spectral width of the output radiation of the mode-locked laser is about 10 nm (Fig. 3), which indicates that the compressed pulse is almost the bandwidth-limited pulse (for the bandwidth-limited Gaussian pulse with a duration of 200 fs, the spectral width at the given wavelength is 8.4 nm). Figure 3 demonstrates the spectrum of the laser radiation. The presence of the intracavity spectral filter accounts for the double-humped spectrum of the all-normal-dispersion mode-locked laser [7, 9].

An important feature of the proposed laser lies in the fact that the minimization of the number of fiber elements allows a decrease in the number of the intracavity fiber connections and an increase in the accuracy of the adjustment of the cavity length. In the mode-locked laser, the length of the laser cavity determines the pulse repetition rate, which can be predetermined in metrological and several other applications [14].

## CONCLUSIONS

We propose and experimentally study an original all-fiber ytterbium femtosecond laser with a simplified configuration of the ring cavity that contains a minimum number of elements for the mode-locked laser with the completely positive dispersion of the cavity medium. An almost ultimate decrease in the number of fiber elements makes it possible to decrease the number of the intracavity fiber connections and to increase the accuracy at which the cavity length can be fixed. The minimum pulse duration is 200 fs at a mean power of 35 mW and a central wavelength of 1070 nm.

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