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Wide-Spectrally-Tunable CW and Femtosecond Linear Fiber Lasers with Ultrabroadband Loop Mirrors Based on Fiber Circulators

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Abstract—It is demonstrated for the first time that the fiber circulator-based loop reflectors exhibit an extremely wide spectral range. Fiber reflectors based on a commercially available circulator for a wavelength of 1064 nm provide a reflectance of greater than 90% (50%) in a spectral band with a width of 75 (180) nm. The application of such a reflector in a linear CW Yb laser in combination with the second prism reflector allows the smooth tuning of the laser wavelength in the range with a width of greater than 90 nm. The application of two ultrabroadband circulator-based reflectors in the linear all-fiber all-positive-dispersion mode-locked Yb laser makes it possible to generate unique combined femtosecond–picosecond pulses whose shortest component has a duration of less than 190 fs. The spectrum of ultrashort pulses is smoothly tuned in the range 1065–1115 nm owing to the prism reflector.

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INTRODUCTION

The fiber elements that serve as reflectors in fiber cavities exhibit relatively narrow working spectral bands, which represents a conventional problem for the linear fiber lasers upon the generation of ultrashort pulses or the wide-range tuning of the radiation wavelength. A simple reflective Bragg grating with a periodic structure has a relatively high reflectance in a narrow spectral interval (no greater than 0.5–1.0 nm) [1, 2]. The gratings with aperiodic structures exhibit broader reflection bands that reach several nanometers [3, 4] and even 20 nm [5]. However, the maximum reflectance of such gratings is significantly less than 100% (e.g., 50% in [4]). Recent results show a possibility of aperiodic gratings with relatively high reflectances in a range with a width of several hundred nanometers [6]. Note that the fabrication of such gratings represents a serious problem and a significant phase modulation of the pulses reflected by such a grating can play a negative role in several applications. An alternative approach employs classical external broadband bulk mirrors, which are placed in the vicinity of the ends of the fiber cavity, or broadband coatings deposited on ends of the fiber that serves as the fiber cavity. A disadvantage of this approach lies in the coupling of such a fiber laser with the remaining fiber components (e.g., amplifiers).

In this work, we demonstrate for the first time that the ultrabroadband fiber mirrors can be based on conventional optical circulators. In accordance with the results from [7, 8], a circulator with the connected input and output ports can serve as a fiber reflector (the so-called circulator-based loop reflector). In this work, we demonstrate that such a fiber reflector exhibits a relatively high reflectance of greater than 80–90% in a spectral interval with a width of tens of nanometers

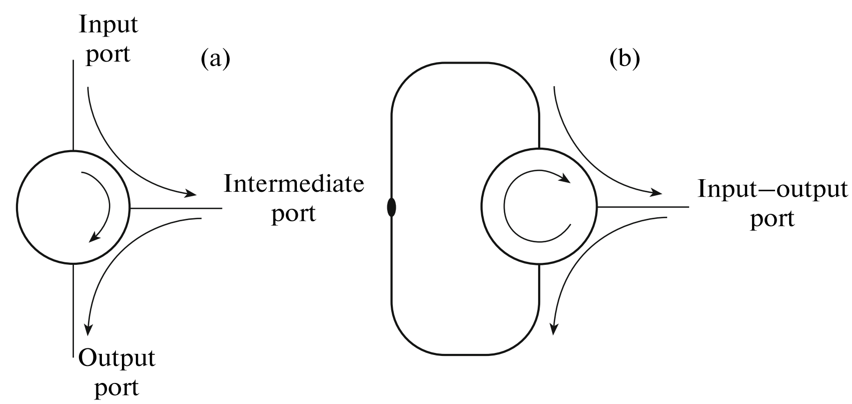

Fig. 1. Scheme of (a) conventional fiber circulator and (b) circulator-based fiber reflector.

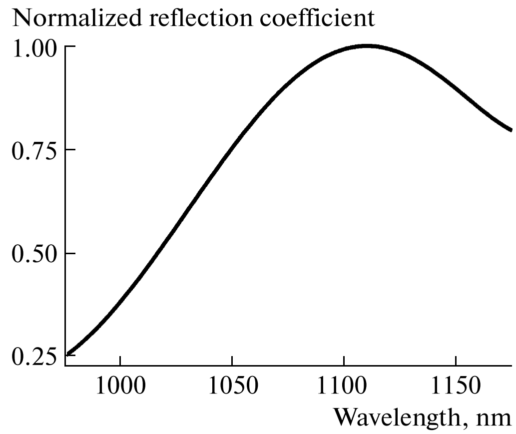

Fig. 2. The measured spectral curve of the reflectance of the circulator-based mirror.

and a reflectance of greater than 50% in a spectral band with a width of 180 nm. The ultrabroadband working range of the fiber reflectors allows new approaches in the design of linear fiber lasers in which the laser wavelength must be tuned in a maximally wide spectral range or the nonselectivity of the cavity elements must be maximized (femtosecond lasers).

Below, we present the parameters of the wavelength-tunable CW and femtosecond fiber Yb lasers with the ultrabroadband loop mirrors.

EXPERIMENT

In the experiments, we employ the PM circulators optimized for the spectral range 1060–1070 nm. A typical level of loss of the circulators is 1.5 dB, and the channel isolation is no worse than 23 dB. A circulator with the connected input and output ports works as a reflector (Fig. 1), so that the radiation fed to the entrance of the loop circulator is returned by the same fiber. To determine the reflection spectrum of the loop circulator, we perform independent measurements of the transmission spectra of the channels and find the reflection spectrum of the circulator-based mirror. Figure 2 demonstrates the measured spectral dependence of the reflectance of the circulator-based mirrors. The relatively smooth measured dependence yields a decrease in the reflectance to 50% when the radiation wavelength differs from the wavelength corresponding to the maximum reflectance by about 90 nm. Thus, the circulator-based mirror provides a reflectance of greater than 50% in the spectral band with a width of about 180 nm. For a reflectance of greater than 90%, the working band of the circulator-based mirror is no less than 75 nm. Note that the maximum reflectance of such an ultrabroadband circulator-based reflector is reached at about 1110 nm in spite of the fact that the central working wavelength of the circulator is 1064 nm.

In the first experiment, we test the range of the wavelength tuning of the linear ytterbium-doped fiber laser with the circulator-based mirror. Figure 3 shows the scheme of such a laser. The Littrow prism with a highly reflecting broadband coating in the range 1050–1200 nm serves as the second mirror of the laser cavity. The wavelength tuning is performed owing to the rotation of the prism, and the radiation is outcoupled from the cavity using a fiber polarization beam splitter. The maximum output power of the laser is 28 mW. Figure 4 demonstrates the tuning curve of the laser corresponding to the rotation of the Littrow prism. The width of the laser wavelength-tuning band is 90 nm (from 1045 to 1135 nm).

In the second experiment, we use the second circulator-based mirror instead of the Littrow prism and insert two fiber polarization controllers to the laser cavity. Figure 5 shows the laser scheme. Note the absence of specific elements (fibers, gratings, etc.) for dispersion compensation and the absence of additional spectrally selective elements that limit the spectrum of lasing. The two additional polarization controllers allow the tuning of the laser to the mode-locking regime. In this regime, we obtain the stable generation of ultrashort pulses. The maximum output power of the laser is 150 mW at a wavelength of 1110 nm for a pump power of 0.5 W at a wavelength of 980 nm. The output power is limited by the maximum power allowed by the fiber polarization splitter.

Figure 6 demonstrates the autocorrelation function of the output laser pulses. It is seen that the autocorrelation function consists of a narrow central peak with a duration of 190 fs and a pedestal with a duration of

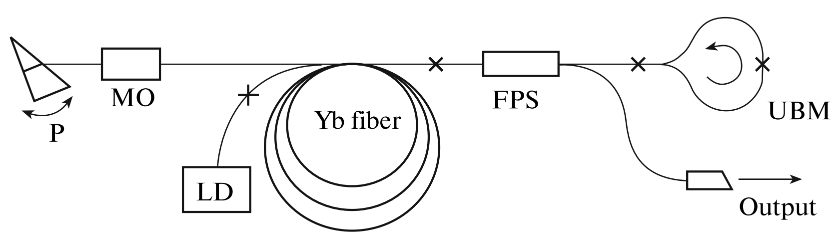

Fig. 3. Scheme of linear ytterbium laser with the proposed reflector: LD pumping laser diode, UBM ultrabroadband mirror, FPS fiber polarization splitter, MO microscope objective, P Littrow prism.

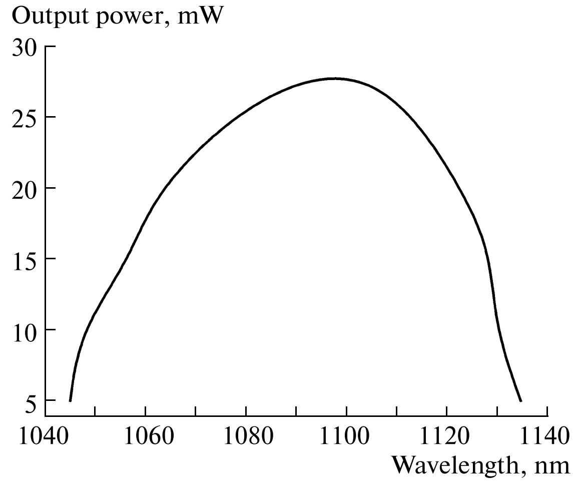

Fig. 4. Wavelength distribution of the laser power resulting from the rotation of the Littrow prism.

about 10 ps. Thus, the laser generates the combined femtosecond–picosecond pulses whose femtosecond component has a duration of 190 fs. Such a short structure with a duration of 190 fs is obtained for the first time using the all-positive-dispersion laser in the absence of the external compression.

In the third experiment, one of the two circulator-based mirrors of the mode-locked laser is replaced by the prism reflector from the first experiment. In such a configuration, we obtain the stable mode-locking with similar combined femtosecond–picosecond pulses and the rotation of the prism allows the wavelength tuning of the radiation of ultrashort pulses in the band with a width of 50 nm (from 1065 to 1115 nm).

We also verify the sensitivity of the circulator-based mirrors with respect to temperature variations and find that the spectral characteristics remain unchanged in the temperature interval 20–150°C: the wavelength

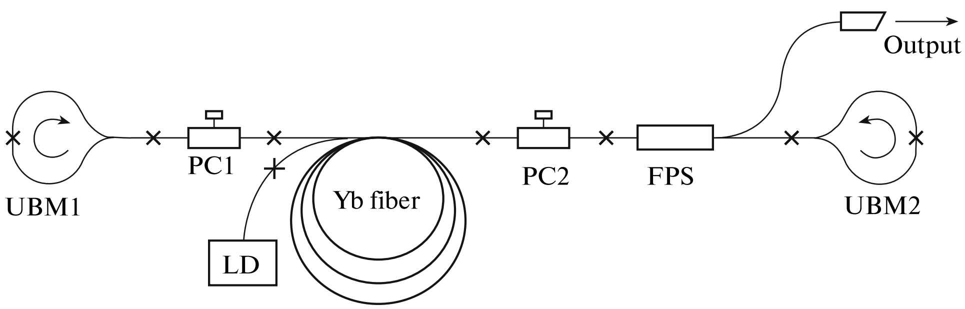

Fig. 5. Scheme of the proposed ultrashort-pulse ytterbium laser with the linear cavity and two ultrabroadband fiber reflectors: LD pumping laser diode, UBM1 and UBM2 ultrabroadband fiber mirrors, PC1 and PC2 fiber polarization controllers, and FPS fiber polarization splitter.

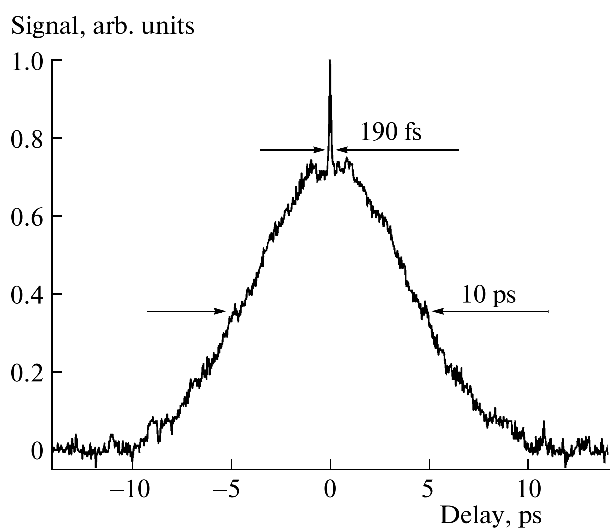

Fig. 6. Autocorrelation function of the combined femtosecond–picosecond laser pulses.

corresponding to the maximum reflectance is stable with an accuracy of 0.5 nm in the entire temperature range.

CONCLUSIONS

It is demonstrated that the conventional fiber circulators can be used to create ultrabroadband fiber reflectors that provide the generation of ultrashort pulses in linear fiber lasers. The application of ultrabroadband fiber reflectors in CW linear fiber lasers makes it possible to simplify the laser wavelength tuning in a wide spectral range. The loop fiber mirrors based on commercially available circulators that are proposed and tested in this work can be a promising alternative to the Bragg gratings in several applications.

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