Optics Communications 324 (2014) 141–146

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Extra-broadband wavelength-tunable actively mode-locked short-cavity fiber ring laser using a bismuth-based highly nonlinear erbium-doped fiber

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ARTICLE INFO

Article history:
Received 28 December 2013
Received in revised form
20 February 2014
Accepted 18 March 2014
Available online 29 March 2014

Keywords:
Optical fiber lasers
Mode locked lasers
Noise
Wavelength tuning
Rare-earth materials

ABSTRACT

We demonstrate an ultra-wideband wavelength-tunable actively mode-locked short-cavity laser employing a 151-cm-long bismuth-based highly nonlinear erbium-doped fiber (Bi-HNL-EDF). A wavelength tuning range of 87 nm from 1533 nm to 1620 nm can be achieved because the Bi-HNL-EDF has an ultra-wide gain bandwidth. High nonlinearity of the Bi-HNL-EDF also collaborates with spectral filtering by an optical bandpass filter to suppress the supermode noise quite effectively. Total length of the fiber ring cavity is as short as 16 m. Thus, stable and clean 5.6–6.1 ps pulses with a repetition rate of 10 GHz are successfully obtained over the wavelength tuning range almost completely covering both the conventional wavelength band (1530–1565 nm) and the longer wavelength band (1565–1625 nm). The bismuth-based short-cavity fiber laser also shows good performance in the back-to-back bit-error-rate measurements, and maintains bit-error-free mode-locking operation throughout the entire wavelength tuning range.

1. Introduction

The generation of broadband wavelength-tunable optical short pulses with high repetition rate is of considerable interest for many applications, such as optical sampling and sensing, wavelength division multiplexing and time division multiplexing, as well as optical soliton transmission. Among many optical pulse generators, actively mode-locked fiber ring lasers (AMLFRLs) have become very popular sources due to their ability to generate wavelength-tunable and transform-limited (TL) short pulses with small timing jitter and gigahertz repetition rates [1–14].

Silica-based erbium-doped fibers (Si-EDFs) are commonly employed as gain media for AMLFRLs. Therefore, the typical wavelength tuning range of the Si-EDF-based AMLFRLs is less than 50 nm and is around the conventional wavelength band (C-band) region (1530–1565 nm). In order to extend the tunable range toward the longer wavelength band (L-band) region (1565–1625 nm), longer Si-EDFs and careful optimization of the pump powers are required [15]. However, short length gain media are attractive for constructing AMLFRLs.

Meanwhile, the typical cavity length of AMLFRLs is 10–100 m, and the corresponding order of harmonics is 500–5000 for 10-GHz mode-locking. Such a long cavity length introduces the system vulnerability to external perturbation. In addition, due to such a high harmonics order, the laser cavity also has a large number of competing supermodes. Beating between the supermodes introduces intensity fluctuation of the mode-locked pulses known as supermode noise. Several techniques to suppress the supermode noise have been proposed and demonstrated so far, such as insertion of an intracavity high finesse Fabry–Perot etalon [11], a semiconductor optical amplifier (SOA) [12,13], and a silica-based highly nonlinear dispersion-shifted fiber (HNL-DSF) [14]. However, the Fabry–Perot etalon is usable only for a single repetition frequency. On the other hand, use of the SOA is advantageous in that it is usable in any repetition frequency, does not elongate the cavity, and is applicable to multiwavelength fiber lasers. However, the SOA is an active element which causes additional noise and cost. In this respect, the use of self-phase modulation (SPM) in a silica-based highly nonlinear passive fiber element and spectral filtering by an optical bandpass filter (OBPF) is an attractive technique for noise suppression [14]. In this method, higher intensity pulses are spectrally broadened by the SPM and then suffer higher loss through the OBPF. Therefore, fast intensity limiting is achieved, and the pulse intensities can be equalized. The length of the silica-based HNL-DSF required for the stabilization, however, is reported to be at least several tens of meters. Employing such a long element in the ring cavity makes the laser system more sensitive to external perturbation.

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http://dx.doi.org/10.1016/j.optcom.2014.03.050
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In our previous papers, we have proposed and experimentally demonstrated effective suppression of the supermode noise by using the SPM effect in a short length bismuth-oxide-based highly nonlinear fiber (Bi-HNLF) [20], [23–25]. The Bi-HNLF has an extremely high nonlinear coefficient compared with that of the conventional silica-based HNL-DSFs. Therefore, the length of the Bi-HNLF required for the noise suppression can be dramatically shortened. However, the increase of the cavity length by inserting the fiber element cannot be avoided. In addition, due to its large insertion loss, the wavelength tuning range of the laser output also becomes narrower than the original bandwidth of the gain medium.

In this paper, we report an extra-broadband wavelength-tunable short-cavity AMLFRL using a 151-cm-long bismuth-oxide-based highly nonlinear erbium-doped fiber (Bi-HNL-EDF). This Bi-HNL-EDF is used as both a gain medium and an SPM-based noise suppressor, and thus additional nonlinear fiber element is not included in the fiber ring cavity. Since the Bi-HNL-EDF has an ultra-wide gain bandwidth covering both the C-band and the L-band, a wavelength tuning range of 87 nm from 1533 nm to 1620 nm can be achieved. The supermode noise can be suppressed effectively because the Bi-HNL-EDF has also a high nonlinear coefficient γ of 64.2 $W^{-1}\,km^{-1}$. The total cavity length is as short as 16 m due to the short length of Bi-HNL-EDF. Thus, clean and near-TL 5.6–6.1 ps pulses with a repetition rate of 10 GHz are successfully obtained for the entire wavelength tuning range. The bismuth-based fiber laser also shows good bit-error-rate (BER) performance, and maintains bit-error-free operation throughout the wavelength tuning range.

2. Experimental setup

A schematic of the experimental setup is shown in Fig. 1. A 151-cm-long Bi-HNL-EDF supplied from Asahi-Glass Co., Ltd. [16–19,21,22,26] was used as both the gain medium and the SPM-based noise suppressor. The length of the Bi-HNL-EDF was optimally determined so as to maximize the wavelength tuning range. The erbium concentration was 3250 ppm. The absorption peaks around 980 nm, 1480 nm, and 1530 nm were 90 dB/m, 130 dB/m, and 210 dB/m, respectively. The refractive indexes of the core and the cladding were 2.03 and 2.02 at 1550 nm, respectively. The core and cladding diameters were 5.1 μm and 124 μm, respectively. The nonlinear coefficient γ was as high as 64.2 $W^{-1}\,km^{-1}$. The nonlinear coefficient γ was estimated from four-wave mixing measurements [19,27]. The group-velocity dispersion (GVD) was -130 ps/nm/km at 1550 nm. Such a large normal GVD was mainly attributed to the material dispersion of the high refractive index glass. However, because of the short fiber length, the total dispersion of the Bi-HNL-EDF was compatible with or smaller than those of the Si-EDFs. Therefore, its effect on pulse generation was not so serious [19]. Both ends of the Bi-HNL-EDF were fusion spliced to conventional SiO_2 fibers. The fiber-to-fiber loss was 2.3 dB at 1310 nm. The Bi-HNL-EDF was bidirectionally pumped with two high power laser diodes (LDs). A 974-nm LD with an output power of $+28.6$ dBm was used for the forward pumping, and a 976-nm LD with an output power of $+28.6$ dBm was used for the backward pumping. Both pump beams were coupled in the ring cavity through wavelength-division

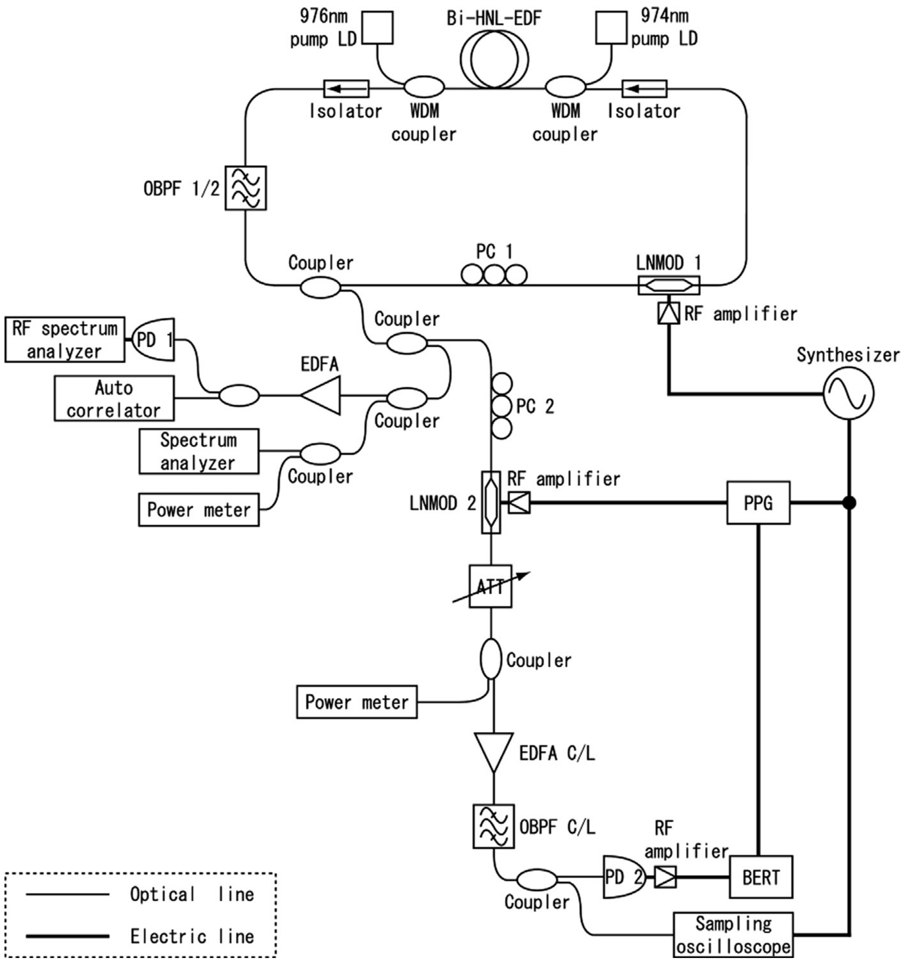

Fig. 1. Schematic of the experimental setup.