Mode-Locked Bi-Doped All-Fiber Laser With Chirped Fiber Bragg Grating

Samuli Kivistö, Regina Gumenyuk, Janne Puustinen, Mircea Guina, Evgeny M. Dianov, and Oleg. G. Okhotnikov

***Abstract*—We demonstrate a Bi-doped fiber laser with dispersion compensation provided by a linearly chirped fiber Bragg grating. Reliable self-starting mode-locking was achieved by using an InGaAsN semiconductor saturable absorber mirror. The all-fiber laser generated short optical pulses with a duration of 1.9 ps at ∼1165 nm. The large anomalous dispersion of the fiber grating ensured operation in the soliton pulse regime. This in turn enabled us to increase the repetition rate of the output pulse train up to 100.6 MHz via harmonic mode-locking.**

***Index Terms*—Bismuth, fiber Bragg gratings, fiber lasers, mode-locked lasers.**

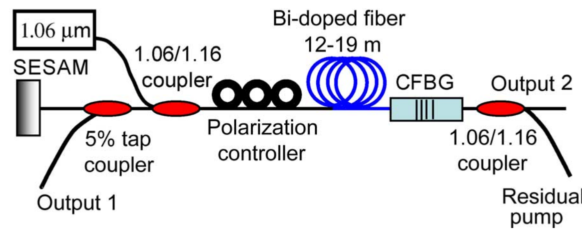

Fig. 1. Bi-doped all-fiber laser setup. The self-starting mode-locked operation was initiated by an InGaAsN-based SESAM. The soliton regime was provided by a CFBG.

I. Introduction

AMONG different techniques for dispersion compensation implemented in ultrashort-pulse fiber lasers, those based on fiber technology are most attractive because they preserve the low-loss and compact characteristics of an all-fiber cavity. However, recently demonstrated dispersion compensators based on photonic crystal and photonic bandgap fiber bring additional losses to the laser cavity due to the distinctive mode mismatch with standard single-mode fibers [1], [2]. Dispersion compensation using chirped fiber Bragg grating (CFBG) is another attractive method that benefits from the flexible and mature technology used for inscription of the gratings in optical fibers. CFBGs have been used to compensate the fiber dispersion or to produce positively chirped pulses in Yb-doped mode-locked fiber lasers at 1 μm [3]–[6].

Recent work in the field of gain fibers has led to the demonstration of active fibers with gain at 1100- to 1400-nm wavelength range by using Bi–ion as dopant [7], [8]. Continuous-wave Bi-doped fiber lasers have been demonstrated to deliver output powers with watt-level [9], [10]. The development of mode-locked Bi-fiber lasers has, however, remained hindered due to the relatively low value of the gain coefficient in the fiber, rendering a long-length cavity to achieve the sufficient gain. Preliminary investigations of pulse generation in a mode-locked Bi-doped fiber laser operating with net normal cavity dispersion regime without dispersion compensation led to the generation of large pedestal pulses with a duration of ∼50 ps [11].

In this letter, we report the first demonstration of a Bi-doped all-fiber laser with dispersion compensation provided by a CFBG. The length of the Bi-doped fibers required to generate sufficient gain was ∼15 m resulting in a large cavity dispersion that was balanced by the CFBG in order to exploit the soliton pulse shaping. The compact and low-loss all-fiber laser demonstrated in this study delivers 1.9-ps pulses at a fundamental repetition rate of ∼6 MHz and a wavelength of ∼1165 nm. We also demonstrate harmonic mode-locking, which enables us to increase the pulse repetition rate. The laser could operate in mode-locking regime with a repetition rate of up to 100.6 MHz corresponding to 16th harmonic of the cavity frequency. This value is one order of magnitude higher than the highest repetition rate reported previously for mode-locked Bi-lasers.

II. Experimental Details and Results

The experimental setup of the Bi-doped all-fiber laser is shown in Fig. 1. The linear cavity laser comprised Bi-doped fiber with ∼1.2-dB/m absorption at 1062 nm pumped with a single-mode Yb-fiber system through a 1062/1165-nm dichroic fiber coupler. A butt-coupled semiconductor saturable absorber mirror (SESAM) acting as a cavity end reflector was used for self-starting passive mode-locking. The opposite end of the cavity was terminated by a CFBG, coupling 10% of the signal to the output. A 5% fiber tap splitter was used for characterization purposes. A polarization controller was used to optimize the laser operation. A pump-blocking fiber coupler was spliced to the output of the laser to separate the residual pump and the signal light.

The Bi-doped silica fiber was drawn from a preform synthesized by the surface-plasma chemical vapor deposition method

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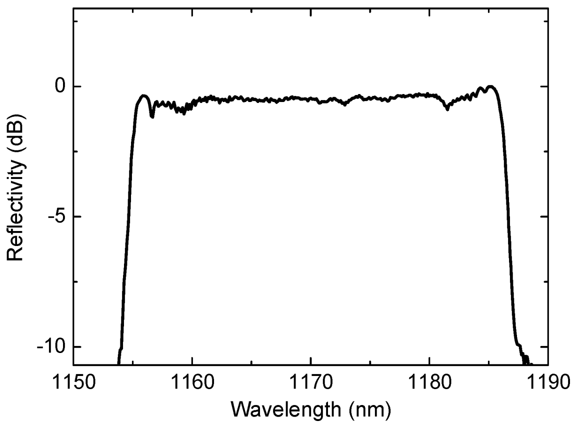

Fig. 2. Reflectivity response of the CFBG. The center wavelength is 1170 nm and the reflectivity is ∼90%.

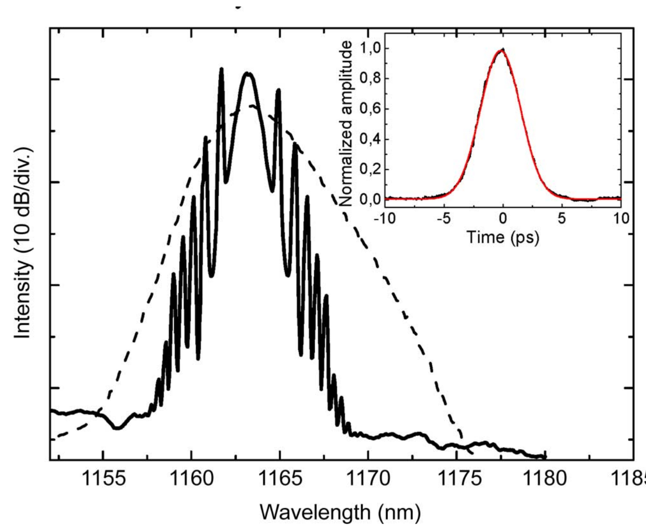

Fig. 3. Spectrum and autocorrelation (inset) of the pulses generated by the fiber oscillator with the CFBG as a dispersion compensator. The red line in the inset is the Sech^2-fitting giving the pulsewidth of ∼1.9 ps. The total cavity length was ∼21 m. Optical spectrum of the laser without dispersion compensation is shown by the dashed line.

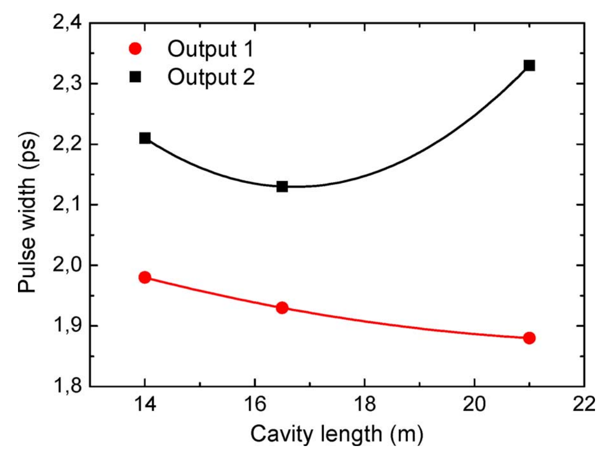

Fig. 4. Measured pulsewidth for different cavity lengths at different cavity outputs. Solid lines are the fittings.

under oxygen deficiency. The core glass was composed of 97 mol% of SiO_2 and 3 mol% of Al_2O_3. The Bi concentration in the core glass was $\sim 3 \cdot 10^{18}$ cm^{-3}. The glass composition and the bismuth concentration were determined by means of X-ray microprobe analysis. The fiber had an outer diameter of 125 μm, a core diameter of 8.4 μm, a core/cladding refractive index difference of $\Delta n = 5.5 \cdot 10^{-3}$, and a cutoff wavelength of ∼1100 nm [12]. The dispersion of the fiber at the wavelength of 1165 nm was calculated to be $\sim -0.013\ \mathrm{ps/(nm \cdot m)}$. The splice loss between the gain and a standard single-mode fiber was ∼0.3 dB.

The InGaAsN-based SESAM was grown by solid-source molecular beam epitaxy. The absorber section consisting of four InGaAsN quantum wells with a width of 6 nm was grown on the top of a 24.5 pair GaAs–AlAs distributed Bragg reflector (DBR). The DBR's stopband had a bandwidth of ∼150 nm and a center wavelength of ∼1140 nm. The absorption recovery time of the SESAM was measured to be ∼2 ps.

The CFBG was imprinted into the core of an H_2-loaded single-mode fiber using a phase-mask technique [13], [14]. The fiber was exposed to 248-nm ultraviolet light from a KrF excimer laser through a phase mask with a length of 10 mm using a beam scanning technique. Optimization of the scanning and writing parameters allowed for a broadband and flat reflection response of the CFBG to be achieved. The reflectivity of the CFBG ensuring the optimal feedback to the cavity and adequate output coupling was found to be ∼90%. The bandwidth of the grating ranged from 1155 to 1186 nm, as seen in Fig. 2. The grating dispersion was estimated to be ∼3.0 ps/nm using the soliton sidebands in the mode-locked pulse spectrum [15].

Mode-locking experiments were performed with different lengths of doped fiber. First a Bi-doped fiber with a length of ∼19 m was used; the overall cavity length was ∼21 m. The corresponding autocorrelation trace and the optical spectrum measured at Output 1 are shown in Fig. 3. The laser generated low-noise pulses of ∼1.9-ps duration (full-width at half-maximum) with Kelly spectral sidebands indicating the operation in the soliton regime. The spectral width and the calculated time-bandwidth product of the pulses were 0.95 nm and 0.40, respectively. The effect of the cavity length on the pulse duration at Outputs 1 and 2 is illustrated in Fig. 4. While the pulse duration decreased gradually with an increase in the fiber length at the SESAM end, it started to increase for cavity lengths over ∼18–20 m at locations near the CFBG. The changes in the pulsewidth were expected due to strong temporal and spectral pulse reshaping in a long dispersion-managed fiber laser cavity [5], [16]. Particularly, the pulses were slightly down-chirped at the SESAM position, up-chirped before the CFBG, and down-chirped after reflection from the CFBG, as derived from the pulsewidth and time-bandwidth product observed at different cavity locations. The time-bandwidth product at Output 2 ranged from 0.5 to 0.6 depending on the cavity length. The threshold pump powers for the self-start of the mode-locking were ∼400, ∼350, and ∼300 mW for the cavity lengths of 14, 16.5, and 21 m, respectively. The maximum average output power was found to increase from 4 to 6 mW for 850 mW of launched pump power when the cavity length was increased from 14 to 21 m.

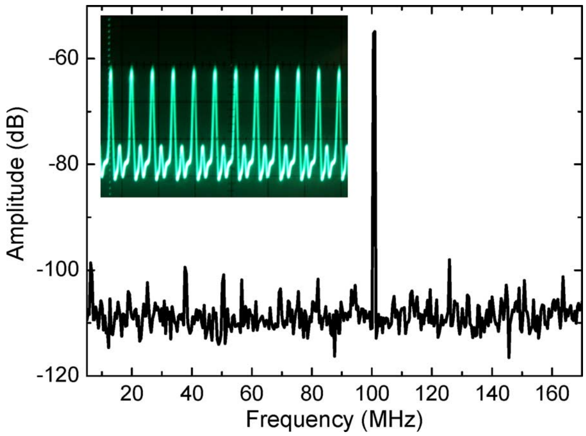

Fig. 5. Radio-frequency spectrum of the 16th harmonic frequency. The inset shows an oscilloscope picture of the pulse train at a repetition rate of 100.6 MHz.

The large net anomalous cavity dispersion promoted soliton breakup and allowed multiple soliton pulses to be formed. For certain positions of the polarization controller, the Bi-fiber laser operated with multiple soliton pulses having equal temporal spacing, i.e., highly ordered harmonic mode-locking [17]. After a build-up of the mode-locking, the soliton pulses, first randomly ordered or bunched, were transformed into a highly uniform periodic pulse train, demonstrating a strong repulsing force in the cavity [17]. The ordered mode-locking with harmonic number determined by the pump power was observed to be an inherent characteristic of the steady-state pulse regime. As a consequence, the repetition rate could be tuned from 6.3 MHz up to 100.6 MHz (corresponding to 16th harmonic of the cavity frequency) by varying the pump power. A radio-frequency spectrum of the 16th harmonic frequency is shown in Fig. 5. As can be seen, the adjacent modes are suppressed by more than 45 dB indicating the strong soliton pulse self-ordering effect in the cavity [17].

Mode-locked operation was also investigated without dispersion compensation by replacing the CFBG with a broadband fiber loop mirror having a $\sim$90% reflectivity at the laser wavelength. The recorded optical spectrum is shown in Fig. 3 (the dashed line). Without dispersion compensation, the laser operated only with a single pulse in the cavity having a large pulse pedestal that exceeded the autocorrelation scanning range of $\sim$200 ps.

III. Conclusion

We have reported a mode-locked Bi-doped all-fiber laser delivering 1.9-ps pulses. The dispersion compensation based on high-performance CFBG technology enabled laser operation in the soliton regime with a long-length cavity, typical for Bi-fibers with moderate gain. By taking advantage of harmonic mode-locking and soliton self-ordering mechanism, the repetition rate of the laser could be increased up to 100.6 MHz corresponding to a 16th harmonic fundamental cavity frequency.

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