Injection-Seeded Actively Mode-locked Erbium-Doped Fiber Ring Laser for Frequency Measurement in Telecommunication Band

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Received January 5, 2009; accepted February 13, 2009; published March 31, 2009

Abstract— In this paper the mode-locking of an erbium-doped fiber ring laser with frequency shifted feedback is described. We use the configuration with an acousto-optical modulator inserted in the laser cavity that produces 1.7 ps pulses with a 40 MHz repetition frequency. The corresponding optical frequency comb has a bandwidth of more than 10 nm, centered at 1558 nm. The laser operates with external injection from a DFB telecommunication laser diode which can be used for controlling the offset frequency of an optical comb. To our knowledge, this is the first demonstration of external injection of a mode-locked fiber laser using a telecommunication laser diode.

The developments of mode-locked lasers have been a huge research field in the last years. Erbium-doped fiber lasers are especially interesting. They have numerous advantages (e.g. wide gain bandwidth, narrow linewidth, reliability) and have found applications in many fields ranging from metrology to telecommunications[1]. Among several mode-locking techniques Frequency Shifted Feedback (FSF) lasers have always been mentioned as potential light sources for applications in fiber optic gyroscopes, device characterization, metrology, optical reflectometry, frequency measurements, high resolution spectroscopy, imaging and medical diagnosis. A complete description of these lasers can be found in [2]. They can be used for widely tunable operation [3,4] as well as in the case of high power Yb fiber lasers [5]. The application of FSF mode-locked lasers in frequency measurements requires their absolute stabilization. Ryu *et al.* have presented the injection seeding of an optical frequency comb (OFC) with an external cavity diode laser [6]. This technique was previously demonstrated in the case of multi-wavelength sources [7] and Q-switched lasers [8]. Ryu *et al.* have shown that by using an acousto-optical modulator (AOM) a 1.8 THz wide OFC can be generated and the frequency of its modes can be controlled by an external laser injected into the cavity.

In this paper we propose active mode-locking of an erbium-doped fiber ring laser using an acousto-optic modulator. The all-fiber polarization independent configuration of our laser makes it stable, reliable and resistant to fiber bending, squeezing, etc. The injection seeding of a telecommunication DFB laser diode (LD) can be used to stabilize the offset frequency of the comb. Our laser produces an optical frequency comb more than 10 nm wide, with a 41.5 MHz repetition frequency and the average output power of 4.9 mW.

Figure 1 shows the configuration of our mode-locked laser. The ring-resonator includes: a gain section, polarization-independent isolator, output coupler (90:10) and acousto-optical modulator. The modulator is driven by a RF generator (HP 8648, 21 dBm output power). The output from the pumping source (a 980 nm laser diode, 200mW output power) is coupled into the ring resonator through a WDM coupler. We used 2 meters of highly doped erbium doped fiber (HD EDF) as a gain medium (unpumped absorption of 80 dB/m at 1530 nm). The AOM that we used had fixed collimators and was designed to be driven with a 40 MHz signal. Nevertheless, we could change modulation frequency from 37 to 43 MHz to adjust it to a free spectral range of the laser (Figure 2 shows how losses introduced by the AOM depend on modulation frequency). A polarization independent isolator was used to guarantee unidirectional

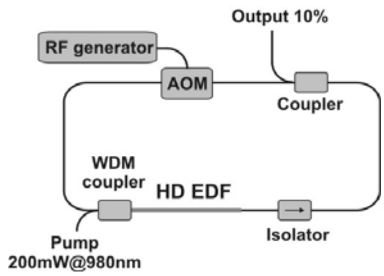

Fig. 1. Configuration of the AOM mode-locked fiber ring laser

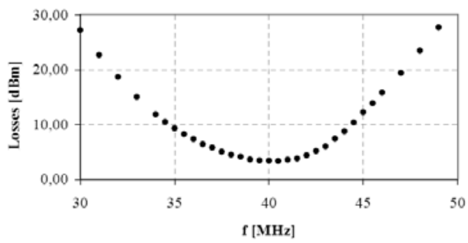

Fig. 2. Characteristic of the AOM – losses vs. modulation frequency

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operation. The fourth leg of the output coupler can be used for injection-seeding with a laser diode.

Our laser has several advantages. It is self-starting and all-fiber configuration. In comparison with the setup presented in [5] our laser does not have any polarization depended elements. No polarization adjustment is necessary and the laser is immune to fiber touching, bending etc.

Figure 3 shows the RF spectrum of the beating signal observed with a 40 GHz photodiode and a 10 GHz spectrum analyzer. We can see sharp frequency components at the multiples of the fundamental cavity repetition rate (41.5 MHz). The autocorrelation trace and optical spectrum are shown in Figure 4. Pulse autocorrelation was recorded with a two-photon absorption autocorrelator. Pulse duration was measured to be 1.7 ps (assuming the Gaussian shape). Measured average output power was 4.9 mW.

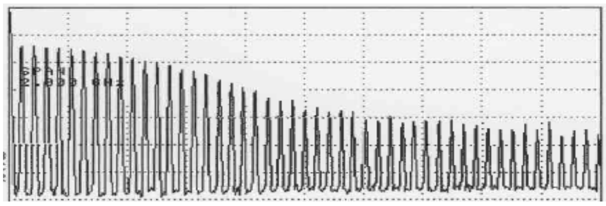

Fig. 3. RF spectrum of the OFC beating signal (200 MHz/div, 10 dB/div)

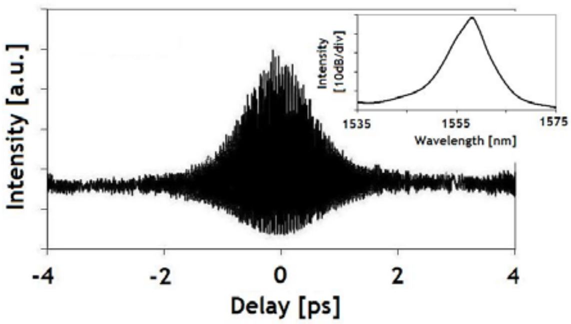

Fig. 4. Pulse autocorrelation trace and its optical spectrum

The optical spectrum has a 3dB bandwidth of 2.1 nm. However, we have to emphasize that the useful bandwidth is much wider. We are able to obtain a clear beating signal between an OFC and a telecommunication laser diode (1.5 MHZ linewidth) even though the laser diode operates at 1553 nm, where the comb lines are more than 20 dB below the peak of the OFC (Figure 5 and 6 show the setup configuration and results, respectively). Even if the beating signal is weak the S/N ratio can be increased by optical filtering. The useful bandwidth of an optical comb (the bandwidth where a beating signal with a laser diode can be still obtained) is 12 nm.

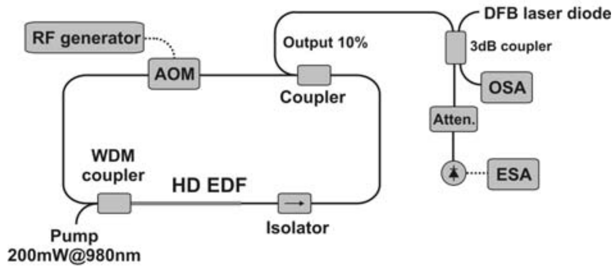

Fig. 5. Setup for measuring the beating signal between an OFC and a DFB laser diode (OSA – optical spectrum analyzer, ESA – electrical spectrum analyzer, Atten. – attenuator)

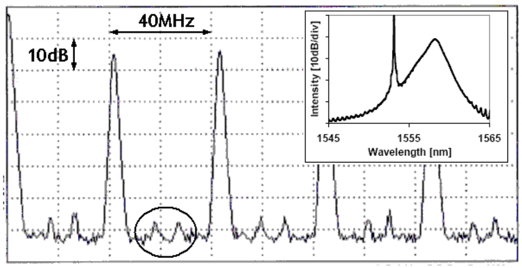

Fig. 6. RF spectrum and optical spectrum (inset). Beating signal between comb lines and a DFB laser diode are shown

As mentioned, Ryu *et al.* [5] have shown that an external cavity diode laser can be used for the external seeding of an optical comb. In our experiment we used a typical telecommunication DFB diode for the injection. The linewidth of the diode was 1.5 MHz, the output power was 10 mW and the linewidth was 1553 nm. Because we used a fourth leg of the output coupler for external seeding, only 1 mW of the laser diode power was injected into the laser cavity. Figure 7 shows the configuration of the laser and its optical spectrum. The RF spectrum of the beating signal with and without injection seeding is shown in Figure 8. What we can observe on the RF spectrum is the beating of comb lines. When an LD is injected we also see the beating between the LD and OFC modes. We can observe the broadening of all frequency components in the RF spectrum because the second signal dominates due to a relatively wide linewidth of the laser diode (1.5 MHz). Both signals cover each other because the injected laser diode determines the frequency of one of the optical comb lines thus it controls the absolute frequency of the comb (offset frequency). It is interesting to compare the results shown in Figure 6 and 8. In both cases the laser diode power that reaches the photodetector is similar. However, when an LD is not injected into the laser cavity, an OFC and a laser diode operate independently. The beating signal between an LD and an OFC moves between the beating signals of the comb components (Figure 6). When part of the LD light is injected into an OFC, one of the comb lines is tied with a laser diode which results in the RF spectrum shown in Figure 8.

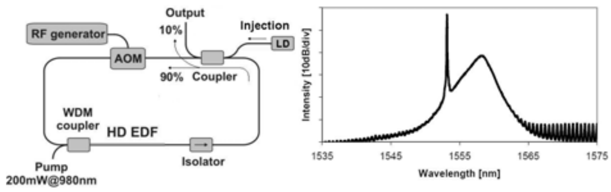

Fig. 7. Configuration of an injection-seeded actively mode-locked laser and its optical spectrum

Fig. 8. RF spectrum of the beating signal with and without DFB LD injection (upper and lower trace respectively, 40MHz/div, 10dB/div)

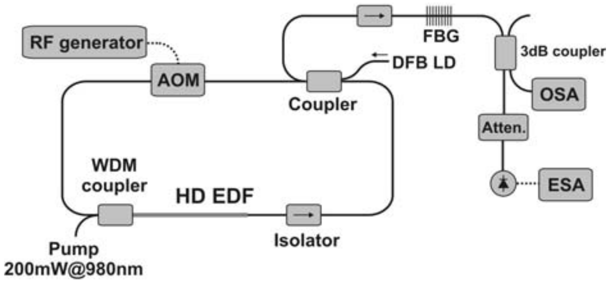

Fig. 9. Setup for measuring the beating signal of comb lines when the injected DFB LD is filtered by fiber Bragg grating (FBG)

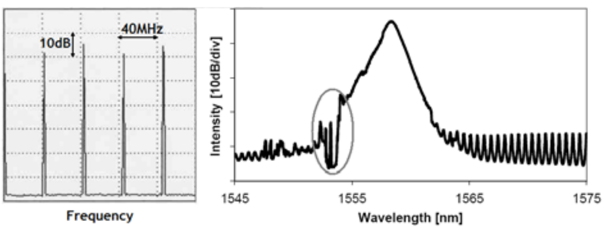

Fig. 10. RF spectrum of the beating signal (left) and optical spectrum (right) of the injection-seeded OFC. Injected LD was filtered using fiber Bragg grating

We have also recorded the RF spectrum of an externally seeded OFC when the injected laser diode was filtered by fiber Bragg grating (Figure 9). We wanted to be sure that injection from the laser diode did not influence the linewidth of comb lines (which is, typically, a few orders narrower than the linewidth of a DFB laser diode). The results are shown in Figure 10. As can be seen, the linewidth of comb lines was not affected by the injected laser diode.

In this paper we have proposed an injection-seeded actively mode-locked fiber laser with frequency shifted feedback. We have obtained stable 1.7 ps pulses with a 41.5 MHz repetition frequency and 4.9 mW average output power. The effective bandwidth of an optical frequency comb is 12 nm. Within this bandwidth we have been able to obtain a beating signal between comb components and a typical telecommunication DFB laser diode. We have also shown that injection-seeding of the laser diode determines the frequency of a single OFC component. In this way we have been able to control the offset frequency of the whole OFC. We have also shown that the injection of an LD does not influence the linewidth of the OFC lines. The proposed laser has an all-fiber configuration, the mode-locking is self-starting and it does not require any polarization adjustment. It is stable, reliable and insensitive, for instance, to fiber bending and touching.

In future work we would like to stabilize an LD to the absorption line of acetylene (C2H2) or hydrogen cyanide (HCN). An OFC stabilized in such a way can be used as a low-cost source for frequency metrology and as a frequency standard in the telecommunication band.

The presented work was supported by the Polish Ministry of Science, under Grant N51502932/2079.

References

[1] J. Ye, S.T. Cundiff "Femtosecond Optical Frequency Comb: Principle, Operation, and Applications", 2005 Springer Science + Business Media, Inc. Boston.

[2] H. Sabert, E. Brinkmeyer "Pulse Generation in Fiber Lasers with Frequency Shifted Feedback", *J. Lightwave Technol.*, vol. 12, pp. 1360-1368, 1994.

[3] S.U. Alam, A.B. Grudinin "Tunable picosecond frequency-shifted feedback fiber laser at 1550 nm" *IEEE Photon. Technol. Lett.*, vol. 16, pp. 2012-2014, 2004.

[4] Michal P. Nikodem, Ewelina Kluzniak, and Krzysztof Abramski, "Wavelength tunability and pulse duration control in frequency shifted feedback Er-doped fiber lasers," *Opt. Express* 17, 3299-3304 (2009).

[5] A.M. Heidt, J.P. Burger, J.-N. Maran, and N. Traynor, "High power and high energy ultrashort pulse generation with a frequency shifted feedback fiber laser," *Opt. Express* 15, 15892-15897 (2007).

[6] H.Y. Ryu, H.S. Moon, H.S. Suh "Optical frequency comb generator based on actively mode-locked fiber ring laser using an acousto-optic modulator with injection-seeding, *Opt. Express* 15, pp. 11396-11401, 2007.

[7] S. Bennett, B. Cai, E. Burr, O. Gough, A.J. Seeds "1.8-THz Bandwidth, Zero-Frequency Error, Tunable Optical Comb Generatorr for DWDM Applications", *IEEE Photon. Technol. Lett.*, vol. 11, pp. 551-553, 1999.

[8] P.D. Dragic "Injection-Seeded Q-Switched Fiber Ring Laser", *IEEE Photon. Technol. Lett.*, vol. 16, pp. 1822-1824, 2004.

