Dual-Wavelength 10-GHz Actively Mode-Locked Erbium Fiber Laser Incorporating Highly Nonlinear Fibers

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***Abstract*—We demonstrated a dual-wavelength actively mode-locked erbium-doped fiber ring laser with 0.8-nm wavelength spacing at a repetition rate of 10 GHz. A 1-km highly nonlinear fiber is introduced in the nonpolarization-maintaining cavity to suppress the gain competition of the homogeneously broadened gain medium in a self-driven manner. Output pulses at 1557.36 and 1558.17 nm are generated simultaneously. Amplitude fluctuations less than 0.45% and 1.7% of two wavelengths are measured. The corresponding timing jitters are less than 80 and 90 fs, respectively.**

***Index Terms*—Actively mode locking, fiber laser, inhomogeneous gain broadening, nonlinear fiber optics.**

I. Introduction

ACTIVELY mode-locked erbium-doped fiber lasers (ML-EDFLs) are very attractive for the generation of ultrashort optical pulses at multiple wavelengths with multiple gigabit per second repetition rate [1]. Compared with the compact, inhomogeneously gain broadened semiconductor-based multiwavelength (MW) laser source [2], EDFLs are competitive for the all-fiber structure and high pulse energy. Although the generation of ML ultrashort pulses of an EDFL is well known, there exist great challenges to apply the ML-EDFL to MW optical communications due to its stability and temporal-spectral properties [3].

Previously, various techniques to generate MW-ML-EDFL have been proposed [4]–[8]. Due to the homogeneously broadened gain property, many two- or four-wavelength EDFLs are developed with wavelength spacing larger than homogenous linewidth ($\sim$3.5 nm) to overcome gain competitions [3]–[5]. Although an MW-EDFL with 16 wavelengths has been presented by cooling an EDF to 77 K using liquid nitrogen [9], the increased complexity and cost make it impractical to many applications. Recently, many researchers employ the cavity birefringence [6] or intracavity chirped fiber Bragg gratings [7] to reduce the cross-gain saturation. Dual-wavelength ML-EDFL with 0.7-nm wavelength spacing has been demonstrated at a repetition rate of 2.6 GHz [8]. However, building a practical, stable MW-EDFL at high repetition rate with synchronized outputs is still a hard task.

Manuscript received April 12, 2005; revised August 14, 2005. This project was supported in part by the Open Fund of Key Laboratory of OCLT, Beijing University of Post and Telecommunications, MOE, China.

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Digital Object Identifier 10.1109/LPT.2005.859156

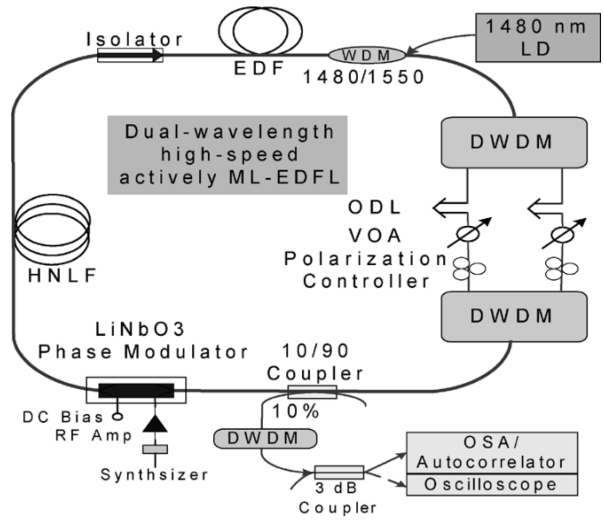

Fig. 1. Experimental setup. TOF: tunable optical filter.

In this letter, we propose a novel MW-ML-EDFL. Two wavelengths with 0.8-nm wavelength spacing anchored on ITU-T grids are ML at 10 GHz simultaneously. Instead of the complex temporal-multiplexing [7], [8], 1-km dispersion-shifted highly nonlinear fiber (HNLF) is incorporated in the ring cavity to suppress the gain competition using interchannel multiple four-wave mixing (FWM). The fiber nonlinearity is also used to improve the pulse stability. The dual-wavelength operation is achieved by utilizing a pair of dense wavelength-division multiplexers (DWDMs) and variable optical delay lines (ODLs). Although the same gain medium is shared in the nonpolarization-maintaining (non-PM) cavity, the improved pulses' qualities make this configuration promising for generating economic high speed MW-EDFL sources.

II. Dual-Wavelength ML-EDFL Configuration

The setup of the MW-ML-EDFL is shown in Fig. 1. It has a ring configuration containing a $LiNbO_3$ phase modulator driven by a 10-GHz radio-frequency (RF) synthesizer. The active element is a 7.66-m EDF (Er^{3+} concentration is 2000 ppm) pumped with a 90-mW 1480-nm laser diode. A polarization-independent isolator is used to assure unidirectional oscillation. The measured center wavelengths of DWDM are 1556.55, 1557.36, 1558.17, and 1558.98 nm, respectively. The 3-dB bandwidth is 0.58 nm and the extinction ratio is greater than 30 dB. The 1557.36 and 1558.17 nm are selected as lasing

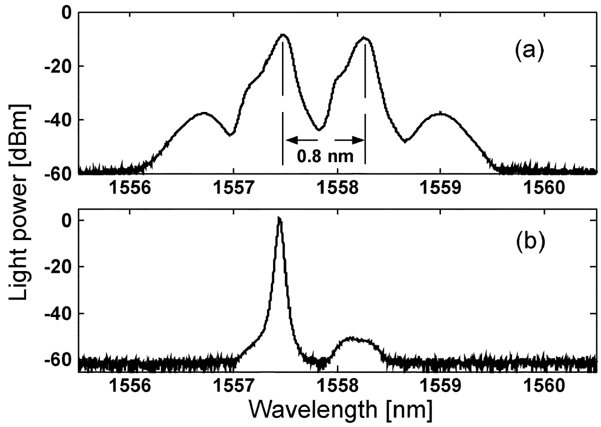

Fig. 2. Optical spectrum of dual-wavelength CW operation. (a) With HNLF and (b) without HNLF. Resolution is 0.01 nm.

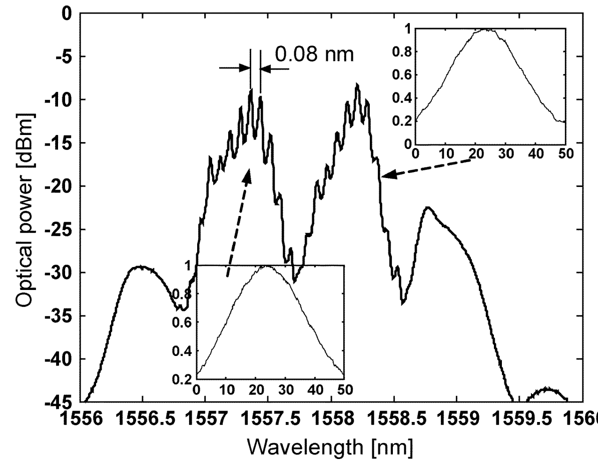

Fig. 3. Optical spectrum of dual-wavelength ML-EDFL laser output. The insets are pulse autocorrelation traces.

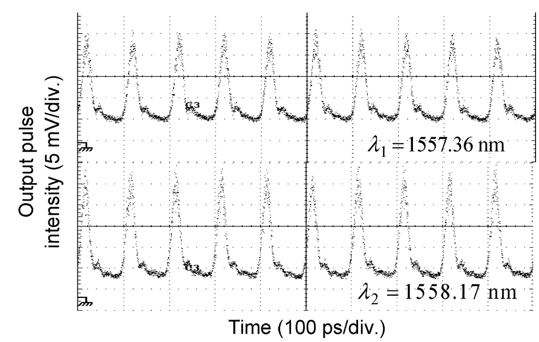

Fig. 4. Dual-wavelength ML-EDFL 10-GHz pulses at 1557.36 (upper trace) and 1558.17 nm (lower trace).

wavelengths and each channel is followed by an adjustable ODL, a variable optical attenuator (VOA) and a polarization controller. The delay lines are tuned to ensure different wavelength pulses arrive the modulator at the same time. The pulses are taped and monitored from a 10/90 fused coupler.

In experiments, although the VOA can be carefully adjusted to balance the net gain/loss of each wavelength, the gain competition between the lasing wavelengths deteriorates the mode-locking performance significantly. We add 1-km HNLF in the cavity to suppress the cross-gain saturation effect by using the interchannel FWM. The zero-dispersion wavelength (ZDW) of the HNLF is 1559 nm and the dispersion slope is 0.023 ps/nm^2/km. The phase-matching condition for FWM is readily satisfied for the four channels of DWDM because its channel wavelengths are quite close to ZDW. The HNLF has an effective area of 10.3 μm^2 and a nonlinear coefficient of 10 W$^{-1}\cdot$ km^{-1}. The typical loss is less than 0.75 dB/km for 1550 nm and the cutoff wavelength is below than 1290 nm. The net dispersion of cavity is 0.41 ps/nm.

III. Experimental Results

We first implement the continuous-wave (CW) operation of the ring EDFL. As shown in Fig. 2(a), two wavelengths at 1557.36 and 1558.17 nm appear simultaneously with HNLF by tuning the VOA appropriately. Both lasing spectrum are broadened due to the parametric process [10]. Two sidebands are stimulated due to the phase-matched FWM and they are exactly corresponds to the other two wavelengths of DWDM. However, Fig. 2(b) shows that the cavity without HNLF can only support one wavelength 1557.36-nm lasing with the same VOA setting. It is then expected that the fiber nonlinearity can be used to release the strong gain competition and enhance the MW mode locking.

With 1-km HNLF, the fundamental repetition rate of the ring laser is around 195 kHz. The laser is then harmonically ML at 10.0189 GHz with 1557.36- and 1558.17-nm output simultaneously. The average laser output power at each wavelength is about 1 mW. The optical spectrum of the total two-wavelength output is shown in Fig. 3. The 10-GHz frequency combs are clearly shown.

Fig. 4 demonstrates corresponding time-domain 10-GHz pulses of two wavelengths that are recorded by a 45-GHz photodetector and a 50-GHz oscilloscope. Another DWDM is used after the output coupler to monitor different wavelengths. Although we have not implemented cavity stabilization scheme as with other lasers, the laser system can persist more than 1 h in the laboratory. Since pulse dropout in actively ML laser is mainly dependent on the intracavity pump power, we do not expect pulse dropouts. We measured the pulse dropout rate to be less than 10^{-10} by driving the laser at 10-GHz clock signal from pulse-pattern generator (Anritsu MP1763C). The missing pulses are examined with a bit-error-rate tester (Anritsu MP1764C). The results clearly indicate that pulses at two wavelengths within the homogenous linewidth of EDF can be harmonically ML successfully although all pulses overlap during the amplification. The autocorrelation traces of pulses are measured and plotted in the insets of Fig. 4. The pulsewidths (full-width at half-maximum) of 1557.36 and 1558.17 nm are 17.2 and 18.7 ps assuming Gaussian shape. The time-bandwidth products are 0.39 and 0.41, hence, our laser generates nearly transform-limited pulses.

It is well known that both timing jitter and amplitude fluctuation are key parameters for the ML fiber lasers used in high-speed systems [11]. For each wavelength, we measured its RF power spectrum of the first-order (10 GHz) and the second-order (20 GHz) harmonic to calculate the pulse energy fluctuation and timing jitter according to the Von der Linde method [11], [12]. Fig. 5 shows the first-order RF spectrum of two wavelengths. For both wavelengths, the supermode noise suppression is more than 60 dB over 1-MHz span at 10 GHz.

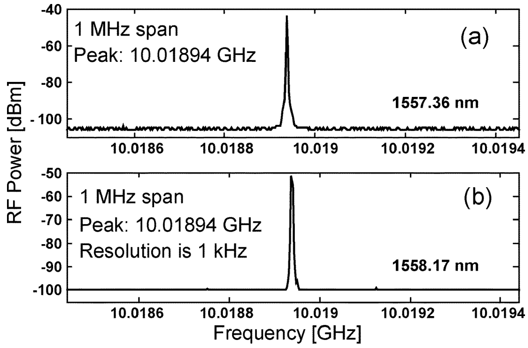

Fig. 5. RF power spectrum of output pulses. (a) 1557.36 nm. (b) 1558.17 nm.

We calculated that the amplitude fluctuation is 0.45% and the timing jitter is approximately 80 fs for 1557.36 nm. Similarly, for the 1558.17-nm output, the amplitude and timing jitter are 1.7% and 90 fs, respectively. The very high amplitude stability is quite remarkable although the fiber laser is ML at such a high harmonic.

IV. Discussions

We have achieved ultrastable dual-wavelength output pulse trains and we believe that the gain clamping effect in EDF are compensated by the parametric FWM between four channels of DWDM. The physical insights can be explained as follows. Two lasing signals with wavelengths λ_1 (1557.36 nm) and λ_2 (1558.17 nm) (corresponding to angular frequencies ω_1 and ω_2) can be formed by adjusting VOAs, and then are launched into the 1-km HNLF to act as pumps. Due to the high nonlinear coefficient and low dispersion (flat dispersion slope near ZDW), two Stokes sidebands at frequencies $\omega_3 = 2\omega_1 - \omega_2$ and $\omega_4 = 2\omega_2 - \omega_1$ are generated by two degenerative-FWM processes [10]. The two new wavelengths are exactly the other two side channels of DWDM. At the same time, a single nondegenerate FWM process occurs between four wavelengths (i.e., $\omega_1 + \omega_2 = \omega_3 + \omega_4$). As discussed and proved in [13], the multiple FWM processes hold an important unique property of self-stability for EDFL. Although the two degenerate FWM processes transfer energy from two central pumps to two sideband waves, there exists a power transfer between two pump waves which is different from the conventional coupled-mode models of nondegenerate FWM. Due to the power conservation, the power exchange between two pumps is three times more than that between two created sidebands. The energy flow transfers from higher power wave to lower power wave compensate the EDF gain competition in a self-driven manner. In our dual-wavelength laser, all wavelengths experience amplification in EDF. Because of the homogeneous gain broadening, one pump wavelength (let us say λ_1) is dominant and its power is greater than that of λ_2. However, after propagation along the HNLF, multiple FWM processes take place ($\omega_1 + \omega_2 = \omega_3 + \omega_4$, $\omega_4 + \omega_1 = 2\omega_2$, and $\omega_3 + \omega_2 = 2\omega_1$) and lead to power transfer from λ_1 to λ_2. The power transfer will continue during the propagation in HNLF. Therefore, interchannel FWM effectively alleviates the gain competition in the EDF and benefits the dual-wavelength mode locking.

Also, the use of HNLF and the DWDM spectral filtering are crucial to the output pulse stability. The 10-GHz frequency combs generated through actively mode-locking are close to the ZDW of HNLF and intrapulse FWM among these longitudinal modes is generated. New sidebands with 10-GHz spacing appear on the spectra as seen in Fig. 3. All sidebands are simultaneously phase-locked under nearly phase-matching condition and a stable mode locking with constant amplitude is achieved [14]. Furthermore, our proposed scheme can be extended to generate more wavelengths by choosing fiber nonlinearity, dispersion map, comb filter and high-power pump lasers to broaden the effective wavelength window for FWM and increase the ML channel number. The compact, highly nonlinear microstructured fiber can also be used to provide enough nonlinearity with reduced cavity length.

V. Conclusion

A novel self-stable dual-wavelength 10-GHz ML-EDFL with 0.8-nm wavelength spacing has been demonstrated in the non-PM ring cavity. The gain competition in homogenously broadened EDF is suppressed by using the interchannel multiple FWM in 1-km HNLF. Picosecond pulses at 1557.36 and 1558.17 nm were generated simultaneously and synchronously. No pulse dropouts were observed. The measured timing jitters of two wavelengths are 80 and 90 fs, and the corresponding amplitude fluctuations are estimated as 0.45% and 1.7%, respectively. Fiber nonlinearity plays an important role to improve the laser quality.

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