Optically Injected Rational-Harmonic Mode-Locking of Erbium-Doped Fiber Laser

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ABSTRACT

Harmonic and rational-harmonic mode-locking of erbium-doped fiber lasers (EDFLs) with wavelength tunability is achieved by seeding optical pulses from a gain-switched Fabry-Perot laser diode that is feedback-injection controlled with the slave EDFLs via optical circulator.

Keywords: optical pulse injection, harmonic, rational harmonic, mode-locking, erbium-doped fiber laser, feedback injection, wavelength tunable, gain-switching, Fabry-Perot laser diode

1. INTRODUCTION

Active mode-locking of erbium-doped fiber lasers (EDFLs) via optical pulse injection has currently caused considerable interests due to its capability in generation of high-repetition-rate picosecond optical pulse train for versatile applications [1]. The advantages of these mode-locked sources against the directly gain-switched laser diode sources include high peak power, short pulsewidth, narrow linewidth, and nearly transform-limited pulse shape [2]. Recently, novel mode-locking schemes using distributed feedback (DFB) or Fabry-Perot laser diode (FPLD) as mode-locker have also been demonstrated [3, 4] with repetition frequency up to 2 GHz [5, 6]. In comparison with the conventional mode-locking techniaue, the optical injection mode-locking has shown to exhibit lower super-mode noise, relatively high average output power, and better stability. To date, the pulse repetition frequency is limited by modulation bandwidth of FPLD at ~10 GHz when operating at fundamental or harmonic mode-locking condition. Nonetheless, the pulse repetition rate can further be increased up to 40 GHz or higher by employing rational harmonic mode-locking (RHML) technique. However, there are still some unknown properties of the EDFL mode-locked with a feedback-injected FPLD. In this paper, the characterizations of harmonic and rational harmonic mode-locked EDFLs using optical pulse injection via an intracavity gain-switched FPLD (GS-FPLD) are demonstrated. The effect of GS-FPLD driven frequency on the evolution of mode-locking process of EDFLs. The key parameters of the EDFL operated at harmonic and rational-harmonic mode-locking schemes such as pulsewidth, pulse amplitude, single-side band (SSB) phase noise and timing jitter are compared.

2. EXPERIMENTAL SETUP

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The experimental setup of the GS-FPLD mode-locked EDFL (ML-EDFL) is illustrated in Fig 1. A gain-switching system which consists of a RF synthesizer (HP 8648A), a power amplifier (with maximum power of 30 dBm), a comb generator (HP 33004A), and a DC current source is employed to drive the FPLD via a Bias-Tee. The 1.55-μm GS-FPLD operated at 20℃ with average power of 0.2 mW is employed as a master laser or an optical pulsed mode-locker, which injects into and feedback controlled concurrently by the close-loop, dual-directional pumped EDFA with maximum output power of 21 dBm via an optical circulator (OC). This generates an optical pulse-train with full-width-at-half-maximum (FWHM) of ranging from 30 ps to 60 ps at different frequencies. The output coupling ratio of the ML-EDFL is 35%. The OC in connection with a polarization controller (PC) is employed to couple the output of GS-FPLD into EDFA and part of the EDFL output into GS-FPLD. The pulsewidth and pulse amplitude of the EDFL are monitored by a digital sampling oscilloscope (HP 54750A, f_{3dB}>50 GHz) connecting with a high-speed photodetector (New Focus 1014, f_{3dB}>45 GHz). The single-sided band (SSB) phase noise of the GS-FPLD input and the ML-EDFL output pulses were determined by using a microwave spectrum analyzer (ROHDE & SCHWARZ FSEK 30, f_{3dB}>40 GHz) with resolution bandwidth of 1 Hz. The corresponding timing jitter of the optical pulses can be calculated from the SSB phase-noise-density spectrum of the optical pulse [7, 8].

3. RESULTS AND DISCUSSIONS

When the driven frequency of the GS-FPLD deviates from the harmonic frequency of the fundamental longitudinal mode of EDFL, the EDFL acts like a close-loop pulse amplifier in which the injected GS-FPLD pulse competes the gain with the survived ones in the EDFL loop. Such an unstable resonant-amplification process eventually leads to a broadened output pulse with numerous sidelobes of gradually attenuated amplitudes. As the driving frequency of the RF synthesizer approaches the harmonic of the fundamental frequency, the mode-locking process is initiated with increasing peak power and symmetrical pulse-shape. The stable optical pulses can thus be obtained via the fine adjustment on the polarization of the circulating light feedback into the GS-FPLD through the PC. By adjusting the frequency of GS-FPLD to fit the 141th harmonic (about 507.177 MHz) of fundamental mode, a perfect mode-locked pulse-train with sidelobe-free trailing edge can be obtained, as shown in Fig. 2. The output pulsewidth of the ML-EDFL is about 50 ps, which is comparable to that of typical EDFL operating at pulsed mode-locking scheme but still far larger than that of the injected pulses generated by the GS-FPLD. The pulse amplitude of the EDFL (~21 mW) is almost two orders of magnitude than that of the injected pulse. The broadening in optical pulses from 30 to 50 ps is mainly attributed to the inevitable dispersion of pulse in such a long fiber ring cavity, which can further be compressed via standard fiber- or grating-based techniques. Theoretically, the laser cavity loss is modulated at a frequency of $p\Delta f$ for harmonic mode locking, where Δf is the free spectral range (FSR) of the laser cavity and p is an integer. This generates a pulse-train with the repetition rate equivalent to the modulation frequency. On the other hand, an optical pulse train with repetition rate of $(np\pm1)\Delta f$ can also be produced by RHML the EDFL at modulation frequency of $(p\pm1/n)\Delta f$, where n is another integer that denotes the multiplication factor. This alternatively generates a pulse-train with a repetition rate significantly higher than the modulation frequency. It is seen in experiment that if we slightly detune the frequency to fit the RHML condition, the high-repetition-rate optical pulses at double modulation-frequency can be generated from the EDFL. The repetition rate of the RHML pulse-train is the same as the 2^{nd} harmonic of the fundamental frequency of the EDFL. However, we have observed the difficulty in obtaining RHML pulses with the multiplication factor n of greater than 3. It is subsequently realized that a stronger pulse-to-pulse amplitude fluctuation caused by the unmatched harmonics of the modulation frequency could be involved into the RHML process under the case of n>3 [2]. Such a fluctuation can only be eliminated only by using special pulse amplitude equalization techniques [1, 9] that relies on optical filters or optical nonlinearities. At present, the minimum timing jitters of the GS-FPLD and harmonic mode-locked EDFL controlled by using an ultralow-phase-noise frequency synthesizer are 318 and 717 fs (obtaining by integrating the SSB phase noise at offset frequencies of ranging from DC to 100 Hz).

Figure 3 plots the output pulsewidths of GS-FPLD and ML-EDFL as a function of repetition frequency. The relationship between the injection and mode-locked pulsewidths can be obtained by slightly adapting the theoretical formula of active mode-locked laser, [8, 9]

$$\Delta\tau = 0.445 \cdot \left(\frac{g_0}{a_m}\right)^{1/4} \left(\frac{1}{f_m \cdot \Delta\nu}\right)^{1/2}, \tag{2}$$

where $\Delta\tau$ is the mode-locked pulsewidth, g_o is the linear gain coefficient, α_m is the amplitude modulation coefficient, f_m is the modulation frequency, and $\Delta\nu$ is the transition linewidth. In order to use this equation in our experiments, we set that g_o is directly proportional to the injection optical pulse amplitude, α_m as a constant, $\Delta\nu$ is inverse proportional to the pulsewidth of GS-FPLD, and f_m is the repetition frequency of optical pulses. In comparison, the trend of experimental results is in good agreement with that of theoretical simulations. The measuring errors are less than 5%. Under current mode-locking scheme, the wavelength-tuning of EDFL can easily be demonstrated by controlling the operation temperature of the GS-FPLD. For example, the output of the temperature-dependent wavelength of the FPLD is shown in Fig. 5. The wavelength tuning was obtained by changing the GS-FPLD temperature from 20℃ to 45℃ but maintain its bias current at just below threshold (I_{th} from 16 to 20 mA). Under this condition, the wavelength of output of the EDFL linearly increases from 1553 to 1557 nm as the FPLD temperature increases. This corresponds to a wavelength-tuning slope of about 0.16 nm/℃.

4. CONCLUSIONS

In conclusion, we investigated in detail the characterization of actively ML-EDFL induced by injecting pulses of GS-FPLD. We show many features of output pulses are dominated by the injection of GSLD pulses and use the active mode-locked laser theoretic values to analyze the experimental results. Just like the general active mode-locking laser system, the correlated phase noise is induced from electrical signal which drives Mach-Zehnder modulator. Therefore, the quality of GSLD injection pulses is also the major factor of the correlated phase noise to degrade the ML-EDFL performance.

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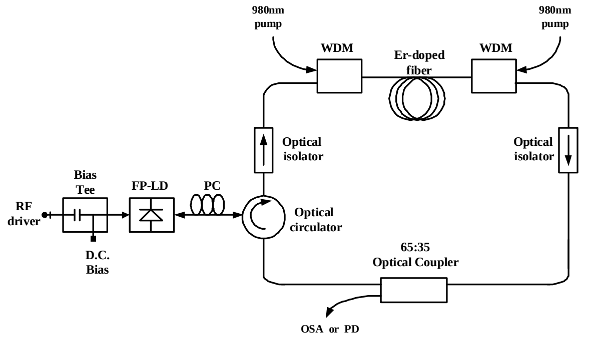

Fig. 1 The experimental setup of harmonic and rational-harmonic mode-locked EDFL via optically feedback injection controlled laser diode under gain-switching mode .

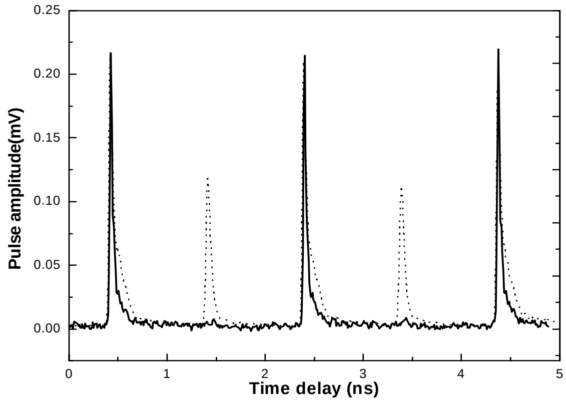

Fig. 2 Optical pulsetrains of EDFL under harmonic (solid line) and rational-harmonic (dotted line) mode-locked schemes.

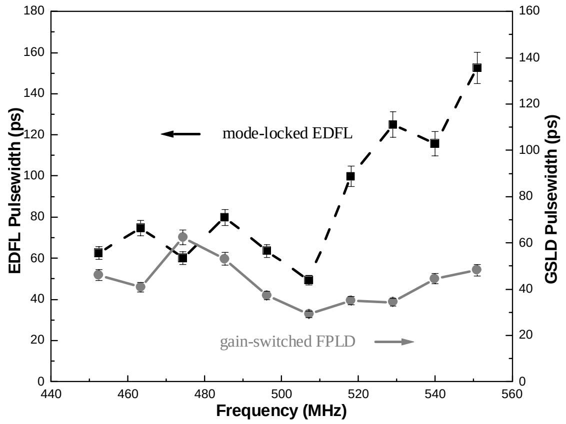

Fig. 3 The pulsewidth of injection GSLD and mode-locked EDFL as a function of harmonic frequencies.

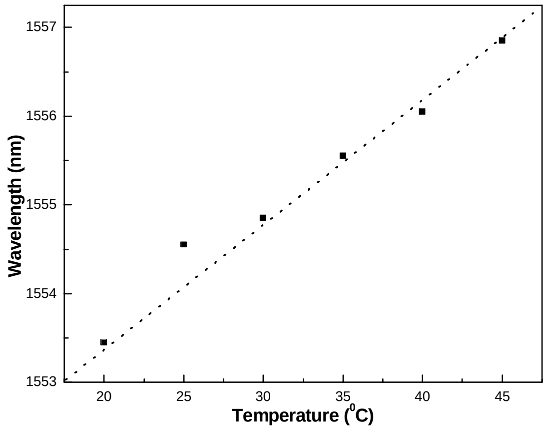

Fig. 4 The wavelength tunability of EDFL controlled by tuning temperature of GSLD.