Rational Harmonic Mode-Locking of Erbium-Doped Fiber Laser at 40 GHz Using a Loss-Modulated Fabry–Pérot Laser Diode

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***Abstract*—Rational harmonic mode-locking of an Erbium-doped fiber ring laser (EDFL) at repetition frequency of 40 GHz is demonstrated by using a purely loss-modulated Fabry–Pérot laser diode (FPLD) at 1 GHz. The FPLD is neither lasing nor gain-switching, which requires a threshold modulation power of 18 dBm to initiate harmonic mode-locking of the EDFL. After chirp compensation, the nearly transform-limited pulsewidth and spectral linewidth of 3 ps and 1.3 nm are obtained at repetition frequency of 40 GHz, which corresponds to a time-bandwidth product of 0.31. The EDFL gradually evolves from harmonic mode-locking to injection-locking mode as the FPLD changes from loss-modulation to gain-switching mode by increasing its dc driving current.**

***Index Terms*—Erbium-doped fiber laser (EDFL), Fabry–Pérot laser diode (FPLD), harmonic mode-locking, injection-locking, loss modulation, rational harmonic mode-locking.**

I. Introduction

SHORT-PULSED erbium-doped fiber lasers (EDFLs) have been comprehensively investigated to generate high-bit-rate (>10 GHz) optical carriers for versatile applications such as wavelength-division-multiplexing (WDM)/time-division-multiplexing transmission in fiber-optic communication networks, sampling and switching in photonic network systems [1], [2]. Harmonic and rational harmonic active mode-locking schemes are currently the main technologies to meet these demands. Typical mode lockers to achieve loss modulation of the EDFL cavity are a Mach-Zehnder integrated-optic modulator [3], a semiconductor multiple quantum-well electroabsorption modulator [4], and a gain-switched Fabry–Pérot laser diode (FPLD) [5], etc. To overcome the difficulty of gain-depletion modulation in the EDFL with extremely long carrier lifetime (~10 ms), versatile repetition frequency multiplication schemes have recently emerged, such as the fiber dispersion induced pulse splitting [6], the intracavity fiber Fabry–Pérot filter (FFPF)-based high-repetitive pulse extraction [7], and the optical pulse-injection-induced frequency multiplication [8], [9], etc. In particular, the harmonic mode-locking of EDFL can also be demonstrated using cross-gain-modulated semiconductor optical amplifier [10] or directly modulated laser diode [11]. In this work, the rational harmonic mode-locking of EDFL using a purely loss-modulated FPLD are investigated. The FPLD can be driving at either loss-modulation or gain-switching via the adjustment of dc current and radio-frequency (RF) power. The evolution of the EDFL lasing mechanism from mode-locking to injection-locking is observed as the FPLD changes from loss-modulation to gain-switching mode. The 40-GHz rational harmonic mode-locked EDFL pulse train generated using a loss-modulated FPLD at repetition frequency of 1 GHz is characterized.

Manuscript received July 25, 2003; revised April 27, 2004. This work was supported in part by the National Science Council under Grant NSC92-2215-E-009-028.

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Digital Object Identifier 10.1109/LPT.2004.831057

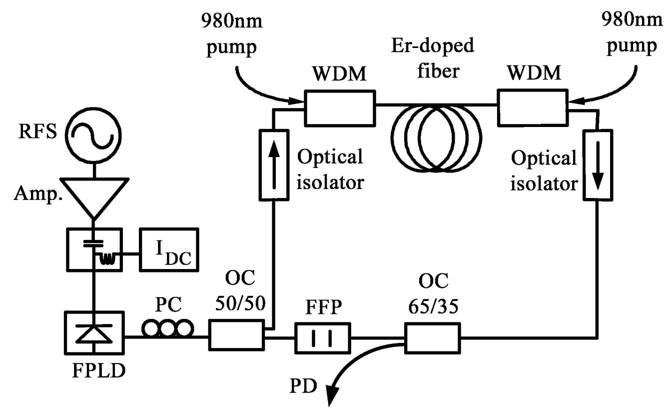

Fig. 1. Embodiment of an FPLD mode-locked EDFL. Amp: RF power amplifier. PD: high-speed photodetector. RFS: radio-frequency synthesizer. WDM: WDM coupler.

II. Principle and Experimental

Fig. 1 plots the setup of an EDFL rational harmonic mode-locked using a purely loss-modulated FPLD. An Erbium-doped fiber amplifier (EDFA) with maximum gain of 17 dB is connecting with a 1560-nm FPLD via a 50% optical coupler (OC) to construct an EDFL ring cavity. A polarization controller (PC) before the FPLD is used to adjust the intensity of the injection light. There is no direct feedback from the EDFA output to the EDFA input. A 35% OC is employed to monitor the EDFL output. The EDFL cavity length is 50 m, corresponding to a fundamental cavity frequency (f_c) of around 4.48 MHz. The FPLD exhibits a threshold current and a longitudinal mode spacing of 13 mA and 1.2 nm, respectively. To achieve pure loss-modulation instead of lasing, the FPLD is un-dc-biased but modulated using an RF synthesizer (Rohde & Schwarz, SML01) in connection with a power amplifier, which generates RF power from 0 to 30 dBm. To achieve perfectly gain-switched lasing,

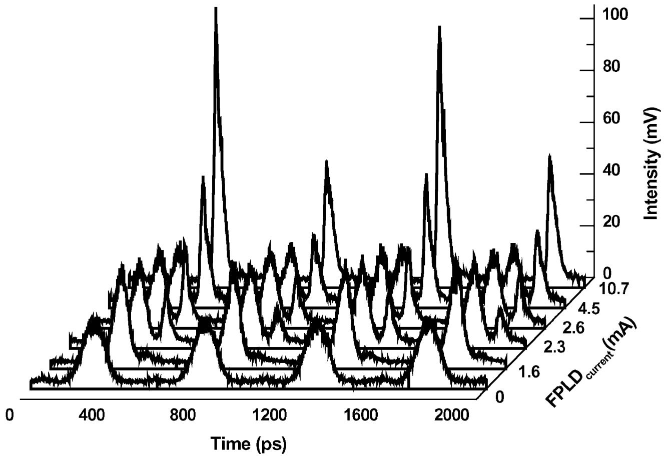

Fig. 2. Evolution of EDFL from mode-locking to injection-locking with increasing dc driving current of FPLD.

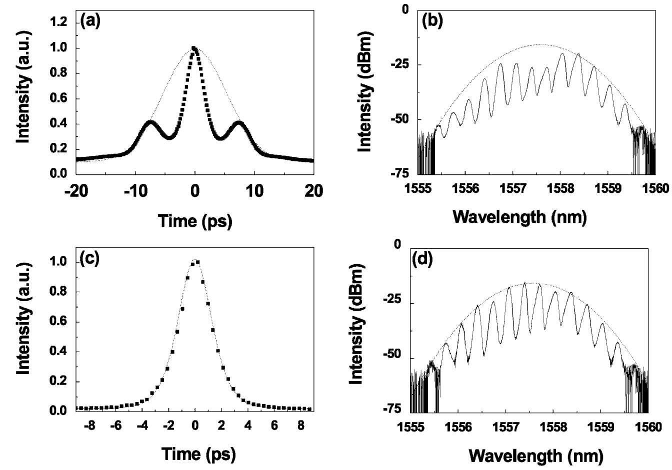

Fig. 3. (a) and (c) Autocorrelation traces (solid-square curves with dashed fitting lines). (b) and (d) Output spectra (solid curves with dashed fitting lines) of the FPLD mode-locked EDFL pulses before and after dispersion compensation. (a) and (b) Measured before dispersion compensation. (c) and (d) Measured after chirp compensation.

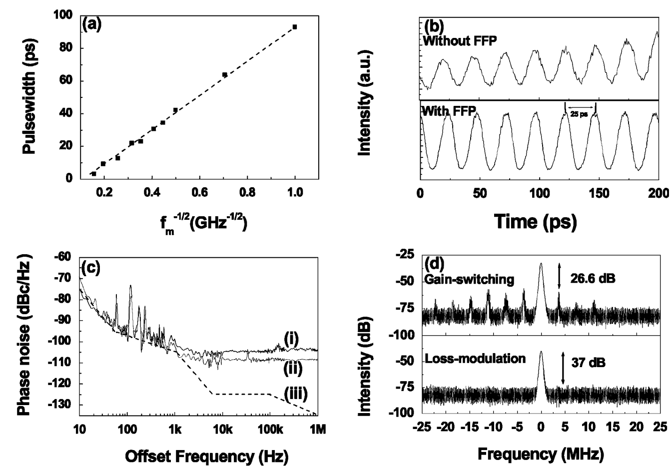

Fig. 4. (a) EDFL pulsewidth as a function of inverse square root of pulse repetition frequency. (b) 40-GHz EDFL pulse trains without (upper) and with (lower) intracavity FFPF. (c) SSB phase noise spectra of the EDFL with FPLD at loss-modulation (trace i) and gain-switching (trace ii) modes. (d) Supermode noise spectra of EDFL with FPLD at loss-modulation (lower) and gain-switching (upper) modes.

the RF power and the dc bias level of the FPLD are adjusted to >24 dBm and >10 mA using a biased-Tee circuit. The EDFL output is monitored by a digital sampling oscilloscope [(DSO) Agilent $86\,100A + 86\,116A, f_{3\,\mathrm{dB}} = 53$ GHz], and by an optical autocorrelator (Femtochrome, FR-103XL) with temporal resolution of 175 fs.

III. Results and Discussion

With either a large-signal modulated or a gain-switched FPLD, the EDFL was reported to be stably mode-locked or injection-locked [11], [13]. In contrast, the RF-modulated FPLD is not lasing in our case. The harmonic mode-locking of the EDFL is initiated as the modulation power of the FPLD exceeds 18 dBm, providing mode-locking pulsewidth and peak power of about 93 ps and 330 mW, respectively. The harmonic orders of the FPLD mode-locked EDFL is 228 (corresponding to frequency of 1.020 127 GHz). The perfect mode-locking is achieved by driving the FPLD at dc current of <1.5 mA and RF power of <21 dBm. However, the gain-switching of the FPLD starts up when the dc driving current of the FPLD increases, which leads to an injection-locked EDFL pulse train arising after the mode-locking one (see Fig. 2). The injection-locked pulsewidth are 26.4 ps, which exhibits a nearly identical pulse shape with that of the gain-switched FPLD (about 21 ps). The loss-modulation mechanism of the FPLD disappears and the mode-locking no longer exists after gain competing with the injection-locking process. Under the gain-switched FPLD seeding, the injection-locking is more pronounced than the mode-locking in the EDFL.

The rational harmonic mode-locking is achieved by detuning the modulation frequency of the FPLD (f_m) from nf_c to $(n \pm 1/p)f_c$, where f_c is the fundamental mode frequency of the EDFL, n and p are the harmonic and rational harmonic mode-locking orders, respectively. The frequency-detuning changes the pulse repetition rate from nf_c to $(np \pm 1)f_c$, which is exactly p times the modulation frequency f_m. In experiment, the modulation frequency is detuned by 113 kHz to obtain 40th-order rational harmonic mode-locking (corresponding to $n = 228$ and $p = 40$). In comparison, the frequency multiplication of the gain-switched FPLD in EDFL is rarely hard to be obtained and maintained due to the narrower locking bandwidth. The autocorrelated EDFL pulse exhibits a significant pedestal adjacent to the principle pulse, as shown in Fig. 3(a). The measured pulsewidth and linewidth are 13.6 ps and 1.25 nm, which correspond to a time-bandwidth product ($\Delta\tau\Delta\nu$) of 1.36. The elimination of such pulse shoulders relies on the chirp compensation by using dispersion compensated fiber. After propagating through a 32-m-long Corning DCF with dispersion constant of -81 ps/nm/km, a pedestal-free EDFL pulse shape with a deconvoluted pulsewidth of 3 ps is shown in Fig. 3(c). A nearly identical spectrum with 3-dB linewidth of 1.3 nm is plotted in Fig. 3(d). The time-bandwidth product ($\Delta\tau\Delta\nu$) of 0.31 is nearly the transform-limit of sech^2 function. The autocorrelation-measured pulsewidth and peak power of rational harmonic mode-locked EDFL is reduced from 93 to 3 ps and from 330 to 140 mW, respectively, as the rational harmonic mode-locking order increases from 1 to 40 [see Fig. 4(a)], which is linearly proportional to the inverse square root of the repetition frequency, i.e., $(pf_m)^{-1/2}$.

Originally, the peak amplitudes of adjacent EDFL pulses in rational harmonic mode-locking scheme are not equalized due to the lasing of mismatched lower-harmonic supermodes [see upper trace of Fig. 4(b)]. This has be improved by adding an intracavity high-finesse FFPF (MOI FFP-TF 1550-040M1000-6.5, Finesse $= 1000$, Bandwidth $= 40$ MHz, Free Spectral Range $= 40$ GHz), as shown in lower trace of Fig. 4(b) [12]. The pulse train with equalized peak amplitudes is monitored by using DSO at four-time averaging mode. The average power fluctuation of the modified EDFL system is within 0.74%. Moreover, the single sideband (SSB) phase noise spectra and supermode noises of EDFL using the FPLD at loss-modulation and gain-switching modes are compared. The analysis reveals that the uncorrelated SSB phase noise (-105 dBc/Hz at offset frequency >10 kHz from carrier) of the mode-locked EDFL with a loss-modulated FPLD is 3 dB higher than that with a gain-switched FPLD, as shown in Fig. 4(c). Since the uncorrelated phase noise is strongly correlated with the spontaneous emission noise of the FPLD-EDFL link, it is consequential that driving the FPLD at well below threshold inevitably introduces larger spontaneous emission noise. The FPLD mode-locked EDFL pulse has an root mean square timing jitter of 0.49 ps in the integral region from 10 Hz to 100 kHz, whereas the jitter of the FPLD injection-locked EDFL pulse is smaller (0.33 ps). Improving the phase noise performance of the FPLD mode-locked EDFL, thus, relies on increasing the driving current of the FPLD. However, such operation easily turns the EDFL from mode-locking to injection-locking since the FPLD is gain-switching at larger currents.

Fig. 4(d) compares the supermode noise spectra of the EDFL with the FPLD operating at different schemes. With the loss-modulated FPLD, the supermode noise was suppressed with a supermode suppression ratio (SMSR) of 37 dB, whereas, the SMSR of the EDFL injection-locked by a gain-switched FPLD is slightly lower (26.6 dB). Since the FPLD is playing not only a loss modulator but also an FFPF in the proposed configuration, which thus, bring the EDFL a comparable supermode noise suppression response with that of a similar mode-locked EDFL system using an electrooptic modulator and an FFPF. The use of the FPLD-based modulator essentially releases the requirement of ultrahigh modulation bandwidth electrooptic or electroabsorption modulators, which further benefits from the advantages such as the improvement in the extinction ratio of the pulses (due to the operation of the FPLD at loss-modulation mode). Although the modulation bandwidth of the FPLD is limited at several gigahertz, high-repetition pulse train of EDFL can still be obtained by using rational harmonic mode-locking operation.

IV. Conclusion

We have demonstrated the rational harmonic mode-locking of the EDFL with repetition frequency up to 40 GHz by using an FPLD purely loss-modulated at 1 GHz. The FPLD is neither lasing nor gain-switching in contrast to conventional approaches. The harmonic mode-locking threshold of the EDFL is below 18 dBm. The highest rational harmonic mode-locking order of 40 is achieved by slightly detuning the FPLD modulation frequency of 113 kHz. The peak power and pulsewidth of rational harmonic mode-locked EDFL pulse after chirp compensation are decreased from 330 to 140 mW and from 93 to 3 ps, respectively, as the repetition frequency of pulse train increases up to 40 GHz. The adjacent peak amplitudes of the EDFL pulses are completely equalized using an FFPF. The FPLD mode-locked EDFL exhibits SSB phase noise and SMSR of -105 dBc/Hz (at offset frequency >10 kHz from carrier) and 37 dB, respectively. By increasing the dc driving current for the FPLD, the evolution between harmonic mode-locking and injection-locking mechanisms in the EDFL due to the change of the FPLD from loss-modulation mode to gain-switching mode has been investigated. The injection-locking becomes the dominant mechanism at larger FPLD currents due to the gain depletion effect, which eventually diminishes the rational harmonic mode-locking pulse train in the EDFL.

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