Chapter 4

10 GHz regenerative mode-locking of erbium-doped fiber laser

4.1 Introduction

A stable optical short pulse source with high repetition rate is very important for realizing future ultrahigh speed optical communication in terms of both transmission [4.1, 4.2] and ultrafast signal processing [4.3, 4.4]. When a perturbation such as a mechanical vibration or thermal expansion is applied to a fiber laser cavity, the change in the longitudinal mode spacing is much bigger than that of ordinary lasers because the cavity is much longer. Hence, it is usually difficult to maintain the optimum operational condition over a long period. However, a regenerative mode-locking technique overcomes this problem because the instantaneous harmonic cavity mode is always fed back to the cavity. Previously, Nakazawa *et al.* have reported the excellent characteristics such as a short pulsewidth, long term stability, and high spectral quality by using a regenerative mode-locking technique [4.5]. Later on, Nakazawa *et al.* developed a regeneratively mode-locked laser with a phase-locked-loop (PLL) technique, which can be locked to an external electrical signal [4.6]. For high-speed communication systems, both timing jitter and supermode noise of the optical source are key parameters for determining system performance. In this paper, we demonstrate that by using the PLL and PZT controller link to set up a regeneratively mode-locked erbium-doped fiber laser (RML-EDFL) and investigate its characteristic, including SSB phase noise and timing jitter.

4.2 Experimental Setup

Figure 4.1 shows the setup of RML-EDFL. The laser consisted of an EDFA, a pair of isolator, a PZT (piezo-electric transducer), a optical coupler (OC), a polarization controller (PC), a LiNbO3 MZM (Mach-Zehnder intensity modulator), an optical delay line, a phase controller, a clock data recovery (CDR) and a phase locked loop (PLL). The PZT was driven by error signal which represent the phase difference between the laser clock and the synthesizer signals. The PZT is employed to change cavity length by applying a DC voltage between 0 and 10 V to it. A LiNbO3 MZM biased at half-wave voltage ($V_\pi \cong 4.3$ V) and a PC is used to optimize the polarization orientation of the circulating pulses. To obtain a sinusoidal harmonic signal between the longitudinal laser modes, part of output beam is coupled into a CDR which consists of a high speed photodetector, a 10GHz high Q filter and a high gain amplifier. After adjusting the phase between the pulse and modulation peak, it enables regenerative mode-locking to be realized. When an error signal which is output from PLL is fed back to the PZT, the repetition rate is stabilized. However, the harmonic mode-locking is exactly achieved when the optical delay line is properly adjusted to be coincides with one harmonic longitudinal-mode frequency of the EDFL. The cavity length is 89 m corresponding to a longitudinal mode spacing of 2.25 MHz.

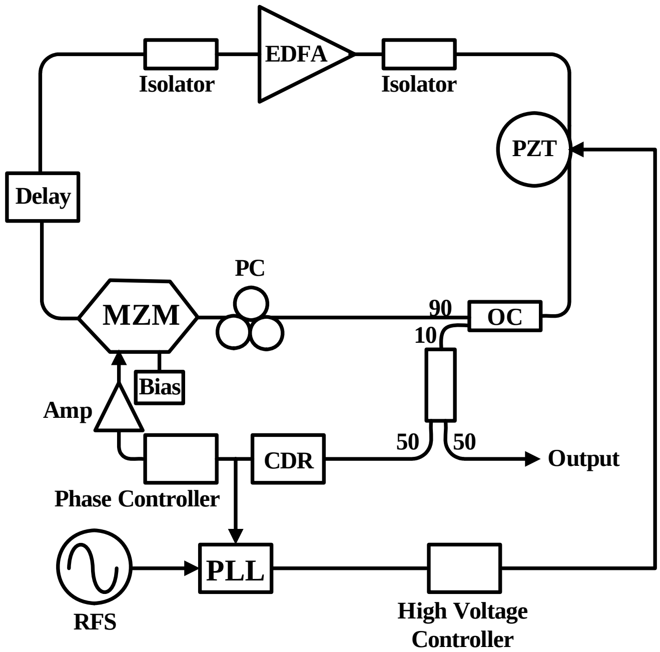

Fig. 4.1 The schematic diagram of the PLL regeneratively mode-locked EDFL. MZM: Intensity modulator; Amp: power amplifier; PZT: piezo-electric transducer; EDFA: erbium-doped fiber amplifier; OC: optical coupler; RFS: RF synthesizer; PLL: phase locked loop; CDR: clock data recovery.

4.3 Results and Discussion

4.3.1 Phase noise and Timing jitter: Free-running case

In free-running case of 10 GHz mode-locked erbium-doped fiber laser (ML-EDFL), we measured the sing-side-band (SSB) phase noise and timing jitter. The noise spectra of the output pulse of the laser was measured electrically with a high speed photodetector (New Focus Model 1014) and RF spectrum analyzer (HP8565E). Fig. 4.2 shows SSB phase noise versus frequency offset from the 10 GHz carrier frequency. Figs. 4.2(c) and (e) represent the SSB phase noise of free-running case at 10 GHz ML-EDFL and the synthesizer at 10GHz component, and its SSB phase noise is -87.6 dBc/Hz and -116.2 dBc/Hz (measured at 100 kHz offset frequency from carrier), respectively. The timing jitter is calculated by integrating the region of the SSB phase noise spectrum from 10 Hz to 10 MHz. The timing jitter of free-running case and the synthesizer is estimated to be 3.06 ps and 2 ps, respectively, as shown in Figs. 4.3(c) and (d).

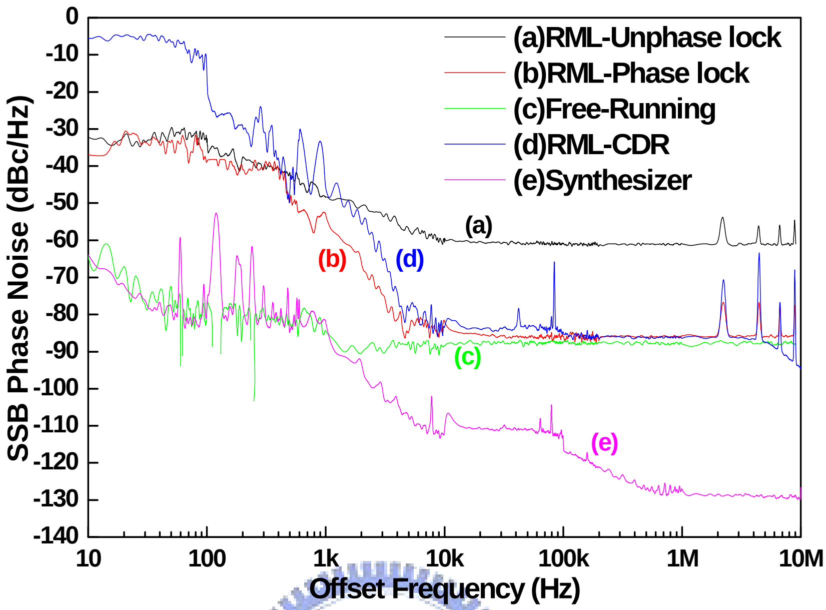

Fig. 4.2 The sing-side-band (SSB) phase noise spectra (a) RML-Unphase lock, (b) RML-Phase lock, (c) Free-Running, (d) RML-CDR, (e) Synthesizer.

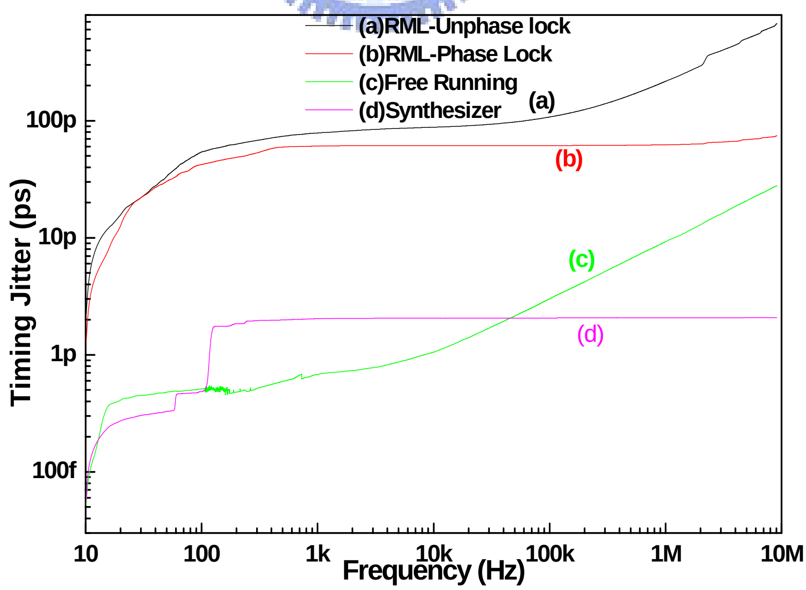

Fig. 4.3 The timing jitter (a) RML-Unphase lock, (b) RML-Phase lock, (c) Free-Running, (d) Synthesizer.

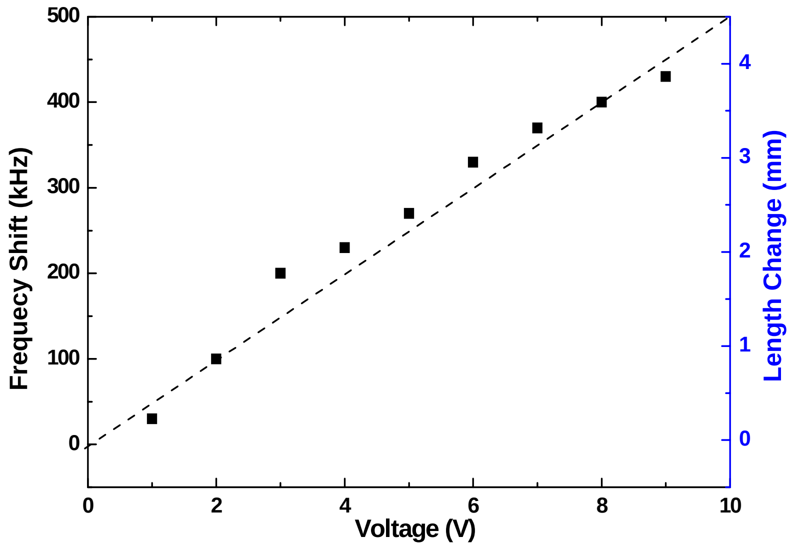

Fig. 4.4 The characteristic of voltage versus frequency shift and length change for the PZT.

4.3.2 Phase noise and Timing jitter: Regenerative case

In 10 GHz RML-EDFL, we discuss the SSB phase noise and timing jitter of the output pulse. First, we measure the characteristic of the PZT and it is found that it exhibits a linear characteristic for the dependence of frequency shift on input voltage, as shown in Fig. 4.4. When the voltage applied to the PZT, the repetition frequency change per voltage is 30 kHz/V. Part of the fiber cavity is wound on a PZT in order to change the length by applying a voltage signal. The output pulsewitdh of 16.7 ps and the average power of 210 μW are measured (see Fig. 4.5). The output optical spectrum is shown in Fig. 4.6 and the longitudinal mode-spacing is 0.08 nm corresponding to 10 GHz. When the RML-EDFL is operated at phase-lock condition, the SSB phase noise and timing jitter are -86.2 dBc/Hz and 61.3 ps, respectively. In contrast with not phase-lock condition, it is clearly found that the SSB phase noise of -60.7 dBc/Hz and timing jitter of 107 ps are degraded seriously. Fig. 4.2(d) shows the SSB phase noise (-84.7 dBc/Hz) of the CDR at 100 kHz offset frequency. The extremely large SSB phase noise below the 10 kHz offset frequency in RML-EDFL is attributed to the amplified supermode noise from the CDR. Therefore the large timing jitter is obtained by integrating SSB phase noise spectrum from 10 Hz to 10 MHz.

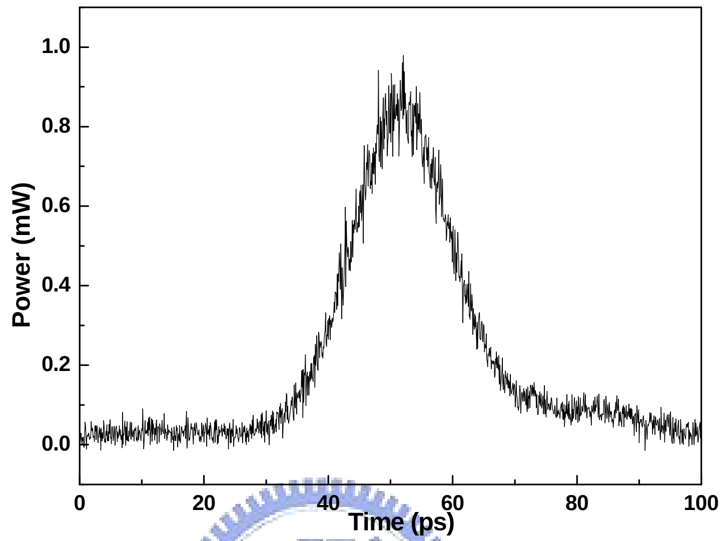

Fig. 4.5 The output pulsewidth in regeneratively mode-locked erbium-doped fiber laser.

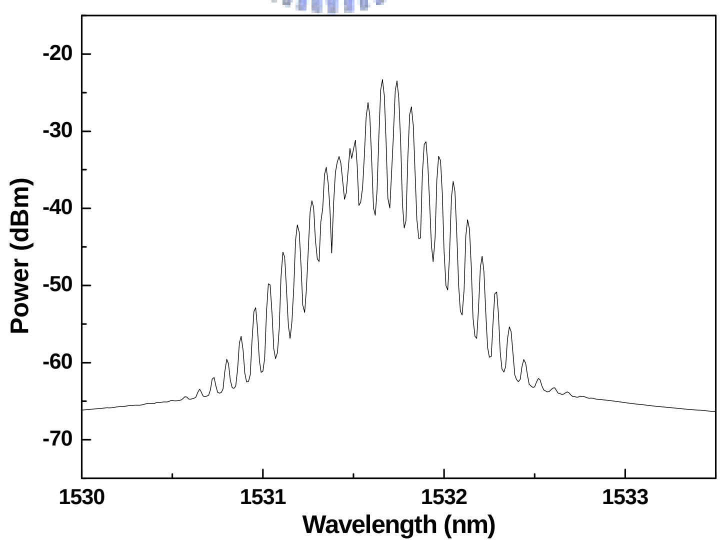

Fig. 4.6 The output optical spectrum in regeneratively mode-locked erbium-doped fiber laser.

4.4 Conclusions

In conclusion, we succeeded in constructing the RML technique with a repetition rate of 10 GHz from phase lock loop (PLL) and PZT controller link. We have measured the SSB phase noise and timing jitter from the noise spectra of the RML-EDFL. The measured SSB phase noise and estimated timing jitter are -86.2 dBc/Hz and 61.3 ps, respectively, which indicate the bad laser output characteristics as compared with the free-running case. This is because the noise source is mainly introduced from the CDR due to amplified supermode noise beatimg.

4.5 References

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