Chapter 1
Introduction

1.1 Noise sources in mode-locked fiber lasers

In general mode-locked erbium-doped fiber lasers (ML-EDFL), the noise sources generated from mode-beating induced supermode noise (SMN), environmental perturbations, pumping power fluctuations and single-sided-band (SSB) phase noise are very important to realize future ultrahigh speed optical communication in terms of both transmission and ultrafast signal processing. The relaxation time of the erbium ions in the erbium-doped fiber, the gain medium with the cavity, is much longer (of the order of order of milliseconds) than the cavity mode spacing (of the order of tens of microseconds). Therefore, the saturation of the gain medium cannot uniformly stabilize the energy amongst all the cavity modes. As a result, more than one supermode oscillates within the cavity. The superposition of these oscillating supermodes, which is known as supermode noise, gives rise to the unequal distribution of energies amongst the generated optical pulses. Consequently, the optical pulses exhibit amplitude noise [1.1]. In addition to amplitude fluctuations, the optical pulses in the ML-FRL also experience noise due to changes in their cavity round-trip time. This occurs due to variations in the optical path length caused by perturbations in the surrounding temperature. For environmental perturbation, it also leads to the noise by thermal perturbation and variations, caused by random motion of the current carriers and environmental temperature.

Any such thermal perturbation and variations lead to a mismatch between the external modulation period and the cavity round-trip time of the mode-locked optical pulses. However, this condition seriously results the instability of the laser output. Another type of noise (SSB phase noise) that plays an important role in quantum electronics is that of spontaneous emission in laser oscillators and amplifiers. A necessary condition for laser amplification is that the atomic population of a pair of levels 1 and 2 be inverted. If $E_2 > E_1$, gain occurs when $N_2 > N_1$. Assume that an optical wave with frequency $\nu \cong (E_2-E_1)/h$ is propagating through an inverted population medium. This wave will grow coherently due to the effect of stimulated emission. In addition, its radiation will be contaminated by noise radiation caused by spontaneous emission front level 2 to level 1. Some of the radiation emitted by the spontaneous emission will propagate very nearly along the same direction as that of the stimulated emission and cannot be separated from it. Therefore the laser output has a finite spectral width related to phase fluctuation and the signal to-noise ratio achievable at the output of laser amplifiers [1.2] is limited because of the intermingling of spontaneous emission noise power with that of the amplified signal. The SSB phase noise and timing jitter originated from driving electronic, amplified spontaneous emission and environmental perturbation are different ways of quantifying the same phenomenon. The random timing jitter describes timing variations caused by less predictable influences. Temperature, which affects the mobility of semiconductor crystal material, can cause random variations in carrier flow. Semiconductor process variations, such as non-uniform doping density, can also cause timing jitter.

In ML-EDFL, the erbium-doped fiber amplifier (EDFA) is served as gain medium for providing the light source. The mechanism of resulting light source results in pumping power fluctuations generated from laser pumping source of 980 or 1480 nm. On the other hand, the noise is contributed by the active components. Therefore, it can not be eliminated completely in the system. We only decrease the noises to get better performance in the output pulses. In order to reduce the noises in ML-EDFL, it is demonstrated that the noises are suppressed by using the different technologies.

1.2 Review of noises suppression technologies

In 1992, Sanders *et al.* reported the reduction of the SMN from a mode-locked EDFL by using intra-cavity spectral filtering [1.3]. Seo *et al.* have minimized the SSB phase noise (or timing jitter) of EDFL with external injection-seeding in 1996 [1.4]. To suppress SMN and intensity noise, Duan. *et al*. reported that by adding an using the semiconductor optical amplifier (SOA) as a high-pass filter it can be in pulses greatly suppressed in 2002 [1.5]. Nakazawa *et al.* in developed a regeneratively mode-locked laser with a phase-locked-loop (PLL) technique, which can be locked to an external electrical signal, to suppress timing jitter in 1997 [1.6]. Gupta *et al.* also reported that by using the regenerative technique to suppress SSB phase noise and SMN in stable output pulse in 2000 [1.7]. The ML-EDFL's have been stabilized against amplitude noise of the optical pulses in terms of minimizing or eliminating supermode noise in the laser cavity via above various techniques.

1.3 Motivation and Chapter Description

In order to obtain a low SSB phase noise (timing jitter) and supermode-noise-free laser source, we propose a FPLD injection-mode-locking EDFL (FPLD-IML-EDFL) link as compare with harmonically mode-locking Erbium-doped fiber laser (HML-EDFL) in first work. In second work, the SSB phase noise, pulse-to-pulse timing jitter, and supermode noise characteristics of the HML-EDFL with intra-cavity SOA filter are theoretically investigated and experimentally compared with a start-of-the-art FPLD-IML-EDFL. We demonstrate that the supermode noise suppression ratio (SMSR) of the SOA-filtered HML-EDFL can be significantly improved without sacrificing its pulsewidth, SSB phase noise, and timing performances, by concurrently adding an optical band pass filter (OBPF) and adjusting the driving current of the SOA. The performances of both configurations are also compared.

The thesis is separated into five chapters. Chapter 1 Noise sources in mode-locked fiber lasers and noises suppression technologies. Chapter 2 describes phase noise and timing jitter of harmonic mode-locked and injection-locked erbium-doped fiber lasers. Chapter 3 discusses suppression of phase and supermode noise in a harmonic mode-locked erbium-doped fiber laser with a semiconductor optical amplifier based high-pass filter. Chapter 3 introduces 10 GHz regenerative mode-locking of erbium-doped fiber laser. At last, Chapter 5 concludes the experimental results.

1.4 References

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