

# Chapter 1

## Introduction

In 1989 year, the first active mode-locked fiber used EDFA to be achieved by D. C. Hanna *et al*[1]. Mode-locked fiber laser is a promising pulse source of use in high speed communication system. Optical pulses at high repetition rates can be achieved by harmonic or rational mode-locking.

The explosive growth in demand for telecommunication service witnessed in recent years have led to immense research efforts being focused towards increasing the capacity of optical transmission. Today's single-mode-optical fibers can provide a huge transmission bandwidth of 25 THz in the 1.5  $\mu$  m wavelength region, which is far beyond the requirements of today's telecommunications. In 1993, utilizing newly developed key technologies including transform-limited pulse sources, MUX/DEMUX circuits and timing extraction phase lock loops, the first successful 100 Gb/s 50 km transmission was conducted by eightfold OTDM together with twofold polarization multiplexing (PDM), where the actual switching speed was as high as 40 Gb/s[2]. Since then, OTDM transmission technologies have been made a lot of progress toward much faster and longer optical transmission systems.

Mode-locked erbium-doped fiber lasers are compact and environmentally stable and can generate dropout-free ultrashort pulses with a very high repetition rate, a large extinction ratio, and a very low phase noise. These features make them particularly well suited for studying the transmission of return to zero (RZ) pulses, e.g., solitons, at

data rates where there are no other short pulse sources that are as clean available. Additionally, those sources have application in optical high-data-rate analog to digital conversion. An actively mode-locked laser with a sigma configuration has been demonstrated to generate a stable train of 70 ps pulses with a repetition rate of 10 GHz and a pulse dropout ratio of less than  $10^{-14}$  [3]. Due to the stringent requirements imposed upon lasers that are used in optical communication systems, it is important to develop theoretical models that enable the user to accurately analyze laser performance. Such models will give researchers the means to better understand the physics of the laser and to control and optimize its performance. Prior work for studying actively mode-locked fiber lasers or storage rings [4], [5] has been largely based on solving the Ginzburg–Landau equation, modified to include amplifier filtering and active mode-locking. This work, which is based on earlier pioneering work by Haus[6] and by others [7], includes a number of simplifying assumptions. The most important assumption in the reduced model is that: 1) every pulse in the laser cavity is the same. This assumption, which is certainly false in general, makes it impossible to study important dynamic effects in harmonically mode-locked fiber lasers and to find the precise limits on the stable operating regime; however, it is a reasonable assumption when studying an already-established stable pulse train. Other assumptions are: 2) the pulse change is small at any fixed point in the laser from one roundtrip to the next; 3) the bandwidth of the pulse is small compared to the bandwidth of the gain medium and/or the optical filtering; and 4) the time duration of the pulse is much shorter than the period of the mode-locking. Additionally, to use soliton perturbation

theory, one must assume that 5) the pulse shape remains nearly hyperbolic-secant during its roundtrip through the laser. These assumptions enable one to obtain analytical results and to find out explicitly the dependence of the generated pulses on the cavity parameters. In order to obtain a good quantitative agreement between the theory and experiments, however, one should use a more comprehensive approach that models all the major physical phenomena that affect the laser behavior. One of the important effects that cannot be accurately modeled using a single pulse analysis is pulse dropout. Since fiber lasers for optical communication systems operate at high repetition rates, they are harmonically modelocked so that many pulses simultaneously propagate inside the cavity. The first proposition of mode-locking appear by the research of Gürs and Müller[8,9] on ruby lasers. The first papers clearly identifying the mechanism published in 1964 by DiDomenico[10], Hargrove *et al* [11], and Yariv[12]. The case of active mode-locked is that Hargrove *et al* achieved mode-locking by internal loss modulation inside the resonator. Mocker and Collins[13] showed that the saturable dye used in ruby lasers to Q-switch the laser could also be used to be mode-locking. Q-switching is a process in which the laser is caused to emit pulses that are many roundtrips in duration. The saturation absorber is bleached by the radiation in the resonator. The emission of radiation stops when the gain medium is depleted, and the process starts all over again. Mocker and Collins observed that the Q-switched pulse broke up into a train of very short pulses separated by the roundtrip time. The train carried the same energy as the Q-switched pulse and hence the pulses were of much greater peak intensity than the pulses produced by Q-switching alone.

That was the first example of passive mode-locking. For several years, techniques were developed for measurement of these pulses and for their use to probe nonlinear response of optical media. The measurement accuracy was impaired by the somewhat unpredictable nature of the transient mode-locking. This drawback was overcome when Ippen *et al*[14] generated the first CW saturable absorber mode-locking. Shortly thereafter this led to production of pulses of sub-picosecond duration[15]. The reproducible character of these pulses improved the accuracy of pump-probe measurements by four orders of magnitude. The work continued unabated for the next decade producing shorter and shorter pulses[16-18]. Ultimately, a record 6-fs pulse duration was achieved by Fork *et al* using pulse compression external to the cavity[19]. The pulse compression technique uses the Kerr nonlinearity of an optical medium. The pulses propagating through the medium with nonlinear phase shifts that induce spectral broadening and pulse compressing.

The analytic theory of active mode-locking was firmly established in a classic paper by Siegman and Kuizenga[20]. The soliton laser[21] consisted of two resonators, one active the other passive and containing a fiber, coupled via a semitransparent mirror to the laser resonator. The two resonators were feedback stabilized to within a fraction of a wavelength. The operation of this laser was explained afterwards as an interference phenomenon between the pulses circulating in the two subresonators and interfering at the semitransparent mirror[22]. Through proper phasing a net pulse shaping is produced analogous to that of a fast saturable absorber. The process was dubbed additive pulse mode-locking(APM)[23]. The principle was generalized to fiber ring lasers in which the APM action is

produced by a birefringent element in the resonator. Via polarization controllers the pulse is split into two co-propagating versions in the fiber. The interference of the two polarizations at the output polarizer leads to effective fast-saturable-absorber action.

The Kerr-lens mode-locking(KLM) were written by several laboratories[24-27]. The effect of a fast saturable absorber is simulated by Kerr focusing: the high intensity part of the beam is focused by the Kerr-effect, whereas the low intensity parts remain unfocused. If such a beam is passed through an aperture, the low intensity parts are attenuated, thereby shortening the pulse.

There is another variant of this pulse shaping by the Kerr-effect and dispersion, in a way analogous to dispersion-managed soliton propagation[28]. The dispersion in the ring may be made to vary from normal to anomalous by proper splicing of fiber segments. The pulse inside the resonator stretches and compresses[29]. The net dispersion may be zero, yet soliton-like pulse shaping is still possible[30]. The reason for this is the fiber nonlinearity that causes the pulse spectrum to be narrower in the segment with normal dispersion than in the segment with anomalous dispersion. Thus, on the average, the pulse experiences anomalous dispersion which balances the Kerr-effect.

A major problem with this mode of operation is pulse dropout, some pulses may drop from the pulse train and cause errors in the system. The laser dynamics that lead to supermode competition and pulse dropout cannot be studied using a single pulse analysis, since a single pulse cannot be dropped. Therefore, single-pulse models cannot accurately predict the limits on the desirable operating regime. Several methods for eliminating dropouts have

been demonstrated experimentally [31]; however, stable operation could only be obtained over a limited range of pulse durations and the limits have been poorly understood. In principle, one can study the dynamics of supermode competition by studying a long string of pulses, but in practice it is not feasible even computationally to study strings that are greater than about 24 pulses in length. We have verified that computational results converge very slowly so that even 24 pulses were not enough to obtain an accurate solution, nor do the results agree well with experiments.

In Chapter 2, we utilize time-domain ABCD matrix to analyze the pulsewidth and chirp parameters of our designed AM mode-locked figure eight fiber laser. We experiment to analyze, moreover, the repetition rate, pulsewidth, rise time, falling time and root-mean-square jitter.

In Chapter 3, we utilize FM and AM mode locking of the homogeneous laser theory to analyze the pulsewidth and chirp parameters of our designed PM mode-locked figure eight fiber laser. We experiment to analyze, moreover, the repetition rate, pulsewidth, rise time, falling time and root-mean-square jitter.

In Chapter 4, comparing the simulation of the transmission system uses the Dispersion-Compensated Fiber and the different pulse shapes of the same repetition rate to do simulation to analyze the performance. The power penalty uses time-domain ABCD matrix to derive broadening factor. We also propose the theoretical model considering intersymbol interference(ISI) and timing jitter to analyze the bit error rate(BER). We can find the optimum value of dispersion compensation. At last, the conclusions will be proposed in Chapter 5.