NONLINEAR FIBER RING LASERS

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Statement of Originality

I hereby certify that the work embodied in this thesis is the result of original research and has not been submitted for a higher degree to any other University or Institution.

__________________________  ____________________________
Date                        LAI Wenn Jing
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Wenn Jing LAI  
Singapore, May 2006

"Most people say that it is the intellect which makes a great scientist. They are wrong: it is character.” — Albert Einstein, Swiss-American mathematician, physicist and public philosopher (1879-1955)
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Summary

The demand for communication bandwidth has increased tremendously over the years. Many research and development works focus on generating ultra-fast and narrow optical pulses to meet this increasing demand. Although the generation of high speed and short optical pulses by mode-locking technique is well known, the applications of such pulses challenge its designer on its stability and spectral issues. With the increase in transmission capacity and the use of wavelength division multiplexing (WDM), phenomena such as four wave mixing (FWM), stimulated Raman scattering (SRS), and other nonlinear interactions; Gordon-Haus timing jitter, channel cross talk, etc. have put a limit to the performance of the high speed optical communications. It will be a bottleneck issue with present electronic devices in manipulating and analyzing the high-speed optical signals. Hence, photonic-based signal processing devices are essential when the repetition frequency of the optical signal gets higher.

As a start, I study the building blocks of a 10 GHz active mode-locked erbium doped fiber ring laser and its corresponding regenerative structure for better stability [W1]. Their system performances are examined. About 11 ps optical pulses are obtained for both structures. Fractional temporal Talbot effect, which is interference between dispersed pulses, has been used to increase the system rate. 4-times multiplication has been achieved with a base frequency of 10 GHz, and hence 40 GHz pulse operation [W2]. Phase plane analysis, a class of nonlinear control theories, is used to study the laser system stability. The analysis shows transient and steady state behaviors of the system. Influences of lasing mode amplitude, filter bandwidth and noise are examined. A
remarkable result is that no stable operation can be obtained even under perfect multiplication condition [W3 – W4].

I generate ultrafast optical pulses with slow electronic devices, to solve photonic-electronic bottleneck problem, without much increase in the cost of generation. This may lead to a new era of optical communications, and closer to Shannon’s channel capacity for optical fiber. A Gaussian-like modulating signal is introduced, and its corresponding mode-locking model is developed. For Gaussian modulating signal with duty cycle less than 30 %, the generated pulse width is shorter than that of the cosinusoidal modulating signal [W5]. In addition, stable operation region for soliton-Gaussian-like pulses is determined [W6]. With this type of modulating signal, a record high rational harmonic detuning order has been achieved in the active harmonically mode-locked fiber ring laser: 1230\textsuperscript{th} order, with a base modulation frequency of 100 MHz, and hence 123 GHz operation [W7 and W8]. Also, phase plane analysis is applied for the system stability studies [W5].

More interestingly, Tera-Hertz operation, i.e. 1.315 THz repetition frequency with Time-Bandwidth Product of 0.496, is observed in parametric amplifier based fiber ring laser [W9 – W11]. The main essence of the operation is the frequency detuned in the pulse pump signal. The increase in the repetition frequency is due to the rational harmonic detuning and modulation instability of the system. Moreover, its regenerative counterpart has also been constructed for better stability.

Finally, the bidirectional lightwaves propagation behaviors in an erbium doped fiber ring laser are investigated [W12 – W14]. By exploiting this bidirectional operation, I propose a nonlinear optical loop mirror (NOLM) – nonlinear amplifying loop mirror

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(NALM) fiber ring laser operating in nonlinear region. The optical bistability, bifurcations and chaos phenomena of the proposed structure have been examined. Three operation regimes are obtained numerically, namely single operation, period doubling operation and chaotic operation; however only two are observed experimentally due to hardware limitations.

This research work focuses mainly on nonlinear system behaviors of fiber ring lasers, which includes self phase modulation, four-wave mixing, parametric amplification, optical bistability, bifurcation and chaos. Although some of the nonlinear effects are undesirable for system design, I am able to turn these unfavorable behaviors into real use, such as ultra-high speed operation, narrow pulse generation and optical switching. The main achievements of this work have been published in papers [W1 – W14].
List of Publications


Acronyms

ACF   Autocorrelation function
AM   Amplitude modulation
APM   Additive pulse mode-locking
ASE   Amplified spontaneous emission
AWG   Arrayed waveguide grating
BER   Bit error rate
BPF   Band pass filter
CSA   Communications signal analyzer
CSRZ   Carrier suppressed return-to-zero
ccw   counter clockwise
cw   clockwise
CW   Continuous wave
DCF   Dispersion compensating fiber
DFB   Distributed feedback
DM   Dispersion management
DSF   Dispersion shifted fiber
DWDM   Dense wavelength division multiplexing
EDF   Erbium doped fiber
EDFA   Erbium doped fiber amplifier
EDFL   Erbium doped fiber laser
ESA   Excited state absorption
FBG   Fiber Bragg grating
FP   Fabry Perot
FRL   Fiber ring laser
FSR   Free spectra range
FWHM   Full width half maximum
FWM   Four wave mixing
GVD   Group velocity dispersion
HNLF   Highly nonlinear fiber
KLM   Kerr lens mode-locking
LCFG   Linearly chirped fiber grating
MZ   Mach-Zehnder
ML   Mode-locked
MLFRL   Mode-locked fiber ring laser
MZM   Mach-Zehnder modulator
NALM   Nonlinear amplifying loop mirror
NLSE   Nonlinear Schrödinger equation
NOLM   Nonlinear optical loop mirror
OPO   Optical parametric oscillator
OTDM   Optical time division multiplexing
OTDR   Optical time domain reflectometer
PA   Parametric amplifier
PC   Polarization controller
<table>
<thead>
<tr>
<th>Abbreviation</th>
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<tbody>
<tr>
<td>PCF</td>
<td>Photonic crystal fiber</td>
</tr>
<tr>
<td>PDM</td>
<td>Polarization division multiplexing</td>
</tr>
<tr>
<td>PLL</td>
<td>Phase lock loop</td>
</tr>
<tr>
<td>PMD</td>
<td>Polarization mode dispersion</td>
</tr>
<tr>
<td>PMF</td>
<td>Polarization maintaining fiber</td>
</tr>
<tr>
<td>PO</td>
<td>Parametric oscillator</td>
</tr>
<tr>
<td>PZT</td>
<td>Piezoelectric transducer</td>
</tr>
<tr>
<td>QED</td>
<td>Quantum electrodynamics</td>
</tr>
<tr>
<td>RF</td>
<td>Radio frequency</td>
</tr>
<tr>
<td>RMLFRL</td>
<td>Regenerative mode-locked fiber ring laser</td>
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<tr>
<td>ROA</td>
<td>Raman optical amplifier</td>
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<tr>
<td>SMF</td>
<td>Single mode fiber</td>
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<tr>
<td>SNR</td>
<td>Signal to noise ratio</td>
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<tr>
<td>SOA</td>
<td>Semiconductor optical amplifier</td>
</tr>
<tr>
<td>SRD</td>
<td>Step recovery diode</td>
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<tr>
<td>SRS</td>
<td>Stimulated Raman scattering</td>
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<td>SSFM</td>
<td>Split step Fourier method</td>
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<tr>
<td>TBRRM</td>
<td>Talbot based repetition rate multiplication</td>
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<tr>
<td>TDM</td>
<td>Time division multiplexing</td>
</tr>
<tr>
<td>VRC</td>
<td>Variable ratio coupler</td>
</tr>
<tr>
<td>VSWR</td>
<td>Voltage standing wave ratio</td>
</tr>
<tr>
<td>WDM</td>
<td>Wavelength division multiplexing</td>
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<td>XPM</td>
<td>Cross phase modulation</td>
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Chapter 1  Introduction

1.1  Background

With the invention of optical maser in 1958 [Schawlow and Townes, 1958], many research fields have bloomed in the optical field. One of them is ultra-fast optics, which had begun in mid 1960s with the production of narrow pulses by the mode-locked lasers [Gürs and Müller, 1963, Statz and Tang, 1964]. Today, ultra-fast pulse generation remains as an active research field. As the technologies achieve ultra-high speed transmission and greater sensitivity, the performance of fiber optic devices and systems will begin to approach their fundamental physical limits. These critical issues must be addressed in order to reach a level of understanding needed to engineer future communication networks.

Transmission using short pulses is a fundamental technology for high-speed long haul system. Among many optical transmission formats, optical soliton [Hasegawa and Tappert, 1973] - a very stable optical pulse resulted from the balancing effect between anomalous dispersion and fiber nonlinearity; offers a great potential to realize such a system. The optical soliton was first observed experimentally by Mollenauer, Stolen and Gordon in 1980 [Mollenauer et al., 1980], and the first soliton laser was constructed later
[Mollenauer and Stolen, 1984]. Since then, the research interest in soliton in optical communication community has increased tremendously. [Hasegawa, 1983] has proposed the use of soliton for transoceanic transmission, compensating the fiber loss by Raman gain, with no pulse regeneration over the entire distance. This proposal only gained in practicality after the extensive developments of erbium doped fiber amplifiers (EDFAs) [Nakazawa et al., 1989].

Many works have been done to boost the information carrying capacity of optical fibers, such as by increasing the modulation frequency, decreasing the channel spacing and utilizing efficient modulation schemes. Recent progress on optical technology has pushed the transmission limit into the Tera-Hertz range by means of time division multiplexing (TDM), wavelength division multiplexing (WDM) or polarization division multiplexing (PDM). [Nakazawa et al., 2000] had demonstrated 1.28 Tbit/s transmission over 70 km by optical time division multiplexing (OTDM) 128 channels at 10 Gbits/s, and [Sotobayashi et al., 2001] had showed a 3.24 Tbit/s transmission capacity by 81 wavelength channels at 40 Gbit/s with carrier suppressed return-to-zero (CSRZ) format. More recently, [Bigo et al., 2001] had successfully transmitted 10.2 Tbit/s (2 x 128 WDM channels x 42.7 Gbit/s) signal over 100 km by using PDM/ WDM technique. Technology advancements over the last two decades have definitely laid a good foundation for future optical communication systems.
1.2 Motivations

The demand for communication bandwidth has increased greatly over the years. It is simply due to the increase in data, voice and video transfer over the Internet. As a matter of fact, the usage of optical fiber in optical communications is still far below the channel capacity predicted by Shannon [Shannon, 1948, Tang, 2001].

With single channel, 40 GHz optical systems have become very popular in research field before penetrating to the commercial market as the electronics at 40 GHz has matured [Yoneyama et al., 2000]. Recent reports on the generation of 40 GHz optical pulses [Hansryd and Andrekson, 2001; Nakazawa and Yoshida, 2000; Yoshida et al., 1999; Bakhshi and Andrekson, 2000, Yang et al., 2004, Abedin and Kubota, 2004], possibly higher rate in the near future, has motivated me to design and construct ultra-fast and stable fiber laser sources for optical communications and applications.

Although the generation of high speed and short optical pulses by mode-locking techniques is well known, the applications of such optical pulses challenge its designer on its stability and spectral issues. On the theoretical side, the dynamics of fiber ring laser is very complex, and there are many problems related to the laser design remain unsolved. Furthermore, with the increase in transmission capacity and the use of WDM, phenomena such as four wave mixing (FWM), stimulated Raman scattering (SRS), and other nonlinear interactions; Gordon-Haus timing jitter, channel cross talk, etc. have restricted the performance of high speed optical communications.

It will be a bottleneck issue with present electronic devices in manipulating and analyzing high-speed optical signals. Hence, photonic-based signal processing devices are
essential when the repetition frequency of the optical signal gets higher. Various optical sampling techniques have been reported [Jungerman et al., 2002, Li et al., 2004] for characterizing high-speed optical signals. Other than optical sampling; optical logics [Zhang et al., 2004], switches and memories are also drawing much attention in this regard. I am keen to design novel optical systems in performing these operations, by using some peculiar properties of the fiber lasers.

1.3 Objectives

The main aim of this research work is to study both the linear and nonlinear behaviors of fiber ring lasers. I begin with the investigations of active mode-locked erbium doped fiber ring laser, in obtaining ultra-high repetition frequency for optical communications. In order to increase the system line rate without increasing the base band frequency of the modulator, some techniques have to be used.

Besides the fast operation speed, system stability is another concern for my laser systems. Hence, some stable laser structures and system stability studies are to be adopted. Moreover, nonlinearities such as self phase modulation, four-wave-mixing, parametric action, optical bistability of the fiber lasers are to be investigated.
1.4 Major Contributions of the Thesis

This thesis gives detailed investigations on the system behaviors of several fiber ring laser systems, namely active mode-locked erbium doped fiber ring laser, regenerative active mode-locked erbium doped fiber ring laser, fractional temporal Talbot based repetition rate multiplication system, parametric amplifier based fiber ring laser, regenerative parametric amplifier based fiber ring laser, and NOLM-NALM fiber ring laser.

Although some of the laser structures are common in literature, I tackle the issue from different perspectives, and hence arrive at novel system observations and analyses, such as phase plane analysis for system stability studies, Gaussian-like modulating signal in mode-locked laser systems, and frequency detuning in parametric amplifier based fiber ring laser.

The phase plane analysis, which is a subsidiary of the nonlinear control engineering, is used for the first time, to the best of my knowledge, in the laser system behavior analysis. I use it to analyze the transient and steady state behaviors of the fractional temporal Talbot based repetition rate multiplication system and rational harmonic detuning in active harmonically mode-locked erbium doped fiber ring lasers.

Conventionally, the modulating signal of a mode-locked laser system is a cosinusoidal signal. However, with a change in the pulse shape and duty cycle of the modulating signal, I achieve record high order rational harmonic mode-locked laser system. I develop an analytical mode-locking model for the Gaussian-like modulating signal, and determine its stability region for soliton-Gaussian-like pulses. In addition,
some notable remarks from the analysis have made this modulating signal a potential one in optical communications.

Phase matching condition is an essential criterion in parametric amplification systems. However, by applying some frequency detuning to the system, interesting phenomenon can be observed. I study the frequency detuning behavior in the parametric amplifier based fiber ring laser system, and ultra-high repetition rate operation is observed. I believe that this ultra-high speed operation is resulted from the combination of rational harmonic detuning and modulation instability of the system.

With my proposed nonlinear optical loop mirror - nonlinear amplifying loop mirror (NOLM-NALM) fiber ring laser, bidirectional lightwaves propagation is observed. In addition, different operation regimes are obtained numerically, namely single operation, period doubling operation and chaotic operation. However, due to hardware limitations, only the first two operations are observed experimentally. This laser structure will have good potential in various photonics applications, such as optical flip-flops and optical buffer loop, due to its peculiar operation characteristics.

1.5 Outline

The thesis is divided into four parts as shown in Fig. 1-1. The first part introduces the theories used throughout the thesis, which includes laser fundamental, pulse forming mechanism: mode-locking process and some lightwave propagation effects in the optical fiber.
The second part of the thesis, which constitutes Chapter 3, 4 and 5; is devoted to the ultra-fast operation of fiber ring lasers. I begin with a 10 GHz active mode-locked fiber ring laser and its regenerative counterpart. System behaviors such as gain performance, dispersion characteristics, mode-locking conditions, nonlinear effects are investigated. Subsequently, some techniques have been studied and used to increase the system repetition rate. Fractional temporal Talbot effect, which is the interference between dispersed optical pulses, is used to achieve four-times frequency multiplication, with base frequency of 10 GHz. Furthermore, phase plane analysis is used for the system performance studies. Rational harmonic detuning in a mode-locked laser system with a Gaussian-like modulating signal is also investigated. With this, I achieve a record-high harmonic detuning order, i.e. 660th and 1230th orders. A model based on the Gaussian-like modulating signal is developed for system analysis. In addition, I investigate the behaviors of a parametric amplifier based fiber ring laser that leads to Tera-Hertz optical pulse operation. The main principles for this ultra-high speed optical pulse generation are the combinations of modulation instability and frequency detuning. The major achievements of this part of the thesis have been published in papers [W1 – W11].

The third part of the thesis, i.e. Chapter 6, explores the properties of nonlinear optical loop mirror (NOLM) and nonlinear amplifying loop mirror (NALM) and their possible applications in optical switching and secured optical communications. I theoretically and experimentally investigate the behavior of the NOLM-NALM fiber ring laser. The basic principle of the structure is the asymmetrical nonlinear phase shifts of the lightwaves traveling within the laser. Optical bifurcations and quasi-periodic operation (route to chaos) have been confirmed from the analysis obtained both experimentally and
analytically. The main work done based on the NOLM-NALM laser structure has been published in paper [W12 – W14].

Finally, the conclusions and future prospects of this research work are given in the final part of the thesis.

Figure 1-1: Thesis outline
Chapter 2  Laser Theory

Light Amplification by Stimulated Emission Radiation (LASER) has been predicted by Albert Einstein in his theory of stimulated emission as early as 1917. However, it took about four decades before the first functioning ruby laser was realized by Maiman in 1960. Scientists were amazed by this technical breakthrough but laser technology itself had no real applications at that time. This is not exceptional; discoveries may need time before it is being put into use. Today, laser is used in a wide range of applications, such as communication, manufacturing, sensor, construction industry, medicine, military system, etc. Laser has many advantages over the normal light sources, for instance: very intense, monochromatic, plane polarized, etc. There are now different types of lasers covering different EM spectrum making them very useful for many different applications. I do not know yet if this laser knowledge and technology will be useful in the future, but I do know that the future applications are based on today's research. In this chapter, I will focus on the main ingredients of a laser, as well as the wave propagation properties in an optical medium. This will serve as an adequate foundation for the subsequent chapters in this thesis.
2.1 Fundamental of Laser Dynamics

There are three essential components that make up a laser, namely active medium, pump source and resonant cavity. The medium can be gaseous, liquid, or solid, as long as it provides the condition for laser transition. Normally, a laser is distinguished by its medium, for example fiber laser, dye laser, solid-state laser, semiconductor laser and gas laser. The medium is excited by a pump source, creating an inverted population. Most lasers are pumped electrically, meaning via collisions with either electrons or ions. Dye lasers and many solid state lasers are pumped optically; i.e. with flash-lamp type light source, or semiconductor laser. There are also chemically pumped lasers, using chemical reactions as an energy source, however are not very efficient.

The resonant cavity accounts for the amplification of the light since the path through the laser medium is passed by repeated passes back and forth, i.e. round trips. Typically this amplification grows exponentially. The more photons there are to produce stimulated emission, the higher the rate at which new coherent photons are produced. There are two general types of resonant cavity, namely Fabry-Perot and ring cavities, as shown in Fig. 2-1 and Fig. 2-2.

Fabry-Perot cavity usually consists of two mirrors separated by a distance of a multiple of half a wavelength of light; one on each end that reflect photons back and forth so that stimulated emission continues to build up. Standing wave is formed as a result of the boundary conditions that it has to satisfy within the Fabry-Perot cavity. Whereas in ring cavity, closed loop structure is formed. Usually co- and counter-
propagating running waves are oscillating within the ring. As far as this thesis is concerned, the ring cavity structure will be assumed in the following chapters.

![Figure 2-1: Typical Fabry-Perot laser](image)

![Figure 2-2: Typical ring laser configurations (A: active medium, M: mirror)](image)

### 2.2 Mode-locking Concept

Most continuous wave (CW) lasers have multi-longitudinal modes output. However, the output will only be seen in those modes for which the cavity gain is greater than the loss. If the phase relationship can be fixed or locked, then the modes constructively interfere at some points in the cavity and destructively interfere elsewhere, resulting in a single circulating pulse. If these modes of different frequencies but with random phases are added, a randomly distributed, noise-like, average output will be
produced. On the other hand, if modes of different frequencies and with same phase are added, a total field intensity output with periodic characteristic will be produced. Hence, achieving such phasing or mode locking has become a powerful method for ultra-short pulse generation.

The longitudinal mode separation or fundamental cavity frequency of a fiber ring laser cavity is $f_c = \frac{c}{nL}$, where $c$ is the speed of light in free space, $n$ is the refractive index of the fiber and $L$ is the length of ring cavity. The repetition frequency of a harmonically mode-locked fiber ring laser system will be a multiple of the fundamental cavity frequency, i.e. $f_r = qf_c$, where $q$ is the $q^{th}$ harmonic of $f_c$. If the gain bandwidth, which is associated with the emission linewidth of the laser transition, is greater than this mode separation, then there will be more than one longitudinal mode oscillating in the cavity. Normally, each of these modes is independent to each other.

![Figure 2-3: Ideal mode-locking lasing spectrum](image)

Let the time-varying amplitude of the $k^{th}$ mode be expressed as $E_k(t) = E_k e^{i(\omega_k t + \phi_k)}$, where $E_k$ is the amplitude, $\omega_k = 2\pi f_k$, is the angular frequency, $\phi_k$ is the phase of that $k^{th}$ mode. Assume that there are $N$ modes of equal amplitude, $E_k = E_0$ oscillating simultaneously in the cavity. The total intensity will be [Siegman, 1986]
\[ I(t) = |E(t)|^2 = E_0^2 \sum_{k=0}^{N-1} e^{j(\omega_k t + \phi_k)} e^{-j(\omega_0 t + \phi_0)} = NE_0^2 \] \[ \text{[Eq 2-1]} \]

By mode locking, all the modes oscillate in the same phase, i.e. \( \phi_k = \phi_0 \) for all \( k \).

\[ E(t) = E_0 e^{j\phi_0} \sum_{k=0}^{N-1} e^{j\omega_k t} = E_0 e^{j\phi_0} \left[ \frac{1 - e^{jN\omega t}}{1 - e^{j\omega t}} \right] \] \[ \text{[Eq 2-2]} \]

Therefore, the total intensity is

\[ I(t) = E_0^2 \left\| \frac{1 - e^{jN\omega t}}{1 - e^{j\omega t}} \right\|^2 = E_0^2 \frac{\sin^2 (N\omega t/2)}{\sin^2 (\omega t/2)} \] \[ \text{[Eq 2-3]} \]

The maximum value for \( I(t) \) can be determined as follows:

\[ I(t)_{\text{max}} = \lim_{\omega t/2 \to 0} E_0^2 \frac{\sin^2 (N\omega t/2)}{\sin^2 (\omega t/2)} = E_0^2 N^2 \] \[ \text{[Eq 2-4]} \]

As the number of modes increases, the pulse width decreases and amplitude increases. The period of this function is \( T = 2\pi/\omega_0 \), where \( \omega_0 \) is the angular repetition frequency and the pulse width can be approximated as \( \Delta t = T/N \approx 1/\Delta v \), where \( \Delta v \) is the full width of the generation band. Thus, mode locking results in a periodic intense pulse train, in contrast to the noisy and fluctuating output of the non-mode-locked case.

As for the real mode-locked laser, there will be a continuum of oscillating modes with non-equal amplitude distribution, i.e. \( E_k \neq E_0 \), which is Gaussian distributed:

\[ E(t) = e^{j\phi_0} \sum_{k=-(N-1)/2}^{(N-1)/2} E_k e^{j\omega_k t} = e^{j\phi_0} \int E_k e^{j\omega_k t} dk \] \[ \text{[Eq 2-5]} \]

This integral is a Fourier transform. Therefore, the amplitude of a multi-longitudinal mode in time domain is given by the transform of the amplitude distribution of modes in frequency domain. The mode-locking of a continuum of oscillating modes with a Gaussian distribution of amplitude will result in Gaussian pulses.
\[ E^2(t) \sim e^{-2 \ln 2 \frac{t}{\Delta v}} \]  

[Eq 2-6]

The pulse width of the half height of such pulses is \( \Delta t = \frac{2 \ln 2}{\pi \Delta v} = 0.441 \frac{\lambda}{\Delta v} \). This is valid provided the mode-locking is considered for the simple relation, i.e. fixed phase relationship. In this case, the generated pulse is the transform limited pulse. The duration of such pulses is minimal and is defined by the oscillating spectra width.

In general, there are two main types of mode-locking mechanisms, namely active and passive mode locking. Active mode-locking uses external driving source, such as amplitude or phase modulator to achieve mode-locking operation at modulation frequency of the source. Whereas passive mode-locking employs a nonlinear element, such as saturable absorber in the cavity which then generates optical pulse trains at the fundamental frequency of the laser. By using the active mode locking technique, higher repetition rate optical pulse train can be obtained (~GHz), however with broader pulse width (~ps). Furthermore, the generated optical pulses can be synchronized to the master clock. On the other hand, with the passive mode-locking mechanism (i.e. Additive Pulse Mode-locking (APM), Kerr Lens Modulation (KLM)), narrower pulse width can be generated (~fs), but lower repetition rate (~MHz). If active and passive mode-locking techniques are combined in one laser structure, the third method of mode-locking is introduced, called hybrid mode-locking. In a hybrid mode-locked laser [Guo et al., 2001], the optical pulses are generated in the same way as a passive mode-locked laser and synchronized by an electrical signal like an active mode-locked laser. Both techniques will be discussed in the following sections, however, with emphasis given to the active one.
2.2.1 Active Mode-locking

Active mode-locking has been demonstrated by many researchers, either with amplitude modulation (AM) [Bakhshi and Andrekson, 2000, Gupta et al., 2002], frequency modulation (FM) [Abedin et al., 1998, Yang et al., 2004] or cross phase modulation (XPM) [Greer and Smith, 1992] techniques. A research group at MIT [Roth et al., 2004] has designed and demonstrated a 40 GHz mode-locked hybrid fiber/semiconductor laser that has potential as the transmitter in the next generation (OC-768) fiber optic telecommunication systems. [Abedin and Kubota, 2004] has also demonstrated an active mode-locked dispersion managed erbium-doped fiber ring laser with repetition rate as high as 40 GHz with the use of photonic crystal fibers (PCFs) as the nonlinear medium. The high nonlinearity and large anomalous dispersion of the PCF resulted in a significant reduction in the cavity length required.

Other than the experimental works, the analytic theory of active mode-locked fiber laser by a homogeneous gain medium was firmly established in a classic paper by Kuizenga and Siegman in 1970, and the process was studied in time domain. McDuff and Harris however studied the phenomenon in the frequency domain as injection locking of cavity modes [McDuff and Harris, 1967]. Later, Haus [Haus, 1975] showed the combination of these two interpretations.

In AM mode-locking, the cavity loss is perturbed at a frequency which equals the cavity longitudinal mode spacing or its harmonics, and pulses are generated at a rate of the modulation frequency. The same working principle is applied to FM mode-locking; however, the phase of electric field is perturbed instead of the cavity loss. It is well known that the FM mode-locked pulses tend to jump back and forth between the two
phase states: up-chirp and down-chirp, resulting in unstable operation [Siegman, 1986].

Hence, I focus on AM mode-locking in the discussion here.

![Figure 2-4: AM mode-locking](image)

For an ideal AM mode-locking with a modulation index of \( M \) and an angular modulation frequency of \( \Omega_m \), the lasing operation is governed by the master equation as [Haus, 2000]

\[
\frac{1}{T_R} \frac{\partial a(T,t)}{\partial T} = \left[ (g-l) + \left( \frac{1}{\Omega_T^2} + jD \right) \frac{\partial}{\partial t} - \frac{M\Omega_m^2 t^2}{2} - j\delta |a|^2 \right] a(T,t)
\]  

[Eq 2-7]

This equation describes the pulse evolution of one round trip in the laser cavity, with the assumption that various effects affecting pulse evolution per round trip are small enough that they are additive. Here \( a(T,t) \) represents the slowly varying pulse envelope and the normalization \( \int |a(T,t)|^2 \, dt = W_p(T) \) gives the energy of the pulse. Note that \( T \) is the time scale of pulse evolution and \( t \) is the time scale of the individual pulses, while \( T_R \) is one round trip time. \( g \) and \( l \) are the gain and loss per round trip, \( D = \beta_2 L/2 \) with an average group velocity dispersion \( \beta_2 \) and cavity length \( L \), \( \delta = \gamma L \) with nonlinear coefficient of \( \gamma = \frac{2\pi n_2}{\lambda A_{\text{eff}}} \), where \( \lambda \) is the carrier wavelength, \( n_2 \) is the nonlinear refractive
\[ A_{ef} \] is the effective mode cross sectional area in cm², and \( \Omega_t \) is the bandwidth of the optical transmission of the laser cavity. Normally this bandwidth corresponds to the filter bandwidth incorporated in the laser.

Based on [Eq 2-7], there are two operating regimes, namely linear and nonlinear operation regimes. When the initial CW cavity power is very low, the cavity is considered as linear, and Gaussian pulse is generated. However, when the initial CW cavity power is high, so that the Kerr effect is of the same order as the group velocity dispersion (GVD), and soliton pulse is generated, i.e. the soliton-shaping effect is stronger than the pulse shaping effect of the modulator. In theory, a soliton pulse will propagate indefinitely without changing its shape. However, in practice, due to the inherent losses of the fiber, it is necessary to amplify the signal periodically.

By applying perturbation method to the master equation, it can be shown that the stable fundamental soliton pulses can be generated under the two conditions [Haus and Mecozzi, 1992, Kärtner et al., 1995, Jones et al., 1996], as follows:

\begin{align*}
\text{Condition 1:} & \quad \frac{\pi^2}{24} M\Omega_m^2 \tau^2 + \frac{1}{3\Omega_j^2 \tau^2} < \text{Re} \left[ \frac{M\Omega_m^2}{2} \left( \frac{1}{\Omega_j^2} - jD \right) \right]^\frac{1}{2} \quad \text{[Eq 2-8]} \\
\text{Condition 2:} & \quad \frac{\pi^2}{24} M\Omega_m^2 \tau^2 - \frac{1}{3\Omega_j^2 \tau^2} < 0 \quad \text{[Eq 2-9]}
\end{align*}

where \( \tau \) is the soliton pulse width. Under condition 1, the soliton pulses experience zero net gain or loss, but noise being suppressed. In other words, the laser pump power will have a limit, due to gain saturation, beyond which the background noise will have sufficient gain to build up. The shortest achievable pulse width, at maximum pump power, can be estimated from the left boundary of the stable region decided by condition.
1. Under condition 2, energy fluctuations of the generated soliton pulses are damped, resulting in stable output pulses. It should be pointed out that the above analysis only considers the effects of average laser parameters and not local characteristics of the laser cavity. Nevertheless, it gives a clear picture for stable soliton pulse generation. Figure below shows the stable operation region where Condition 1 and Condition 2 are simultaneously met.

![Figure 2-5: Stability region of soliton pulses](image)

2.2.2 Passive Mode-locking

Passive mode locking is a result of Kerr effect, which is based on the nonlinear intensity dependent index of refraction. It can be realized by slow or fast saturable absorbers [Haus, 2000], Kerr lens mode locking (KLM) [Spence et al., 1991], additive pulse mode-locking (APM) [Kean et al., 1989, Ippen et al., 1989], etc. More recently,
[Yamashita et al., 2005] had also demonstrated passive mode-locking by incorporating a carbon nanotube based saturable absorber within a Fabry-Perot laser.

The use of nonlinear optical loop mirror (NOLM) and nonlinear polarization rotation in optical fibers are two means of achieving fast saturable absorption. The resultant intensity profile in the cavity, before mode-locking realization, is fluctuating due to the random phases of the individual modes. This will be the case until the intensity in the cavity reaches, due to pumping, a value which is large enough to saturate the absorber. Then the absorber will start to act in a nonlinear fashion by discriminating between high and low intensities pulses. The absorber passes the initially high intensity pulses with lower loss because they tend to saturate it, and absorbs the low intensity ones. If the process continues, it will turn into an effectively transparent barrier, to the high intensity pulses after many round trips. Eventually, only one extremely narrow pulse remains in the cavity because all the other pulses are almost completely annihilated. This pulse is circulating periodically in the cavity that generates an output in the form of a mode-locked pulse train.

2.3 Optical Pulse Propagation

As optical pulses propagate in an optical fiber, their temporal and spectral characteristics are subject to changes, which depend on the properties of fiber and the pulse itself. Usually, the propagation effects can be classified as linear or nonlinear, depending on the optical intensity of the pulse. Linear effects, i.e. when the optical intensity is low, mainly affect the pulse temporal shape, such as pulse broadening and
attenuation. Nonlinear effects, i.e. when the optical intensity gets higher, however will cause the spectral changes, such as spectral broadening, frequency shift and additional frequency generation. This section provides an introduction to various linear propagation effects such as attenuation and dispersion; as well as nonlinear effects such as self phase modulation and four-wave mixing.

2.3.1 Attenuation and Amplification

Fiber attenuation is the reduction of signal strength or light power over the length of the fiber and it is measured in decibels per kilometer (dB/km). Attenuation of an optical signal varies as a function of wavelength. It is very low, as compared to other transmission media such as copper, coaxial cable, and etc., with a typical value of 0.35 dB/km at 1300 nm and 0.2 dB/km at 1550 nm for standard single-mode fiber. This gives an optical signal the ability to travel longer distances without regeneration or amplification.

Attenuation is caused primarily by scattering and absorption. The scattering of light from molecular level irregularities in the glass structure leads to the general shape of the attenuation curve, as shown in Fig. 2-6. Further attenuation is caused by light absorption by residual materials, such as metals or water ions, within the fiber core and inner cladding. Light leakage due to bending, splices, connectors, or other outside forces are other sources of attenuation.
Fortunately, the fiber losses can be compensated by optical amplifiers. With the demand for longer transmission lengths and higher transmission capacity increases, the optical amplifiers have become an important element in long-haul optical transmission systems and to support dense division wavelength multiplexing (DWDM). There are many different types of optical amplifiers, such as semiconductor optical amplifier (SOA), erbium-doped fiber amplifier (EDFA), Raman optical amplifier (ROA), etc.

The structure of SOA is similar to basic laser, however, without feedback - two specially designed slabs of semiconductor material on top of each other, with another material sandwich in between forming the ‘active layer’. An electrical current is set running through the device in order to excite electrons which can then fall back to the non-excited ground state and give out photons. Incoming optical signal stimulates emission of light at its own wavelength. EDFA functions by adding erbium - rare earth ions, to the fiber core material as a dopant; typically in levels of a few hundred parts per million (ppm). The fiber is highly transparent at the erbium lasing wavelength of $\sim 1.5$
µm. When pumped by a laser diode, optical gain is created, and amplification occurs. When light is transmitted through matter, part of the light is scattered in random directions. A small part of the scattered light has frequencies equal to the vibration frequencies of the material scattering system. ROA functions within this small scattering range. If the initial beam is sufficiently intense and monochromatic, a threshold can be reached, beyond which light at the Raman frequencies is amplified, and exhibits the characteristics of stimulated emission, and is called stimulated Raman scattering (SRS).

### 2.3.2 Group Velocity Dispersion

Dispersion is a phenomenon in which the propagation velocity of an EM wave is wavelength dependent. In reality, small thermal fluctuations and quantum uncertainties prevent any light source from being truly monochromatic, which means that the photons in an optical pulse in fact consists of a range of different frequencies. In communication technology, “dispersion” is used to describe any process by which a signal propagating in a physical medium is degraded or broaden because various wave components of the signal have different propagation velocities within the physical medium. Dispersion relation in a Taylor series with carrier frequency $\omega_0$ is [Agrawal, 2002]

$$\beta(\omega) = n(\omega) \frac{\omega}{c} = \sum_{j=0}^{\infty} \frac{\beta_j}{j!} (\omega - \omega_0)^j$$

$$= \beta_0 + \beta_1 (\omega - \omega_0) + \frac{\beta_2}{2} (\omega - \omega_0)^2 + \frac{\beta_3}{6} (\omega - \omega_0)^3 + ...$$

[Eq 2-10]
where $\beta_n = \left. \frac{\partial^2 \beta}{\partial \omega^2} \right|_{\omega = \omega_n}$, with $\beta_n$ is the mode propagation constant, $\beta_1$, $\beta_2$, and $\beta_3$ represent the reciprocal of group velocity, GVD and third order dispersion respectively, and $n(\omega)$ is the refractive index approximated by the Sellmeier equation [Agrawal, 2002]:

$$n^2(\omega) = 1 + \sum_{j=1}^{m} \frac{B_j \omega_j^2}{\omega_j^2 - \omega^2}$$  \[Eq 2-11\]

with $B_j$ is the oscillator strength of $j^{th}$ resonant frequency, $\omega_j$. $\beta_2$ is responsible for pulse broadening, and it vanishes around zero dispersion wavelength and becomes negative in the anomalous dispersion region. In normal dispersion region (refractive index increases with the frequency of light), higher-frequency components travel slower than the lower-frequency components. However, this phenomenon is reversed in anomalous dispersion region (refractive index decreases with the frequency of light). Third order dispersion can distort the optical pulses in both linear and nonlinear regimes. Its effect is more severe when GVD approaches zero.

In optical communications, single mode fiber is used to eliminate the multimode dispersion. It is designed so that the material dispersion and waveguide dispersion cancel one another at the wavelength of interest. The exact wavelength at which zero dispersion occurs depends on the refractive index profile, fiber composition (the amount of dopants) and core diameter. It is possible to make the zero dispersion wavelength lies between 1.3 and 1.6 $\mu$m. This region of wavelengths is of great interest because the minimum absorption loss for silica fibers occurs around 1.55 $\mu$m and the amplification region of EDFA is also around that vicinity. As a result, minimum loss and minimum
dispersion, together with signal amplification can be obtained at the same wavelength range.

Pulse broadening, and hence chromatic dispersion, can be a major problem in optical communication systems for obvious reasons. A broadened pulse has lower peak intensity than the initial pulse launched into the fiber, making it more difficult to detect. Worse yet, the broadening of two neighboring pulses may cause them to overlap, leading to errors at the receiving end of the system. Other than the chromatic dispersion, higher order dispersion is also another limiting factor in ultra-high speed optical communication system. The optical transmission limit due to this higher order dispersion has been studied by Amemiya [Amemiya, 2002]; with a remarkable conclusion that the transmission lengths are limited by the factor of $1/B^n$, where $B$ is the bit rate and $n$ is the dispersion order.

One interesting fact about the anomalous dispersion of the light pulse propagation has been reported by [Wang et al., 2000]. They demonstrated experimentally superluminal light pulse propagation in a lossless anomalous dispersive medium. Superluminal implies faster than the speed of light in vacuum. The experiment has created a great deal of excitement and rekindled discussion on some fundamental issues, such as the principle of causality, the validity of Einstein’s special theory of relativity, and the possibility of a signal traveling faster than the speed of light in vacuum and so on. In a nutshell, none of the principles are violated; the observed superluminal velocity arises due to temporally advanced reshaping of different frequency components, which have undergone anomalous dispersion inside the medium.
2.3.3 Self Phase Modulation

Self-phase modulation (SPM) refers to the phenomenon in which the laser beam propagating in a medium interacts with the medium and imposes a phase modulation on itself. The refractive index of a material is not only dependent on the wavelength of the light traveling through it as discussed in the previous section, but also dependent on the intensity of the incident light. For a very intense optical pulse, the fiber refractive index changes with the relation [Agrawal, 2001]:

$$n(I) = n_0 + n_2 I$$  \hspace{1cm} [Eq 2-12]

where \(n_0\) is the refractive index of the material, \(n_2\) is the Kerr nonlinear refractive index and \(I\) is the intensity of the pulse. An optical pulse will experience phase retardation, which is proportional to the intensity-induced change in fiber refractive index [Agrawal, 2002], so that the phase delay (negative phase) is maximum at the time of peak intensity and decreases in magnitude towards both ends of the pulse.

A temporally varying phase delay implies that the instantaneous optical frequency differs across the pulse from its center frequency; the self-frequency change will be equivalent to the time derivative of the phase delay. Since the phase delay is directly proportional to the pulse intensity, the self-frequency change is also proportional to the derivative of the pulse intensity with respect to time. Fig. 2-7 shows the amplitude profile, Kerr phase retardation and its instantaneous frequency of a pulse. The variation of the frequency is negative at the leading edge and becomes positive near the trailing edge of the pulse. The variation of the pulse frequency can be treated as a frequency chirp, which is due to the modulation of the pulse's own phase as a result of Kerr nonlinearity, known as SPM, which leads to spectral broadening. The Kerr coefficient, \(n_2\) in silica fibers is in
the range of $2.2 \times 10^{-20}$ to $3.4 \times 10^{-20}$ m$^2$/W and is defined to be positive if the refractive index increases with increasing intensity. However, a more commonly used measure of the nonlinearity of a fiber is its effective nonlinearity, $\gamma = 2\pi n_2/(\lambda A_{\text{eff}})$, where $\lambda$ is the optical wavelength and $A_{\text{eff}}$ is the effective mode area of the fiber [Agrawal, 2001]. For example, standard SMF-28 fiber has an $A_{\text{eff}}$ of $\sim 60$ $\mu$m$^2$ at 1550 nm, and $\gamma$ is around the range of $1.5 - 2.3$ W$^{-1}$km$^{-1}$.

Figure 2-7: Amplitude profile, Kerr phase delay and instantaneous frequency of a pulse in optical fiber

### 2.3.4 Four-Wave Mixing

Fiber four-wave mixing (FWM) is another nonlinear process based on the modulation of refractive index in the fiber. The underlying process is the nonlinear wave mixing at four different frequencies with fiber as the nonlinear medium. Fig. 2-8 illustrates the additional frequencies generated through FWM, with the following relationship [Agrawal, 2001]:

$$\omega_{jk} = \omega_i + \omega_j - \omega_k$$  \hspace{1cm} [Eq 2-13]
The nondegenerate process starts as two waves at angular frequencies $\omega_1$ and $\omega_2$ co-propagate through the fiber. As they propagate with different frequencies, they will beat with each other continuously. The intensity modulated beat note at frequency $\omega_2 - \omega_1$ will modulate the intensity dependent refractive index of the fiber. If a third wave at frequency $\omega_3$ is added, this will, from the modulated refractive index, become phase modulation at frequency $\omega_2 - \omega_1$. Hence, developing sidebands at frequencies $\omega_3 \pm (\omega_2 - \omega_1)$. In a second process, $\omega_3$ will beat with $\omega_1$ and phase modulate $\omega_2$. As a consequence, $\omega_2$ will generate sidebands at $\omega_2 \pm (\omega_3 - \omega_1)$, where $\omega_2 + (\omega_3 - \omega_1)$ will coincide with $\omega_2 + (\omega_1 - \omega_3)$. In the degenerate case, $\omega_2$ and $\omega_3$ will coincide and we will have only two new frequencies.

For FWM process to be resonant, it requires both phase-matching condition and symmetrical frequency positioning between the waves, as follows [Agrawal, 2001]:

\[
\omega_1 + \omega_2 = \omega_3 + \omega_4 \quad \text{[Eq 2-14]}
\]
\[
\Delta \beta = \beta_1 + \beta_2 - \beta_3 - \beta_4 = 0 \quad \text{[Eq 2-15]}
\]
Here $\beta_j = \omega_j n(\omega)/c$ for $j = \{1, 2, 3, 4\}$ is the propagation constant of each wave. $\Delta \beta$ is the low power propagation mismatch. The propagation of the four waves with identical polarization states can be described by four coupled-mode equations, where $E_j$ is the complex amplitude of the wave, as follows [Agrawal, 2001]:

$$\frac{dE_1}{dz} = j\gamma_1 \left[ (|E_1|^2 + 2(|E_2|^2 + |E_3|^2 + |E_4|^2))E_1 + 2E_2^* E_3 E_4 \exp(j\Delta \beta z) \right] \tag{Eq 2-16}$$

$$\frac{dE_2}{dz} = j\gamma_2 \left[ (|E_2|^2 + 2(|E_1|^2 + |E_3|^2 + |E_4|^2))E_2 + 2E_1^* E_3 E_4 \exp(j\Delta \beta z) \right] \tag{Eq 2-17}$$

$$\frac{dE_3}{dz} = j\gamma_3 \left[ (|E_3|^2 + 2(|E_1|^2 + |E_2|^2 + |E_4|^2))E_3 + 2E_1 E_2^* E_4 \exp(-j\Delta \beta z) \right] \tag{Eq 2-18}$$

$$\frac{dE_4}{dz} = j\gamma_4 \left[ (|E_4|^2 + 2(|E_1|^2 + |E_2|^2 + |E_3|^2))E_4 + 2E_1 E_2 E_3^* \exp(-j\Delta \beta z) \right] \tag{Eq 2-19}$$

where $\gamma_j$ is the nonlinear coefficient of $\omega_j$ component, and * denotes complex conjugate. In equations [Eq 2-16 to 2-19], the first, second and third terms at the right hand side describe the SPM, cross phase modulation (XPM) from the other waves and parametric interactions respectively. The coefficients are normalized so that $|E_j|^2 = P_j$ are the optical power measured in $W$.

The corresponding equations for the partially degenerate process, e.g. when ($\omega_1 = \omega_2$) can be obtained by omitting [Eq 2-16], setting $E_1 = E_2$ in [Eq 2-17 to 2-19] and modifying frequency and phase condition in [Eq 2-14] and [Eq 2-15]. As a result, the factor 2 will be removed from the parametric interaction term in [Eq 2-17 to 2-19]. The fiber loss may be included by adding the term $-(\alpha/2)E_j$ to the right hand side of each equation $j$.

From Fig. 2-8, one could easily imagine the problems associated with WDM systems and FWM. The new frequency components generated through FWM from
different channels will lead to crosstalk between the channels. In order to reduce the
crosstalk, the channel powers have to be reduced, and hence the system SNR will be
affected. Several techniques have been proposed to reduce the crosstalk, such as unequal
channel spacing [Forghieri et al., 1994] and polarization interleaving channel [Inoue,
1991].
Chapter 3  Active Mode-locked Fiber Ring Lasers

A fiber amplifier can be converted into a laser by placing it inside a cavity designed to provide optical feedback. Such lasers are called fiber lasers. Fiber laser is an important element in all optical fiber communication systems, sensors and photonic switching systems. There are a number of operating characteristics that make the fiber lasers particularly attractive. The lasers have been shown to have: quantum limited noise, narrow pulse width (passive mode-locked fiber laser), higher repetition rate (active mode-locked fiber laser), transform limited pulses, etc. Compared with laser diode, fiber laser has many advantages, such high average optical power, low timing jitter, low pulse dropout ratio, wide wavelength tunability range, high efficiency and compatibility with fiber devices [Siegman, 1986, Abedin and Kubota, 2004]. Despite the advantages of the fiber laser, there are also difficulties, such as environmental sensitivity, unpredictable pulse spacing, bistable operation and extra spectral components. Hence, many designs have been examined, to optimize the laser operation for desired applications.

Mode-locking, a well known technique as described in the previous chapter has been used to generate optical pulses from a laser. It was first appearing in the work of [Gürs and Müller, 1963] on ruby laser and [Statz and Tang, 1964] on He-Ne laser. With the invention of Mollenauer’s soliton laser [Mollenauer and Stolen, 1984], many mode-
locked laser configurations started to boom in this area. Out of which are the simple fiber ring lasers [Ahmed and Onodera, 1996; Gupta et al., 2002], sigma lasers [Carruthers and Duling, 1996, Horowitz et al., 2000], sagnac loops [Das and Lit, 2004], figure-eight lasers [Soong and Kim, 2002], etc.; either with active or passive mode-locking technique.

3.1 Building Blocks of Active Mode-Locked Fiber Ring Laser

With the basic laser knowledge from previous chapter, let us now move on to the actual design and working mechanisms of a fiber laser. In this section, I will focus on the main building blocks that make up an active mode-locked fiber ring laser, which includes laser cavity, active medium, filter and modulator.

3.1.1 Laser Cavity Design

The most common laser cavity is known as Fabry-Perot cavity, which is made by placing the gain medium in between the two high reflecting mirrors. Ring cavities are often used to realize unidirectional operation in a laser, with the help of optical isolator. In the case of fiber ring laser, the ring cavity can be made without using mirrors, resulting in all-fiber cavity.

The total cavity length is an important design parameter, which determines the repetition frequency of the laser. The longitudinal mode separation or rather the
fundamental cavity frequency of a ring laser is: $f_c = \frac{c}{nL}$, where $L$ is the total length of cavity, $c$ is the speed of light in vacuum, and $n$ is the refractive index of the medium.

By a proper choice of refractive index profile, fiber core size and material composition, the cavity can be designed to support only one electromagnetic mode, i.e. single mode operation, with two possible polarizations. Field patterns of greater transverse variation are not guided but lost to radiation. However, there will be two polarized states of propagating lightwaves in the ring [Chen and Haus, 2000], hence two simultaneously propagating rings, which could interfere or hop between one another. This is due to the difference in group velocities of two different polarizations. In principle, there is no exchange of power between the two polarization components. If the power of the light source is delivered into one polarization only, the power received remains in that polarization. In practice, however, slight random imperfection or uncontrollable strains in the fiber result in random power transfer between the two polarizations [Saleh and Teich, 1991].

If this polarization effect is not treated properly, random pulse splitting will occur; hence, degrade the system performance and challenge the system stability. Therefore, for a better laser performance, polarization-maintaining fiber (PMF) and all polarization maintaining optical components [Nakazawa and Yoshida, 2000] could be used to maintain a constant polarization state of the lightwaves travel in the laser cavity, nevertheless with higher loss. Alternatively, a polarization controller could be used to resolve the problem.

The minimum pulse width occurs when the cavity GVD is zero in a homogeneous mode-locked laser [Kuizenga and Siegman, 1970]; however, in
inhomogeneous mode-locked laser, the generation of single soliton-like pulses is limited within a certain range of negative GVD [Lu et al., 2002]. In the small negative GVD region, the gain bandwidth limits the spectral broadening, whereas in large negative GVD region, the non-soliton spectral components destabilize the soliton pulse shaping process, and the laser generates only the incoherent pulses. Hence, small GVD is preferred for good laser performance. Generally, the resonant dispersion from the gain medium has a negligible effect on a mode-locking process for a homogeneously broadened laser [Zhou et al., 1994].

### 3.1.2 Active Medium and Pump Source

In order to compensate for the cavity losses, an amplifying element must be included, and EDFA is commonly used in this regard. The main transition of interest in EDFA is the high gain $^4I_{13/2} \rightarrow ^4I_{15/2}$ transition centered around 1550 nm, because the $^4I_{13/2}$ is the only metastable state for common oxide glasses at room temperature [Miniscalco, 1991] and gain is only available for these materials at 1500 nm $^4I_{13/2} \rightarrow ^4I_{15/2}$ emission band. The peak absorption and emission wavelengths occur around 1530 nm, therefore the operating wavelength must be chosen in the band that the emission cross section is much greater than the absorption cross section, which is around 1550 nm, the third optical communication window.

EDFA pumping with laser diode is possible around 810, 980 and 1480 nm. However, the pump wavelength of 810 nm suffers from strong excited state absorption (ESA), which causes an undesirable waste of pump photons. As a result, 980 nm and
1480 nm are more commonly used. 980 nm (InGaAs/ GaAs based lasers) pumping wavelength provides higher gain efficiency and SNR for small signal amplifiers [Digonnet, 2001]. It also gives better noise figures and quantum conversion efficiencies for power amplifiers. Quantum conversion efficiency is defined as number of photons added to signal for every pump photon coupled into the fiber. The power conversion efficiency for power amplifier is higher for 1480 nm (InGaAsP/ InP based lasers) pumping because the energy per pump photon is lower, based on $E_{ph} = \frac{hc}{\lambda}$, where $E_{ph}$ is the photon energy, $h$ is the Plank’s constant, $c$ is the speed of light in vacuum and $\lambda$ is the wavelength.

Most pump power is consumed within the first portion from the ends, leaving the middle part of the fiber present with signal and amplified spontaneous emission (ASE). At this part of the EDF, ASE will act as a pump source on the signal. This is possible only when the signal is on the long wavelength side of the ASE peak. Thus, bi-directional pumping scheme may be viewed as three series-connected amplifiers, with the middle amplifier being pumped by forward and backward propagating ASE generated in the surrounding amplifiers. The major part of gain improvement is indirectly achieved through strong ASE attenuation in the middle part of EDF [Pedersen et al., 1991].
3.1.3 Optical Filter

Optical band pass filter (BPF) is used to reduce the noise generated in the system, especially ASE. It also provides stabilization against the energy fluctuation of the pulses propagating through the cavity. When the pulse energy increases beyond the design average, it will shorten the pulse width and broaden the spectrum due to strong nonlinear effect. Pulses with a broader spectrum experience excess loss and thus energy-increase is reduced by the filtering. The reverse is true for the decrease of energy. This energy equalization by filtering acts against the gain variation over the erbium bandwidth. However, filtering is associated with the noise penalty. The pulses generated by laser require higher gain to compensate for the filter insertion loss. However, noise at the center frequency is not affected by the filter and sees excess gain. This noise eventually affects the pulse generated.
Besides the noise reduction capability, filter is also used for mode selection. The tunability of filter facilitates the selectibility of center-operating wavelength of laser. The wavelength tuning range should be within the gain bandwidth. With 3 dB bandwidth of 1 nm (≈ 125 GHz @ 1550 nm), there will be 12 longitudinal modes locked in the laser if a 10 GHz repetition pulse train is desired. However, this number will reduce to 3 if a 40 GHz pulse train is required. The number of longitudinal modes locked within a laser depends on its separation, i.e. repetition frequency and the laser bandwidth, which is very much affected by the filter bandwidth; i.e. number of longitudinal modes = (filter bandwidth) / (repetition frequency).

The larger the number of modes locked in the mode-locking, the narrower the width and the higher the intensity of the pulse generated. Therefore, a wider-band filter is needed for 40 GHz operation, however with increase in system noise level. This is the trade-off between the pulse width and system SNR.

### 3.1.4 Modulator Design

Modulator is an essential component in a mode-locked fiber ring laser. Amplitude modulator is used due to its ability to generate more stable pulses as compared to phase modulator, where the pulses have the tendency to switch randomly between two phases maxima of the modulation signal. Structurally, there are two main types of modulators, namely bulk and integrated-optic. Bulk modulators are made out of discrete pieces of nonlinear optical crystal. They feature very low insertion losses and high power handling capability. Integrated-optic modulators use waveguide technology to lower the drive
voltage. They are fiber pigtailed and compact. Due to their small size and compatibility with single mode fiber, they are widely used in many fiber laser designs [New Focus, 2002].

Both X-cut and Z-cut LiNbO$_3$ (integrated-optic modulator) are commonly used to fabricate modulators by in-diffusion of titanium to form waveguides. The other process for patterning single mode optical waveguide on LiNbO$_3$ is annealed proton exchange. In Z-cut designs, the coplanar traveling wave electrode is placed over the optical waveguide. It is possible to reverse the polarity of the modulating electric field by offsetting the electrode, forming a phase reversal electrode structure. Velocity mismatch between the microwave and optical fields in the traveling wave device can be overcome over a large modulation frequency range by suitably choosing a pattern of phase reversals. In X-cut devices, phase reversal designs are not possible since the waveguide must be placed in the gap between the electrodes to utilize the strong r$_{33}$ electro-optic coefficient. To achieve fast operation the device must be made short to overcome velocity mismatch.

The high-frequency response is limited mainly by microwave-optical velocity mismatch, since microwave loss in the short active length of the device is not large. The response at high frequencies can be improved by using a SiO$_2$ buffer layer between the electrode and the waveguide. The low dielectric constant of the buffer layer increases the microwave velocity nearer to the optical velocity, which reduces the velocity mismatch. Also, the buffer layer reduces the optical insertion loss by shielding the optical mode from the conductive electrodes [Jungerman et al., 1990].

At lower frequency (<40 GHz), X-cut structure is preferred due to its better modulation response. It is because X-cut structure has a better overlap between the
applied electric and the optical field and the absence of the phase reversals. However, when the operating frequency approaches 40 GHz, the Z-cut device is more efficient than the X-cut.

The optical transfer function of a LiNbO$_3$ electro-optic modulator can be expressed by [Zhu et al., 2001]

$$T(t) = 1 + \cos(\pi \frac{V_b + V_m \sin(\omega_m t)}{V_p})$$  \[Eq 3-1\]

where $\omega_m$ is the modulation frequency, $V_b$ is the bias voltage, $V_m$ is the modulation amplitude and $V_p$ is the half wavelength voltage that creates a $\pi$ phase shift. For the most linear operation the modulator must be biased half-on, i.e. in quadrature. Variation in the bias point with changing environmental conditions is a serious problem in LiNbO$_3$ devices.

Three main types of bias drift are generally reported: bias variation due to temperature changes via the pyroelectric effect; long term drift after applying an external electrical signal to set the bias point; and optical damage to the device due to the photorefractive effect causing bias point changes [Jungerman et al., 1990]. Pyroelectric effect is a change of electric polarization in a crystal due to the change of temperature, it is much more severe in Z-cut than in X-cut LiNbO$_3$. Over-coating Z-cut devices with a conductive layer to bleed off surface charges significantly reduces the pyroelectric bias drift. However, the drift in X-cut devices is very small; hence, no temperature control is required. Electrically biasing a modulator produces a slow drift to the final bias value. This drift depends on the bias voltage applied, the time over which the bias is applied and
the temperature. Lastly, the photorefractive effect caused by the high optical power may contribute to the bias point drift too.

3.2 AM Mode-locked Erbium-Doped Fiber Ring Laser

In an active mode-locked fiber ring laser (MLFRL), the gain medium, modulator, filter, optical isolator, polarization controller, optical fiber couplers and other associated optics are inter-connected to form a closed loop optical path, and the details are described below. By combining all of the above design considerations, a dual-pump EDF ring laser as shown in Fig. 3-2 is constructed. The laser design is based on a fiber ring cavity where a ~25 meter EDF with Er$^+$ ion concentration of $4.7 \times 10^{24}$ ions/m$^3$ is pumped by two diode lasers at 980 nm: SDLO-27-8000-300 and CosetK1116 with maximum forward pump power of 280 mW and backward pump power of 120 mW. Some of the datasheets of components used in the experiment are given in the Appendices section. Bi-directional pumping will lead to higher gain efficiency than co-pumping and counter-pumping schemes. An optimum EDF length is chosen for maximal gain to ensure good performance of the amplifier, and its calculation is given in the Appendices section.

The responsivities of the pump diode lasers are 0.7 and 0.6 respectively. The dark currents measured at -5 V is about 0.005 µA. The pump lights are coupled into the cavity by the 980/1550 nm WDM couplers; with the insertion losses for 980 nm and 1550 nm signals are about 0.48 dB and 0.35 dB respectively. A polarization independent optical isolator ensures unidirectional lasing, and provides peak isolation of 47 dB. Besides that,
it can be used to minimize the backward traveling ASE. The birefringence of the fiber is compensated by a polarization controller (PC). A tunable FP filter with 3 dB bandwidth of 1 nm and wavelength tuning range from 1530 nm to 1560 nm is inserted into the cavity to select the center wavelength of the generated signal as well as to reduce the noise in the system. In addition, it is used for longitudinal modes selection in the mode-locking process.

Pulse operation is achieved by introducing a JDS Uniphase 10 GHz lithium niobate, Ti:LiNbO_3, Mach-Zehnder amplitude modulator (MZM) into the cavity with half wave voltage, V_π, of 5.8 V and insertion loss of ≤ 7dB. The modulator is DC biased near the quadrature point such that it operates around the linear region of its characteristic curve and driven by a sinusoidal signal generated by an Anritsu 68347C Synthezed Signal Generator. The modulating depth should be < 1 to avoid signal distortion. The output coupling of the laser is optimized by a 10/90 coupler. 90% of the optical field power is coupled back into the cavity ring loop, while the remaining portion is taken out as the output of laser and is analyzed using a New Focus 1014B 40 GHz photo-detector, Ando AQ6317B Optical Spectrum Analyzer, Tektronix CSA 8000 80E01 50GHz Communications Signal Analyzer or Agilent E4407B RF Spectrum Analyzer.
By reducing the output coupling, it reduces the cavity loss and thus the round trip gain, thereby lowering the ASE power. The environmental perturbations such as temperature change, mechanical vibration, pressure variation, etc. will introduce some random phase fluctuations that broaden the linewidth. The laser is most susceptible to these perturbations when the output coupling and hence the loss is high, so by reducing the intra-cavity loss, the effects of these perturbations is minimized.

All connections between the components are made using connectors for easy access to different points of the system and fast component replacement. The loss introduced by each connector is assumed to be less than 0.5 dB. The splicing loss in the system is assumed to be small and can be neglected. Nevertheless, these 'easy access connections' will give rise to certain amount of back reflections, which will disturb the
system performance. With the help of isolator, these back reflections can be significantly reduced. The dispersion value of SMF used in my fiber laser construction is about 17 ps/ nm/ km (-21.7 ps²/ km) around 1550 nm, which is in the anomalous dispersion region, hence suitable for soliton pulse generation.

3.3 Regenerative Active Mode-locked Erbium Doped Fiber Ring Laser

One problem with MLFRL is the thermal drift of the cavity length. The change in optical path length with temperature is \( L \frac{\partial n}{\partial T} (m/ ^\circ C) \) [Tamura and Nakazawa, 1996], where \( L \) is the cavity length, \( n \) is the refractive index and \( T \) is the temperature. With \( \frac{\partial n}{\partial T} = 1.1 \times 10^{-5} / ^\circ C \) for silica fiber [Tamura and Nakazawa, 1996] and for a typical fiber length of 30 m, the optical path length fluctuates by 0.33 mm / ^\circ C. This translates to a frequency fluctuation of about 110 kHz/ ^\circ C for a 10 GHz modulation frequency. Accordingly, slight thermal variations are able to cause the pulses to lose synchronism with the modulator. Other than the thermal fluctuations, fiber lasers are sensitive to small environmental perturbations, such as polarization change, acoustic and mechanical vibrations.

Hence, the lasers do not exhibit long-term stability without stabilization techniques. One of the most obvious stabilization schemes is dynamic adjustment of the cavity length. [Shan and Spirit, 1993] have demonstrated a stabilization technique by piezoelectric transducer (PZT). A portion of the fiber in the cavity is wound around a
piezoelectric drum. By driving the drum with proper error signal, the cavity length is adjusted to keep the cavity frequency synchronous with the fixed modulator drive frequency. The control of this technique in MHz range would be difficult because of the need for either a high-voltage amplifier to drive the PZT or a PZT with a high expansion coefficient. Another technique utilizes the nonlinear polarization rotation effect to suppress the pulse amplitude fluctuations have been proposed by [Doerr et al., 1994]. Alternatively, regenerative feedback where the modulation frequency is derived directly from the pulse train can be used to stabilize the modulation. Any change in the cavity length will automatically adjust the modulation frequency to maintain the pulse-modulator synchronism. The use of regenerative feedback technique to stabilize the fiber laser was first demonstrated by [Nakazawa et al., 1994].

Figure 3-3: Block diagram of regenerative mode-locked fiber ring laser
Both the amplitude and phase noises of MLFRL and regenerative mode-locked fiber ring laser (RMLFRL) have been well studied by [Gupta et al., 2000] using spectral domain technique. It has been found that the regenerative configuration exhibits superior performance compared to the active structure, both in reduced amplitude and phase noises.

The experimental setup of the proposed RMLFRL is shown in Fig. 3-4. The newly added components are clock recovery unit, RF amplifier and modulator driver. The basic operation of RMLFRL is similar to that of MLFRL. The difference of these two schemes is the source of modulation signal. In MLFRL, the modulating signal is directly taken from the signal generator, however the modulating signal of RMLFRL is the feedback signal generated by the clock recovery unit. This will improve the laser stability as described before. Clock recovery unit is used to generate a RF sinusoidal wave at about 9.953GHz (OC-192 standard) in order to drive the modulator prior to the modulator driver and RF amplifier, which are used to amplify the RF signal in the feedback loop. Higher frequency clock recovery circuits (OC-768 standard) can be used for 40 GHz operation. However, cost is one of the main considerations for this high frequency setup.

By using this optical-RF feedback to control the modulation of the intensity modulator, the output optical noise must be significantly greater than the electronic noise for the start-up of the mode-locking and lasing. In other words, the loop gain of the optical-electronic feedback loop must be greater than unity. Thus, it is necessary for the EDFA to operate in the saturation mode and the total average optical power circulating in the loop must be sufficiently adequate for the detection at the photo-detector and
electronic preamplifier. Under this condition, the optical quantum shot noise dominates the electronic shot noise.

![Figure 3-4: Regenerative active mode-locked fiber ring laser](image)

**3.4 Results and Discussion**

The experimental procedures and precautions for MLFRL and RMLFRL are given in Appendix III. A systematic experimental procedure must be followed in order to ensure accurate results and avoid unnecessary faults or problems in the later stage of the experiments. Extra care must be given to the handling of the equipment and components to prevent possible damages, due to their high operating frequency and sensitivity.
3.4.1 Noise Analysis

There are two major sources of noise generated at the input of photo-detector, namely optical quantum shot noise generated by the detection of optical pulse trains and electronic random thermal noise generated by the small signal electronic amplifier following the detector. The optical quantum shot noise spectral density \( A^2/Hz \) is defined as \( S_s = 2qRP_{av} \) with \( R \) is the responsivity of detector, \( q \) is the electronic charge and \( P_{av} \) is the average optical power. Suppose that a 1 mW (or 0 dBm) average optical power is generated at the output of mode-locked laser and with detector responsivity of 0.8, then the optical quantum shot noise spectral density will be \( 2.56 \times 10^{-22} A^2/Hz \).

Usually the electronic amplifier will have a 50 \( \Omega \) equivalent input resistance, \( R_{eq} \), referred to the input of the optical preamplifier as evaluated at the operating repetition frequency. This gives a thermal noise spectral density of \( S_R = \frac{4kT}{R_{eq}} \) with \( k \) the Boltzmann’s constant, which equals to \( 3.312 \times 10^{-22} A^2/Hz \) at 300 K.

Depending on the electronic bandwidth, \( B_e \) of the electronic preamplifier and optical bandwidth, \( B_o \) of the photo-detector, the total equivalent electronic thermal noise, \( i^2_{NT} \) and optical quantum noise, \( i^2_{NS} \) (square of noise current) are given as follows:

\[
\begin{align*}
  i^2_{NT} &= S_R B_e \\
  i^2_{NS} &= S_s B_o
\end{align*}
\]  

[Eq 3-2]

Under the worst case scenario, when a wideband amplifier of a 3 dB electrical and optical bandwidth of 10 GHz, the equivalent electronic noise at the input of the electronic amplifier is \( 3.312 \times 10^{-11} A^2 \), i.e. an equivalent noise current of 5.755 \( \mu A \) and
the equivalent optical noise is $2.56 \times 10^{-11} \text{ A}^2$, i.e. an equivalent noise current of 5.060 µA are present at the input of the clock recovery unit. This corresponds to a SNR of 40.4 dB. If a narrowband amplifier of 50 MHz 3 dB bandwidth centered at 10 GHz is employed, the equivalent electronic and optical noises current will be 0.129 µA and 0.113 µA respectively, and the corresponding SNR is 73.3 dB.

The average optical power generated by the mode-locked laser must be high to obtain a high SNR at the input of the photo-detector. In order to counteract with the noises and losses within the ring laser, EDFA with high output and saturation power should be employed.

### 3.4.2 Temporal & Spectral Analyses

With a +17 dBm ($V_{\text{rms}} = 1.58 \text{ V}, V_{\text{peak}} = 2.24 \text{ V}$) modulating signal of about 9.954365 GHz applied to the MZM that is biased near the quadrature point (around 2.9 V, half of $V_p$) on its transfer characteristic curve, the observed pulse train and spectrum of MLFRL are shown in Fig. 3-5. As for RMLFRL, the frequency and power level of the modulating signal are set by the clock recovery unit with clock frequency of about 9.953 GHz ± 10 MHz and modulator driver with saturation power of +23 dBm. The corresponding output waveforms are shown in Fig. 3-6. The polarization controller prior to the modulator is adjusted to a desired position that gives maximum output intensity. The EDFA is pumped at the deep saturation region to ensure full inversion of the erbium ions. The shortest and most stable optical pulses are obtained by careful adjustment of the RF drive frequency for the MLFRL and polarization of the circulating
light. As discussed before, RMLFRL provides better stability as compared to MLFRL. Higher peak power is obtained in RMLFRL configuration, hence reduces the number of pulses being dropout, and better system stability.

The Time-Bandwidth-Products for MLFRL and RMLFRL are 0.38 and 0.50 respectively, close to the transform limited value (0.315 for sech$^2$ pulse and 0.441 for Gaussian pulse), however with a bit of frequency chirping. This nonlinear chirping in the initial mode-locked pulses will degrade the quality of the multiplied pulses if fractional temporal Talbot effect is employed to increase the system repetition rate.

A triggering signal for the oscilloscope must be generated for RMLFRL. The RF feedback signal produced by the clock recovery circuitry has to be divided into two paths: triggering and driving signals. Hence, the RF signal generated by the clock recovery unit and later amplified by the RF amplifier must be at least 3 dB more than the minimum power required by the oscilloscope.

A slight wavelength or frequency shift is observed in RMLFRL. This is because the RF modulating frequency may vary within the bandwidth of the clock recovery unit; and hence, the lasing mode may lock to another mode of the ring cavity.

Figure 3-5: (a) Optical pulse train and (b) spectrum of MLFRL
3.4.3 Measurement Accuracy

To maintain the fidelity of measurements, every component in the system needs to have a bandwidth greater than the 3 dB bandwidth of the signal, or equivalently, an impulse response faster than the fastest part of the signal. For a transform limited secant or Gaussian pulse, the equipment 3 dB bandwidth should be greater than $0.315 / \text{FWHM}$ (for secant pulse) or $0.441 / \text{FWHM}$ (for Gaussian pulse). From the measurements taken (as shown in Fig. 3-5 and Fig. 3-6), the signal bandwidth of the both configurations are $\sim 34 \text{ GHz}$ and $\sim 45 \text{ GHz}$ respectively, which are within the 3 dB bandwidth of the photodetector (45 GHz) and the oscilloscope (50 GHz). As for the signal with bandwidth greater than the equipment 3 dB bandwidth, the measurement made by the equipment is incorrect because the pulse width shown on the scope is depending on the convolution of many bandwidths, including those of the signal, photodiode and the oscilloscope. However, the pulse width of the signal can still be estimated using the following relationship [New Focus, 2002]:
\[
\tau_{measured} = \sqrt{\tau_{optical}^2 + \tau_{photodiode}^2 + \tau_{jitter}^2 + \tau_{electrical}^2}
\]  \[\text{Eq 3-3}\]

where \(\tau_{measured}\) is the measured signal pulse width on the oscilloscope; \(\tau_{optical}\) is the optical pulse width; \(\tau_{photodiode}\) is the impulse response of the photo-detector; \(\tau_{jitter}\) is the timing jitter, including pulse-to-pulse laser timing fluctuation, synthesizer jitter and etc.; and \(\tau_{electrical}\) is the impulse response of the electrical equipment.

Rise time (10%-90%) of the photodetector, \(\tau_{photodiode} = 9\) ps

Rise time of the Tektronix CSA 8000, 80E01 module, \(\tau_{electrical} = 7\) ps

Time jitter of CSA, \(\tau_{jitter} = 2.5\) ps when locked to 10 MHz reference

Other important factors to keep in mind are the bandwidths of the cables, connectors and pulse-to-pulse jitter of the laser. Because the sampled oscilloscope trace is made up of data taken from many different pulses, time jitter can broaden the measured signal. The pulse widths measured for non-feedback and feedback loop are 11.12 ps and 11.10 ps respectively.

### 3.4.4 EDF Co-operative Up-Conversion

The output characteristics of EDFA used in the systems are shown in Fig. 3-7. A saturation power of about 18 dBm and a maximum gain of about 30 dB and a noise figure of about 7 dB are obtained through measurement. The power conversion efficiency of EDF is about 50%.
Both the non-feedback and feedback configurations are operating in the deep saturation mode to ensure sufficient power to sustain the nonlinear effect within the ring cavity. However, this may lead to some side effects within the system. The amplifier efficiency may degrade due to Er$^{3+}$ ion - Er$^{3+}$ ion interaction, through co-operative up conversion [Miniscalco, 1991]. When two excited ions interact, one can transfer its energy to the other, leaving itself in the ground state and the other in higher $^4I_{9/2}$ state. In oxide glasses, the $^4I_{9/2}$ level quickly relaxes through multi-phonon emission back to the $^4I_{13/2}$ state, the net result of the process being to convert one excitation into heat [Miniscalco, 1991]. Since co-operative up conversion requires two interacting ions in the excited state, it will not be evident at low pumping levels. Nevertheless, at high pump powers it will appear as accelerated and non-exponential decay [Miniscalco, 1991]. This up conversion process leads to loss of inversion without emission of a stimulated photon.

Polarization hole burning is another important effect that is related to the saturation properties of EDFA. Nominally, the amplifier gain is polarization insensitive. However, if one polarization saturates the amplifier, a slight excess gain is left over in the
other polarization. Noise can grow in this polarization and affect the system performance [Wang et al., 1998].

### 3.4.5 Pulse Dropout

When energy in the cavity is very low, the nonlinear effect can be neglected. This results in noisy pulses, exhibiting amplitude and pulse shape fluctuations. This noisy behavior, which leads to supermode competition in the frequency domain, is due to lack of stabilization from the nonlinear effects, so that the pulse amplitude can change without affecting its bandwidth. When the pump power is increased to such a level where the nonlinear effects become important and it will eventually decrease the pulse duration. The direct interaction between pulses in the active mode-locked laser is weak due to the presence of modulator; however, the pulses interact indirectly via the amplifier. Because of the slow response time of the EDFA (millisecond life time of erbium), the pulses all affect the amplifier saturation, leading to highly complex dynamics. Complex interactions of all pulses with the gain medium and mode locker lead to some pulses to drop out and others to stabilize with similar shapes and amplitudes. The dropout occurs since some pulses can decrease their loss in the mode locker by increasing their energy and decreasing their duration due to soliton shortening effect. The increase in the energy of those pulses decreases the amplifier gain due to amplifier saturation effects and causes net loss in a round trip to other pulses that will eventually drop, while the remaining pulses will possess nearly identical shapes and amplitudes. Fig. 3-8 shows the average output pulse train with pulse dropout effect. As the pump power increases, the fraction of pulses that dropout decreases. However, it is expected the number of filled slots is also
depending on the previous state of the laser. The amplitude of the pulses will be stabilized when all the slots are filled, and this is achieved by a higher pump power. When the repetition rate increases, the minimum average power that is needed for stable operation will also increase.

The output pulse train of the harmonically mode-locked fiber ring laser will experience some pulse dropouts if the operating intracavity power is below the minimum required power for stable operation [Horowitz et al., 2000, Horowitz and Menyuk, 2000]:

\[
P_{\text{min}} = \sec h^{-1} \left( \frac{1}{\sqrt{2}} \frac{ED\omega_m^{3/2}}{\pi \gamma_{nl}} \left[ \frac{8M\omega_k^2 \langle x^2 \rangle}{G(\omega_m^2)} \right]^{1/4} \right)
\]  

[Eq 3-4]

where \( E \) is the energy enhancement factor [Smith et al., 1997], \( D \) is the average dispersion, \( M \) is the modulation depth, \( G \) is the average gain coefficient, \( \omega_m \) is the modulation frequency, \( \omega_g \) is the amplifier bandwidth, \( \gamma_{nl} \) is the nonlinear coefficient, and

\[
\langle x^2 \rangle = \frac{\int_{-\infty}^{\infty} |f(x)|^2 x^2 \, dx}{\int_{-\infty}^{\infty} |f(x)|^2 \, dx}, \quad \langle \omega^2 \rangle = \frac{\int_{-\infty}^{\infty} |df(x)/dx|^2 \, dx}{\int_{-\infty}^{\infty} |f(x)|^2 \, dx}, \quad \text{and } f(x) \text{ is the pulse shape function.}
\]

\[
\frac{\langle \omega^2 \rangle}{\langle x^2 \rangle} = \frac{4(2 \sec h^{-1}(2^{-1/2}))^4}{\pi^2} \text{ for hyperbolic secant pulses and } \frac{\langle \omega^2 \rangle}{\langle x^2 \rangle} = [4 \ln 2]^2
\]

for Gaussian pulses. When the intracavity power is less than \( P_{\text{min}} \), the laser generates a limited number of short and intense pulses with a pulse width shorter than \( \tau_{\text{max}} \), while other pulses are dropped from the pulse train. \( \tau_{\text{max}} \) is the maximum value of full width at half maximum for stable operation as follows [Horowitz et al., 2000]:

\[
\tau_{\text{max}} = \left[ \frac{2G(\omega_m^2)}{M\omega_k^2 \langle x^2 \rangle} \right]^{1/4}
\]  

[Eq 3-5]
With Gaussian pulse shape assumption, average dispersion of 17 ps/nm/km, modulation depth of 0.5, 10 GHz modulation frequency, average gain of 12 dB (G = 15.85), amplifier bandwidth is approximated to the filter bandwidth of ~125 GHz @ 1550 nm, nonlinear coefficient of $2 \, \text{W}^{-1} \, \text{km}^{-1}$, and assume minimum power enhancement factor of 1, the calculated $\tau_{\text{max}}$ and $P_{\text{min}}$ are 21.15 ps and 18.08 mW (12.55 dBm) respectively. Stable soliton pulse operation is hardly achievable with current amplifier and components set. To reduce the pulse dropout, lower dispersion and higher nonlinearity fiber can be used in place of SMF, reduce the modulation frequency and use higher gain amplifier.

Another possible reason for this pulse dropout is the supermode competition [Horowitz et al., 2000] between the modes locked within the laser. With a total cavity length of about 30 meters, the fundamental cavity frequency is about 6.8966 MHz (Please note: n is assume to be typical value of 1.45). For a repetition rate of 10 GHz, the locking will occur around 1450th harmonic mode. Approximately, there are 1450 pulses simultaneously propagate inside the laser cavity some of them may drop from the pulse.
train and cause errors in the system. In RMLFRL, the output pulses will be used to drive the amplitude modulator of the laser. The clock information will be successfully extracted by the clock recovery unit even with pulse dropouts.

### 3.5 Conclusions

Mode locked fiber ring lasers operating without and with RF feedback providing regenerative mode locking are demonstrated. The opto-electronic RF feedback can certainly provide a self-locking mechanism under the condition that the polarization characteristic of the ring laser is controllable. This could be implemented by ensuring that all fiber paths are under constant operating condition. The regenerative mode-locked fiber ring laser can self-lock even under the DC drifting effect of the modulator bias voltage (over several hours).

In order to successfully generate stable ultra-fast and ultra-short pulses, the modes in the mode-locked fiber ring laser must retain their phase relationship at all times so that the mode locking is stable. This requires all modes experience the same round trip cavity time. In general, this will not be the case due to the presence of frequency dependent dispersion in the cavity. That is the pulse will experience group velocity dispersion as it travels through the cavity. Therefore, the dispersion value of the cavity should be kept as minimum as possible.
Chapter 4  Ultra-Fast Repetition Rate Generators

The generation of high repetition rate pulses is very important for future ultrahigh bit rate optical communication systems. Active MLFRL is a potential source of such pulses. However, the pulse repetition rate is usually limited by the bandwidth of the intracavity modulator. Hence, some techniques have to be applied to increase the repetition frequency of the pulses generated. In this chapter, I will focus on the generation of high repetition frequency optical pulses using the fractional temporal Talbot effect and brief explanation on some other repetition rate multiplication techniques. The stability studies using phase plane analysis will also be given. Phase plane analysis is commonly used in nonlinear control system, and this is for the first time, at least to the best of my knowledge, that the technique is being applied in the repetition rate multiplication laser system.

4.1 Repetition Rate Multiplication Techniques

In order to increase the system line rate, many repetition rate multiplication techniques have been proposed and demonstrated. Out of which are rational harmonic
detuning [Lin et al., 2004], fractional temporal Talbot effect [Azana and Murie, 1999 & 2001], intracavity optical filtering [Gupta et al., 2002], higher order FM mode-locking [Abedin et al., 1998], optical time domain multiplexing [Daoing et al., 1999, Yamada et al., 1995], etc. [Longhi et al., 2000] had shown a 16-times multiplication; achieving 40 GHz, 10 ps pulse train from a base rate of 2.5 GHz mode-locked optical pulses using a 100 cm linearly chirped fiber grating. More recently, [Azana et al., 2003] demonstrated the use of short superimposed amplitude and phase fiber Bragg grating (FBG) structures to generate ultra-high repetition rate pulse bursts, i.e. 170 GHz optical pulse train from a 10 GHz mode-locked fiber laser. Besides FBG, dispersive fiber has also been used to achieve the same objective [Arahira et al., 1998, Chestnut et al., 2002].

4.1.1 Fractional Temporal Talbot Effect

Self-imaging effect of a plane periodic grating, when the grating is illuminated by a monochromatic light beam, was reported by Talbot in 1836 [Talbot, 1836], known as Talbot effect. This effect has been widely used in several optics fields, such as holography, image processing and synthesis, photolithography, optical testing, optical computing and optical metrology. Whereas, fractional Talbot effect refers to the superimposition of shifted and complex weighted replicas of the original object resulted from the diffraction of a periodic object at fractions of the Talbot distance [Hamam, 1997] in spatial domain, and fractional temporal Talbot effect refers to the interference effect between dispersed pulses in optical fiber [Azana and Muriel, 2001] and is in time domain. By using this interference effect, one can achieve system repetition rate multiplication. The essential element of this technique is the dispersive medium, such as
linearly chirped fiber grating (LCFG) and dispersive single mode fiber. Out of which, LCFG can be designed to provide the required bandwidth and dispersion characteristics in a more compact form.

When a pulse train with repetition rate of $f_r$ is transmitted through optical fiber, the phase shift of $k^{th}$ individual lasing mode due to GVD is [Arahira et al., 1998]

$$\varphi_k = \frac{\pi\lambda^2 D z k^2 f_r^2}{c} \quad [\text{Eq 4-1}]$$

where $\lambda$ is the center wavelength of the mode-locked pulses, $D$ is the GVD of fiber, $z$ is the fiber length, and $c$ is the speed of light in vacuum. This phase shift generally induces pulse broadening and distortion. When $\varphi_k$ is $2\pi k^2$ (no phase shift between the lasing modes) or its multiple, the initial pulse shape is restored even after fiber transmission as long as the coherence of each lasing mode is maintained. This corresponds to

$$z_r = \frac{2c}{\lambda^2 |D| f_r^2} = \frac{2}{\Delta\lambda f_r |D|} \quad [\text{Eq 4-2}]$$

Where $\Delta\lambda = f_r \lambda^2 / c$ is the spacing between spectral components of the pulse train. In contrast, when the fiber length is equal to $z_r / (2m)$, (where $m = 2,3,4, \ldots$), every $m^{th}$ lasing modes oscillates in phase and the oscillation waveform maximums accumulate. However, the phases of other modes become mismatches, weakening their contributions to pulse waveform formation. This leads to the generation of a pulse train with a multiplied repetition frequency with $m$-times. The highest repetition rate obtainable is limited by the duration of the individual pulses, as pulses start to overlap when the pulse duration becomes comparable to the pulse train period, i.e. $m_{\text{max}} = \Delta T / \Delta t$, where $\Delta T$ is the pulse train period and $\Delta t$ is the pulse duration.
The pulse width does not change much even after the multiplication, because every $m^{th}$ lasing mode dominates in pulse waveform formation of $m$-times multiplied pulses. The pulse waveform therefore becomes identical to the one generated from the mode-locked laser, with the same spectral envelope. Optical spectrum does not change after the multiplication process, because this technique utilizes only the change of phase relationship between lasing modes and does not use the nonlinearity of fiber. The effect of higher order dispersion might degrade the quality of the multiplied pulses, i.e. pulse broadening, appearance of pulse wings and pulse-to-pulse intensity fluctuation. In this case, any medium to compensate for the higher order dispersion would be required in order to complete the multiplication process. In order to achieve higher multiplications the input pulses must have a broad spectrum. The fractional Talbot length must be very precisely determined in order to receive high quality pulses. If pulses exist in the nonlinear regime and experience anomalous dispersion along the fiber, solitonic action will take place and prevent the linear Talbot effect from occurring.

4.1.2 Other Repetition Rate Multiplication Techniques

In this section, I would like to give a brief description on other repetition rate multiplication techniques available to date, such as intracavity filtering and optical time division multiplexing. Rational harmonic detuning is another simple technique, which has been widely adopted to increase the repetition rate. However, I will only discuss it in the next chapter.
Intracavity optical filtering uses modulators [Gupta et al., 2002] and a high finesse Fabry-Perot filter (FFP) within the laser cavity to achieve higher repetition rate. In a conventional AM harmonically mode-locking, a RF modulation frequency $f_m = qf_c$ is applied to modulator placed inside the ring cavity to lock the phase of the longitudinal modes with frequency spacing equal to $f_m$. In a MLFRL, when intracavity optical filtering via a FFP with free spectral range (FSR) equal to $f_m$ is introduced, the phase-locked longitudinal modes with frequency spacing equal to FSR are synchronized to the transmission peaks of FFP and are passed through the filter, while the intermediate cavity resonance modes are blocked by the FFP. This results in the generation of highly stable optical pulse trains with repetition rate equal to FSR.

When the modulation frequency is a subharmonic multiple of the FSR of FFP is applied to the modulator, the generated optical pulses will have repetition rate equal to FSR. It is important that the modulation frequency $f_m$ must not only be a harmonic multiple of the cavity resonance frequency $f_c$, but also a subharmonic multiple of FSR of FFP, such that $f_m = \text{FSR}/m$, where $m$ is the subharmonic number. When the FSR of FFP is an integer multiple $m$ of one of the longitudinal modes of the cavity, the intermediate modes are suppressed, resulting in an optical pulse train with repetition frequency of FSR or $f_r = mf_m$, hence increasing the repetition rate of the optical pulse train. In addition, selective filtering of randomly oscillating intermediate longitudinal modes via intracavity FFP also leads to enhanced pulse stability in the generated optical pulse train, e.g. lower supermode noise, amplitude noise, phase noise or timing jitter.

Another method used to increase the repetition frequency of the system is optical time division multiplexing (OTDM) technique. It is done by creating certain time delay
for each multiplexed optical path, so as to fill up the gap between the original optical pulses. [Daoping et al., 1999] has shown an 8-times repetition rate multiplication utilizing three loop-connecting fiber couplers, achieving 20 GHz optical pulse train. Yamada and group have also demonstrated 640 GHz - 1.28 THz pulse trains by using a seven-step Mach-Zehnder interferometer, which is formed on silica based planar lightwave circuit [Yamada et al., 1995]. [Seo et al., 2003] have also demonstrated 500 GHz optical pulse train generation using arrayed waveguide grating (AWG) under this principle. However, owing to coherent interference between the OTDM channels, the maximum feasible increase in the system line rate using a practical multiplexer is limited. Also, the multiplied pulses suffer from severe amplitude modulation and each burst of pulses lies at different wavelength. Furthermore, this technique requires a precise adjustment of the optical path delay.

4.2 Phase Plane Analysis

Phase plane analysis is a graphical method of studying the second-order nonlinear systems. The result is a family of system motion of trajectories on a two-dimensional plane, which allows us to visually observe the motion patterns of the system. Nonlinear systems can display more complicated patterns in the phase plane, such as multiple equilibrium points and limit cycles. Do not underestimate the usefulness of visualizing things. Sometimes a picture is worth a thousand words. Phase plane analysis has been used to analyze many practical systems, such as automatic control systems, movement studies, intersegmental coordination, etc.
Second order nonlinear systems have two state variables, and a phase plane is simply a plot of the two state variables against each other. It is called a phase plane because state variables were called phase variables in the old days.

In the phase plane, a limit cycle is defined as an isolated closed curve. The trajectory has to be both closed, indicating periodic nature of the motion, and isolated, indicating the limiting nature of the cycle [Slotine et al., 1991]. If all neighboring trajectories approach the limit cycle, we say the limit cycle is stable or attracting, otherwise the limit cycle is unstable or marginally stable. Stable limit cycles models systems that exhibit self-sustained oscillations. In other words, these systems oscillate even in the absence of external periodic forcing. If the system is perturbed slightly, it always returns to the standard cycle [Strogatz, 1994].

![Phase planes with (a) stable, (b) marginally stable and (c) unstable limit cycles](image)

**Figure 4-1**: Phase planes with (a) stable, (b) marginally stable and (c) unstable limit cycles

### 4.3 Experimental Setup

The input to the fractional temporal Talbot multiplier is the output pulse train obtained from the 10 GHz active harmonically MLFRL as described in Section 3.2. The multiplier is made up of a rim of about 3 km of dispersion compensating fiber (DCF),
with the dispersion value of \(-98\ \text{ps/nm/km}\). The schematic of the experimental setup is shown in Fig. 4-2. The variable optical attenuator is used to reduce the optical power of the pulses generated by the MLFRL, hence remove their nonlinear effect before enter the multiplier. Based on the calculation, the required length of DCF for 4-times multiplication on a 10 GHz signal is 3.185457 km.

![Schematic of experimental setup](image)

**Figure 4-2: Fractional temporal Talbot based repetition rate multiplication system**

### 4.4 Results and Discussion

The original and multiplied pulse trains and their spectra are shown in Fig. 4-3. The input to the multiplier is a 10.217993 GHz pulse train, obtained from the active harmonically MLFRL, operating at 1550.2 nm, as shown in Fig. 4-3 (a) & (b). The spectra of the un-multiplied and multiplied signals are the same. This is simply because the Talbot effect is using only the linear phase difference to achieve the repetition rate.
multiplication and not the fiber nonlinearity, hence, no change in the spectra should be observed. The linewidth separations for the both cases are about 0.08 nm.

![Figure 4-3: Original 10 GHz un-multiplied (a) pulse train and (b) its spectrum; 40 GHz multiplied (c) pulse train and (d) its spectrum](image)

The stability of high repetition rate pulse train is one of the main concerns for practical high speed optical communications systems. Conventionally the stability analyses of such pulses are based on the linear behavior of the laser in which we can analytically analyze the system behaviors in both time and frequency domains. However, when the MLFRL is operating under nonlinear regime, none of these standard approaches can be used, since direct solution of nonlinear different equation is generally impossible, hence time-frequency domain transformation is not applicable. Although fractional temporal Talbot based repetition rate multiplication systems are based on the linear behavior of the laser, there are some inherent nonlinearities affecting its stability,
such as saturation of the embedded gain medium, non-quadrature biasing of the modulator, fiber nonlinearities, etc., hence, nonlinear stability approach must be adopted. Here, I focus on the stability and transient analyses of the Talbot based multiplied pulse trains using phase plane analysis – a class of nonlinear control analytical techniques [Slotine et al., 1991]. This is the first time, to the best of my knowledge that the phase plane analysis is being used to study the stability and transient performances of the fractional temporal Talbot based repetition rate multiplication systems.

The system modeling for the fractional temporal Talbot multiplier is done based on the following assumptions:

- Perfect output pulse from MLFRL without any timing jitter.
- The multiplication is achieved under ideal conditions (i.e. with exact fiber length for certain dispersion values).
- No fiber nonlinearity and noise are involved in the system.
- Both equal and Gaussian lasing mode amplitude analyses are used.
- The simulation is accurate to picosecond optical pulses. When the mode-locked optical pulses reach femtosecond or sub-femtosecond region, more fundamental considerations have to be included.
4.4.1 **Uniform Lasing Mode Amplitude Distribution**

Uniform lasing mode amplitude distribution is assumed at the first instance, i.e. ideal mode-locking condition. The system is simulated using Matlab software and based on the summation of individual mode as described in Section 2.2. The simulation parameters are based on the 10 GHz pulse train, centered at 1550 nm, with a fiber dispersion factor of -98 ps/km/nm, a 1 nm flat-top passband filter is used in the cavity of MLFRL. The estimated Talbot distance is 25.484 km.

The original pulse (direct from the mode-locked laser) propagation behavior and its phase plane are shown in Fig. 4-4 (a) and Fig. 4-5 (a). As for the phase planes shown in the following sections, the x-axes are $E(t)$ - signal energies and y-axes are their derivatives; solid and dotted lines represent the real and imaginary parts of the energies respectively. From the phase plane obtained, one can observe that the origin is a stable node and the limit cycle around that vicinity is a stable limit cycle. This agrees very well to my first assumption: ideal pulse train at the input of the multiplier. The pulse propagation behavior and its corresponding phase plane for 2-times, 4-times and 8-times GVD multiplication are also presented in Fig. 4-4 and Fig. 4-5. The amplitude fluctuations are quite significant for 8-times multiplication. This is mainly due to the filter bandwidth used in this case, i.e. 1 nm ($\sim$125 GHz @ 1550 nm), which limits the number of modes locked for this operation. Further explanation can be found in Section 4.4.3.

As the multiplication factor increases, the system trajectories are moving away from the origin. As for the 4-times and 8-times multiplications, there is neither stable limit cycle nor stable node on the phase planes even with the ideal multiplication parameters. Here we see the system trajectories spiral out to an outer radius and back to
inner radius again, which shows the periodic motion of the system. The change in the radius of the spirals reveals the fluctuations in the pulse amplitude. Hence, with the increase in multiplication factor, the system trajectories become more complicated.

Figure 4-4: Pulse propagation of (a) original pulse, (b) 2x, (c) 4x and (d) 8x multiplication with 1 nm filter bandwidth and equal lasing mode amplitude analysis.

Figure 4-5: Phase plane of (a) original pulse, (b) 2x, (c) 4x and (d) 8x multiplication with 1 nm filter bandwidth and equal lasing mode amplitude analysis; x-axes: $E(t)$, y-axes: $dE(t)/dt$. 
Although fractional temporal Talbot repetition rate multiplication uses only the phase change effect in multiplication process, the inherent nonlinearities still affect its stability indirectly. Despite the reduction in the pulse amplitude [Azana and Muriel, 1999], I observe uneven pulse amplitude distribution in the multiplied pulse train. The percentage of unevenness increases with the multiplication factor of the system.

### 4.4.2 Gaussian Lasing Mode Amplitude Distribution

Gaussian lasing mode amplitude distribution models the practical filter used in the system. It gives us a better insight on the system behavior. The parameters used in the simulation are exactly the same except that the flat-top filter has been changed to Gaussian-like passband filter. The system trajectories and uneven pulse amplitude distribution are more severe than those in the uniform lasing mode amplitude analysis. Simulations for the remaining sections are done based on this Gaussian lasing mode amplitude distribution.

![Figure 4-6: Pulse propagation of (a) original pulse, (b) 2x, (c) 4x and (d) 8x multiplication with 1 nm filter bandwidth and Gaussian lasing mode amplitude analysis](attachment:image.png)
4.4.3 Filter Bandwidth Influence

The bandwidth of the filter used in MLFRL affects the stability of fractional temporal Talbot repetition rate multiplication system. The earlier analyses are based on 1 nm filter bandwidth. The number of modes locked within a laser system increases with the filter bandwidth, as described in Section 3.1.3, which gives us a better quality of the mode-locked pulses. The simulations shown below are based on the Gaussian lasing mode amplitude distribution, 3 nm and 7 nm filter bandwidth, and other parameters remain unchanged. With wider filter bandwidth, the pulse width and the percentage pulse amplitude fluctuation decreases, and suggests better stability condition.
Figure 4-8: Pulse propagation of (a) original pulse, (b) 2x, (c) 4x and (d) 8x multiplication with 3 nm filter bandwidth.

Figure 4-9: Phase plane of (a) original pulse, (b) 2x, (c) 4x and (d) 8x multiplication with 3 nm filter bandwidth; x-axes: $E(t)$, y-axes: $dE(t)/dt$. 

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Figure 4-10: Pulse propagation of (a) original pulse, (b) 2x, (c) 4x and (d) 8x multiplication with 7 nm filter bandwidth

Figure 4-11: Phase plane of (a) original pulse, (b) 2x, (c) 4x and (d) 8x multiplication with 7 nm filter bandwidth; x-axes: $E(t)$, y-axes: $dE(t)/dt$
4.4.4 Nonlinear Effects

When the input signal enters the nonlinear region, the Talbot multiplier loses its multiplication capability as predicted earlier. The additional nonlinear phase shift due to the high input power is added to the total phase shift and destroys the phase change condition of the lasing modes required by the multiplication condition. The additional nonlinear phase shift also changes the pulse shape and the phase plane of the multiplied pulses. The nonlinear phase shift is [Ogusu, 1996]:

$$\theta_{NL} = \frac{2\pi}{\lambda} \frac{n_2 n_0}{2h_0} |E|^2 L = \frac{2\pi}{\lambda} n_2 \frac{P}{A_{eff}} L$$  \[Eq 4-3\]

where $n_0$ and $n_2$ are the linear and nonlinear refractive indexes of the fiber respectively. $n_0$ is the wave impedance in the vacuum, $E$ is the optical electric field, $P$ is the optical power, $A_{eff}$ is the effective mode area depending on the modal field profile in the fiber and $L$ is the length of DCF. The parameters used in the simulation are: $n_2 = 3.0 \times 10^{-20}$ m$^2$/W, $n_0 = 1.45$, $A_{eff} = 50 \mu m^2$.

Figure 4-12: Pulse propagation of (a) original pulse, (b) 2x, (c) 4x and (d) 8x multiplication with 3 nm filter bandwidth and input power = 1 W
Figure 4-13: Phase plane of (a) original pulse, (b) 2x, (c) 4x and (d) 8x multiplication with 3 nm filter bandwidth and input power = 1W; x-axes: $E(t)$, y-axes: $dE(t)/dt$

### 4.4.5 Noise Effects

The above simulations are all based on the noiseless situation. However, in a practical optical communication systems, noises are always the sources of nuisance which can cause system instability, therefore it must be taken into consideration for the system stability studies. Since the optical intensity of the $m$-times multiplied pulse is $m$-times less than the original pulse, it is more vulnerable to noise, as shown in Fig. 4-14 & 4-15, with 50 dB SNR. The signal is difficult to differentiate from the noise within the system if the power of multiplied pulse is too small. The phase plane of the multiplied pulse is distorted due to the presence of the noise, which leads to poor stability performance. It shows a total random fashion of the system trajectories, as depicted in Fig. 4-17 under 20 dB SNR, i.e. noisy environment.
Figure 4-14: Pulse propagation of (a) original pulse, (b) 2x, (c) 4x and (d) 8x multiplication with 7 nm filter bandwidth and 50 dB SNR.

Figure 4-15: Phase plane of (a) original pulse, (b) 2x, (c) 4x and (d) 8x multiplication with 7 nm filter bandwidth and 50 dB SNR; x-axes: $E(t)$, y-axes: $dE(t)/dt$. 

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Figure 4-16: Pulse propagation of (a) original pulse, (b) 2x, (c) 4x and (d) 8x multiplication with 7 nm filter bandwidth and 20 dB SNR

Figure 4-17: Phase plane of (a) original pulse, (b) 2x, (c) 4x and (d) 8x multiplication with 7 nm filter bandwidth and 20 dB SNR; x-axes: $E(t)$, y-axes: $dE(t)/dt$
4.5 Conclusions

I have demonstrated 4-times repetition rate multiplication by using fiber fractional temporal Talbot effect; and hence 40 GHz pulse train is obtained from 10 GHz mode-locked fiber laser source. However, its stability is of great concern for the practical use in optical communications systems. Although the fractional temporal Talbot repetition rate multiplication technique is linear in nature, the inherent nonlinearities of system may disturb its stability. Therefore any linear approach may not be suitable in deriving the system stability. Stability analysis for this multiplied pulse train has been studied by using the nonlinear control stability theory - phase plane analysis. Unfortunately, from the analysis model, the stability of the multiplied pulse train can hardly be achieved even under perfect multiplication conditions. Furthermore, I observe uneven pulse amplitude distribution in the fractional temporal Talbot multiplied pulse train, which is due to the energy variations between the pulses that cause some energy beating between them. Another possibility is the divergence of the pulse energy variation in the vicinity around the equilibrium point that leads to instability.

The pulse amplitude fluctuation increases with the multiplication factor. Better stability condition can be achieved with wider filter bandwidth. The nonlinear phase shift and noises in the system challenge the system stability of the multiplied pulses. They not only change the pulse shape of the multiplied pulses, but also distort the phase plane of the system.
Chapter 5  Tera-Hertz Fiber Ring Laser

Although some repetition rate multiplication techniques have been proposed and demonstrated, as discussed in the previous chapter, the frequencies achieved are still within tens and hundreds of GHz range, and still far below the optical fiber transmission capacity predicted by Shannon. This leaves plenty of rooms for us to explore the possibilities of the generation of ultra-high speed optical pulse trains, which is the key player in the ultra high bit rate optical communication systems.

In this chapter, I modify the modulating signal used in the conventional active mode-locking laser system, and develop a theoretical model for it. The stability of the generated pulses is also studied. Novel fiber laser structure in generating Tera-Hertz optical pulses is also presented.

5.1 Gaussian Modulating Signal

The theory of mode-locking has been well developed by [Haus, 2000], with the assumption that the modulating signal is a conventional cosinusoidal periodic signal. However, for modulating signals other than that, the model may not be appropriate in
determining the system behavior. Hence, a more fitting mode-locking model needs to be developed. Here, I investigate a similar mode-locking system, however with a different modulating signal, i.e. Gaussian modulating signal.

5.1.1 Mode-Locking Analysis

In this section, I develop a set of mode-locking equations for the mode-locked pulses with Gaussian modulating signal, which is often generated by step recovery diodes, and used in many applications, particularly in my laser setup.

A Gaussian pulse train can be described as follows [Kreyszig, 1999]:

\[ f(t) = \sum_{n=-\infty}^{\infty} a_n \exp(jn\Omega_m t) \]  \hspace{1cm} [Eq 5-1]

with,

\[ a_n = \frac{1}{T} \int_{-T/2}^{T/2} M \exp(-\frac{t^2}{2\sigma^2}) \exp(-jn\Omega_m t) dt \]  \hspace{1cm} [Eq 5-2]

where \( j^2 = -1 \), \( T \) is the period, \( \Omega_m = 2\pi / T \), \( M \) is the peak amplitude of the Gaussian pulse and \( \sigma \) is the half duration of the pulse at 1/e point, and \( a_n \) can be solved using the following property [Abramowitz and Stegun, 1972]:

\[
\int \exp(-(ax^2 + 2bx + c)) \, dx = \frac{1}{2} \sqrt{\pi/a} \exp\left(\frac{b^2 - ac}{a}\right) \text{erf}\left(\sqrt{a}x + \frac{b}{\sqrt{a}}\right) + \text{const}
\]

and let \( a = 1/(2\sigma^2) \), \( b = jn\Omega_m \), and \( c = 0 \).
\[ a_n = \frac{M}{T} \int_{-\frac{T}{2}}^{\frac{T}{2}} \exp\left(-\frac{t^2}{2\sigma^2} + jn\Omega_n t\right) dt \]

\[ = M \sqrt{\frac{\pi \sigma}{2T}} \left[ \exp\left(-\frac{n^2\Omega_n^2 \sigma^2}{2}\right) \text{erf} \left( \frac{x}{\sqrt{2}\sigma} + j\sqrt{2}n\pi \frac{\sigma}{T} \right) \right]^{-\frac{T}{2}} \]

\[ = M \sqrt{\frac{\pi \sigma}{2T}} \exp\left[-2(n\pi \frac{\sigma}{T})^2\right] \cdot \left[ \text{erf} \left( \frac{T}{2\sqrt{2}\sigma} + j\sqrt{2}n\pi \frac{\sigma}{T} \right) - \text{erf} \left( -\frac{T}{2\sqrt{2}\sigma} + j\sqrt{2}n\pi \frac{\sigma}{T} \right) \right] \]

\[ \text{[Eq 5-3]} \]

and \( a_n = a_{-n} \). \( a_0 \) can be easily determined, as shown in [Eq 5-11]. However the following properties need to be used to solve for \( a_1 \) [Abramowitz and Stegun, 1972]:

\[ \text{erf} \left( x + jy \right) = \text{erf} \left( x \right) + \frac{\exp(-x^2)}{2\pi x} \left[ (1 - \cos 2xy) + j \sin 2xy \right] \]

\[ + \frac{2}{\pi} \exp(-x^2) \sum_{n=1}^{\infty} \frac{\exp(-n^2)}{4n^2 + 4x^2} \left[ f_n(x, y) + jg_n(x, y) \right] + \varepsilon(x, y) \]

\[ f_n(x, y) = 2x - 2x \cosh ny \cos 2xy + n \sinh ny \sin 2xy \]

\[ g_n(x, y) = 2x \cosh ny \sin 2xy + n \sinh ny \cos 2xy \]

\[ \left| \varepsilon(x, y) \right| = 10^{-16} \left| \text{erf} \left( x + jy \right) \right| \]

\[ \text{[Eq 5-4]} \]

\[ \text{erf} \left( -x \right) = -\text{erf} \left( x \right) \]

\[ \text{[Eq 5-5]} \]

Generally, several axial modes will be lasing in a laser if the gain level is higher than the threshold level required. By following the procedures proposed by [Haus, 2000], the mode-locking equation can be modified to as follows, with \( \Omega_n = \Delta\Omega \) is the modulation frequency that produces sidebands at \( \omega_0 \leq \Delta\Omega \), with \( \omega_0 \) is the central carrier frequency. These injections lock the adjacent modes, which in turn lock their neighbors. \( A_n \) is the amplitude of the axial mode of frequency \( \omega_0 \pm n\Delta\Omega \). The amplitude changes within each pass through the amplifier of loss \((1-l)\) and peak gain \((1+g)\), where \( l << 1 \) and \( g << 1 \), is
\[
\Delta A_n = \left[ \frac{g}{1 + \left( \frac{n\Delta \Omega}{\Omega_g} \right)^2} - l \right] A_n + \sum_{m=-\infty}^{\infty} a_m A_{n+m} - \sum_{m=-\infty}^{\infty} a_m A_n + a_0 A_n \tag{Eq 5-6}
\]

The terms at the right hand side describe the gain and loss of the laser, contributions from the Gaussian side-bands, contributions to the Gaussian side-bands, and the average DC component of the \( n^{th} \) mode itself.

This expression can be transformed into a standard operator by the following approximations:

- The discrete frequency spectrum with Fourier components at \( n\Delta \Omega \) is replaced by a continuum spectrum, a function of \( \Omega = n\Delta \Omega \).

- The frequency dependent gain can be expanded to second order in \( n\Delta \Omega \).

\[
\frac{1}{1 + \left( \frac{\Omega}{\Omega_g} \right)^2} = 1 - \left( \frac{\Omega}{\Omega_g} \right)^2 + \left( \frac{\Omega}{\Omega_g} \right)^4 - \left( \frac{\Omega}{\Omega_g} \right)^6 + \ldots
\]

\[
= 1 - \left( \frac{\Omega}{\Omega_g} \right)^2 + O(\Omega^4)
\tag{Eq 5-7}
\]

Hence, arrive at the following:

\[
\Delta A(\Omega) = (g - l) A(\Omega) - g \left( \frac{\Omega}{\Omega_g} \right)^2 A(\Omega)
\]

\[
+ \sum_{n=-\infty}^{\infty} a_n A_n(\Omega) - \sum_{n=-\infty}^{\infty} a_n A(\Omega) + a_0 A(\Omega)
\tag{Eq 5-8}
\]

where \( A \) is the amplitude of the axial mode frequency of \( \Omega \), \( \Omega_g \) is the gain bandwidth of the amplifier within the system, \( \Omega_m = 2\pi f_m \) is the modulation frequency, \( a_0 \) is the DC
value of the modulating signal and $\Lambda_n(\Omega)$ is the amplitude of the $n^{th}$ mode separation from the central frequency, i.e. $n\Omega_m$.

I approximate the above equation with a second order differential equation with the assumption that the contributions of higher order components are small and negligible. The steady state solution to the equation is a Gaussian pulse, and the pulse width and net gain relationship are as follows.

$$\tau^4 = \frac{g}{a_1\Omega_m^2\Omega_g^2} \quad [Eq \ 5-9]$$

$$g - l + a_0 = a_1\Omega_m^2\tau^2 \quad [Eq \ 5-10]$$

where [Abramowitz and Stegun, 1972],

$$a_0 = M\sqrt{\frac{2\pi}{T}}\sigma \erf \left( \frac{T}{2\sqrt{2}\sigma} \right) \quad [Eq \ 5-11]$$

$$a_1 = C \left\{ 2\erf(x) + \frac{\exp(-x^2)}{\pi x} [1 - \cos(2xy)] + \frac{4}{\pi} \exp(-x^2) \sum_{p=1}^{\infty} \frac{\exp(-\frac{1}{4}p^2)}{p^2 + 4x^2} f_p(x, y) + \epsilon(x, y) \right\}$$

$$= 2C \left\{ \erf(x) + \frac{\exp(-x^2)}{\pi x} + \frac{4x}{\pi} \exp(-x^2) \sum_{p=1}^{\infty} \frac{\exp(-\frac{1}{4}p^2)}{p^2 + 4x^2} (1 + \cosh py) \right\} \quad [Eq \ 5-12]$$

$$C = \frac{M}{2\sqrt{\pi}} y \exp(-y^2) \quad [Eq \ 5-13]$$

$$x = \frac{T}{2\sqrt{2}\sigma} \quad [Eq \ 5-14]$$

$$y = \frac{\sqrt{2\pi}}{T} \frac{\sigma}{2x} \quad [Eq \ 5-15]$$

$$f_p(x, y) = 2x - 2x \cosh py \cos 2xy + p \sinh py \sin 2xy$$

$$= 2x(1 + \cosh py) \quad [Eq \ 5-16]$$

$$\epsilon(x, y) = 10^{-16} \left| \erf(x, jy) \right| = 0 \quad [Eq \ 5-17]$$
where \( e(x,y) \) is the allowable error of the system, which is neglected in my simulation. From the obtained equations, the system gain condition, [Eq 5-10] has been improved by the DC component of the Gaussian modulating signal.

As for the rational harmonic mode-locking case, which will be presented later in Section 5.2, the generated pulse width should be modified to include the effect of the detuning factor, and it is proportional to \( a_1 \sqrt{q + \frac{1}{m}} \) for \( q \)th harmonic mode-locking and \( m \) detuning factor. When the detuning factor, \( m \) is large, the contribution of \( \frac{1}{m} \) becomes negligible, thus, the pulse width is very much determined by the \( a_1 \) parameter, which is in turn determined by the duty cycle of the modulating signal.

The relationship between the pulse width and duty cycle is shown in Fig. 5-1, where duty cycle is defined as \( \rho = 2 \sqrt{\ln 2} \sigma / T \). For the cosinusoidal modulating signal, the pulse width does not depend on the duty cycle. In this simulation, only the effect of the duty cycle is considered, and other system parameters are held constant. I use the same average modulation power for both cases in order to obtain a fair comparison, i.e. the Gaussian modulation index or rather peak power varies with its duty cycle.
From the obtained result (Fig. 5-1), we see that the generated mode-locked pulse width is in fact proportional to the duty cycle of the Gaussian modulating signal. The narrowest mode-locked pulses are formed at the minimum duty cycle, and increases with the duty cycle. For practical case consideration, at relatively low (but nonzero) duty cycles, the minimum pulse width is determined by other system parameters, such as amplifier gain, gain bandwidth, modulation frequency, etc.; based on [Eq 5-9]. For a minimum obtainable pulse width, the modulating signal must first fulfill the gain condition as stated in [Eq 5-10]. However, when the duty cycle is too large, i.e. broad modulating pulse, the pulses generated are comparative to CW signal, since it has lost its mode-locking capability. A better operating region for this Gaussian modulating signal is duty cycle less than 30 %, whereby the pulses generated are narrower than that of the
cosinusoidal modulating signal. As a matter of fact, this type of signal is readily generated by a step recovery diode, which is used in my experimental setup.

Furthermore, I would like to examine the pulse width dependency on duty cycle with fixed modulation index, i.e. the peak power is fixed regardless of duty cycle; another words, the average modulation power varies with duty cycle. The simulation is done based on the equivalent cosinusoidal peak modulating power to that of the Gaussian case with 10 % (P10), 20 % (P20), and 30 % (P30) duty cycles. The results are shown in Fig. 5-2.

![Pulsewidth dependency on duty cycle](image)

**Figure 5-2:** Relationship between normalized pulse width and duty cycle for fixed peak modulation power at 10% (P10), 20% (P20) & 30% (P30) duty cycle. (Solid line – Gaussian modulating signal, dotted line – cosinusoidal modulating signal)

For fixed modulation powers, the pulses show the narrowest width around the 5 % - 30 % too. Thus, for fixed modulation index, we will have a more stable pulse
generation around the minimum point; the variation of pulse width is minimum around that region. The relationship between the pulse width and duty cycle is also valid for other modulation signals, e.g. square pulse train, etc, since the relationship is dependent on the contributions of the frequency components of the signals, \(a_n\).

For conventional mode-locking system, i.e. with cosinusoidal modulating signal, the maximum rational harmonic detuning factor, \(m_{\text{max}} = 2\pi[M/(2g)]^{\frac{1}{2}}(f_M/f_n)^{\frac{1}{2}}\), which is proportional to the square root of the number of modes locked within the system. However, with Gaussian modulating signal, this factor becomes \(m_{\text{max}} = 2\pi[a_i/ g]^{\frac{1}{2}}(f_M/f_n)^{\frac{1}{2}}\), which not only depends on the number of modes locked, but also inversely proportional to the duty cycle of the modulating signal. The relationship can be easily obtained by inverting the pulse width dependency chart, and is shown below.

Figure 5-3: Relationship between normalized maximum allowable multiplication factor and duty cycle (Solid line – Gaussian modulating signal, dotted line – cosinusoidal modulating signal)
Hence, the maximum allowable multiplication factor, $m_{\text{max}}$, relative to the cosinusoidal modulating signal; can be improved by reducing the duty cycle to less than 30%. Other than the theoretical considerations, the factor $m_{\text{max}}$, is also limited by the availability of the modulator driver, i.e. step recovery diode, and the filter bandwidth, which limits the gain bandwidth, and hence the number of modes locked within the system.

5.1.2 Stability Region

Having known the pulse width generated by the Gaussian modulating signal, I should now aim to determine the stable operation condition of this type of modulating signal. As discussed in Chapter 2, in order to generate stable soliton pulses in an active mode-locked laser system, two conditions have to be fulfilled: (1) soliton pulse must experience a lower loss in the cavity than the Gaussian pulse, and (2) energy fluctuation of the soliton must be damped, mathematically shown in [Eq 2-8 & Eq 2-9]. When condition 1 is met, the soliton will have sufficient gain to survive however the Gaussian noise is not given enough gain to build up. Condition 2 implies that the filter loss must be larger than the modulator loss so as to weaken the soliton energy fluctuation caused by the modulator [Haus and Mecozzi, 1992]. A positive soliton energy fluctuation shortens the pulse and broadens the spectrum. On the one hand, the decreased pulse width decreases the modulator loss as the soliton becomes more concentrated around the maximum transmission of the modulator. On the other hand, the filter loss increases as a result of the broadened spectrum. For stability, the filtering effect must be stronger than the modulation effect.
For an active mode-locked laser system with Gaussian-like modulating signal, the pulse width and net gain relationship with cavity dispersion taking into account are as follows:

\[
\frac{1}{\tau^2} = \frac{a_0 \Omega_m^2}{\frac{1}{\Omega_f^2} - jD}
\]  

[Eq 5-18]

\[
g - l + a_0 = a_1 \Omega_m^2 \tau^2
\]  

[Eq 5-19]

where \(a_0\) and \(a_1\) are the Fourier coefficients for the Gaussian modulating signal as described in the previous section, \(g\) and \(l\) are the gain and loss of the system respectively. Physically, \(a_0\) and \(a_1\) are the DC component and the strength of the modulating signal respectively, which are duty cycle dependent. One thing to note is the system net gain can be increased by the DC component of the modulating signal. \(\Omega_m\) is the angular modulation frequency, \(D = \beta_2 L / 2\) with an average group velocity dispersion \(\beta_2\) and cavity length \(L\), \(\lambda\) is the carrier wavelength, and \(\Omega_f\) is the bandwidth of the optical transmission of the laser cavity. Normally this bandwidth is corresponding to the bandwidth of the optical band pass filter incorporated in the laser.

By considering timing jitter and frequency perturbation produced by the modulator and filter of the system \([Haus and Mecozzi, 1992 & 1993]\), and following the procedure presented by \([Haus and Mecozzi, 1992]\), the stability conditions stated in Chapter 2 have been modified to as follows:

**Condition 1:**

\[
\frac{\pi^2}{12} a_1 \Omega_m^2 \tau^2 + \frac{1}{3 \Omega_f^2 \tau^2} < \text{Re} \left[ a_1 \Omega_m^2 \left( \frac{1}{\Omega_f^2} - jD \right) \right]^{\frac{1}{2}}
\]  

[Eq 5-20]

**Condition 2:**

\[
\frac{\pi^2}{12} a_1 \Omega_m^2 \tau^2 < \frac{1}{3 \Omega_f^2 \tau^2}
\]  

[Eq 5-21]
The stability conditions [Eq 2-8] and [Eq 5-20] can be deduced by using the following property:

\[
\sqrt{x + jy} = \text{Re} + j\text{Im} = \frac{1}{\sqrt{2}} \left\{ \sqrt{x^2 + y^2} \pm x + j\cdot\text{sign}(y) \cdot \sqrt{x^2 + y^2} - x \right\}
\]  

[Eq 5-22]

where \(\text{sign}(y) = 1\) if \(y > 0\), \(\text{sign}(y) = -1\) if \(y < 0\) and \(\text{sign}(y) = 0\) if \(y = 0\).

It should be stressed that the equations used to deduce the system stability conditions is only valid when the pulse change per round trip is small. This sets the upper limit to the maximum nonlinear phase shift that the soliton may acquire per round trip: stability of a periodically amplified soliton requires the nonlinear phase shift \(< < 4\pi\) [Mollenauer et al., 1986]. Fig. 5-4 shows the stability region for the both cosinusoidal and Gaussian-like modulating signal in an active mode-locked laser system. The lined regions are the stable soliton operation regions, where both stability conditions are simultaneously met.

Figure 5-4: Stable operation region for soliton in an active mode-locked laser system with conventional cosinusoidal modulating signal (M) and Gaussian-like modulating signal (a₁).
From Fig. 5-4, the condition 1 for both cases requires \((1/\Omega_2 D) < 1.53\), i.e. for a given fixed filter bandwidth, a minimum anomalous dispersion is required. This is because the dispersion, which is balanced by SPM for soliton, increases the Gaussian loss and thus suppresses the Gaussian noise (Condition 1 for both cases). However, the dispersion should not be too large, so as to keep the nonlinear phase shift \(< 4\pi\).

Furthermore, as depicted in the figure, the pulse width of the Gaussian case is much shorter than the cosinusoidal case, with the same modulation frequency, which has also been shown in the previous section. By inspection, the stable operation region for Gaussian-like modulating signal is smaller than that of the conventional one, i.e. more stringent control parameters are required for the stable operation. Steeper slope for condition 2 also reveals that larger modulation fluctuation in the Gaussian modulating case.

By linear approximation of \(a_1\) parameter, which is valid for coarse system estimation, I am able to show the system stability behavior with respect to the duty cycle, \(\rho\) of the Gaussian modulating signal, as shown in Fig. 5-5. For small duty cycle, one can expect to have a bigger stable soliton operation region.
5.1.3 Parameters Deviation

Having determined the stable operation region for the system, I shall now move on to the system performances on the parameter deviations. From \[\text{Eq 5-18}\], one can easily deduce the following:

\[
\frac{d\tau}{\tau} = -\frac{1}{2} \frac{d\Omega_m}{\Omega_m} \quad \text{[Eq 5-23]}
\]
\[
\frac{d\tau}{\tau} = -\frac{1}{4} \frac{da_i}{a_i} \quad \text{[Eq 5-24]}
\]

By recognizing \(\Omega_m = q\Omega_c = q\eta (nL)\), where \(q\) is the \(q^{th}\) harmonic, \(n\) is the refractive index of the optical fiber, \(L\) is the length of the ring cavity. Hence,

\[
\frac{d\tau}{\tau} = -\frac{1}{2} \left( \frac{dn}{n} + \frac{dL}{L} \right) \quad \text{[Eq 5-25]}
\]
Assuming no temperature and cavity length variations in the system, and taking the intensity dependency of the refractive index [Eq 2-12] into the consideration, I achieve the following:

\[
\frac{d\tau}{\tau} = \frac{n_z dI}{2(n_0 + n_z I)}
\]  

[Eq 5-26]

where \( n_0 \) and \( n_z \) are linear and nonlinear refractive indexes respectively, and \( I \) is the intensity of the pulse. Therefore the pulse width variation can be related to the fluctuations of the modulation frequency, modulating strength, refractive index, cavity length, and pulse intensity by [Eq 5-23] to [Eq 5-26].

The pulse width variations due to the fluctuations of modulating frequency, \( a_1 \) parameter, pulse intensity and duty cycle of the modulating signal are shown in the following figures. The simulations are done based only on the effect of particular parameter of interest, and the other parameters are held constant. Hence, the axes shown in the figures are relative to their own set of coefficients. \( a_1 \) parameter variations with respect to duty cycle are given in Fig. 5-8 and Fig. 5-9. The two curves are obtained using the fixed peak modulation power and fixed average modulation power analyses respectively.

From the obtained results, the change in pulse width is gentler towards high modulating frequency, modulating power and pulse intensity. One thing to note is that the pulse width and \( a_1 \) relationship is only valid for \( a_1 \leq 1 \). This is simply because the model developed so far is for under modulating cases. For high intensity and modulating strength, nonlinear effect starts to take place, and stabilizes the pulse, and hence minimizes the pulse width variations. In contrast, for low intensity situation, the pulse is
easily deviated by small fluctuations, such as noise. For high modulating frequency, i.e. large spectral separation; any small fluctuation in the frequency will not contribute much to pulse width variation.

Figure 5-6: Relationship between pulse width and modulating frequency (Ω_m), modulating strength (a_l) and pulse intensity (I)

Figure 5-7: Variations of pulse width with respect to modulating frequency (Ω_m), modulating strength (a_l) and pulse intensity (I)
For the fixed peak modulation power analysis, there is no pulse width variation for duty cycle greater than 10 % (Fig. 5-10). The pulse width is invariant to duty cycle under the same peak modulating power. On the other hand, for fixed average modulation power analysis (Fig. 5-11), i.e. the peak modulation power is inversely proportional to the duty cycle of the modulating signal; the pulse width variation increases with duty cycle for duty cycle less than 40 %, after which it decreases with duty cycle. The pulse width
variation peaks at duty cycle $\cong 40\%$. In other words, this is the unstable operating point for Gaussian modulating mode-locked laser system. I refer to the recommendation made in the previous section, that the duty cycle of the Gaussian-like modulating signal should be less than 30% for better system performance, and note that the pulse width variation is in fact proportional to the duty cycle. Hence, in order to minimize the pulse width variation, the duty cycle of the Gaussian-like modulating signal should be kept as small as possible.

Figure 5-10: Pulse width variation with respect to duty cycle for fixed peak modulation power analysis (Inset: zoom in area for duty cycle $= 0\%$ to $10\%$)
5.2 Rational Harmonic Detuning

Rational harmonically mode-locked fiber ring lasers have attracted much attention due to their ability to generate higher repetition rate optical pulses. By applying slightly deviated frequency from the multiple of fundamental cavity frequency, higher rate pulses can be achieved [Wu and Dutta, 2000, Lin et al., 2004]. Recently, [Lin et al., 2004] have achieved 40th order of rational harmonic mode-locking using a loss-modulated Fabry-Perot laser diode, with the base frequency of 1 GHz. [Zhu et al., 2004] demonstrated two-step 80 GHz high quality pulse train generation involving 4th order rational harmonic mode-locking on a 10 GHz modulation signal in conjunction with a frequency doubler. The mode-locked fiber laser was stabilized using a regenerative-type base line extraction feedback technique.
By applying slight frequency deviation, \( \Delta f = \frac{f_r}{m} \), where \( m \) is the integer and \( f_r \) is the fundamental cavity frequency, the modulation frequency of the harmonically mode-locked laser, \( f_m \), becomes

\[
f_m = qf_e + \frac{f_e}{m}
\]

\[
mf_m = (qm + 1)f_e
\]

\[
f_r = mf_m
\]

[Eq 5-27]

where \( q \) is the \( q^{th} \) harmonic of the fundamental cavity frequency and \( f_r \) is the repetition frequency of the system, which has been increased to \( m \)-times of \( f_m \). However, this technique suffers from inherent pulse amplitude instability, which includes both amplitude noise and unequal pulse amplitude, furthermore, it gives poor long-term stability. The problem is due to the millisecond gain lifetime of erbium which causes self-pulsation operation in MHz or GHz range mode-locked fiber lasers; the fiber laser cannot equalize the pulse energies, and hence the output may contain unequal pulse amplitudes or even pulse dropouts. This self-pulsation behavior contributes to the laser output power fluctuations. In addition, the long lifetime of Er-doped fibers cannot filter out the pump power perturbations resonating at the laser relaxation frequency, and hence disturb the laser stability [Ding and Cheo, 1996].

Some pulse amplitude equalization techniques have been proposed to solve the problem. Out of which are two-photon absorption (TPA) semiconductor mirror [Thoen et al., 2000], double pass modulator [Shiquan et al., 2003], linear and nonlinear optical filter combination [Zhao et al., 2002], etc.
5.2.1 Experimental Setup

The experimental setup of the active harmonically mode-locked fiber ring laser is shown in Fig. 5-12. The principal element of the laser is an optical close loop with an optical gain medium, a Mach-Zehnder amplitude modulator (MZM), PC, BPF, optical couplers and other associated optics.

![Figure 5-12: Active mode-locked fiber ring laser with Gaussian-like modulating signal](image)

The gain medium used in this fiber laser system is an EDFA with a saturation power of about 16 dBm. A polarization independent optical isolator is used to ensure unidirectional lightwave propagation as well as to eliminate back reflections from the fiber splices and optical connectors. A free space filter with 3 dB bandwidth of 4 nm at 1555 nm is inserted into the cavity to select the operating wavelength of the generated signal and to reduce the noise in the system. In addition, it is responsible for the longitudinal modes selection in the mode-locking process. The birefringence of the fiber is compensated by a PC, which is also used for the polarization alignment of the linearly
polarized lightwave before entering the planar structure modulator for better output efficiency. Pulse operation is achieved by introducing an asymmetric coplanar traveling wave 10 GHz lithium niobate, Ti:LiNbO$_3$ MZM into the cavity with half wave voltage, $V_\pi$ of 5.8 V and insertion loss of $\leq 7$ dB. The modulator is DC biased near the quadrature such that it operates around the linear region of its characteristic curve. I adopt amplitude modulation in this experiment because it gives better stability than the frequency modulation. The modulator is driven by a 100 $\pm$ 5 MHz, $\sim$100 ps step recovery diode (SRD), which in turn driven by a RF amplifier (RFA) and a RF signal generator. The modulating signal generated by the step recovery diode is a $\sim$1 % duty cycle Gaussian pulse train. The output coupling of the laser is optimized using a 10/90 optical coupler. 90 % of the optical field power is coupled back into the cavity ring loop, while the remaining portion is taken out as the output of laser and analyzed using oscilloscope and spectrum analyzer.

SRD is also known as charge storage diode, since its operation depends on the ability to store charge [Kirkby, 1999], can be used to generate short electrical pulses from a cosinusoidal wave drive. It is a simply a PIN junction diode that has a special doping profile, to give a special characteristic curve. Like a normal PN diode, SRD conducts when forward biased. However, it also shows significant conduction when reversed biased, but only for a short while. The transition from the conducting and non-conducting states of the reversed biased diode occurs in a time frame of typically less than 100 ps. This means the current waveform has a high harmonic content and can be used to generate short pulses [Chudobiak, 1996, Kirkby, 1999].
5.2.2 Results and Discussion

The theoretical background of the phase plane analysis has been given in the previous chapter. Here, I will focus on the modeling of rational harmonically mode-locked fiber ring laser system with the following assumptions:

- The mode-locking condition has been achieved and the detuned frequency is perfectly adjusted according to the fraction number required, m.

- Optical amplifier gain saturation. This is valid because I am operating the laser in multiple pass optical amplification situations, where the laser will eventually saturate.

- Small harmonic distortion.

- No fiber nonlinearity and noise are included in the analysis.

- Gaussian lasing mode amplitude distribution analysis.

- Gain bandwidth is determined by the filter bandwidth.

- Linearly polarized light is used in the system.

I do not consider the initial pulse forming process of the laser. This is simply because it involves the dynamics of the optical amplifier and adds to the complexity of the system, which is not the interest of this study. Furthermore, I am looking at the pulse propagation behavior, once rational harmonic mode-locking has been achieved, as time progresses. Harmonic distortion is applied to the system by introducing small variations to different harmonics up to m-order for an m-fraction detuned system. The overlap
between the linewidth of the actual lasing mode (without frequency detuning) and the detuning amount also contributes to the distortion, and is considered in my simulation.

The phase plane of a perfect 10 GHz mode-locked pulse train with bandwidth of 4 nm and centered at wavelength of 1550 nm; without any frequency detuning is shown in Fig. 5-13 and its corresponding pulse train is shown in Fig. 5-14(a). From the phase plane obtained, one can easily observe that the origin is a stable node and the limit cycle around that vicinity is a stable limit cycle, hence leading to stable system trajectory. 4-times multiplication pulse trains, i.e. \( m = 4 \), without and with 5% harmonic distortion are shown in Fig. 5-14(b) and 5-14(c) respectively. Their corresponding phase planes are shown in Fig. 5-15(a) and 5-15(b).

For the case of zero harmonic distortion, which is the ideal situation, the generated pulse train is perfectly multiplied with equal amplitude and the phase plane has stable symmetry periodic trajectories around the origin too. However, for practical case, i.e. with 5 % harmonic distortion, it is obvious that the pulse amplitude is unevenly distributed, which agrees very well with many experimental findings [Zhu et al., 2001 & 2004, Gupta et al., 2001, Wu and Dutta, 2000]. Its corresponding phase plane shows more complex and asymmetric system trajectories, hence reflecting its undesirable amplitude fluctuations.
Figure 5-13: Phase plane of a 10 GHz mode-locked pulse train

Figure 5-14: Normalized pulse propagation of (a) original pulse; detuning fraction of 4, with (b) 0% and (c) 5% harmonic distortion noise
I define the percentage of amplitude fluctuation, $\% F$ as follows:

$$\% F = \frac{E_{\text{max}} - E_{\text{min}}}{E_{\text{max}}} \times 100\%$$  \[\text{Eq 5-28}\]

where $E_{\text{max}}$ and $E_{\text{min}}$ are the maximum and minimum peak amplitude of the generated pulses. For any practical mode-locked laser system, fluctuations above 50% should be considered as unacceptable. Therefore, this is one of the limiting factors in a rational harmonic mode-locking fiber laser system. The relationships between the percentage fluctuation and harmonic distortion for three multipliers ($m = 2, 4$ and $8$) are shown in Fig. 5-16. Thus, the obtainable rational harmonic mode-locking is very much limited by the harmonic distortion of the system. For high multiplier, a small change in the harmonic distortion leads to a large change in the system output, and hence poor system stability. By increasing the system bandwidth, i.e. bandwidth of the filter used in the system, more modes will be locked within the system, and hence improve the pulse quality. However, this may increase ASE noise level of the system, hence challenges its stability. Therefore this is a trade off between the pulse quality and system stability.
Figure 5-16: Relationships between amplitude fluctuation and percentage harmonic distortion

For large fluctuation, it means no repetition rate multiplication, but with additional noise components; a typical pulse train and its corresponding phase plane are shown in Fig. 5-17 (lower plot) and Fig. 5-18 respectively, with $m = 8$ and 20% harmonic distortion. The asymmetric trajectories of the phase graph explain the amplitude unevenness of the pulse train. Furthermore, it shows a more complex pulse formation process and undesirable pulse stability. Hence, it is clear that for any harmonic modelocked laser system, the small side pulses generated are largely due to improper or not exact tuning of the modulation frequency of the system. An experimental result is depicted in Fig. 5-21(a) for comparison.
Figure 5-17: 10 GHz pulse train (upper plot), pulse train with \( m = 8 \) and 20% harmonic distortion (lower plot)

Figure 5-18: Phase plane of the pulse train with \( m = 8 \) and 20% harmonic distortion

By careful adjustment of the modulation frequency, polarization, gain level and other parameters of the fiber ring laser, I obtain the 660\(^{th}\) and 1230\(^{th}\) order of rational harmonic detuning in the mode-locked fiber ring laser with base frequency of 100 MHz, and hence 66 GHz and 123 GHz repetition frequency pulse operation. The autocorrelation traces and optical spectra of the pulse operations are shown in Fig. 5-19.
With Gaussian pulse assumption, the obtained pulse widths of the operations are 2.55 ps and 2.29 ps respectively. For the 100 MHz pulse operation, i.e. without any frequency detuning, the generated pulse width is about 91 ps. Thus, not only did I achieve an increase in the pulse repetition frequency, but also a decrease in the generated pulse width. This pulse narrowing effect is partly due to SPM effect of the system, as observed in the broadened optical spectra. Another reason for this narrow pulse width is the low duty cycle of the modulating signal as described in the previous section. Besides the uneven pulse amplitude distribution, high level of pedestal noise is also observed in
the obtained results. For 66 GHz pulse operation, a 4 nm bandwidth filter is used in the setup, and it is removed in the 123 GHz operation. It is done so to allow more modes to be locked during the operation, thus, to achieve better pulse quality. In contrast, this increases the level of difficulty significantly in the system tuning and adjustment. As a result, the operation is very much determined by the gain bandwidth of the EDFA used in the laser setup.

The simulated phase planes for the above pulse operation are shown in Fig. 5-20. They are done based on the 100 MHz base frequency, 10 round trips condition and 0.001% of harmonic distortion contribution. There is no stable limit cycle in the phase graphs obtained; and the system stability is hardly achievable, which is a well-known fact in the rational harmonic mode-locking. Asymmetric system trajectories are observed in the phase planes of the pulse operations. This reflects the unevenness of the amplitude of the pulses generated. More complex pulse formation processes have also been revealed in the phase graphs obtained. Additionally, poor long-term stability is also observed for both cases, since the trajectories are spiraling unequally with decreasing amplitude around the phase planes.

By a very small amount of frequency deviation, or improper modulation frequency tuning in the general context, I obtain a pulse train of ~100 MHz with small side pulses in between as shown in Fig. 5-21. It is rather similar to Fig. 5-17 (lower plot) shown earlier despite the level of pedestal noise in the actual case. This is mainly because I do not consider other sources of noise in my modeling, except the harmonic distortion.
5.3 Parametric Amplifier Based Fiber Ring Laser

New high power light sources and optical fibers with high nonlinearity, as well as the need of amplification outside the conventional erbium band have increased the interest of optical fiber parametric amplifiers (PA). It offers a wide gain bandwidth and may in similarity with the Raman amplifier be tailored to operate at any wavelength [Hansryd et al., 2002]. As the parametric gain process does not rely on energy transitions
between energy states, it enables a wideband and flat gain profile contrary to Raman and Erbium doped fiber amplifiers. The underlying process is based on the highly efficient four-photon mixing relying on the relative phase between the four interacting photons, as discussed in Chapter 2. In this section, I will study the behavior of parametric amplifier in a fiber ring laser.

### 5.3.1 Parametric Amplification

Parametric amplification is achieved by manipulating the mixing between four lightwaves at three frequencies, basing on the fact that the fiber refractive index is intensity dependent (more detailed explanation can be found in Chapter 2). A signal at frequency $\omega_s$ and a pump at $\omega_p$ will mix and modulate the refractive index of the fiber such that a third lightwave, also at $\omega_p$, will create sidebands at $\omega_p \pm (\omega_s - \omega_p)$ which will result in signal gain and the generation of idler [Hansryd et al., 2002].

The parametric gain is very much dependent on the phase condition between the four lightwaves during the transmission through the nonlinear medium, which can be categorized into linear and nonlinear phase shifts. Linear phase shift is due to the group velocity dispersion of the medium, whereas the nonlinear phase shift is dependent on the pump power and the nonlinear coefficient of the medium. Under perfect phase matching condition, i.e. no phase mismatch, the maximum obtainable single pass gain in optical fiber in dB is given as follows [Hansryd et al., 2002]:

$$G_{\max} = 10 \log \left[ \frac{1}{4} \exp(2\gamma P_p L) \right]$$

[Eq 5-29]
where $\gamma$ is the nonlinear coefficient of the fiber, $P_p$ is the pump power and $L$ is the effective length of the fiber.

### 5.3.2 Experimental Setup

Experimental setup of the parametric amplifier based fiber ring laser is shown in Fig. 5-22. CW distributed feedback (DFB) laser operating at 1547 nm is used as the pump source for the laser. The CW signal is modulated by a MZM, which is driven by a 100 MHz SRD, hence achieving ~100 MHz pulse train with duty cycle of ~1%. This is the Gaussian-like modulating signal used to modulate the system.

The signal is then amplified by an EDFA with CW saturation power of about 16 dBm and filtered by a free space filter with 3 dB bandwidth of 1 nm at 1547 nm before coupled into the ring via a 3 dB coupler. The filter is used to remove the noise generated by EDFA, and pass only the amplified pumping signal. The fiber ring consists of an optical close loop with a 200 m highly nonlinear fiber (HNLF) with zero dispersion wavelength, $\lambda_0$ at 1542 nm, dispersion slope of 0.032 ps/nm$^2$/km and nonlinear coefficient, $\gamma = 10$ W$^{-1}$km$^{-1}$, an optical isolator, a 1.5 km SMF with insertion loss of 0.25 dB/km and a PC with insertion loss of about 1 dB. HNLF is the main nonlinear component in the loop that is used to generate the parametric gain. The isolator is to ensure unidirectional operation and minimize the back reflections from connectors used in the ring. The insertion loss of the isolator is about 1 dB. Since FWM is polarization dependent, the PC becomes the key player in the loop. SMF is the dispersive material in the system, dispersion relation of $D(\lambda) = S_0/4*(\lambda - \lambda_0)^2/\lambda^3$, where $S_0 = 0.092$ ps/ nm$^2$/ km
and \( \lambda_0 = 1310 \text{ nm} \). With \( \lambda = 1547 \text{ nm} \), the dispersion of SMF is 17.29 ps/nm/km. The signal and pump are then fed back to the loop via the 3 dB coupler. HNLF, SMF and PC are interconnected using connectors for easy access, while the other components are spliced together in the loop. With \( \sim 0.5 \text{ dB} \) connector loss and \( \sim 0.1 \text{ dB} \) splice loss assumptions; the total loop loss is estimated to be \( \sim 9.5 \text{ dB} \). For easy calculation, 10 dB loop loss is assumed.

Figure 5-22: Parametric amplifier based fiber ring laser

5.3.3 Results and Discussion

5.3.3.1 Parametric Amplifier Action

The pumping wavelength is chosen in such a way that it is near to the zero dispersion wavelength of HNLF and possess a small anomalous dispersion value to give good gain efficiency. With 200 m of HNLF, peak pump power of 33 dBm, pumping wavelength \( \lambda_p \) of 1547 nm and nonlinear coefficient \( \gamma = 10 \text{ W}^{-1}\text{km}^{-1} \), I obtain a maximum single pass gain of 28.6 dB theoretically. The simulated PA gain profile is shown in Fig. 5-
23. I obtain a closed loop gain of about 19.5 dB experimentally, as shown in Fig. 5-24. With total loop loss estimation of about 10 dB, the result agrees very well to the theoretical calculation.

In the figures that follow, I investigate the effect of the length of HNLF, pump power and pump wavelength used in affecting the PA gain profile. Gain lope will decrease with the decrease in length of HNLF and pump power. The amplified signal wavelength will shift towards the pump wavelength when the pump power is reduced, however no change in the HNLF case. Gain bandwidth of the amplifier will increase if the pump wavelength is set closer to the zero dispersion wavelength of the HNLF. Furthermore, the signal wavelength will also be shifted away from the pump wavelength.

Figure 5-23: Simulated PA gain profile
Figure 5-24: PA gain curve obtained experimentally

Figure 5-25: Effect of HNLF length on PA gain profile
Figure 5-26: Effect of peak power on PA gain profile

Figure 5-27: Effect of pump wavelength on PA gain profile
5.3.3.2 Ultra-High Repetition Rate Operation

The total cavity loop length is measured to be 1842.8 m, and its corresponding fundamental frequency is 112.2 kHz. Hence, the locking occurs at about 890\textsuperscript{th} harmonic mode. In a conventional active harmonically mode-locked fiber ring laser, the mode-locker, i.e. modulator is placed within the ring cavity. However, in this PA based fiber ring laser, the mode locking process is controlled by the modulated pump signal. In the following discussion, I assume that the phase condition in the HNLF is matched, so that good gain response in the laser can be obtained. This assumption is valid since the gain curves are obtained as per desired.

Under frequency unmatched situation, i.e. the modulation frequency is not multiple of fundamental cavity frequency, I obtain an optical pulse with pulse width of ~70 ps, which is slightly shorter than the modulated pump pulse ~90 ps, hence, gives a compression factor of ~1.2x, as shown in Fig. 5-28. When the frequency condition is matched, I observe strong SPM in the pump signal, and with a compression factor of ~1.5x. The results are shown in Fig. 5-29.

![Figure 5-28: (a) Optical spectrum and (b) pulse shape observed when phase condition is matched](image-url)
Mode separation is not observable since the 100 MHz operation is too narrow to be seen on the optical spectrum analyzer. When the modulation frequency starts to deviate from the mode-locking frequency, some side modes start to appear, as depicted in Fig. 5-30 (a) and Fig 5-31 (a). The mode separations measured are 5.7 nm and 10.5 nm respectively, centered at 1547 nm. The corresponding repetition frequencies are about 714 GHz and 1.315 THz. The autocorrelation traces are shown in Fig. 5-30 (b) and Fig. 5-31 (b), and the estimated FWHM are about 0.6 ps and 0.3 ps. From the obtained results, Time-Bandwidth-Products are estimated to be 0.529 and 0.496 respectively. Hence, there is a small chirping found in the pulses generated, however are close to Gaussian transform limited pulse. As a whole, I observe linear relationship between mode separation (or repetition frequency, $f_r$) and detuned frequency, $\Delta f$; i.e. $f \propto |\Delta f|$, as shown in Fig. 5-32. I believe that the generation of these pulses is not mainly due to the frequency detuning, but also the interference between the pump pulses from one round trip to another, and the modulation instability due to the interaction between the nonlinear and dispersion effects within the cavity.
Figure 5-30: (a) Optical spectrum and (b) autocorrelation trace observed when the phase condition is matched and modulation frequency is detuned for 714 GHz

Figure 5-31: (a) Optical spectrum and (b) autocorrelation trace observed when the phase condition is matched and modulation frequency is detuned for 1.315 THz

Figure 5-32: Repetition frequency and mode separation vs detuned frequency
In summary, there are four operation regions for this PA based mode-locked fiber ring laser system, as follows:

Region I: Phase condition is not matched, hence no gain action. Modulation frequency is not a multiple number of the fundamental cavity frequency. Noisy operation is observed in this region.

Region II: Phase condition is matched, hence parametric gain (gain lope), and new wavelength components are generated. However, modulation frequency is not matched with the cavity frequency.

Region III: Phase condition and modulation frequency conditions are both matched, and hence gain and mode-locking actions. Pulse shortening and spectral broadening effects are observed.

Region IV: Phase condition and modulation frequency conditions are both matched, and hence gain and mode-locking actions, however, with some frequency detuning in the modulation frequency. Ultra-high repetition rate optical pulse train is observed.

**5.3.3.3 Ultra-Narrow Pulse Operation**

As has been predicted and verified by many literatures [Haus and Wong, 1996], the shortest pulse width of a laser is obtainable when the cavity dispersion is minimum.
Hence, the 1.5 km SMF (dispersion) is removed from the cavity and the laser behavior is observed. The shortest pulse achieved from my laser under perfect tuning (i.e. without detuning) is shown below. The obtained FWHM is 3.36 ps; with Gaussian pulse assumption, the actual pulse width of the system is therefore 2.38 ps.

![Autocorrelation trace](image1.png)

![Oscilloscope pulse shape](image2.png)

**Figure 5-33:** (a) Autocorrelation trace and (b) oscilloscope pulse shape for pulse generated by PA based mode-locked fiber ring laser

### 5.3.3.4 Intracavity Power

I investigate the effect of intracavity power in affecting the generated pulse width by inserting a variable optical attenuator into the laser cavity. The relationship between the intracavity power and the pulse width is shown in Fig. 5-34. Shorter pulse is achieved with larger cavity loss. This is because the larger the cavity loss, the lesser the gain saturation effect of the system. Hence, better gain distribution of the system, and better pulse generation. For a high intracavity power, nonlinear effects become dominant, higher order FWM starts to take place. Furthermore, the shape of the pulses generated will no longer be Gaussian-like, but rectangular shape. However, when the intracavity
power is too low, the noise starts to disturb the system stability or may even lose the pulse.

![Pulsewidth Vs Intracavity Power](image)

**Figure 5-34: Pulse width Vs Intracavity power**

### 5.3.3.5 Soliton Compression

High peak power pump pulse (about 33 dBm; based on average power of 16 dBm, duty cycle of ~10% and average loss of 3 dB), with initial pulse width of about 77 ps (through measurement) is passed through the 200 m HNLF and followed by a length of SMF. Soliton compression is observed and shown in Fig. 5-35.

The nonlinear and dispersive lengths of a system are [Agrawal, 2001]:

\[ L_{NL} = \frac{1}{\gamma P} \quad L_D = \frac{T_o^2}{|\beta_2|} \]  

[Eq 5-30]

where \( \gamma \) is the nonlinear coefficient, \( P \) is the peak power of the incident pulse, \( T_o \) is the half width at 1/e intensity point and \( \beta_2 \) is the group velocity dispersion. \( T_o \) is related to \( T_{FWHM} \) (full width at half maximum) as \( T_{FWHM} = 2\sqrt{\ln 2}T_o \approx 1.665T_o \), for Gaussian pulse
and $T_{\text{FWHM}} = 2 \cosh^{-1} \sqrt{2} T_o = 1.763 T_o$, for sech$^2$ pulse. The latter relation is chosen for the following calculations because of the soliton effect. Hence, dispersive length can be written as $L_D = T_{\text{FWHM}}^2 / (3.11 \beta_2)$.

Using the experimental data from previous section, the calculated nonlinear length, $L_{NL}$ and dispersive length, $L_D$ are about 0.05 km and 72.92 km respectively. The HNLF used in my experiment is 200 m, which is much longer than the nonlinear length calculated, so as the nonlinear effect. Therefore, the corresponding dispersive length has to be reconfirmed for a balance soliton effect. From the chart obtained, soliton shortening effect peaks at SMF $\cong$ 2.9 km, beyond which, the pulse broadening effect will start to take place. With $\beta_2$ of about 20.328 ps$^2$/km, the $T_{\text{FWHM}}$ is about 13.5 ps, which gives a maximum compression factor of about 5x.

**Figure 5-35: Soliton pulse compression**
5.4 Regenerative Parametric Amplifier based Mode-Locked Fiber Ring Laser

In order to improve the stability of the PA based mode-locked fiber ring laser and to promote self-locking condition, I include a regenerative feedback loop into the system. The conceptual block diagram is shown in Fig. 5-36. The generated output pulse train will be fed into the feedback circuit to reduce the error signal or rather the deviation between the harmonic cavity frequency and the modulating frequency that drive the modulator. The concept is similar to RMLFRL as described in Chapter 3.

![Figure 5-36: Block diagram of regenerative PA based mode-locked fiber ring laser](image)

5.4.1 Experimental Setup

The experimental setup of the regenerative PA based mode-locked fiber ring laser is shown in Fig. 5-37. The system is similar to the experimental setup described in the
previous section, however with some modifications. The dispersive material i.e. 1.5 km SMF has been removed to ensure short pulse generation. In addition, a low pass FBG filter with cut off wavelength at 1537 nm is inserted to select signal wavelength and block pump and idler wavelengths. The main add-in to the system is the regenerative part, which made up of RF amplifiers, phase shifter, mixer and RF filter.

Part of the output signal is taken out as the feedback signal. It is converted into an electrical signal by PIN photo-detector (PD) and amplified by RF amplifier (RFA). Phase shifter (PS) is used to adjust the electrical phase, i.e. electrical length of the signal, so that it will match with the optical frequency of the signal. The feedback signal will be mixed with the RF signal generated by the RF signal generator. The mixer will then produce an error signal based on the mismatch of the two signals. A RF low pass filter is used to block the high frequency components of the signal so as to have a better quality driving signal.

![Figure 5-37: Regenerative PA based mode-locked fiber ring laser](image-url)
5.4.2 Results and Discussion

The generated pulse train is similar to the case described in the previous section, however with improved stability. The optical spectrum and autocorrelation trace are shown in the following figures. With this regenerative feedback configuration, the output pulse maintains its shape when it is properly locked for a period of about ten hours under laboratory condition.

![Optical spectrum and autocorrelation trace of regenerative PA based mode-locked fiber ring laser](image)

Figure 5-38: (a) Optical spectrum and (b) autocorrelation trace of regenerative PA based mode-locked fiber ring laser

The generated feedback signal (which is derived from the output pulses) and the output mode-locked pulses are shown in the following diagrams. Some cares have to be taken for the feedback path, such as the power of input signal to the RFA has to be below its maximum allowable value to avoid component damage and saturation effect. When saturation occurs, the feedback signal will be distorted and affect the error signal generated from the mixer. Also, the electronic feedback path has to be properly terminated when not in used to eliminate possible standing wave. A 50 Ω terminator is usually a good choice.
5.5 Conclusions

I have developed a model for Gaussian modulating signal in an active mode-locked laser system, and studied its pulse width dependency on duty cycle. For Gaussian modulating signal with duty cycle less than 30%, one can expect to have pulse width shorter than that of the cosinusoidal case under similar system parameters. In addition, I have also showed the stable operation region for soliton-Gaussian pulse generation in an
active mode-locked laser system using the Gaussian-like modulating signal. Smaller duty cycle will lead to a wider stable operation region and looser control parameters.

By applying the Gaussian-like modulating signal in the active harmonically mode-locked fiber ring laser, I obtained a record-high harmonic order multiplication in the mode-locked fiber ring laser system, and achieved 123 GHz operation. Stability analysis using phase plane technique has also been performed.

Furthermore, the scope of the investigation was extended to include parametric amplification in a mode-locked fiber ring laser system to achieve ultra-high bit rate operation, by using the frequency detuning technique and modulation instability. Other effects such as soliton compression, intracavity power influences are also investigated. Regenerative structure is also constructed for better stability.
Chapter 6  NOLM-NALM Fiber Ring Laser

The nonlinear phenomenon of optical bistability has been studied in nonlinear resonators since 1976 by placing a nonlinear medium within a laser cavity formed by multiple mirrors [Gibbs et al., 1976]. As for the fiber based devices, single mode fiber was used as the nonlinear medium inside a ring cavity in [Nakatsuka et al., 1983]. Since then, the study of nonlinear phenomena in fiber resonators has remained as a topic of considerable interest.

Fiber ring laser is a rich and active research field in optical communications. Many fiber ring laser configurations have been proposed and constructed to achieve different objectives. It can be designed for CW or pulse operations; linear or nonlinear operations; fast or slow repetition rate; narrow or broad pulse width, etc; for various kinds of photonic applications.

The simplest fiber laser structure is an optical closed loop with a gain medium and some associated optical components such as optical couplers. The gain medium used can be any rare earth element doped fiber amplifier; such as erbium and ytterbium, semiconductor optical amplifier, parametric amplifier, etc; as long as it provides the gain requirement for lasing. Without any mode-locking mechanism, the laser will operate in
the CW regime. By inserting an active mode-locker into the laser cavity, i.e. either amplitude or phase modulator, the resulting output will be an optical pulse train operating at the modulating frequency, when the phase condition is matched, as discussed in Chapter 3 and 4. This often results in a high-speed optical pulse train, however with broad pulse width. There is another kind of fiber laser, which uses the nonlinear effect in generating optical pulses, and is known as passive mode-locking technique. The technique has been briefly mentioned in Chapter 2. Saturable absorber, stretched pulse mode-locking [Tamura et al., 1993], nonlinear polarization rotation [Yandong et al., 2002], figure-eight fiber ring lasers, etc are grouped under this category. This type of laser generates shorter optical pulses in exchange of its repetition frequency. This is the trade off between the active and passive mode-locked laser systems.

Although there are different types of fiber lasers, with different operating regimes and principles, one common criterion is the uni-directionality, besides the gain and phase matching conditions. Unidirectional operation has been proved to offer better lasing efficiency, less sensitive to back reflections and good potential for single longitudinal mode operation [Siegman, 1986], and can be achieved by incorporating an optical isolator within the laser cavity. [Shi et al., 1995] has demonstrated a unidirectional inverted S-type erbium doped fiber ring laser without the use of optical isolator, but with optical couplers. In their laser system, the lightwaves are passed through in one direction and suppressed in the other using certain coupling ratios, hence, achieving unidirectional operation. However, only the power difference between the two CW lightwaves was studied, and the works did not extend further into unconventional and nonlinear regions of operation.
In this chapter, I study the bidirectional lightwaves propagation in an erbium doped fiber ring laser and observe the optical bistability behavior. This optical bistability behavior has been well reported previously [Oh and Lee, 2004, Mao and Lit, 2003, Luo et al., 1998], however only in unidirectional manner. I exploit this commonly known as undesirable bidirectional lightwaves propagation in constructing a kind of fiber laser configuration based on nonlinear optical loop mirror (NOLM) and nonlinear amplifying loop mirror (NALM) structure. This laser configuration is similar to the one demonstrated by [Shi et al., 1995], however, I operate the laser in different region of the operation, focus on its nonlinear dynamics, and observe optical bifurcation phenomenon. Also, I investigate the switching capability of the laser based on its bistability behavior.

6.1 Optical Bistability, Bifurcations and Chaos

All real physical systems are somehow nonlinear in nature. Apart from systems designed for linear signal processing, many systems have to be nonlinear by assumption, for instance flip-flops, modulators, demodulators, amplifiers, etc. In this section, I will focus on the optical bistability, bifurcations and chaos of a nonlinear optical system.

An optical bistable device is a device with two possible operation points. It will remain stable in any of the two optical states, one of high transmission and the other of low transmission, depending upon the intensity of the light passing through it. Here, I discuss the effect of optical nonlinearity together with the proper feedback; can give rise to optical bistability and hysteresis. This is expected as these two effects are also observed
in nonlinear electronic circuits with feedback, such as Schmitt trigger, as well as hybrid optical devices, such as an acousto-optic device with feedback [Banerjee, 2004].

A typical bistability curve is shown in Fig. 6-1, with \( Y_i \) and \( Y_o \) are the input and output parameters respectively. For an input value between \( Y_1 \) and \( Y_2 \), there are three possible output values. The middle segment, with negative slope, is known to be always unstable. Therefore the output will eventually have two stable values. When two outputs are possible, which one of the outputs is eventually realized depends on the history of how the input is reached, and hence the hysteresis phenomenon. As the input value is increased from zero, the output will follow the lower branch of the curve until the input value reaches \( Y_2 \). Then it will jump up and follow the upper branch. However, if the input value is decreased from some points after the jump, the output will remain on the upper branch until the input value hits \( Y_1 \), then the output will jump down and follow the lower branch. Hence, the bistability region observed is from \( Y_1 \) to \( Y_2 \).

![Bistability curve](image)

**Figure 6-1: Bistability curve**
In an optical ring cavity, the lightwave can be separated into two components propagating in opposite directions. These two components interact with each other through atomic medium, which leads to gain competition. Hence, in a ring laser, the lightwaves may propagate in one direction or another depending on the initial configuration and are thus running waves in general. To eliminate this randomness, a device such as optical isolator is often added into the ring cavity to block the unwanted wave. Up to this point, the experiments presented so far in this thesis are optical isolator incorporated.

There are two different types of optical bistability, namely: absorptive bistability and dispersive bistability in a nonlinear ring cavity comprising a two-level gain medium as nonlinear medium. Absorptive bistability is the case when the incident optical frequency is close or equal to the transition frequency of atoms from one level to another. The system is in perfect resonance condition. In this case, the absorption coefficient becomes a nonlinear function of the incident frequency.

On the other hand, if the frequencies are far apart, the gain medium behaves like a Kerr-type material and the system exhibits what is called dispersive bistability. A nonzero atomic detuning will introduce saturable dispersion in response to medium. In this case the material can be modeled by an effective nonlinear refractive index, which is a nonlinear function of the optical intensity [Banerjee, 2004].

For optical bistability in a ring cavity, there is a possible instability due to the counter-propagating wave. Hence, it is interesting to know the lightwaves behavior in both co- and counter-propagating directions. The bidirectional operation of an optical bistable ring system has not yet been studied thoroughly. Although some studies have
been done relating to the bistability properties of ring cavities, they focused on forcing the system to support only unidirectional operation [Meystre, 1978]. The restriction to unidirectional propagation has been quite consistent with the experimental results; however the exceptions were noted [Orozco et al., 1989]. Unfortunately, no further investigation has been carried out since then.

It was discovered that the nonlinear response of a ring resonator could initiate a period doubling (bifurcation) route to optical chaos [Ikeda, 1979]. In a dynamical system, a bifurcation is a period doubling, quadrupling, etc., that accompanies the onset of chaos. It represents a sudden appearance of a qualitatively different solution for a nonlinear system as some parameters are varied. A typical bifurcation map is shown below; with $g$ and $\gamma$ are the input and output system parameters respectively. Period doubling action starts at $g \approx 1.5$, and period quadrupling at $g \approx 2$. Region beyond $g \approx 2.3$ is known as chaos.

![Bifurcation Map](image)

**Figure 6-2: Typical bifurcation map**
Each of the local bifurcations may give rise to distinct route to chaos if the bifurcations appear repeatedly when changing the bifurcation parameter. These routes are important since it is difficult to conclude from experimental data alone whether irregular behavior is due to measurement noise or chaos. Recognition of one of the typical routes to chaos in experiments is a good indication that the dynamics may be chaotic [Ogorzalek, 1997].

- **Period doubling route to chaos** - When a cascade of successive period-doubling bifurcation occurs when changing the value of the bifurcation parameter, it is often the case that finally the system reaches chaos.

- **Intermittency route to chaos** - The route to chaos caused by saddle-node bifurcation. The common feature of which is a direct transition from regular motion to chaos.

- **Torus breakdown route to chaos** - The quasi-periodic route to chaos results from a sequence of Hopf bifurcations.

It is well-known that self pulsing often leads to optical chaos in the laser output, following a period doubling or a quasi periodic route. The basic idea is that the dynamics of the intracavity field is different from one round trip to another in a nonlinear fashion. The characteristics of a chaotic system [Kennedy, 1993] are:

- **Sensitive dependence on initial conditions** - it gives rise to an apparent randomness in the output of the system and the long-term unpredictability of the state. Because the chaotic system is deterministic, two trajectories that
start from identical initial states will follow precisely the same paths through the state space.

- Randomness in the time domain - in contrast to the periodic waveforms, chaotic waveform is quite irregular and does not appear to repeat itself in any observation period of finite length.

- Broadband power spectrum - every periodic signal may be decomposed into Fourier series, a weighted sum of sinusoids at integers multiples of a fundamental frequency. Thus a periodic signal appears in the frequency domain as a set of spikes at the fundamental frequency and its harmonics. The chaotic signal is qualitatively different from the periodic signal. The aperiodic nature of its time-domain waveform is reflected in the broadband noise like power spectrum. This broadband structure of power spectrum persists even if the spectral resolution is increased to a higher frequency.

A typical example of the chaotic system is Lorenz attractor, or more commonly known as butterfly attractor, with following system description, with a = 10, b = 28 and c = 8/3.

\[
\begin{align*}
\frac{dx}{dt} &= a(y-x) & \text{[Eq 6-1]} \\
\frac{dy}{dt} &= x(b-z) - y & \text{[Eq 6-2]} \\
\frac{dz}{dt} &= xy - cz & \text{[Eq 6-3]}
\end{align*}
\]
6.2 Nonlinear Optical Loop Mirror

The concept of nonlinear optical loop mirror (NOLM) was proposed by [Doran and Wood, 1988]. It is basically a fiber based Sagnac interferometer that uses the nonlinear phase shift of optical fiber for optical switching. This configuration is inherently stable since the two arms of the structure reside in the same fiber and same optical path lengths for the signals propagating in both arms, however in opposite direction. There is no feedback mechanism in this structure since all lightwaves entering the input port exit from the loop after a single round trip. The NOLM in its simplest form contains a fiber coupler, with two of its output ports are connected together, as shown in Fig. 6-4, with $\kappa$ is the coupling ratio of the coupler, $E_1$, $E_2$, $E_3$ and $E_4$ are the fields at port 1, 2, 3 and 4 respectively.
Under lossless condition, the input-output relationships of a coupler with coupling ratio of $\kappa$ are

$$E_3 = \sqrt{\kappa} E_1 + j \sqrt{1 - \kappa} E_2$$  \hspace{1cm} [Eq 6-4a] \\
$$E_4 = \sqrt{\kappa} E_2 + j \sqrt{1 - \kappa} E_1$$  \hspace{1cm} [Eq 6-4b]

where $j^2 = -1$. If low intensity light is fed into port 1, i.e. no nonlinear effect, the transmission, $T$ is

$$T = \frac{P_{\text{out}}}{P_{\text{in}}} = 1 - 4\kappa(1 - \kappa)$$  \hspace{1cm} [Eq 6-5]

If $\kappa = 0.5$, all light will be reflected back to the input, therefore the name loop mirror; the counter propagating lightwaves in the loop will have different intensities, and thus leads to different nonlinear phase shifts. This device can be designed to transmit high power signal while reflecting it at low power levels, thus acting as an all-optical switch.
After L propagation, the output signals, $E_{3L}$ and $E_{4L}$ become as follows with nonlinear phase shifts taken into account:

$$E_{3L} = E_{3} \exp(j \frac{2\pi n_2 L}{\lambda} |E_{3}|^2) \quad \text{[Eq 6-6a]}$$
$$E_{4L} = E_{4} \exp(j \frac{2\pi n_2 L}{\lambda} |E_{4}|^2) \quad \text{[Eq 6-6b]}$$

where $|E_{3}|^2$ and $|E_{4}|^2$ are the light intensities of the two arms, $n_2$ is the nonlinear coefficient, L is the loop length, $\lambda$ is the operating wavelength of the signal, and let $E_{1} = E_{01} \exp(j \omega_1 t)$ and $E_{2} = E_{02} \exp(j \omega_2 t)$:

$$|E_{3L}|^2 = |E_{3}|^2$$
$$= \kappa |E_{1}|^2 + (1 - \kappa) |E_{2}|^2 + j \sqrt{\kappa (1 - \kappa)} (E_{1*} E_{2} - E_{1} E_{2*})$$
$$= \kappa |E_{01}|^2 + (1 - \kappa) |E_{02}|^2 - 2 \sqrt{\kappa (1 - \kappa)} E_{01} E_{02} \sin[(\omega_2 - \omega_1) t] \quad \text{[Eq 6-7a]}$$

$$|E_{4L}|^2 = |E_{4}|^2$$
$$= \kappa |E_{2}|^2 + (1 - \kappa) |E_{1}|^2 + j \sqrt{\kappa (1 - \kappa)} (E_{2*} E_{1} - E_{2} E_{1*})$$
$$= \kappa |E_{02}|^2 + (1 - \kappa) |E_{01}|^2 + 2 \sqrt{\kappa (1 - \kappa)} E_{01} E_{02} \sin[(\omega_2 - \omega_1) t] \quad \text{[Eq 6-7b]}$$

The last term of [Eq 6-7] represents the interference pattern between $E_{1}$ and $E_{2}$. Most literatures consider only simple case with single input at port 1, i.e. $E_{2} = 0$, and hence reduce the interference effect between the signals, and the outputs at port 1 and 2 are given as follows:

$$|E_{o1}|^2 = |E_{01}|^2 \left\{ 2\kappa (1 - \kappa) \left[ 1 + \cos \left( 1 - 2\kappa \frac{2\pi n_2 |E_{01}|^2 L}{\lambda} \right) \right] \right\} \quad \text{[Eq 6-8a]}$$

$$|E_{o2}|^2 = |E_{02}|^2 \left\{ 1 - 2\kappa (1 - \kappa) \left[ 1 + \cos \left( 1 - 2\kappa \frac{2\pi n_2 |E_{02}|^2 L}{\lambda} \right) \right] \right\} \quad \text{[Eq 6-8b]}$$
However, for a more complete study, I consider inputs at both ports; and the outputs will be

\[
|E_{o1}|^2 = \kappa |E_{4l}|^2 + (1 - \kappa) |E_{3l}|^2 + j \sqrt{\kappa(1-\kappa)} (E_{4l}^* E_{3l} - E_{3l}^* E_{4l})
\]

\[
= [\kappa^2 + (1 - \kappa)^2] |E_{o1}|^2 + 2 \kappa (1 - \kappa) |E_{o1}|^2 - 2 (1 - 2 \kappa) \sqrt{\kappa(1-\kappa)} E_{o1} E_{o2} \sin[(\omega_2 - \omega_1)t] + j \sqrt{\kappa(1-\kappa)} (E_{o1}^* E_{o2} \exp(j\Delta \theta) - E_{o2}^* E_{o1} \exp(-j\Delta \theta))
\]

\[
= |E_{o1}|^2 [2 \kappa (1 - \kappa) [1 + \cos(\Delta \theta)]] + |E_{o2}|^2 [1 - 2 \kappa (1 - \kappa) [1 + \cos(\Delta \theta)]]
\]

\[\Delta \theta = \theta_3 - \theta_4\]

\[
= 2 \pi n_2 L \left\{ (1 - 2 \kappa) \left\{ \frac{|E_{o2}|^2}{\lambda_2} - \frac{|E_{o1}|^2}{\lambda_1} \right\} - \frac{4 \sqrt{\kappa(1-\kappa)} E_{o1} E_{o2} \sin[(\omega_2 - \omega_1)t]]}{\sqrt{\lambda_1 \lambda_2}} \right\}
\]

where

and \( \lambda_1 \) and \( \lambda_2 \) are the operating wavelengths of \( E_1 \) and \( E_2 \) respectively.

For \( \lambda_1 = \lambda_2 \), and \( E_2 = p E_1 \) with \( p \) is a constant, the switching characteristics for (a) \( \kappa = 0.45 \) and (b) \( \kappa = 0.2 \) are shown in Fig. 6-5, Transmisivity 1 and Transmisivity 2 are the transmissions, \( T \) [Eq 6-5] at port 1 and 2 respectively. Switching occurs only for large energy difference between the two ports, i.e. \( p >> 1 \). Also, as can be seen from the figure, the switching behavior is better for coupling ratio close to 0.5.
6.3 Nonlinear Amplifying Loop Mirror

The structure of the nonlinear amplifying loop mirror (NALM) is somehow similar to NOLM structure, and it is an improved exploitation of NOLM. For NALM configuration, a gain medium with gain coefficient, $G$ is added to increase the asymmetric nonlinearity within the loop [Fermann et al., 1990]. The amplifier is placed at one end of the loop, closer to port 3 of the coupler, and is assumed short relative to the total loop length, as shown in Fig. 6-6. One lightwave is amplified at the entrance to the loop, while the other experiences amplification just before exiting the loop. Since the intensities of the two lightwaves differ by a large amount throughout the loop, the differential phase shift can be quite large.
By following the analysis procedure stated in the previous section, I arrive at the
input-output relationships as follows:

\[
|E_{o1}|^2 = G_1 \left[ |E_{o2}|^2 \left[ 2\kappa (1 - \kappa) \left| 1 + \cos(\Delta \theta) \right| \right] + |E_{o1}|^2 \left[ 1 - 2\kappa (1 - \kappa) \left| 1 + \cos(\Delta \theta) \right| \right] \right]
\]
\[\quad - 2\sqrt{\kappa (1 - \kappa)} E_{o1} E_{o2} \left[ (1 - 2\kappa) \sin((\omega_2 - \omega_1) t) \left| 1 + \cos(\Delta \theta) \right| + \cos[(\omega_2 - \omega_1) t] \sin(\Delta \theta) \right] \]  
[Eq 6-62]

\[
|E_{o2}|^2 = G_2 \left[ |E_{o2}|^2 \left[ 2\kappa (1 - \kappa) \left| 1 + \cos(\Delta \theta) \right| \right] + |E_{o1}|^2 \left[ 1 - 2\kappa (1 - \kappa) \left| 1 + \cos(\Delta \theta) \right| \right] \right]
\]
\[\quad + 2\sqrt{\kappa (1 - \kappa)} E_{o1} E_{o2} \left[ (1 - 2\kappa) \sin((\omega_2 - \omega_1) t) \left| 1 + \cos(\Delta \theta) \right| + \cos[(\omega_2 - \omega_1) t] \sin(\Delta \theta) \right] \]  
[Eq 6-73]

\[
\Delta \theta = 2\pi n_2 L \left\{ \frac{(1 - \kappa - G \kappa) |E_{o2}|^2}{\lambda_2} - \frac{|E_{o1}|^2}{\lambda_1} \right\}
\]
\[\quad - 2(G + 1) \sqrt{\kappa (1 - \kappa)} E_{o1} E_{o2} \sin((\omega_2 - \omega_1) t) \frac{\sin(\Delta \theta)}{\sqrt{\lambda_1 \lambda_2}} \]  
[Eq 6-84]
6.4 NOLM-NALM Fiber Ring Laser

The configuration of NOLM-NALM fiber ring laser is shown in Fig. 6-7. It is simply a coupled loop mirrors, with NOLM (ABCEA) on one side and NALM (CDAEC) on the other side of the laser, with a common path in the middle section (AEC). One interesting feature about this configuration is the feedback mechanism of the fiber ring: one is acting as the feedback path to another, i.e. NOLM is feeding-back part of NALM’s signal and vice versa.

As a matter of fact, complex systems tend to encounter bifurcations, which when amplified, can lead to either order or chaos. The systems can transit into chaos, through period doubling; or order through a series of feedback loops. Hence, bifurcations can be considered as critical points in this system transitions.

In the formulated process, I ignore the nonlinear phase shift due to laser pulsation. The assumption is valid because of the saturation effect of gain medium, as well as the energy stabilization provided by the filter.

![Diagram of NOLM-NALM fiber ring laser](Image)
I numerically simulate the laser behavior by combining the effects described in the previous section, and obtain the bifurcation maps based on the CW operation as shown in Fig. 6-8 & Fig. 6-9, with $P_{o1}$ and $P_{o2}$ are the output powers at point A and C respectively, with $\kappa_1 = 0.55$ and $\kappa_2 = 0.65$; $L_a$, $L_b$ and $L_c$ are 20 m, 100 m and 20 m respectively; nonlinear coefficient of $3.2 \times 10^{-20}$ m$^2$/W; gain coefficient of 0.4/m at 1550 nm with EDF length of 10 m and a saturation power of 25 dBm; and fiber effective area of 50 $\mu$m$^2$. $\kappa_1$ and $\kappa_2$ are the coupling ratios of couplers from port 1 to port 3 at point A and C respectively; $L_a$, $L_b$ and $L_c$ are the fiber lengths of left, mid and right arm of the laser cavity. The maps are obtained with 200 iterations. Fig. 6-8 shows the bifurcation maps with SPM consideration only whereas Fig. 6-9 considers both SPM and XPM effects.

In constructing the bifurcation maps of the system, I separate the lightwaves into clockwise (cw) and counter clockwise (ccw) directions; similarly for couplers involved in the system, i.e. four couplers are used in simulating this bifurcation behavior. Initial conditions are set to be the pump power of EDFA. I then propagate the lightwaves in both directions within the fiber ring, with various components effects taking into account, such as coupling ratios, gain, SPM and XPM. The outputs are then served as inputs to the system for the next iteration. The process is repeated for a number of times, i.e. 200 times. Each iterated set of outputs is then combined to construct the bifurcation maps.

There are some similarities between Fig. 6-8 and Fig. 6-9. Both of them indicate different operating regions at different power levels. With both SPM and XPM effects taking into account (Fig. 6-9), the transition from one operation state to another is faster,
leads to earlier chaotic operation with lower pump power. This is simply because the effect of XPM is twice the SPM. For simplicity, I discuss only the bifurcation behavior of Fig. 6-8 to illustrate the transition behavior from one state to another.

From the map obtained (Fig. 6-8), under this set of system parameters, there are three operation regions for this NOLM-NALM fiber ring laser. The first is the linear...
operation region (0 W = P < 6 W), where there are single-value outputs, and the output power increases with the input power. Period doubling effect starts to appear when the input power reaches ~ 6 W. This is the second operation region (6 W = P < 8 W) of the laser, where double-periodic and quasi-periodic signals can be found here. When the input power goes beyond 8 W, the laser will enter into chaotic state of operation.

Poincare map of the above system configuration with high pump power is shown in Fig. 6-10. It shows attractor pattern of the system when the laser is operating in the chaotic region. The powers required for the operations can be reduced by increasing the lengths of the fibers, $L_a, L_b$ and $L_c$.

![Poincare Map](image)

**Figure 6-10:** Poincare map of the system with high pump power with $\kappa_1 = 0.55$ and $\kappa_2 = 0.65$

By setting $\kappa_2 = 0$, the laser will behave like a NOLM. With an input pulse to port 1 of coupler A and I observe pulse compression at its output port, $P_{o1}$, as shown in Fig. 6-11 and Fig. 6-12. Fig. 6-12 presents the transmission capability of the setup, $P_{o1}$ for
various $\kappa_i$ values, when the input is injected to port 1 and $\kappa_i = 0$. When $\kappa_i = 0.5$, I observe no transmission at the output, as the entire injected signal has been reflected back to port 1, where the mirror effect takes place. By changing the coupling ratio of $\kappa_2$, I am able to change zero transmission point away from $\kappa_i = 0.50$. Fig. 6-13 shows the transmisivities of $P_{o1}$ and $P_{o2}$ for various sets of $\kappa_i$ and $\kappa_2$, it reveals the complex switching dynamics of the laser as well as pulse compression capability.

Figure 6-11: Input and output comparison with $\kappa_2 = 0$ and (a) $\kappa_1 = 0.41$ and (b) $\kappa_1 = 0.49$

Figure 6-12: Output pulse behavior for various $\kappa_1$ values, when $\kappa_2 = 0$ for small input power (Inset: top view of the pulse behavior)
<table>
<thead>
<tr>
<th>$k^2$</th>
<th>$P_{o1}$</th>
<th>$P_{o2}$</th>
</tr>
</thead>
<tbody>
<tr>
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<td><img src="image1.png" alt="Graph" /></td>
<td><img src="image2.png" alt="Graph" /></td>
</tr>
<tr>
<td>0.2</td>
<td><img src="image3.png" alt="Graph" /></td>
<td><img src="image4.png" alt="Graph" /></td>
</tr>
<tr>
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<td><img src="image5.png" alt="Graph" /></td>
<td><img src="image6.png" alt="Graph" /></td>
</tr>
<tr>
<td>0.8</td>
<td><img src="image7.png" alt="Graph" /></td>
<td><img src="image8.png" alt="Graph" /></td>
</tr>
</tbody>
</table>
6.5 Experiment Setups and Analyses

6.5.1 Bidirectional Erbium Doped Fiber Ring Laser

I start with a simple erbium doped fiber ring laser; an optical closed loop with EDFA and some fiber couplers. It is used to study bi-directional lightwave propagations behavior of the laser. The EDFA is made of a 20 m erbium doped fiber (EDF), and dual pumped by 980 and 1480 nm diode lasers, with a saturation power of about 15 dBm. The slope efficiencies of the pump lasers are 0.45 mW/mA and 0.22 W/A respectively. No isolator and filter is used in the setup to eliminate direction and spectra constraints. Two outputs are taken out from a 10 dB output coupler for examinations, i.e. Output1 in counter clockwise (ccw) direction, and Output2 in clockwise (cw) direction. All connections within the fiber ring are spliced together to reduce possible reflections within the system. Output1 and Output2 as shown in Fig. 6-14 are taken for investigations.
The ASE spectrum of laser covers the range from 1530 nm to 1570 nm. By increasing both the 980 nm and 1480 nm pump currents to their maximum allowable values, I obtain bidirectional lasing, which is shown in Fig. 6-15. The upper plot is lightwave propagating in cw direction while the other one in ccw direction. To obtain bidirectional lasing, gain and loss must be balanced for the two lightwaves that propagate around the cavity in opposite directions [Mohebi et al., 2002]. The pump lasers used in the setup are not identical (in terms of power and pumping wavelength), and this gives rise to different lasing behaviors for both cw and ccw directions. Due to the laser diode controllers’ limitation, the maximum pumping currents for both 980 nm and 1480 nm laser diodes are capped at 300 mA and 500 mA respectively, which correspond to 135 mW and 110 mW in cw and ccw pump directions. This explains the domineering cw lasing as shown in the figure. One thing to note is that the lasings in both directions are not very stable due to the disturbance from the opposite propagating lightwaves and ASE noise due to the absence of filter. Output1 is mainly contributed by back reflections from
the fiber ends and connectors, as well as some back-scattered noises. Since all connections within the fiber ring are spliced together, the reflections due to connections are minimum. However, there are still some unavoidable reflections from the fiber ends, which contribute to the lightwaves in opposite directions. Besides that, back-scattered noise also adds to the lightwaves in opposite directions.

Figure 6-15: (a) ASE spectrum of the laser measured in cw direction (Output2); (b) Lasing characteristics in both directions (upper trace: Output 2, lower trace: Output1)

I maintain 980 nm pump current, and adjust 1480 nm pump current upwards and then downwards to examine the bistability behavior of the laser. The bistable characteristics at a lasing wavelength of ~1562.2 nm for both cw and ccw directions are shown in Fig. 6-16 and Fig. 6-17, with log and linear scales for the vertical axes. I obtain ~15 dB difference between the two propagating lightwaves. The bistable region obtained is ~30 mA of 1480 nm pump current at a fixed value of 100 mA of 980 nm pump current. No lasing is observed in the ccw lightwave propagation. This bistable region can be further enhanced by increasing the 980 nm pump current. By fixing 980 nm pump current at ~175 mA, I obtain a bistable region as wide as ~70 mA of 1480 nm pump current. When the 980 nm pump current is maintained at a higher level (> 175 mA), the
lasing of Output2 remains even when the 1480 nm pump is switched off, as shown in Fig. 6-17. This bistable behavior is mainly due to the saturable absorption of EDF.

This mechanism enables controllable and adjustable bistable region, which one pumping condition is used to determine the width of the bistable region, while the other manipulates the bistability operation.

![Figure 6-16: Hysteresis loops obtained from the EDFRL for 980 nm pump current = 100 mA (a) log scale; (b) linear scale](image1)

![Figure 6-17: Hysteresis loops obtained from the EDFRL for 980 nm pump current = 200 mA (a) log scale; (b) linear scale](image2)
6.5.2 NOLM-NALM Fiber Ring Laser

The experimental setup of the NOLM-NALM fiber ring laser is shown in Fig. 6-18. It is simply a combination of NOLM on one side and NALM on the other side of the laser, with a common path in the middle section. Principal element of the laser is an optical close loop with an optical gain medium, two variable ratio couplers (VRC), a tunable BPF, optical couplers and other associated optics. The gain medium used in the fiber laser system is the one used in the preceding experiment. Two VRCs, with coupling ratios ranging from 20 % to 80 % and insertion loss of about 0.2 dB are added into the cavity at positions shown in the figure to adjust the coupling power within the laser. They are interconnected in such a way that the output of one VRC is the input of the other. A tunable BPF with 3 dB bandwidth of 2 nm at 1560 nm is inserted into the cavity to select operating wavelength and reduce system noise. One thing to note is that the lightwaves are traveling in both directions, as there is no isolator is used in the laser. Output1 and Output2 as shown in the figure are taken as laser outputs.

Figure 6-18: Experimental setup of NOLM-NALM fiber ring laser
One interesting phenomenon observed before the BPF is inserted is wavelength tunability. The lasing wavelength is tunable from 1530 nm to 1560 nm (almost entire EDFA C-band), by changing the coupling ratios of VRCs. I believe that this wavelength tunability is due to the change of traveling lightwaves’ intensities, which contributes to nonlinear refractive index change, and in turn modifies dispersion relations of the system, and hence lasing wavelength. Therefore, the VRCs within the cavity not only determine the directionality of lightwave propagation, but also lasing wavelength.

For a conventional erbium doped fiber ring laser, bistability is not observable when the pump current is far above the threshold value, where saturation starts to take place. However, a small hysteresis loop has been observed in my laser setup even with high pump current, i.e. near saturation region, when changing the coupling ratio of one VRC while that of the other one remains unchanged, as shown in Fig. 6-19. Changing the coupling ratio, is directly altering the total cavity power, and hence modifying its gain and absorption behavior. As a result, a small hysteresis loop is observable even with a constant high pump power, which can be an added advantage to the existing bistable state.
Figure 6-19: Hysteresis loop observed while changing the coupling ratio of one VRC while maintaining that of the other, when operating at high pump current.

The power distribution of Output1 and Output2 of the NOLM-NALM fiber laser obtained experimentally is depicted in Fig. 6-20. I obtain switching between outputs by tuning the coupling ratios of VRC1 and VRC2. The simulation results for transmisivities for various coupling ratios under linear operation are shown in Fig.6-21, since the available pump power of my experiment setup is insufficient to create high power within the cavity. Both the experimental and numerical results have come to some agreements, but not all, since the model developed is simple and does not consider polarization, dispersion characteristics etc. of the propagating lightwaves.

With this setup, i.e. with additional degree of freedom, one can change the zero transmission point and switching behavior of a NOLM-NALM structure. It also adds more asymmetricity to the system.
Figure 6-20: Experimental results for Output1 (Op1) and Output2 (Op2) for various coupling ratios (k1 – coupling ratio of VRC1, k2 – coupling ratio of VRC2)

Figure 6-21: Simulation results for transmissivities of Output1 (solid line) and Output2 (dotted line) for various coupling ratios of VRC1 and VRC2
6.5.3 Amplitude Modulated NOLM-NALM Fiber Ring Laser

The schematic of AM modulated NOLM-NALM fiber ring laser is depicted in Fig. 6-22. A few new photonic components are added into the laser cavity. A 10 GHz MZM is used in the inner loop of the cavity with half wave voltage, $V_\pi$ of 5.3 V. The modulator is DC biased near the quadrature point so that it operates in the linear region and to ensure minimum chirp imposing on the modulated lightwaves. It is driven by a sinusoidal signal derived from an Anritsu 68347C Synthesizer Signal Generator. Two PCs are placed prior to the inputs of MZM in both directions to ensure proper polarization alignment into it. A wider bandwidth, i.e. 5 nm tunable FP filter is used in this case to allow more longitudinal modes within the laser for possible mode-locking process.

![Figure 6-22: Experimental setup for AM NOLM-NALM fiber laser](image)

Pulse operation is obtained with insertion of MZM, by means of active harmonic mode-locking technique. Both propagation lightwaves are observed. By proper adjustment of the modulation frequency, PCs and VRCs, unidirectional pulse operation
at modulating frequency is obtained. However, it is highly sensitive to the environmental change. The lightwave propagation direction of the laser can be controlled by the VRCs. The unidirectional pulse operation is shown in Fig. 6-23.

![Figure 6-23: Unidirectional pulse operation in AM NOLM-NALM fiber laser: (a) Experimental results; (b) simulation results](image)

However, with slight deviations to the system parameters, i.e. slight modulation frequency detuned or PCs adjustments; period doubling and quasi-periodic operations are observed, as shown in Fig. 6-24. This effect is due to interference between bidirectional propagating lightwaves, which have suffered nonlinear phase shifts in each direction, since EDFA is operating in its saturation region. Furthermore, lightwave in one direction is feedback signal for another one. The intensity modulation of MZM is not identical for co- and counter- interactions between lightwaves and traveling microwaves on the surface of optical waveguide. This contributes to the mismatch of locking condition of the laser.

This laser structure has a very interesting nature. By proper adjustment of the laser system parameters, such as coupling ratios, lightwave polarization and modulation...
frequency; one can make use of this laser setup to encrypt information for secured optical communication. However, stability is still a concern for this setup.

Figure 6-24: Quasi-periodic operation in AM NOLM-NALM fiber laser; (a) photograph of oscilloscope trace, (b) XY plot of Output1 and Output2, (c) simulated XY plot, (d) simulated Poincare map
6.6 Conclusions

Bidirectional optical bistability in a dual-pumped erbium doped fiber ring laser without isolator has been studied. A ~70 mA 1480 nm pump current bistable region has also been obtained. With this bidirectional bistability capability, I experimentally constructed and numerically simulated a NOLM-NALM fiber laser for its switching and bifurcation behaviors. From the simulated bifurcations maps, three basic operation regions can be identified, namely unidirectional, period doubling and chaos operations. The VRCs used in the setup not only control the lightwave directionality, but also its dispersion characteristics. Unidirectional lightwave propagation; without isolator, were achieved in both continuous wave and pulse operations by tuning the coupling ratios of VRCs within the laser system. Bifurcations were also obtained from AM NOLM-NALM fiber laser. However, chaotic operation was not observed experimentally due to hardware limitation of the system, which required higher gain coefficient and input power as predicted in my simulation.

The proposed laser model is somehow comparable to optical flip-flop. The optical flip-flop concept has been used in optical packet switches and optical buffers [Zhang et al., 2004, Dorren et al., 2003, Langenhorst et al. in 1996, Liu et al., 2004]. Moreover, this NOLM-NALM fiber laser possesses many interesting optical behaviors, which could be useful in many photonics applications, such as photonic flip-flops, optical buffer loop, photonic pulse sampling devices, and secured optical communications.
Chapter 7  Conclusions and Future Recommendations

7.1  Conclusions

The basic elements, working mechanisms and system behaviors of an active mode-locked erbium doped fiber ring laser have been examined. Regenerative mode-locked laser structure has also been constructed for better stability.

Fractional temporal Talbot based repetition rate multiplication system has been constructed for high repetition rate system, and achieved 40 GHz pulse operation. However, stability is a great concern for this system setup. I use, for the first time, the phase plane analysis in the laser system stability studies. The analysis gives transient and steady state behaviors of the system. Furthermore, the influences of lasing mode amplitude, filter bandwidth and noise are investigated.

I challenged the conventional mode-locking system, where a Gaussian-like modulating signal was used. An analytical mode-locking model for this type of modulating signal has been developed. I arrived at a concluding remark that the generated mode-locked pulses will be shorter than that of the conventional cosinusoidal modulating
signal if the duty cycle of the Gaussian-like modulating is less than 30%. With this type of modulating signal, I achieved a record high rational harmonic detuning in my active harmonically mode-locked fiber ring laser, i.e. 1230th order, with a base modulation frequency of 100 MHz, and hence 123 GHz pulse operation. Also, phase plane analysis is applied in the system stability analysis.

Wave-mixing process has also been studied in my parametric amplifier based fiber ring laser. The gain profile of this type of laser was examined. By employing slight frequency detuned to the system, Tera-Hz operation was obtainable. In addition, regenerative structure for this type of laser has also been constructed for improved stability.

Optical bistability, bifurcations and chaos phenomena have been well studied in my proposed NOLM-NALM fiber ring laser. I focused on the bidirectional lightwaves propagation behaviors in the system. Three operation regimes are obtained numerically: single operation, period doubling operation and chaotic operation. Two out of three operations are observed experimentally due to hardware limitations. I believe that this laser structure will have good potential in various photonics applications due to its interesting operating characteristics.

### 7.2 Future Recommendations

Having generated the Giga- and Tera- Hertz optical pulse trains, one may want to incorporate them into high bit rate lightwave transmitters suitable for the use in
telecommunications and data-communication systems, either with WDM, OTDM or PDM systems. This involves investigations of possible nonlinear behaviors of system, such as self and cross phase modulations, possible new frequency components generation, etc; chromatic dispersions, higher order dispersions, polarization mode dispersions and their possible compensation, timing jitter, bit error rate, bandwidth distance product, etc when operating at this ultra-high speed.

Other than the ultra-fast mode-locked laser systems, one may enter the territory of ultra-short mode-locked laser systems, where femtosecond laser can be used as optical clock in conjunction with certain atoms or ions [Holzwarth et al., 2001, Ye et al., 2003]. It is a strong candidate in this new breakthrough due to its broad spectrum. With this femtosecond technology, the clock might stay accurate in about four billion years. The ability to count optical oscillations of more than $10^{15}$ cycles per second facilitates high precision optical spectroscopy, and is expected to outperformed today's state-of-the-art caesium clocks. The fundamental block diagram of the proposed optical clock system is shown in Fig. 7-1, comprises an ultra-narrow pulse source (femtosecond laser) and feedback mechanisms (phase lock loops, PLL).

![Figure 7-1: Fundamental block diagram of optical clock system](image)
The femtosecond laser emits an optical pulse train at nominal repetition frequency of $f_r$. The spectrum of pulse train is a uniform comb of phase coherent continuous waves separated by $f_r$. Frequency of the $n$th mode of this comb is $f_n = nf_r + f_o$, where $f_o$ is the frequency offset common to all modes that results from the difference between group- and phase-velocity inside the laser cavity. This $f_o$ can be determined either by self-referencing [Diddams et al., 2001] or phase locking [Ye et al., 2003] techniques. In addition to $f_o$, a second heterodyne beat frequency, $f_b$ is measured between an individual comb element $f_m = mf_r + f_o$ ($m$ is an integer) and the local oscillator of certain atom standard, $f_s$. Two phase-locked loops are used to control $f_o$ and $f_b$, thereby fixing the clock output $f_r$, such that all oscillators used in the clock are referenced to the laser oscillator itself, $f_r$. When $f_o$ and $f_b$ are phase-locked, every element of the femtosecond comb, as well as their frequency separation $f_r$, is phase-coherent with laser locked to the $f_s$ standard. Thus, $f_r$ is the countable microwave output of the clock, which is readily detected by a photo-detector [Diddams et al., 2001].

Such clock references will find applications in precise tests of fundamental physics, measurement of fundamental constants and their possible variation with time, more accurate determination of atomic transitions in spectroscopy, tests of special and general relativity theories and quantum electrodynamics (QED).
References


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90. New Focus, “Application Note 1 - Insights into High-Speed Detectors and High-Frequency Techniques”, 2002


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Appendices

I - Optimum Length of EDF

In order to determine a suitable EDF length for mode-locked fiber ring lasers, stimulated absorption and emission cross-sections of the pump and signal beam in EDF must be known first. If no erbium ions are excited, the absorption cross-section can be determined directly from an attenuation measurement using [Pedersen et al., 1991]

$$\sigma_{a}^{p,s} = \frac{\text{att}(\lambda_{p,s})}{10 \log_{10} e \cdot 2\pi \int_{0}^{a} \rho_{E_{r}}(r)I_{01}^{01}(\lambda_{p,s}, r)rdr}$$

where subscript p or s denotes the pump or signal wavelength, $\rho_{E_{r}}(r)$ is erbium concentration, att($\lambda$) is attenuation in dB/m at wavelength $\lambda$, a is core and doping radius and $I_{01}$ is normalized LP$_{01}$ mode. The emission cross-section can be obtained from gain measurement, which implied that all erbium ions are excited

$$\sigma_{e}^{p,s} = \frac{g(\lambda_{p,s})}{10 \log_{10} e \cdot 2\pi \int_{0}^{a} \rho_{E_{r}}(r)I_{01}^{01}(\lambda_{p,s}, r)rdr}$$

where $g(\lambda)$ is gain in dB/m. From the above equations, one can notice that

$$2\pi \int_{0}^{a} \rho_{E_{r}}(r)I_{01}^{01}(\lambda_{p,s}, r)rdr$$

is in fact the overlap between waveguide mode and doped region. From the refractive index and erbium concentration profiles described above, we assume near full (98%) overlap between these two elements, therefore the resultant

XI
integral give rise to \(-0.98\rho_{\text{eff}}\). Alternatively, the emission cross-sections can be obtained using the following relationship [Miniscalco, 1991]

\[
\sigma^e(\lambda) = \sigma^a(\lambda) \exp\left(\frac{\varepsilon - \frac{hc}{\lambda}}{kT}\right)
\]

where \(\varepsilon\) is net free energy required to excite one Er\(^{3+}\) ion from \(^4I_{15/2}\) to \(^4I_{13/2}\) state at temperature \(T\) and \(k\) is Boltzmann’s constant.

It should be noted that the gain or attenuation measurement should be performed on a short fiber to avoid saturation due to ASE. In addition, pump power must be high enough to fully invert all Er\(^{3+}\) ions in the fiber. Furthermore, intrinsic losses of the associate optics must be considered carefully.

From the measurements, the absorption and emission cross-sections for both the pump wavelength (980 nm) and signal wavelength (1550 nm) are \(\sigma_p^a = 2.0192 \times 10^{-25}\) m\(^2\), \(\sigma_p^e = 4.1833 \times 10^{-33}\) m\(^2\), \(\sigma_s^a = 1.3541 \times 10^{-25}\) m\(^2\) and \(\sigma_s^e = 2.0291 \times 10^{-25}\) m\(^2\) respectively.

Following steps are taken to determine a suitable fiber length for the mode-locked fiber ring laser. At first, a piece of EDF with length \(L\) is chosen. \(R\) in the following equation is determined by measuring signal and pump power at the output, \(P_{s\text{out}}\) and \(P_{p\text{out}}\) for given input signal and pump power, \(P_{s\text{in}}\) and \(P_{p\text{in}}\).[Lin et al., 1992]

\[
\left[ (P_{s\text{out}} - P_{s\text{in}}) \cdot \frac{1}{I_{ss}^c} - \frac{\sigma_p^c}{\sigma_p^a I_{ss}} + \ln \left( \frac{P_{s\text{out}}}{P_{s\text{in}}} \right) \cdot \frac{1}{R} \right] \left[ \frac{\sigma_p^c}{\sigma_p^a I_{ss}} \right] = \left[ (P_{p\text{out}} - P_{p\text{in}}) \cdot \frac{\sigma_s^c}{\sigma_s^a I_{sp}} - \frac{1}{I_{sp}} - \ln \left( \frac{P_{p\text{out}}}{P_{p\text{in}}} \right) \cdot \frac{1}{R} \right]
\]
where \( h \) is Plank's constant and \( \tau \) is spontaneous emission decay life time, which is about 10 ms. For maximal gain, \( \frac{dP_s}{dP_p} = 0 \), hence, the optimum output pump power will be

\[
P_{\text{out},\text{op}} = \frac{1}{R \left( \frac{\sigma_s^a}{\sigma_p^a I_{sp}^a} - \frac{1}{I_{sp}^a} \right)}
\]

The maximal gain, \( G \), is calculated using numerical method for arbitrary \( P_{in}^s \) and \( P_p^s \), by the following equation

\[
\frac{\lambda_s}{\lambda_p} \frac{P_{in}^s}{P_{out,\text{op}}^s} (G - 1) + \frac{\sigma_p^a}{\sigma_s^a} \ln(G) = \frac{P_{in}^s}{P_{out,\text{op}}^s} - 1 - \ln \left( \frac{P_{in}^s}{P_{out,\text{op}}^s} \right)
\]

Subsequently, the absorption constant, \( \alpha_s \) and intrinsic saturation power, \( P_{is}^s \) for the signal beam are measured. Without pump power, \( P_{out}^s \approx P_{is}^s \exp(-\alpha_s L) \) for small input signal power, when \( P_{is}^s \) approaches \( P_{is}^s \). Finally, the optimum fiber length of maximal gain is

\[
L_{\text{op}} = -\frac{1}{\alpha_s} \left\{ \ln(G) + \frac{hc}{\lambda_s P_{is}^s} \left[ \frac{(P_{out,\text{op}}^s - P_{in}^s)\lambda_p}{hc} + P_{in}^s\lambda_p (G - 1) \right] \right\}
\]

The maximal gain and optimum length for the EDF used in the experiment are found out to be about 30 dB and 25.9 meter.
II - Experimental Procedures and Precautions

A typical experimental procedure can be as follows:

• Get the performance analysis of each individual optical component.

• Measure optical losses of the ring. With all the optical components connected in an open ring structure, i.e. broken ring, monitor the wavelength and optical power of CW signal from the output coupler under saturation pumping condition.

• Close the ring and monitor average optical power at the output coupler.

• Determine if an optical amplifier is required for signal detection or is sufficient for opto-electronic RF feedback condition.

• Set the biasing condition for modulator.

• Tune the synthesizer or electrical phase for the generation and locking of signal.

• Monitor the laser output using optical oscilloscope and spectrum analyzer.

Some precaution measures must be taken during the experiment, as follows:

• Optical damage threshold - excessive optical intensities can lead to dielectric breakdown and destruction of the optical fiber itself. The bulk optical damage threshold for silica is about 50 GW/cm² at 1064 nm for a single pulse focus to a 5 µm diameter [Digonnet, 2001]. Assuming an
effective mode area of 50 $\mu$m$^2$, the maximum peak power that can be guided in the standard optical fiber is about 25 KW, which corresponds to energy of 250 $\mu$J for a 10 ns pulse. The peak power handling can be pushed farther by using fibers with a larger mode field diameter, or multimode fibers when a diffraction-limited beam is not required.

- Maximum optical power – ensure that the input optical power to any optical detecting equipment (e.g. photo-detector, optical oscilloscope, optical spectrum analyzer, etc) is below the maximum rated power since we are operating at the nonlinear region (high optical power). An optical attenuator can be added prior to the measuring equipment if necessary.

- Electrostatic discharge – high-speed photo-detector is sensitive to electrostatic discharge and can be damaged by it. Therefore, some care must be taken into account to prevent damage of equipment. Always ground cables and connectors prior to connecting them to the photo-detector output. Use the wrist strap while handling the detector. Discharge the AC coupled instruments before connecting them.

- Sensitivity of the equipment – ensure the triggering signal of the measuring equipment (e.g. optical spectrum analyzer) is above the sensitivity of the equipment.

- Voltage standing-wave ratio (VSWR) – VSWR is the ratio of maximum to the minimum amplitude of a standing wave that might occur because of the impedance mismatch at the end of the transmission line,
\[ \text{VSWR} = \frac{1 + |R|}{1 - |R|} \]

where R is the reflection coefficient. Be aware of the reflected standing wave of the RF components, which may damage the components. Ensure the line is properly terminated if it is not in use.

- When laying the fiber in the fiber polarization controller, make sure that the fiber is in contact with the inside of the groove loops, but not be pulled too snug against the groove as this cause optical losses due to induced birefringence as the paddles are rotated with respect to each other.
III - Datasheets
1500 Series Pumps

Up to 150 mW fiber Bragg grating stabilized 980 nm pump modules

The JDS Uniphase 1500 Series are low cost pump modules for use in erbium doped fiber amplifiers (EDFAs) used in dense wavelength division multiplexed (DWDM) fiber optic networks, utility preamplifiers or medium power EDFAs for metropolitan area fiber networks.

The 1500 Series is designed to meet the performance and cost requirements for low to medium power multi-purpose EDFAs known as utility amps. Major applications for these utility amps include pre-amps for high data rate receivers used in long haul DWDM networks and broadband CATV networks.

The 1500 Series utilizes our fiber Bragg grating technology and advanced high volume manufacturing techniques. The use of fiber Bragg gratings with pump lasers creates wavelength stabilized pumps that result in more stable EDFA performance independent of input signal wavelength.

Key Features
- Medium kink-free powers to 150 mW
- Fiber Bragg grating stabilized
- Integrated TEC and thermistor

Applications
- WDM for medium power EDFAs
- Single channel preamplifiers
- Utility amplifiers for WDM and CATV
- Booster amplifiers for metropolitan area networks

Compliance
- Telcordia™ GR-468-CORE
### Absolute Maximum Ratings

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Condition</th>
<th>Min</th>
<th>Max</th>
<th>Units</th>
</tr>
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<tbody>
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<td></td>
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<td></td>
</tr>
<tr>
<td>Forward Current</td>
<td></td>
<td>500</td>
<td>mA</td>
<td></td>
</tr>
<tr>
<td>Forward Current Transient</td>
<td>1μs max</td>
<td>1</td>
<td>A</td>
<td></td>
</tr>
<tr>
<td>Reverse Voltage</td>
<td></td>
<td>4.5</td>
<td>V</td>
<td></td>
</tr>
<tr>
<td>Reverse Current</td>
<td></td>
<td>20</td>
<td>μA</td>
<td></td>
</tr>
<tr>
<td>Monitor Photodiode</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reverse Current</td>
<td></td>
<td>5E-9</td>
<td>A</td>
<td></td>
</tr>
<tr>
<td>Reverse Voltage</td>
<td></td>
<td>20</td>
<td>V</td>
<td></td>
</tr>
<tr>
<td>MPD Forward Current</td>
<td></td>
<td>5</td>
<td>mA</td>
<td></td>
</tr>
<tr>
<td>Thermistor</td>
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<td></td>
</tr>
<tr>
<td>Voltage</td>
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<td>5</td>
<td>V</td>
<td></td>
</tr>
<tr>
<td>Current</td>
<td></td>
<td>2</td>
<td>mA</td>
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</tr>
<tr>
<td>Thermoelectric Cooler</td>
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</tr>
<tr>
<td>Voltage</td>
<td></td>
<td>4</td>
<td>V</td>
<td></td>
</tr>
<tr>
<td>Current</td>
<td></td>
<td>2.5</td>
<td>A</td>
<td></td>
</tr>
<tr>
<td>Package</td>
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<td></td>
</tr>
<tr>
<td>Storage Temperature</td>
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<td>-40</td>
<td>+75</td>
<td>°C</td>
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<tr>
<td>Operating Temperature</td>
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<td>-20</td>
<td>+70</td>
<td>°C</td>
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<tr>
<td>Fiber Pigtail</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Fiber Temperature</td>
<td></td>
<td>-40</td>
<td>+85</td>
<td>°C</td>
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<tr>
<td>Tensile Stress</td>
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<td>N</td>
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<td>Bend Radius</td>
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<td>12.5</td>
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### Electro-Optical Performance

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<th>Symbol</th>
<th>Test Condition</th>
<th>Min.</th>
<th>Max.</th>
<th>Units</th>
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<tr>
<td>Spectrum</td>
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<td></td>
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<td></td>
</tr>
<tr>
<td>Peak Wavelength</td>
<td>$\lambda_1$</td>
<td></td>
<td>974</td>
<td>985</td>
<td>nm</td>
</tr>
<tr>
<td>Power in Band</td>
<td>$P_{\text{band}}$</td>
<td>$P_{\text{op}}$</td>
<td>$P_{\text{max}}$</td>
<td>90</td>
<td>%</td>
</tr>
<tr>
<td>Spectral Shift w/temperature</td>
<td>$\Delta \lambda / \Delta T$</td>
<td>-</td>
<td>0.02</td>
<td>nm/°C</td>
<td></td>
</tr>
<tr>
<td>Spectrum Stability</td>
<td>$\Delta \lambda / \Delta t$</td>
<td>23°C, $I_{\text{max}}$, t = 60 seconds</td>
<td>0.1</td>
<td>nm</td>
<td></td>
</tr>
<tr>
<td>Optical Power Stability</td>
<td>$P_{\text{opt}} / \Delta t$</td>
<td>23°C, $I_{\text{max}}$, t = 60 seconds</td>
<td>0.5</td>
<td>%</td>
<td></td>
</tr>
<tr>
<td>Laser Diode</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Threshold Current</td>
<td>$I_{\text{th}}$</td>
<td></td>
<td>-</td>
<td>25</td>
<td>mA</td>
</tr>
<tr>
<td>Slope Deviation</td>
<td>$\Delta I / \Delta I$</td>
<td>50 mA &lt; I &lt; $I_{\text{max}}$</td>
<td>no negative slope</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Laser diode forward voltage</td>
<td>$V_{\text{fwdLD}}$</td>
<td>$I_{\text{max}}$</td>
<td>-</td>
<td>2.5</td>
<td>volts</td>
</tr>
<tr>
<td>Monitor Photodiode</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Current</td>
<td>$I_{\text{opd}}$</td>
<td></td>
<td>50</td>
<td>-</td>
<td>μA</td>
</tr>
<tr>
<td>Thermoelectric Cooler Operation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TEC voltage</td>
<td>$V_{\text{TEC}}$</td>
<td>$\Delta T = 45°C$, $I_{\text{max}}$</td>
<td>-</td>
<td>2.5</td>
<td>volts</td>
</tr>
<tr>
<td>TEC current</td>
<td>$I_{\text{TEC}}$</td>
<td>$\Delta T = 45°C$, $I_{\text{max}}$</td>
<td>-</td>
<td>1.5</td>
<td>amps</td>
</tr>
<tr>
<td>Thermistor resistance</td>
<td>$R_{\text{therm}}$</td>
<td></td>
<td>9.3</td>
<td>10.5</td>
<td>KΩ</td>
</tr>
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### Fiber Pigtail Specifications

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td></td>
<td>5M</td>
</tr>
<tr>
<td>Mode-field Diameter</td>
<td>6.5 ± 1</td>
<td>μm</td>
</tr>
<tr>
<td>Cladding Diameter</td>
<td>125 ± 2</td>
<td>μm</td>
</tr>
<tr>
<td>Jacket Diameter</td>
<td>250</td>
<td>μm</td>
</tr>
</tbody>
</table>

1. All specifications are at BOI for an operating temperature range for $T_{\text{ase}}$ = -20 to 70 °C and back reflection < -50 dB.
1500 Series Pumps | 3

Package Dimensions

Dimensions in millimeters except where indicated

```
2.0  26.0
15.0 12.7  4.5
15 NOM (14x)

0.38 (14x) LEAD WIDTH

FLEXIBLE POLYMER STRAIN RELIEF

Ø 5.0
Ø 6.9
Ø 2.5 THRU (4x)

2.6  30.0
```

```
60 NOM

4.6  20.8  6.5  15  9.5
13 NOM

POINT A

750 NOM TO CENTER OF GRATING

FIBER LENGTH MINIMUM 1.5 METERS MEASURED FROM POINT A

FLEXIBLE Ø 900 micron RECOAT

2.8 TO LEAD CENTER (2x)

2.54 (12x) LEAD SPACING TOLERANCE IS NON-ACCUMULATIVE

CASE GROUND

1.5 LEAD C/L POSITION

11.26 MAX

6.59

0.25 (14x) LEAD THICKNESS
```

Lead Connection

```

Electrical Schematic
(Package Viewed From Top)

Lead Connections

1  Cooler (+)
2  Thermistor
3  Monitor PD Anode
4  Monitor PD Cathode
5  Thermistor
6  N/C
7  N/C
8  N/C
9  N/C
10  Laser Anode
11  Laser Cathode
12  N/C
13  Case Ground
14  Cooler (-)
```
1500 Series Pumps | 4

User Safety

Safety and Operating Considerations

The laser light emitted from this laser diode is invisible and may be harmful to the human eye. Avoid looking directly into the fiber when the device is in operation.

CAUTION: THE USE OF OPTICAL INSTRUMENTS WITH THIS PRODUCT WILL INCREASE EYE HAZARD.

Operating the laser diode outside of its maximum ratings may cause device failure or a safety hazard. Power supplies used with the component must be employed such that the maximum peak optical power cannot be exceeded.

CW laser diodes may be damaged by excessive d.c. current or switching transients. When using power supplies, the laser diode should be connected with the main power on and the output voltage at zero. The current should be increased slowly while monitoring the laser diode output power and the drive current.

Careful attention to heatsinking and proper mounting of this device is required to insure specified performance over its operating life. To maximize thermal transfer to the heatsink, the heatsink mounting surface must be flat to within .001" and the mounting screws must be torqued down to 1.5 in.-lb.

ESD PROTECTION — Electro-static discharge is the primary cause of unexpected laser diode failure. Take extreme precaution to prevent ESD. Use wrist straps, grounded work surfaces, and rigorous anti-static techniques when handling laser diodes.

21 CFR 1040.10 Compliance

Because of the small size of these devices, each of the labels shown is attached to the individual shipping container. They are illustrated here to comply with 21 CFR 1040.10 as applicable under the radiations control for health and safety act of 1968.

Ordering information

For more information on this or other products and their availability, please contact your local JDS Uniphase sales representative or JDS Uniphase directly at 408 943-4200, or by fax 408 943-4252, or via email at sales.ca@us.jdsuniphase.com. Visit our Web site at www.jdsuniphase.com.
10 Gb/s Integrated Amplitude Modulator with Attenuator

The JDS Uniphase 10 Gb/s Integrated Amplitude Modulator with Attenuator provides intrinsic attenuation flexibility for multichannel systems.

The module employs an integrated attenuator that allows pre-emphasis of all International Telecommunications Union (ITU) wavelengths in a dense wavelength division multiplexing (DWDM) optical link.

The 10 Gb/s Integrated Amplitude Modulator with Attenuator is supplied in a mini package and qualifies to Telcordia GR-468-CORE. JDS Uniphase assures high reliability and performance at all times.

Key Features
- Wide optical bandwidth for use in C- and L-band erbium doped fiber amplifier (EDFA) DWDM links
- Separate DC bias electrode for long-term stability and reliability
- Low drive voltage for ease of use with wide range of commercially available drivers
- High modulator on/off extinction ratio
- Continuously tunable attenuation

Applications
- Ideal for OC-192 C-band and L-band DWDM applications

Compliance
- Telcordia GR-468-CORE
10 Gb/s Integrated Amplitude
Modulator with Attenuator

Eye Diagram

10 Gb/s Integrated Amplitude Modulator with Attenuator Detail

Pinout

<table>
<thead>
<tr>
<th>Pin</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>RF input</td>
</tr>
<tr>
<td>2</td>
<td>No connector</td>
</tr>
<tr>
<td>3</td>
<td>No connector</td>
</tr>
<tr>
<td>4</td>
<td>Ground</td>
</tr>
<tr>
<td>5</td>
<td>Bias input</td>
</tr>
<tr>
<td>6</td>
<td>Ground</td>
</tr>
<tr>
<td>7</td>
<td>Attenuator</td>
</tr>
<tr>
<td>8</td>
<td>Ground</td>
</tr>
</tbody>
</table>

5 pin Lead Ø 0.81 Pitch 3.08mm Lead to be soldered on package end for bonding

End View
# 10 Gb/s Integrated Amplitude Modulator with Attenuator

## Specifications

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>General</strong></td>
<td></td>
</tr>
<tr>
<td>Material</td>
<td>Lithium niobate</td>
</tr>
<tr>
<td>Crystal orientation</td>
<td>X-cut, y-propagating</td>
</tr>
<tr>
<td>Waveguide process</td>
<td>Titanium-indiffused</td>
</tr>
<tr>
<td><strong>Optical</strong></td>
<td></td>
</tr>
<tr>
<td>Operating wavelength</td>
<td>1530 to 1605 nm</td>
</tr>
<tr>
<td>Insertion loss (with connector) (note1)</td>
<td>( \leq 7 ) dB</td>
</tr>
<tr>
<td>On/off extinction ratio, low frequency</td>
<td>( \geq 20 ) dB</td>
</tr>
<tr>
<td>Optical return loss</td>
<td>( \leq 45 ) dB</td>
</tr>
<tr>
<td><strong>Electrical</strong></td>
<td></td>
</tr>
<tr>
<td>RF port</td>
<td></td>
</tr>
<tr>
<td>V( \pi ) at 10 Gb/s PRBS</td>
<td>( \leq 6.8 ) V</td>
</tr>
<tr>
<td>S( 21 ) electro-optic bandwidth (-3 dBc) (note2)</td>
<td>( \geq 10 ) GHz</td>
</tr>
<tr>
<td>S( 11 ) return loss</td>
<td></td>
</tr>
<tr>
<td>0.13 to 2.5 GHz (note3)</td>
<td>( \leq -14 ) dB</td>
</tr>
<tr>
<td>3 to 9 GHz (note3)</td>
<td>( \leq -10 ) dB</td>
</tr>
<tr>
<td>9 to 15 GHz (note3)</td>
<td>( \leq -6 ) dB</td>
</tr>
<tr>
<td>RF input power</td>
<td>27 dBm</td>
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<tr>
<td>Chirp, alpha parameter</td>
<td>( \pm 0.2 )</td>
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<tr>
<td>Bias port</td>
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<tr>
<td>V( \pi ) at DC</td>
<td>( \leq 5.8 ) V</td>
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<tr>
<td>Impedance</td>
<td>( \geq 10,000 ) ( \Omega )</td>
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<tr>
<td>Attenuator port</td>
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</tr>
<tr>
<td>V( \pi ) attenuator</td>
<td>( \leq 8.4 ) V</td>
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<tr>
<td>Attenuation range</td>
<td>( \geq 15 ) dB</td>
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<tr>
<td><strong>Mechanical</strong></td>
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<tr>
<td>Input fiber</td>
<td>Fujikura SM-15-P-8/125-UV/UV-400</td>
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<tr>
<td>Output fiber</td>
<td>SMF-28 or Fujikura SM-15-P-8/125-UV/UV-400</td>
</tr>
<tr>
<td>Input connector</td>
<td>FC/SPC</td>
</tr>
<tr>
<td>Output connector</td>
<td>FC/SPC</td>
</tr>
<tr>
<td>RF connection</td>
<td>K connector</td>
</tr>
<tr>
<td>Bias connection</td>
<td>DC feedthroughs</td>
</tr>
<tr>
<td><strong>Environmental</strong></td>
<td></td>
</tr>
<tr>
<td>Operating temperature</td>
<td>0 to 70 °C</td>
</tr>
<tr>
<td>Storage temperature</td>
<td>-40 to 80 °C</td>
</tr>
</tbody>
</table>

1. Insertion loss is measured at the maximum of the modulator’s transfer function and does not include the 3 dB loss incurred when operating at quadrature.
2. Relative to 30 MHz.
3. Variances with temperature and wavelength included.
10 Gb/s Integrated Amplitude
Modulator with Attenuator  |  4

Ordering Information
For more information on this or other products and their availability, please contact your local JDS Uniphase account manager or JDS Uniphase directly at 1-800-498-JDSU (5378) in North America and +800-5378-JDSU worldwide or via e-mail at sales@jdsu.com.

Sample: 21010278

<table>
<thead>
<tr>
<th>Product Code</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>21010278</td>
<td>10Gb/s data modulator with attenuator, PMF in &amp; SMF out, FC/UPC</td>
</tr>
</tbody>
</table>

SM-15 is a registered trademark of Fujikura Europe Limited.
SMF-28 and Fujikura SM 15-P-8/125-UV-400 are registered trademarks of Corning Incorporated.
Telcordia is a registered trademark of Telcordia Technologies Incorporated.
Viltron K is a registered trademark of Anritsu Corporation.
EOSPACE: OC-192* Modulator
(Measured Responses)

- Insertion loss < 3 dB max, ~2.5 dB typical.
- BW >12.5 GHz (with respect to 0.130GHz reference)
- Vπ@1GHz < 4.5 V max, ~ 4 V typical.
- Vπ (PRBS) @10^6 Gb/s ~ 5 V
- DC Bias port Vπ: < 6 V max, < 4 V typical.

Examples of EOSPACE OC-192* Modulator (Version A) Eye Diagrams at 10^6 Gb/s
( Note that eye diagrams are affected not only by the modulator, but also the driver electronics & optical receivers )

(data taken and provided to us by our customers)
MANUALLY ADJUSTABLE POLARIZATION INSENSITIVE TUNABLE FILTERS

Features:
• Narrow linewidth
• Polarization insensitive
• Wide wavelength range
• Singlemode, multimode, and polarization maintaining fiber versions
• High resolution

Applications:
• Dense Wavelength Division Multiplexing (DWDM)
• Tunable sources
• Spectral analysis
• Quality control and measurement
• Product development
• Fiber optic component manufacturing

Product Description:
Tunable filters consist of a collimating optical assembly, an adjustable narrow bandpass filter, and a focusing optical assembly to collect the light again. Tunable filters are available in three versions - a manually adjustable version, a motor driven version for OEM applications, and a digital version with a display and computer interface.

The manual tunable filter is a pigtailed component with a rotating stage that allows for the manual adjustment of the angle of incidence between the beam and the filter. The filter works based on the principle that by adjusting the angle of incidence between the filter and the incident beam one controls the wavelength at which the filter transmits.

Filter linewidths are normally defined in terms of Full Width at Half Maximum (FWHM). The standard filter used in tunable filters has a smooth, rounded transmission spectrum that is the result of a single Fabry Perot type cavity. A Fabry Perot cavity is simply made up of two reflectors separated by a fixed spacer of some thickness. Other filter designs are available. For instance, flat top bandpass filters are made by stacking multiple cavities together. By increasing the number of cavities one can increase the roll-off slope therefore improving the out-of-band rejection level. For more information on custom filters please contact OZ Optics.

OZ Optics tunable filters now utilize a new optical technique to control Polarization Dependent Losses (PDL). This new design reduces PDL to below 0.3dB, while at the same time making the spectral response polarization insensitive. This feature makes it ideal for today’s DWDM system applications.

Tunable filters using singlemode, multimode and Polarization Maintaining (PM) fibers are offered. In general, OZ Optics uses polarization maintaining fibers based on the PANDA fiber structure when building polarization maintaining components and patchcords. However OZ Optics can construct devices using other PM fiber structures. We do carry some alternative fiber types in stock, so please contact our sales department for availability. If necessary, we are willing to use customer supplied fibers to build devices.

06/02 OZ Optics reserves the right to change any specifications without prior notice.
### Ordering Information For Standard Parts:

<table>
<thead>
<tr>
<th>Bar Code</th>
<th>Part Number</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>13553</td>
<td>TF-11-11-1520/1570-0/125-S-40-3S3S-3-1-1.2</td>
<td>Polarization insensitive manual tunable filter in U-bracket for 1520-1570nm with 1 meter long, 3mm OD jacketed 9/125 SM fiber pigtailed, 40dB return loss, super FC/PC connectors and 1.2nm FWHM Fabry Perot filter.</td>
</tr>
<tr>
<td>13554</td>
<td>TF-11-11-1520/1570-0/125-S-50-3U3U-3-1-1.2</td>
<td>Polarization insensitive manual tunable filter in U-bracket for 1520-1570nm with 1 meter long, 3mm OD jacketed 9/125 SM fiber pigtailed, 50dB return loss, ultra FC/PC connectors and 1.2nm FWHM Fabry Perot filter.</td>
</tr>
<tr>
<td>14150</td>
<td>TF-11-11-1520/1570-0/125-S-60-3A3A-3-1-1.2</td>
<td>Polarization insensitive manual tunable filter in U-bracket for 1520-1570nm with 1 meter long, 3mm OD jacketed 9/125 SM fiber pigtailed, 60dB return loss, angled FC/PC connectors and 1.2nm FWHM Fabry Perot filter.</td>
</tr>
<tr>
<td>13555</td>
<td>TF-11-11-1570/1620-0/125-S-40-3S3S-3-1-1.2</td>
<td>Polarization insensitive manual tunable filter in U-bracket for 1570-1620nm with 1 meter long, 3mm OD jacketed 9/125 SM fiber pigtailed, 40dB return loss, super FC/PC connectors and 1.2nm FWHM Fabry Perot filter.</td>
</tr>
<tr>
<td>13556</td>
<td>TF-11-11-1570/1620-0/125-S-50-3U3U-3-1-1.2</td>
<td>Polarization insensitive manual tunable filter in U-bracket for 1570-1620nm with 1 meter long, 3mm OD jacketed 9/125 SM fiber pigtailed, 50dB return loss, ultra FC/PC connectors and 1.2nm FWHM Fabry Perot filter.</td>
</tr>
<tr>
<td>13557</td>
<td>TF-11-11-1570/1620-0/125-S-60-3A3A-3-1-1.2</td>
<td>Polarization insensitive manual tunable filter in U-bracket for 1570-1620nm with 1 meter long, 3mm OD jacketed 9/125 SM fiber pigtailed, 60dB return loss, angled FC/PC connectors and 1.2nm FWHM Fabry Perot filter.</td>
</tr>
<tr>
<td>13614</td>
<td>TF-11-11-1570/1570-0/125-P-60-3A3A-3-1-1.2</td>
<td>Polarization insensitive manual tunable filter in U-bracket for 1570-1570nm with 1 meter long, 3mm OD jacketed 8/125 PM fiber pigtailed, 60dB return loss, angled FC/PC connectors and 1.2nm FWHM Fabry Perot filter.</td>
</tr>
<tr>
<td>13613</td>
<td>TF-11-11-1570/1620-0/125-P-60-3A3A-3-1-1.2</td>
<td>Polarization insensitive manual tunable filter in U-bracket for 1570-1620nm with 1 meter long, 3mm OD jacketed 8/125 PM fiber pigtailed, 60dB return loss, angled FC/PC connectors and 1.2nm FWHM Fabry Perot filter.</td>
</tr>
</tbody>
</table>

### Standard Product Specifications:

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resolution</td>
<td>Typically less than 0.1nm</td>
</tr>
<tr>
<td>Tuning Range</td>
<td>50nm</td>
</tr>
<tr>
<td>Wavelength Range: (C-band), (L-band) and (S-band) standard</td>
<td>Other ranges available on request.</td>
</tr>
<tr>
<td>Linewidth (FWHM)</td>
<td>1.1 ± 0.1nm standard over tuning range. As narrow as 0.3nm is available as an option.</td>
</tr>
<tr>
<td>Wavelength/Temperature Sensitivity</td>
<td>Typically less than 0.002nm/C</td>
</tr>
<tr>
<td>PDL</td>
<td>Typically less than 0.3dB</td>
</tr>
<tr>
<td>Insertion Loss</td>
<td>Typically less than 2.5dB for complete device over full tuning range.</td>
</tr>
<tr>
<td>Power Handling</td>
<td>Up to 200mW for standard package.</td>
</tr>
</tbody>
</table>

### Sample Test Data For Tunable Filters

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>PDL (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1520.04</td>
<td>0.30</td>
</tr>
<tr>
<td>1530.00</td>
<td>0.20</td>
</tr>
<tr>
<td>1539.98</td>
<td>0.10</td>
</tr>
<tr>
<td>1550.04</td>
<td>0.15</td>
</tr>
<tr>
<td>1560.00</td>
<td>0.30</td>
</tr>
<tr>
<td>1569.98</td>
<td>0.30</td>
</tr>
</tbody>
</table>

Figure 2: Typical Transmission Curves of 1.2nm C-Band Tunable filters
Ordering Examples For Standard Parts:

A customer wants to use a broadband source as a manual tunable source in order to test the spectral characteristics of optical components at different wavelengths. Both the light source and components have FC/PC receptacles and the wavelength region of interest for the components is throughout the C-band. The broadband source is polarized randomly and therefore the tunable source required should be polarization insensitive.

The component required for this application is a polarization insensitive manual tunable filter. With this filter connected to the broadband light source and by adjusting the angle at which the beam is incident on the filter the transmitted wavelength from the broadband source can be tuned from 1520 to 1570nm.

<table>
<thead>
<tr>
<th>Bar Code</th>
<th>Part Number</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>13553</td>
<td>TF-11-11-1520/1570-S-40-3S3S-3-1-1.2</td>
<td>Polarization insensitive manual tunable filter in U-bracket for 1520-1570nm with 1 meter long, 3mm OD jacketed 9/125 SM fiber pigtails, 40dB return loss, super FC/PC connectors and standard 1.2mm FWHM Fabry Perot filter.</td>
</tr>
</tbody>
</table>

Ordering Information For Custom Parts:

OZ Optics welcomes the opportunity to provide custom designed products to meet your application needs. As with most manufacturers, customized products do take additional effort so please expect some differences in the pricing compared to our standard parts list. In particular, we will need additional time to prepare a comprehensive quotation, and lead times will be longer than normal. In most cases non-recurring engineering (NRE) charges, lot charges, and a 1 piece minimum order will be necessary. These points will be carefully explained in your quotation, so your decision will be as well informed as possible. We strongly recommend buying our standard products

Questionnaire For Custom Parts:

1. What wavelength range are you interested in?
2. What linewidth do you require?
3. What type of fiber is being used? Singlemode, multimode or PM fiber?
4. Are you using a polarized or randomly polarized light source?
5. What return losses are acceptable in your system?
6. What connector types are you using?
7. What fiber length and jacket diameter do you need?

TF-11-11-W-alb-F-LB-XY-JD-L-LW

W: Wavelength range in nanometers: Example: 1520/1570
    abl: Fiber core/cladding sizes in microns:
         9/125 for 1300/1550nm Corning SMF28 fiber
         9/125 for 1550nm PANDA style PM fiber

F: Fiber type:
   M=Multimode
   S=Singlemode
   P=Polarization Maintaining

LB: Backreflection level: 40, 50 or 60dB for singlemode or PM fibers only.
(60dB for 1290 to 1620nm wavelength ranges only) 35dB for multimode fibers

LW: FWHM linewidth in nm. Standard filter is a Fabry Perot. For a flat top profile filter, add the letter F to the end of the number.

L: Fiber length in meters

JD: Fiber Jacket type:
    1=900 micron OD hytrel jacket
    3=3mm OD Kevlar reinforced PVC cable

XY: Input & Output Connector codes:
    3S=Super NTT/FC/PC
    3U=Ultra NTT/FC/PC
    3A=Angled NTT/FC/PC
    8=AT&T-ST
    SC=SC
    SCA=Angled SC
    LC=LC
    LCA=Angled LC
    MU=MU
    X=No Connector

Ordering Examples For Custom Parts:

Example 1:

A customer wants to reduce the ASE noise and manually tune the transmitted wavelength for a special broadband light source between the C and L bands, 1550 to 1600nm, with a very narrow linewidth.

A custom version of the manually tunable filter will meet this requirement with a narrow linewidth custom filter used in the component.

<table>
<thead>
<tr>
<th>Bar Code</th>
<th>Part Number</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>N/A</td>
<td>TF-11-11-1550/1600-9/125-S-50-3U3U-3-1-0.3</td>
<td>Polarization insensitive manual tunable filter for 1550-1600nm with 1 meter long, 3mm OD jacketed 9/125 SM fiber pigtails, 90dB return loss and ultra FC/PC connectors. Custom 0.3mm FWHM Fabry Perot filter.</td>
</tr>
</tbody>
</table>
Example 2:
A customer wants to reduce the out of band noise of a polarized light source and tune the transmitted wavelength using a 0.3nm linewidth tunable filter.

The component required for this application is a polarization maintaining tunable filter.

<table>
<thead>
<tr>
<th>Bar Code</th>
<th>Part Number</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>N/A</td>
<td>TF-11-11-1520/1570-8/125-P-60-3U3U-3-1-0.3</td>
<td>Polarization maintaining manual tunable filter for 1520-1570nm with 1 meter long, 3mm OD jacketed 8/125 PM fiber pigtails, 60dB return loss, angled FC/PC connectors and 0.3nm FWHM Fabry Perot filter.</td>
</tr>
</tbody>
</table>

Frequently Asked Questions (FAQs):

Q: What is the filter linewidth?
A: The standard filter is a 1.2nm FWHM Fabry-Perot filter. This can be customized to suit the customer’s requirements.

Q: What is the largest tuning range available?
A: The standard tuning range is 50nm, however the filter can be operated over a 100nm range with some effects on the linewidth and insertion loss in the shorter wavelength (high angle of incidence) region.

Q: What is a Fabry-Perot filter? Are there other types available?
A: A Fabry-Perot filter has a smooth, rounded transmission spectrum that is the result of a single Fabry Perot type cavity. This shape is known as a Lorentz profile. A Fabry Perot cavity is simply made up of two reflectors separated by a fixed spacer of some thickness. By adjusting the spacer thickness one can adjust the pass bandwidth of the filter. Other shapes of filters are available. For instance, flat top bandpass filters are made by stacking multiple cavities together. By increasing the number of cavities one can increase the roll-off slope therefore improving the out-of-band rejection level. For more information on what custom filters are available please contact OZ Optics.

Q: How do you define your linewidths?
A: Standard filters are specified by their Full Width Half Maximum (FWHM). This the transmitted linewidth at -3dB from the peak transmission. For custom filters linewidths such as the passband at -0.3dB and -25dB can be specified.

Q: Is the shape of the transmission curve affected by polarization?
A: No, OZ Optics tunable filters utilize an optical technique to control Polarization Dependent Losses (PDL). This design reduces PDL to minimal levels, while at the same time making the spectral response polarization insensitive.

Q: How well does the filter block unwanted wavelengths?
A: For standard single cavity Fabry Perot filters the typical linewidth at -20dB is ~12nm. This type of filter is good for selecting specific channels in a DWDM system or cleaning up the ASE noise from a broadband source. The filter may transmit light at specific wavelengths. Significantly outside the operating wavelength range. For custom applications requiring different out-of-band isolation please contact OZ Optics.

Q: What linewidth do I need in a 200GHz DWDM system? 100GHz? 50GHz?
A: Typical linewidths associated with these frequencies are 1.2, 0.8 and 0.3nm respectively. This ultimately depends on the channel width and isolation levels required for the system in question. OZ Optics can work with you to build the filter that best suits your requirements.

Q: Is the unit calibrated?
A: No, the manual tunable filter is a low cost, flexible solution to tunable filter needs and is not calibrated due to its manual use. However, OZ Optics does take great care in the production of these units in order to meet or exceed the optical properties required by the customer.

Application Notes

Introduction To Thin Film Filters:
In many fiber-optic applications we need to use light with a specific frequency or wavelength (λ). Although a laser may be an excellent source of monochromatic radiation, we might need a source of light providing controlled, variable wavelength. Bandpass filters provide an effective means of transmitting a well-defined band of light while blocking unwanted wavelengths emanating from a broadband source.

OZ Optics’ Tunable Filter uses a narrow wavelength bandpass filter. With increased angle of incidence, the filter transmits light of decreased wavelength (Figure 3)

![Figure 3. Conceptual design of a tunable filter.](image)
Application Notes: (cont’d)

The typical output wavelength distribution is demonstrated in Figure 4.

The main problem with typical tunable filters that has been solved by OZ Optics is their polarization sensitivity. As the angle of incidence increases, the sensitivity to polarized light also increases. (See Figure 5) This is a very important point in optical systems as the separation of the S and P polarizations causing large PDL can have detrimental affects on the system.

OZ Optics’ tunable filters utilize an optical technique to control PDL making the spectral response polarization insensitive. The polarization insensitivity is accomplished through the precision alignment of optical components on both the input and output side of the filter. As demonstrated in Figure 6, below, the light is first split into its respective polarizations and then one of the polarizations is rotated such that the light incident on the filter is all the same polarization. After passing through the filter the other polarization is rotated and then the beams are combined for the final focusing and collection into the fiber. By rotating the light and having a common polarization pass through the filters the PDL effect of the filter at high angles of incidence is avoided. Therefore, the spectral response of S and P polarizations remain the same for increasing angles of incidence. See figure 7.

Figure 4: Use of a broadband source and a tunable filter to create a narrow-band signal.

Figure 5: Differences in spectral width and attenuation between “P” and “S” polarized light.

Figure 6: A perspective sketch showing the splitting and recombining of the polarizations in a tunable filter.

Figure 7: “S” and “P” polarized output light at a high angle of incidence in the OZ Optics filter.
Erbium-Doped Fiber

EDF-980-T1

FEATURES:
• Optimized for use in C-band EDFA
• High numerical aperture allows for tighter coil design
• Superior power conversion efficiency
• Designed to achieve low splice loss
• Excellent spool-to-spool uniformity
• World-class gain flatness across entire C-band

Stockeye’s EDF-980-T1 erbium-doped fiber optimizes the performance of C-band erbium-doped fiber amplifiers (EDFAs). The high numerical aperture of this fiber ensures low bend losses which allows a tighter coil design within the EDFA. Other features include excellent power conversion efficiency and low splice loss to standard SMF fiber. Stockeye’s proprietary doping technique achieves the highest aluminum levels in the industry for unmatched gain flatness in the C-band.

Technical Specifications

<table>
<thead>
<tr>
<th>Parameter</th>
<th>EDF-980-T1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cut off wavelength</td>
<td>800 - 950 nm</td>
</tr>
<tr>
<td>Mode field diameter @ 1550nm</td>
<td>5.0 - 6.6 µm</td>
</tr>
<tr>
<td>Numerical aperture</td>
<td>0.27 - 0.31</td>
</tr>
<tr>
<td>Background loss near 1100 nm</td>
<td>&lt; 15 dB/km</td>
</tr>
<tr>
<td>Peak absorption near 1530 nm</td>
<td>5.0 - 8.0 dB/m</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>EDF-980-T1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cladding diameter</td>
<td>125 ± 1 µm</td>
</tr>
<tr>
<td>Core-cladding concentricity</td>
<td>&lt; 0.3 µm</td>
</tr>
<tr>
<td>Coating diameter</td>
<td>245 ± 10 µm</td>
</tr>
<tr>
<td>Proof test level</td>
<td>≥ 200 kpsi</td>
</tr>
<tr>
<td>Coating type</td>
<td>UV-cured dual acrylate</td>
</tr>
</tbody>
</table>

For more information contact us at opticalsales@stockeryale.com or call a sales representative at (603) 870-8286.
Corning® Optical Fiber

Product Information

PI1036  
Issued: 10/98  
Supersedes: 2/96  
ISO 9001 Registered

GENERAL

Corning® SMF-28™ single-mode fiber is considered the “standard” optical fiber for telephony, cable television, submarine, and private network applications in the transmission of data, voice and video services. Corning SMF-28 fiber is manufactured to the most demanding specifications in the industry.

SMF-28 fiber is optimized for use in the 1310 nm wavelength region. The information-carrying capacity of the fiber is at its highest in this transmission window, and it is also where dispersion is the lowest. SMF-28 fiber also can be used effectively in the 1550 nm wavelength region.

Corning’s enhanced, dual layer acrylate CPC6 coating provides excellent fiber protection and is easy to work with. CPC6 can be mechanically stripped and has an outside diameter of 245 μm. CPC6 is optimized for use in many single and multi-fiber cable designs including loose tube, ribbon, slotted core, and tight buffer cables.

SMF-28 fiber is manufactured using the Outside Vapor Deposition (OVD) process, which produces a totally synthetic, ultra-pure fiber. As a result, Corning SMF-28 fiber has consistent geometric properties, high strength and low attenuation. Corning SMF-28 fiber can be counted on to deliver excellent performance and high reliability, reel after reel. Measurement methods comply with ITU recommendations G.690, IEC 60793-1 and Bellcore GR-20-CORE.

FEATURES & BENEFITS

• Versatility in 1310 nm and 1550 nm applications.
• Outstanding geometrical properties for low splice loss and high splice yields.
• OVD manufacturing reliability and product consistency.
• Optimized for use in ribbon, loose tube, and other common cable designs.

OPTICAL SPECIFICATIONS

• Attenuation

<table>
<thead>
<tr>
<th>Uncabled Fiber Attenuation Cells</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength (nm)</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>1310</td>
</tr>
<tr>
<td>1550</td>
</tr>
</tbody>
</table>

* Lower attenuation available in limited quantities.

Point Discontinuity

No point discontinuity greater than 0.10 dB at either 1310 nm or 1550 nm.

Attenuation at the Water Peak

The attenuation at 1383±3 nm does not exceed 2.1 dB/km.
OPTICAL SPECIFICATIONS, (continued)

<table>
<thead>
<tr>
<th>Attenuation vs Wavelength</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range (nm)</td>
</tr>
<tr>
<td>1265 - 1330</td>
</tr>
<tr>
<td>1525 - 1575</td>
</tr>
</tbody>
</table>

The attenuation in a given wavelength range does not exceed the attenuation of the reference wavelength (λ) by more than the value α.

<table>
<thead>
<tr>
<th>Attenuation With Bending</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mandrel Diameter (mm)</td>
</tr>
<tr>
<td>32</td>
</tr>
<tr>
<td>75</td>
</tr>
<tr>
<td>75</td>
</tr>
</tbody>
</table>

The induced attenuation due to fiber wrapped around a mandrel of a specified diameter.

- Cable Cutoff Wavelength (λ_{cutoff})
  \( \lambda_{cutoff} < 1260 \text{ nm} \)

- Mode-Field Diameter
  8.80 to 9.80 μm at 1310 nm
  9.50 to 11.50 μm at 1550 nm

- Dispersion
  Zero Dispersion Wavelength (\( \lambda_0 \)): 1301.5 nm ≤ \( \lambda_0 \) ≤ 1321.5 nm
  Zero Dispersion Slope (S_{\lambda_0}): ≤ 0.092 ps/(nm²·km)

<table>
<thead>
<tr>
<th>Fiber Polarization Mode Dispersion (PMD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PMD Link Value</td>
</tr>
<tr>
<td>Maximum Individual Fiber</td>
</tr>
</tbody>
</table>

*Compiles with IEC SC 86A/WG1, Method 1, September 1997

- The PMD link value is a term used to describe the PMD of concatenated lengths of fiber (also known as the link quadrature average). This value is used to determine a statistical upper limit for system PMD performance.

  Individual PMD values may change when cabled. Corning's fiber specification supports emerging network design requirements for a 0.5 psec/km maximum PMD.

<table>
<thead>
<tr>
<th>Dispersion Calculation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dispersion = ( D(\lambda) = \frac{S_{\lambda_0}}{4} \left[ \frac{\lambda_0^4}{\lambda^4} - 1 \right] ) ps/(nm²·km), for 1200 nm ≤ ( \lambda ) ≤ 1600 nm, ( \lambda ) = Operating Wavelength</td>
</tr>
</tbody>
</table>

ENVIROMENTAL SPECIFICATIONS

<table>
<thead>
<tr>
<th>Environmental Test Condition</th>
<th>Induced Attenuation (dB/km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1310 nm</td>
<td>1550 nm</td>
</tr>
<tr>
<td>Temperature Dependence -60°C to +85°C*</td>
<td>≤ 0.05</td>
</tr>
<tr>
<td>Temperature-Humidity Cycling -10°C to +85°C*, up to 98% RH</td>
<td>≤ 0.05</td>
</tr>
<tr>
<td>Water Immersion, 23°C</td>
<td>≤ 0.05</td>
</tr>
<tr>
<td>Heat Aging, 85°C*</td>
<td>≤ 0.05</td>
</tr>
</tbody>
</table>

*Reference temperature = +23°C

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DIMENSIONAL SPECIFICATIONS

Standard Length (km/reel):  2.2 - 25.2

* Longer spliced lengths available at a premium.

Glass Geometry

Fiber Curl: ≥ 4.0 m radius of curvature
Cladding Diameter: 125.0 ± 1.0 µm
Core-Clad Concentricity: ≤ 0.5 µm
Cladding Non-Circularity: ≤ 1.0%  

Defined as: \[ 1 - \frac{\text{Min. Cladding Diameter}}{\text{Max. Cladding Diameter}} \] x 100

Coating Geometry

Coating Diameter: 245 ± 5 µm
Coating-Cladding Concentricity < 12 µm

MECHANICAL SPECIFICATIONS

Proof Test:
The entire length of fiber is subjected to a tensile proof stress ≥ 100 kpsi (0.7 GN/m²).*

* Higher proof test available at a premium.

PERFORMANCE CHARACTERIZATIONS

Characterized parameters are typical values.

Core Diameter:
8.3 µm

Numerical Aperture:
0.13
NA was measured at the one percent power angle of a one-dimensional far-field scan at 1310 nm.

Zero Dispersion Wavelength (\(\lambda_0\)):
1312 nm

Zero Dispersion Slope (S\(\lambda\)):
0.080 ps/(nm²•km)

Refractive Index Difference:
0.36%

Effective Group Index of Refraction (N\(\text{eff}\)):
1.4675 at 1310 nm
1.4681 at 1550 nm

Fatigue Resistance Parameter (n\(\lambda\)):
20

Coating Strip Force:
Dry: 0.6 lbs. (2.7 N)
Wet, 14 days room temperature: 0.6 lbs. (2.7 N)
Refractive Index Profile (typical fiber)

<table>
<thead>
<tr>
<th>Radius (μm)</th>
<th>Δ Refractive Index (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-25</td>
<td>0.0</td>
</tr>
<tr>
<td>-15</td>
<td>0.0</td>
</tr>
<tr>
<td>-5</td>
<td>0.0</td>
</tr>
<tr>
<td>5</td>
<td>0.0</td>
</tr>
<tr>
<td>15</td>
<td>0.0</td>
</tr>
<tr>
<td>25</td>
<td>0.0</td>
</tr>
</tbody>
</table>

Spectral Attenuation (typical fiber)

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Attenuation (dB/km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>800</td>
<td>a 1.81</td>
</tr>
<tr>
<td>1000</td>
<td>b 0.56</td>
</tr>
<tr>
<td>1200</td>
<td>c 0.34</td>
</tr>
<tr>
<td>1400</td>
<td>d 0.55</td>
</tr>
<tr>
<td>1600</td>
<td>e 0.19</td>
</tr>
</tbody>
</table>

Ordering Information

To order Corning® SMF-28™ optical fiber, contact your sales representative, or call the Telecommunications Products Division Customer Service Department at 910-395-7659 (North America) and +1-607-974-7174 (International). Please specify the following parameters when ordering.

- Fiber Type: Corning® SMF-28™ single-mode fiber
- Coating: CPCG (245 μm outer diameter)
- Fiber Attenuation Cell: _______ dB/km
- Fiber Quantity: _______ ft/
- Other: (Requested ship date, etc.)

CORNING

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Count on Corning® Fiber

Corning fiber is made in the USA.

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