“Dispersive and Nonlinear Effects in Highspeed Reconfigurable WDM Optical Fiber Communication”

by

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DISPERSE AND NONLINEAR EFFECTS IN HIGH-SPEED RECONFIGURABLE WDM OPTICAL FIBER COMMUNICATION SYSTEMS

by
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Dedication

To my parents, brother and wife,

for their everlasting love and support.
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Abstract

Chromatic dispersion, polarization mode dispersion (PMD) and nonlinear effects are important issues on the physical layer of high-speed reconfigurable WDM optical fiber communication systems.

For ≥10 Gbit/s optical fiber transmission system, it is essential that chromatic dispersion and PMD be well managed by dispersion monitoring and compensation. One the other hand, dispersive and nonlinear effects in optical fiber systems can also be beneficial and has applications on pulse management, all-optical signal processing and network function, which will be essential for high bite-rate optical networks and replacing the expensive optical-electrical-optical (O/E/O) conversion.

In this Ph.D. dissertation, we present a detailed research on dispersive and nonlinear effects in high-speed optical communication systems. We have demonstrated: (i) A novel technique for optically compensating the PMD-induced RF power fading that occurs in single-sideband (SSB) subcarrier-multiplexed systems. By aligning the polarization states of the optical carrier and the SSB, RF power fading due to all orders of PMD can be completely compensated. (ii) Chromatic-dispersion-insensitive PMD monitoring by using a narrowband FBG notch filter to recover the RF clock power for 10Gb/s NRZ data, and apply it as a...
control signal for PMD compensation. (iii) Chirp-free high-speed optical pulse generation with a repetition rate of 160 GHz (which is four times of the frequency of the electrical clock) using a phase modulator and polarization maintaining (PM) fiber. (iv) Polarization-insensitive all-optical wavelength conversion based on four-wave mixing in dispersion-shifted fiber (DSF) with a fiber Bragg grating and a Faraday rotator mirror. (v) Width-tunable optical RZ pulse train generation based on four-wave mixing in highly-nonlinear fiber. By electrically tuning the delay between two pump pulse trains, the pulse-width of a generated pulse train is continuously tuned. (vi) A high-speed all-optical XOR gate based on polarization rotation induced by Kerr effect in a single highly–nonlinear fiber. (vii) Wavelength-shift-free 3R-regeneration of 40-Gbit/s optical RZ signal by OPA with a clock-modulated pump in highly-nonlinear fiber.

These techniques will play key roles in future high-speed dynamic WDM optical fiber communication systems and reconfigurable networks.
Chapter 1
Introduction

This chapter provides a brief perspective of the progress in the field of optical communication systems. Fiber properties such as chromatic dispersion, polarization mode dispersion (PMD), and various nonlinear effects which are considered as important effects in the high speed fiber communication systems are discussed briefly.

1.1 Progress in Optical Fiber Communication Systems

Optical fiber communication systems use high carrier frequencies (~100 THz) in the visible or near-infrared region of the electromagnetic spectrum and employ optical fibers for information transmission. Such systems have been deployed worldwide since 1980 and revolutionized the technology of telecommunications [1]. The optical communication technology, together with microelectronics, brings the advent of the “information age”. The major breakthrough in optical fiber transmission came after invention of Erbium-Doped Fiber Amplifier (EDFA). Due to the wide gain bandwidth of the EDFA, the wavelength-division multiplexing (WDM) channels can be simultaneously amplified and transmitted over long distances. The bit rates have reached 3.73-Tb/s (373 × 10-
Gb/s, C+L band) over 11,000 km [2], 1.28-Tb/s (32 × 40-Gb/s, C band) over 4500 km [3], and 10.2-Tb/s (256 × 42.7-Gb/s, C+L band) over 100 km for WDM systems [4].

The demand for network bandwidth is outpacing even the astounding advances of recent years. The ever-increasing fiber optic base and the acceptance of WDM as an established technology are waiting to fulfill the enormous future potential of next-generation Internet services. The proliferation of online services and network access providers coupled with low cost computers result in exponentially increasing numbers of customers, with increasing bandwidth demands to support multimedia and other revolutionary applications. Faster processors fuel this demand, as today’s computers are outdated tomorrow. People spend more and more time online to perform everyday tasks. Because of its high capacity and performance, optical fiber communications have already replaced many conventional communication systems in point-to-point transmission and networks and also have been considered as a good candidate for wireless backbone.

To fully utilize the bandwidth of the fiber and achieve a high performance, the physical effects on the physical layer of optical fiber communication systems must be detailed studied. Optical signals suffer from many physical effects in the fiber, including chromatic dispersion, polarization mode dispersion (PMD) and fiber nonlinearities. For high-speed reconfigurable WDM optical communication
systems, it is essential that chromatic dispersion and PMD be well managed by using some type of dispersion compensation. Furthermore, for automated timely tunable dispersion compensation, some methods of dispersion monitoring have to be implemented. By managing fiber chromatic dispersion, PMD and nonlinearities, the capacity of optical systems has been greatly expanded over the past few years [1]. There are still a lot of issues in this area need to be addressed and better solutions need to implement to achieve ultra-high capacity and performance systems. On the other hand, nonlinear effects in optical fiber transmission system can also be beneficial and has applications on pulse management, all-optical signal processing and network function [5], which will be essential for high bite-rate optical networks and replacing the expensive optical-electrical-optical (O/E/O) conversion.

1.2 Dispersive Effects in Optical Fiber Communication Systems

Fiber dispersive effects include chromatic dispersion and polarization-mode dispersion (PMD). Both effects degrade the performance of high-speed optical fiber communication systems.

1.2.1 Chromatic Dispersion

When an electromagnetic wave propagates through fiber, the medium response depends upon optical frequency $\omega$. This property, referred to as chromatic dispersion, manifests through the frequency dependence of the refractive index $n(\omega)$.
Fiber dispersion plays a critical role in propagation of optical pulses since different spectral components associated with the pulse travel at different speeds given by \( c/n(\omega) \). Consequently, the optical pulse at the output of the fiber will be distorted. Dispersion effect can be considered by expanding the mode-propagation constant \( \beta \) in a Taylor series around the center frequency \( \omega_0 \) [5]

\[
\beta(\omega) = n(\omega) \frac{\omega}{c} = \beta_0 + \beta_1(\omega - \omega_0) + \frac{1}{2} \beta_2(\omega - \omega_0)^2 + \ldots
\]

(1.1)

Where

\[
\beta_m = \left[ \frac{d^m \beta}{d\omega^m} \right]_{\omega=\omega_0} \quad (m = 0, 1, 2, \ldots)
\]

The pulse envelope travels at the group velocity \((v_g = \frac{1}{\beta_1})\), while the parameter \( \beta_2 \) is responsible for pulse broadening to the first order. \( \beta_2 \) also depends on the wavelength (i.e., frequency) of the optical signal. The wavelength for which \( \beta_2 = 0 \) is often referred to as dispersion-zero wavelength \((\lambda_0)\); \( \lambda_0 = 1.3 \, \mu m \) for standard single mode fiber (SMF). More commonly used system parameter is the dispersion parameter \( D \); the quantity \( D \) is related to \( \beta_2 \) by the equation

\[
D = \frac{d\beta_1}{d\lambda} = -\frac{2\pi c}{\lambda^2} \beta_2
\]

(1.2)

The unit of \( D \) is ps/(nm-km). \( D \) for SMF is about +17 ps/(nm-km) at 1.5 \( \mu m \).

Tailoring the waveguide profile can change dispersion parameters. In dispersion shifted fibers (DSF), \( \lambda_0 \) is in the neighborhood of 1.5 \( \mu m \) and \( D \) usually between \(-2.5\) and \(+2.5\) ps/nm-km at 1.5 \( \mu m \). The dispersion parameter, \( D \) as a function of wavelength for both SMF and DSF is shown in Figure 1.1. Negative \( D \)
values are referred normal dispersion ($\beta_2$ is positive), and positive D values are referred anomalous dispersion ($\beta_2$ is negative). The wavelength dependency of D is usually considered through dispersion slope which is $dD/d\lambda \approx 0.08$ ps/nm$^2$-km (for both SMF and for DSF around 1.5 $\mu$m).

![Dispersion parameter D versus wavelength of SMF and DSF](image)

**Figure 1.1** Dispersion parameter D versus wavelength of SMF and DSF [3].

Both negative and positive dispersion cause pulse broadening at the output of the fiber. The broadening increases with the fiber length, imposing a limit on the maximum distance and/or data rate without regeneration. Therefore, chromatic dispersion must be mitigated for high-speed or long-distance systems. Even though it is possible to manufacture fiber with zero dispersion, it is not practical to use such fiber for WDM transmission, because of large four wave mixing (FWM) induced penalties. Therefore, that chromatic dispersion must be managed, rather than eliminated in optical fiber transmission systems. There are several important aspects
of optical systems and networks that make tunable dispersion compensation solutions attractive, especially in high-speed optical networks.

As shown in Figure 1.2, because of the non-zero spectral with of modulated data (optical pulse stream), dispersion leads to pulse broadening, proportional to the distance and with the data rate, thus imposing a limit on the maximum distance transmission without regeneration. Dispersion-limited distance can be approximated by determining the transmission distance at which a pulse is broadened by one bit interval. The estimated dispersion limited distance \( L_D \) for a signal having non-return to zero (NRZ) intensity modulation can be obtained by

\[
L_D = \frac{c}{\lambda^2 DR^2}
\]

where \( R \) is the data rate, \( T (= 1/R) \) is the bit time, \( c \) is speed of light, and \( \lambda \) is the wavelength of the optical signal. The dispersion limited distance decreases as square of bit rate. One criterion for detecting this limit for an externally modulated NRZ signal is [8]:

\[
B^2 DL \leq 104,000 (Gb/s)^2 \cdot ps/nm
\]

which corresponds to a dispersion-induced power penalty of 1dB. For single-mode fibers with \( D=17 \) ps/nm/km, the maximum distance is approximately 1000 km for a bit rate of \( B = 2.5 \) Gb/s, but decreases to about 60 km for \( B = 10 \) Gb/s and 5 km for \( B = 40 \) Gb/s in an externally modulated system. Some method of dispersion
compensation must be employed for a system to operate beyond these distance limits.

\[ v = \text{velocity} \]

\[ f_{\text{Carrier}} \]

\[ \frac{\text{ps}}{\text{nm} \cdot \text{km}} \]

\[ f \{\text{distance, bit rate}\} \]

Figure 1.2 Chromatic dispersion induces optical pulse broadening, proportional to the transmission distance and with the data rate.

For \( \geq 10\)-Gb/s data rates that are transmitted over \( \geq 100 \) km, it is essential that chromatic dispersion be well managed by using some type of dispersion compensation. In theory, compensation of chromatic dispersion for high-speed or long-distance systems can be fixed in value. However, static, fixed dispersion compensation is inadequate when system conditions can change in the following scenarios: (i) reconfigurable optical networks for which a given channel's accumulated dispersion will change when the network routing path is reconfigured, and (ii) \( \geq 40\)-Gb/s long-distance links for which chromatic dispersion and signal degradation may change substantially due to normal changes in temperature [9]. The required accuracy in dispersion compensation increases dramatically with the data
rate. While the amount of residual dispersion that is tolerable at 10-Gb/s is large, of the order of 1000 ps/nm, in 40-Gb/s systems this margin shrinks to only 60 ps/nm. Thus the use of tunable modules is the only way of managing accumulated dispersion.

1.2.2 Polarization Mode Dispersion (PMD)

Single-mode fibers actually support two perpendicular polarizations of the original transmitted signal (fundamental mode). In an ideal fiber (perfect) these two modes are indistinguishable, and have the same propagation constants owing to the cylindrical symmetry of the waveguide. However, practical fibers are not perfect and, as a result, the two perpendicular polarizations may travel at different speeds and consequently arrive at the end of the fiber at different times. This phenomenon is called polarization mode dispersion (PMD).

As shown in Figure 1.3, the major cause of PMD is the asymmetry of the fiber-optic strand. Asymmetry is simply the fact that the fiber core is slightly out-of-round, or oval. Fiber asymmetry may be inherent in the fiber from the manufacturing process, or it may be a result of mechanical stress on the deployed fiber. The inherent asymmetries of the fiber are fairly constant over time, while the mechanical stress due to movement of the fiber can vary, resulting in a dynamic aspect to PMD.
The mechanical stress on the optical fiber can originate from a variety of sources. One source that is very difficult to control is the day/night and seasonal heating and cooling of the optical fiber. Although much fiber is deployed in the ground and often within conduits, it is still subject to temperature variations and corresponding mechanical stress.

Another source of mechanical stress can originate from nearby sources of vibration. For example, much fiber is deployed alongside railroad tracks because of the ease of right-of-way and construction. However, vibration from passing trains can contribute to stress on the optical fiber. And wind can cause swaying of the fiber cable and can contribute to PMD of fiber deployed aerially.

Figure 1.3 Origin of PMD.
The difference in propagation constants (differential phase velocity) of these two modes is responsible for PMD in the fiber, and can be related to the difference in refractive indices between the two orthogonal polarization axes as

\[ \beta_o - \beta_e = \frac{\omega n_o}{c} - \frac{\omega n_e}{c} = \frac{\omega \Delta n_{\text{eff}}}{c} \]  \hspace{1cm} (1.5)

where \( n_o \) and \( n_e \) are the effective refractive indices of two orthogonal axes, and \( \Delta n_{\text{eff}} \) is the differential index of refraction. The differential index of refraction is a measure of birefringence in the fiber, and is usually between \( 10^{-7} \) and \( 10^{-5} \).

Since PMD is caused by the different transmission speeds of the signal's two states-of-polarization (SOPs) as they propagate along a fiber having a small birefringence, and the birefringence of a fiber changes randomly along a fiber link, PMD is a statistically random quantity. PMD is characterized by differential group delay (DGD) between two principal states of polarization (SOPs) after a given length of fiber. Because of random variations in the perturbations along a fiber span, PMD in long fiber spans accumulates in a random-walk-like process that leads to a square root of transmission-length dependence [10]. Therefore, PMD does not have a single value for a given span of fiber. Rather, it is described in terms of average DGD, and a fiber has a distribution of DGD values over time. The probability of the DGD of a fiber section being a certain value at any particular time follows a Maxwellian distribution (see Figure 1.4). The probability of \( DGD = \Delta \tau \) is given by:

\[
\text{PDF}(\tilde{\Delta} \omega) = \frac{32\tilde{\Delta} \omega^2}{\partial^2 \langle \tilde{\Delta} \omega \rangle^3} \exp\left( \frac{4\tilde{\Delta} \omega^2}{\partial \langle \tilde{\Delta} \omega \rangle^2} \right) \]  \hspace{1cm} (1.6)
with mean value \(<\Delta \tau>\). PMD is usually expressed in ps/km\(^{1/2}\) in long fiber spans, and the typical value of \(<\Delta \tau>\) is 0.1 to 10 ps/km\(^{1/2}\) [7,11,12].

![Figure 1.4 Probability distribution of DGD in a typical fiber.](image)

Additionally, in a cascaded fiber link, there may be many discrete components (i.e., isolators, couplers, wavelength multiplexers), which are polarization dependent due to molecular asymmetry (anisotropy) of the waveguide material. Although PMD caused by polarization dependence of a single component may be negligible, cascaded components may add significant PMD in a long link. The combined PMD-induced broadening in a long link may be up to a few tens of ps, which can degrade systems operating at \(\geq 10\) Gbit/s. In systems operating at \(\geq 40\) Gbit/s, PMD has been proved to be deleterious. In order to enable ultra-fast TDM/WDM communications over long distances of optical fiber, the remaining critical issue of PMD must be considered.
In addition to the time variance of DGD, PMD also varies over wavelengths, known as higher-order PMD. This variance results in an optical dispersion that is a function of both the channel bandwidth and the value of DGD over that bandwidth [7]. Figure 1.5 is a graphical representation of the effect of PMD (both first- and higher-order) on an optical pulse. The optical pulse and its constituent photons travel from the source, or transmitter, at distance = 0, along the single-mode optical fiber. At some distance after PMD has affected the pulse, the polarized energy is separated by some time (i.e., DGD). If DGD is severe, the receiver at some distance $L$ cannot accurately decode the optical pulse, and bit errors can result. If the bit errors caused by PMD are too numerous, then the transmitted information is too corrupt to recover and the transmission link should be considered out of service.

![Graphical representation of the effect of PMD on an optical pulse.](image)

The quantity of bit errors encountered at the receiver is directly influenced by the amount of PMD in a fiber optic transmission span. DGD of this magnitude, in a 10-Gb/s transmission system, can be expected to result in a bit-error rate that is severe enough to cause service problems. Some general rules on limitations of distances caused by PMD are given in Table 1.1.
Table 1.1 Limitations of transmission distances caused by PMD

PMD induced problems can be reduced simply by regeneration, i.e., shortening the optical transmission distance. However, from a network point of view, a regeneration site is an inefficient and costly optical-electronic conversion site. Adding to the expense and inefficiency of a regeneration site is the fact that most long-haul transmission systems are now multiwavelength, dense wavelength division multiplexing (DWDM) systems. In this application, the transmission link must first be demultiplexed, then regenerated, then multiplexed again. This is a very costly operation compared to the preferred alternative of a multiwavelength amplifier. From a network and cost perspective, a more efficient method of addressing the PMD problem is to fix the effects of PMD while the transmission is in an optical state, before a receiver tries to decode the bits. A PMD compensator (PMDC), deployed at the destination of the transmission system, can reduce the effects of the PMD in the fiber and ensure that the optical bits are correctly decoded by the receiver before they
are to be routed and switched. The most reliable and efficient PMDC technology is the use of adaptive optics to realign and correct the pulses of dispersed optical bits.

1.3 Fiber Nonlinearities

There are two categories of fundamental optical nonlinear effects that can cause degradation of the transmitted signal. They are refractive-index effects and stimulated scattering effects. Refractive index effects are associated with modulation of the refractive index due to changes in the light intensity. Stimulated scattering effects arise from parametric interactions between light and acoustic or optical phonons (due to lattice or molecular vibrations) in the fiber.

The refractive index $n$ of silica is not a constant but increases with power (or light intensity) according to the relationship:

$$\tilde{n}(\omega, P) = n_0(\omega) + n_2 I = n_0(\omega) + n_2 \frac{P}{A_{\text{eff}}}$$

where $n_0(\omega)$ is the linear refractive index of silica, $n_2$ is the intensity-dependent refractive index coefficient, and $I = P/A_{\text{eff}}$ is the effective intensity in the medium. The typical value of $n_2$ is $2.6 \times 10^{-20}$ m$^2$/W. This number takes into account the averaging of the polarization states of the light as it travels in the fiber. The intensity dependence of the refractive index gives rise to three major effects [5,13]: (i) self-phase modulation (SPM), (ii) cross-phase modulation (XPM), and (iii) four wave mixing (FWM). All these three nonlinear effects can significantly degrade the
performance of a WDM lightwave system [14,15]. XPM and FWM are more severe in multi-channel WDM systems, while SPM can occur in both single channel and WDM systems.

The relevant power-times-distance products for amplified transmission systems can be so large as to make fiber nonlinear effects the dominant factor in determining the design of long-distance systems. System specifications such as the non-regenerated span length $L$, amplifier spacing $l_A$, number of WDM channels $N$, channel frequency spacing $\Delta f$, and power per channel $P_0$ are all affected. Understanding how system performance is degraded by fiber dispersion in the presence of fiber nonlinearities is crucial for designing amplified transmission systems. One the other hand, nonlinear effects can also be beneficial: refractive-index effects has applications on pulse compression and logic gates for all-optical signal processing and network function; and stimulated scattering effects can be used for signal amplification [5].

### 1.3.1 Self Phase Modulation (SPM)

Self-phase modulation (SPM) is the phenomenon where any modulation on the signal power gives rise to modulation of the signal phase and spectral broadening. The nonlinear contribution of the index of refraction due to optical
power $P$ results in a phase change $\Phi_{NL}$, which for light propagating in a fiber given by [5]

$$\Phi_{NL} = \gamma P L_{\text{eff}}$$

(1.8)

where the quantities $\gamma$ and $L_{\text{eff}}$ are defined as

$$\gamma = \frac{2m_2}{\lambda A_{\text{eff}}} \quad \text{and} \quad L_{\text{eff}} = \frac{1 - e^{-\alpha L}}{\alpha}$$

in which $A_{\text{eff}}$ is the effective mode area of the fiber, and $\alpha$ is the fiber attenuation loss. $L_{\text{eff}}$ is the effective nonlinear length of the fiber that accounts for the fiber loss, and $\gamma$ is the nonlinear coefficient measured in rad/(km-W). Although nonlinear coefficient is small, the lengths and powers that have been made possible by the use of the optical amplifiers (EDFAs) can cause the nonlinear phase large enough to play a significant role in the state-of-the-art lightwave systems [5,7].

When an intensity-modulated signal travels through an optical fiber, the peak of the pulse accumulates phase more quickly than the wings due to nonlinear refractive index. This results in a nonlinear chirping of the signal. The SPM induced chirp may interact with dispersion induced chirp and can cause a totally different behavior depending upon positive or negative dispersion values [5,7]. In the normal dispersion regime ($D < 0$), the SPM induced nonlinear-chirp will add to the dispersion-induced linear-chirp, thereby causing not only the enhanced pulse broadening but also distorting the shape of the pulse. In the anomalous dispersion regime ($D > 0$), the SPM induced nonlinear-chirp will tend to partially negate the
dispersion induced linear-chirp, thereby slightly reducing the pulse broadening, but still will distort the pulse shape. Therefore, SPM induced chirp can impose a limitation on bit rate and transmission distance in lightwave systems. The SPM induced chirp is dependent upon the power and the shape of the optical pulse. Therefore, if the power and the shape of the pulse is right, the SPM induced chirp and the dispersion-induced chirp can completely negate each other in anomalous dispersion regime (D > 0) [6]. The pulse with the right shape and power is called soliton.

1.3.2 Cross-Phase Modulation (XPM)

Cross-phase modulation (XPM) is the phenomenon in which intensity fluctuations in one channel propagating in the fiber modulate the phase of all the other channels or alternatively all the WDM channels (at different wavelengths) in the fiber modulate the phase of any one channel [5,16]. In a multi-channel system, the excess bandwidth generated by this XPM effect is given by

$$\Delta B = \frac{d\Phi_{sl}}{dt} = \gamma L_{\text{eff}} \frac{dP_1}{dt} + 2\gamma L_{\text{eff}} \frac{dP_2}{dt}$$  \hspace{1cm} (1.9)

Note that the XPM induced chirp is twice as much as that of the SPM induced chirp. This factor of 2 arises from counting of terms in the expansion of the nonlinear polarization inside the fiber [5,16]. Therefore, it appears that XPM can impose more severe limitation than SPM for WDM systems because effect is twice as large for each interfering channel, and there can be a lot of interfering channels. However,
fiber dispersion plays a significant role in the system impact of XPM [5]. Due to
dispersion, pulses at different wavelengths travel with different speeds inside the
fiber because of group velocity mismatch. In normal dispersion regime (D < 0), a
longer wavelength travels faster while the opposite occurs in the anomalous-
dispersion regime (D > 0). This feature leads to a walk-off effect that tends to reduce
XPM effect.

1.3.3 Four-wave mixing (FWM)

Like SPM and XPM, four-wave mixing (FWM) is also generated by the
intensity-dependence of refractive index of silica. However, impact on performance
of WDM system is completely different. In FWM, the beating between two channels
of a WDM system at their difference frequency, modulates the phase of one of the
channels at that frequency, generating new tones as sidebands [17]. When three
waves of frequencies $f_i$, $f_j$, and $f_k$ interact through fiber nonlinearity, they generate a
wave of frequency

$$ f_{ijk} = f_i + f_j - f_k $$

Therefore, three waves give rise to nine new optical waves by FWM. In WDM
system with equally spaced channels, most of the product terms generated by FWM
fall at the channel frequencies, giving rise to crosstalk. The center channels are more
vulnerable to this cross talk since the number of FWM products, which fall on center
channels, is higher than those, which fall on end channels [7,17]. The efficiency of
FWM depends on the channel spacing and the fiber dispersion. Increasing channel spacing or fiber dispersion will reduce mixing efficiency.

High-speed WDM systems require simultaneously high launched power and low dispersion values. This greatly enhances the efficiency of FWM, making FWM the dominant nonlinear effect in WDM lightwave systems. FWM can impose severe limitation on bit rate/channel, transmission distance, and number of WDM channels [7].

Dispersion limits the maximum transmission distance and the bit rate. But, the effects of XPM and FWM are reduced by dispersion because dispersion destroys the phase matching conditions. In order to achieve good system performance, it is important to consider the chromatic dispersion and the nonlinear effects of the transmission fiber together. Dispersion management is a solution for this dilemma: use two different types of fibers having opposite dispersions periodically. The total accumulated dispersion is zero after some distance, but the absolute dispersion is non-zero at all points along the link. The result of this dispersion management scheme is that the total effect of dispersion is negligible for all channels, and non-zero dispersion causes phase mismatch between channels thereby destroying efficient nonlinear interactions.

1.3.4 Stimulated Scattering
The nonlinear effects described above are governed by the power dependence of refractive index, and are elastic in the sense that no energy is exchanged between the electromagnetic field and the dielectric medium. A second class of nonlinear effects results from stimulated inelastic scattering in which the optical field transfers part of its energy to the nonlinear medium. Two important nonlinear effects fall in this category [5]: (i) stimulated Raman scattering (SRS), and (ii) stimulated Brillouin scattering (SBS). The main difference between the two is that optical phonons participate in SRS, while acoustic phonons participate in SBS. In a simple quantum-mechanical picture applicable to both SRS and SBS, a photon of the incident field is annihilated to create a photon at a downshifted frequency. The new photon is propagated along the original signal in the same direction in SRS, while the newly generated photon propagates in the backward direction in SBS. Furthermore, the downshifted frequency range where new photons can be generated is ~30 THz in SRS and only ~30 MHz in SBS. Therefore, SBS does not impose any significant limitations in high-speed (Gb/s systems) digital lightwave systems. However, SRS can impose some limitations on WDM systems because the effect of SRS is to deplete the energy of some channels (higher frequency channels) on behalf of the other channels (low frequency channels). The effect of SRS is not very significant unless the number of channels are more than 100 [7]. On the other hand, SRS can be used for signal amplification in a fiber (so called Raman amplifier). Raman amplifier is becoming more and more cost effective now and is extensively developed in recent years because of some its unique features. Indeed, unlike
EDFA, Raman amplification can virtually occur at any wavelength by properly choosing the pump wavelength and a large bandwidth can be achieved by combing several pump wavelength.

1.5 Summary

In this chapter, we introduced the most important dispersive and nonlinear effects in optical fiber transmission systems. Chromatic dispersion, PMD, and different fiber nonlinearities have been discussed briefly.
Chapter 2

Optical Compensation of the PMD-Induced RF Power Fading for Single-Sideband Subcarrier-Multiplexed Systems

In this chapter, we demonstrate a novel technique for optically compensating the PMD-induced RF power fading that occurs in single-sideband (SSB) subcarrier-multiplexed systems. By aligning the polarization states of the optical carrier and the SSB, RF power fading due to all orders of PMD can be completely compensated.

2.1 PMD-Induced RF Power Fading

Subcarrier multiplexing (SCM) has several important applications in optical systems including: cable television, antenna remoting, microwave photonics, and for control and routing information in optically-switched networks. However, deleterious RF power fading has been reported in the transmission of analog and digital SCM signals over fiber due to polarization mode dispersion (PMD) [18,19].

As discussed in Chapter 1, PMD is caused primarily by the asymmetry of the optical fiber core that causes a birefringence such that light polarized along one axis will travel faster than light polarized along the orthogonal axis. A key feature of
PMD is its statistical behavior, since the relative orientation between the state-of-polarization (SOP) of the input signal and the principal-states-of-polarization (PSPs) of the fiber varies randomly with time [19]. The differential group delay (DGD) between the fast and slow PSPs, i.e. first-order PMD, is a random process with a Maxwellian probability distribution, such that network outages can occur due to rare events in the tail of the distribution.

The deleterious PMD-induced power-fading effect in SCM can be described in the time domain as follows. The light can be decomposed along two orthogonal PSPs, with one axis traveling faster than the other. The time delay between the faster and slower axes causes a phase difference in the corresponding received subcarrier signals. This phase difference induces destructive interference and may lead to serious RF power fading that is a function of subcarrier frequency and accumulated DGD [20]. Another explanation involves the polarization state in the optical frequency domain. PMD-induced RF power fading occurs when the polarization state of the optical carrier wave is not aligned with the polarization state of the subcarrier, since PMD will cause the polarization state of the carrier and subcarrier to wander at different rates.

In general, double-sideband (DSB) transmission will be affected by chromatic dispersion because of the relative time (phase) shift that develops between the upper and lower sidebands due to frequency-dependent velocities in the fiber. To
avoid this, many SCM systems employ single-sideband (SSB) subcarriers and are therefore relatively immune to chromatic dispersion [21]. However, PMD-induced RF power fading remains a problem even for SSB signals [19], since the relative polarization state of the carrier to the SSB changes through the transmission fiber. For example, in a 40-GHz optical SSB SCM system, the RF power is completely faded with 12.5-ps instantaneous DGD. Furthermore, we note that higher-order PMD can cause additional power fading [22,23].

Therefore, robust transmission of an SCM signal may necessitate the use of some technique to compensate or mitigate the power fading effects of PMD. Published work includes: (i) using a first-order PMD compensator [19], and (ii) employing polarization diversity, which requires two optical detectors [24].

We propose and demonstrate a novel technique for optical compensation of the PMD-induced RF power fading that occurs in SSB SCM transmission systems. Given that the PMD-induced power fading in the optical domain is caused by the difference between the polarization states of the SSB signal and the optical carrier, we can overcome this problem by: (i) splitting the optical carrier and the SSB signal at the receiver using a narrowband optical grating filter, (ii) realigning their polarization states relative to each other, and (iii) recombining them. In this way, first-order and all-higher-order PMD-induced RF power fading can be completely compensated. We show that RF power fading of the 5% distribution tail can be
decreased from 13.5 dB to <1.5 dB for both 300 experimental samples as well as for a 10,000-sample simulated system. The technique is independent of the DGD of the optical fiber link and the subcarrier frequency.

2.2 Concept of optical compensation of PMD-induced RF power fading for SSB SCM systems

Figure 2.1 shows the concept of PMD-induced RF power fading in SSB SCM systems. At the transmitter, the optical carrier and the SSB have the same SOP. After propagating through the optical fiber link, first-order and higher-order PMD cause the SOPs of the optical carrier and the SSB to vary by different amounts. To properly recover the modulated data, the SSB must beat with the carrier in the receiver. However, only the portions of the signals that have the same polarization will effectively interfere, so a relative SOP difference will cause the received RF power to fade. Complete fading will occur when the SSB is orthogonal to the optical carrier. However, if the SOPs can be realigned such that they are the same for both the optical carrier and the SSB, the PMD-induced RF power fading can be completely removed. It is important to note that it is not sufficient to recover the faded RF signal by using only first-order PMD compensation [19]. On the other hand, no matter changes of the SOP are induced by first-order or higher-order PMD, since our technique is based on realigning the SOP of the optical carrier with the
SSB, the PMD-induced RF fading will be compensated. And it is independent of the DGD of the fiber link and the subcarrier frequency.

Figure 2.1 Explanation of PMD-induced RF power fading in an SSB SCM system in the optical domain.

2.3 Experimental Setup

Figure 2.2 shows the experimental setup. We first generate an 18~20 GHz double sideband signal by externally modulating the 1550 nm optical carrier. An SSB signal is obtained by using a fiber Bragg grating (FBG) to filter out the lower sideband. The light then propagates through a PMD emulator. Generally, the optical carrier and the SSB will have different SOPs at the output of the PMD emulator, since the PMD will induce different changes in the SOP for the optical carrier and the SSB. At the receiver, a circulator and a narrowband FBG filter is used to separate the optical carrier and the SSB. The FBG has a reflection of 99.7% at the optical carrier wavelength of 1550 nm, with a bandwidth of 0.1 nm. The reflected
optical carrier passes through a polarization controller (PC) that is used to align its SOP with the SSB. The optical carrier and SSB are then recombined with a coupler and sent to the receiver. By adjusting the PC to maximize the received RF power, the faded RF signal can be completely recovered after detection. We adjust the PC manually during the experiment, and it is possible to make the PC adjustment automatically by using an electrically tunable PC.

![Experimental setup for the optical compensation technique.](image)

**2.4 Results and Discussions**

Several experiments were performed using different PMD emulator configurations. Initially, the emulator simply consisted of a PC followed by a single section of polarization maintaining (PM) fiber to generate only first-order PMD (DGD). Different fiber lengths were used to obtain different DGD values. By tuning the PC, the optical input was launched into the PM fiber with 50/50 splitting between the two PSPs. The subcarrier frequency was set to 20 GHz. The optical spectrum of the light is shown for different points in the setup in Figure 3.3. The spectrum of the signal exiting the emulator is shown in Figure 2.3 (a). The spectra of the carrier and
the sideband after being separated by the FBG filter are shown in Figure 2.3 (b) and (c), respectively. We can see that the filter reduces the power of the optical carrier in the spectrum of the SSB by about 25 dB. After the SOP of the optical carrier is aligned with the SSB, the optical carrier and the SSB are recombined and the spectrum is shown in Figure 2.3 (d).

When an equal amount of optical power is distributed between the fast and slow PSPs, RF power fading at the receiver can be calculated using the following equation [24]:

$$ F = \cos^2 (\varphi f \cdot \bar{\Delta \delta}) $$  \hspace{1cm} (2.1)

where $F$ is the RF power fading factor ($F = 0$ for complete fading), $f$ is the frequency of the subcarrier, and $\bar{\Delta \delta}$ is the DGD value. Figure 2.4 shows the measured RF power fading due to first-order PMD with and without compensation. The theoretical curve is plotted as a solid line. Without compensation, the RF power fading is $> 3$ dB when the DGD value is $>12.5$ ps and increases rapidly when the DGD value is close to 25 ps (corresponding to $\frac{1}{2}$ the period of the subcarrier). However, after compensation, the RF power fading is reduced to less than 1 dB.
Figure 2.3 Optical Spectrum of (a) the light at the PMD emulator output; (b) the optical carrier after FBG filtering; (c) the SSB after passing through the FBG; (d) after recombination of the optical carrier and the SSB using an optical coupler.
To investigate the higher-order PMD compensation ability of this new technique, we used a PMD emulator with 15 sections of PM fiber separated by polarization controllers that are randomly varied between each experimental sample. This emulator will generate both Maxwellian distributed DGD values as well as higher-order PMD effects [25]. Furthermore, the emulator could be configured to yield an average DGD of either 31 or 42 ps. The amount RF fading was measured for 300 independent samples for both of these average DGD values as well as two subcarrier frequencies, 18 and 20 GHz, as shown in Figure 2.5 (a – d). Additionally, a computer simulation was used to generate the “theoretical distribution” curve from a set of 10,000 random samples.
Figure 2.5 Power fading distribution after the PMD emulator with and without optical compensation: (a) average DGD=42 ps, subcarrier frequency=20 GHz; (b) average DGD=42 ps; subcarrier frequency=18 GHz; (c) average DGD=31 ps, subcarrier frequency=20 GHz; (d) average DGD=31 ps, subcarrier frequency=18 GHz.
Ideally the distributed RF power fading can be totally compensated to 0 dB using our technique. The results show that without compensation, 5% of the samples exhibit more than 13.5 dB of RF power fading. The experimental results differ a little from the simulation results because only 300 samples were taken during the experiments. Using our technique, all of the compensated data exhibit less than 1.5 dB RF power fading, which may be caused by a small residual misalignment left between the SOPs of the optical carrier and the SSB. Therefore, the 5% power fading tail is improved by more than 12 dB using our compensation technique. By extrapolation, the improvement will be even greater for lower probability areas of the tail. The performance of this technique is independent of the average DGD of the optical fiber link and the subcarrier frequency.

Figure 2.6 shows the measured bit error rate (BER) versus the received optical power for a 155 Mbit/s binary-phase-shift-keyed (BPSK) signal modulated onto the 20 GHz subcarrier. The back-to-back BER is measured without the PMD emulator. The average DGD of the PMD emulator was 31 ps. We choose an arbitrary sample for which the RF fading was approximately 14 dB at the emulator output. Using this sample, we could not get a measurable BER directly after the PMD emulator, since the data is almost entirely lost without compensation. On the other hand, the power penalty is around 0.4 dB with compensation. This penalty is consistent with the calculation result of the power penalty induced by the optical interference effect when the optical carrier and the SSB branches are recombined.
Since the power of the optical carrier in these two branches differs by 25 dB, the effect is small.

Figure 2.6 Measured BER vs. received optical power for 155 Mbit/s BPSK signal at 20 GHz. The compensated signal exhibited 14 dB of RF fading before compensation.

2.5 Summary

In this chapter, we propose and demonstrate a novel technique for optically compensating the PMD-induced RF power fading that occurs in single-sideband (SSB) subcarrier-multiplexed systems. By aligning the polarization states of the optical carrier and the SSB, RF power fading due to all orders of PMD can be completely compensated. The 5% RF power fading tail is improved from 13.5 dB to <1.5 dB, as verified from both experimental measurement (300 samples) and computer simulation (10,000 samples). This technique is independent of the DGD of the optical fiber link and the subcarrier frequency.
Chapter 3

Chromatic-Dispersion-Insensitive PMD Monitoring for NRZ Data Based on Clock Power Measurement

In this chapter, we demonstrate chromatic-dispersion-insensitive PMD monitoring by using a narrowband FBG notch filter to recover the RF clock power for 10Gb/s NRZ data, and apply it as a control signal for PMD compensation.

3.1 Chromatic-Dispersion-Insensitive PMD Monitoring

As we mentioned in Chapter 1, high-bit-rate transmission systems (≥10 Gb/s/channel) are highly susceptible to deleterious optical-fiber-based effects, such as chromatic dispersion (CD), polarization-mode dispersion (PMD), and nonlinearities. In particular, PMD accumulates due to either high-PMD legacy fiber or PMD of many in-line components. Deleterious PMD effects are stochastic, time varying, and temperature dependent. Moreover, the instantaneous first-order PMD (i.e., differential group delay (DGD)) follows a Maxwellian probability distribution, always with some finite possibility of network outage.
A key challenge for systems deployment is that these effects are not static but change with time, including: (i) temperature changes, (ii) reconfigurable optical networking, (iii) wavelength drifts, and (iv) periodic repair and maintenance. These degradations may require the monitoring of signal quality in order to either dynamically tune a compensator or simply to determine the network location that must be diagnosed and repaired.

One straightforward method of monitoring optical signal quality is to electronically determine either the Q of the eye diagram or actually measure the bit-error-rate. Unfortunately, this approach cannot distinguish between the various effects that may cause signal degradation. Several types of PMD monitors have been reported, including: (a) adding a subcarrier tone [26], (b) measuring the signal’s degree-of-polarization (DOP) [27], (c) spectral analysis of the detected signal [28], and (d) measuring the chromatic-dispersion-generated clock tone [29]. However, each of these techniques suffers from one or more of the following disadvantages: (i) high cost and complexity, (ii) necessitating transmitter modification, (iii) low sensitivity, and (iv) sensitive to CD.

In this chapter, we propose and demonstrate chromatic-dispersion-insensitive PMD monitoring of non-return-to-zero (NRZ) data based on clock power measurement using a narrowband fiber Bragg grating (FBG) notch filter. The clock tone does not appear at the receiver for NRZ data. Using a narrowband FBG notch
filter to filter off one of the optical clock sidebands, the RF clock tone can be recovered from the beating between the carrier and the remaining optical clock sideband. The recovered RF clock power depends on the relative polarization state of the carrier to the optical clock sideband, which is determined by PMD of the transmission link. CD only affects the phase of the recovered RF clock tone but not the amplitude. Therefore, the recovered RF clock power can be used as a PMD monitoring signal, and is insensitive to CD. Using a FBG notch filter with a 10-dB bandwidth of 15 GHz at the receiver, we measured the recovered clock power to monitor PMD in a 10Gb/s NRZ system. The variation of the detected clock power is within 1.5 dB when the accumulated dispersion increases from 0 to 600 ps/nm. For 300 independent samples using the 10 GHz recovered clock as a feedback control signal to a PMD compensator, the 5% worst case value of the power penalty is reduced from 6.0 dB to 1.5 dB.

### 3.2 Clock Power Recovered Using Notch Filter for NRZ Data

Figure 3.1 shows the concept for using a narrowband FBG notch filter to recover the RF clock power and use it for PMD monitoring. Ideally the clock tone does not appear at the receiver for NRZ data. However, using a narrowband FBG notch filter to filter off one of the optical clock sidebands, the RF clock tone can be recovered from the beating between the carrier and the remaining optical clock sideband. The recovered RF clock power depends on the relative state of polarization (SOP) of the carrier to the optical clock sideband. At the transmitter, the optical
carrier and the optical clock sideband have the same SOP. After propagating through the optical fiber link, PMD cause the SOPs of the optical carrier and the optical clock sideband to vary by different amounts. Only the portion of the clock sideband that has the same polarization as the carrier can effectively interfere, so the resulted RF clock power is determined by PMD of the transmission fiber link. On the other hand, CD can only affect the phase of the recovered RF clock tone but not the amplitude. Therefore, the recovered RF clock power can be used as a PMD monitoring signal, and it is insensitive to CD.

Figure 3.1 Concept of PMD monitoring for NRZ data based on the recovered clock using a narrowband FBG notch filter.

Figure 3.2 shows the experimental setup. After propagating through the transmission link, which consists of a single mode fiber (SMF) and a PMD emulator, 1% of the 10 Gb/s NRZ signal is tapped off for PMD monitoring. A FBG notch
filter with a 10-dB bandwidth of 15 GHz is placed in front of a photodetector to filter off the upper optical clock sideband in order to recover the RF clock power. When both CD and DGD are zero, as shown in Figure 3.3, there is no clock power without filter, but the clock is regenerated by 28 dB with the filter in place. Figure 4.4 shows the corresponding optical spectrum.

![Figure 3.2 Experimental setup.](image)

![Figure 3.3 Electrical spectrum: (a) w/o and (b) w/ filter.](image)
We perform both first-order and all-order PMD monitoring. For first-order PMD (DGD), we launch the input signal to a first-order PMD emulator, which consists of a polarization controller (PC) and a piece of polarization maintaining (PM) fiber. The power splitting ratio between the two principle-polarization-states is 0.5. Figure 3.5 shows the simulation and experimental results of the relative recovered RF clock power changing with different DGD value. When we change the length of the SMF from 0 to 35 km. (i.e. the corresponding CD increases from 0 to 600 ps/nm.) The variation of the RF clock is < 1.5 dB.
To investigate all-order PMD monitoring of this technique, we then used a PMD emulator which has 30 sections of PM fiber with polarization controllers distributed between the sections to realize different polarization coupling and therefore emulate both Maxwellian distribution of DGD and higher-order PMD effects [30]. The average DGD of the PMD emulator is 42 ps. We take 300 samples with CD at 0 and 600 ps/nm. As shown in Figure 3.6, the distribution of the relative recovered clock power is essentially unchanged as the CD varies. And the experimental distributions are close to the 10000 samples simulation results.

Figure 3.5 Relative clock power as a function of DGD for different CD.
3.3 PMD Compensation Using the Recovered Clock Power as a Feedback Signal

Using the recovered clock power as a feedback signal, we compensate PMD in the transmission link (with an average DGD of 42 ps) using a PC and a piece of 50-ps PM fiber. The PC is adjusted to maximize the recovered clock. As shown in Figure 3.7, for 300 experimental samples, the 5% worst case of the power penalty distribution tail is reduced from 6 dB to 1.5 dB using this monitoring technique.
3.4 Summary

In this chapter, we propose and demonstrate chromatic-dispersion-insensitive PMD monitoring by using a narrowband FBG notch filter to recover the RF clock power for 10Gb/s NRZ data. Using a FBG notch filter with a 10-dB bandwidth of 15 GHz at the receiver, we measured the recovered clock power to monitor PMD in a 10Gb/s NRZ system. The variation of the detected clock power is within 1.5 dB when the accumulated dispersion increases from 0 to 600 ps/nm. Applying the recovered clock power as a control signal for PMD compensation, for 300 independent samples, the 5% worst case value of the power penalty is reduced from 6.0 dB to 1.5 dB.
Chapter 4

40-GHz RZ and CS-RZ Pulse Generation Using a Phase Modulator and PM Fiber

In this chapter, we demonstrate chirp-free RZ and CS-RZ pulse generation with a repetition rate of 40 GHz using a phase modulator driven by a 20 GHz clock and a single piece of polarization maintaining (PM) fiber.

4.1 Generation of High-Speed RZ and CS-RZ Optical Pulse Train

The generation of a high-speed optical pulse train is critical for many applications, including transmission and signal processing. Specifically, return-to-zero (RZ) modulation formats can be created from pulse trains and have been shown to be robust to fiber-based degrading effects for many high-speed, long-distance systems. This applies to conventional RZ as well as carrier-suppressed RZ (CS-RZ).

The most common method for generating a high-speed optical pulse train for ultimately producing RZ modulated data is to use a Mach-Zehnder intensity modulator that is driven by an electrical clock at the desired data rate (e.g., 40 GHz for a 40-Gbit/s data channel) [31]; note that CS-RZ is produced using an intensity modulator driven at half the bit rate with a different bias [32]. This technique
requires the use of a high-speed modulator and driver for RZ generation and tends to produce pulses that are chirped.

Recently, two methods have been reported for generating a high-speed optical pulse train [33,34], which employs a phase modulator that is driven by a clock at only half the bit rate. The first method [33] used an optical filter after the phase modulator to convert 20-GHz phase modulation into 40-GHz amplitude modulation, but it induces chirp in the optical pulses. The second method [34] used a Mach-Zehnder interferometer after the phase modulator, also translating phase modulation into amplitude modulation, but without any induced chirp. However, the employment of a planar waveguide interferometer adds complexity and cost to the implementation.

We demonstrate a simple technique that generates an RZ and a CS-RZ 40-GHz optical pulse train from a 20-GHz electrical drive clock. We use a phase modulator that is followed by a single piece of polarization-maintaining (PM) fiber. After 20-GHz sinusoidal phase modulation, the light is split equally into the two principal-states-of-polarization (PSPs) of the PM fiber. Differential group delay (DGD) provides a one-bit time shift (25 ps) between the two polarization components of the light. At the output of the PM fiber, due to beating of the two replicas of the light, one polarization, aligned 45° with respect to the PSPs, generates an RZ pulse train, whereas the orthogonal polarization generates a CS-RZ pulse train.
with a repetition rate of 40 GHz. Based on fundamental principles, the generated pulse trains are chirp free. This technique may be cost-effective and seamlessly integrated with optical fiber systems.

### 4.2 Concept of Pulse Generation Using a Phase Modulator and PM Fiber

Figure 4.1 shows a conceptual diagram of RZ and CSRZ pulse generation using a phase modulator and a single piece of PM fiber.

![Conceptual diagram of RZ and CSRZ pulse generation using a phase modulator and PM fiber.](image)

Figure 4.1 Concept of RZ/CSRZ pulse generation using a phase modulator and PM fiber.

For 40 GHz pulse generation, \( f = 40 \ GHz \) and \( T = 1/f = 25 \ ps \). After phase modulation by a 20-GHz (\( f/2 \)) sinusoidal clock tone with a modulation depth (peak to peak) of \( \pi \), the light is aligned at 45° relative to the PSPs of the PM fiber, so that the power splitting ratio between the two principle-polarization-states is 0.5. The light splits equally into the two PSPs of the PM fiber with a DGD of 25 ps. The DGD
makes a one-bit time shift \((T=25\,\text{ps})\) between the two polarization components of the light. The optical fields of these two replicas can be described by the following equations:

\begin{align}
E_1 &= \frac{A}{\sqrt{2}} \cos\left(\frac{\pi}{2} \sin\frac{\pi t}{T} + \omega t\right) \\
E_2 &= \frac{A}{\sqrt{2}} \cos\left[\frac{\pi}{2} \sin\frac{\pi(t-T)}{T} + \omega t\right] = \frac{A}{\sqrt{2}} \cos\left(-\frac{\pi}{2} \sin\frac{\pi t}{T} + \omega t\right) \tag{4.1}
\end{align}

At the output of the PM fiber, after a polarizer aligned at 45° relative to the PSPs, the two replicas of the light beat together, producing the following optical field:

\begin{align}
E_3 &= \frac{E_1 + E_2}{\sqrt{2}} \propto A \cos\left(\frac{\pi}{2} \sin\frac{\pi t}{T}\right) \cos(\omega t) \tag{4.2}
\end{align}

The resulting field has the characteristics of a 40-GHz chirp-free 33% RZ pulse train. With the polarizer aligned to the orthogonal polarization direction (-45° relative to the PSPs), the output optical field can be expressed as:

\begin{align}
E_4 &= \frac{E_1 - E_2}{\sqrt{2}} \propto A \sin\left(\frac{\pi}{2} \sin\frac{\pi t}{T}\right) \sin(\omega t) \tag{4.3}
\end{align}

This field has the characteristics of a 40-GHz chirp-free 67% CS-RZ pulse train. Figure 2 shows the simulation results for waveforms of the generated RZ and CS-RZ pulse trains.
To further prove that the generated pulse trains are chirp free, we simulated 40-Gb/s data transmission using the generated RZ and CS-RZ pulse trains as the 40-GHz pulse train sources. We modulate 40 Gb/s \(2^{23}-1\) PRBS data and transmit it through different lengths of single mode fiber (SMF) with a dispersion of 16 ps/nm/km. Figure 4.3 shows the Q-penalty as a function of dispersion value. For comparison, we also simulated the transmission of 33% theoretical RZ data with a rise time of \(\frac{1}{4}\) bit time. We can see that the generated 33% RZ pulse has quite similar performance to the purely theoretical 33% RZ. The small difference is caused by pulse shape differences between the generated RZ pulse and the theoretical 33% RZ pulse.
4.3 Experimental Setup

The experimental setup is shown in Figure 4.4. The phase modulator is driven by a 20 GHz clock tone. This is followed by a polarization controller (PC) used to align the light to be along the direction of 45° with respect to the PSPs of the PM fiber, which has a DGD of 25 ps. Another PC is used to align the polarization beam splitter (PBS) to also be 45° to the PSPs of the PM fiber. The generated RZ pulse train is obtained at one output port of the PBS and the generated CS-RZ is obtained at the other output port. Note that the PBS is only used here as a polarizer in order to observe the generated pulse trains in the experiment. In a real application, a LiNbO₃ intensity modulator, following the pulse generator, can perform this
function while simultaneously modulating data onto the pulse train. And both of the PCs could be eliminated by 45° splicing the PM fiber.

![Diagram of experimental setup](image)

Figure 4.4 Experimental setup for 40G RZ/CS-RZ pulse train generation

### 4.4 Results and discussion

Figure 4.5 shows the optical spectrum of the generated RZ and CS-RZ pulse trains. We can see that the unwanted 20 GHz tone in the spectrum of the RZ pulse train is suppressed by more than 20 dB, while the optical carrier is suppressed by more than 30 dB in the spectrum of the CS-RZ pulse train. The residual 20 GHz clock components may be caused by misalignment of the PM fiber.
Figure 4.5. Optical spectrum of pulse trains:
(a) RZ and (b) CS-RZ.

Figure 4.6 shows the waveforms of the generated RZ and CS-RZ pulse trains observed by a 40G photodiode. The observed waveforms are not identical to the simulation results in Figure 2 due to the bandwidth limitation of the photodiode.

Figure 4.6. Waveforms of pulse trains:
(a) RZ and (b) CS-RZ.
Note that a similar scheme with PM fiber can replace one-bit-delay interferometer at the receiver as a decoder for an optical DPSK transmission system.

4.5 Summary

In this chapter, we demonstrate a simple technique that generates an chirp-free RZ and a CS-RZ 40-GHz optical pulse train from a 20-GHz electrical drive clock. We use a phase modulator that is followed by a single piece of polarization-maintaining (PM) fiber as a one-bit delay interferometer. The unwanted 20 GHz tone in the spectrum of the pulse train is suppressed by more than 20 dB.
In this chapter, we extend our work in the last chapter to demonstrate chirp-free CS-RZ pulse generation with a repetition rate of 160 GHz, which is four-fold of the frequency of the electrical clock.

5.1 Generation of High-Speed Optical Pulse Train beyond 40 GHz

An ever-growing fraction of the research-and-development community in optical communications is performing experiments at speeds higher than 40-Gbit/s. An invaluable element for any ultra-high-speed system is a pulse-train generator at the data clock speed or bit rate. Such a generator can be used as an optical clock, for optical sampling, or to imprint optical data bits. Presently, the ready availability of a low-cost high-speed pulse train has been elusive.

There are various methods that can generate high-speed pulse trains. The most common method is to use an actively-mode-locked laser, either by mode-locking at a very high rate (i.e., 140 GHz) [35] or by passively splitting/delaying/multiplexing a very-short-pulse train [36]. In general, mode-
locked lasers are not considered low-cost elements. Other published methods include: tunable-rate pulse generation using a specially designed dual-wavelength DFB laser diodes [37]; the rate multiplication process through the temporal fractional Talbot effect of chirped pulses[38]; and spectral selection by arrayed waveguide gratings [39], where each burst of pulses lies at different wavelength; using spectral selection by a Fabry-Perot (FP) optical filter to multiply 10 GHz pulse train to 40 GHz, which needs either high finesse or additional components such as semiconductor optical amplifiers [40].

In last chapter, we have demonstrated the technique that generates chirp-free return-to-zero (RZ) and carrier-suppressed RZ (CS-RZ) optical pulse trains at a repetition rate that is double the frequency of the electrical clock. In that method, a phase modulator and polarization-maintaining (PM) fiber are used in a single-stage subsystem to double 20-GHz phase modulation to 40-GHz pulse trains.

In this chapter, we significantly extend our previous work to demonstrate 160-GHz chirp-free pulse generation at a repetition rate which is four-fold of the frequency of the electrical clock. To achieve this, we use a two-stage subsystem that uses a 40-GHz phase modulator plus two low-cost PM fibers and two polarizers. The mechanism for the four-fold increase in the two stages is as follows: an 80-GHz optical pulse train is generated by constructive beating of a 40-GHz phase modulated light at the first stage, then it is split equally into the two principal-states-of-
polarization (PSPs) of the PM fiber at the second stage. Differential group delay (DGD) provides a one-bit-time shift (6.25 ps) between the two polarization components of the light. At the output of the PM fiber, due to the destructive beating of the two replicas of the light, one polarization, aligned -45° with respect to the PSPs, generates a 50% CS-RZ pulse train with a repetition rate of 160 GHz. The unwanted low frequency tones are suppressed by more than 15 dB, and the measured pulse width is 3.3 ps. Again, we emphasize that our method has the potential to be a cost-effective source of high-speed optical pulses, which can be seamlessly integrated with optical fiber systems.

### 5.2 Concept of Pulse Generation with a Four Fold Repetition Rate

Figure 5.1 shows a conceptual diagram of an optical CS-RZ pulse generation at a repetition rate which is four-times of the frequency of the electrical clock using a phase modulator and two PM fibers and two polarizers.
Figure 5.1 Concept of CS-RZ pulse generation with a four fold repetition rate using a phase modulator and PM fiber.

Figure 5.2 shows details of the first and second stage of PM fiber in the setup.
Figure 5.2 Details of (a) the first and (b) the second stage of PM fiber in the setup.

For 160-GHz pulse generation, \( f=160 \text{ GHz} \) and \( T=1/f=6.25 \text{ ps} \). After phase modulation by a 40-GHz \((f/4)\) sinusoidal clock tone with a modulation depth (peak to peak) of \( \pi \), at the first stage, the light is aligned at 45° relative to the PSPs of the first PM fiber, so that the power splitting ratio between the two principle-polarization states is 0.5. The light splits equally into the two PSPs of the PM fiber with a DGD of 2T \((2T=12.5 \text{ ps})\). The DGD makes a two-bit time \((2T)\) shift between the two polarization components of the light. Similar to Chapter 4, the optical fields of these two replicas can be described by the following equations:

\[
E_1 = \frac{A}{\sqrt{2}} \cos\left(\frac{\pi}{2} \sin\frac{\pi t}{2T} + \omega t\right);
\]

\[
E_2 = \frac{A}{\sqrt{2}} \cos\left[\frac{\pi}{2} \sin\frac{\pi (t-2T)}{2T} + \omega t\right] = \frac{A}{\sqrt{2}} \cos\left(-\frac{\pi}{2} \sin\frac{\pi t}{2T} + \omega t\right) \tag{5.1}
\]

At the output of the PM fiber, after a polarizer aligned at 45° relative to the PSPs, the two replicas of the light beat together, producing the following optical field:

\[
E_3 = \frac{E_1 + E_2}{\sqrt{2}} \approx A \cos\left(\frac{\pi}{2} \sin\frac{\pi t}{2T}\right) \cos(\omega t) \tag{5.2}
\]
The resulting field has the characteristics of an 80-GHz chirp-free 33% RZ pulse train. Note that if the polarizer aligned to the orthogonal polarization direction (-45° relative to the PSPs), the output optical is an 80-GHz chirp-free 67% CS-RZ pulse train.

In the second stage, the 80-GHz RZ pulse train is again aligned at 45° relative to the PSPs of the second PM fiber, so that split equally into the two PSPs of the PM fiber with a DGD of $T (T=6.25 \text{ ps})$. The DGD makes a one-bit time ($T$) shift between the two polarization components of the light. At the output of the PM fiber, after a polarizer aligned at -45° relative to the PSPs, the two replicas of the light destructively interfere with each other, producing the following optical field:

$$E_4 = f(t) \propto A \left[ \cos\left(\frac{\pi}{2} \sin\left(\frac{\pi}{2T}\right)\right) - \cos\left(\frac{\pi}{2} \cos\left(\frac{\pi}{2T}\right)\right) \right] \cos(\omega t)$$

(5.3)

Which is a 160-GHz 50% CS-RZ pulse train with a period of $T (T=6.25 \text{ ps})$. And it is **chirp free** as we can see from the equation. Figure 5.3 shows the waveform simulation results of the generated 80-GHZ 33% RZ and 160-GHz CS-RZ pulse trains.
Figure 5.3 Simulation results for waveforms of pulse trains: (a) 80-GHz 33% RZ and (b) 160-GHz 50% CS-RZ.

5.3 Experimental Setup
The experimental setup is shown in Figure 5.4. The phase modulator is driven by a clock tone with a frequency of $f/4$. This is followed by a polarization controller (PC) used to align the light to be along the direction of 45° with respect to the PSPs of the PM fiber, which has a DGD of 2T. Another PC is used to align the polarization beam splitter (PBS) to also be 45° to the PSPs of the PM fiber. The generated RZ pulse train with a repetition rate of $f/2$ is obtained at one output port of the PBS. After the first stage, another PC is used to align the generated $f/2$ optical RZ pulse train to be 45° to the PSPs of the PM fiber, and another PC is used to align the polarizer to be -45° to the PSPs of the second PM fiber. The generated CSRZ pulse train with a repetition rate of $f$ is obtained after the polarizer. Note that in a real application, all the PCs could be eliminated by 45° splicing the PM fiber.

![Figure 5.4 Experimental setup for 160G CR-RZ pulse train generation](image)

### 5.4 Results and discussion

As proof of four-fold frequency multiplication effect in our technique, first we demonstrate 40-GHz CS-RZ ($f=40 \ \text{GHz}$) pulse generation by providing a 10-GHz clock to the phase modulator and using DGD value of 50 ps and 25 ps for the
two PM fibers respectively. Figure 5.5(a) shows the optical spectrum of the generated 40-GHz RZ pulse trains. We can see that the unwanted lower tones (10 & 20 GHz) in the spectrum are suppressed by about 23 dB, Figure 5.5(b) shows the waveform of the generated pulse trains observed by a 40G photodiode.

![Figure 5.5 Generated 40G CS-RZ pulse trains: (a) Optical spectrum and (b) waveform](image)

Then we demonstrate 160 GHz ($f=160 \text{GHz}$) pulse generation by modulating the phase using a 40-GHz clock and replacing the two PM fibers in the setup with DGD values of 12.5 ps (2T) and 6.25 ps (T) respectively.

Figure 5.6 (a) shows the optical spectrum of the 80-GHz 33% RZ pulse train at the output of the first stage, and we can see that the unwanted 40GHz tone in the spectrum of the RZ pulse train is suppressed by about 17 dB. We also measure its pulse width by using an autocorrelator with a scale factor of 7.41 ps/ms, and the
result is shown in Figure 5.5(b). By using the pulse shape factor of 0.71, we get measured pulse width of 4.5 ps, which is close to theoretical value of 4.16 ps.

Figure 5.6 Generated 80G RZ pulse trains at the first stage: (a) optical spectrum and (b) autocorrelator measurement.

Then we measure the properties of the 160-GHz 50% CSRZ pulse train at the output of second stage. Figure 6(a) shows its optical spectrum: the unwanted lower tones (40 & 80 GHz) are suppressed by about 15 dB. The residual lower clock components may be caused by misalignment of the PM fibers. Figure 6(b) shows the pulse width measurement result obtained using the autocorrelator. By using the pulse shape factor of 0.75, we get measured pulse width of 3.3 ps, which is also close to theoretical value of 3.12 ps.
Figure 5.6 Generated 160G CS-RZ pulse trains at the second stage: (a) optical spectrum and (b) autocorrelator measurement.

5.5 Summary

In this chapter, we demonstrate chirp-free CS-RZ pulse generation with a repetition rate of 160 GHz using a phase modulator driven by a 40 GHz clock and two low-cost polarization-maintaining fibers. The unwanted low frequency tones are suppressed by more than 15 dB. The measured pulse width is 3.3 ps.
Chapter 6
Polarization-Insensitive All-Optical Wavelength Conversion Using Dispersion-Shifted Fiber with a Fiber Bragg Grating and a Faraday Rotator Mirror

In this chapter, we demonstrate a simple technique for polarization-insensitive all-optical wavelength conversion based on four-wave mixing in dispersion-shifted fiber (DSF) with a fiber Bragg grating and a Faraday rotator mirror.

6.1 Four-Wave Mixing Wavelength Conversion and PolarizationInsensitive Operation

In high-speed wavelength-division multiplexed (WDM) optical networks, wavelength conversion is an important function for translating data carried on one wavelength to another, to reduce wavelength blocking and provide more flexibility in network management [41]. All-optical wavelength conversion based on four wave mixing (FWM) in optical fibers has the following potential advantages: (i) it eliminates optical-electrical-optical (O/E/O) conversion and thus enables transparent all-optical networks, (ii) it is ultra-fast and transparent to both modulation format and
bit rate, (iii) it induces negligible signal degradation since there is little chirp or added noise, and (iv) the optical fiber itself is low cost, low loss, and seamlessly compatible with the transmission fiber. However, FWM in fiber strongly depends (i.e., >20 dB) on the relative state-of-polarization (SOP) of the signal relative to the pump. Therefore, polarization-insensitive operation is essential for any future application of fiber FWM-based wavelength conversion since there is generally no control of the signal’s polarization in real optical networks.

There are several techniques reported for polarization-insensitive FWM wavelength conversion in fiber: (i) a polarization diversity method using a fiber loop with a beam splitter which requires an in-line tunable polarization controller [42], (ii) a scheme using non-degenerate FWM operation that requires two orthogonal pumps of different wavelengths [43], and (iii) a method using a pump composed of cross-polarized high frequency pulses in which the pump is modulated at speeds much higher than the data rate [44]. There are also reports using Faraday rotator mirrors (FRM) for polarization-insensitive phase conjugation in fiber [45] and wavelength conversion in periodically poled lithium niobate (PPLN) waveguide [46]. However, a high-speed wavelength conversion using fiber with an FRM has yet to be studied.

We demonstrate a simple technique to minimize polarization sensitivity in a fiber-based FWM wavelength converter using a fiber Bragg grating (FBG) and an FRM. The FBG is set to reflect only the pump wavelength without changing its
polarization state and pass the signal wavelength to the FRM, which rotates the signal’s polarization state by 90°. Both the pump and the signal make a dual pass through dispersion-shifted fiber (DSF). However, the rotation of the signal polarization on the return pass guarantees that both orthogonal polarization components of the incoming signal wave will efficiently mix with the pump to produce a polarization-insensitive wavelength-converted output. We experimentally demonstrate that the residual polarization sensitivity is reduced from >22 dB to 2 dB with 4 km of DSF. The power penalty incurred in wavelength conversion is less than 1 dB for a 20-nm conversion distance, and the difference in power penalty for different polarization states is less than 0.3 dB. Theoretically, this technique will have negligible polarization sensitivity when the propagation loss of the pump through the DSF approaches 0.

6.2 Concept of Polarization-Insensitive Technique Using an FBG and an FRM

Figure 6.1 shows the concept of the technique for polarization-insensitive FWM wavelength conversion using an FBG and an FRM. The FBG is designed to only reflect the pump wavelength without changing its polarization state; the signal wavelength is outside the reflection band of the FBG and passes through to the FRM, where the signal is reflected and the wave’s polarization state is rotated by 90°. Both the pump and the signal make a dual pass through the DSF. Only the polarization component of the signal wave that is the same as the polarization state of the pump
contributes to wavelength conversion during a single-pass through the DSF. However, the rotation of the signal polarization on the return pass guarantees that both orthogonal polarization components of the incoming signal will efficiently mix with the pump during either the forward pass or backward pass through the DSF. Thus the wavelength-converted output will be polarization-insensitive. Note that this method can extend to multi-channel wavelength conversions, since it does not require controlling the polarization state of each input signal channel.

![Figure 6.1 Concept for polarization-insensitive FWM wavelength conversion.](image)

**6.3 Experimental Setup**

The experimental setup is shown in Figure 6.2. The polarization controller (PC) aligns the pump light to be linearly polarized when incident on the FBG, so that the polarization sensitivity of the wavelength converter is minimum. The FBG has a
reflectivity of 99.5% at the pump wavelength with a bandwidth of 0.5 nm. Both the signal at \( \lambda_s \) and the pump at \( \lambda_p \) are coupled into the circulator. After a dual pass through the DSF, the converted wave, \( \lambda_c \), is produced at a wavelength \( \lambda_c \) \((1/\lambda_c=2/\lambda_p-1/\lambda_s)\). After the output of the circulator, an optical filter separates the converted wave, \( \lambda_c \), from the other wavelengths. The polarization dependent loss (PDL) of the DSF, FBG, FRM and circulator is negligible. The polarization mode dispersion (PMD) of the DSF is less than 1 ps. The nonlinear coefficient \( \gamma \) of the DSF is 2.6/w/km. The zero dispersion wavelength of the DSF is 1553.8 nm, and the dispersion slope is 0.07 ps/nm\(^2\)/km.

Figure 6.2 Experimental setup for polarization-insensitive FWM wavelength conversion.

### 6.4 Results and discussion

For a conventional single-pass scheme (without the FBG and FRM), the conversion efficiency is highest when the polarization state of the signal is the same as the polarization state of the pump. However, when the polarization state of the signal is orthogonal to the polarization state of the pump, there is no converted wave,
resulting in large (>20 dB) polarization sensitivity. For our dual pass scheme with the FBG and FRM, the theoretical polarization sensitivity equals twice the loss of the pump while passing forward through the DSF. Figure 6.3 shows both our experimental and simulation results for the residual polarization sensitivity of the dual pass system. The simulation results come from the calculation of a MATLAB program under phase-matched conditions, without considering Rayleigh, Raman and Brillouin scattering effects. We use 2 km, 4 km and then 10 km DSF in our setup. The losses of the pump while passing forward through the DSF are 0.6 dB, 1.0 dB, and 2.3 dB respectively, and the corresponding measured polarization sensitivities are 1.2 dB, 2.0 dB, and 4.7 dB respectively, which are consistent with the simulation results. Theoretically, our technique will have negligible polarization sensitivity when the propagation loss of the pump through the DSF is low. For example, for 100 m of highly nonlinear DSF [47], the propagation loss of the pump through the fiber is 0.05 dB, so the corresponding polarization sensitivity would be 0.1 dB.
Figure 6.3. Polarization sensitivity of the dual pass system vs. the loss of the pump while passing forward through the DSF.

In our experiment for the 4 km DSF, the pump is tuned to the zero dispersion wavelength of the DSF (1553.8 nm). Figure 6.4 shows the power of the converted wave at the output of the circulator as a function of the power of the input pump and signal wave, for both up and down conversion, when the polarization state of the input signal is aligned to the polarization state of the pump. The insert picture is the spectrum of wavelength conversion at the output of the circulator. We can see that the power of the converted wave is proportional to the square of the power of the pump wave, and proportional to the power of the signal wave, which is consistent with the theory.
Figure 6.4. (a) Power of the converted wave vs. pump wave when power of signal wave=6 dBm. (b) Power of the converted wave vs. signal wave when power of pump wave=8 dBm.

Figure 6.5 shows the dependence of conversion efficiency (the power of the converted wave at the output of the circulator divided by the power of the input signal wave) on the wavelength conversion distance (the distance between the wavelength of the converted wave and the signal wave), when the pump power is 8 dBm. Conversion efficiency is about –22 dB for up to a 20-nm conversion distance and is symmetric for up conversion and down conversion, for both continuous wave and 10 Gb/s data signals.
Figure 6.5. Conversion efficiency vs. conversion distance.

Figure 6.6 shows both simulation and experimental results of polarization sensitivity of the 4 km DSF, for both single and dual pass configurations. By placing a half-wave plate right after the input signal and rotating it from 0° to 90°, we varied the angle between the polarization state of the signal and the pump from 0° to 180°. The polarization sensitivity for a single pass was larger than 22 dB. For dual pass, the conversion efficiency changed by 2 dB when the angle between the polarization state of the signal and the pump changed from 0° to 90°, then returned to the original value when the angle changed from 90° to 180°, in a manner consistent with the simulation results. The 2 dB residual polarization sensitivity in our experimental setup was due to the 1 dB pump propagation loss through the DSF.
To determine the power penalty induced by wavelength conversion, 10 Gb/s $(2^{23}-1)$ PRBS non-return-to-zero (NRZ) data was modulated onto the signal wave. BER measurements were performed for both the original signal wave and the converted wave. The power penalty for the converted signal compared to the original signal is measured at $10^{-9}$ BER. Figure 6.7 shows that, within a 20-nm wavelength conversion distance, for both up conversion and down conversion, the power penalty induced by wavelength conversion is less than 1 dB. For the best polarization state (when the polarization state of the input signal is the same as the

---

**Angle between pump and signal polarization states (degrees)**

Figure 6.6. Experimental polarization sensitivity for up conversion (top) and down conversion (bottom), both single pass and dual pass.
pump) and the worst polarization state (the polarization state of the input signal is orthogonal to that of the pump), the power penalty difference is less than 0.3 dB.

**Power Penalty (dB)**

![Graph showing Power Penalty (dB) vs Conversion Distance](image)

**Conversion Distance $\lambda_c - \lambda_s$ (nm)**

Figure 6.7. Power penalty induced by wavelength conversion at BER = $10^{-9}$.

A key disadvantage of fiber-based wavelength converters is that the pump must be located close to the zero dispersion wavelength. In conventional fiber, which has a large dispersion slope, the pump wavelength can only be tuned by <1 nm, thereby making this a fixed wavelength converter. However, in order to make a tunable wavelength converter, non-conventional fiber with a reduced dispersion slope could be used to create a reasonably-wide tuning range (>8 nm) [48]. Our polarization-insensitive technique using a widely tunable FBG [49] could be applied to such a scheme.
6.5 Summary

In this chapter, we demonstrate a simple technique for polarization-insensitive fiber four-wave mixing wavelength conversion using a fiber Bragg grating and a Faraday rotator mirror. We experimentally demonstrate that the residual polarization sensitivity is reduced from more than 22 dB to 2 dB with 4 km of DSF. For 10 Gbit/s NRZ data, the power penalty incurred in wavelength conversion is less than 1 dB for a 20-nm conversion distance, and the difference in power penalty for different polarization states is less than 0.3 dB.
Chapter 7

Width-Tunable Optical RZ Pulse Train Generation Based on Four-Wave Mixing in Highly-Nonlinear Fiber

In this chapter, we demonstrate a simple technique for width-tunable optical RZ pulse train generation based on four-wave mixing in highly-nonlinear fiber. By electrically tuning the delay between two pump pulse trains, the pulse-width of a generated pulse train is continuously tuned.

7.1 Width-Tunable Optical Pulse Generation

Narrow optical return-to-zero (RZ) pulse trains have many applications in optical communications including: RZ data transmission, soliton systems, optical packet switching network signaling, all-optical switching, and various optical-signal-processing techniques [50-55]. Achieving maximum performance in nearly all optical systems can depend critically on matching the optical pulse width to the optimal overall system parameters. A laudable goal is the ability at the transmitter to tune the pulse width in order to optimize system performance.
Perhaps the best illustration of the importance of tunable pulse-width generation is the use of RZ pulses for long-distance transmission. There are many scenarios for which RZ pulses with different pulse-widths are more robust to various fiber-based degradations, such as nonlinearity and polarization-mode-dispersion (PMD). Previous reports have shown that the performance of a link can vary significantly depending on the pulse width, even for small changes in fiber characteristics and small difference of pulse width [50-54]. For example, when changing a pulse width from 50 to 35 ps in a 10-Gbit/s system, the achievable transmission distance could change from 600 km to 2000 km [54]. Other applications for a pulse-width tunable pulse train include optical time division multiplexing (OTDM), all-optical 3R and optical sampling [55].

In previous published work [54], width-tunable pulse trains have been accomplished by adjusting both the chirp applied to the pulse and the dispersion value of a tunable dispersive element. This method needs to overdrive the phase modulator to provide sufficient chirp, which is difficult at higher (~ 40 Gb/s) bit-rates. Furthermore, any non-ideal property of the tunable dispersion element, such as group velocity dispersion ripple and non-uniform transmission spectrum, will affect the quality of the tunable pulses, limiting the system performance.

We demonstrate width-tunable optical pulse generation based on four-wave mixing (FWM) in highly-nonlinear fiber (HNLF). The technique involves: (i)
generating two parallel optical pulse trains on different wavelengths, (ii) combining them in a fiber to generate FWM, and (iii) varying the delay between the two pulse trains. Due to FWM, a product term will be generated that is a stream of optical pulses whose width is determined by the overlap time between the two original pulses. Moreover, the fiber nonlinearity compresses the pulse-width in the generated pulse train [56,57]. In our experiment, by electrically tuning the delay, the full width of half maximum (FWHM) of a 5G pulse train is tuned continuously from 85 ps to 25 ps, and the FWHM of a 10G pulse train is tuned continuously from 33 ps to 18 ps. And the simulation results show that the FWHM of a 40G pulse train can be tuned continuously from 10.6 ps to 2.9 ps. A transmission experiment is performed to examine the quality of the generated tunable pulses. Negligible power penalty is observed after transmission through 59-km of single mode fiber (SMF) and 11.4-km dispersion compensation fiber (DCF) for different pulse widths at 10-Gb/s.

### 7.2 Concept of Width-Tunable Pulse Generation Based on FWM in HNLF

A conceptual diagram of our technique for width-tunable pulse generation based on FWM in HNLF is shown in Figure 7.1. Two RZ pulse trains with fixed pulse-width of $T$ at wavelengths $\lambda_1$ and $\lambda_2$ are launched into an HNLF. The delay between the two pulse trains is $\tau$. Due to FWM in HNLF, a new pulse train is generated at a wavelength of $\lambda_3$ ($1/\lambda_3 = 2/\lambda_2 - 1/\lambda_1$). Since FWM is an ultra-fast
process, and the new pulse at $\lambda_3$ can be generated only when the pulses at $\lambda_1$ and $\lambda_2$ are both present (overlapping each other in the time domain), the pulse-width of the generated pulse is approximately $T-\tau$. Therefore, because $\tau$ can be tuned continuously, the pulse-width of the generated pulse at $\lambda_3$ can also be tuned continuously.

Figure 7.1 Concept of width-tunable pulse generation based on four-wave mixing in HNLF: the pulse-width of the generated pulse at $\lambda_3$ can be tuned continuously by tuning $\tau$.

7.3 Experimental Setup

Figure 7.2 shows the experimental setup. The wavelength of laser 1 ($\lambda_1$) is 1548 nm, and the wavelength of laser 2 ($\lambda_2$) is set at 1552 nm, which is the zero-dispersion wavelength of the HNLF. We first generate chirp-free pulse trains at both
λ₁ and λ₂ by externally modulating an RF clock using LiNbO₃ modulators to both of the wavelengths. The delay between the two pulse trains can be tuned continuously by tuning the electrical delay τ between the RF clock sent to modulator 1 and the clock sent to modulator 2. Both λ₁ and λ₂ are amplified by an EDFA followed by a bandpass filter with a 3-dB bandwidth of 0.7 nm, then coupled into 1km of dispersion-shifted HNLF, with a non-linear coefficient of 9.1W⁻¹km⁻¹ and a fiber loss of 0.45 dB/km.

A polarization controller (PC) is used to align the polarization states of λ₁ to λ₂ to achieve the highest FWM efficiency. After propagation through the HNLF, a new pulse train is generated at the wavelength λ₃ = 1556 nm. An optical filter with a bandwidth of 1 nm separates λ₃ from the residual signals. A 40G photo detector and a 50G oscilloscope are used after the optical filter to capture the waveforms of the generated pulse train. By electrically tuning the delay, we continuously tune the pulse-width of the generated pulse train at λ₃. This experiment was demonstrated at both 5 and 10 GHz clock rates.
7.4 Results and discussion

The peak powers of $\lambda_1$ and $\lambda_2$ launched into the HNLF are both approximately 10 dBm. The optical peak power of the output of the HNLF at $\lambda_3$ is approximately -5 dBm. When the frequency of the RF clock is 5 GHz, the FWHM of the 5G input pulse trains at both $\lambda_1$ and $\lambda_2$ is 98 ps, with a rise time of 27 ps. As shown in Figure 7.3, by electrically tuning the delay $\tau$ from 0 to 80 ps, the FWHM of the generated 5G pulse train at the output $\lambda_3$ is continuously tuned from 85 ps to 25 ps. When the frequency of the RF clock is 10 GHz, the FWHM of the 10G input pulse trains at both $\lambda_1$ and $\lambda_2$ is 44 ps, with a rise time of 18 ps. By tuning the delay $\tau$ from 0 to 40 ps, the FWHM of the generated 10G pulse train at the output $\lambda_3$ is continuously tuned from 33 ps to 18 ps. The experimental results are consistent with the simulation results for both 5G and 10G data rates. We also simulate our system.
at 40G data rates by setting the FWHM and the rise time for the input 40G pulse train to $\frac{1}{2}$ and $\frac{1}{8}$ of the bit time, respectively. Simulation results show that the FWHM of the generated 40G pulse train can be continuously tuned from 10.6 ps to 2.9 ps by tuning the delay, $\tau$ from 0 to 9 ps.

Figure 7.3 The FWHM of generated pulse train vs. the delay $\tau$ at different repetition rates.

Figure 7.4(a) shows three examples of waveforms generated from a 5G pulse train with FWHMs of 30 ps, 50 ps and 80 ps. Figure 7.4(b) shows three examples
of waveforms generated from a 10G pulse train with FWHMs of 20 ps, 25 ps and 30 ps. Figure 7.5(a) shows the optical spectrum at the output of the HNLF and Figure 7.5(b) shows the details of the optical spectrum of the 10G generated 25-ps pulse train, with a resolution of 0.01 nm.
Figure 7.4 Waveforms of the generated pulse train: (a) 5G; (b) 10G.
Figure 7.5 Optical spectrum (a) at the output of HNLF; (b) of 10G generated 25-ps pulse train.
From both the experimental and simulation results, we conclude that the maximum FWHM of the generated pulse train at $\lambda_3$ is about 80% of the FWHM of the input pulse train. This can be attributed to the nonlinear compression effect of the pulse shape during FWM. Note that if the rise and fall times are faster, the FWHM of the generated pulses can be greater than 80% of the input pulses. The minimum FWHM of the generated pulse train is limited by the rise time of the input pulses. As stated previously, the pulse-width between these maximum and minimum FWHMs can be changed linearly by electrically adjusting the delay, $\tau$.

Using this width-tunable pulse generation as a 10G pulse train source, we modulate 10G ($2^{23}-1$) PRBS data and transmit it through transmission links with a 0-dBm launched power. The receiver is thermal-noise limited. First we compare the performance of 25-ps pulse signal with that of a regular pure 50% RZ signal through different lengths of single mode fiber (SMF) without dispersion compensation. As shown in Figure 7.6, the induced power penalties follow the same trend, which means the generated pulse train has negligible chirp. For the same transmission distance, the power penalty difference between 25-ps and 50-ps RZ signals is mainly caused by the differences of pulse widths and profiles.
We also transmit different pulse-width signals through 59 km of SMF and 11.4 km of DCF, with a zero residual chromatic dispersion. Figure 7.7 shows the BER measurement results for 25-ps pulse-width signal. We can see that there is a negligible power penalty after transmission. Similarly, the power penalties for other pulse-width signals are also negligible. Therefore, the generated pulse train is suitable for high speed transmission.
7.5 Summary

In this chapter, we demonstrate a simple technique for width-tunable optical RZ pulse train generation based on four-wave mixing in highly-nonlinear fiber. By electrically tuning the delay between two pump pulse trains, the pulse-width of a generated pulse train is continuously tuned. In our experiment, the FWHM of a 5G pulse train is tuned from 85 ps to 25 ps, and the FWHM of a 10G pulse train is tuned from 33 ps to 18 ps. And the simulation results show that the FWHM of a 40G pulse train can be tuned continuously from 10.6 ps to 2.9 ps. Negligible power penalty is
observed after 59-km SMF and 11.4-km DCF transmission for different pulse widths at 10-Gb/s.
Chapter 8

All-Optical XOR Gate Using Polarization Rotation in Single Highly–Nonlinear Fiber

In this chapter, we demonstrate a high-speed all-optical XOR gate based on polarization rotation induced by Kerr effect in a single highly–nonlinear fiber.

8.1 All-Optical XOR Gate

Future high-speed optical communication networks, especially packet-switched networks, may rely on the processing of signals completely in the optical domain. Such processing could occur either: (i) in the data plane, such as for header replacement, so that no optical-to-electronic conversion is necessary, or (ii) in the control plane, such as for determining correlation, destination and contention resolution, so that high-speed resolution can be achieved. A key building block in many areas of optical signal processing is the XOR logic gate. The XOR logic gate is a commonly used device in half adders, pattern recognition circuits, ultrahigh speed pattern generation, data encoding and encryption circuits [58-61].

Previous reported techniques for achieving the all-optical XOR function include: (i) fiber based interferometers [60,61], which may be limited by instability
unless special design is applied; (ii) utilization of integrated Mach-Zehnder interferometers based on semiconductor optical amplifiers (SOAs) [62-64], and using cross-polarization modulation in SOAs [65] which results in different bits on different wavelengths at the output. Due to the carrier dynamic in the SOAs, SOA based techniques may suffer from additional noise and speed limitations (unless special high-speed SOAs are used [63]), and some of the techniques require more than one SOA to achieve the XOR function.

In this chapter we demonstrate a 10 Gbit/s all-optical XOR gate using polarization rotation induced by the Kerr effect in a single 2-km highly–nonlinear fiber (HNLF). Due to the Kerr effect, two different input light waves at $\lambda_1$ and $\lambda_2$ induce birefringence in the HNLF, thereby rotating the polarization state of a third light wave at $\lambda_3$. The resulting amount of induced birefringence is determined by the on/off state of the two input waves. The resulting output at $\lambda_3$ after a polarizer represents the XOR operation of the two input signals. We are able to obtain an on-off extinction ratio at the output of our all-optical XOR gate of 25 dB using a 2 km spool of HNLF with a non-linear coefficient of $9.1 \text{ W}^{-1}\text{km}^{-1}$. The results can be further improved through the use of fiber with a higher non-linear coefficient. Since nonlinear effects in fiber are ultra-fast, the ultimate speed limitation of our proposed XOR gate is above 100 Gbit/s.
8.2 Concept of All-Optical XOR Gate Using Polarization Rotation in Single Highly–Nonlinear Fiber

A conceptual diagram of our XOR generation technique is shown in Figure 8.1. At the input of the HNLF the polarization states of the input waves at $\lambda_1$ and $\lambda_2$ are orthogonal to each other. Both of these inputs are aligned 45° with respect to the third "dummy" continuous wave (CW) signal at $\lambda_3$. A polarizer is placed at the output of the HNLF, aligned orthogonal to the original polarization state of $\lambda_3$. When both $\lambda_1$ and $\lambda_2$ are off, there is no output at $\lambda_3$ after the polarizer. When only the input signal at $\lambda_1$ is present, the Kerr effect creates a difference in optical index between the polarization direction aligned with $\lambda_1$ and the direction orthogonal to $\lambda_1$ (i.e., the polarization direction of $\lambda_2$). In this condition, the polarization state of $\lambda_3$ will rotate due to the birefringence induced by the presence of $\lambda_1$. Since the output at $\lambda_3$ is no longer orthogonal to the polarizer, a portion of the signal will pass through and an output at $\lambda_3$ will be present after the polarizer. Similarly, when only the input signal at $\lambda_2$ is present, $\lambda_3$ will experience a polarization rotation and an output at $\lambda_3$ will be present after the polarizer. However, when both input signals at $\lambda_1$ and $\lambda_2$ are present, the birefringence induced by $\lambda_1$ and $\lambda_2$ will cancel, resulting in a net zero rotation of the polarization state of $\lambda_3$. In this situation, the polarization state of $\lambda_3$ at the output of the fiber will be orthogonal to the polarizer and no signal at $\lambda_3$ will be present at the output of the polarizer.
Based on the four above-mentioned situations, the polarizer output at $\lambda_3$ is the XOR operation of the input signals at $\lambda_1$ and $\lambda_2$ (see logic table in Figure 8.1). It is worth noting that the Kerr effect is insensitive to the wavelengths chosen for $\lambda_1$, $\lambda_2$ and $\lambda_3$, as long as the three wavelengths are located within a small dispersion range. Furthermore, walk-off effects can be controlled by limiting the length of the HNLF.

![Figure 8.1](image)

Figure 8.1 Concept for all-optical XOR gate based on Kerr effect in a single highly–nonlinear fiber.

Figure 8.2 shows simulation results obtained using the VPI software modeling tool. The 2 km HNLF used in the simulation has a non-linear coefficient of 9.1 $W^{-1}km^{-1}$, with a zero dispersion wavelength at 1552 nm. The optical power of both inputs is approximately 16 dBm, with $\lambda_1$ and $\lambda_2$ having wavelengths of 1548 and 1550 nm, respectively. The input power of $\lambda_3$ is approximately 3 dBm at a wavelength of 1554 nm. Input data patterns at 10 Gbit/s are shown (10100100 at $\lambda_1$ and 10000111 at $\lambda_2$), along with the resulting output pattern at $\lambda_3$ after the polarizer.
The resulting output represents the XOR operation of the two input data streams. Similar simulation results were also obtained at 40 Gbit/s date rate.

![Simulation results of the output pattern at λ₃ with the input patterns at λ₁ and λ₂ at 10 Gbit/s.](image)

Figure 8.2 Simulation results of the output pattern at λ₃ with the input patterns at λ₁ and λ₂ at 10 Gbit/s.

### 8.3 Experimental Setup

Figure 8.3 shows the experimental setup of our all-optical XOR Gate. The wavelengths of laser 1 (λ₁) and laser 2 (λ₂) are 1548 nm and 1550 nm, respectively and the dummy wavelength λ₃ is 1554 nm. The input signals λ₁ and λ₂ are combined through a PBS, the output of which is coupled with λ₃ by a 90:10 coupler into 2 km of HNLF. The HNLF has a non-linear coefficient of 9.1 W⁻¹km⁻¹ and a fiber loss of
0.45 dB/km, with a zero dispersion wavelength at 1552 nm. The polarization-mode dispersion (PMD) of the HNLF is less than 1 ps. Through tuning of PC3, the polarization state of $\lambda_3$ is aligned perpendicular to the direction of the polarization state of $\lambda_2$ by minimizing their resulting four-wave mixing product term. The polarization state of $\lambda_3$ is then rotated $45^\circ$ through a rotation of the $\lambda/2$ plate by $22.5^\circ$. PC4 is used to adjust the polarization state of $\lambda_3$ at the output of the HNLF to be orthogonal to the polarizer when both $\lambda_1$ and $\lambda_2$ are off. The distinction ratio of the polarizer is approximately 35 dB and sets a limit on the resulting XOR extinction ratio. An optical filter with a bandwidth of 0.5 nm is used after the polarizer to separate the desired signal at $\lambda_3$ from the residual wavelengths.

Figure 8.3 Experimental setup for all-optical XOR gate based on Kerr effect in a single highly–nonlinear fiber.
8.4 Results and discussion

In Figure 8.4 we illustrate the output optical power of $\lambda_3$ as a function of the input power when only $\lambda_1$ or $\lambda_2$ is on. The input power of $\lambda_3$ into the HNLF is approximately 3 dBm. As shown in Fig. 8.3, as the optical power of $\lambda_1$ or $\lambda_2$ at the input of the XOR gate increases from 0 to 0.11 W, the output power of $\lambda_3$ changes continuously from about $-40$ dBm to $-15$ dBm. It can be observed that there is negligible difference between the results when either $\lambda_1$ or $\lambda_2$ is on. The highest output power of $\lambda_3$ is 18 dB less than the input power of $\lambda_3$ in our experiment. By using a HNLF with a larger non-linear coefficient, a larger rotation of $\lambda_3$ can be obtained. The output signal at $\lambda_3$ will therefore be more aligned with the polarizer and a larger output level will be observed.
In Figure 8.4, the output vs. input optical power of the XOR gate is shown. For CW inputs at $\lambda_1$ and $\lambda_2$, the input optical power of both $\lambda_1$ and $\lambda_2$ is 0.11 W. Due to loss in components, the corresponding power at the input of the HNLF is 16 dBm (just below the stimulated Brillouin scattering threshold). When $\lambda_1$ and $\lambda_2$ are both off or on, the output power of the XOR gate at $\lambda_3$ is $-40$ dBm and increases to $-15$ dBm when only one of $\lambda_1$ or $\lambda_2$ is on. The on-off extinction ratio of the XOR gate is therefore 25 dB. According to Figure 8.4, the on-off extinction ratio increases as the input optical power of $\lambda_1$ and $\lambda_2$ increases. Note that the input optical power of $\lambda_1$ and $\lambda_2$ should be lower than the stimulated Brillouin scattering threshold, which can
be increased by using shorter fiber with higher nonlinearity. After the HNLF, $\lambda_1$, $\lambda_2$, and the other wavelengths generated by four wave mixing are filtered away by an optical bandpass filter.

![Graphs showing optical spectrum](image)

Figure 8.5 The output optical spectrum of the XOR gate when inputs $\lambda_1$ or $\lambda_2$ are continuous waves: (a) $\lambda_1$ off and $\lambda_2$ off; (b) $\lambda_1$ off and $\lambda_2$ on; (c) $\lambda_1$ on and $\lambda_2$ off; (d) $\lambda_1$ on and $\lambda_2$ on.

In Figure 8.6 we illustrate the input and output waveforms for 10 Gbit/s NRZ data. The input patterns are at $\lambda_1$ and $\lambda_2$ and the resulting XOR output pattern is at $\lambda_3$. For the input data pattern 011001001 at $\lambda_1$ and input data pattern 0011101100 at
\( \lambda_2 \), the resulting data pattern at \( \lambda_3 \) is 0101100101. This demonstrates XOR functionality.

![Figure 8.6](image)

Figure 8.6 The input patterns at \( \lambda_1 \) and \( \lambda_2 \) and the resulting output pattern at \( \lambda_3 \) for 10 Gbit/s data.

Figure 8.7 shows the eye diagram of the output of the XOR gate when using 10 Gbit/s \((2^{23}-1)\) PRBS NRZ data. The signal-to-noise ratio (SNR) of the input data at \( \lambda_1 \) is 18.7 dB and at \( \lambda_2 \) is 19.6 dB, while the SNR of the output data is 15.7 dB. The corresponding SNR penalty at the output compared to the input data at \( \lambda_2 \) is 3 dB, which could be caused by polarization fluctuation/instability of the polarization states in the system. Since the Kerr effect in fiber is ultra-fast and the delay of output signal response due to input signal change is less than 10 ps, the data rate of our proposed XOR gate can be above 100 Gbit/s in principle.
Since the Kerr effect is proportional to the fiber nonlinearity, by using HNLF with higher nonlinearity [66] or using HNL holey fiber [67], both the output power and extinction ratio of the XOR gate can be improved considerably and the required input optical power can be decreased. For example, using a HNLF with a non-linear coefficient of 20 W^{-1}km^{-1} [66] in our scheme, with the same input optical power levels, both the output power and extinction ratio of the XOR gate are expected to increase by approximately 10 dB. We can also achieve the same induced birefringence by using shorter fiber with higher nonlinearity, thereby reducing polarization instability and increasing the stimulated Brillouin scattering threshold. Note that we can simultaneously obtain the XNOR gate operation on the orthogonal polarization state of $\lambda_i$. 

Figure 8.7 Eye diagram of output of XOR gate for 10 Gbit/s PRBS data.
8.5 Summary

In this chapter, we demonstrate a 10 Gbit/s all-optical XOR gate based on polarization rotation induced by Kerr effect in a single highly–nonlinear fiber. Using 2-km of highly–nonlinear fiber with a non-linear coefficient of 9.1 W⁻¹km⁻¹, we obtain a 25-dB extinction ratio at the XOR output.
Chapter 9

3R Regeneration of a 40-Gbit/s Optical Signal by Optical Parametric Amplification in a Highly-Nonlinear Fiber

In this chapter, we demonstrate wavelength-shift-free 3R-regeneration of 40-Gbit/s optical RZ signal by OPA with a clock-modulated pump in highly-nonlinear fiber.

9.1 3R Regeneration of High-Speed Optical Signal

In order to achieve high throughput and efficiency, future transparent optical networks may require an optical data signal to traverse long-distances and many switching nodes all-optically before reaching its destination. Of course, the data signal will become degraded in both time and amplitude by many possible effects, including fiber-based dispersion and nonlinearities as well as non-idealities of optical devices inside a switching node [68]. Therefore, there has been much interest in a high-speed 3R (retiming, reshaping, re-amplification) regenerator as a network element [69].
There have been several published results on optical 3R regenerators. In planar optoelectronic devices, 3R was achieved using a wavelength shifter in the form of: (i) a semiconductor optical amplifier (SOA) that employed cross-gain- or cross-phase-modulation [70], and (ii) an electro-absorption (EA) modulator that employed cross-absorption-modulation [71]; these methods generally induced wavelength shift of the signal. Since fiber-based nonlinear effects have the potential of operating at a much higher speed than optoelectronic devices, there have also been reports on using a wavelength shifter in the form of highly-nonlinear fiber (HNLF), which the regenerated signal are also at a different wavelength.[72,57]. An additional wavelength converter has been used to demonstrate wavelength-shift free 3R-regenerator [36].

Previously an optical parametric amplification (OPA) with a clock-modulated pump has been used to make a continuous wave (CW) becoming a high-quality pulse train source [56]. Here we demonstrate 3R regeneration of a 40-Gbit/s optical signal by OPA with a clock-modulated pump in a highly-nonlinear fiber (HNLF). We use a recovered 20-GHz clock to drive an OPA pump laser and produce a clean carrier-suppressed RZ (CS-RZ) pulse optical pulse train. This pump pulse train mixes with the degraded 40-Gbit/s data signal in the OPA to achieve retiming/reshaping/re-amplification. After the 3R regenerator, the power penalty of the signal is improved by 2.6 dB at $10^{-9}$, and the signal optical power is amplified by 7 dB. We emphasize that the regenerated data remains on its original wavelength, such that no
wavelength shifting is required to achieve our results and thereby potentially making network control and management somewhat less complex.

### 9.2 Concept of 3R Regeneration by Optical Parametric Amplification in Fiber With a Clock-Modulated Pump

Figure 9.1 shows a conceptual diagram of 3R signal regeneration using OPA in HNLF with a clock-modulated pump.

Figure 9.1 Concept of 3R regeneration using OPA in HNLF with a clock-modulated pump.

First we recover the clock at the half bit rate of the degraded data via a clock recovery module, and use it to modulate the pump light to become a clean CS-RZ pulse train at bit rate. Then both the degraded signal and the pump pulse train are...
combined together into a HNLF. The signal is amplified by OPA based on four wave mixing (FWM). Since the OPA efficiency is proportional to the square of the pump power, in the time domain, a pump pulse train makes a CW signal wave into a pump train with a narrower pulse width due to nonlinear effects. When the signal wave carrying degraded data, the data will be retimed and reshaped. Due to the inherent amplification of OPA, the data will be amplified at the same wavelength. By filtering out the signal wave, the 3R regenerated data is obtained without a wavelength shift.

9.3 Experimental Setup

The experimental setup is shown in Figure 9.2. The wavelength of the signal (λs) is 1546.8 nm, and the wavelength of the pump (λp) is set at 1551.8 nm. First we generate a 40-Gbit/s optical RZ signal by modulating a 40-GHz clock and 40 Git/s (2^{11}-1) PRBS data to the signal wave. Then the 40 Gbit/s RZ data is degraded by passing through 2.2 km of single mode fiber with a dispersion value of 39 ps/nm, and attenuated by an attenuator to -25 dBm, then amplified by EDFA back to 0 dBm to add ASE noise. 1% signal power is tapped to a 40G photodiode and a clock recovery which recovers clock at 20 GHz. Then the CW pump wave is modulated by the 20 GHz clock to become a 40-GHz CS-RZ pulse train. In order to further reduce stimulated Brillouin smattering (SBS), the pump wave is then randomly phase modulated by a 10 Gbit/s PRBS signal, which is synthesized to the recovered clock, so as to minimize the power penalty caused by phase modulation. Both the
signal and pump wave are coupled into 1-km of dispersion-shifted HNLF, with a non-linear coefficient of 9.1W⁻¹km⁻¹ and a fiber loss of 0.45 dB/km. The zero-dispersion wavelength of the HNLF is 1552 nm. After the OPA process in the HNLF, an optical filter with a 3-dB bandwidth of 0.5 nm separates 3R regenerated signal wave from the residual signals.

![Diagram](image)

Figure 9.2 (a) Experimental setup for 3R regeneration using OPA in HNLF with a clock-modulated pump. (b) Details of 3R regenerator.
9.4 Results and discussion

Figure 9.3(a) shows the recovered 20-GHz clock. The pump light is modulated by this 20-GHz clock and becomes a 40-GHz CS-RZ optical pulse train, whose waveform is shown in Figure 9.3(b).

![Figure 9.3](image)

(a) Recovered 20-GHz clock and (b) waveform of the 40-GHz CS-RZ pump pulse train.

The optical power of the signal wave and the pump wave at the input of HNLF are -9 dBm and 20 dBm respectively. Figure 9.4 shows the optical spectrum at the output of the HNLF.
Figure 9.4 Optical spectrum at the output of the HNLF.

Figure 9.5 (a), (b), (c) shows the detailed optical spectrum of the signal at the input of the HNLF, at the output of the HNLF, and after the optical filter respectively. We can see that the optical spectrum of the signal is broadened after OPA, which means the pulse width of the RZ signal is narrowed by OPA. After the 0.5-nm filter, the optical spectrum of the signal is changed back to be similar to the original optical spectrum. And the measured optical power of the signal wave after the filter is -2 dBm, which means the signal is amplified by 7 dB after 3R regeneration.
Figure 9.5 Detailed optical spectrum of the signal at (a) the input of the HNLF; (b) the output of the HNF; (c) after the optical filter.
The eye diagram of the signal before and after the 3R regeneration is shown in Figure 9.6 (a) and (b). We can see the quality of the 40 Gbit/s RZ signal is improved after the 3R regeneration.

Figure 9.6 (a) Eye before the 3R generator; (b) eye after 3R generator;

Figure 9.7 shows the BER measurement results. We can see the power penalty at BER of $10^{-9}$ is improved by 2.6 dB through the 3R regenerator. The power penalty compared to back to back is 0.2 dB.
9.5 Summary

In this chapter, we demonstrate wavelength-shift-free 3R-regeneration of 40-Gbit/s optical RZ signal by OPA with a clock-modulated pump in highly-nonlinear fiber. The power penalty is improved by 2.6 dB, and the signal power is amplified by 7 dB.
Chapter 10

Conclusion

Management of fiber physical effects is essential in high-speed reconfigurable WDM optical fiber communication systems and networks. The physical effects in optical fiber include chromatic dispersion, polarization mode dispersion (PMD) and nonlinear effects. For $\geq 10$ Gbit/s optical fiber transmission system, it is critical that chromatic dispersion and PMD be well monitored and compensated by using some type of dispersion monitoring and compensation. One the other hand, dispersive and nonlinear effects in optical fiber systems can also be beneficial and has applications on pulse management, all-optical signal processing and network function, which will be essential for high bit-rate optical networks and replacing the expensive optical-electrical-optical (O/E/O) conversion.

In this Ph.D. dissertation, we present a detailed study on dispersive and nonlinear effects in high-speed optical communication systems. We have demonstrated:

(i) A novel technique for optically compensating the PMD-induced RF power fading that occurs in single-sideband (SSB) subcarrier-multiplexed systems. By
aligning the polarization states of the optical carrier and the SSB, RF power fading due to all orders of PMD can be completely compensated. The 5% RF power fading tail is improved from 13.5 dB to <1.5 dB, as verified from both experimental measurement (300 samples) and computer simulation (10,000 samples). This technique is independent of the DGD of the optical fiber link and the subcarrier frequency.

(ii) Chromatic-dispersion-insensitive PMD monitoring by using a narrowband FBG notch filter to recover the RF clock power for 10Gb/s NRZ data. Using a FBG notch filter with a 10-dB bandwidth of 15 GHz at the receiver, we measured the recovered clock power to monitor PMD in a 10Gb/s NRZ system. The variation of the detected clock power is within 1.5 dB when the accumulated dispersion increases from 0 to 600 ps/nm.

(iii) Chirp-free high-speed optical pulse generation with a repetition rate of 160 GHz (which is four times of the frequency of the electrical clock) using a phase modulator and polarization maintaining (PM) fiber. The unwanted low frequency tones are suppressed by more than 15 dB, and the measured pulse width is 3.3 ps.

(iv) Polarization-insensitive all-optical wavelength conversion based on four-wave mixing in dispersion-shifted fiber (DSF) with a fiber Bragg grating and a
Faraday rotator mirror. We experimentally demonstrate that the residual polarization sensitivity is reduced from more than 22 dB to 2dB with 4 km of DSF.

(v) Width-tunable optical RZ pulse train generation based on four-wave mixing in highly-nonlinear fiber. By electrically tuning the delay between two pump pulse trains, the pulse-width of a generated pulse train is continuously tuned. In our experiment, the FWHM of a 5G pulse train is tuned from 85 ps to 25 ps, and the FWHM of a 10G pulse train is tuned from 33 ps to 18 ps. And the simulation results show that the FWHM of a 40G pulse train can be tuned continuously from 10.6 ps to 2.9 ps.

(vi) A high-speed all-optical XOR gate based on polarization rotation induced by Kerr effect in a single highly–nonlinear fiber. Using 2-km of highly–nonlinear fiber with a non-linear coefficient of 9.1 W⁻¹km⁻¹, we obtain a 25-dB extinction ratio at the XOR output.

(vii) Wavelength-shift-free 3R-regeneration of 40-Gbit/s optical RZ signal by OPA with a clock-modulated pump in highly-nonlinear fiber. The power penalty is improved by 2.6 dB, and the signal power is amplified by 7 dB.
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