Advanced modulation formats for high capacity optical communication systems

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Advanced Modulation Formats for High Capacity Optical Communication Systems

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School of Electrical & Electronic Engineering

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in fulfillment of the requirement for the degree of
Doctor of Philosophy**

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Summary

Due to the ever-increasing capacity requirement for communication networks, the number of wavelength-division multiplexing (WDM) channels and channel bit rate continue to increase in optical transmission systems. As a result, WDM channel spacing has to be reduced in order to accommodate more channels with higher bit rates, which in turn increases the impact of transmission impairments of optical fiber systems. These impairments include optical amplifier noise, group-velocity-dispersion (GVD), polarization-mode-dispersion (PMD), nonlinear effects such as self-phase-modulation (SPM), cross-phase-modulation (XPM), and four-wave-mixing (FWM), as well as their interaction with dispersion. These impairments may ultimately limit the distance capacity product of an optical transmission system. One technology that could improve the system performance under such impairments is to use advanced modulation formats rather than the conventional non-return-to-zero on-off-keying (NRZ-OOK).

The performance of differential phase-shift keying (DPSK) modulation format in WDM systems using semiconductor optical amplifiers (SOAs) as in-line amplifiers is investigated. The results show that the use of DPSK modulation format can significantly reduce cross-gain modulation (XGM) effect in such WDM systems. For the first time, an 8-channel 10.709Gb/s WDM transmission over more than 1000km using SOAs as in-line amplifiers is demonstrated, with more than 6dB of power margin over the forward error correction (FEC) (with 7% redundancy) threshold. After further optimizing the SOA operation parameters, 16x10.709Gb/s WDM transmission over 640km transmission using SOAs as in-line amplifiers based on

DPSK format is achieved, at a power margin of 4.5dB over FEC threshold. This is, to the best of our knowledge, the largest bit rate distance product ($BL=109.7\text{Tb}\cdot\text{s}^{-1}\cdot\text{km}$) reported.

The spectra difference between DPSK and OOK that has been observed, in particular the absence of discrete clock components for DPSK and its pulse carved formats, suggests that it may offer better tolerance to other nonlinear effect, such as stimulated Brillouin scattering (SBS), compared to OOK modulated systems. The performance of an RZ-DPSK modulated transmission system with Raman amplification is evaluated, particularly, the SBS threshold in such system is examined. It is found that the RZ-DPSK modulated system has much higher SBS threshold than the RZ-OOK modulated system in a Raman amplified system. Hence, it is possible to use higher launch power in the RZ-DPSK system, and consequently, the span length can be extended. Error free single-span transmissions of single-channel and 8-channel over 310km standard single mode fiber (SMF) are demonstrated, using RZ-DPSK format and bidirectional Raman pumps.

RZ-DPSK modulation format is more tolerant to fiber nonlinearities, compared with RZ-OOK format partially due to its pulse train like amplitude with periodic nature. Minimum shift keying (MSK) may tolerate more dispersion and nonlinear effects than other currently considered optical modulation formats, simply because that MSK has the properties of constant amplitude and continuous phase at every bit transition instants. A novel approach for implementing optical MSK transmitters and receivers is proposed and the principle on the generation and detection of the externally modulated optical MSK signal using the proposed MSK transmitter and receiver is

presented in details in this thesis. 10.709Gb/s MSK signal is successfully generated and detected experimentally. Both theoretical derivation and experimental generation show that the generated optical externally modulated MSK signal exhibits the properties of constant amplitude and continuous phase change at the bit transition instants. The MSK signal also has very compact optical spectrum and much lower side-lobes than that of RZ-DPSK and RZ-OOK signals. The performance of the optical MSK modulated system is evaluated, optimized, and compared with that of 50% duty cycle RZ-DPSK and 50% duty cycle RZ-OOK modulated systems by both numerically and experimentally. The results show that the MSK signal exhibits the largest tolerance against fiber dispersion and SPM effect among these formats.

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List of Acronyms

Abbreviations	Full Expressions
AMZI	asymmetric Mach-Zehnder interferometer
APD	avalanche photodiode
ASE	amplified spontaneous emission
ASK	amplitude-shift keying
BER	bit error rate
BERT	bit error rate tester
CD	chromatic dispersion
CPFSK	continuous-phase frequency-shift keying
CRZ	chirped return-to-zero
CS-RZ	carrier-suppressed return-to-zero
CW	continuous wave
DCF	dispersion compensation fiber
DFB	distributed feedback
DGE	dynamic gain equalizer
DI	delay interferometer
DPFSK	discontinuous-phase frequency-shift keying
DPSK	differential phase-shift keying
DQPSK	differential quadrature phase-shift keying
DWDM	dense wavelength-division multiplexing
EAM	electro-absorption modulator
EDFA	erbium-doped fiber amplifier
FEC	forward error correction
FSK	frequency-shift keying
FWHM	full width at half maximum
FWM	four wave mixing
GVD	group velocity dispersion
IM/DD	intensity modulation/direct detection
IM/PM	intensity modulation/phase modulation
ISI	inter-symbol interference
ITU	international telecommunication union
ITU-T	international telecommunication union-telecommunication
LD	laser diode
LED	light emitting diode
LSB	lower side band
MSK	minimum-shift keying
MZM	Mach-Zehnder modulator
NRZ	non-return-to-zero
OOK	on-off keying
OQPSK	offset quadrature phase-shift keying
OSNR	optical signal-to-noise ratio
PM	phase modulator
PMD	polarization mode dispersion
PRBS	pseudo random bit stream

PSK	phase-shift keying
QAM	quadrature-amplitude modulation
RZ	return-to-zero
SBS	stimulated Brillouin scattering
SMF	single mode fiber
SGM	self-gain modulation
SOA	semiconductor optical amplifier
SPM	self-phase modulation
SRS	stimulated Raman scattering
SSB	single side band
USB	upper side band
WDM	wavelength-division multiplexing
XGM	cross-gain modulation
XPM	cross-phase modulation

Chapter 1

Introduction

1.1 Background and Motivations

The past decades have witnessed a tremendous growth in the need for communications capacity, both in terms of data rates and in geographic coverage. To an increasing extent, optical fiber has been the medium of choice to cope with this vast growth of traffic volume. On-off keying (OOK) modulation has been the dominant modulation technique for encoding information bits onto optical carrier. At the receiver end, the received OOK signal is directly detected using a photodetector, which converts the light into electrical signal. This is commonly called direct detection. In 1980s and early 1990s, coherent detection was studied intensively, with an attempt to improve the receiver sensitivity over OOK modulated direct detection systems [1-3]. At the same time, studies on other modulation formats, such as phase-shift keying (PSK) and frequency-shift keying (FSK) became possible with coherent detections. However, with the invention and fast development of erbium-doped fiber amplifier (EDFA) in late 1980s, OOK modulation technique with direct detection became much more attractive due to its simplicity in generation and detection. The rapid adoption of wavelength-division multiplexing (WDM) technique in mid 1990s to increase the transmission capacity to Tb/s in a single optical fiber has generated renewed interest in alternative modulation formats to achieve better tolerance against transmission impairments. And with the availability of the delay interferometer, PSK and FSK formats can be detected with direct detection.

The ever-increasing capacity requirement for communication networks has resulted in the push for higher capacity and longer reach for optical transmission systems over the past few years. The number of the WDM channels and channel bit rate continue to increase in optical transmission systems. As a result, WDM channel spacing has to be reduced in order to accommodate more channels with higher bit rates, which in turn increases the transmission impairments of optical fiber. These impairments include optical amplifier noise, group velocity dispersion (GVD), polarization mode dispersion (PMD), nonlinear effects such as self-phase modulation (SPM), cross-phase modulation (XPM), and four wave mixing (FWM), as well as their interaction with fiber dispersion. These impairments may ultimately limit the distance-capacity product of an optical transmission system. One technology that could improve the performance of transmission systems under such impairments is to use advanced modulation formats rather than simple non-return-to-zero OOK (NRZ-OOK) format which has been widely used in today's optical communication systems. A number of advanced modulation formats have been shown to be effective in providing better immunity to dispersion and/or nonlinear fiber impairments as well as allowing higher channel density or spectral efficiency [4-5].

The requirements for such modulation formats for both single-channel and WDM transmission system applications include:

- Compact modulation spectrum
- Large dispersion tolerance and small linear crosstalk
- High nonlinearity tolerance
- Simple configuration of transmitter and receiver.

A number of advanced modulation formats that meet these criteria to varying degrees have been proposed. These include return-to-zero OOK (RZ-OOK), carrier-suppressed RZ-OOK (CSRZ-OOK), differential PSK (DPSK), RZ-DPSK, CSRZ-DPSK, differential quadrature phase-shift keying (DQPSK) and its pulse carved forms, and their variations. It is well accepted that phase modulation formats (PSK) have several advantages over amplitude modulation formats (ASK)/OOK. Firstly, PSK has a 3dB lower requirement in optical signal to noise ratio (OSNR) over OOK when balanced detection is employed. Secondly, PSK is more tolerant to signal power fluctuations in the receiver decision circuit than OOK. Thirdly, PSK is more robust to narrow-band optical filtering than OOK. And fourthly, PSK is more resilient than OOK against some fiber nonlinear effects, such as XPM and stimulated Brillouin scattering (SBS). Many studies have been carried out to compare the system performance with different modulation formats, and to focus on improving the performance of available advanced modulation formats. In particular, (RZ-)DPSK has demonstrated excellent system performance, especially in long haul transmission systems and systems with channel bit rate upto 40Gb/s. However, little work has been done on applying (RZ-)DPSK format in certain applications, such as WDM transmission systems using semiconductor optical amplifiers (SOAs) as in-line amplifiers, and long single-span transmission WDM systems. (RZ-) DPSK format is expected to provide better system performance due to its better tolerance on nonlinear effects than (RZ-)OOK format.

There is also a need to explore other new configurations to improve transmission performance or to reduce the required components for multiple channel signal generation with these formats. Externally modulated optical minimum-shift keying

(MSK) format has not been proposed before. In digital communication systems, MSK exhibits the properties of constant amplitude and continuous phase at every bit transition instant, narrow power spectrum and low side lobes. It has been widely used in satellite communications and high-rate microwave systems due to advantages such as reduction of out-of-band interference and better tolerance to amplifier nonlinearity. Therefore, it is expected that optical MSK to have the advantages of larger dispersion tolerance, to be more robust against linear crosstalk, and larger SPM tolerance, compared with RZ-DPSK. These features may make optical MSK a preferable data format for high speed and high spectral efficiency WDM systems. These motivate the study to investigate the implementation of high bit rate optical MSK systems and their transmission performance.

1.2 Objectives

This thesis aims to explore some novel applications of the available advanced optical modulation formats and to develop a novel optical modulation format which has high tolerance against fiber dispersion and nonlinearity in high speed, high capacity optical transmission systems. The main objectives of the thesis are:

- To study various available optical signal modulation formats and to compare their performance in high capacity optical transmission systems. These modulation formats includes RZ-OOK, DPSK, and RZ-DPSK. In particular, to investigate the performance of SOAs amplified WDM system and long single-span transmission system with Raman pumps using phase modulated formats.
- To propose a new technique to implement the externally modulated optical MSK format. MSK has narrower spectrum, lower side lobes, and continuous phase at bit transition instants. However, its performance and implementation

issues have not been reported by other research groups before the study was carried out in this thesis.

- To study the performance of high bit-rate optical transmission systems using optical MSK modulation format, in terms of dispersion tolerance, linear crosstalk, SPM tolerance, SBS threshold, and the phase noise, both numerically and experimentally. The performance of optical MSK format will be compared with that of other advanced modulation formats, such as RZ-OOK with 50% duty cycle and RZ-DPSK with 50% duty cycle.
- To characterize and optimize the externally modulated optical MSK system, such as the optimum bandwidth of the optical filter and electrical filter, which are included in the receiver module usually, and the optimum fiber launching powers, for both single mode fiber (SMF) and dispersion compensation fiber (DCF).

1.3 Major Contributions

The major contributions of this thesis are listed as follows:

1) DPSK in SOA Amplified WDM Systems

The work presented here is the first investigation and demonstration of DPSK modulation format in a WDM transmission system using SOAs as in-line amplifier. The performance of DPSK modulation format in WDM systems using SOA as in-line amplifiers is investigated and it is shown that the use of DPSK modulation format can significantly reduce cross gain modulation (XGM) effect in such WDM systems. For the first time, an 8-channel 10.709Gb/s WDM transmission over more than 1000km using SOAs as in-line amplifiers is demonstrated, with more than 6dB power margin

over the forward error correction (FEC) threshold (with 7% redundancy). After further optimizing the SOA operation parameters, 16x10.709Gb/s WDM transmission using SOAs as in-line amplifiers based on DPSK modulation format over 640km transmission is achieved, at a power margin of 4.5dB over FEC threshold. This is, to the best of our knowledge, the largest bit rate-distance product ($BL=109.7\text{Tb}\cdot\text{s}^{-1}\text{ km}$) reported.

2) RZ-DPSK in Raman Pumped Single-span Transmission Systems

Detailed performance of the RZ-DPSK and RZ-OOK modulated optical transmission systems in Raman pumped system is examined and compared. To increase the single-span transmission distance over standard SMF without applying hybrid optical fiber solution and/or remote-pumping amplification techniques, the performance of the RZ-DPSK and RZ-OOK modulated systems is studied and compared. It is found that the RZ-DPSK modulated system has higher SBS threshold than the RZ-OOK modulated system in a Raman pumped system. Hence, it is possible to use higher launch power in the RZ-DPSK system, and consequently, the span length can be extended. Furthermore, it is found that the limiting factor in the RZ-DPSK system is the SPM effect, while it is the SBS effect in the RZ-OOK system. A single-channel and 8-channel WDM single-span transmission over 310km standard SMF are demonstrated using RZ-DPSK format and bidirectional Raman pumping. In both transmission experiments, error free transmission can be achieved, without applying FEC technique.

3) Generation and Detection of Optical MSK Data Format

The novel implementation of an externally modulated optical MSK data has been proposed. To further improve the spectral efficiency in high speed WDM transmission

systems, a configuration to generate the externally modulated optical MSK format is proposed for the first time, which exhibits the properties of constant amplitude and continuous phase at every bit transition instant, narrow power spectrum and low side lobes. The principle on the generation and detection of the externally modulated optical MSK signal is presented in details. The 10.709Gb/s optical MSK data has been successfully generated and detected by experiment using the proposed scheme.

4) Performance Evaluation of the MSK Signal

The evaluation and comparison of the performance of the proposed externally modulated optical MSK data with that of RZ-OOK (50% duty cycle) and RZ-DPSK (50% duty cycle) by both simulation and experiment are presented. Simulation results show that the MSK signal has the best tolerance against fiber dispersion and SPM, and smallest linear crosstalk among these formats. Experimental results agree with that of simulation on predicated negative penalty against SPM and good dispersion tolerance for the implemented MSK. The measured SBS thresholds of both MSK and RZ-DPSK are more than 10dB higher than that of an RZ-OOK system.

5) Optimization of Operation Parameters for MSK Modulated Systems

The system parameters for the externally modulated optical MSK system are optimized. To obtain the best performance, the system parameters of the externally optical modulated MSK system are examined and optimized. These include the optimization of filter bandwidth for the optical filter and electrical filter used in the receiver module, and the optimization of fiber launch powers into SMF and DCF.

1.4 Organization

The thesis is organized into six chapters.

In Chapter 1, an introduction is given to present the motivation, objectives, and major contributions made by the author in the thesis.

Chapter 2 introduces the basic configuration of an optical transmission system and fundamental techniques of generating various ASK, PSK, and FSK formats. The existing works on performance comparison between different ASK formats, and among ASK, PSK, and FSK formats are reviewed.

Chapter 3 presents the use of DPSK format to suppress the XGM effect induced by an SOA. An $8 \times 10.709 \text{ Gb/s}$ DPSK modulated WDM transmission over 1050km standard SMF and a $16 \times 10.709 \text{ Gb/s}$ transmission over 640km are successfully demonstrated without applying FEC technique. The RZ-DPSK format is also used to provide higher SBS threshold comparing to that in an OOK modulated system. A single-channel and 8-channel WDM single-span transmission over 310km standard SMF is demonstrated, using RZ-DPSK format and bidirectional Raman Pumping. Error free transmissions are achieved in both single-channel and multi-channel systems, without applying FEC technique.

In Chapter 4, the transmitter and receiver configurations for generating the externally modulated optical MSK data are proposed for high speed and high spectral efficiency WDM systems. It is shown that using the conventional CS-RZ pulse train and pure

dual-mode CS-RZ pulse train for the OQPSK modulator can result in different MSK signals.

Chapter 5 examines and compares the performance of the proposed externally modulated optical MSK system with the performance of the 50% duty cycle RZ-DPSK and 50% duty cycle RZ-OOK modulated systems, in term of

- Fiber dispersion tolerance
- Linear crosstalk penalty
- SPM tolerance
- SBS threshold in a Raman pumped system
- Phase noise

The optimum optical and electrical filter bandwidths of the MSK receiver and the optimum SMF and DCF launch powers in the MSK modulated system are also studied in this chapter.

Chapter 6 summarizes the thesis with suggestions for further research.

Chapter 2

Review of Optical Modulation Formats

It is well known that high capacity wavelength-division multiplexed (WDM) transmission systems with 10Gb/s and/or 40Gb/s per channel suffer from various impairments arising from amplified spontaneous emission (ASE) noise, fiber nonlinear effects, chromatic dispersion (CD), and polarization mode dispersion (PMD). To improve the transmission performance of WDM systems, a wide variety of techniques have been reported and investigated. These include: (1) the use of advanced modulation formats, (2) new fiber types, (3) techniques for dispersion, dispersion slope and PMD compensation, (4) management of nonlinear impairments, (5) distributed amplification scheme, (6) signal equalization, and (7) forward error correction (FEC). Among these techniques, the use of advanced modulation formats has been demonstrated as an effective solution in managing transmission impairments. Theoretically speaking, different data formats exhibit different waveforms and spectra, leading to different signal qualities at the receiver end of a given transmission link, while links with different system parameters (such as reach, channel spacing, fiber type, amplifier schemes, etc.) may also require individual optimal data formats. The ideal modulation format for long-haul, high speed, WDM transmission links is the one that has a compact spectrum, low susceptibility to fiber nonlinear effects, large dispersion tolerance, and a simple and cost-effective configuration for generation and detection.

There are a number of modulation formats widely used in research in optical transmission systems. They can be broadly classified into amplitude-shift keying (ASK) (also known as on-off keying (OOK)), phase-shift keying (PSK), frequency-shift keying (FSK), and their combinations [6-11]. OOK encodes data by turning on or off the amplitude of light. There are a number of variations for the OOK format, including non-return-to-zero (NRZ), return-to-zero (RZ), and duobinary [12]. There are also a number of different forms for the RZ-OOK format, including simple RZ, carrier-suppressed RZ (CSRZ), chirped RZ (CRZ) [13], and vestigial sideband RZ (VSB-RZ). PSK encodes data by modulating the phase of light. There are several variations for the PSK format, including differential PSK (DPSK), RZ-DPSK, CSRZ-DPSK, and differential quaternary PSK (DQPSK) and its pulse carved forms. FSK encodes data by changing the frequency of light. There are a few variations for the FSK format, including discontinuous phase FSK, continuous phase FSK (CPFSK), and minimum-shift keying (MSK). Many studies have been focused on improving the performance of the existing advanced modulation formats as well as exploring some new configurations to improve transmission performance or to reduce the required components for multiple-channel signal generation with these formats.

This chapter first introduces a general optical transmission system. The basic principles to generate various externally modulated optical ASK, PSK, and FSK formats, and their corresponding spectra and eye diagrams are presented and discussed in section 2.2 to section 2.4 respectively. Section 2.5 provides a literature review on a number of modulation formats used currently in laboratories and field trials, and the comparison of their performance in WDM transmission systems.

2.1 Data Modulation and Detection

A general optical fiber transmission system for either digital or analog transmission is shown in Fig. 2.1. In the transmission terminal, a serial bit stream in electrical form is presented to an information encoder or signal shaping circuit, then to a driver. The amplified data is then used to modulate the light provided by a light source (laser or LED) directly or via an optical modulator. The data modulated light is then launched into the fiber transmission link. As the light travels along the fiber, it may experience various impairments including fiber dispersion and nonlinearity, and amplifier noise. At the receiver end, the light is fed to a photodetector which converts the received optical signal into an electrical signal. The signal is then electrically amplified and fed to the decoder/demodulator to reconstruct the original bit stream.

Figure 2.1: The diagram of an optical fiber transmission system

The process of imposing information onto a continuous wave (CW) light is called modulation. This can be realized either by directly varying the laser drive current with

the information stream to produce a varying optical output power for ASK formats, or by using an external optical modulator to change the optical power, phase, or frequency emitted from a laser. External modulation is preferred for high-speed systems (>10 Gb/s) to minimize undesirable effects such as chirping. Both direct modulation and external modulation can provide amplitude-, frequency-, or phase-shift keying of the optical carrier by the information signal. Currently, two most widely used external modulators are electro-absorption modulators (EAMs) and Lithium-Niobate (LiNbO_3) Mach-Zehnder modulators (MZMs) [14].

Intensity modulation direct detection (IM/DD) is a simple digital modulation scheme whereby an electrical bit stream modulates the intensity of an optical carrier and the received optical signal is incident directly onto a photodetector which converts the received optical signal into its electrical signal. On the other hand, a coherent lightwave system transmits information by modulating the amplitude, or the frequency, or the phase of the optical carrier and detects the received signal by using homodyne or heterodyne detection techniques. In direct detection systems, typically, the dominant noise is signal-spontaneous beat noise, which is additive and signal-dependent. The spectral efficiency can not exceed 1b/s/Hz [15], since only one bit per symbol can be encoded, when binary modulation technique with direct detection technique is used. Higher spectral efficiency can be achieved using non-binary intensity/phase modulation (IM/PM). Quadrature-amplitude modulation (QAM) is a well-known example of a non-binary IM technique. Kerr nonlinearities in the fiber restrict the usable input power density to less than 10^{-14}W/Hz , limiting the spectral efficiency to about 5b/s/Hz [16]. Direct detection incurs a significant loss of spectral efficiency, and coherent detection is required to approach the fundamental efficiency

limits. In DWDM systems, using coherent detection enables purely electrical filtering to be used for demultiplexing, which enables ultra-dense WDM [17]. However, coherent detection is much more difficult to implement than direct detection. This is because coherent detection requires a local oscillator laser at the receiver, and needs some means to match the polarization state of the local oscillator to that of the received signal [16-17]. Unless specifically stated, otherwise only direct detection systems will be considered in this thesis.

2.2 Amplitude-Shift Keying (ASK)

As mentioned earlier, there are different variations of the ASK (OOK) formats. The classification of currently known optical amplitude modulation is illustrated in Fig. 2.2. In this section, only NRZ, RZ and CS-RZ will be discussed in detail since they are most widely studied in today's optical communication systems.

Figure 2.2: Classification of typical optical amplitude modulation

2.2.1 Non-Return-to-Zero On-Off Keying (NRZ-OOK)

The non-return-to-zero on-off keying (NRZ-OOK) is the simplest format among all the optical modulation formats, which is usually referred to as NRZ. This format

imprints data onto an optical carrier by switching light on or off. Historically, this was the first, and is still the most widely deployed optical modulation format.

Fig. 2.3 shows the simulated spectrum, with a resolution of 0.01nm which is the same for the rest of this chapter, and eye diagram of an optical NRZ signal with raised cosine data pulses. The simulations are carried out by using the commercial software, VPItransmissionmaker. The optical spectrum, defined as the bit-pattern-averaged squared magnitude of the optical field's Fourier transform [14], is composed of a continuous portion, which reflects the shape of the individual NRZ data pulses, and discrete tones at integer multiples of the data rate. The weight of these tones is determined by the NRZ shape and/or rise/fall times.

Figure 2.3: Optical spectrum and eye diagram of an NRZ signal

NRZ can be generated by either direct or external modulation of a semiconductor laser. The data rate that can be achieved using direct modulation is limited by device characteristics including parasitic effects and is typically less than 10 Gb/s. However this scheme is cost effective due to its simplicity and low driving voltage required. Large frequency chirping also limits its application in long haul system, while proper

optical pre-filtering would make it attractive for distance up to a few hundred kilometers [18]. Direct modulation is a popular scheme for optical access networks and metro networks, where transmission distance is short. For external modulation, a CW laser and an electro-optic modulator are required. This scheme can achieve higher bandwidth and better transmission performance.

As shown in Fig. 2.4, NRZ modulation format can be generated using an external electroabsorption modulator (EAM) or a Mach-Zehnder modulator (MZM) [19]. For multiple-channel application, a WDM multiplexer is used to combine channels into a WDM optical signal. EAMs have the advantage of low drive voltages (typically 2V), and are cheap relatively. However, some residual chirp will be produced, the dynamic extinction ratio (ER) typically is less than 10dB, and it has a limited optical power handling capability of less than 10dBm typically. On the other hand, MZMs have excellent extinction performance (typically 20dB), can be made chirp free, and have lower insertion losses than EAMs, but the driving voltage is much higher (V_π is 6 to 9V typically).

Figure 2.4: NRZ modulation format generated using (a) EAM and (b) MZM [19]

2.2.2 Return-to-Zero On-Off Keying (RZ-OOK)

In the case of RZ-OOK, information is encoded through the presence or absence of optical pulses. Each of the pulses does not occupy a complete bit duration, but only a certain percentage of it, called the duty cycle. Usually, RZ-OOK is generated from an optical NRZ signal by carving out pulses with an additional modulator, termed *pulse carver*. Typically, pulse carvers are implemented using sinusoidally driven EAMs or MZMs [19], as shown in Fig. 2.5.

Figure 2.5: RZ modulation format generated using (a) EAM and (b) MZM as pulse carver [19]

Using an EAM, as shown in Fig. 2.5(a), biasing the modulator well into its absorption region, and letting only the peak portion of the sinusoidal drive signal reach appreciable transmission, short optical pulses can be realized, such as pulses with duty cycle below 33%. Under such biasing condition, the extinction ratio can be around 20dB. However, the drawback of EAM is its high insertion loss. If a MZM is used for

pulse carving, three distinct operating conditions can be used to generate RZ formats with different pulse widths.

- Sinusoidally driving the MZM at the data rate between the transmission minimum and maximum produces optical pulses with a full-width-half-maximum (FWHM) of 50% of the bit duration (i.e., duty cycle of 50%), as shown in Fig. 2.5 (b) (dashed line). Decreasing the modulation swing while adjusting the modulator bias can achieve good extinction between pulses, and the duty cycle can in principle be reduced to 36%. However, this would incur a significant excess insertion loss since the modulator is no longer driven to its transmission maximum. Increasing the drive voltage to reduce the pulse width is not possible with MZMs, due to the periodic nature of the MZM transmission function.
- Sinusoidally driving the MZM with a $2V\pi$ driving voltage and at half the data rate between its transmission minima produces a pulse whenever the drive voltage passes a transmission maximum, as shown in Fig. 2.5 (b) (solid line). In this way, duty cycle of 33% can be realized.
- Sinusoidally driving the MZM with a $2V\pi$ driving voltage and at half the data rate between its transmission maximum results in pulses with 67% duty cycle and with alternating phase. This resulting format is also called carrier-suppressed RZ (CS-RZ), which will be explained in next section.

The simulated spectra and eye diagrams of 50% duty cycle RZ (solid line) and 33% duty cycle RZ (dashed line), as produced by a MZM in push-pull operation, are shown in Fig. 2.6. As shown in this figure, the spectrum of the RZ-OOK with 50%

duty cycle is narrower than that of the RZ-OOK with 33% duty cycle. However, the side lobes of the RZ-OOK with 50% duty cycle is higher. The optical spectrum of RZ is wider than that of NRZ format, as seen in Fig. 2.3 and 2.6.

Figure 2.6: Optical spectra and eye diagrams for 50% duty cycle RZ (solid line) and 33% duty cycle RZ (dashed line), as produced by MZMs

2.2.3 Carrier-Suppressed Return-to-Zero (CS-RZ)

Carrier-suppressed return-to-zero (CS-RZ) is a pseudo-multilevel modulation format, characterized by reversing the sign of the optical field at each bit transition. The sign reversals occur at every bit transition, and are completely independent of the information-carrying part of the signal. CS-RZ is most conveniently realized by sinusoidally driving a MZM pulse carver at half the data rate between its transmission maxima, as shown in Fig. 2.7. Since the optical field transfer function of the MZM changes its sign at the transmission minimum (dashed), phase inversions between adjacent bits are produced. Thus, on average, the optical field of half the '1'-bits has positive sign, while the other half has negative sign, resulting in a zero-mean optical signal. As a consequence, the carrier at the optical center frequency vanishes, and hence it is called carrier-suppressed RZ (CS-RZ).

Figure 2.7: CS-RZ modulation format generated using MZM as pulse carver [19]

The simulated spectrum and eye diagram of a CS-RZ optical signal with a 67% duty cycle, as generated by a MZM in push-pull configuration for pulse carving, are shown in Fig. 2.8. For comparison, the spectrum of a 50% duty cycle RZ signal is also given in dashed line. It shows that CS-RZ re-distributes spectral tones and its spectrum is also relatively more compact.

Figure 2.8: Optical spectrum and eye diagram of a 67% duty cycle CS-RZ optical signal, and the spectrum of a 50% duty cycle RZ signal (dashed line)

2.3 Phase-Shift Keying (PSK)

PSK is a modulation scheme that encodes data by modulating the phase of light. There are different variations for the PSK format. The classification of currently used optical phase modulation is shown in Fig. 2.9. In this section, only DPSK will be discussed in detail.

Figure 2.9: Classification of currently used optical phase modulation

As described earlier, for direct detection, the receiver is only responded to optical power variations (for this reason, intensity modulation and direct detection technique is most widely used in today’s optical communication systems). To detect the modulation of the optical field's phase, phase-to-amplitude converting elements have to be inserted into the optical path before the detection module. Since these elements are unable to offer an absolute optical phase reference, the phase reference has to be provided by the signal itself, i.e. each bit acts as a phase reference for another bit, which is at the heart of all differential phase-shift keying formats.

Binary differential phase-shift keying (BDPSK, or simply DPSK) encodes information with a binary phase change between adjacent bits. A logical ‘1’ is encoded as π -degree, whereas a logical ‘0’ is encoded as 0-degree, or vice versa. A

phase jump occurs at bits transition between “1” and “0”. Like OOK, DPSK can be implemented in RZ and NRZ forms. The main advantage of DPSK over OOK is its 3dB lower optical signal-to-noise ratio (OSNR) requirement at the receiver with balanced detection [20]. This enhancement directly translates into increased transmission distance, reduced optical power requirement, or relaxed component specifications.

Phase modulation can be achieved either using a MZM, or by means of a straight-line phase modulator (PM), resulting in different amplitude and phase waveforms [21]. Fig. 2.10 shows the two configurations for the generation of RZ-DPSK or CSRZ-DPSK signals. Depending on the modulation frequency of the clock signal and the bias conditions for the second MZM modulator shown in Fig. 2.10, RZ-DPSK with 50% or 33% duty cycle or CSRZ-DPSK with 67% duty cycle can be obtained respectively. If the pulse carving modulator is not used, the generated format is NRZ-DPSK. As shown in Fig. 2.10 (a), a PM only modulates the phase of the optical field, resulting in a constant envelope. A subsequent pulse carver converts the NRZ-DPSK signal to RZ-DPSK or CSRZ-DPSK signals. Since phase modulation does not occur instantaneously, a PM inevitably introduces frequency chirp across bit transitions. When using a MZM for phase modulation, since the phase of the optical field changes its sign upon transitioning through a minimum in the MZM’s power transmission curve, an instantaneous phase jump occurs, hence a near-perfect 180° phase shift is obtained. The benefit of a highly accurate phase modulation comes at the expenses of some residual modulation (intensity dips) at the transition of two adjacent bits. As shown in Fig. 2.10 (b), the width of the resulting intensity dips depends on the drive signal’s bandwidth and driving voltage. Nevertheless, since DPSK encodes

information in the optical phase rather than in the intensity, these dips have minor importance, especially for RZ-DPSK and CSRZ-DPSK formats, where the pulse carver cuts out the amplitude-modulation-free center portions of the bits only, and thus largely eliminates the effect of any residual dips. Furthermore, using a PM for phase modulation, any drive waveform imperfections get directly mapped onto the optical phase, thus potentially degrading performance, and insufficient drive bandwidth causes severe penalties, since it results in pattern-dependent, reduced phase shifts. However, using an MZM for phase modulation, any drive waveform imperfections are only translated into optical intensity variations, but the information-bearing optical phase is left intact. And insufficient drive bandwidth only affects the residual intensity dips as well as the broadening of the “1” bit eye rail due to bit patterning effect, but leaves intact the perfect π phase shifts. Hence, little impact on the performance of RZ-DPSK is observed for MZMs [21-22].

Figure 2.10: RZ-DPSK or CSRZ-DPSK modulation format generated using (a) a straight-line phase modulator and (b) a MZM

Fig. 2.11 shows the simulated spectra and eye diagrams for NRZ-DPSK (solid line) and 33% duty cycle RZ-DPSK (dashed line), as generated by a MZM for phase modulation. The carrier-free nature of the spectra is owing to the balance of $-|E|$ and $+|E|$ amplitude levels. Note that a ‘0’-bit rail in the eye diagrams is absence, which is

characteristic for phase-coded formats. The deep amplitude dips between two bits in the NRZ-DPSK eye represent the residual amplitude modulations of the MZM caused by the finite NRZ drive signal bandwidth.

Figure 2.11: Optical spectra and eye diagrams of NRZ-DPSK (solid line) and 33%-duty cycle RZ-DPSK (dashed line), as produced by a MZM for phase modulation

Since DPSK cannot be received directly with direct detection technique, an optical 1-bit delay interferometer (DI) is usually used before the receiver to convert the differential phase modulation into amplitude modulation. The DI splits the phase modulated signal into two paths and introduces an one bit duration delay into one of the paths. Using a balanced receiver, the advantage of 3dB lower OSNR requirement can be obtained for DPSK over OOK.

2.4 Frequency-Shift Keying (FSK)

Frequency-shift keying (FSK) is another modulation scheme where data is encoded on carrier frequency. FSK transmitters can be built using two different approaches: continuous-phase FSK (CPFSK) and discontinuous-phase FSK (DPFSK), denoted by CPFSK and DPFSK, respectively [23]. DPFSK can be achieved using two different lasers operating at different frequencies. A switch is used to direct the output signal of

the two lasers to the output fiber of the transmitter depending on the binary signal to be transmitted. CPFSK is more straightforward and can be achieved via direct modulation of a single laser diode with the data stream. The accompanying intensity modulation can be minimized by biasing the laser at large current with small modulation current or compensated via further external intensity modulation with inverted data pattern. This method is again limited by the bandwidth and flatness of the frequency modulation response of the laser.

FSK can also be realized by using external FSK modulator [24] which has almost the same structure as a single side band (SSB) modulator, as shown in Fig. 2.12. Two sub-Mach-Zehnder modulators are embedded in each arm of a main MZ modulator. The FSK modulator has an electrode at the main MZM for high-speed FSK signal modulation, instead of a dc-biased electrode in the SSB modulator. The two sub-MZMs are biased at the null point and driven by sinusoidal signals which have the same frequency of f_m but with a phase difference of $\pi/2$. When optical phase difference between the arms of main MZM is $-\pi/2$ or $\pi/2$, upper side band (USB) or lower side band (LSB) component at f_m is constructively generated, while the other side band components are destructively suppressed. If a NRZ baseband data at a bit rate of B is fed to the electrode of the main MZM, USB or LSB is generated according to the bit sequence of data. Thus, external FSK modulation is achieved when the mark and space levels induce the phase difference of $\pi/2$ and $-\pi/2$, respectively. In this scheme, the frequency deviation and modulation speed of the FSK signal are $2f_m$ and B , respectively.

In the above-discussed external FSK modulation, optical phase continuity is not assured during the change between USB and LSB. To obtain CPFSK signal, synchronized modulation can be used where the optical frequency is shifted at the instant when USB and LSB have the same phase [25]. This condition is satisfied when clock signals driving the two sub-MZMs have a frequency of half the data bit rate ($f_m = B/2$) and the delay between clock and data is properly selected. The externally modulated optical minimum-shift keying (MSK) format that will be discussed in chapter 4 of the thesis is a special case of CPFSK. Detailed discussion on MSK will be given there. Fig. 2.13 and 2.14 show the spectra and eye diagrams of CPFSK and MSK formats, respectively.

Figure 2.12: (a) optical SSB modulator, (b) optical FSK modulator [24]

Figure 2.13: CPFSK format. (a) spectrum, (b) eye diagram with balanced detection [25]

Figure 2.14: MSK format. (a) spectrum, (b) eye diagram with balanced detection

2.5 Performance Comparison of Different Data Formats

The modulation formats discussed above offer different levels of tolerance to transmission impairments arising from amplified spontaneous noise, dispersion, crosstalk, and fiber nonlinear effects in WDM optical transmission systems. This section provides a performance comparison among a number of modulation formats that are studied intensively.

2.5.1 Performance Comparison among NRZ, RZ, and CS-RZ

Although NRZ modulation format is the first and widely used optical modulation format, bandwidth limitation caused by transmission impairments, such as dispersion or PMD often leads to inter-symbol interference (ISI) in the bit sequence detected when such format is used, as shown in Fig. 2.15 [14]. In optical communications, ISI is particularly harmful, since detection noise often grows linearly with signal amplitude, which is valid in PIN receivers, avalanche photodiode (APD) receivers and optically pre-amplified receivers. In a PIN or APD receiver (without optical pre-amplifier), the detected signal after filtering is corrupted by two types of noise, i.e. thermal noise and shot noise dominantly.

The thermal noise of a receiver arises from the fact that electrons in a receiver circuit have some probability of generating a current even in the absence of an optical signal. This noise is often referred to as Johnson noise. The shot noise is due to the Poissonian distribution of the electron-hole generation by the photon stream.

However, optical receiver often uses optical pre-amplification to boost the weakly received signal to appreciable power levels prior to detection, in order to achieve high sensitivity. At the same time, fundamentally unavoidable, amplifier spontaneous emission (ASE) is introduced by the amplification process and becomes the dominant noise in such systems. Upon detection, the random ASE field beats against the signal field, as well as against itself, leading to signal-ASE noise and ASE-ASE beat noise after electrical filtering. The signal-ASE beat noise grows linearly with signal power.

Figure 2.15: Eye diagram for NRZ and RZ signals, under the same average optical input power and same filtering condition. ISI affects NRZ performance while it is not seen for RZ [14]

A. Tolerance on Optical Noise between NRZ and RZ

In the past decades, performance comparison on tolerance to optical noise, fiber nonlinearities, and dispersion, between NRZ and RZ are carried out both theoretically and experimentally [26-35]. The studies show that RZ offers a 2dB gain over NRZ format, in terms of the receivers sensitivity [19, 36]. This is based on the fact that the same average power is received for both NRZ and RZ modulation formats since the average received power is normally limited by the saturation power of EDFAs. As a

result, for RZ format, the pulse energy is concentrated in a shorter time interval, providing a larger eye opening for the same filter bandwidth and the possibility of enhanced noise rejection at decision point. However, the performance significantly depends on the NRZ waveform, the type and the characteristics of the receiver. As pointed out in [37], if optimum receivers are used, NRZ has the same sensitivity as the RZ with arbitrary duty cycle. The empirical 2dB sensitivity improvement for RZ modulation over NRZ is achievable in sub-optimal receivers.

B. Tolerance on CD and PMD between NRZ, RZ, and CS-RZ

The simulation results in [28, 34] show that when a system is assumed to have chromatic dispersion (CD) alone, RZ format incurs smaller power penalties than NRZ format in the weak-dispersion regime. However, RZ format tends to be degraded more rapidly by CD than NRZ format. In other words, for stronger CD, the power penalties of RZ format increase rapidly and become much larger than the NRZ format. Intuitively, this is because the signal power spectrum has a wider main lobe for RZ than for NRZ. However, when 40Gb/s signals propagate in a pulse-overlapped or “pseudo linear” regime [38], RZ outperforms NRZ-OOK in this regime [27, 38].

As a generally accepted wisdom, RZ is a format that would always be more robust to polarization mode dispersion (PMD) than NRZ, due to the higher temporal confinement of the RZ pulses [34]. However, the robustness of RZ compared to NRZ with respect to first-order PMD depends strongly on the receiver and should not be considered to be a property of the modulation format alone. P. Winzer showed in simulation and experiment that NRZ had superior PMD tolerance than RZ when the receiver bandwidth was high. When the electrical bandwidth was around 0.75R for

optically pre-amplified receivers, and around $0.6R$ for receivers without optical pre-amplifier, the two formats exhibited the same performance. Below these receiver bandwidths, RZ outperformed NRZ in PMD tolerance [33].

Narrower signal spectrum generally leads to an increased dispersion tolerance. CS-RZ format has a better dispersion tolerance compared to RZ format, due to its narrow pedestal shape of the optical spectrum than the conventional RZ format [39].

C. Tolerance on Nonlinear Effects between NRZ, RZ, and CS-RZ

In Forghieri's simulation [29], fiber nonlinear effects, such as self-phase modulation (SPM), cross-phase modulation (XPM), stimulated Brillouin scattering (SBS), and stimulated Raman scattering (SRS), are considered individually. From his analytical results, it is shown that SBS and SRS have the same effects on RZ and NRZ modulated system; but XPM grows as $1/\rho$ and SPM and FWM grow as $1/\rho^2$, where ρ is the duty cycle. Hence, NRZ appears more robust than RZ in nonlinear impairments. However, this is a purely theoretical analysis and it only considers one impairment at one time. Many studies carried out in recent years show that RZ provides better nonlinear tolerance than NRZ format, and RZ normally offers a better performance in high speed optical communication system. In particular, data pattern dependence of SPM for NRZ means that its pattern effect is much higher than that of RZ. Hayee showed by both simulation and experiment that power penalties due to nonlinearity is more severe in NRZ as compared to RZ, in dispersion-managed WDM systems [28].

In recent years, CS-RZ format has been studied and proposed in a number of transmission experiments because of its higher tolerance to the mixed effect of SPM

and group velocity dispersion (GVD) and its narrower pedestal shape on the optical spectrum compared to the conventional RZ format [40-42]. Simulation results have shown that in a non-fully compensated system, in which the pulse shape of the individual channel would not be fully recovered to the original shape at the end of each span, the eye penalties of the CS-RZ modulated system increase slower than that in a RZ case as the average channel power increases. This performance improvement can be attributed to the factor that there was less nonlinear pulse-to-pulse interaction for consecutive ones in CS-RZ format, and hence less distortion. This is because CS-RZ can maintain the pulse shape even on consecutive ones. This pulse-shape confinement is the result of the 180° phase shift imposed between consecutive ones. The 180° phase shift between consecutive bit slots gives a narrow signal spectrum. Y. Miyamoto *et al.* showed that CS-RZ is more superior than NRZ with a 4.5dB enhancement in dynamic range of channel output power, in a system operated in non-zero dispersion-shifted fiber with terminal dispersion compensation [42]. This is because CS-RZ format can be considered as a two-carrier signal with a frequency spacing equal to the bit rate, and each carrier is NRZ modulated, so the power densities of the two NRZ components of the CS-RZ signal are half that in the NRZ signal.

The generation of FWM is proportional to the square of the two dedicated component powers, and its dependence on the channel power shows a rapid nonlinear increase. As a result, CS-RZ has lower four wave mixing (FWM) crosstalk than the NRZ signal. However, this FWM penalty improvement is true only when WDM channel spacing is greater than 100GHz. It has been shown that CS-RZ format will cause severe FWM penalty in 75GHz-spaced WDM systems and it is not suitable for transmission of

DWDM signals at 43Gb/s with a channel spacing of 50GHz if a standard configuration is considered. This is because in a 43Gb/s CS-RZ signals spaced at 75GHz, a CS-RZ signal spectrum contains two major line components at a frequency of $f_{c,i} \pm 21.5GHz$, where $f_{c,i}$ is the original carrier frequency of the i^{th} channel. In the presence of neighboring channels, different combinations of line components will generate FWM light at various optical frequencies. If some of those FWM components fall within the signal bandwidth of a channel, strong coherent beat noise will be imposed on the signal and will lead to a severe eye opening penalty. In the 75GHz spaced WDM, two major FWM components at frequencies $f_{c,i} \pm 10.5GHz$ fall well within the signal bandwidth of the central channel. Hence, this leads to severe system penalty [40, 43].

In summary, the evaluation on which modulation format, NRZ, RZ, or CS-RZ, provides a better system performance is dependent on a number of factors and system parameters, which include dispersion compensation technique, data bit rate, number of channels, channel spacing, receiver filter and which impairment is the most dominant factoring a particular system, etc.. Different conclusions may be drawn with different considerations and different impairments. However, it is well recognized that RZ has better transmission performance than NRZ for typical systems with ITU standards. Nevertheless, NRZ can be used for shorter distances, particularly in terrestrial systems, or for data rates lower than 10Gb/s where the added performance benefit of RZ does not justify the additional complexity.

2.5.2 Performance Comparison between ASK and PSK

Comparing with OOK, DPSK modulation format has several advantages and reacts differently to system impairments. In a DPSK modulated system, a 3dB improvement in OSNR requirement can be achieved for a given bit error rate (BER) if a balanced receiver is employed [44-46]. This, in turn, gives an increased system margin, which can be used to reduce the input power to the fiber spans, to increase the length of the fiber link, or to relax components specifications. DPSK with balanced detection has also been demonstrated to offer large tolerance to signal-power fluctuations in the receiver since its decision threshold is independent of the input power. Furthermore, DPSK is more tolerant to tight optical filtering than OOK, especially when balanced detection is employed. The reason for the higher robustness to tight optical filtering in balanced detected DPSK lies in its better tolerance to ISI [36, 46]. OOK can take a severe hit in eye opening due to pulse distortions brought by the optical filter. Such distortions are mitigated for DPSK due to the duobinary nature of the DI-demodulated DPSK signals [21].

In 10Gb/s transmission systems, simulation and experiment studies on CD and PMD tolerance [34, 47-53] showed that DPSK can tolerant more PMD for both PMD uncompensated and compensated systems [34, 47] and some CD advantage has been reported for NRZ-DPSK [48, 53]. However, transmission performance in fiber is also affected by Kerr nonlinearity, which reveals as FWM, SPM and XPM [54]. The extent of these effects depends on several system design factors, including average optical power, peak optical power, modulation format, transmission regime, and the nonlinear interaction of signal with ASE noise. Simulations and experiments have shown that DPSK and its pulse carved forms are more tolerant than OOK to some

nonlinear effects, such as SPM and XPM [48, 55-56]. Hence, many recent high speed long-haul 10Gb/s and 40Gb/s WDM transmission records are held by (RZ-) DPSK modulation systems [45, 57-60]. The reasons for this are that the phase-shift keyed formats have 3dB lower peak power than their OOK counterparts at the same average optical power, and constant pulse amplitude, i.e., power is present in every bit slot, which reduces bit-pattern dependent nonlinear effect [21].

However, DPSK format is more sensitive to phase disturbances caused by fiber nonlinearities. This is because amplitude fluctuations caused by ASE noise can be converted into phase noise by Kerr nonlinearity, and this nonlinear phase noise can limit the performance of PSK transmission systems [61]. It has been shown experimentally that the advantage of DPSK is not applicable in a 10Gb/s DWDM transoceanic length system given the potential large waveform distortions and more stringent phase noise requirements on signal lasers [61-62]. K. Ishida *et al.* also showed that in a transoceanic system, the Q degradation of RZ-DPSK was 3dB larger than that of RZ-ASK after transmission over 9180km, due to nonlinear phase noise effect [63]. However, J. X. Cai *et al.* showed that Q-factor improvement of 2-3dB for most of the channels using RZ-DPSK format over that of RZ-OOK format after transmission over 11,000km, also in a 10Gb/s system [58]. Hence, the system performance depends heavily on the design parameters, such as pump power, number of channels, channel spacing, repeater spacing, etc. [58, 61-63]. Generally speaking, it appears that long-haul 10Gb/s single-channel OOK systems can outperform DPSK systems, which are limited by the nonlinear phase noise caused by Gordon-Mollenauer effect [64]. However, the single-channel performance is highly system

dependent, and there can be cases in which DPSK will outperform OOK. For 40Gb/s systems, the effect of nonlinear phase noise is much smaller.

In 10Gb/s WDM systems, both experimental measurements and computer simulations indicate that (RZ-)DPSK and OOK perform similarly at a spectral efficiency of 0.2b/s/Hz [63-64]. At a spectral efficiency of 0.4b/s/Hz and higher, (RZ-)DPSK, due to its increased robustness to XPM, can outperform OOK [58, 64-65]. However, the system performance again is dependent on many factors, including channel power and dispersion map. At 40Gb/s, intrachannel effects in the pulse-overlapped (pseudolinear) regime dominantly limit signal transmission [38]. In particular, intrachannel FWM (IFWM) transfers power between bit slots as pulses disperse into each other and mix due to fiber nonlinearity. The resulting effect in OOK is amplitude fluctuations on the “1”s, and “ghost pulses” (residual power) on “0”s [38]. In (RZ-)DPSK systems, the phase fluctuations from this mixing are more detrimental than amplitude fluctuations. In intrachannel XPM (IXPM), intensity fluctuations of the dispersed, overlapped pulses modulate the optical phase. The resulting effect in OOK is timing jitter and the phase fluctuations are detrimental. As mentioned earlier, undistorted (RZ-)DPSK has 3dB lower peak power than OOK for a given average power, since it has power in each bit slot. In the pulse-overlapped regime, nonlinear (RZ-)DPSK penalties can be reduced because of this more smoothly distributed power [66]. Also, correlation between the nonlinear phase shifts experienced by adjacent bits, combined with differential detection, should reduce nonlinear DPSK penalties [67]. Experimental results have consistently shown that (RZ-)DPSK has better performance than OOK in 40Gb/s single-channel and WDM systems. While the OOK signal is severely limited by IFWM, the (RZ-)DPSK signal is not. The performance of (RZ-)DPSK (with

balanced detection) is more than 5dB better than that of OOK [22, 68]. Field trial and laboratory transmission experiments show that spectral efficiency as high as 0.8b/s/Hz can be achieved using (RZ-)DPSK format at 40Gb/s systems [60, 69]. Hence, (RZ-)DPSK could be the major modulation format to be used in next generation transmission systems, especially for systems with channel bit rate of 40Gb/s and beyond.

2.5.3 Performance Comparison among FSK, ASK, and PSK

As introduced in section 2.4, FSK format can be generated by direct modulation scheme or using external modulators. The performance of the direct modulated FSK systems have been studied and compared with ASK and PSK in [70-73]. It has been shown that FSK with a differential receiver also provides around 3dB lower OSNR requirement than ASK, which is similar to a DPSK modulated system. Compared with ASK, FSK transmission with differential detection provides 47% and 32% increased dispersion tolerance for 1dB and 2dB OSNR penalty respectively [72]. However, DPSK with balanced detection still provides the largest dispersion tolerance [71]. In terms of nonlinearity tolerance, particularly the SPM effect, FSK shows higher tolerance than ASK in a single span standard single mode fiber (SMF) transmission (80km), but only performs comparable to ASK in a three-span transmission (240km) [71]. Nevertheless, a 10.7Gb/s FSK transmission with span loss of 61dB has been demonstrated experimentally [72-73].

On the other hand, there is no performance comparison of externally modulated FSK, especially CPFSK, with other ASK and PSK formats being reported today. The performance of an externally modulated MSK format, which is a special case of

CFPSK, will be studied and compared with other externally modulated ASK and PSK formats in chapter 5.

2.6 Conclusions

In this chapter, optical fiber transmission systems and the basic principles of generating various externally modulated optical ASK, PSK, and FSK signals are explained and discussed. The performance comparison among various modulation formats such as ASK, PSK, and FSK by researchers in the past 20 years shows that which format provides a better system performance is heavily dependent on many factors and system design parameters, which include dispersion compensation technique, data bit rate, number of channels, channel spacing, receiver filter and which impairment is the most severe one in a particular system, etc. Different conclusions may be drawn for different considerations and different system impairments. Nevertheless, (RZ-)DPSK has demonstrated excellent system performance, especially in high spectral efficiency systems and systems with channel bit rate of 40Gb/s and above. It is generally accepted that (RZ-)DPSK might be the major modulation format to be used in next generation optical transmission systems.

Chapter 3

PSK Formats in SOA Amplified Transmission System and Single-span Transmission System

3.1 Introduction

From the literature review in chapter 2, it has been well accepted that phase modulated formats (PSK) have several advantages over amplitude modulated formats (ASK). Firstly, PSK has 3dB lower requirement in optical signal-to-noise ratio (OSNR) over ASK when a balanced detection is employed. This, in turn, can be used to achieve longer reach, to increase the system margins, or to relax component tolerances. Secondly, PSK is more tolerant to signal power fluctuations in the receiver decision circuit than ASK due to the fact that the decision threshold for PSK bit error rate (BER) testing is independent of the input power in the balanced detection. Thirdly, PSK is more robust to narrow-band optical filtering than ASK. And fourthly, PSK is more resilient than ASK to some fiber nonlinear effects, such as cross-phase modulation (XPM) and stimulated Brillouin scattering (SBS), due to the fact that PSK format has constant pulse amplitude, lower peak power for the same average power, and the absence of discrete clock tones.

PSK formats have been extensively studied in long haul and ultra-long haul WDM transmission systems which use Erbium-doped fiber amplifiers (EDFAs) and/or Raman amplifiers as in-line amplifiers. However, there has been very little work on evaluating the system performance of PSK modulated WDM systems using

semiconductor optical amplifiers (SOAs) as in-line amplifiers and of PSK modulated long single-span WDM transmission using bidirectional Raman pumps.

Comparing with other types of optical amplifiers, SOAs provide many advantages. These include compact size, ease of integration with other devices, ultra-wide available gain spectrum, and possibly low cost. SOAs have been used in many applications as an essential device for all optical networks, optical signal processing, and all optical switching. However, in amplification applications, SOA can not operate at its saturation power regime, due to its speedy gain dynamics that would cause its gain to be modulated by the bit pattern on the input signal [74-76]. With very fast gain dynamics of around 100ps typically, a number of nonlinear effects can be generated easily, such as self-gain modulation (SGM), saturation-induced self-phase modulation (SPM), cross-gain modulation (XGM), cross-phase modulation (XPM) and four-wave mixing (FWM). These nonlinear effects cause severe degradation and make SOA's usage as in-line amplifiers impractical [77-79]. However, due to the fact that the signal power of DPSK format is constant in nature, it would be possible to use it in SOA-based WDM transmission link to reduce the XGM effect. This motivates us to study the suppression capability on the XGM effect in a DPSK modulated WDM transmission system using SOAs as in-line amplifiers. Longer transmission distance and larger bit rate-distance product should be expected.

Using Raman amplification and advanced modulation formats like RZ-DPSK have shown promising results in long haul transmissions [80-81]. The spectra difference between DPSK and OOK that has been observed, in particular the absence of discrete clock components for DPSK and its pulse carved formats, suggests that it may offer

better tolerance to other nonlinear effect, such as SBS, comparing with OOK modulated systems. This motivates us to study the performance of an RZ-DPSK modulated transmission system with Raman pumps, particularly, to examine the SBS threshold in a bidirectional Raman pumped RZ-DPSK transmission system.

The motivation for the SBS threshold study is mainly to achieve longer repeater spans (i.e. to reduce the number of repeaters), and hence potentially to lower the operating costs of medium and long haul terrestrial systems. Previous studies on long single span length (>200km) were achieved by deliberately arranging fibres with different core areas (hybrid optical fiber solution) [82-83] and/or through the use of remote-pumping amplifiers [82]. However, in order to make full use of the widely deployed standard SMF plants, and to avoid complicated cabling and facilitate future upgrades, the use of hybrid optical fiber solution and remote-pumping amplifiers is not desirable. A better scheme should be proposed, such as using advanced modulation formats like RZ-DPSK, instead of using the simplest modulation format as NRZ-OOK.

The rest of this chapter is organized as follows. Section 3.2 discusses the WDM transmission using SOAs as in-line amplifiers. In this section, the basic property of an SOA is first introduced. This is followed by experiments which show that DPSK signal indeed can suppress the XGM effect induced by an SOA. The optimal power and optimal operating current of an SOA are studied experimentally. Transmission experiments are also demonstrated in this section. Section 3.3 discusses the study on a single-span transmission system with bidirectional Raman pumps. In this section, the SBS thresholds of both the RZ-OOK and RZ-DPSK modulated systems are studied.

An error free unrepeated transmission of 8x10.709Gb/s RZ-DPSK signals with bidirectional Raman pumping is demonstrated.

3.2 WDM Transmission using SOAs as in-line amplifiers

3.2.1 Fundamental of SOAs

As early as the 1960s, it was recognized that a gallium arsenide laser diode could be used as an amplifier of infrared light if the reflectivity of its facets was reduced. And great interest on SOAs has been shown in the scientific literature since the beginning of 1990s. Over the pass decades, SOAs have shown many advantages, such as compact size, ease of integration with other devices, ultra-wide available gain spectrum, and possible low cost. However, comparing with other types of optical amplifiers, due to the fast gain dynamics of an SOA, SOA can not operate at its saturation power regime in amplification applications. This is because the speedy gain dynamics would cause its gain to be modulated by the bit pattern on the input signal. With such very fast gain dynamics, a number of nonlinear effects can be generated easily, such as SGM, saturation-induced SPM, XGM, XPM, and FWM. These nonlinear effects cause several drawbacks and make SOA's usage as in-line amplifiers impractical.

By ignoring the dispersive effects due to the negligible material dispersion and short amplifier length, and assuming the pulse duration is much shorter than carrier lifetime ($\tau_p \ll \tau_c$), pulse propagation in SOAs can be written as [17],

$$\frac{\partial P}{\partial z} = g(z, \tau)P(z, \tau) \quad (3.1)$$

$$\frac{\partial \phi}{\partial z} = -\frac{1}{2}\beta_c g(z, \tau) \quad (3.2)$$

$$\frac{\partial g}{\partial z} = -g(z, \tau)P(z, \tau)/E_{sat} \quad (3.3)$$

where P is the optical power, ϕ is the phase shift, g is the optical gain, $\tau = t - \frac{z}{v_g}$ is the reduced time, v_g is the group velocity, β_c is the linewidth enhancement factor due to the carrier induced index changes, and $E_{sat} = P_s \cdot \tau_p$ is the saturation energy.

Equations (3.1) to (3.3) give the amplification process of optical pulses in SOAs. Equation (3.1) describes the amplification of the pulse power, equation (3.2) shows the phase modulation on the optical carrier and hence broadens the spectrum width, and equation (3.3) shows the nonlinear amplification process caused by the gain saturation. Integrating equation (3.1) and (3.2), the amplification factor $G(\tau)$ is given by

$$G(\tau) = \frac{G_0}{G_0 - (G_0 - 1)\exp[-E_0(\tau)/E_{sat}]} \quad (3.4)$$

where G_0 is the unsaturated amplifier gain and $E_0(\tau) = \int_{-\infty}^{\tau} P_{in}(\tau')d\tau'$ is the partial energy of the input pulse with $E_0(\infty)$ equals the input pulse energy E_{in} .

Equation (3.4) shows that this amplification process is related to the input pulse shape and is the integration over the pulse duration. The amplifier gain is different for the different parts of the pulse. The leading edge experiences the full gain G_0 as the amplifier is not yet saturated. While the trailing edge experiences the least gain since

the whole pulse has saturated the amplifier gain. The shape dependence of the amplification factor $G(\tau)$ implies that the output is distorted, and the distortion is itself shape dependent. This is the SGM phenomenon, which is also called pattern effects, as shown in Fig. 3.1(b). Furthermore, as shown in equation (3.2), the gain saturation leads to a time-dependent phase shift across the pulse.

Integrating equation (3.2) over the amplifier length, equation (3.2) becomes

$$\phi(\tau) = -\frac{1}{2}\beta_c \int_0^L g(z, \tau) dz = -\frac{1}{2}\beta_c \ln[G(\tau)] \quad (3.5)$$

Since the phase of the pulse is modulated by the pulse itself through gain saturation, this phenomenon is referred to as saturation-induced SPM. SPM and the associated frequency chirp can impair lightwave systems considerably [17]. The spectrum of the amplified pulse becomes broader and contains several peaks of different amplitudes.

Although SOAs can be used to amplify several channels simultaneously, they suffer from a fundamental problem related to their short gain recovery time. (The gain recovery time for SOAs is in the range of few hundred pico-second. While for EDFAs, the gain recovery time is in the range of 1ms~10ms.) Ideally, the signal in each channel should be amplified by the same amount. In practice, several nonlinear phenomena in SOAs induce interchannel crosstalk, which is undesirable and should be minimized for practical lightwave systems. Two such nonlinear phenomena are XGM and FWM. Equation (3.6) gives the total power P in a multi-channel amplification case as

$$P = \sum_{j=1}^M P_j + \sum_{j=1}^M \sum_{k \neq j}^M 2\sqrt{P_j P_k} \cos(\Omega_{jk}t + \phi_j - \phi_k) \quad (3.6)$$

where M is the number of channels, and $\Omega_{jk} = \omega_j - \omega_k$ is the beat frequency.

Hence, the gain of a specific channel is saturated not only by its own power but also by the power of its neighboring channels, which is known as XGM whose effect is shown in Fig. 3.1(c). It is undesirable in WDM systems since the amplifier gain changes with time depending on the bit patterns of neighboring channels. As a result, the amplified signal appears to fluctuate more or less randomly. Such fluctuations degrade the effective signal-to-noise ratio (SNR) at the receiver. Equation (3.6) also shows that due to the beat frequency Ω_{jk} , interchannel crosstalk can be induced by transferring a part of the signal from one channel to another. This interchannel crosstalk occurs regardless of the channel spacing [74-76]. Interchannel crosstalk induced by FWM occurs for all WDM systems irrespective of the modulation format used. FWM can occur even for widely spaced channels as a result of intraband processes, such as spectral hole burning and carrier heating [74]. This can cause crosstalk and severely affect system transmission performance if the mixing products fall within the band of other signal channels.

Figure 3.1: Impact on eye patterns by SGM and XGM pattern effects from SOA. (a) original signal, (b) one-channel after one SOA, (c) 6-channels after one SOA

3.2.2 Reduction of XGM Effect Arising from SOAs

Using conventional OOK modulation formats, such as NRZ-OOK and RZ-OOK, the XGM effect of SOAs may introduce a large amount of distortion to individual

channels in a WDM transmission system, which in turn may considerably degrade the transmission performance of the system [78]. This limits SOA's use to only in modest-distance, moderate-channel-count environments such as access or metro network. Transmission systems using SOAs as in-line amplifiers for 8x10Gb/s over 240km, 8x20Gb/s over 160km, and 32x2.5Gb/s over 125km were reported in [77-79]. Recently another SOA-based transmission system with 4x10Gb/s over 500km was demonstrated using cascaded SOAs and a new wavelength modulation technique, where a pair of wavelengths with 0.3nm spacing was used for a single signal channel to maintain a constant amplitude [84]. Although this paired-wavelength technique can improve the transmission distance, it has two problems. Firstly, it requires two wavelengths for a single channel, leading to increased implementation cost. Secondly, if the two wavelengths of the wavelength pair are far apart, the chromatic dispersion will soon destroy the constant amplitude, while a too closed wavelength separation will make it very difficult for the receiver to separate them. Due to the fact that the signal power of DPSK format is constant in nature, it would be possible to use it in SOA-based WDM transmission link to reduce the XGM effect. G. Onishchukov reported the error free transmission of a single-channel DPSK at 1300nm over 500km using SOAs as in-line amplifiers [85].

Figure 3.2 shows the experimental setup of an 8x10.709Gb/s DPSK and SOA-based WDM system. Eight distributed feedback (DFB) lasers in the wavelength range of 1542nm-1561nm with 400GHz channel spacing are combined using a polarization maintained WDM multiplexer. The light is externally modulated by a 10Gb/s LiNbO₃ phase modulator, which is driven with 10.709Gb/s DPSK, 2²³-1 pseudorandom bit stream (PRBS) signal. 10.709Gb/s is the typical data rate for systems with FEC at 7%

overhead, although the FEC technique is not used in the transmission. A recirculating loop is constructed to evaluate the long distance transmission. The total length of the loop is 150km, which includes three sections of 40km single mode fiber (SMF) and one section of 30km SMF, and the total fiber loss in the loop is about 31.8dB. For DPSK signals, phase modulation may transform into amplitude modulation when it propagates through dispersive fiber. Therefore, no pre-compensation is used in the experiment. Dispersion compensation fiber (DCF) modules are placed after each section of SMF to achieve full dispersion compensation. The DCF used are from Fujikura Ltd, which is the dispersion compensation fiber module for G.652. Same type of DCF has been used in all the experiments throughout this thesis. Each span is amplified by an SOA to compensate the loss of SMF and DCF. Hence, there are four SOAs used in the recirculating loop. The SOA used in the experiment is non-gain-clamped with a saturation output power of about 8dBm under 200mA driving current, and its noise figure is about 6dB typically. Therefore, with total input power of -4dBm (-13dBm/channel), the output power of the SOA is about 8dBm(-1dBm/channel) at this operating current. An EDFA is used to compensate the losses introduced by the devices for the loop operation, which includes a dynamic gain equalizer (DGE), an acousto-optical switch, and a 3dB coupler. The demultiplexed signal is demodulated by an asymmetric Mach-Zehnder Interferometer (AMZ) with 1-bit delay between the two arms and detected by a balanced receiver.

Figure 3.2: Experimental setup of a recirculating loop using SOAs as in-line amplifiers and DPSK modulation format

It is well known that FWM effect in SOAs is severe and it is one of the dominant limiting factors in SOA-based WDM transmission system. First of all, FWM effect in this PSK modulated WDM system is investigated.

FWM is an ultra-fast nonlinear effect, which can transfer both intensity information and phase information from the input signals to their mixing products. For signals whose wavelengths are chosen to follow the ITU-T grid, since the channel spacing is constant, some of the mixed products may fall within the band of other signals. This crosstalk may severely affect the transmission performance and is the major limiting factor in the transmission system under study.

The effect of FWM in SOA is investigated experimentally by measuring the ratio of the signal power of a given signal channel to the power of the FWM components at this channel contributed by signals at other wavelengths. The measurement is carried out with different channel spacing ranging from 100GHz to 400GHz. After 1050km

transmission, the ratio and Q-factor for the central channel (here, the 5th channel, $\lambda = 1550.5\text{nm}$) are shown in Fig. 3.3. The Q-factor is given by the following expression:

$$Q = \frac{|\mu_1 - \mu_0|}{\sigma_1 + \sigma_0} \quad (3.7)$$

where μ_1 and μ_0 are the mean values of the data “1” and data “0”, respectively, and σ_1 and σ_0 are the standard deviations of the data “1” and data “0”, respectively, at the sampling time. The Q-factor is a dimensionless quantity and it is usually expressed in decibels as $20\log(Q)$.

It is obvious that when channel spacing is increased, the FWM effect is weakened. The lower the FWM effect, the higher the Q-factor. On the other hand, with non-constant channel spacing, following the algorithms suggested in [86], the Q-factor penalty is much lower than the results shown in Fig. 3.3. This indicates that FWM is the main factor affecting the transmission performance. However, this non-constant channel spacing technique is not used in the transmission study here.

Figure 3.3: Q-factors and the corresponding FWM power vs. channel spacing

In summary, in DPSK modulated transmission systems using SOAs, XGM effect is no longer the limiting factor of the system performance, instead, FWM effect becomes dominant in determining the maximum transmission distance.

3.2.3 Optimal Operation Conditions for SOAs

As discussed in section 3.2.2, FWM is the main factor affecting the transmission performance. FWM effect in SOAs is an ultra-fast non-linear interaction between the optical fields in the active semiconductor materials. In a WDM system with equal channel spacing with SOAs as in-line amplifiers, the new wavelength components generated through the FWM effect in SOAs may fall into the signal channel wavelengths, giving rise to crosstalk, which can be the limiting factor for the performance of the transmission system. In such a transmission system, the maximum optical power injected into the SOAs is limited by the FWM effect, and the minimum input power is limited by the spontaneous emission noise generated in SOAs. As a result, there exists an optimal input power to optimize the system performance.

For N WDM channels launched into an SOA, the total number of mixing products generated in the SOA is $M = \frac{1}{2}(N^3 - N^2)$ [87]. The performance of the signal at the s -th wavelength channel may be affected by the FWM products generated from the combinations of the p -, q -, and r -th channels. These channels satisfy the following condition: $p + q - r = s$, where s represents the selected signal channel frequency. The channel combinations for the total FWM products can be classified into three categories. One is the case where the p -, q -, and r -th channel frequencies are different

but the r -th channel frequency is identical to the selected signal channel ($p \neq q \neq r = s$). The second case is where all channels, including the selected channel, are different ($p \neq q \neq r \neq s$). The last case is where the p - and q -th channels are identical, while different from the r -th channel ($p = q \neq r$). This can be expressed as

$$\sum_{pqr} = \sum_{p \neq q \neq r = s} + \sum_{p \neq q \neq r \neq s} + \sum_{p = q \neq r} \quad (3.8)$$

Due to the existence of FWM from the first category, i.e. the FWM generated from the p - and q -th channels and the FWM product has the same frequency as the signal channel, it is unable to be separated from the intended data channel. Fig. 3.4 shows the experimental setup for the evaluation of optimal operation conditions for SOAs. Sixteen DFB lasers are located in the wavelength range of 1536.61nm-1560.61nm with 200GHz channel spacing. The outputs of the sixteen DFB lasers are multiplexed by a polarization maintaining array waveguide grating (PM-AWG). The multiplexed signal is encoded with 10.709Gb/s NRZ-DPSK signal using a phase modulator, which is driven by a PRBS data signal with a word length of $2^{23}-1$. No polarization controller at the modulator output is used to reduce the FWM effect. The SOA is biased at an operating current of 221mA. The selected channel for the measurement is at 1549.32nm, which is closer to the center wavelength channel within the wavelength range and experiences the most severe FWM.

Figure 3.4: Experimental setup for evaluating the optimal operation condition for SOA

As an initial setup, the FWM crosstalk that falls into the selected channel (1549.32nm) is measured using an optical spectrum analyzer as a function of the input power of the evaluated channel. Fig. 3.5 (a) shows the optical spectrum of the multichannel signals after the amplification from one-stage SOA. The high peaks are signal, which includes data signal, FWM products and ASE noise, and small peaks are FWM products and ASE noise. In the case of equally spaced channels, most new frequencies coincide with the existing channel frequencies. Hence, the magnitude of the new frequency components does not coincide with the existing channel frequencies are relatively small. These new frequency components are contributed mainly by the second and the third cases as discussed above. The wavelength of the selected channel is adjusted from 1549.32 to 1548.51nm in order to be separated from the FWM products at 1549.32nm, which are also contributed mainly by the second and the third cases as discussed above. The power of the FWM products from the first case can not be extracted from the signal power at 1548.51nm, according to the above discussion. Ignoring the FWM product from the first case and the high-order FWM products, the OSNR can be roughly estimated by dividing the signal power at 1548.51nm by the power of FWM at 1549.32nm, where OSNR is generally defined as the ratio of the signal channel power to the power of the ASE in a specified optical bandwidth, usually taken by convention to be 0.1nm. Throughout this thesis, the measured OSNR is also with 0.1nm resolution.

As seen from the Fig. 3.5(b), ASE noise dominates at low input power. When the input signal power increases, the output OSNR reaches its highest value, and a further signal power increase leads to OSNR degradation due to FWM effect. Hence, there is

an optimal input power providing a maximum OSNR. Fig. 3.5 (b) shows that the optimal input power of the evaluated channel is around -3.35 dBm to -1.3 dBm for the particular SOA setup.

Figure 3.5: (a) Optical spectrum to illustrate the measurement method; (b) FWM, ASE noise and OSNR as a function of input power, at a fixed amplifier operation current of 221mA

Figure 3.6 (a) shows the OSNR curves as a function of the input power, at different amplifier bias current. The lower the operating current, the higher the achievable maximum OSNR and the higher the optimal input power is. However, this also means

a lower amplifier gain, which will led to a shorter amplifier span, as shown in Fig. 3.6 (b). In a WDM transmission system, each span is amplified by an SOA to compensate the fiber loss. Therefore, when a minimum required gain from SOA is fulfilled, the smaller the operating current, the higher the obtainable OSNR. For example, in a system with a span loss of 12dB, the operating current can be around 172mA in order to provide a sufficient gain and the corresponding optimal input power is in the range of -3.35dBm to -1.3dBm .

Figure 3.6: OSNR and amplification gain versus input power for different amplifier operating currents

Similar studies with different SOAs from different manufacturers have also been carried out using the same experiment setup. Similar trend can be obtained although the optimal SOA operation current and optimal input power are different.

3.2.4 Transmission Experiments Using SOAs as In-line Amplifiers

In this section, the experimental results of SOA-based transmission systems are discussed. Firstly, with 400GHz channel spacing, an 8x10.709Gb/s transmission over 1050km standard SMF is achieved with 6dB power margin over the FEC threshold, using SOAs as in-line amplifiers and DPSK modulation format. Secondly, with the optimum operating conditions obtained in section 3.2.3, a 16x10.709Gb/s DPSK modulated signal is transmitted over 640km with a power margin of 4.5dB over FEC threshold, which is the largest bit rate-distance product ($BL = 109.7\text{Tb}\cdot\text{s}^{-1}\cdot\text{km}$) reported.

3.2.4.1 8x10.709Gb/s WDM transmission over 1050km SMF using cascaded in-line SOAs and DPSK modulation format

The experimental setup is the same as that in Fig. 3.2. The channel spacing is 400GHz and the total launched power is 8dBm. From the study results presented in section 3.2.2, it has shown that when the channel spacing becomes narrower, the FWM effect is severer, and the Q-factor is lower. In order to transmit the distance as long as possible, the FWM effect has to be within an acceptable range. And considering the bandwidth available in C-band for 8-channel transmission, 400GHz is chosen to be the channel spacing for this experiment. The total launch power is decided based on

the quick performance measurement among a few different launch powers, since this transmission experiment is carried out before the optimization study presented in section 3.2.3. Fig. 3.7 illustrates the Q-factor for the eight channels at different transmission distances - 750km, 900km and 1050km. The inset A shows the waveform of channel 5 before demodulation after 1050km of transmission, where small ripples can still be observed, which is the result of residual dispersion in the transmission link. The inset B is the eye diagram of the demodulated signal, which shows a wide and clear eye opening. The Q-factor for all the eight channels are higher than 15, which give more than 6 dB power margins over the forward error correction (FEC) (7% redundancy) threshold, which has a Q-factor of 9.2 dB corresponding a BER of 10^{-4} . This margin can be traded-off for increased repeater spacing, increased system reach and/or increased capacity.

Figure 3.7: The Q-factor versus wavelength after 750km, 900km, and 1050km transmission

The trends of the three lines in Fig. 3.7 also indicate that signals at longer wavelengths have better performance than that at shorter wavelengths. This might be because the FWM efficiency for down conversion (to shorter wavelength) is higher than that for up conversion [88]. Furthermore, the worse OSNR at shorter wavelengths may also partially contribute to this observation. It can also be found that the Q-factor for signals at 1550.92nm is slightly lower than the neighboring channels. This is mainly because this channel suffered more FWM crosstalk from the neighboring channels than other channels. The FWM effect is strongly polarization dependent, the more the co-polarized components that the two input signals have, the higher the FWM efficiency will be. In this experiment, since all the signals are combined using polarization maintained WDM, the polarization state of the signals are completely parallel to each other. Therefore, it is the worst case that was investigated. Better transmission performance can be expected if even and odd channels can be orthogonally polarization multiplexed.

It is worth to point out that in this particular experiment setup, the SMF is only 40km per span and it is compensated by the DCF before entering a SOA for amplification. This arrangement reduces the pattern effects in a SOA. And since the fiber length is relatively short and the fiber launch power is low, the phase noise caused by the fiber Kerr nonlinearity is not severe. Instead, the XGM and FWM effects from the SOAs are much more serious, as the results shown in section 3.2.2.

The successful transmission of 8x10.709Gb/s channels over 1050km using SOAs as in-line amplifiers and DPSK modulation format, to the best of our knowledge, is the longest distance transmission of WDM signal using cascaded SOAs reported. It is

found that, unlike conventional OOK system, XGM effect is no longer the ultimate factor limiting the transmission performance. Instead, FWM effect becomes dominant in determining the maximum transmission distance.

3.2.4.2 16×10.709Gb/s WDM transmission over 640km SMF using cascaded in-line SOAs and DPSK modulation format

With the knowledge of the optimum operating conditions for SOAs obtained in Section 3.2.3, even with narrower channel spacing of 200GHz, bit rate-distance product larger than the transmission in Section 3.2.4.1 should be possible. Figure 3.8 shows the experimental setup of a 16×10.709Gb/s WDM system, which is similar to the setup used in Section 3.2.4.1. Sixteen DFB lasers are located in the wavelength range from 1536.61nm to 1560.61nm with 200GHz channel spacing. The total length of the recirculating loop is 160km, which includes four sections of 40km SMF and DCF. The total fiber loss in the loop is about 32.9dB. The dispersion introduced by the SMF is fully compensated by the DCF in each loop. Each span is amplified by an SOA to compensate the loss of SMF and DCF. Hence, there are four SOAs used in the recirculating loop. An erbium-doped fiber amplifier (EDFA) is used to compensate the losses introduced by the devices for the loop operation, which includes a DGE, a 3dB coupler and an acousto-optical switch. The spectrum of the DGE can be flexibly controlled by a computer. In this experiment, the DGE can be used not only to equalize the gain for different channels, but also to isolate the ASE noise outside the transmission band. The demultiplexed signal is demodulated by an AMZI before the balanced detection. The received signal power is measured at point A in Fig. 3.8, before the AMZI.

Figure 3.8: Experimental setup of a recirculating loop using SOAs as in-line amplifiers and DPSK modulation format

By adjusting the operating current, the amplification gains of the SOAs are maintained to a proper value to compensate the loss of SMF and DCF ($\sim 12\text{dB}$). The BER curves (without FEC) of 1549.32nm channel after 640km transmission are measured at different input powers and are shown in Fig. 3.9 (a), where BER is mathematically defined as the probability of incorrect identification of a bit by the decision circuit of the receiver, i.e., the sum of the probability of a bit 1 being read as bit 0 and the probability of a bit 0 being read as 1. The results show that the optimal input power is between -5.35dBm and -3.35dBm . Due to the loss of each span which is not exactly 12dB , the range is a little different from that obtained in section 3.2.3. The Q-factor of the 16 channels after 640km transmission distance is also illustrated in Fig. 3.9 (b), at the optimal operating current of about 172mA and the optimal input power of -3.35dBm . All the channels have at least 4.5dB power margins over the FEC threshold, which is 9.2 dB for Reed Solomon with 7% redundancy. The Q-factor is measured based on the decision-circuit method, which is the most accurate method to

measure the Q-factor since it includes the ISI effect, dispersion and nonlinear effects [89].

Figure 3.9: (a) BER versus received power after 640km transmission for four different input powers; (b) Q-factor for all the 16 channels after 640km transmission, at the optimal operating current of 172mA and optimal input power of -3.35dBm

The results above show that DPSK can be used to eliminate the XGM effect induced by SOAs. As explained earlier, in a DPSK modulated transmission system, XGM effect is no longer the limiting factor of the system performance. Instead, FWM effect becomes dominant in determining the maximum transmission distance. However, it is worth to mention that, phase modulated system is more sensitive to chromatic dispersion because the chromatic dispersion would change the phase relationship. This causes the pattern effects in SOAs. Due to the reason that in our particular experiment setup, the SMF is only 40km per span and it is fully compensated by the DCF before entering a SOA for amplification. This arrangement reduces the conversion from phase modulation to amplitude modulation. Hence, the pattern effects in the SOA is weak. And also because the fiber launch power is not high in our experiment setup, the accumulated phase noise caused by the fiber Kerr nonlinearity is not severe in such system. 8x10.709Gb/s WDM transmission over 1050km standard

SMF is achieved with 6dB power margin over the FEC threshold. This is, to the best of our knowledge, the longest distance reported at that time using cascaded SOAs. By further optimizing the input power and operating current of SOAs, 16x10.709Gb/s DPSK modulated signals are transmitted over 640km with a power margin of 4.5dB over the FEC threshold. This is, to the best of our knowledge, the largest bit rate-distance product ($BL = 109.7\text{Tb}\cdot\text{s}^{-1}\cdot\text{km}$) reported.

3.3 Single-span Transmission System with Raman Amplification

The results obtained in section 3.2 have proved that DPSK format can suppress the XGM effect induced by SOAs. These results suggest that SOAs can be used as in-line amplifiers for WDM transmission systems using DPSK format with relatively short amplification spacing. The spectra difference that has been observed, in particular the absence of discrete clock tones for DPSK and its pulse carved formats, suggests that it may offer better tolerance to other nonlinear effect, such as SBS, comparing with OOK modulated systems. This has motivated the study to examine the SBS threshold in a Raman pumped RZ-DPSK transmission system. For the purpose of comparison, the performance of the RZ-OOK transmission system with bidirectional Raman pumps is also investigated.

Higher SBS threshold implies that the use of higher fiber launch power is possible, and hence span length can be longer. Using longer repeater spans (i.e. to reduce the number of repeaters), is to potentially lower the operating costs of medium and long haul terrestrial systems. Previous studies on long single-span length (>200km) systems were achieved by deliberately arranging fibres with different core areas (hybrid optical fiber solution) [82-83] and/or through the use of remote-pumped

amplifiers [82]. However, in order to make full use of the widely deployed standard SMF plants, and to avoid complicated cabling and facilitate future upgrades, the use of hybrid optical fiber solution and remote-pumped amplifiers is not desirable and hence is avoided in the study here.

In long single-span transmissions, system performance is mainly limited by OSNR. In order to increase OSNR, one can decrease the system noise, and/or increase the signal power. Bidirectional Raman pumping is an enabling technique for achieving long span transmissions, since it can reduce accumulated amplified spontaneous emission (ASE) noise and hence reduce the degradation of OSNR [90]. However, Raman pumping may reduce the SBS threshold, especially when a high co-pump power is used. Therefore, the signal power can not be increased too much to further increase the system OSNR. Emori *et al.* [91] studied the signal power penalty due to SBS in a co-pumped Raman system with a simple NRZ-OOK format. Funatsu *et al.* [92] compared the SBS effect in a counter-pumped system between RZ-DPSK format and CSRZ-OOK format. In this section, the impact of data format on SBS effect in a standard SMF system with different Raman pumping schemes is studied. The results show that SBS threshold in an RZ-DPSK system is more than 10dB higher than that in an RZ-OOK system, and SBS reflection is dominated by co-pumping, while counter-pumping has minor effect. An error free ($\text{BER}@10^{-10}$) 8x10.709Gb/s single-span transmission over 310km standard SMF is demonstrated, using RZ-DPSK format and bidirectional Raman pumping, without applying FEC technique.

3.3.1 SBS Threshold Evaluation

Raman amplification and advanced modulation formats like RZ-DPSK have shown promising results in long haul transmissions [80-81]. However, due to the fact that in silica fibers the Brillouin gain constant is larger than the Raman gain constant, significant SBS generation occurs generally at pump power levels below the level required for Raman amplification. Emori *et al.* [91] studied the signal power penalty due to the SBS effect in a co-pumped Raman system. But it was done on a simple NRZ modulated system. Since Brillouin gain is modulation format dependent [93], it is necessary to study the difference of SBS effect between transmission systems with different modulation formats, where bidirectional Raman pumps are used.

3.3.1.1 Stimulated Brillouin Scattering Effect

The Brillouin process can be understood as the conversion of a photon to a lower-energy photon such that the energy difference appears in the form of a phonon [93]. SBS generates a Stoke wave propagating in the opposite direction (i.e., backward direction) of the incident light wave, and the frequency of the Stoke wave is down-shifted by an amount that depends on the wavelength of incident signal. The intensity of the Stokes wave grows exponentially once the input power exceeds the threshold value. This Brillouin process is weak at low input powers. However, it increases exponentially at high power levels, resulting in nonlinear phenomena and can affect the performance of lightwave system considerably in the following ways. The SBS effect removes power from the signal once the signal power exceeds the threshold level, and induced large fluctuations in the remaining signal, resulting in degradation of both the OSNR and the BER.

In optical fibers, the threshold power P_{th} for SBS in continuous-wave signals can be estimated using [94]

$$P_{th-SBS} \approx \frac{21A_{eff}}{g_B \cdot L_{eff}} \quad (3.9)$$

where g_B is the Brillouin gain coefficient, A_{eff} is the effective core area, and L_{eff} is the effective interaction length. And

$$L_{eff} = \int_0^L e^{-\alpha z} dz = \frac{1 - \exp(-\alpha L)}{\alpha} \quad (3.10)$$

where α is the fiber loss coefficient and L is the fiber length.

With $\alpha=0.2\text{dB/km}$, $g_B \approx 5 \times 10^{-11} \text{m/W}$, and $A_{eff} = 50 \mu\text{m}^2$ as typical values, P_{th} can be as low as 1mW for CW signals near the $1.55 \mu\text{m}$ wavelength region. Whereas, the Raman threshold can be estimated as [94]

$$P_{th-SRS} \approx \frac{16A_{eff}}{g_R \cdot L_{eff}} \quad (3.11)$$

where g_R is the Raman gain coefficient. Using the same typical values as above, as $g_R \approx 1 \times 10^{-13} \text{m/W}$, P_{th-SRS} is about 500mW in the spectral region near $1.55 \mu\text{m}$.

Hence, SBS is a nonlinear process that can occur in optical fibers at input power levels much lower than those needed for stimulated Raman scattering (SRS). It manifests itself through the generation of a backward propagating Stokes wave that carries most of the input energy, if the Brillouin threshold is reached.

In fiber-optic communication systems, the signal spectral width $\Delta\nu_p$ varies considerably depending on the bit rate and the format at which the input signal is modulated. The SBS threshold increases for CW beams whose spectral width ($\Delta\nu_p$) is

larger than the Brillouin-gain linewidth ($\Delta\nu_B \sim 20\text{MHz}$) [94]. The amount by which the threshold power increases depends on the modulation format used for the data transmission. The SBS threshold also depends on whether the amplitude, phase, or frequency of the optical carrier is modulated for information coding [93-96]. Aoki *et al.* showed that the maximum input power or the SBS threshold for ASK, FSK and PSK modulated lights is 2, 4, and 2.5 times higher, respectively, than the threshold for unmodulated light, in a direct modulated optical coherent system [97].

3.3.1.2 Experimental Evaluation of the SBS Threshold

Figure 3.10 shows the experimental setup used for evaluating the impact of data formats on the SBS threshold under different pumping schemes. A 1550.92nm DFB laser with linewidth of about 10MHz is encoded with RZ-OOK or RZ-DPSK formats using two LiNbO₃ modulators. The 10.709Gb/s NRZ data is a PRBS with a word length of $2^{23}-1$. The 150km standard SMF has a total power loss of 31.2dB, including the loss from connectors. The chromatic dispersion in the SMF is fully compensated by a DCF. There are two pump sources in each Raman amplifier, which are at 1425nm and 1453nm. The two pump lasers have been depolarized in the Raman amplifier module. Hence the Raman gain does not depend on the polarization of the pump lasers. The pump power for them is set to 100mW and 180mW correspondingly for the co-pump, and 260mW and 400mW for the counter-pump. Thereby the Raman gain is 4.9dB and 10.6dB from the co-pumps and counter-pumps, respectively. The optical power launched into the DCF is strictly kept below -1dBm for different pump conditions. The backward-propagating power is measured at the 2x2 coupler after the residual Raman pump power is filtered out, and the OSNR (at 0.1nm) is measured at the 10:90 coupler and it can be changed through an optical attenuator (*att1*). Another

attenuator (*att2*) is used to maintain the same optical power into the detector under different conditions, so the effect of receiver can be maintained the same. The same single-ended receiver is used to detect both RZ-OOK and RZ-DPSK modulated signals to facilitate comparison. In the RZ-DPSK modulated system, the 3dB advantage from the balanced detection is not considered in this study.

A fiber span is usually called a “long” span if its length is equal to or greater than 150km [90]. In this experimental study, a 150km SMF is used. Nevertheless, the results in this study are also applicable to fiber spans exceeding 150km in length.

Figure 3.10: Experimental setup for the SBS threshold study

Fig. 3.11 to Fig. 3.13 show the back-reflected power versus fiber launch power under different pumping conditions, for RZ-DPSK and RZ-OOK formats. The pump powers used in Fig. 3.11 and Fig. 3.12 are as following. Counter-pump-1 is about 125mW and 181mW, counter-pump-2 is about 191mW and 290mW, counter-pump-3 is about 260mW and 400mW, and counter-pump-4 is about 325mW and 508mW for pumps at 1425nm and 1453nm correspondingly. Co-pump-1 is about 51mW and 128mW, co-

pump-2 is about 100mW and 180mW, co-pump-3 is about 150mW and 210mW, for pumps at 1425nm and 1453nm correspondingly. No-pump means that all the Raman pumps are switched off. In Fig. 3.13, the pump powers used are co-pump about 100mW and 180mW, counter-pump about 260mW and 400mW for pumps at 1425nm and 1453nm correspondingly. Bidirectional pump combines the case in co-pump and counter-pump. Again, no-pump means that all the Raman pumps are switched off. As shown in Fig. 3.11 and Fig. 3.12, the backward-propagating power contributed from the counter-pump cases is similar to the no-pump case, which means the backward-propagating power contributed from the counter-pump is negligible due to the long fiber span and large span loss in this investigation, while it is significant from the co-pump since the backward-propagating power in the co-pump cases is obviously higher than that in the no-pump case. In the RZ-DPSK modulated system, the SBS threshold is not noticeable (refer to Fig. 3.11 (a) and Fig. 3.12 (a)), even with a fiber launch power of about 20dBm, for both separated counter- and co-pumps cases. However, in the RZ-OOK modulated system, the SBS threshold is clearly present (refer to Fig. 3.11(b) and Fig. 3.12 (b)), even for both the no-pump and counter-pump cases, when the fiber launch power is around 10dBm. And the SBS threshold occurs with a lower fiber launch power in the co-pump cases, around 5.5dBm to 9.5dBm, depending on the co-pump power.

The backward-propagating power in a bi-directional pumped system is mainly caused by the co-pumping, as shown in Fig. 3.13. In Fig. 3.13(a), the backward-scattered power increases linearly with the fiber launch power, especially for the no-pump and co-pump cases, and there is no abrupt tuning point. This means that the SBS threshold in this system does not occur if the launch power is within 20dBm (The maximum

output power of the EDFAs available in our laboratory is 20dBm). This implies that in the RZ-DPSK system, when the launch power is less than 20dBm, Rayleigh scattering rather than SBS is the main contributor to the backward-scattered power, and it is SPM that limits the system performance, as seen in its eye diagram. However, the RZ-OOK system leads to a different conclusion. As shown in Fig. 3.13(b), there is an abrupt change in the slope of each backscatter curves, which occurs at a launch power of 6.6dBm for the co-pump and bidirectional-pump cases, and at 10.7dBm for no-pump and counter-pump cases. The intersect point of the slope tangents is used to experimentally determine the SBS threshold. The backward-scattered power increases exponentially after the threshold, and the SBS effect is the dominant transmission impairment. The eye diagram in Fig. 3.13(b) shows a typical eye pattern degraded by SBS with the predominant noise in the digital “one” level. Comparing Fig. 3.13(a) with Fig. 3.13(b), it can be seen that the SBS threshold in the RZ-DPSK system is more than 10dB higher than that in the RZ-OOK system (note that no SBS threshold is noticeable for the RZ-DPSK system in the experiment). This increased threshold can be attributed to the absence of discrete spectral tones in the RZ-DPSK system, since those discrete spectral tones in OOK formats have narrow linewidth and possess large amount of optical signal power. Another reason is the lower peak power for the same average power for RZ-DPSK comparing with that of RZ-OOK as discussed before in chapter 2.

Figure 3.11: Backward-propagating power vs. fiber launch power with different counter-pump powers. (a) RZ-DPSK system, (b) RZ-OOK system

Figure 3.12: Backward-propagating power vs. fiber launch power with different co-pump powers. (a) RZ-DPSK system, (b) RZ-OOK system

Figure 3.13: Backward-propagating power vs. fiber launch power, under different pumping conditions. (a) RZ-DPSK system (b) RZ-OOK system. The eye diagrams in (a) and (b) are with the same launch power (13.5dBm)

Because of the backward scattering, the fiber launch power for obtaining the optimum OSNR should be smaller in the cases of co-pumping or bidirectional pumping than

that in a system with no-pump or only counter-pump, as shown in Fig. 3.14. The backward-scattered power increases as the co-pump power increases, but the launch power to obtain the optimum OSNR decreases as the co-pump power increases, as shown in Fig. 3.15. However, this is not observed in the counter-pump cases. The backward-scattered power and the optimum launch power remain the same when the counter-pump increases, as shown in Fig. 3.16. The pump powers used in Fig. 3.15 and Fig. 3.16 are the same as those in Fig. 3.12 and Fig 3.11 respectively, except that the co-pump-4 of about 200mW and 230mW for pumps at 1425nm and 1453nm correspondingly is added in Fig. 3.15. It should be noticed that higher OSNR does not necessarily provide better BER, as shown in Fig 3.17. This is because although the OSNR is good, the severe SPM effect which may have caused distortion on the eye and the spectrum. Hence, the BER measured could be worse. In the measurement, the launch power for optimum BER is about 2~3dB lower than that for the optimum OSNR.

Figure 3.14: OSNR vs. fiber launch power, under different pumping conditions in RZ-DPSK system

Figure 3.15: Reflected power and OSNR vs. launch power with different co-pumping powers in RZ-DPSK system

Figure 3.16: Reflected power and OSNR vs. launch power with different counter-pumping powers in RZ-DPSK system

Figure 3.17: OSNR and BER vs. launch power with bidirectional Raman pumps in RZ-DPSK system

Similar relationship between the OSNR and the BER is also observed in an RZ-OOK modulated system. However, due to its lower SBS threshold, its launch powers for the optimum OSNR and BER are lower than that in the RZ-DPSK modulated system, and this in turn, limits the span length. Under the same bidirectional pumping condition, 12.6dBm is the launch power for the optimum OSNR and 9.5dBm for RZ-OOK for the best BER, but they are 15.5dBm and 13.6dBm for the RZ-DPSK system correspondingly. In this system, the OSNR can be as high as 35dB, because the fiber length used in this study is 150km. But the OSNR is reduced by changing the *Att1* to provide a reasonable range for BER measurement.

In summary, this study shows that the backward-scattered power is mainly caused by the co-pump, and the counter-pump has minor effect. The RZ-DPSK modulated system has higher SBS threshold than that in the RZ-OOK modulated system. Hence, it is possible to use higher launch power in the RZ-DPSK system, and consequently, the span length can be longer. Furthermore, it is found that the limiting factor in the RZ-DPSK system is the SPM effect, while it is the SBS effect in the RZ-OOK system.

A 310km single-span transmission is carried out in a RZ-DPSK modulated system, which is presented in the next sub-section.

3.3.2 Single-span Transmission Using RZ-DPSK format and Bidirectional Raman Pumps

As mentioned previously, in order to make full use of the widely deployed standard SMF fiber plants, to avoid complicated cabling and to facilitate future upgrades, hybrid optical fiber solution and/or remote-pumping amplifiers technique is not desirable and is avoided in our experiment. With the results found in section 3.3.1, it is known that the SBS threshold in an RZ-DPSK modulated systems is much higher than that in an RZ-OOK modulated system. Hence, using RZ-DPSK modulation format, larger fiber launch power is possible, leading to a longer single-span transmission distance.

An error free single 10.709Gb/s channel and 8x10.709Gb/s channels single-span transmission over 310km standard SMF is demonstrated, using RZ-DPSK format and bidirectional Raman pumping, without applying FEC technique.

Figure 3.18 shows the experimental setup of eight DFB laser diodes in the wavelength range of 1548-1554nm with 100GHz channel spacing combined by a polarization maintained WDM multiplexer. The CW light is encoded with RZ-DPSK format using two LiNbO₃ modulators, where the first modulator is biased at the null point and driven with 10.709Gb/s NRZ PRBS data with a word length of $2^{23}-1$. No additional fiber is inserted to decorrelate the channel data patterns. The 310km standard SMF has a total loss of 63.35dB, including the loss from connectors. The total fiber

dispersion is 5232.8ps/nm at 1550.92nm and is under-compensated by the DCF. The residual dispersion is about 362.9ps/nm at 1550.92nm, which is optimized to provide the best system performance in the single-channel case. The DCF is divided into two stages (DCF1 and DCF2) which are amplified separately to avoid further severe degradation in OSNR or serious fiber nonlinear effects. The optical power launched into *DCF1* and *DCF2* is controlled at around 3dBm by adjusting the gains from *EDFA2* and *EDFA3*. Each Raman amplifier has two pump sources, which are at 1425nm and 1453nm. The pump powers are set to 150mW and 210mW respectively for the co-pump, and 325mW and 508mW for the counter-pump. The gain provided by the bidirectional pumps is dependent on fiber launch power, since the amplifiers are working under saturation mode. The system OSNR can also be changed via an optical attenuator (*att1*), even when the pump powers are fixed. Another attenuator (*att2*) is used to control the optical power launched onto the photodetector under different conditions. The demultiplexed signal is demodulated by an AMZI with 1-bit delay between the two arms and detected by a balanced receiver.

Figure 3.18: Experimental setup for single span transmission

In section 3.3.1, it is found that in an RZ-DPSK modulated single-span system with bidirectional Raman pumping, the SBS effect induced by the co-pump is not the performance limiting factor due to its high SBS threshold ($>20\text{dBm}$). Instead, the SPM limits the maximum fiber launch power. Figure 3.19 shows the OSNR and the BER versus the fiber launch power for the single-channel case (at 1550.92nm). When the launch power is between 9 to 13dBm , error free transmission can be achieved without applying FEC technique. Due to the SPM, the eye pattern and spectrum become distorted as the launch power is further increased beyond 13dBm , even though the OSNR is still increasing. Since double Rayleigh back scattering (DRBS), which can not be measured by an optical spectrum analyzer, also contributes to the OSNR degradation [98], the actual OSNR is smaller than the measured value. Hence, the BER is reducing although the measured OSNR is still increasing. In the single-channel transmission, the fiber launch power is set to 13dBm , in order to gain higher OSNR and better BER. The Raman gain from co-pumping is about 5.6dB , while the Raman gain from bidirectional pumping is more than 20dB . For the multi-channel system, the launch power is 9dBm per channel, and the Raman gain is about $2\sim 3\text{dB}$ lower than that in the single-channel transmission case, due to the gain saturation.

Figure 3.19: OSNR and BER vs. fiber launch power in single-channel transmission

As shown in Fig. 3.20, all the channels exhibit slightly different OSNRs after 310km transmission, although their back-to-back OSNRs are all about 40dB. The channel power increases slightly from the first channel (shortest wavelength) to the last channel, due to the effect of inter-channel stimulated Raman scattering (SRS). Channel 1 has the smallest signal power, thereby the smallest OSNR. Fig. 3.21 shows the BER versus received optical power for both single channel and multiple channels transmission, where only the 1st, 4th (middle channel) and last channel are shown in the multiple channels case. These curves indicate that multi-channel system suffers more penalty than that of single channel case. The power penalty at BER of 10^{-9} is about 2dB for channel 8, and about 6dB for channel 1 and 4, comparing with the single channel transmission. The large power penalty in channel 1 is due to the smaller OSNR caused by the SRS and non-optimized residual dispersion. Although the OSNR in channel 4 is higher than that in channel 1, they have similar BERs, since channel 4 suffers more XPM and FWM. But nevertheless, error free can still be achieved without applying FEC, if the receiver power is greater than -10dBm.

Figure 3.20: OSNR of eight channels after transmission

Figure 3.21: BER vs. received power for the single-channel and 8-channel transmissions

In summary, the study shows that the backward-scattered power is mainly caused by the co-pump, and the counter-pump imposes minor effect. The RZ-DPSK modulated system has higher SBS threshold than that in the RZ-OOK modulated system. Hence, it is possible to use higher launch power in the RZ-DPSK system, and consequently, the span length can be longer. Furthermore, it is found that the limiting factor in the RZ-DPSK system is the SPM effect, while it is the SBS effect in the RZ-OOK system. A single-channel and 8-channel WDM single-span transmissions over 310km standard SMF have been demonstrated, using RZ-DPSK format and bidirectional Raman pumping. Although it shows that the multi-channel system suffers more penalty than that of the single-channel case due to inter-channel nonlinear effects, error free transmission can still be achieved, without applying FEC technique.

3.4 Conclusions

In this chapter, DPSK modulation format has been successfully used to considerably suppress the XGM effect in WDM transmission systems using SOAs as in-line

amplifiers. 8x10.709Gb/s WDM transmission over 1050km standard SMF is achieved with 6dB power margin over the FEC threshold. By further optimizing the input power and the operating current of SOAs, a 16x10.709Gb/s DPSK modulated signal is transmitted over 640km with a power margin of 4.5dB over the FEC threshold. This is, to the best of our knowledge, the largest bit rate-distance product ($BL = 109.7 \text{ Tb}\cdot\text{s}^{-1}\cdot\text{km}$) reported for WDM transmission systems with SOA-based in-line amplification. It is found that in a DPSK modulated transmission system with SOAs, the XGM effect is no longer the limiting factor for the system performance, instead, the FWM effect is dominant in determining the maximum transmission distance.

The experimental investigations show another advantage offered by phase modulated formats is the higher SBS threshold compared to OOK modulated system. The study on the SBS effect in single-span transmission system with bidirectional Raman pumping, for both RZ-OOK and RZ-DPSK modulated systems, shows that the backward-scattered power is mainly caused by the co-pump, and the counter-pump gives minor effect. The SBS threshold in an RZ-DPSK modulated system is more than 10dB higher than that in the RZ-OOK modulated system. Hence, it is possible to use a higher launch power in the RZ-DPSK modulated system, and consequently, the span length can be longer. Based on this conclusion, a single-channel and 8-channel WDM single-span transmissions over 310km standard SMF are demonstrated, using RZ-DPSK format and bidirectional Raman pumping. Although it is shown that the multi-channel system suffers more penalty than the single-channel case due to inter-channel nonlinear effects, error free transmission has been achieved, without applying FEC technique.

Chapter 4

Generation and Detection of Externally Modulated

Optical MSK Format

4.1 Introduction

In Chapter 3, the novel applications using phase-shift keyed formats, such as WDM transmission systems using SOAs as in-line amplifiers and DPSK modulation format, and long single-span transmission systems using bidirectional Raman pumps and RZ-DPSK modulation format, have been studied. These studies show that DPSK and RZ-DPSK formats are indeed very attractive in overcoming the impairments caused by optical nonlinear effects including self-phase modulation (SPM) and stimulated Brillouin scattering (SBS) in fiber, and cross-gain modulation (XGM) induced in SOAs. However, one major limitation of RZ-DPSK format is its relative large spectrum width. This has limited its dispersion tolerance and robustness against linear crosstalk. It has been shown that the spectral efficiency of the RZ-DPSK modulated WDM system is limited to 0.43bit/s/Hz [99] (without using the polarization multiplexing technique). As a result, there is a need to provide alternative modulation formats which address at least one of the above-mentioned limitations while maintaining the advantages offered by RZ-DPSK format.

In digital communications, it has been shown that out-of-band interference due to band limiting and amplifier nonlinearity can be reduced if the modulation format exhibits less phase changes at symbol transitions [100]. This suggests that further improvement in optical transmission systems is possible if phase transitions can be

made smoother or even completely continuous. MSK, which has been widely used in satellite communications and high-rate microwave systems, is such a continuous phase modulation scheme [101].

Due to its compact spectrum and lower side lobes, MSK is expected to be more tolerant to fiber dispersion than other currently used optical modulation formats. Its constant amplitude nature and continuous phase at every bit transition instant may also make it more robust to SPM and XPM effects comparing with other modulation formats. This is because nonlinear effects that can severely affect the WDM system performance are mainly induced by intensity fluctuation, even for DPSK modulated systems. A DPSK modulated system provides constant amplitude at the beginning of the transmission. Due to the existing of dispersion in the transmission fiber, the constant amplitude is no longer held after transmission along a certain distance of fiber. The speed and the amount of variation depend on the phase transient. Since MSK exhibits the smallest phase transient, as compared to other phase modulated formats, MSK modulated systems may have slower variation, which needs to be studied further.

One major challenge in using MSK in optical transmission systems is its optical implementation. In 1980s and early 1990s, MSK was investigated in coherent optical systems [102-104]. During that time period, direct modulation of a laser diode (LD) was the only way to achieve frequency-shift keying (FSK) modulation. With the careful control of laser linewidth and modulation index, continuous-phase FSK (CPFSK) and MSK formats were achieved [102-106]. With revived interest in optical FSK, recently, Wedding [107] and Klekamp [108] also used direct modulation

technique to achieve FSK and MSK in 10Gb/s systems. In direct modulation, the DFB laser usually is biased at high bias current, so that the residual amplitude modulation extinction ratio can be low. However, one major limitation of using direct modulation scheme is that the modulation speed is limited by the LD response speed, and is very difficult to achieve data rates as high as 40Gb/s or beyond. Furthermore, the thermal modulation in the low frequency part of the laser FM response can lead to performance degradation in FSK systems [105]. This can limit the performance of a directly modulated MSK systems. In the past one year, a few external modulation schemes to achieve optical CPFSK have been reported [109-110]. These include a new external MSK modulation scheme described in this thesis [111-112] and a parallel work by a Japanese group [113] and subsequent work by a Chinese group [114]. In our proposal, the newly designed modulator is named as offset quadrature phase-shift keying (OQPSK) modulator, which consists of two arms. The upper arm has a 1-bit delay ($\Delta\tau=T_b=1/R$) and a Mach-Zehnder modulator (MZM) (denoted by MZM2), while the lower arm has another MZM (denoted by MZM3) and a phase shifter to make the two arms have 90-degree phase difference. The details for the transmitter and receiver configurations and operational principle are presented in sections 4.3 and 4.4 [111-112]. In [113], a 10Gb/s externally modulated MSK signal was achieved through precise initial phase control on an externally modulated CPFSK signal which was obtained by a specially designed FSK modulator. This means an extra modulator is required for phase modulation of the data before the CPFSK modulator. In [114], a 16Gb/s externally modulated MSK signal was achieved where electrical processing of the data was performed before the data was used for modulation in an optical single side band (SSB) modulator. This approach needs a complicated encoding and demodulation scheme.

In this chapter, a novel approach for implementing externally modulated optical MSK is described in detail. Using this proposed approach, 10.709Gb/s MSK signal is successfully generated, and its transmission performance is examined and compared with other modulation formats. The details for the proposed MSK transmitter and receiver configuration, and the generation and detection principle of this externally modulated optical MSK signal are given in Sections 4.3 and 4.4, respectively. Different from the direct modulation of lasers [107-108], our proposed method can be easily applied to generate 40Gb/s MSK optical signals.

The rest of this chapter is organized as follows. Section 4.2 introduces the basic theory of the MSK modulation format. The proposed optical MSK transmitter and receiver configurations are presented in section 4.3. The analysis of the MSK signal generated by the proposed approach is given in Section 4.4. The experiment setup for generating of the externally modulated MSK signal is presented in section 4.5.

4.2 Basic Theory of MSK Modulation Format

MSK can be viewed as either a sinusoidal weighted offset-quadrature phase-shift keying (OQPSK), or a special case of continuous-phase frequency-shift keying (CPFSK) with modulation index $h=0.5$. In this section, it is shown that these two implementation methods indeed provide essentially the same outcome.

4.2.1 MSK based on OQPSK

MSK format can be viewed as an OQPSK signal with sinusoidal weighting. In digital communications, a MSK signal can be expressed as [115]

$$s(t) = a_{odd}(t) \cos\left(\frac{\pi t}{2T}\right) \cos(2\pi f_c t) + a_{even}(t) \sin\left(\frac{\pi t}{2T}\right) \sin(2\pi f_c t) \quad (4.1)$$

Where a_{odd} and a_{even} are the odd-numbered bits and even-numbered bits respectively, T is the period of bit duration, and f_c is the carrier frequency.

Figure 4.1 shows the various components of the MSK signal described in (4.1). Fig. 4.1 (a) shows the odd-numbered bits and the even-numbered bits used in this illustration. Fig. 4.1 (b) shows the odd-numbered bit stream waveform of the odd-bits $\{a_{odd}\}$, where the corresponding values of the odd-numbered bits are shown as ± 1 inside the waveform. The odd-numbered signal obtained by multiplying the waveform in Fig. 4.1(b) by $\cos 2\pi f_c t$ is shown in Fig. 4.1(c). Similarly, the sinusoidally shaped bit stream waveform of the even-bits and its corresponding even-numbered signal are shown in Figs. 4.1(d) and (e), respectively. The composite MSK signal $s(t)$, the addition of the signals in Fig. 4.1(c) and Fig. 4.1(e), is shown in Fig. 4.1(f) [115].

Figure 4.1: MSK waveform [115]

To better understand the properties of the MSK signal, Equation (4.1) can be rewritten in a different form as below. In the k -th bit period, the values of $a_{odd}(t)$ and $a_{even}(t)$ are either 1 or -1 .

$$\begin{aligned}
 s(t) &= \pm A \cos\left(\frac{\pi t}{2T}\right) \cos(2\pi f_c t) \pm A \sin\left(\frac{\pi t}{2T}\right) \sin(2\pi f_c t) \\
 &= \pm A \cos\left(2\pi f_c t + d_k \frac{\pi t}{2T}\right) \\
 &= A \cos\left(2\pi f_c t + d_k \frac{\pi t}{2T} + \phi_k\right) \\
 &= A \cos\left[2\pi\left(f_c + d_k \frac{1}{4T}\right)t + \phi_k\right], \quad kT \leq t \leq (k+1)T \quad (4.2)
 \end{aligned}$$

where $d_k=1$ when $a_{odd}(t)$ and $a_{even}(t)$ have opposite signs, and $d_k=-1$ when $a_{odd}(t)$ and $a_{even}(t)$ have same signs; and $\phi_k = 0$ or π corresponding to $a_{odd}(t)=1$ or -1 .

In order to show that MSK carrier phase is always continuous at bit transitions, the excess phase of the MSK signal is examined, referenced to the carrier phase, which is given by

$$\theta(t) = d_k \frac{\pi t}{2T} + \phi_k = \pm \frac{\pi t}{2T} + \phi_k \quad (4.3)$$

Because ϕ_k is a constant in the interval $[kT, (k+1)T]$, $\theta(t)$ increases or decreases linearly in the interval $[kT, (k+1)T]$. However, to ensure phase continuity at bit transitions, at the end of the k -th bit period, it must fulfill

$$d_k \frac{\pi(k+1)T}{2T} + \phi_k = d_{k+1} \frac{\pi(k+1)T}{2T} + \phi_{k+1} \pmod{2\pi} \quad (4.4)$$

It has been proven that this requirement in equation (4.4) is always satisfied for the MSK signal generated in (4.1) [100].

Hence, from Equations (4.3) and (4.4), the phase information can be obtained, as shown in Fig. 4.1 (g), where it is linearly changing within the bit interval and is continuous at bit transitions.

4.2.2 MSK based on CPFSK

MSK format can also be viewed as a special case of CPFSK format with modulation index $h=0.5$. For smooth phase transition, the mark and space frequencies are selected such that they are separated from the center frequency by an exact odd multiple of one-half of the bit rate (i.e. the frequency difference is $\Delta f = m/(2T)$, where T is one bit duration and m is a positive integer greater than or equal to 1). This ensures that the phase transition is smooth when its analog output signal changes from a mark to a space frequency, or vice versa. In MSK, m is equal to 1 to ensure that the frequency difference between mark and space frequencies is minimum.

A CPFSK signal can be expressed as [100]

$$s(t) = A \cos \left[2\pi f_c t + \frac{\pi h d_k (t - kT)}{T} + \pi h \sum_{i=0}^{k-1} d_i \right], \quad kT \leq t \leq (k+1)T$$

which can be re-written as

$$s(t) = A \cos \left[2\pi f_c t + h d_k \frac{\pi}{T} + \phi_k \right], \quad kT \leq t \leq (k+1)T \quad (4.5)$$

where

$$\phi_k = \pi h \left(\sum_{i=0}^{k-1} d_i - k d_k \right)$$

Here h is the modulation index which determines the frequency shift during the bit interval.

With $h=0.5$, Equation (4.5) becomes

$$s(t) = A \cos(2\pi f_c t + d_k \frac{\pi t}{2T} + \phi_k), \quad kT \leq t \leq (k+1)T \quad (4.6)$$

which is exactly the same as Equation (4.2).

Hence, MSK can be viewed as either an OQPSK signal with sinusoidal pulse weighting or a CFPSK signal with a frequency separation equal to one-half the bit rate.

Both schemes are equivalent.

4.2.3 Properties of MSK Signal

From both Equation (4.2) and Fig. 4.1(e), the main properties of the MSK signal can be summarized as follows:

- It has constant amplitude;
- The phase of the carrier is continuous at bit transition instants;
- The signal is an FSK signal whose respective frequencies for the space and the

mark are $f_+ = f_c + \frac{1}{4T}$ and $f_- = f_c - \frac{1}{4T}$ respectively. The frequency

deviation between the space and mark equals half the bit rate, i.e.,

$$\Delta f = f_+ - f_- = \frac{1}{2T}.$$

Frequency separation of $1/(2T)$ is the minimum frequency spacing which allows the two FSK signals to be coherently orthogonal. Hence, it is named as “minimum-shift keying”. Since this frequency spacing is only half as much as the conventional $1/T$ spacing used in noncoherent detection of FSK signals, MSK is also referred as Fast FSK (FFSK).

As studied in [100, 115-116], when there is an abrupt phase discontinuity in the analog output signal, the demodulator at the receiver has trouble in following the frequency shift, which may cause a bit error. In the MSK signal, whenever the output frequency changes, the phase transition is always continuous and smooth, and hence it can be expected that the MSK has a better bit error rate (BER) performance than the conventional binary FSK for a given SNR. Figs. 4.2 (a) and (b) show quadrature phase-shift keying (QPSK) and offset QPSK (OQPSK) signals, respectively. As shown in Figs. 4.2 (a) and (b), the phase transitions of the QPSK and OQPSK signals are abrupt and not continuous.

Figure 4.2: (a) Phase variation of QPSK, (b) Phase variation of OQPSK [115]

Figure 4.3 shows the power spectrum density (PSD) of an MSK signal along with those of BPSK, QPSK and OQPSK signals. The main lobe of the MSK spectrum is narrower than that of the BPSK spectrum and wider than that of the QPSK and OQPSK spectra, but the side lobes of the MSK falls off much faster, at a rate

proportional to $(f/R)^{-4}$, where R is the signal's bit rate. In contrast, the side lobes of the QPSK (or OQPSK) spectrum falls off at a rate proportional to only $(f/R)^{-2}$. The side lobe of the BPSK spectrum also falls off at a rate proportional to $(f/R)^{-2}$ even though its main spectral lobe width is double than that of the QPSK (or OQPSK) [100]. The bandwidth containing 99% of the power, denoted by $B_{99\%}$, is approximately $1.2R$, $10R$, $20R$ for MSK, QPSK or OQPSK, and BPSK, respectively [100]. It is noted that the bit error probability is the same for all of these formats for a given received power. Therefore, the MSK is very attractive since it has the same BER as other formats while its $B_{99\%}$ is much smaller than that of other formats, and its phase is continuous at bit/symbol boundaries.

Figure 4.3: Power spectral density of BPSK, QPSK (or OQPSK), and MSK

4.3 Novel Optical MSK Transmitter and Receiver Configurations

One particular challenge in using MSK for optical communication system is its generation. As discussed above, MSK based on direct modulation of semiconductor laser suffers from two drawbacks. The first is the nonideal (both low and high frequency) response and residual amplitude modulation. The other is the limited FM response of a laser diode which has limited MSK implementation to 10Gbps and below. As a result it is attractive to implement the modulation scheme using external modulators. One parallel work to that presented in the thesis is the one by a Japanese group as described in [113]. In the work, two parallel MZ modulators were used to implement a single sideband modulator(SSB), a third modulator was used to switch between the two side bands to generate CPFSK signal. However, this scheme only enables the generation of a CPFSK signal with a minimum modulation index equal to 1. To generate MSK, another modulator is needed to change the initial phase of the lightwave carrier between 0 and π based on the data pattern to be transmitted. This scheme is rather complicated although it works well. In this section, a new scheme is proposed which works well and is simpler than the alternatives.

Fig. 4.4 shows the configuration of the proposed high-speed optical MSK transmitter. The first Mach-Zehnder modulator (denoted by MZM1) is used to generate a carrier-suppressed return-to-zero (CS-RZ) pulse stream, which is then fed to the subsequent OQPSK modulator. The MZM1 is driven by a clock signal whose frequency is one quarter of the system bit rate ($R/4$) and is biased at the transmission null point. As shown in Fig. 4.4, the OQPSK modulator consists of two arms. The upper arm has a 1-bit delay ($\Delta\tau=T_b=1/R$) and a MZM (denoted by MZM2), while the lower arm has another MZM (denoted by MZM3) and a phase shifter to make the two arms have 90-

degree phase difference. Both MZM2 and MZM3 are biased at the transmission null point, and they are driven by *even-bits* and *odd-bits* data streams, respectively, with a driving voltage of $2V_{\pi}$. This driving condition provides either 0 or π phase shift in each arm according to the values of the bit streams. The *even-bits* and *odd-bits* data sequences are at a bit rate of $R/2$, which are generated from a pre-coded data source, as shown in Fig. 4.4(b).

In Fig. 4.4(b), the data stream is first pre-coded using an exclusive-OR (XOR) gate and then separated by a 1:2 electrical demultiplexer to form the odd-numbered-bit and even-numbered-bit sequences, which are then used for driving MZM3 and MZM2, respectively. Before the even-numbered-bit sequence is used to modulate MZM2, it is delayed by 1-bit duration ($\Delta\tau=T_b$), in order to synchronize with the CS-RZ pulses in the upper arm. The operation of the proposed MSK transmitter is presented in the next section in detail.

Figure 4.4: Proposed optical MSK transmitter configuration

In order to detect the MSK signal generated by the proposed MSK transmitter, two receiver configurations are proposed. They are shown in Fig. 4.5. The first receiver configuration shown in Fig. 4.5(a) consists of a 1-bit delay interferometer (DI) with a $\pi/2$ phase shift between the two arms and a balanced receiver. The second receiver configuration shown in Fig. 4.5(b) has a 1-bit DI with a 0 degree phase difference between the two arms, and it also has an XOR gate following the balanced receiver. It can be shown that these two receivers can provide the same detected signal which has the same bit pattern as the original data, but their performance is different. The detected data has the same bit rate and pattern as the original data before being differentially encoded. However, in terms of bit error rate performance, the first configuration in Fig. 4.5 (a) outperforms the second configuration in Fig. 4.5(b) by 3dB [115]. This is because that MSK uses antipodal symbol shapes ($\pm \cos(\frac{\pi t}{2T})$ and $\pm \sin(\frac{\pi t}{2T})$) over $2T$ to modulate the two orthogonal carriers. MSK would have the same error rate performance as BPSK if the observation is over $2T$ seconds. When the bit decision is made over an observation interval of T seconds and the phase difference between the two arms is zero, as shown in Fig. 4.5(b), MSK would be worse than BPSK by 3dB since the distance between two symbols in the signal constellation diagram is $\sqrt{2}$ in this case. This 3dB disadvantage of MSK over BPSK

vanishes when the bit decision is made over two bit periods, as used in [114], or by providing a 90-degree phase difference between the two arms in the DI, as proposed in Fig. 4.5(a). Due to this reason, only the first receiver configuration is used in studying the characteristics and the system performance of the proposed optical MSK system, unless otherwise is stated.

Figure 4.5: Two proposed optical MSK receiver configurations

4.4 Operational Principle of the Proposed MSK System

This section describes the details for the operational principle of the MSK system proposed in Section 4.3. Fig. 4.6 shows the bit stream illustration for the proposed MSK generation and detection depicted in Figs. 4.4 and 4.5, where the capital letters “A” to “F” indicate data patterns at the corresponding locations.

Figure 4.6: Bit stream illustration for optical MSK generation and detection. A – Original data, B – Data after pre-coding, C – Demultiplexed odd sequence bits, D – Demultiplexed even sequence bits with one bit delay. E – phase and frequency of the MSK signal, F – detected signal

Referring to Fig. 4.4(a), a CW light is first modulated by MZM1 which is biased at the transmission null point with a driving frequency of $R/4$ (R is the bit rate). The output from the MZM1 is a carrier-suppressed return-to-zero (CS-RZ) pulse train. If this CS-RZ pulse train is approximated by a dual-mode optical field, it can be expressed as

$$E(t) = \frac{1}{2} E_m \{ e^{j2\pi(f_0 + R/4)t} + e^{j2\pi(f_0 - R/4)t} \} = E_m e^{j2\pi f_0 t} \cos \frac{\pi R}{2} t \quad (4.7)$$

where f_0 is the optical carrier frequency, and E_m is the optical field amplitude. It is noted that a pure dual-mode pulse source can be obtained by using a bandpass filter to remove the higher order modes in the optical spectrum of the CS-RZ pulses.

The pure dual-mode pulse train is then fed to the subsequent OQPSK modulator (refer to Fig. 4.4 (a)), where it is split into the two arms. In the upper arm, the pulses are delayed by one bit ($1/R$) and the phase of the pulses is modulated by the even sequence bits (at a bit rate of $R/2$). The even sequence bits are demultiplexed from the original data stream and are also delayed by one bit in order to synchronize with the delayed pulses. The optical field of the upper arm can be expressed as

$$\begin{aligned} E_{up}(t) &= \frac{1}{\sqrt{2}} E_{in} e^{j2\pi f_0(t-1/R)} \cos\left[\frac{\pi R}{2}\left(t - \frac{1}{R}\right)\right] e^{j\frac{\pi}{V_\pi} Data_{even}(t-1/R)} \\ &= \frac{1}{\sqrt{2}} E_{in} e^{j2\pi f_0 t} e^{-j2\pi f_0 T_b} \sin\left(\frac{\pi R}{2} t\right) e^{j\pi a_{even}(t-T_b)} \end{aligned} \quad (4.8)$$

where $T_b=1/R$ is the bit duration, $Data_{even}$ is the even bits, $a_{even} = Data_{even}/V_\pi$ is the bit value of even bits, being 1 or 0, and V_π is the driving voltage of the modulator.

The optical field of the lower arm can be expressed as

$$\begin{aligned} E_{low}(t) &= \frac{1}{\sqrt{2}} E_{in} e^{j2\pi f_0 t} e^{j\phi} \cos\left(\frac{\pi R}{2} t\right) e^{j\frac{\pi}{V_\pi} Data_{odd}(t)} \\ &= \frac{1}{\sqrt{2}} E_{in} e^{j2\pi f_0 t} e^{j\phi} \cos\left(\frac{\pi R}{2} t\right) e^{j\pi a_{odd}(t)} \end{aligned} \quad (4.9)$$

where ϕ is the tunable phase shift, $Data_{odd}$ is the *odd-bits*, and $a_{odd} = Data_{odd}/V_\pi$ is the bit value of *odd-bits*, being 1 or 0.

In (4.8), the carrier frequency f_0 is much greater than the bit rate frequency R , i.e., $f_0/R \gg 1$. It can be expressed as $2\pi f_0/R = 2N\pi + \delta$, where N is a large integer and $0 < \delta < 2\pi$. By adjusting ϕ in (4.9), it is possible to make $\delta - \phi = \pi/2$ so the two arms have a $\pi/2$

phase difference. After combining the optical fields of the two arms, the output of the MSK modulator becomes

$$E_{out}(t) = \frac{1}{2} E_{in} e^{j2\pi f_0 t} e^{j\pi/2} \sin\left(\frac{\pi R}{2} t\right) e^{j\pi a_{even}(t-T_b)} + \frac{1}{2} E_{in} e^{j2\pi f_0 t} \cos\left(\frac{\pi R}{2} t\right) e^{j\pi a_{odd}(t)} \quad (4.10)$$

where a_{odd} and a_{even} are the bit values of the *odd-bits* and *even-bits*, respectively, which are either 1 or 0 within their bit durations.

The real part of the optical field is given by

$$\begin{aligned} E_{out,real}(t) &= \frac{E_{in}}{2} \sin(2\pi f_0 t) \sin\left(\frac{\pi R}{2} t\right) \sin\left(\pi a_{even}(t-T_b) + \frac{\pi}{2}\right) \\ &\quad + \frac{E_{in}}{2} \cos(2\pi f_0 t) \cos\left(\frac{\pi R}{2} t\right) \cos(\pi a_{odd}(t)) \end{aligned} \quad (4.11)$$

which is exactly the same as the mathematical expression in (4.1) of the MSK signal in digital communications [115].

Considering $\cos(\pi a_{odd}(t)) = \pm 1$, Equation (4.10) can also be expressed as

$$\begin{aligned} E_{out}(t) &= \frac{E_{in}}{2} e^{j2\pi f_0 t} \left\{ \cos\left(\frac{\pi R}{2} t\right) \cos(\pi a_{odd}(t)) + j \sin\left(\frac{\pi R}{2} t\right) \cos(\pi a_{even}(t-T_b)) \right\} \\ &= \frac{E_{in}}{2} \exp\left(j \tan^{-1} \left[\tan\left(\frac{\pi R}{2} t\right) \times \frac{\cos(\pi a_{even}(t-T_b))}{\cos(\pi a_{odd}(t))} \right] \right) e^{j2\pi f_0 t} \\ &= \frac{E_{in}}{2} \exp\left(\pm j \frac{\pi R}{2} t \right) e^{j2\pi f_0 t} \end{aligned} \quad (4.12)$$

where the plus sign corresponds to the case when both $a_{odd}(t)$ and $a_{even}(t-T_b)$ have the same bit value within the time interval $kT_b \leq t \leq (k+1)T_b$, and the minus sign is for the case when $a_{odd}(t)$ and $a_{even}(t-T_b)$ have the opposite bit value (i.e., one is 0 and the other one is 1) within the time interval $kT_b \leq t \leq (k+1)T_b$.

Equation (4.12) shows that the generated optical MSK signal has a constant amplitude, and its phase changes continuously and linearly within the time interval $kT_b \leq t \leq (k+1)T_b$ with a slope of $R/4$ or $-R/4$ at each bit transition instant, as shown in Fig. 4.6 “E”. This slope variation corresponds to a frequency-shift keying, and the bit pattern $b(t)$ of this frequency modulation has the same pattern as the original data before differential encoding at point A in Fig. 4.4(b). This also shows that the frequency separation is $R/2$ (i.e. $1/(2T)$), which is the minimum frequency spacing that allows the two FSK signals to be coherently orthogonal. Hence, it is named as “minimum-shift keying”. This agrees with the digital communications theory presented in section 4.2.

Within $kT_b \leq t \leq (k+1)T_b$, $b=1$ or 0 corresponds to a frequency shift of $R/4$ or $-R/4$, so Equation (4.12) can be also expressed as

$$E_{out}(t) = \frac{E_m}{2} \exp(j[b(t) - 0.5]\pi R t) e^{j2\pi f_0 t} \quad (4.13)$$

It should be noted that the optical MSK signal given in (4.12) and (4.13) (that is generated by the proposed MSK transmitter) has the same properties of the MSK signal described in section 4.2.1, such as constant amplitude, continuous phase at the bit transition instants and the frequency deviation between the space and mark equals half the bit rate.

It is worth pointing out that the signals obtained in the upper- and lower-arms of the OQPSK modulator are both CSRZ-DPSK signals, but with a time delay between each other, as shown in equations (4.8) and (4.9). When these two signals are combined together to form the MSK signal, the amplitude of the generated MSK signal is

constant, as derived in equation (4.12). Hence, this is the true MSK signal, but not the pulse carved version of MSK.

The MSK signal can be detected by a receiver as shown in Fig. 4.5 (a). Referring to Fig. 4.5 (a), one output of the DI (i.e., one input of the balanced receivers) can be expressed as

$$E_{Dect}(t) = \frac{E_{in}}{4} \left\{ e^{j[b(t)-0.5]\pi R t} + e^{j[b(t-T_b)-0.5]\pi R(t-T_b) + j\phi - j2\pi f_0 T_b} \right\} e^{j2\pi f_0 t} \quad (4.14)$$

Again expressing $2\pi f_0 T_b = 2N\pi + \delta$, where N is a large integer and $0 < \delta < 2\pi$. ϕ is adjusted to make $\phi - \delta = \pi/2$, so the two arms of the DI have half π phase difference. Equation (4.14) becomes (4.15) if we drop the high frequency optical carrier term.

$$E_{Dect}(t) = \frac{E_{in}}{4} \left\{ e^{j[b(t)-0.5]\pi R t} + e^{j[b(t-T_b)-0.5]\pi R(t-T_b) + j\pi/2} \right\} \quad (4.15)$$

According to the combination of the bit values of $b(t)$ and $b(t-T_b)$, four different results can be obtained as follows:

For $b(t)=0$ and $b(t-T_b)=0$,

$$E_{Dect}(t) = \frac{E_{in}}{4} \left\{ e^{-j1/2\pi R t} + e^{-j1/2\pi R(t-T_b) + j\pi/2} \right\} = 0, \quad |E_{Dect}(t)|^2 = 0 \quad (4.16)$$

For $b(t)=0$ and $b(t-T_b)=1$,

$$E_{Dect}(t) = \frac{E_{in}}{4} \left\{ e^{-j1/2\pi R t} + e^{j1/2\pi R(t-T_b) + j\pi/2} \right\} = \frac{E_{in}}{2} \cos\left(\frac{\pi R t}{2}\right)$$

$$|E_{Dect}(t)|^2 = \frac{|E_{in}|^2}{8} [1 + \cos(\pi R t)], \text{ for } kT_b \leq t \leq (k+1)T_b \quad (4.17)$$

For $b(t)=1$ and $b(t-T_b)=0$,

$$E_{Dect}(t) = \frac{E_{in}}{4} \left\{ e^{j1/2\pi R t} + e^{-j1/2\pi R(t-T_b) + j\pi/2} \right\} = \frac{E_{in}}{j2} \sin\left(\frac{\pi R t}{2}\right)$$

$$|E_{Decf}(t)|^2 = \frac{|E_m|^2}{8} [1 - \cos(\pi R t)], \text{ for } kT_b \leq t \leq (k+1)T_b \quad (4.18)$$

For $b(t)=1$ and $b(t-T_b)=1$,

$$E_{Decf}(t) = \frac{E_m}{4} \{ e^{j1/2\pi R t} + e^{j1/2\pi R(t-T_b) + j\pi/2} \} = \frac{E_m}{2} e^{j1/2\pi R t}$$

$$|E_{Decf}(t)| = \frac{|E_m|^2}{4} \text{ for } kT_b \leq t \leq (k+1)T_b \quad (4.19)$$

Equations (4.16) – (4.19) show the equivalent function of differential decoding of the received MSK stream. Hence, the bit stream detected by the proposed MSK receiver has the same pattern as the original data stream, as shown in Fig.4.6 “F”.

It is noted that the above theoretical derivation has assumed that the CS-RZ pulse train from the modulator MZM1 is pure dual-mode, i.e. its higher order side modes are ignored. When driven using full voltage swing of $2V_\pi$ the carrier will have a duty cycle of 67% rather than 50% for the pure dual-mode source. This can be achieved by either the use of an optical filter to filter out higher order modes, or driving MZM1 with a drive swing less than $2V_\pi$ can also reduce the higher order side modes. However, the investigation in this thesis shows that the higher order side modes do not affect the generation of optical MSK signal, instead, they help to achieve better tolerance against fiber dispersion and nonlinear effects (refer to Chapter 5 for details).

4.5 Experimental Generation of Optical MSK Signal

Based on the principles discussed above, an experimental setup is established to demonstrate the generation of optical MSK signal using the proposed scheme. The first modulator (MZM1) is driven by a 10.709/4 GHz clock signal. At the output of

the MZM1, a 10.709/2 GHz CS-RZ pulse train is produced. MZM1 has a V_π of 6 V and is driven with a swing less than $2V_\pi$ due to insufficient saturation output power of the driver (9V is the maximum output voltage of the modulator driver amplifiers in our lab.). The 10.709 Gb/s OQPSK modulator is fabricated using the PLC-LN hybrid integration technology [117]. The 10.709 Gb/s NRZ data (pseudorandom binary sequence (PRBS) with a word length of $2^{23}-1$) is separated into odd-numbered-bit and even-numbered-bit streams, with a bit rate of 10.709/2 Gb/s in each stream. The modulators MZM2 and MZM3 (inside the OQPSK modulator with details in Fig. 4.4(a)) have a V_π of 4.5V and are driven by a voltage of around $2V_\pi$, which is about 9V. The output of the OQPSK modulator is 10.709 Gb/s optical MSK signal. In this experiment, no XOR gate is used in the MSK transmitter and receiver, since differentially encoded PRBS generated by polynomial gives two identical PRBSs but with an offset.

Fig. 4.7 shows the eye pattern and optical spectrum of the generated MSK signal. The optical spectrum for RZ-DPSK is also shown in the figure for comparison. As seen in Fig. 4.7(a), the optical spectrum of the MSK signal before the balanced receivers is narrower than that of the RZ-DPSK signal, and the side lobes of the MSK spectrum are also lower. Hence, it is expected that the generated MSK signal can achieve higher spectral efficiency and larger dispersion tolerance, and can also reduce crosstalk from the neighbouring channels and ISI effect arising from tight optical filtering. Figs. 4.7 (b) and (c) show that the outputs from the two output ports of the DI have similar optical spectrum, when the receiver configuration in Fig. 4.5(a) is used. In fact, they are the mirror images with respect to the central frequency. When these two spectra overlay each other, it forms the spectrum of the MSK signal, as shown in the inset (A)

of Fig. 4.7(a). This is different from the spectrum of the RZ-DPSK signal. However, if the receiver configuration in Fig. 4.5(b) is used, the spectrum of the demodulated MSK signal will be similar to that of RZ-DPSK spectrum, with one constructive port and one destructive port. The inset (B) in Fig. 4.7(a) is the eye pattern detected by the balanced receiver, and the insets in Figs. 4.7(b) and (c) are the eye patterns at the two output ports of the DI, corresponding to their optical spectra. Here the driving swing of MZM1 for CSRZ pulse generation is less than $2V_\pi$, leading to reduced intensity in higher order side modes. All the eye patterns exhibit relatively flat upper and lower eye lips in the eye diagram.

To further look at the effect of the higher order side modes of the CS-RZ pulse train on MSK format, an MSK signal is generated by simulation using the commercial software, VPItransmissionmaker. In the simulation, two scenarios of pulse generation are considered. In the first scenario, the MZM1 is fully driven with $2V_\pi$ and two higher order side modes are strong, and hence the pulses generated are considered as the conventional CS-RZ pulses. In the second scenario, an additional optical bandpass filter is used following MZM1 to remove the high order side modes, and hence the pulses generated are considered as the pure dual mode CS-RZ pulses. Fig. 4.8 shows the simulated eye patterns of the generated MSK signals after balanced detection for both the scenarios. Strong uneven boarder (ripple) at both the top and/or bottom of the eyes is observed in MSK eye pattern when a conventional CS-RZ pulse train is used for sinusoidal weighting (i.e., without optical filtering), while no ripple is observed when a pure dual-mode pulse train is used (i.e., with optical filtering).

Figure 4.7: Eye patterns and optical spectra of MSK signal, with a drive swing for MZM1 less than $2V_{\pi}$. (a) Optical spectra and eye pattern of MSK signal, (b) DI output port 1, (c) DI output port 2

Figure 4.8: Simulated eye patterns of MSK signal after balanced detection with a drive swing for MZM1 at $2V_{\pi}$. (a) without optical filtering, and (b) with optical filtering

4.6 Conclusions

The theory of MSK format in digital communications shows that MSK can be viewed as either a sinusoidal weighted OQPSK, or a special case of CPFSK with modulation index $h=0.5$. It has been proven that these two implementation methods indeed provide essentially the same outcome. In this chapter, a novel approach for implementing optical MSK transmitter and receiver has been proposed. The principle on the generation and detection of the externally modulated optical MSK signal using the proposed MSK transmitter and receiver is presented in details. 10.709Gb/s MSK signal is successfully generated and detected experimentally. Both the analytical and experimental studies show that the generated optical externally modulated MSK signal exhibits the properties of constant amplitude and continuous phase change at the bit transition instants. Experimental result also shows that the MSK signal has much lower side lobes than that of RZ-DPSK and RZ-OOK signals. Hence, it is expected that the generated MSK signal can achieve higher spectral efficiency and larger dispersion tolerance, and can also reduce crosstalk from the neighbouring channels. The simulation results have also shown that using the conventional CS-RZ pulse train and pure dual-mode CS-RZ pulse train for the MSK modulator result in different MSK signals, in terms of their spectra and eye patterns. The system performance against fiber dispersion, fiber nonlinear effects and linear crosstalk tolerance will be presented in Chapter 5.

Chapter 5

Performance Evaluation of Externally Modulated Optical MSK Signal

5.1 Introduction

A novel approach for generating and detecting externally modulated optical MSK signal has been proposed in Chapter 4. The newly generated MSK signal using the proposed MSK transmitter indeed exhibits the properties of constant amplitude and continuous phase at every bit transition instant. As demonstrated in experiments, the generated MSK signal has a narrower power spectrum and lower side lobes as compared to the RZ-DPSK signal. Therefore, it is expected that the optical MSK format would have a better tolerance against chromatic dispersion, linear crosstalk, and fibre nonlinear effects such as SPM and XPM, compared with the RZ-DPSK format which is studied in Chapter 3. These features may make optical MSK a preferable data format for high speed and high spectral efficiency WDM systems.

In this chapter, the performance of the proposed optical MSK system is evaluated and compared with that of RZ-OOK and RZ-DPSK systems through both simulation and experiment. Unless specifically stated otherwise, both the RZ-DPSK and RZ-OOK signals that are used for performance comparison purpose are with 50% duty cycle, which are generated using two Mach-Zehnder modulators (MZMs), with the pulse carving MZM biased at the quadrature point with V_π driving voltage swing.

The rest of this chapter is organized as follows. In section 5.2, the tolerance against fiber dispersion and linear crosstalk is studied to evaluate the advantages provided by the narrow power spectrum and the low side lobes of the optical MSK signal. The tolerance against SPM and the stimulated Brillouin scattering (SBS) threshold are presented in section 5.3. The phase noise of the MSK modulated system is investigated in section 5.4. The system optimizations, such as optimum bandwidth of the optical filter and electrical filter in the receiver, and the optimum fiber launch powers for both the single mode fiber (SMF) and dispersion compensation fiber (DCF), are studied in section 5.5 and section 5.6.

5.2 Dispersion Tolerance and Linear Crosstalk

As discussed in section 4.5, the optical MSK data is generated by sinusoidal weighting offset-quadrature phase-shift keying (OQPSK), and the sinusoidal function is achieved by using carrier-suppressed (CS) RZ pulse source which is obtained from a Mach-Zehnder modulator (MZM1) biased at transmission null point, as shown in Fig. 4.4. The theoretical derivation for the generated MSK signal has assumed that the CS-RZ pulse train from the modulator MZM1 (refer to Fig. 4.4) is pure dual-mode, where higher order side modes are ignored. This indeed reduces the duty cycle from 67% to 50%, and can be achieved by using an optical bandpass filter. Driving MZM1 with a drive swing less than $2V_{\pi}$ can also reduce the higher order side modes. However the investigation shows that the higher order side modes do not affect the generation of optical MSK signal, instead, they help to achieve better tolerance against fiber dispersion and SPM effect, as will be discussed in this section and the next section. Throughout this chapter, in the simulation (using the commercial software, VPItransmissionmaker), two approaches to achieve the sinusoidal weighing

for OQPSK in the MSK generation are considered. The first approach is to use the conventional CS-RZ pulses which is generated by driving the MZM1 with full $2V_\pi$ swing and without the optical bandpass filter after the modulator MZM1. The second approach is to use the pure dual-mode pulses which are generated by using an additional optical bandpass filter following the modulator MZM1 to remove the higher order side modes. While in the experiments studied here, the CS-RZ signal is achieved with a driving voltage less than $2V_\pi$, due to the maximum available output power of the driver amplifier is less than $2V_\pi$ for MZM1, which is around 12V. Hence, the performance of the MSK signal obtained from experiments is in-between the two cases of the simulation results.

Figure 5.1 shows the simulated spectra of all the formats under study. The optical spectra of both MSK signals are narrower than those of the RZ-DPSK and RZ-OOK signals, and the side lobes of the MSK spectra are also noticeably lower, especially for the MSK signal generated using the pure dual-mode pulses.

Figure 5. 1: Spectra of MSK, RZ-DPSK and RZ-OOK formats

To evaluate the advantages provided by the narrow power spectrum and low side lobes of the optical MSK signal, the tolerance against fiber dispersion and linear crosstalk characteristics between MSK and two other advanced modulation formats, RZ-DPSK and RZ-OOK is compared.

5.2.1 Dispersion Tolerance

Tolerance against fiber dispersion is an important aspect when comparing the performance of different advanced data formats. Large tolerance against fiber dispersion is highly desirable to facilitate the cost effective link design and system installation, particularly at high line rates of 40Gbit/s or beyond. In this section, a detailed comparison of the tolerance against fiber dispersion among MSK, RZ-DPSK, and RZ-OOK formats is presented, by both experiment and simulation. The fiber dispersion tolerance is studied through the variation of either single span of single mode fiber (SMF) or dispersion compensation fiber (DCF) to produce the required dispersion levels. The launched power to SMF is 0dBm and is -6dBm to DCF, which is low enough to make power penalty caused by nonlinear effects negligible within such a short distance. For RZ-OOK, the received signal is directly detected by a PIN based receiver. While for MSK and RZ-DPSK, the received signal is detected using a balanced receiver which consists of a 1-bit delay interferometer (DI) and two PIN photodiodes. The phase difference between the two arms of the delay interferometer is set to 90-degrees for MSK and 0 degree for RZ-DPSK. The electrical filter used in the receiver module has a bandwidth equal to the bit rate for all the formats evaluated. This may not be the optimum bandwidth for each individual format, but it is fair for the comparison purpose.

5.2.1.1 Simulation Investigations

Figure 5.2 shows the simulated eye opening penalty as a function of residual chromatic dispersion for MSK, RZ-DPSK, and RZ-OOK formats in a 10Gb/s system, by using the commercial software, VPItransmissionmaker. Residual chromatic dispersion is referred to the remaining chromatic dispersion in a chromatic dispersion compensated system. In this simulation, eye opening penalty rather than power penalty is used due to the lack of proper limiting amplifier model in the software. As shown in Fig. 5.2, the two MSK formats generated using both conventional CS-RZ pulses and pure dual-mode CS-RZ pulses exhibit larger dispersion tolerance defined by 1dB eye opening penalty, as compared with RZ-DPSK and RZ-OOK. Here the 1dB dispersion tolerance is defined as the allowed residual chromatic dispersion when the eye opening penalty due to the dispersion is 1dB. The 1dB dispersion tolerances for RZ-OOK and RZ-DPSK signals are very similar, which is about $\pm 500\text{ps/nm}$. While the 1dB dispersion tolerances for the MSK signal generated using pure dual-mode CS-RZ pulses is about $\pm 1000\text{ps/nm}$, and $\pm 1500\text{ps/nm}$ for the MSK signal generated using conventional CS-RZ pulses. Hence, the MSK format generated using conventional CS-RZ pulses has the widest dispersion tolerance among all these formats. It is noted that a very small negative penalty (around -0.05dB maximum) is mainly due to the measurement error, not inherited by the formats themselves.

Figure 5. 2: Simulated dispersion tolerance comparison among MSK, RZ-DPSK (50% duty cycle) and RZ-OOK (50% duty cycle)

It is worth to point out that, comparing with the MSK signal generated using pure dual-mode CS-RZ pulses, the dispersion tolerance of the MSK signal generated using conventional CS-RZ pulses is wider, although it has a broader spectrum, as the spectra shown in Fig. 5.1. This sounds contradictory with the well accepted conclusion that narrower spectrum will provide better dispersion tolerance. In order to understand this unusual phenomenon, the chirp at the output of the MSK transmitter is examined using VPItransmissionmaker, since VPItransmissionmaker has the function of providing signal phase and chirp. It is found that there is an additional modulation on the chirp (frequency shift keying) due to the existence of higher order side modes, as shown in Fig. 5.3 (a), when conventional CS-RZ pulse train generated by the modulator MZM1 is used for sinusoidal weighting. If an ideal pure-dual mode is used for sinusoidal weighting, this modulation on the chirp disappears, as shown in Fig. 5.3 (b). To further understand the effect of high order side modes (i.e. the nonlinear chirp) on dispersion tolerance, the dispersion tolerance when the MZM1 is driven by a

driving voltage of V_π , not $2V_\pi$ as in the conventional CS-RZ case is simulated. And in this case studied, the optical bandpass filter is not used. Hence, the high order side modes of this CS-RZ pulses still exist but have smaller amplitude than that of the conventional CS-RZ pulses. Therefore, its dispersion tolerance should be in between the tolerances of the two MSK signals studied in Fig. 5.2.

Fig. 5.4 shows the simulated dispersion tolerance comparison among the MSK signals generated using three different types of CS-RZ pulses, which are the conventional CS-RZ pulses, pure dual-mode CS-RZ pulses, and the CS-RZ pulses driven by half of the driving voltage of the conventional CS-RZ pulses. As shown in this figure, the dispersion tolerance of the MSK generated using driving voltage V_π is indeed in between those of the MSK signals generated by conventional CSRZ pulses and pure dual-mode CSRZ pulses. This indicates that the nonlinear chirp on the phase of the MSK signal generated with higher order side modes help to achieve better tolerance against fiber dispersion.

(a)

Figure 5. 3: The chirp of the MSK signal. (a) Conventional CS-RZ pulses generated by MZM1 used for sinusoidal weighting, and (b) Pure dual-mode pulses used for sinusoidal weighting

Figure 5. 4: Simulated dispersion tolerance comparison among MSK signals under three different conditions of generating the CS-RZ pulses

5.2.1.2 Experimental Investigations

The experimental setup is the same as the simulation setup. Figure 5.5 shows the measured power penalty as a function of residual dispersion for MSK, RZ-DPSK, and RZ-OOK formats, in a 10.709Gb/s system. In this experiment, as explained previously, the CS-RZ signal is achieved with a driving voltage less than $2V_\pi$. Hence, the performance of the MSK signal obtained is in-between the two cases considered in the simulation (i.e. using pure dual-mode CS-RZ pulses and conventional CS-RZ

pulses). Fig. 5.5 shows that the MSK signal exhibits the largest dispersion tolerance defined by 1 dB power penalty among all the three formats. This result agrees with the simulation result presented in section 5.2.1.1, which is shown in Fig. 5.2. The relatively worse tolerance for the MSK format in the experiment is believed to be mainly due to the mismatch between the fixed 100ps delay built-in to the OQPSK modulator and the experimental bit duration of ~ 93 ps, corresponding to 10.709Gb/s (determined by the available clock and data recovery device in our lab). The mismatch also causes a significant distortion on the eye pattern as the SPM getting dominant, which will be discussed in section 5.3.1. the small negative penalty is mainly due to the chirp from the modulators. It is also noted that there is small negative penalty on the RZ-OOK and MSK signals. This small negative penalty is mainly due to the chirp from the modulators. The modulators used to generate the RZ-OOK and MSK signals are not chirp free, and they are with different chirp parameters.

Figure 5. 5: Measured dispersion tolerance comparison among MSK, RZ-DPSK (50% duty cycle) and RZ-OOK (50% duty cycle)

5.2.2 Linear Crosstalk

To study the linear crosstalk characteristic, the linear crosstalk penalty is calculated as a function of spectral efficiency for MSK, RZ-DPSK and RZ-OOK formats in a 7-channel 10Gb/s and 40Gb/s system, where the spectral efficiency is defined as the bit rate divide by the channel spacing. The spectral efficiency corresponds to the spectral density of information and is expressed in bit/s/Hz. Because linear crosstalk and spectral efficiency problem are more severe in 40Gb/s system, linear crosstalk of a 40Gb/s system is also studied in this section. In the simulation, each channel carries a different pseudorandom binary sequence (a length of $2^{10}-1$) to avoid the correlation effect. The seven channels are multiplexed using a multiplexer which is modelled as a third-order Bessel bandpass filter with filter bandwidth of twice the data bit rate. The optical bandpass filter used to demultiplex the central channel at the receiver end is simulated as a second-order Gaussian filter with a bandwidth of 75% of the channel spacing. Fig. 5.6 and Fig. 5.7 show the power penalty from linear crosstalk as a function of spectral efficiency in a 10Gb/s system and a 40Gb/s system, respectively. This penalty is obtained by calculating the sensitivity ($\text{BER}@10^{-9}$) difference between WDM channel and single channel under back-to-back case, which includes the penalty caused by the optical filtering. In the balanced receiver module, two fourth-order Bessel lowpass filters with 7.5GHz and 30GHz cutoff frequencies are used for the 10Gb/s and 40Gb/s systems, respectively. For RZ-OOK, the received signal is detected by a single PIN detector, and the filters used in the receiver are the same as those in the balanced receiver.

As shown in Fig. 5.6, 1 dB power penalty occurs when the spectral efficiency is about 0.46 for RZ-OOK and RZ-DPSK formats, about 0.53 for MSK signal generated using

conventional CS-RZ pulses, and about 0.63 for the MSK signal generated using pure dual-mode CS-RZ pulses. The results shown in Fig. 5.7 are very close to the results from Fig. 5.6. From these two figures, it shows that in both the 10Gb/s and 40Gb/s systems, the MSK formats generated using both conventional CS-RZ pulses and pure dual-mode pulses exhibit less power penalty for higher spectral efficiency ($>0.35\text{bit/s/Hz}$) compared with RZ-DPSK and RZ-OOK, and the MSK format generated using pure dual-mode CS-RZ pulses has the smallest penalty among all these formats. Lower linear crosstalk in the MSK using the pure dual-mode CS-RZ pulses compared to that using conventional CS-RZ pulses can be attributed to the lower side lobes in the optical spectrum, as seen in Fig. 5.8. Fig. 5.6 also shows that in the 10Gb/s system, RZ-OOK outperforms RZ-DPSK in a low spectral efficiency WDM system. But RZ-DPSK is advantageous in a high spectral efficiency (e. g. >0.4) system. This agrees with the results reported in [65, 118].

The linear crosstalk penalties in both the 10Gb/s and 40Gb/s systems are very similar. This is because the linear crosstalk penalty is calculated as a function of spectral efficiency and the channel spacing changes with the spectral efficiency. In principle, the results in the 10Gb/s system should be the same as the one in the 40Gb/s system. The small variation might be due to the fact that the optical noise and the thermal noise are four times higher in the 40Gb/s system than those in the 10Gb/s system.

Figure 5. 6: Linear crosstalk tolerance comparison among MSK, RZ-DPSK and RZ- OOK in a 10Gb/s system

Figure 5. 7: Linear crosstalk tolerance comparison among MSK, RZ-DPSK and RZ- OOK in a 40Gb/s system

Figure 5. 8: Spectra of 40 Gb/s MSK generated using conventional CS-RZ pulses and pure dual-mode CS-RZ pulses

In summary, simulation results show that both MSK signals, generated using conventional CS-RZ pulses and pure dual-mode pulses, exhibit wider fiber dispersion tolerance than the RZ-DPSK and RZ-OOK signals. The dispersion tolerance in the MSK signal generated using conventional CS-RZ pulses is the widest. Experimental results also show that the MSK signal provides the widest dispersion tolerance defined by 1dB power penalty among the formats under study as the fiber dispersion increases, although the tolerance range is not as larger as the simulation results. The simulated linear crosstalk power penalty results show that in both 10Gb/s and 40Gb/s system, the MSK formats generated using both conventional CS-RZ pulses and pure dual-mode pulses exhibit less power penalty as the spectral efficiency increases compared with RZ-DPSK and RZ-OOK, and MSK generated using pure dual-mode CS-RZ pulses has the smallest penalty for higher spectral efficiency among all these formats.

5.3 SPM Tolerance and SBS Threshold

5.3.1 SPM Tolerance

To evaluate the tolerance against fiber nonlinear effect, 10.709Gb/s single-channel data is transmitted over a 4x164km transmission link in a recirculating loop with different data formats, again including MSK, RZ-DPSK, and RZ-OOK. The total fiber loss is about 32.8dB in the simulations and about 33.6dB in experiments which includes the connector losses. Fig. 5.9 shows the setup used to evaluate the tolerance against SPM effect for MSK, RZ-DPSK and RZ-OOK formats, both in simulation and experiment. Each span is fully compensated by a corresponding DCF and amplified with an erbium-doped fiber amplifier (EDFA). The power launched into the DCF is fixed at -6dBm, while the power launched into SMF is varied to change the accumulated self-phase-modulation (SPM). The receiver modules used are the same as those used in the dispersion tolerance evaluation, in section 5.2.1. A pseudorandom bit sequence with a word length of $2^{10}-1$ is used in simulations and $2^{23}-1$ in experiment.

Figure 5. 9: Setup for evaluating tolerance against self-phase modulation

5.3.1.1 Simulation Results

In the simulation, the amplified spontaneous emission (ASE) noise is first deactivated so as to focus on the effect of SPM only. Again, eye opening penalty rather than power penalty is used due to the lack of proper limiting amplifier model in VPItransmissionmaker. Fig. 5.10 shows that the MSK formats generated using both conventional CS-RZ pulses and pure dual-mode pulses provide better tolerance against fiber nonlinear effects compared with the RZ-DPSK and RZ-OOK formats, and the MSK using conventional CS-RZ pulses exhibits the best SPM tolerance among all these formats. It is also noticed that when the fiber launch power is less than 12dBm, the eye opening penalty of the MSK format generated using conventional CS-RZ pulses decreases with the fiber launch power, while the eye opening penalty of the other formats increases positively. In order to understand this negative penalty, the SPM tolerance of different MSK signals generated using different CSRZ pulses is simulated. It is observed that the additional modulation on the chirp, as shown in Fig. 5.3(a), helps to achieve better SPM tolerance. It is believed that this negative penalty might be due to the modulation on the chirp. As mentioned in section 5.2.1.1, the modulation on the chirp is an additional periodic modulation and is nonlinear. And it is caused by the higher order modes in the CS-RZ pulses. In order to verify whether this chip causes the negative penalty and provides better SPM tolerance, another SPM tolerance simulation is carried out, which simulates the SPM tolerance among MSK signals under three different conditions of generating the CS-RZ pulses, i.e. with conventional CS-RZ pulses, with pure dual-mode pulses, and with CS-RZ pulses driven by V_{π} . The simulation is shown in Fig. 5.11 below.

Figure 5. 10: Simulated SPM tolerance comparison among MSK, RZ-DPSK (50% duty cycle) and RZ-OOK (50% duty cycle), when ASE noise is deactivated

Figure 5. 11: Simulated SPM tolerance comparison among MSK signals under three different conditions of generating the CS-RZ pulses

As the result shown in Fig. 5.11, the SPM tolerance of the MSK generated using V_{π} driving swing is indeed in-between those of the MSK signals generated by conventional CSRZ pulses and pure dual-mode CSRZ pulses. This indicates that the

periodic nonlinear chirp on the MSK signal generated with higher order side modes help to achieve better tolerance against self phase modulation.

To further understand the system SPM tolerance with the presence of ASE noise, which is a more realistic case, the ASE noise is activated and the noise figure (NF) of EDFAs is set to 6dB. Figure 5.12 shows the eye opening penalty of SPM as a function of fiber launching power, with the ASE noise activated. It can be seen that when the fiber launching power is large enough (larger than 0dBm in this simulation), the MSK signals, generated using both conventional CS-RZ pulses and pure dual-mode pulses, provide better tolerance against SPM compared with RZ-DPSK and RZ-OOK signals. And the negative power penalty associated with the increase of launching power is still observed for the MSK format generated using conventional CS-RZ pulses. However, when the fiber launching power is small, which is less than 0dBm in this simulation, the power penalty of the MSK signals is larger than that of the RZ-DPSK and RZ-OOK signals. This indicates that the MSK signals are more sensitive to optical noise, although they provide larger tolerance against the SPM, since the ASE noise is more significant when the fiber launching power is small.

Figure 5. 12: SPM tolerance comparison among MSK, RZ-DPSK (50% duty cycle) and RZ-OOK (50% duty cycle), when ASE noise is activated

Table 5.1 shows the receiver sensitivity ($\text{BER}@10^{-9}$) for all the formats studied in back-to-back case. As seen in Table 5.1, both MSK signals require higher receiver power than the RZ-DPSK and RZ-OOK signals, in order to achieve the same BER performance. The MSK signal generated with conventional CS-RZ pulses gives the worst case, which is mainly due to the strong uneven boarder at both the top and/or the bottom of the eye and the smaller eye opening as shown in Fig. 4.8. This result shows that both the MSK modulated systems have worse performance in terms of noise tolerance, comparing with the RZ-DPSK and RZ-OOK systems. However, the MSK signals outperform the others in the tolerance against fiber dispersion and SPM when the fiber launch power is large enough, which is not an issue in a practical transmission link. It is also worthwhile to mention that the receiver sensitivity of the MSK generated with pure dual-mode CSRZ pulses is similar to that of NRZ-DPSK signal, which is about -18.4dBm. It is well known that RZ-DPSK provides 3dB OSNR advantage over RZ-OOK when a balanced receiver is used. However, the receiver sensitivity of RZ-DPSK is worse than that of RZ-OOK, as shown in Table 5.1. This might be because that the thermal noise in a balanced receiver (two PINs) is twice of that in a single-ended receiver (one PIN). And the thermal noise is significant in such systems, since the receiver power is at the receiver sensitivity level. Furthermore, the peak power of the RZ-OOK is higher than that of RZ-DPSK with same average power due to the fact that the intensity mark ratio for RZ-OOK is 0.5 while it is 1 for RZ-DPSK. Hence, the receiver sensitivity of RZ-DPSK is worse than that of RZ-OOK, even though balanced detection is used.

Table 5. 1: Receiver sensitivity of MSK, RZ-DPSK and RZ-OOK formats in back-to-back case

Formats	Receiver sensitivity (dBm)
MSK (with conventional CS-RZ pulses)	-15.9
MSK (with pure dual mode pulses)	-18.1
RZ-DPSK	-20.5
RZ-OOK	-22.1

5.3.1.2 Experimental Results

Figure 5.13 shows the measured power penalty as a function of fiber launch power. For the MSK format, there is also a small negative power penalty observed when the fiber launch power is between 0 to 3.5dBm (as also seen in the simulation results). This negative penalty implies that the eye opening of the demodulated signal at the high launch power is bigger and clearer than that at the low launch power. This is possible because when the signal is transmitted along the fiber, the different types of nonlinear effects will interact with each other. This interaction may cause the improved performance. But this power penalty increases rapidly when the fiber launch power is larger than 5dBm, compared with RZ-OOK and RZ-DPSK formats. As mentioned in the above section, the negative power penalty may be due to the nonlinear chirp of the MSK signal, as it is found that there is an additional modulation on the chirp (frequency-shift keying) due to the presence of higher order side modes in the CS-RZ pulses, when conventional CS-RZ pulse train generated by the modulator MZM1 is used for sinusoidal weighting.

A less negative penalty in this experiment is believed to be due to the driving swing of less than $2V_{\pi}$ in CS-RZ pulse generation. The relatively poor tolerance against the SPM for the MSK signal in the experiment is mainly due to the contribution of the ASE noise and the mismatch between the fixed 100ps delay built-in to the OQPSK modulator and the experimental bit duration of ~93ps, corresponding to 10.709Gb/s

(determined by the available clock and data recovery device in our lab). The mismatch causes a significant distortion in the eye pattern as the SPM is getting dominant. In order to further investigate the effect of this mismatch, simulation is carried out. In the simulation, at the fiber launch power of 6dBm, the penalty is small when there is no mismatch. However, the eye is almost closed when there is 7ps mismatch, as shown in Fig. 5.14(a) and 5.14(b) respectively. If the fiber launch power is increased to 10dBm, the penalty in the no mismatch case is still small, as shown in Fig. 5.14(c), whereas the eye is completely closed in the mismatch case.

Figure 5. 13: SPM tolerance comparison among MSK, RZ-DPSK and RZ-OOK (experiment results)

Figure 5. 14: Simulated eye diagrams of the MSK format. (a) without mismatch at a launch power of 6dBm, (b) with 7ps mismatch at a launch power of 6dBm, (c) without mismatch at a launch power of 10dBm

5.3.2 SBS Threshold

Another fiber nonlinear effect is the SBS effect, which is an important factor, particularly in Raman amplified systems, which has been demonstrated in section 3.3.1. The experimental setup used to study the SBS threshold for the MSK signal is the same as that for the Raman amplified system in Fig. 3.10, which is also shown in Fig. 5.15 here. This study is carried out in a 10.709Gb/s system, with different pumping conditions, such as co-pumping, counter-pumping and bidirectional pumping at different pumping powers. As shown in Fig. 5.15, a 1550.92nm DFB laser is encoded with MSK format using the MSK transmitter presented in Chapter 4. The 10.709Gb/s NRZ data is a pseudorandom binary sequence (PRBS) with a word length of $2^{23}-1$. The 150km standard SMF has 31.2dB total loss, including the loss from fiber connectors. The SMF dispersion is fully compensated by DCF. There are two pump lasers in each Raman amplifier, which are at 1425nm and 1453nm respectively. The pump powers are set to 100mW and 180mW correspondingly for the co-pump, and 260mW and 400mW for the counter-pump. Thereby the Raman gains provided by the co-pump and counter-pump are 4.9dB and 10.6dB respectively. The optical power into the DCF is strictly kept below -1dBm under different pumping conditions. The backward-scattered power is measured at the 4-port coupler after the residual Raman pump power is filtered out, and the OSNR (at 0.1nm) is measured at the 10:90 coupler and can be changed via an optical attenuator (*att1*). Another attenuator (*att2*) is used to maintain the same optical power launched into the detector under different conditions, so that the effect of receiver can be excluded. To facilitate comparison with RZ-OOK and RZ-DPSK signals, the single-ended receiver used to detect the MSK signal is the same as that used in section 3.3.1.

The results in Fig. 5.16 and Fig. 5.17 show that in the MSK modulated system, the backward-propagating power contributed by the counter-pump cases is similar to that in the no-pump case, which means that the backward-propagating power contributed by the counter-pump is negligible due to the long fiber span and the large span loss in this investigation, but the backward-propagating power in the co-pump cases is significant and obviously higher than that in the no-pump case. The pump powers used in Fig. 5.16 to Fig. 5.18 are the same as those used in Fig. 3.11 to Fig. 3.13 respectively, in section 3.3.1.2. These results show that in the MSK modulated system, the SBS threshold is not noticeable, even with a fiber launch power of about 20dBm, for both separated counter- and co-pump cases. The backward-scattered power in a bidirectional pumped system is mainly caused by co-pumping, as shown in Fig. 5.18. This gives the similar conclusion drawn in Chapter 3, Section 3.3.1, even though different signal formats are used.

In these figures, the backward-scattered power increases linearly with the fiber launch power, and there is no abrupt tuning point. This means that the SBS threshold in this system does not occur if the launch power is within 20dBm (The maximum output power of the EDFAs available in our laboratory is 20dBm). This implies that in the MSK system, when the launch power is less than 20dBm, it is SPM that limits the system performance, but not the SBS effect. This also concludes that the SBS threshold in the MSK system is more than 10dB higher than that in the RZ-OOK system, comparing with the results obtained in Section 3.3.1. Again, as explained in Section 3.3.1, this increased threshold can be attributed to the absence of discrete spectral tones in the MSK signal, since those discrete spectral tones in OOK formats have narrow linewidth and possess large amount of optical signal power.

Figure 5. 15: Experiment setup for SBS threshold evaluation

Figure 5. 16: Backward-propagating power vs. fiber launch power for MSK format, with different counter-pump powers

Figure 5. 17: Backward-propagating power vs. fiber launch power for MSK format, with different co-pump powers

Figure 5. 18: Backward-propagating power vs. fiber launch power for MSK format, with bidirectional pumps

Figure 5.19 shows the SBS reflected powers for the RZ-OOK, RZ-DPSK and MSK formats, under the same pumping conditions. As seen in Fig. 5.19, the reflected power from the MSK and RZ-DPSK formats is similar, and there is no SBS threshold observed even when the fiber launch power is close to 20dBm. Due to the EDFA output power limitation (20dBm is the maximum output available in our lab), the SBS threshold for RZ-DPSK and MSK formats could not be measured. However, the SBS

thresholds in both MSK and RZ-DPSK modulated systems are more than 10dB higher than that in an RZ-OOK system. Therefore, the MSK format is also suitable to be used in the single-span transmission systems since higher SBS threshold implies that larger fiber launch power is possible.

Figure 5. 19: Backward-reflected power vs. fiber launch power under different pumping conditions, for RZ-OOK, RZ-DPSK and MSK formats

In summary, the tolerance against SPM effect and SBS threshold has been evaluated and compared among MSK, RZ-DPSK and RZ-OOK, via both experiment and simulation. Simulation results show that the MSK signal exhibits largest tolerance against SPM effect among these formats. Experimental results also confirmed the negative penalty against SPM effect. Nonlinear chirp on the MSK signal generated using conventional CS-RZ pulses helps to achieve better tolerance against SPM. The SBS threshold of both MSK and RZ-DPSK systems is more than 10dB higher than that of an RZ-OOK system.

5.4 Phase Noise

Nonlinear phase noise was first described by Gordon and Mollenauer in 1990 [119]. Nonlinear phase noise arises when optical signals and optical amplitude noise together modulate the fiber refractive index via the Kerr effect.

It is well known that Kerr effect in the fiber produces amplitude-dependent nonlinear effects such as SPM and FWM. While group velocity dispersion alters the temporal shape of a pulse as it traverses the fiber, SPM alters its frequency spectrum. Taken these two effects together, they can have complicated effects and affect different modulation formats in different ways. The phase or frequency modulation schemes have the advantage that the signal amplitude may be constant initially. This delays the major effects of SPM for a while. However, since the fiber refractive index is dependent on optical power through the nonlinear Kerr effect and fluctuations in optical power, which is induced by the optical amplifier ASE noise, would give rise to phase fluctuations at the receiver. This is the well-known Gordon-Mollenauer effect [119]. As stated by Gordon and Mollenauer, this nonlinear phase noise, which increases with the increasing signal power, adds to the usual linear phase noise, and becomes a fundamental problem that limits the transmission distance and launched power in these systems[119-120].

It is well known that DPSK with a balanced receiver provides a 3dB OSNR improvement for a system limited by ASE beat noise [46]. With strong interest in DPSK and other advanced modulation formats recently, nonlinear phase noise has been studied intensively by simulation and experiment [61-63, 121-127]. It has been shown that the 3dB OSNR improvement is reduced [118] or even DPSK penalty [63]

when the Gordon-Mollenauer effect becomes dominant (i.e., nonlinear phase noise is severe). However, in these studies, the system penalty is evaluated based on the overall impairments, not based on the nonlinear phase noise alone. In the simulation presented here, it is observed that part of the nonlinear phase noise is converted to amplitude fluctuation, and the other converted to timing jitter. Hence, by measuring the timing jitter, the penalty caused by the nonlinear phase noise can also be evaluated.

To evaluate the timing jitter as a function of the fiber launch power, a 10Gb/s single channel is transmitted over 30x80km transmission link in a recirculating loop with different data formats, again including MSK, RZ-DPSK, and RZ-OOK. The simulation model is shown in Fig. 5.20. Each span is compensated by a corresponding DCF and amplified with two EDFAs, where their noise figure is set to 6dB. located before and after the DCF. The launch power into the DCF is fixed at -4dBm, while the launch power into the SMF is varied to change the accumulated SPM. The receiver modules used are the same as those used for dispersion tolerance evaluation, in section 5.2.1. A pseudorandom bit sequence with a word length of $2^{10}-1$ is used. Since the nonlinear phase noise depends on the interaction between ASE noise and the fiber nonlinearities, the resulting timing jitter will be affected by the system noise severely. Hence, for fair comparison, the OSNR was fixed at 18dB for all the formats under study, by controlling the attenuator (*att2*). The noise figure in all the EDFAs is set to 6dB.

Figure 5.20: Simulation model for the phase noise investigation

Figure 5.21 shows the peak-to-peak timing jitter as a function of the fiber launch power, with the OSNR fixed at 18dB. The conventionally parameter used to measure timing jitter is the root mean square (RMS) timing jitter, instead of the peak-to-peak timing jitter. However, it is found that the RMS timing jitter measured by VPItransmissionmaker does not function properly. Hence, the peak-to-peak timing jitter is used in this simulation instead, which is defined as the difference between the earliest and latest crossing times for 0 to 1 transitions. And the transitions from 1 to 0 are not considered. As shown in Fig. 5.21, the MSK signal generated using conventional CS-RZ pulses has the worst timing jitter initially, compared to the RZ-DPSK signal and the MSK signal generated with pure dual-mode pulses. However, its timing jitter increases slowly as the fiber launch power increases and the MSK signal generated using conventional CS-RZ pulses outperforms the RZ-DPSK and MSK signal generated with pure dual-mode pulses when the launch power is larger than 8.5dBm. Whereas for the RZ-DPSK signal, the peak-to-peak timing jitter is the smallest when the fiber launch power is less than 7dBm, but the jitter increases tremendously and becomes the worst among the three formats when the launch power

is larger than 8.5dBm. In order to understand the reason why the MSK signal generated using the conventional CS-RZ pulses has the highest timing jitter initially, the systems in the back-to-back case and after transmission are simulated, where the fiber dispersion and nonlinearity in the SMF and DCF are deactivated. The results show that even without the fiber dispersion and nonlinearity, the noise level and the peak-to-peak timing jitter of the MSK signal generated using the conventional CS-RZ pulses are higher than those in other two formats, with a fixed OSNR of 18dB. This gives the same conclusion as the one drawn in the SPM tolerance study (Section 5.3.1), that is, MSK modulated systems are more sensitive to the system noise, but they outperform others if the fiber launch power is large enough. The receiver sensitivity of the MSK signal generated using the conventional CS-RZ pulses is much worse than the other two formats.

Figure 5. 21: Peak-to-peak timing jitter vs. fiber launch power for different formats, with the OSNR fixed at 18dB

In conclusion, both the MSK signals have higher peak-to-peak timing jitter than the RZ-DPSK initially. However, the timing jitter of the MSK signal generated using

conventional CS-RZ pulses increases slowly as the fiber launch power increases and it outperforms the RZ-DPSK signal when the launch power is larger than 8.5dBm.

5.5 Optimization of Receiver Filter Bandwidths

Filter bandwidth optimization of direct detection receivers in the presence of optical noise for high speed transmission systems has attracted great research attention [37, 128-133]. As pointed out in [37], if optimum receivers are used, the non-return-to-zero (NRZ) signal has the same sensitivity as the return-to-zero (RZ) signal with arbitrary duty cycle. The empirical 2dB sensitivity improvement for the RZ modulation over NRZ is achievable in sub-optimal receivers. Winzer et al [129] showed that RZ-DPSK with balanced detection outperforms its single-ended equivalent and RZ-OOK by ~2.7dB on OSNR requirement, at narrower optical filter bandwidths. Hence, using an optimum receiver design, the receiver sensitivity can be improved, and this alleviates the requirement for other system parameters and/or extends transmission distance.

In this section, the receiver optical and electrical filter bandwidths for an externally modulated optical MSK signal described in Chapter 4 are optimized. The optimum optical and electrical filter bandwidths for the RZ-OOK and RZ-DPSK are also presented here, as a comparison with the MSK data.

The schematic for receiver bandwidth optimisation is shown in Fig. 5.22. The optimum filter bandwidth study here is carried out in a 10Gb/s system for two cases, the back-to-back (BTB) and after 8x80km transmission, via simulation using a commercial software, VPItransmissionmaker. Each span consists of 80km SMF and a

corresponding DCF to realise full dispersion compensation. Two erbium-doped fibre amplifiers (EDFAs) are used to compensate for the total fibre loss in each span, which are located before and after the DCF. ASE noise is included to study the effects of different optical signal-to-noise ratios (OSNR). The OSNR could be changed by the attenuator (Att2). For all the formats evaluated, the optical signal with and without transmission pass through a second-order Gaussian optical bandpass filter, with a bandwidth of B_o . For phase modulated formats, a 1-bit delay interferometer (DI) is used for data demodulation, followed by a balanced receiver. For RZ-OOK, no DI and only single-end receiver are used. An electrical fourth-order Bessel lowpass filter with a bandwidth of B_e is used after each PIN detector. A pseudorandom bit sequence with a word length of $2^{10}-1$ is used in this simulation. The launch power is set to 0dBm for the SMF and -6dBm for the DCF.

Figure 5. 22: Schematic for receiver bandwidth optimisation with different formats

Figure 5.23 shows the Q contour plot as a function of the optical and electrical filter bandwidths for all the formats studied. The left column is for the back-to-back case and the right column is for the case after 8x80km transmission. As described before, for the MSK generation, two types of CSRZ pulses are used as the sinusoidal

weighting for offset-quaternary PSK signal, i.e. the conventional CSRZ pulses and the pure dual-mode CSRZ pulses. As shown in Fig. 5.23, for the BTB cases (left column), the optimum optical and electrical filter bandwidths are around $3.3R$ and $0.8R$ for RZ-DPSK, and $3R$ and $0.8R$ for RZ-OOK respectively, which agree with the results obtained in [37, 129], where R refers to the data bit rate. However, the optimum optical and electrical filter bandwidths for MSK generated with conventional CSRZ pulses are $1.6R$ and $1.1R$ respectively. This indicates that the optimum optical filter bandwidth for this MSK signal is narrower than those for RZ-OOK and RZ-DPSK signals, and its optimum electrical filter bandwidth is higher than others. On the other hand, the optimum optical filter bandwidth for the MSK generated with pure dual mode CSRZ pulses is broader, which is between $1.8R$ and $5R$, and its optimum electrical filter bandwidth is around $0.8R$. After $8 \times 80\text{km}$ transmission (right column), the optimum optical filter bandwidths for both MSK signals become very narrow, which are around $1.4R$ and $1.5R$ respectively. And the electrical filter bandwidths are around $1R$ and $0.75R$ respectively. However, the optimum filter bandwidths for the RZ-DPSK and RZ-OOK formats are just slightly reduced, which are around $2.9R$ and $2.6R$ respectively for the optical filter, and $0.8R$ and $0.7R$ respectively for the electrical filter. These results are also listed in Table 5.2 for easy reference.

(b) MSK (with pure dual mode)

(c) RZ-DPSK (50% duty cycle)

(d) RZ-OOK (50% duty cycle)

Figure 5. 23: Q-value as a function of optical and electrical filter bandwidths for different formats. (Left column: back-to-back, and right column: after 8x80km transmission.)

Table 5. 2: Summary of the Q-value as a function of receiver optical and electrical filter bandwidths for different formats

		Optimum optical filter bandwidth	Optimum electrical filter bandwidth
MSK (with conventional CS-RZ pulses)	BTB	1.6R	1.1R
	After transmission	1.4R	1R
MSK (with pure dual-mode pulses)	BTB	1.8~5R	0.8R
	After transmission	1.5R	0.75R
RZ-DPSK	BTB	3.3R	0.8R
	After transmission	2.9R	0.8R
RZ-OOK	BTB	3R	0.8R
	After transmission	2.6R	0.7R

In general, the optimum optical and electrical filter bandwidths after transmission are narrower than those in the BTB cases, for all the formats, although the optimum range could be broader. This is because after transmission, the system OSNR is reduced, which is 35 dB under BTB case and 22 dB after transmission. However, the filter bandwidth cannot be reduced unlimitedly, due to the tradeoff between the noise and inter-symbol interference (ISI) effect. It is also noted that the Q-value for both the MSK signals after transmission does not reduce much. While, for the RZ-OOK, the Q-value penalty is around 1.6 after transmission.

To investigate the impact of fiber nonlinear effect on the optimization of filter bandwidths, another simulation is carried out by controlling the OSNR to be around 15dB for both the BTB and after transmission cases. Fig. 5.24 shows the Q contour plot as a function of the electrical and optical filter bandwidths for all the formats studied. Results in Fig. 5.24 show that if the OSNR remains the same, the optimum optical and electrical filter bandwidths remain almost the same in both the cases of BTB and after transmission. This observation shows that the optimum filter bandwidths are mainly determined by the OSNR in the evaluated system. The slightly better Q-values after transmission in Fig. 5.24(a) are due to the negative penalty

against fiber nonlinear tolerance, while for the RZ-DPSK and RZ-OOK, the Q-values are worse in the case of after transmission, as shown in Fig. 5.24(c) and 5.24(d).

(a) MSK (with conventional CSRZ pulses)

(b) MSK (with pure dual mode)

(c) RZ-DPSK (50% duty cycle)

Figure 5. 24: Q-value as a function of the optical and electrical filter bandwidths for different formats with the same OSNR of 15dB. (Left column: back-to-back, and right column: after 8x80km transmission.)

In summary, the MSK generated with conventional CSRZ pulses exhibits narrower optimal optical filter bandwidth while wider electrical filter bandwidth compared with RZ-OOK and RZ-DPSK. The MSK signal generated with pure dual-mode pulses has similar optimum range to RZ-OOK and RZ-DPSK at high OSNR, while with narrower optimal optical filter bandwidth at low OSNR. It is also noted that the optimum range is mainly affected by OSNR in the evaluated system.

5.6 Optimization of Fiber Launch Power

In all the simulations done above, the launch power entering the SMF and DCF are based on the experiences obtained from other formats. In this section, the powers that are launched into the SMF and the DCF for MSK transmission link are optimized. The results for the RZ-DPSK and RZ-OOK are also presented here for comparison.

The simulation model used in this optimization is similar to the model used in section 5.4. A 10Gb/s single channel is transmitted over a 40x80km transmission link in a recirculating loop with different data formats, again including MSK, RZ-DPSK, and

RZ-OOK. Each span is compensated by a corresponding DCF and amplified by two EDFAs, located before and after the DCF. The noise figure in all the EDFAs is set to 6dB. The receiver modules used are the same as those used for the dispersion tolerance evaluation as presented in section 5.2.1. The optical power launched to the optical receiver is fixed at -10dBm for all the formats, which is sufficient to eliminate the contribution from receiver thermal noise. A pseudorandom bit sequence with a word length of $2^{10}-1$ is used.

Table 5.3 summarizes the optimum SMF and DCF launch powers for different formats. As seen from this table, the MSK signal generated with conventional CS-RZ pulses takes slightly higher SMF launch power. This agrees with the results obtained in section 5.3.1 that the MSK signal generated with conventional CS-RZ pulses can tolerate more distortion from SPM.

Table 5. 3: The optimum SMF and DCF launch powers for different formats

Formats	SMF launch power (dBm)	DCF launch power (dBm)
MSK (with conventional CS-RZ pulses)	4	-3
MSK (with pure dual-mode pulses)	3	-4
RZ-DPSK	2	-2
RZ-OOK	2	-4

Figure 5.25 shows the contours of the Q-value as a function of the SMF and DCF launch powers after 40x80km transmission. There is an optimal combination of launch powers entering the SMF and DCF due to the interaction between the nonlinear effect and the ASE noise, since different formats exhibit different optimal operation ranges and maximal Q-values. With good Consistency with the results in Section 5.3.1, both MSK systems using conventional CSRZ pulses and pure dual-

mode pulses exhibit higher SMF launch power, and the MSK with conventional CSRZ pulses has the highest optimal launch power. This can be attributed to the higher tolerance of MSK signal against SPM. RZ-OOK shows the lowest optimal launch power into both the SMF and DCF. However the RZ-DPSK has the highest maximum Q-value among all the formats evaluated, and the RZ-OOK shows the worst maximum Q-value. The better transmission performance of RZ-DPSK could be due to its better trade-off between SPM effect and ASE noise. Since MSK format exhibits better tolerance against SPM, it is believed that its worse Q-value is due to its worse tolerance against optical noise. However, MSK is expected to exhibit better performance in high spectral efficiency WDM system, particularly with channel rate up to 40 Gb/s or beyond, due to its better tolerance against linear crosstalk. It is worthwhile to note that different dispersion maps, transmission fiber types and amplification schemes may affect the above-obtained outcomes.

Figure 5. 25: Q-value as a function of SMF and DCF launch powers after 40x80km transmission

5.7 Conclusions

In this chapter, the performance of optical MSK format proposed in Chapter 4 is evaluated and compared with that of 50% duty cycle RZ-OOK and 50% duty cycle RZ-DPSK, in terms of dispersion tolerance, linear crosstalk, SPM tolerance, SBS threshold, and phase noise, both numerically and experimentally. The system optimizations, such as the optimum bandwidth of the optical filter and electrical filter, which is included in the receiver module usually, and the optimum fiber launching powers, are also studied in this chapter.

To evaluate the performance of the MSK format, both simulation and experiment are carried out. The simulation results show that both the MSK signals, generated using conventional CS-RZ pulses and pure dual-mode CS-RZ pulses, exhibit larger fiber dispersion tolerance than the RZ-DPSK and RZ-OOK signals. And the dispersion tolerance in the MSK signal generated using conventional CS-RZ pulses is the best. Experiment results also show that the MSK signal provides the best dispersion tolerance defined by 1dB power penalty, although this tolerance range is not as large

as the simulation results. The simulated results of power penalty induced by linear crosstalk show that in both 10Gb/s and 40Gb/s systems, the MSK formats generated using both conventional CS-RZ pulses and pure dual-mode pulses exhibit less power penalty at higher spectral efficiency ($>0.35\text{bit/s/Hz}$) compared with RZ-DPSK and RZ-OOK, and MSK generated using pure dual-mode CS-RZ pulses has the smallest penalty among all these formats.

In the study on the tolerance against SPM effect and SBS threshold, simulation results show that the MSK signal exhibits largest tolerance against SPM effect among the three formats studied. Experimental results also confirm the negative penalty against SPM effect. Nonlinear chirp on the MSK generated using conventional CS-RZ pulses helps to achieve better tolerance against SPM. The measured SBS threshold of both MSK and RZ-DPSK systems is more than 10dB higher than that of an RZ-OOK system.

In terms of the nonlinear phase noise, both MSK signals have higher peak-to-peak timing jitter than RZ-DPSK initially. However, the timing jitter of the MSK signal generated using conventional CS-RZ pulses increases in a slower pace as the fiber launch power increases and it outperforms RZ-DPSK and the MSK signal generated with pure dual-mode pulses when the launch power is larger than 8.5dBm.

In the optimization of the receiver filter bandwidths for the MSK signals, the MSK signal generated with conventional CSRZ pulses exhibits narrower optimal optical filter bandwidth while wider electrical filter bandwidth compared with the RZ-OOK and RZ-DPSK signals. The MSK signal generated with pure dual-mode pulses has

similar optimum range as the RZ-OOK and RZ-DPSK signals at high OSNR, while with narrower optimal optical filter bandwidth at low OSNR. It is also noted that the optimum range is mainly affected by OSNR in the evaluated system.

From the optimization of the fiber launch power, for both SMF and DCF, it is concluded that the MSK signal generated with conventional CS-RZ pulses can allow higher SMF launch power. This agrees with the results obtained in the SPM tolerance evaluation.

In summary, the MSK signal, especially the MSK signal generated using conventional CS-RZ pulses, provides better tolerance to fiber dispersion and linear crosstalk. Hence, the spectral efficiency of the MSK modulated system could be higher. The MSK signal also exhibits better tolerance against SPM and large SBS threshold. Hence, fiber launch power could be higher in the MSK modulated systems. However, the MSK signal has worse noise tolerance capability. This means that it requires a higher receiver input power than other formats under study, which is not an issue for an optically pre-amplified system.

Chapter 6

Conclusions and Future Work

6.1 Conclusions

This thesis studies and evaluates a few advanced modulation formats in detail, which includes RZ-OOK, DPSK, RZ-DPSK, and MSK. The studies show that the use of DPSK modulation format can significantly reduce XGM effect in WDM systems which use SOAs as in-line amplifiers. SOA-amplified WDM transmission with a bit rate distance product of $109.7\text{Tb}\cdot\text{s}^{-1}\cdot\text{km}$ (which was the largest at the time the work was reported) is demonstrated. Due to the absence of discrete clock components in the RZ-DPSK spectrum, the SBS threshold in an RZ-DPSK modulated system is much higher than that in an RZ-OOK system. Hence, the use of higher launch power in the RZ-DPSK system is possible, and consequently, the span length can be extended. Error free single-span transmissions over 310km standard SMF are demonstrated, using RZ-DPSK format and bidirectional Raman amplification. A novel approach for implementing optical MSK transmitter is proposed and a 10.709Gb/s externally modulated MSK signal is successfully generated and detected experimentally. Both theoretical derivation and experimental generation show that the generated MSK signal exhibits the properties of constant amplitude and continuous phase change at bit transition instants. The MSK signal also has very compact optical spectrum. The performance of the optical MSK modulated system is evaluated and optimized.

In Chapter 2, the generation and detection of ASK, PSK, and FSK modulation formats were summarized. A literature survey of performance comparison between different

data formats was also presented. It shows that the use of advanced modulation formats is an effective solution in managing transmission impairments arising from ASE noise, dispersion and fiber nonlinear effects, as well as allowing higher channel density or spectrum efficiency. Among these formats, RZ-DPSK has shown promising performance in transmission and it also now holds records for capacity and transmission distance at 40 Gb/s.

Chapter 3 presented the work on the DPSK and RZ-DPSK formats, which was to further explore the resilient capacity on nonlinear effects in a phase modulated system. In this chapter, DPSK modulation format was successfully used to eliminate the XGM effect induced by SOAs, in a transmission link using SOAs as in-line amplifiers. 8x10.709Gb/s WDM transmission over 1050km standard SMF was achieved with 6dB power margin over FEC threshold. With further optimizing the input power and operating current of SOAs, a 16x10.709Gb/s DPSK modulated signal was transmitted over 640km with a power margin of 4.5dB over FEC threshold. This is, to the best of our knowledge, the largest bit rate-distance product ($BL = 109.7\text{Tb}\cdot\text{s}^{-1}\cdot\text{km}$) reported. And it is found that in a DPSK modulated transmission system, XGM effect is no longer the limiting factor of the system performance, instead, four-wave mixing (FWM) effect becomes dominant in determining the maximum transmission distance.

Another advantage provided by phase-shift keying formats is the higher SBS threshold compared with that in an OOK modulated system. From the study on the SBS effect in single span transmission system with bidirectional Raman pumping, in both RZ-OOK and RZ-DPSK modulated systems, it shows that the backward-scattering power is mainly caused by the co-pump, and counter-pump has minor effect.

The SBS threshold in an RZ-DPSK modulated system is more than 10dB higher than that in the RZ-OOK modulated system. Hence, it is possible to use higher launch power in the RZ-DPSK system, and consequently, the span length can be longer. Based on this conclusion, a single channel and 8-channel WDM single-span transmission over 310km standard SMF was demonstrated, using RZ-DPSK format and bidirectional Raman Pumping. Although it shows that the multi-channel system suffers more penalty than that of single channel case due to inter-channel nonlinear effects, error free can still be achieved, without applying the FEC technique.

In Chapter 4, firstly, the fundamental theory of MSK format was presented. In digital communications, MSK exhibits the properties of constant amplitude and continuous phase at every bit transition instant, narrow power spectrum and low side lobes. Therefore optical MSK is expected to have additional advantages of larger dispersion tolerance, and to be more robust against linear crosstalk, compared with RZ-DPSK. Secondly, Chapter 4 presented the principle on the generation and detection of the externally modulated optical MSK signal for high speed and high spectral efficiency WDM system, which was proposed by us, in detail. A 10.709Gb/s optical MSK data was successfully generated and detected by experiment using the proposed scheme. It has been shown that the generated optical MSK format indeed exhibits the properties of constant amplitude and continuous phase at every bit transition instant, narrow power spectrum and low side lobes.

Chapter 5 evaluated and compared the system performance of an externally modulated optical MSK system, with that of 50% duty cycle RZ-OOK and 50% duty cycle RZ-DPSK. Simulation results show that both MSK signals, generated using

conventional CS-RZ pulses and pure dual mode pulses, exhibit the wider fiber dispersion tolerance than the RZ-DPSK and RZ-OOK signals. And the dispersion tolerance in the MSK signal generated using conventional CS-RZ pulses is the widest. Experiment results also show that the MSK signal provides the widest dispersion tolerance defined by 1-dB power penalty among the formats under study, although the tolerance range is not as large as the simulation results. The simulated linear crosstalk power penalty results show that in both 10Gb/s and 40Gb/s systems, the MSK formats generated using both conventional CS-RZ pulses and pure dual mode pulses exhibit less power penalty as the spectral efficiency increases compared with RZ-DPSK and RZ-OOK, and MSK generated using pure dual mode CS-RZ pulses has the smallest penalty among all these formats.

In the study on the tolerance against SPM effect and SBS threshold between MSK, RZ-DPSK and RZ-OOK, simulation results show that the MSK signal exhibits the largest tolerance against SPM effect among these formats. Experimental results also confirm the negative penalty against SPM effect. Nonlinear chirp on the MSK generated using conventional CS-RZ pulses helps to achieve better tolerance against SPM. The SBS threshold of both MSK and RZ-DPSK systems is more than 10dB higher than that of an RZ-OOK system.

In terms of the nonlinear phase noise, both MSK signals have higher peak-to-peak timing jitter than RZ-DPSK initially. However, the timing jitter of the MSK signal generated using conventional CS-RZ pulses increases more slowly as the fiber launch power increases and it outperforms RZ-DPSK and the MSK signal generated with pure dual mode pulses when the launch power is larger than 8.5dBm.

In the optimization of the receiver filter bandwidths for the MSK signals, the MSK signal generated with conventional CSRZ pulses exhibits narrower optimal optical filter bandwidth while wider electrical filter bandwidth compared with RZ-OOK and RZ-DPSK. The MSK signal generated with pure dual mode pulses has similar optimum range to RZ-OOK and RZ-DPSK at high OSNR, while with narrower optimal optical filter bandwidth at low OSNR. It is also noted that the optimum range is mainly affected by OSNR in the evaluated system.

Lastly, the optimization of the fiber launch power, for both SMF and DCF, shows that the MSK signal generated with conventional CS-RZ pulses can have higher SMF launch power. This agrees with the results obtained in the SPM tolerance evaluation.

6.2 Recommendations for Future Work

There are a number of areas in which the present work may be extended.

Simulation results have shown that the system penalties caused by the mismatch between the delay line in the OQPSK modulator and the system bit rate are severe. However, due to limited resource available an OQPSK modulator matched with the data rate of the existing transmission system can not be made during the period of this study. If an OQPSK modulator with matching data rate can be made, transmission experiments, such as WDM systems using SOAs as in-line amplifiers, and long single-span transmission systems, can be carried out to compare the system performance with those presented in chapter 3. In addition, a better agreement between simulation and experimental results can be realized.

In this thesis, most of the simulation and the experiment works are done in a 10 Gb/s system, while MSK system at 40 Gb/s with 100 GHz channel spacing is expected to exhibit better performance than other formats evaluated in this thesis. A 40 Gb/s optical MSK modulated system can be built and evaluated, especially in experiments, since the system performance limiting factors are different between a 10 Gb/s system and a 40 Gb/s system.

The additional modulation on the chirp (frequency shift keying) observed on the MSK signal generated using conventional CS-RZ pulses is not the residual chirp. It is the additional periodic modulation on the chirp, due to the higher order modes in the CS-RZ pulses. And this chirp is nonlinear chirp, which is different with the linear chirp that is well known. Results from section 5.2 and section 5.3 show that this nonlinear chirp improves the tolerance against chromatic dispersion and self-phase modulation. A theoretical study on the nonlinear chirp in the future work will be able to explain the reason why it can improve the tolerance against chromatic dispersion and self-phase modulation.

In the proposed optical MSK transmitter, the implementation is relatively complicated and costly. A better implementation method can be explored to further simplify the MSK transmitter. The performance between these MSK signals generated using different configurations should be studied and compared.

During the system performance evaluation and comparison among the proposed optical MSK, RZ-OOK, and RZ-DPSK signals, it is observed that the system

performance, such as tolerance against fiber dispersion and nonlinear effects, are very much depending on some parameter settings of certain simulation models. These parameter settings include the extinction ratio of the modulator used for the signal generation, the driving swing applied to the modulators, and the type of modulators used for the phase modulation, which means whether it is a straight line phase modulator, or a Mach-Zehnder modulator. Although there have been many studies on system performance comparison among different advanced modulation formats reported, those conclusions were drawn under the particular conditions and with those particular hardware used. There is no systematic study which reports the effects of extinction ratio, drive swing and modulator type among different advanced modulation formats. Hence, it is worthwhile to study this, and it is not limited to the MSK format proposed in this thesis, but other advanced modulation formats as well.

The application of advanced modulation formats should not be limited to long haul transmission systems only. In the current metro network and optical access network, besides the currently deployed NRZ-OOK format, which is the simplest modulation format, other modulation formats with unique features can be also explored. Since system requirements between long haul transmission systems and metro network and optical access network are different, the system performance with different formats should be studied and evaluated.

Author's Publications

Patent pending

1. **Jinyu Mo** and Yi Dong, "Optical MSK data format", PCT (International) (application no.: PCT/SG2006/000023) and Taiwan Patent (application no.: 095104310), pending. (Invention disclosure submitted in Aug. 2004).

Journal papers

1. **Jinyu Mo**, Guangtao Zhou, Jian Chen, Yang Jing Wen, Yixin Wang, Chao Lu, and Kun Xu, "Single-span transmission of WDM RZ-DPSK signal over 310km standard SMF without using FEC and remote-pumping", *IEEE Photon. Technol. Lett.*, vol. 17, no. 10, pp. 2209-2211, Oct. 2005.
2. **Jinyu Mo**, Yang Jing Wen, Yi Dong, Yixin Wang, and Chao Lu, "Generation, detection and characterization of optical minimum shift keying data format", accepted for publication in *Optics Communications*.
3. **Jinyu Mo**, Yang Jing Wen, Yixin Wang, and Chao Lu, "Performance evaluation of externally modulated optical minimum shift keyed data", accepted for publication in *Optics Engineering*.
4. **Jinyu Mo**, Yang Jing Wen, Yixin Wang, Chao Lu, and Wen-De Zhong, "Externally modulated optical minimum shift keying data for high spectral efficiency WDM systems", submitted to *J. Lightwave. Technol.*.
5. Yi Dong, **Jinyu Mo**, Zhihong Li, Zhaohui Li, Yixin Wang, Chao Lu, "WDM transmission of 16x10.709Gb/s over 640km SSMF using cascaded SOAs and DPSK modulation format", *IEEE Photon. Technol. Lett.*, vol. 16, no. 10, pp. 2359-2361, Oct. 2004.
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3. **Jinyu Mo**, Yi Dong, Yangjing Wen, Shiro Takahashi, Yixin Wang, Chao Lu, "Optical minimum-shift keying modulator for high spectral efficiency WDM systems", in *Proc. ECOC'05*, paper Th1.2.3, Sep. 2005, Scotland.
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6. **Jinyu Mo**, Yang Jing Wen, Yixin Wang, Chao Lu, Zhong Wende, "Optimisation of receiver filter bandwidths for externally modulated optical MSK data", submitted to CLEO2007.
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