Novel High-speed Optical Transmitters for Optical Frequency Shift Keying and Inverse-return-to-zero Signals

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Abstract

Optical frequency-shift keying (FSK) modulation format has recently attracted much research attention. In a fiber nonlinearity-limited optical communication system, constant-intensity optical FSK signal shows high tolerance to nonlinear effects, indicating its potential in long haul transmission. Besides, applications based on optical FSK signals have been proposed to facilitate operations in optical packet switching networks and wavelength division multiplexing passive optical networks (WDM-PON).

Many different optical FSK transmitters have been proposed previously. The major concerns of optical FSK transmitters are the complexity, the flatness of the intensity profile, the range of wavelength spacing, the ability of tuning the wavelength spacing and the bit rate. In this thesis, we propose a novel high-speed optical FSK transmitter which is based on polarization modulation in an optical phase modulator. Such transmitter shows very good flexibility in wavelength spacing and bit rate. The performance and tuning ability have been experimentally investigated and characterized.

As optical FSK signals have showed higher tolerance to dispersion and nonlinearity in long haul transmission, in this thesis, we propose a new modulation format derived from FSK, called optical Return-to-Zero FSK (RZ-FSK). The performance and tolerance to chromatic dispersion and nonlinearity are characterized by experiments and simulations. The results show that optical RZ-FSK, as a long haul transmission modulation format, has a better performance than the conventional optical FSK.

Orthogonal modulation is one of the promising techniques to increase the spectral efficiency. Recently, Inverse Return-to-Zero (Inv-RZ) superimposing on DPSK has been proposed to double the spectral efficiency. However, previous transmitter design was complicated. In this thesis, we propose a new transmitter design for Inv-RZ + DPSK format, which consists of a dual drive optical Mach-Zehnder interferometer (DD-MZI) and an optical phase modulator. This transmitter greatly reduces the complexity, and also shows much better performance.

摘要

近年來，光頻移鍵控（FSK）調製方式吸引了很多研究學者。在一個被光纖非線性所局限著效能的光通訊系統裡，強度恆定的光頻移鍵控對於非線性現象顯示出高度的抵抗性，顯示出其應用在長距離傳輸的潛在能力。另外，學者們提出了一些方案，把光頻移鍵控訊號有效地應用在光包交換網絡和波分複用無源光網絡。

到目前爲止，有很多不同的光頻移鍵控發射機被研發出來。對頻移鍵控發射機的主要考慮有以下幾種：發射機結構的複雜程度，強度的恆定程度，波長間距的範圍和波長間距及比特率的可變性能力。在這篇論文，我們提出了一種全新的高速光頻移鍵控發射機，它的發射原理是基於光相位調制器的偏振調制，有著高度的波長間距及比特率的可變動性。我們對於它的效能及可變性能力進行了實驗的研究。

由於在長距離傳輸方面，光頻移鍵控顯示出對分散及非線性現象有較高的抵抗性，因此光頻移鍵控是其中一種最適合的格式。本文提出了一種新的調制格式，這調制格式衍生自頻移鍵控，叫做光歸零制頻移鍵控（RZ-FSK）。我們通過實驗及軟件模擬調查了它的效能和對色散及非線性現象的抵抗性。結果証明了對比於傳統的光頻移鍵控，光歸零制頻移鍵控作爲長距離傳輸調制格式有著更佳的效能。

正交調制是其中一種有效提高頻譜效率的技術。最近，有學者提出把反歸零制（Inv-RZ）調制在差分相移鍵控之上，從而將頻譜效率增加一倍。但是，他們提出的發射機設計構造複雜。在本論文，我們提出一個新的發射機設計，由一個雙驅動馬赫曾德爾干涉儀（DD-MZI）及一個光相位調制器所組成。這發射機大大地降低了原本的複雜程度，並且顯示出更高的效能。

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1 Background and Introduction

1.1 Optical Frequency Shift Keying (FSK)

1.1.1 Basic concepts

In optical communication system, we use light as the transmission medium. Light is a kind of wave, which can be represented by the following equation:

$$E = A\cos(\omega_c t + \phi_o) \tag{1.1}$$

where |E| is the electric field, |A| is the amplitude, ω_c is the carrier frequency and ϕ_o is the phase of the light field respectively. To carry information, we may modulate the data into its amplitude (Amplitude Modulation, AM), frequency (Frequency Modulation, FM) or phase (Phase Modulation, PM). In a binary system, there are two symbols, mark ("1") and space ("0"). In the case of frequency modulation, these two symbols are represented by the positive or negative frequency deviation of the optical carrier, which is named as optical frequency shift keying (FSK). Fig. 1.1 shows the electric field waveform of a typical FSK signal. The corresponding waveform can be written as

$$E(t) = \sum_n \left\{ a_n g(t - nT)\exp[-j(\omega_1 t + \phi_1)] + \overline{a_n} g(t - nT)\exp[-j(\omega_2 t + \phi_2)] \right\} \tag{1.2}$$

where a_n is the bit information ("1" or "0"), $g(t)$ is the signal baseband waveform, ω_1 and ω_2 are the two carriers' angular frequencies, and ϕ_1 and ϕ_2 are the initial phase values for the carriers with ω_1 and ω_2 respectively.

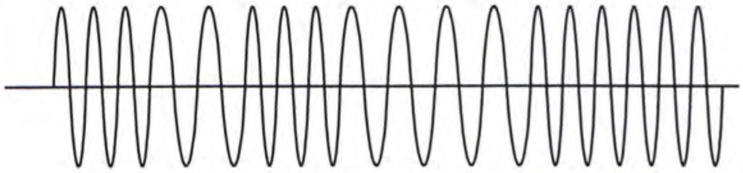


Fig. 1.1 Electric field temporal waveform of a typical FSK signal.

The bandwidth of a FSK signal approximately equals $\Delta f + 2B$, where Δf is the frequency spacing of the two carriers, i.e. $\Delta f = |f_1 - f_2|$, and B is the signal bit rate. If $\Delta f << B$, its bandwidth is about $2B$, which is about the same as the bandwidth of the amplitude shift keying (ASK) signal. If $\Delta f >> B$, its bandwidth is about Δf and is independent of signal bit rate. The choice of Δf is critical for a FSK signal. If Δf is too small, the two carriers will be very close to each other in frequency domain. The spectral efficiency (SE) is high as it uses up less bandwidth but it becomes very difficult to separate (demodulate) them at the receiver side, which would induce power penalty due to interference between the two carriers. If Δf is too large, such interference can be suppressed but the SE is low. The choice of Δf of the FSK signal mainly depends on the requirement of the system application.

In conventional optical transmission systems, power loss and chromatic dispersion (CD) are the two major performance limiting factors. Due to the advent and deployment of Erbium Doped Fiber Amplifiers (EDFAs) and many different approaches of dispersion compensation, these two limiting factors are largely alleviated. Unfortunately, when the data rate and number of channels keep increasing, another limiting factor, called fiber nonlinear effect, arises. Nonlinear effects include Self Phase Modulation (SPM), Cross Phase Modulation (XPM) and Four Wave Mixing (FWM). Since this kind of effects is nonlinear, it is difficult to compensate. It was found that intensity modulation (ASK) led to significant SPM or XPM induced signal degradation. However, the constant-intensity FSK signal has much smaller nonlinear effect induced degradation. Comparing with Differential Phase Shift Keying (DPSK), Non-Return-to-Zero (NRZ) and Return-to-Zero (RZ) modulation formats, optical FSK shows the lowest sensitivity with respect to fiber non-linearity impairments [1]. That is the reason why optical FSK has attracted much attention in recent years.

1.1.2 Applications

Optical FSK modulation format can be applied to perform different functions. In this section, we summarize some system applications proposed recently.

One of the promising optical packet switched network architectures is called optical label switching (OLS). In OLS network, an optical label, which carries routing information, is encapsulated into every incoming optical packet at the ingress router. Label swapping is performed at each core router to update the content of the label. Many labeling schemes and label swapping methods have been proposed and demonstrated, including bit serial labeling [2], subcarrier multiplexed (SCM) labeling [3] and orthogonally modulated labeling [4,5]. In orthogonally modulated labeling, FSK format had been used for either label [4] or payload [5]. In [4], a low-speed FSK or DPSK label was combined with high speed ASK payload to form an optical packet. At the label swapping unit, wavelength label swapping was done by means of wavelength conversion. Since wavelength conversion would erase the angle modulated label while it preserves the ASK payload, FSK or DPSK label swapping could be done by direct modulation via a new laser source or phase modulation via an optical phase modulator. The label swapping procedure is depicted in Fig. 1.2.

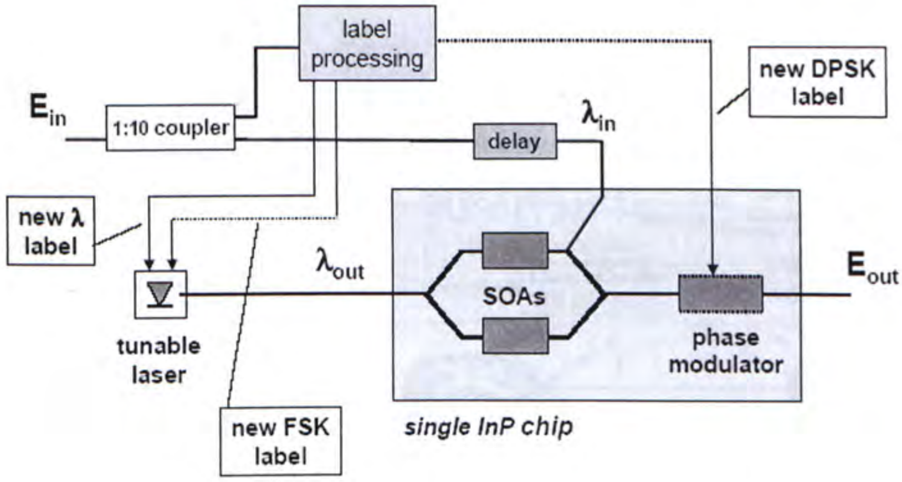


Fig. 1.2 Label swapping scheme in an OLS network. (ASK as payload, FSK / DPSK as label) (Extracted from [4])

In [5], ASK format was used as the low speed label while FSK format was used as the high speed payload. In order to erase the old ASK label and generate a new ASK label at the core router, the optical packet was directed to a label erasing unit followed by an optical intensity modulator, as shown in Fig. 1.3. The incoming packet was first amplified by an EDFA, and then fed into a semiconductor optical amplifier (SOA). The gain saturation of SOA resulted in a considerable reduction in the difference between the mark and the space levels. Apart from gain saturation, SOA would also introduce rotation in the state of polarization (SOP) of the incoming signal due to its intrinsic nonlinear birefringence [6]. The space level with smaller power experienced larger gain as well as larger rotation in SOP than the mark level. Hence, by aligning the following polarizer properly, the intensity of the mark and the space levels could be equalized, and the old ASK label was successfully erased. The new ASK label was then modulated into the optical packet simply by an optical intensity modulator.

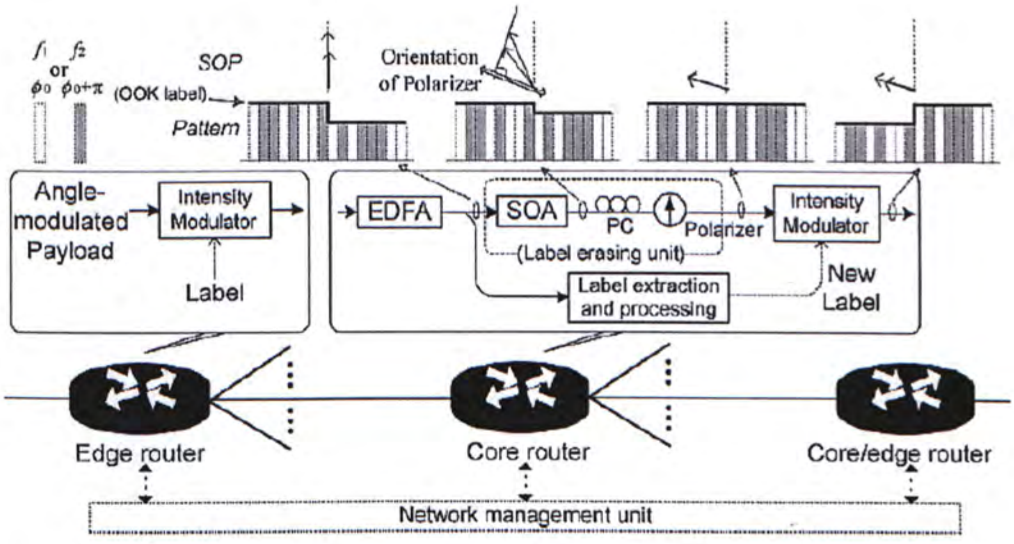


Fig. 1.3 All-optical label swapping in an OLS network (FSK as payload, ASK as label) (Extracted from [5])

The other optical FSK application is applied to wavelength division multiplexing passive optical network (WDM-PON). WDM-PON is a promising access technology to deliver high capacity data to the subscribers. Optical line terminal (OLT) assigns one unique wavelength to each optical network unit (ONU) and communicates with it via that particular wavelength. To further facilitate the wavelength management, a centralized light source (CLS) at the OLT has been proposed. CLS means all the light sources are placed at the OLT, while the upstream signal from the ONU is generated by re-modulating the downstream carrier with the upstream traffic. One approach of CLS WDM-PON is adopting constant intensity modulation format for the downstream signal and re-modulating it at the ONU by the upstream traffic in ASK format. Optical FSK format is one of such constant-intensity format suitable for this application. In [7], 2.5-Gb/s optical FSK signal was used as downstream traffic and it was re-modulated by an optical intensity modulator at the ONU side to form a 2.5-Gb/s optical ASK format upstream traffic, as shown in Fig. 1.4. Since each ONU only consists of one optical intensity modulator and does not have any wavelength-registered light source, the management cost can be largely reduced. Moreover, the power penalty induced by the downstream optical FSK signal to the upstream optical ASK signal was just very little (about 0.2 dB), compared with the case of using a continuous-wave laser as the upstream data carrier, proving the feasibility of such CLS WDM-PON scheme.

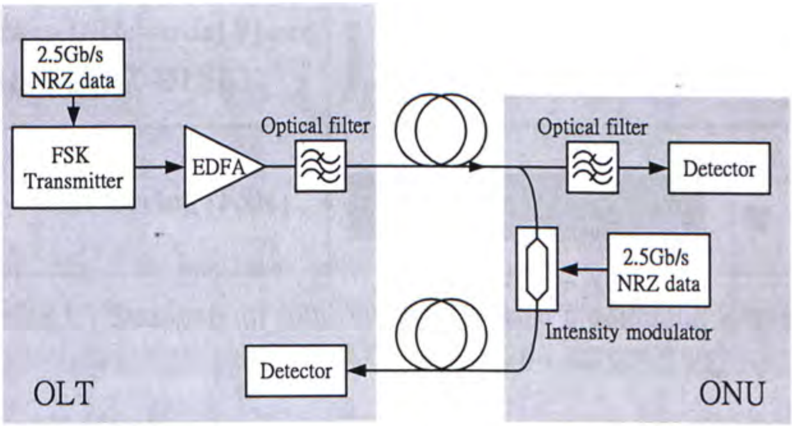


Fig. 1.4 CLS PON architecture using downstream optical FSK signal.

1.2 Modulation Formats

As described in part 1.1, we may use amplitude, frequency or phase to represent the data, which corresponds to ASK, FSK and PSK modulation formats. There have been many different modulation formats proposed previously. Table 1.1 summarizes some of the most commonly used modulation formats in optical transmission systems.

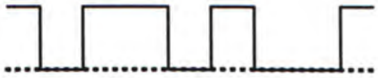
Non-Return-to-Zero (NRZ)	
Return-to-Zero (RZ)	
Differential Phase Shift Keying (DPSK)	 0 phase; π phase
Return-to-Zero Differential Phase Shift Keying (RZ-DPSK)	 0 phase; π phase
Frequency Shift Keying (FSK)	 λ_1; λ_2

Table 1.1 Summary of some commonly used modulation formats

To compare different modulation formats in optical communication systems, three aspects, spectral efficiency, chromatic dispersion tolerance and fiber nonlinearity tolerance, are usually considered.

Spectral efficiency is a measure of how fast the data can be transmitted within a certain bandwidth. It can be calculated by bit rate per bandwidth, in b/s/Hz. The higher the spectral efficiency per channel, the more bandwidth can be reserved for other users. For example, for the same bit rate, the bandwidth required by 50%-duty cycle RZ format is twice that of the NRZ format. Thus the spectral efficiency of NRZ is higher than RZ. In a strongly filtered system, which is very common in Dense WDM (DWDM) environment to reduce the crosstalk from the adjacent channels, modulation formats with higher spectral efficiency generally have better performance.

Fiber chromatic dispersion is one of the major impairments of signal transmission. As the core refractive index of the fiber is frequency dependent, different wavelength components of the signal have different group velocities. As the signal traverses the fiber, the shorter wavelength components of the pulse travel faster than the longer wavelength components. Thus the signal pulse broadens as it travels down the fiber. By the time it reaches the receiver, the pulse may have spreaded over several bit periods and this results in severe inter-symbol interference. The chromatic dispersion is measured in ps/nm/km, and corresponds to the amount of broadening in picoseconds that would occur in an optical pulse with a bandwidth of 1 nm while propagating through 1 km of fiber.

Fiber nonlinearity is another cause of signal impairment, especially in high speed optical transmission with a large number of wavelength channels. The nonlinearities can be classified into two categories: stimulated scattering and effects arising from the nonlinear index of refraction. Stimulated scatterings, including stimulated Brillouin scattering (SBS) and stimulated Raman scattering (SRS), induce intensity-dependent gain or loss. The intensity-dependent refractive index gives rise to three effects. Self phase modulation (SPM), where fluctuations in the signal power give rise to modulation of the signal phase and lead to broadening of the spectrum. Cross phase modulation (XPM), in which intensity fluctuations in one channel propagating in the fiber modulate the optical phase of all other channels. Four wave mixing (FWM), where the beating between wavelength channels at their difference frequency modulates a channel frequency, generating new frequency tones as sidebands. Since these kinds of effects are nonlinear, they are difficult to be removed.

The choice of modulation format depends on many factors. For example, for long haul transmission, although operation and management cost is high, modulation format with high dispersion and fiber nonlinearity tolerance should be considered.

1.3 Orthogonal Modulation

Improving the spectral efficiency is one of the approaches to push the limit of the transmission rate of optical communication systems. Multi-bit per symbol, such as differential quadrature phase shift keying (DQPSK), has been shown and investigated to achieve higher efficiency [8]. On the other hand, orthogonal modulation is another promising method. Orthogonal modulation can be regarded as a special format such that the optical carrier carries intensity and phase information simultaneously. One example is ASK combined with DPSK, as shown in Fig. 1.5. In this case, the extinction ratio (ER) of the ASK signal cannot be too high, since finite power must be reserved for DPSK in every bit slot. However, the ER cannot be too low as large penalty would be introduced to the ASK signal. At the receiver, this orthogonally modulated signal can be demodulated separately to obtain the corresponding ASK and DPSK data.

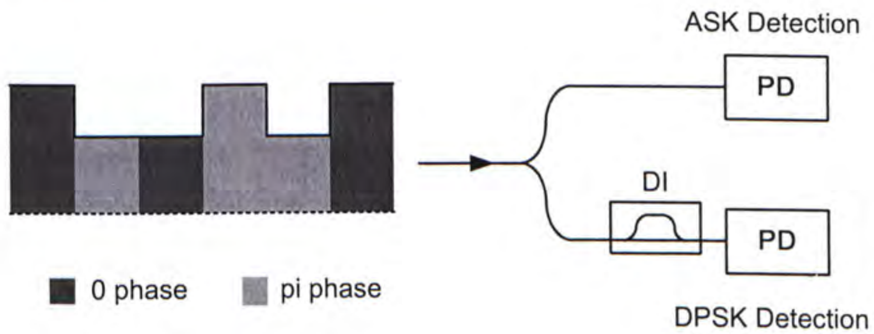


Fig. 1.5 ASK + DPSK orthogonal modulation format

Inverse Return-to-Zero (Inv-RZ) combined with DPSK is another choice. Inv-RZ, as stated by its name, is the inverse of RZ, as shown in Fig. 1.6. If the symbol is space, it is represented by a constant finite intensity lasting for a bit duration. If the symbol is mark, it is represented by an intensity dip, which is often called as dark pulse. From the principle, RZ signal should have better performance than Inv-RZ as the power needed to obtain same BER is smaller. However, using the fact that there is always some power in every bit period of an Inv-RZ signal, it is possible to superimpose a DPSK signal onto it. Unlike the previous ASK+DPSK case, the ER of the Inv-RZ signal does not affect the performance of DPSK signal. Thus, it can be made as large as possible to enhance the performance of Inv-RZ. However, the duty cycle of the Inv-RZ has to be controlled carefully. If the dark pulse is too wide, DPSK signal will be degraded. Basically, negligible power penalty is induced by DPSK to Inv-RZ, and small power penalty is induced by Inv-RZ to DPSK due to the presence of the intensity dips.

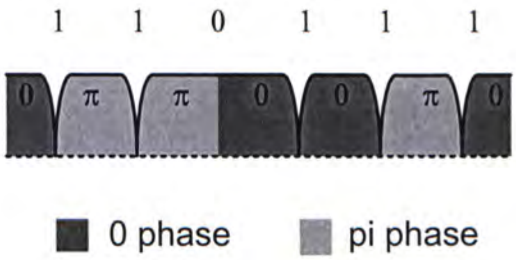


Fig. 1.6 Inv-RZ + DPSK signal

There are still many possibilities for orthogonal modulation, such as optical FSK combined with ASK, as described in section 1.1.2. ASK combined with DQPSK to achieve 3 bits per symbol has also been proposed [9]. Researchers are still looking for more feasible options to pack more bits into a symbol so as to improve the spectral efficiency.

1.4 Thesis Organization

In this thesis, we have proposed two new transmitter designs for high-speed optical FSK and optical Inv-RZ signals. We have also proposed and characterized one new modulation format, namely optical RZ-FSK. The thesis is organized as follows:

Chapter 1 introduces some background knowledge about modulation formats for optical transmission systems, mainly focused on optical FSK and its applications, as well as orthogonal modulation. Some well known modulation formats and previously proposed orthogonal modulation schemes are also discussed..

Chapter 2 summarizes the previous approaches of realizing optical FSK transmitters and compares their pros and cons. A novel high-speed optical FSK transmitter based on polarization modulation has been proposed and its performance is experimentally investigated.

Chapter 3 presents a new modulation format, optical RZ-FSK. Its chromatic dispersion tolerance and fiber nonlinearity tolerance are compared with that of conventional optical FSK signal by both experiments and simulations.

Chapter 4 describes a new transmitter design for Inv-RZ + DPSK orthogonal modulation format. Its performance is characterized experimentally and compared with that of the previously proposed approach.

Chapter 5 summarizes the thesis and suggests possible future works.

2 A Novel Optical Frequency Shift Keying Transmitter Based on Polarization Modulation

2.1 Previous Work on Optical FSK Transmitter Design

As described in chapter 1, optical FSK format is one of the best modulation formats for long haul transmission as it has high nonlinearity tolerance. Therefore, a simple, stable, high speed and flexible optical FSK transmitter design becomes very desirable. Until now, there are a number of approaches proposed to realize such optical transmitter. Here, we briefly explain four previously proposed ones and summarize their pros and cons.

2.1.1 Optical FSK transmitter based on complementary intensity modulation

In the conventional method, two continuous-wave (CW) light from two DFB lasers with different wavelengths are fed into two intensity modulators separately, which are driven by the electrical data signal and its complementarity, as shown in Fig. 2.1.

As a result, two complementary ASK signals are generated. The two ASK signals are combined by a coupler and the output is exactly a FSK signal. The wavelength spacing can be tuned by simply adjusting the wavelengths of two DFB lasers. High speed operation can be achieved by such external intensity modulation, but the complexity is high. Strictly speaking, it consists of two sets of ASK transmitter. Moreover, the two electrical data signals have to be synchronized precisely by tunable electrical delay line.

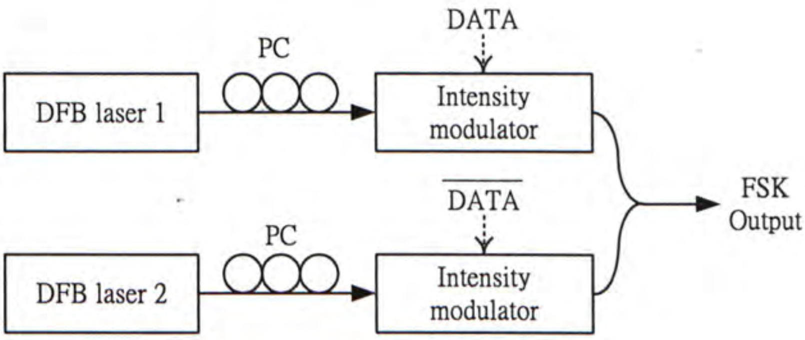


Fig. 2.1 Optical FSK transmitter based on complementary intensity modulation.

2.1.2 Optical FSK transmitter based on direct modulation in a DFB laser

The second method of optical FSK signal generation is realized by direct modulation in a DFB laser [10]. Fig. 2.2 shows the transmitter configuration. It consists of a DFB laser and an electroabsorption modulator (EAM). Firstly, the DFB laser is directly modulated by the electrical data signal.

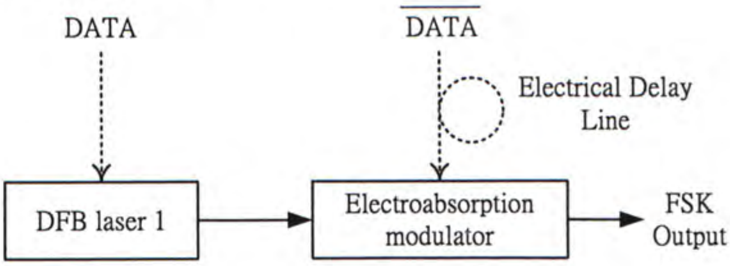


Fig. 2.2 Optical FSK transmitter based on direct modulation in a DFB laser.

Fig. 2.3 (a) shows the optical characteristics of the DFB laser for optical FSK generation. From the curves, we know that direct modulation of DFB laser would results in intensity modulation and frequency modulation simultaneously. In order to obtain FSK signal instead of ASK signal, the DFB laser is operated at a high input current condition (from about 60mA – 80mA in Fig. 2.3 (a)) to maximize the frequency deviation but minimize the intensity fluctuation. Nevertheless, there still exists residual intensity fluctuation at the output FSK signal, as shown in Fig. 2.3 (b). To further suppress the intensity fluctuation, an EAM driven by the complementary electrical data signal is used to intensity modulated the incoming FSK signal. At the output of the EAM, a constant intensity optical FSK signal is generated. Fig. 2.3 (c) shows the intensity fluctuation suppressed FSK signal.

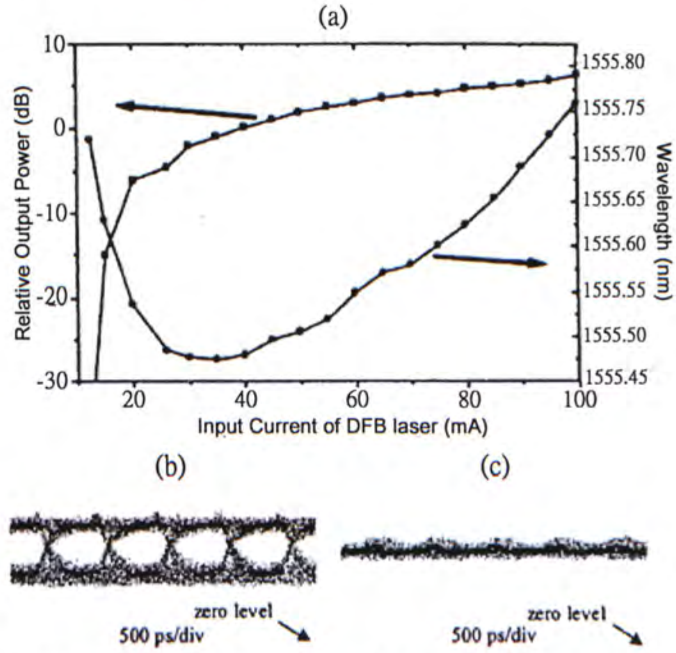


Fig. 2.3 (a) Optical characteristics of the DFB laser. (b) Eye diagram before EA compensation. (c) Eye diagram after EA compensation. (Extracted from [10])

Such design is cost- effective as only one DFB laser and one EAM are necessary. However, the modulation bit rate is limited (~2.5Gb/s) by the modulation response of the commercially available directly modulated DFB laser unless specially designed

DFB lasers are deployed. In addition, the wavelength spacing between the two optical FSK carriers is limited to about 0.3 nm due to limited driving current range. Such closely spaced carriers hinder precise signal demodulation and also further limit the modulation data rate as any overlapping between the spectra of the two carriers would induce severe crosstalk and signal beating.

2.1.3 Optical FSK transmitter based on single side-band (SSB) modulation technique

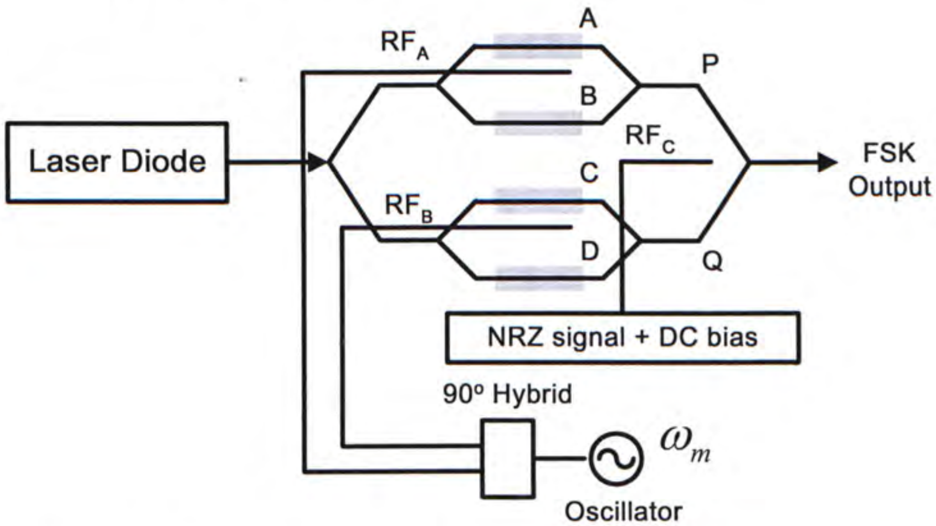


Fig. 2.4 Optical FSK transmitter based on single side-band (SSB) modulation.

This proposed optical FSK modulator consists of a pair of Mach-Zehnder structures as shown in Fig. 2.4 [11]. The device is almost the same as the SSB modulator, except the FSK modulator has an electrode (RF_c), instead of a pure DC-bias electrode in the SSB modulator [12] .There are totally four phase modulators, A, B, C and D. The two sub-Mach-Zehnder structures (A and B, C and D) are in null-bias point (lightwave signals in the paths have 180^o phase difference) by adjusting the DC-bias of RF_A and RF_B. Therefore, the driving signals of phase modulators A, B, C and D are $\cos(\omega_m t)$, $\cos(\omega_m t+\pi)$, $\cos(\omega_m t+\frac{\pi}{2})$ and $\cos(\omega_m t+\frac{3\pi}{2})$ respectively. To eliminate the upper side-band (USB) or the lower side-band (LSB), the lightwave signals in the upper path and the lower path should have 90° phase difference to each other. Then, an electrical signal is applied to RF_C to induce $+90^{\circ}$ or -90° phase difference, to obtain carrier-suppressed SSB modulation comprising USB or LSB. The detail is depicted in Fig. 2.5. The frequency of the output signal can be switched by changing the induced phase at RF_C, thus the optical FSK signal is generated.

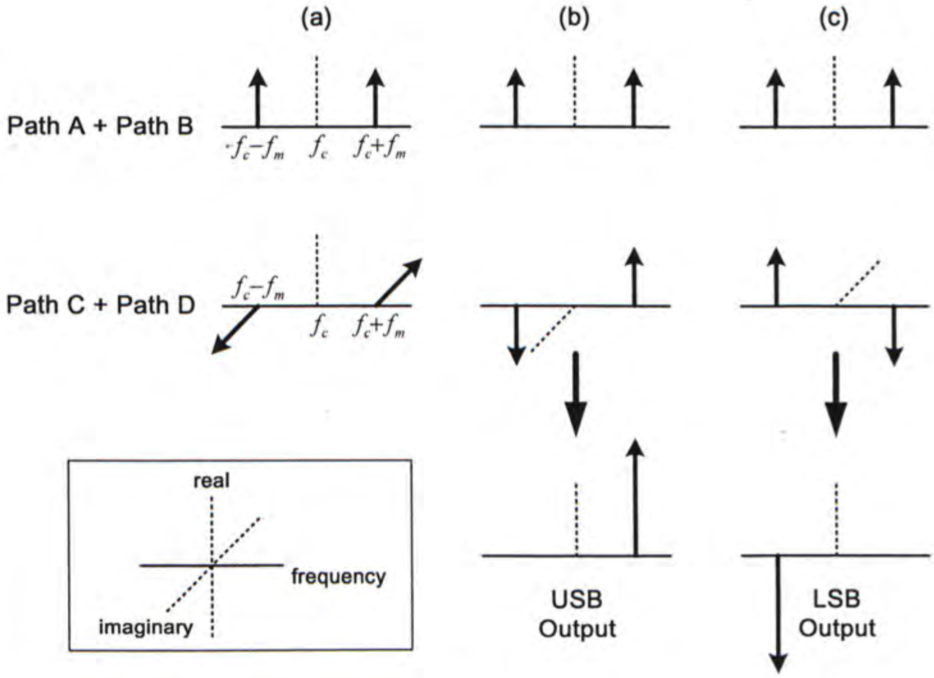


Fig. 2.5 Optical spectra (a) after RF_A and RF_B, (b) after $+90^{\circ}$ phase shift induced by RF_C, (c) after -90° phase shift induced by RF_C.

This scheme requires only one laser source and supports high speed operations. However, the fabrication cost of such specially designed device is quite high. Also, the wavelength spacing range is limited by the local oscillator. The larger the wavelength spacing required, the faster the local oscillator has to be.

2.1.4 Optical Continuous-Phase FSK (CPFSK) transmitter based on asymmetric Mach-Zehnder modulator

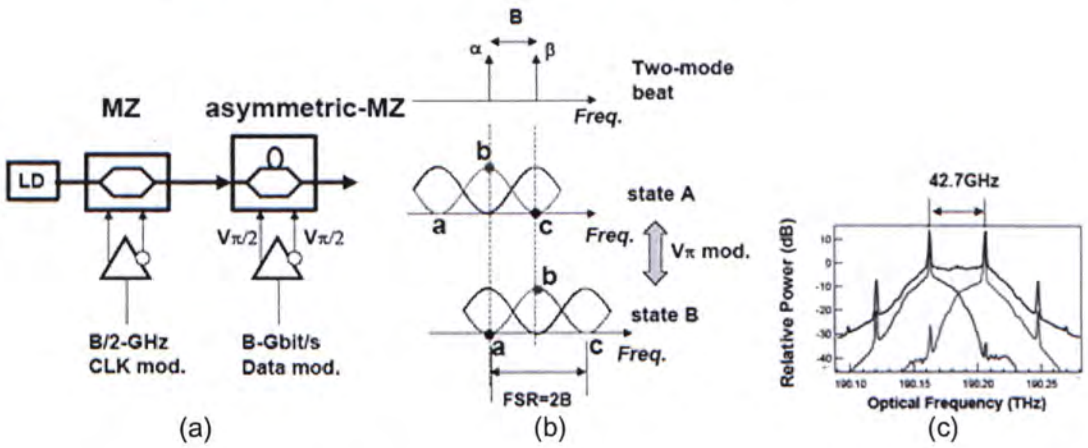


Fig. 2.6 Optical FSK transmitter based on asymmetric MZ modulator. (a) transmitter design, (b) operation principle, (c) corresponding spectrum (Extracted from [13])

In [13], 40-Gb/s FSK signal is demonstrated for the first time. It consists of a MZ modulator and an asymmetric MZ modulator cascaded together. The first MZ modulator is operated in push-pull mode, biased at transmission null point and driven at the frequency of half line rate (*B*/2). Thus a carrier suppressed return-to-zero (CS-RZ) pulse sequence is generated. The corresponding CS-RZ spectrum is shown by the black line in Fig. 2.6(c). Note that the carrier is suppressed and there are some strong clock tones located with the same separation equals to data rate *B*. Then, the CS-RZ signal is fed to the second asymmetric MZ modulator. Since the free spectral range of the MZ modulator is set to 2*B*, if there is a maximum transmission of lower clock tone (α), higher clock tone (β) should have a minimum transmission and vice versa. As a result, by applying data to the asymmetric MZ modulator, the transmission characteristics can be switched between α and β, and the output becomes an optical FSK signal.

The major disadvantage of this design is its low flexibility. The frequency spacing and the bit rate are related. If the bit rate is B bps, the frequency spacing must be B Hz. Moreover, they are all fixed by the asymmetric MZ modulator. Any tuning is impossible unless the asymmetric MZ modulator is interchanged.

2.1.5 Optical FSK transmitter based on phase modulation

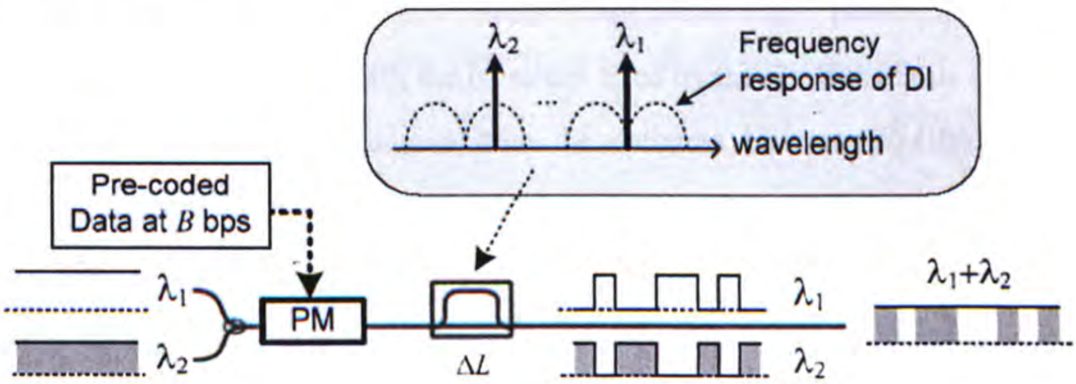


Fig. 2.7 Optical FSK transmitter based on phase modulation. (Extracted from [14])

The last existing FSK transmitter described in this chapter is based on phase modulation [14]. Fig. 2.6 illustrates the operation principle of the transmitter. Two CW light beams with different wavelengths are fed into a phase modulator (PM) driven by pre-coded data for phase modulation. After that, a delay interferometer (DI) is used to turn the differential phase shift keyed (DPSK) signal into amplitude shift keyed (ASK) signal. As shown in Fig. 2.6, the wavelengths of the two optical carriers are chosen in such a way that one wavelength (λ_1) coincides with the minimum transmission point of the DI frequency response while the other wavelength (λ_2) coincides with the maximum transmission point. In equations, they have to satisfy:

$$\lambda_1 = \frac{n_1 \Delta L}{m_1} \quad \text{and} \quad \lambda_2 = \frac{n_2 \Delta L}{m_2 + \frac{1}{2}} \tag{2.1}$$

where n_1 and n_2 are the refractive indices experienced by λ_1 and λ_2 in the DI respectively, ΔL is the propagation distance of one data bit in the DI, m_1 and m_2 are positive integers. In this way, the two ASK signals generated will be complementary and when combined, constant intensity optical FSK signal is formed

This FSK transmitter design is simple. The complexity is low as only one phase modulator is needed for two simultaneous phase modulations. However, there are still some disadvantages. Firstly, the bit rate is fixed by the DI. If the DI is designed for 10-Gb/s system, any detuning from the optimum bit rate (10-Gb/s) would introduce power penalty. Secondly, although the range of wavelength spacing can be very large, it cannot be continuously tuned. It works only if the two wavelengths satisfy the conditions described above. Besides, the DI requires precise temperature control to stabilize its frequency response. Lastly, this design needs pre-coding of data due to the DPSK demodulation property.

2.1.6 Summary

The following table summarizes and compares the five existing optical FSK transmitters described above.

	Complementary Intensity Modulation	Direct Modulation	SSB Modulation	Asymmetric MZ modulator	Phase Modulation
No. of laser source	2	1	1	1	2
Complexity	High	Low	Medium	Medium	Low
Speed	High	Low	High	High	High
Data rate tunability	High	High	High	Low	Low
Range of wavelength spacing	Large	Small	Small	Small	Large
Synchronization of electrical signals	✓	✓	✓	✗	✗
Pre-coding of data	✗	✗	✗	✗	✓

Table 2.1 Summary and comparison of the five previously proposed optical FSK transmitters

2.2 Proposed Optical FSK Transmitter Based on Polarization Modulation

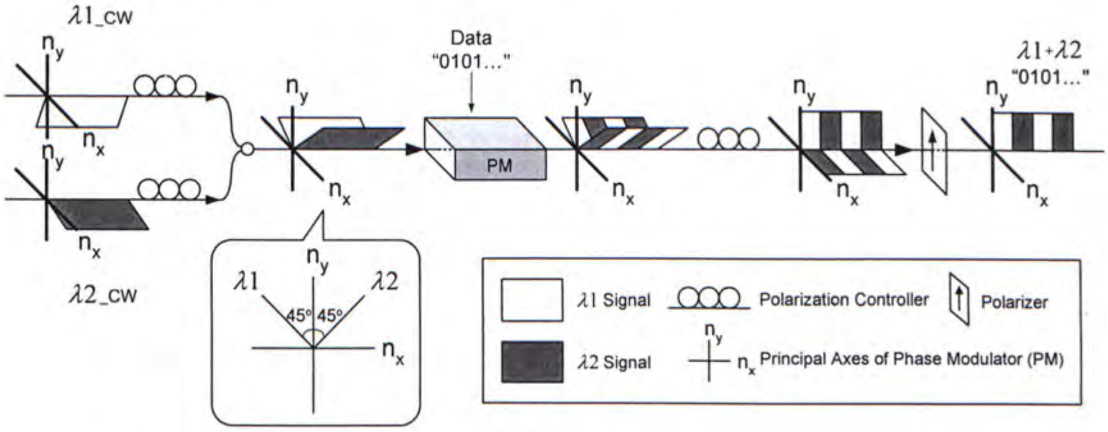


Fig 2.8 Proposed optical FSK transmitter design and operation principle

Fig. 2.8 illustrates the configuration and operation principle of the proposed optical FSK transmitter. Two CW light beams (λ1 and λ2) with small wavelength spacing are combined and fed into an optical phase modulator (PM). Before they are fed into the PM, the polarization of each of them is adjusted by a polarization controller (PC) such that (1) they are linearly polarized and are 45° relative to the principal axes of the PM; and (2) they are orthogonal to each other, as shown in Fig.2.8. Under these conditions, each of these two optical carriers undergoes polarization modulation and becomes a polarization shift keying (PolSK) signal [15]. As their input polarizations are orthogonal to each other, the two generated PolSK signals would behave complementarily and thus the composite signal after a polarizer becomes an optical FSK signal with constant intensity envelope.

To illustrate the operation principles in more detail, we may decompose the 45° polarization of each of the input optical carriers into two equal components, one in n_x

direction and the other in n_y direction. When the input data symbol is "0", no voltage is applied to the PM. Therefore, there is no phase shift induced to both optical carriers. When the input data symbol is "1", a voltage V_π is applied to the PM. Such applied voltage induces π phase shift in n_y-component but no phase shift in n_x-component. This leads to 90^0 rotation of the polarization of each optical carrier. By aligning a polarizer to one of the polarization component of the combined signal ($\lambda1+\lambda2$), the output signal becomes an optical FSK signal in which the data level on each optical carrier behaves complementarily. As shown in Fig. 2.8, an input data symbol "1" will lead to high level on $\lambda2$ and low-level on $\lambda1$ at the output of the aligned polarizer, and vice versa for an input data symbol "0". In practice, there may be some residual phase shift in n_x component, whose value is about one third of phase shift in n_y component in a commercial PM [15]. To solve this, the applied voltage to the PM can be increased to about 1.5 V_π so as to obtain π phase shift difference between the two components. In practical application, the transmitter is usually resided in a controlled environment of the central office, thus the polarization states of the input signals could be easily monitored and maintained at their optimal states, though this may incur some extra monitoring cost. One simple way to perform polarization monitoring at the transmitter is to replace the output polarizer by a polarization beam-splitter (PBS). The power uniformity of the second output (a complementary replica of the generated OFSK signal) of the PBS can then be used to adjust and optimize the input polarizations.

2.3 Experimental Demonstration

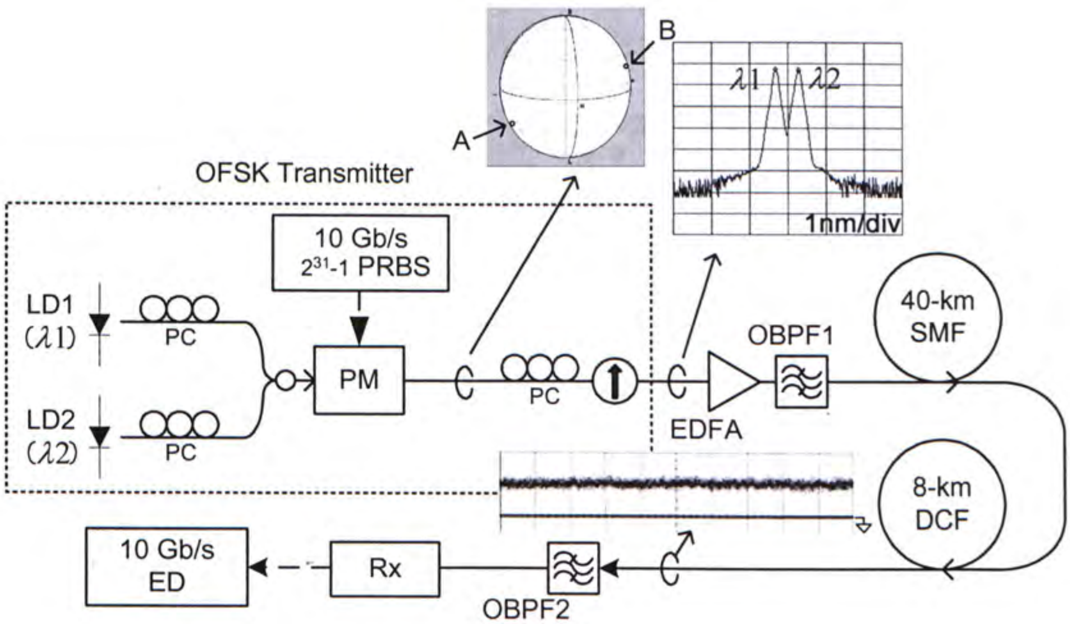


Fig 2.9 Experimental setup. Insets show the output polarization states [(A) bit "1"; (B) bit "0"] of one of the input wavelengths after PM, as well as the optical spectra and waveforms of the optical FSK signal. (ED: Error Detector)

Fig. 2.9 shows the experimental setup to characterize the performance of our proposed optical FSK transmitter. Two CW light beams (λ1=1553.40nm and λ2=1554.01nm) launched by two DFB lasers with 0.61-nm spacing were combined by 50/50 fiber coupler and fed into an optical phase modulator (PM). Their polarizations were optimized by individual PC before entering the PM to satisfy the above stated requirements, i.e. mutually orthogonal, linearly polarized and 45^{o} relative to the principal axes of the PM. The combined signal was then polarization-modulated by a 10-Gb/s NRZ 2^{31}-1 pseudo random binary sequence (PRBS) via the PM. The polarization states of one wavelength are shown in the inset of Fig. 2.9. At the output of the PM, another PC was adjusted such that "0" polarization of λ1 ("1" polarization of λ2) was exactly aligned to the polarizer, and the desired optical FSK signal was generated at the output of the transmitter. Fig. 2.10 shows the captured waveforms of the input wavelengths (λ1 and λ2), as well as the output optical FSK signal (λ1+λ2). It shows that both input wavelengths exhibited complementary data modulation with excellent extinction ratios while the combined signal showed constant intensity envelope. Such generated optical FSK signal was then amplified by an EDFA to about 4 dBm and filtered by an optical bandpass filter (OBPF1) with a 3-dB bandwidth of 0.8 nm to suppress the excessive amplified spontaneous emission (ASE). The center of the optical filter passband was set to be the middle wavelength (1553.70nm) of two input wavelengths. The amplified FSK signal was then transmitted over a piece of 40-km standard single mode fiber (SMF) and was completely dispersion-compensated by a piece of 8-km dispersion compensating fiber (DCF). At the end of the transmission link, it was observed that the constant-intensity envelope of the OFSK signal was preserved. The received signal was filtered by an optical grating filter (OBPF2) with a 3-dB bandwidth of 0.2 nm for signal demodulation before being detected by a 10-Gb/s PIN receiver.

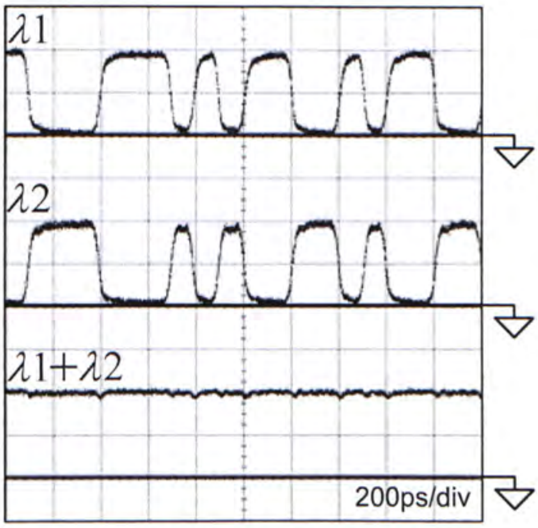


Fig. 2.10 Measured waveforms of individual input wavelengths (λ1 & λ2) and the output OFSK signal (λ1+λ2).

2.4 System Performance

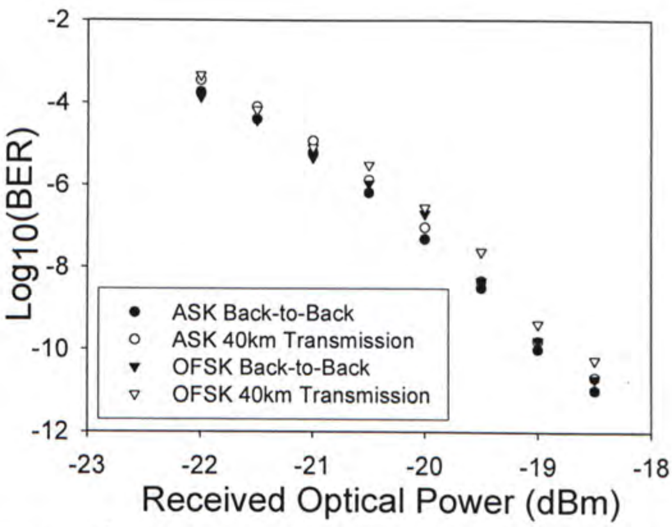


Fig. 2.11 BER of 10-Gb/s ASK and demodulated OFSK signal under two conditions: back-to-back, 40-km transmission (input power=4 dBm)

We have further experimentally characterized the performance of the proposed optical FSK transmitter, and compared with the performance of a conventional ASK signal, as a benchmark. Fig. 2.11 shows the measured transmission performances (with dispersion compensation) between a 10-Gb/s ASK signal using a conventional intensity modulator and a 10-Gb/s FSK signal generated by our proposed transmitter. It is observed that the demodulated FSK signal exhibited negligible power penalty for both the back-to-back case and after 40-km transmission with 4-dBm input optical power, showing that the signal generated by this FSK transmitter had excellent extinction ratio and was comparable to the signal generated by an ASK transmitter.

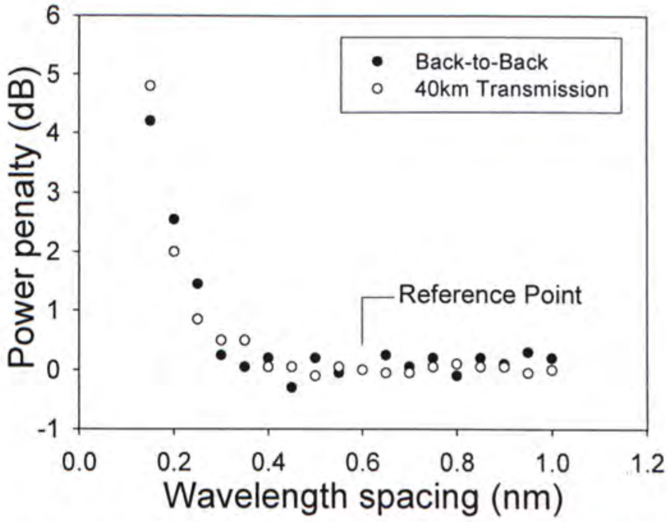


Fig. 2.12 Power penalty at BER=10^{-9} for different wavelength spacing of demodulated optical FSK signal in linear transmission regime (input power= 4 dBm).

We then varied the spacing of the two input wavelengths as well as the operating bit rate to further investigate the performance of our proposed transmitter. The wavelength spacing was tuned from 0.1 nm to 1 nm in 0.05-nm step and the power penalties with reference to the case of 0.6-nm wavelength spacing were measured. The measured results are shown in Fig. 2.12. For any wavelength spacing smaller than 0.3 nm, large power penalty was observed. It was due to interference between the two data spectra of the input wavelengths. As the wavelength spacing increased from 0.3 nm to 1 nm, such interference became less significant and nearly negligible power penalty was observed in this wavelength range. However, any further increase in wavelength spacing would introduce more power penalty due to signal distortion by excessive filtering at OBPF1 and the possible walk-off effect induced by the fiber dispersion. Nevertheless, as larger wavelength spacing means lower spectrum efficiency, thus the optimal wavelength spacing for the optical FSK signal should be within the range from 0.3 nm to 0.6 nm. Note that the frequency spacing can be tuned continuously in our proposed transmitter. Furthermore, the proposed optical FSK transmitter was characterized at different operation data rates at 4-dBm input power level. The measured receiver sensitivity was plotted in Fig. 2.13. It shows that the generated FSK signal at different data rates achieved comparable performance as compared with that of a typical ASK signal in linear transmission regime. Thus, this proves that the proposed OFSK transmitter is data-rate transparent.

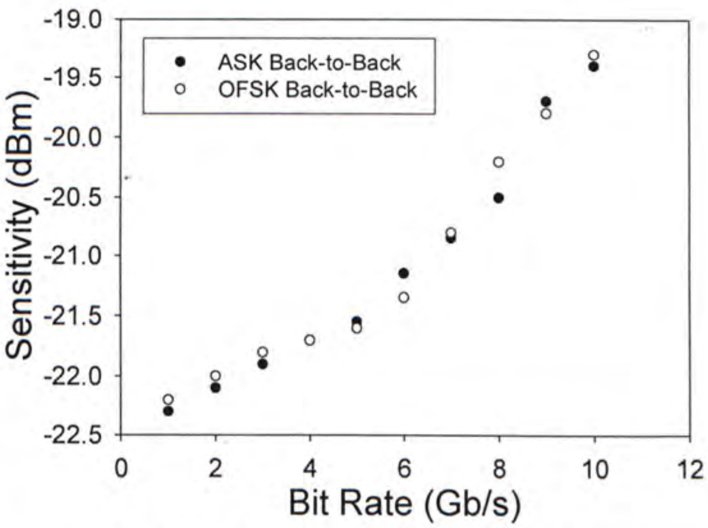


Fig. 2.13 Sensitivity of ASK and demodulated optical FSK signal at different data rates in linear transmission regime (input power= 4 dBm).

2.5 Summary

We have proposed and experimentally demonstrated a novel optical FSK transmitter, which is based on polarization modulation. The transmitter is data rate independent and is capable of continuous tuning of wavelength spacing. Experimental characterization of the transmitter performance has been presented, showing its high flexibility in transmitter design and potential in high-speed system.

3 Optical Return-to-Zero Frequency Shift Keying (RZ-FSK)

3.1 Introduction and Motivation

At the beginning of development of optical networks, non return-to-zero (NRZ) was the most common modulation format deployed. However, nowadays, it has been well agreed that return-to-zero (RZ) format has better chromatic dispersion and fiber nonlinearity tolerance [16-18]. Same situation happened to DPSK. DPSK was discovered to outperform on-off keying (OOK) for 3-dB receiver sensitivity advantage. Later, return-to-zero DPSK (RZ-DPSK) was proposed and showed better transmission performance than DPSK [19-20]. From these two examples, it can be concluded that RZ format performs better than NRZ format. There are two reasons to support this statement. First, as each RZ pulse only lasts for a portion of a whole bit duration, thus at the same average optical power, the peak power of the RZ signal is higher than that of NRZ signal, leading to a higher receiver sensitivity. Second, the intersymbol interference (ISI) due to dispersion and nonlinearity is smaller in RZ format because there is a null (zero power) period between adjacent "ones".

Conventional optical FSK signal described in chapter 1, or called NRZ-FSK, has high tolerance to fiber nonlinearity. To further increase its tolerance to impairments, we propose a new modulation format, RZ-FSK. Fig. 3.1 shows the difference between NRZ-FSK and RZ-FSK.

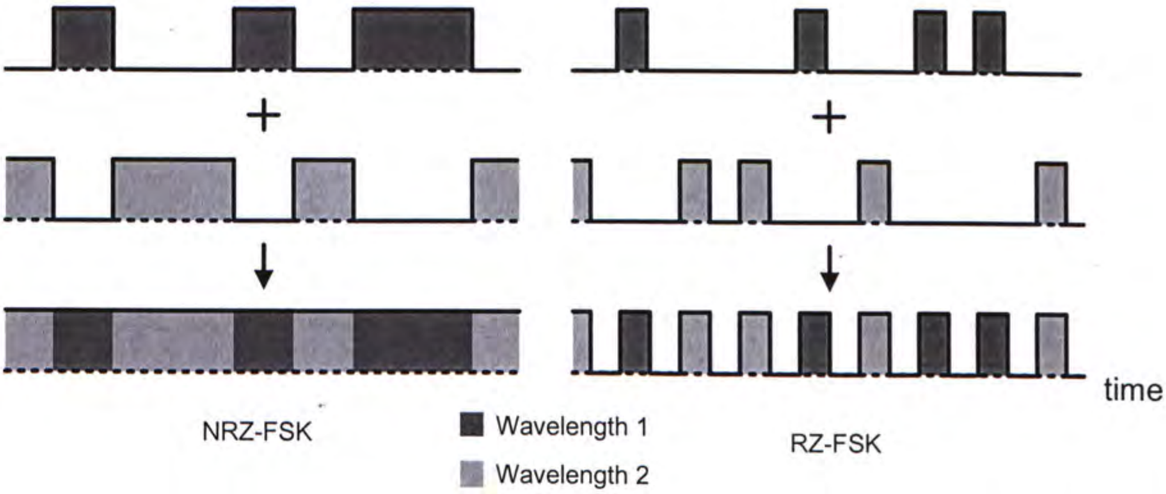


Fig. 3.1 NRZ-FSK and RZ-FSK signals.

By switching conventional NRZ-FSK to new RZ-FSK, we expect that the performance and tolerance to impairments should be enhanced, just similar the cases of NRZ to RZ and NRZ-DPSK to RZ-DPSK.

In this chapter, we will first discuss some comparisons of NRZ vs. RZ and NRZ-DPSK vs. RZ-DPSK from the other works. After that, we will compare NRZ-FSK and RZ-FSK's transmission performance and their tolerance against chromatic dispersion and fiber nonlinearity (SPM), through experiments and simulations.

3.2 Previous NRZ vs. RZ Comparisons

In [18], the transmission performance and tolerance to fiber nonlinearities of 40-Gb/s NRZ and RZ signals were compared. Fig. 3.2 shows the experimental setup used for the comparison. The NRZ transmitter was realized by external intensity modulation of CW light from a DFB laser, while RZ transmitter comprised a tunable modelocked semiconductor laser operating at 10GHz, an external modulator and a fiber delay-line multiplexer, as described in [21].

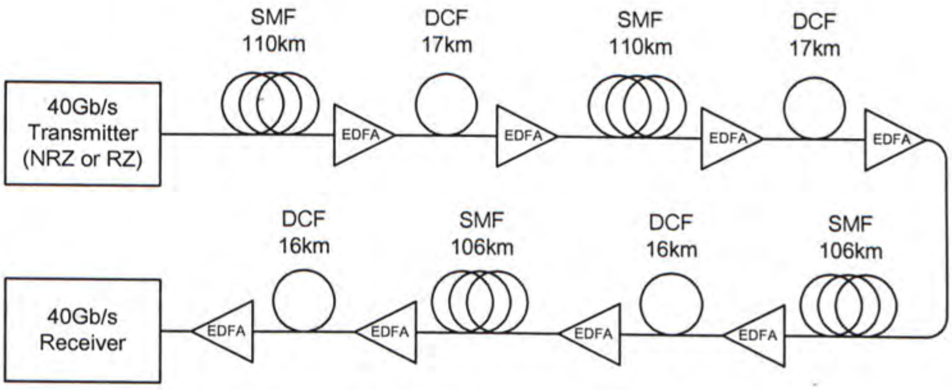


Fig. 3.2 Experimental setup for NRZ / RZ comparison in terms of their transmission performance.

The transmission line consisted of four cascaded SMF spans with a SMF length of 110 km in the first and second spans and a SMF length of 106 km in the other two spans. The dispersion of each span was completely compensated by DCF using a post-compensation scheme. The comparisons were based on three cases: back-to-back, 218 km (the first two spans) and 432 km (total four spans).

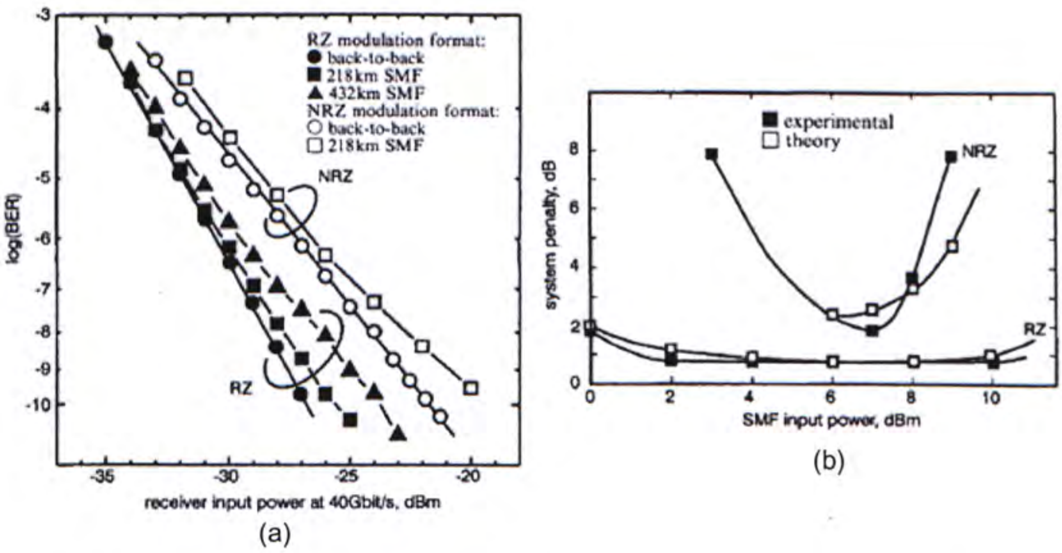


Fig. 3.3 Experimental results. (a) Transmission performance. (b) Nonlinearities tolerance (218km SMF). (Extracted from [18])

Fig. 3.3 shows the experimental results. From Fig. 3.3 (a), it is very clear that RZ signal outperformed NRZ signal in terms of BER performance. The receiver sensitivity of RZ signal was at least 5 dB lower than that of NRZ signal, for the back-to-back case and 218-km transmissioin case. For NRZ 432-km transmission case, error floor was observed. Fig. 3.3 (b) shows their tolerances to fiber nonlinearities. Theoretically, the curves should show a U-shape. Increasing signal power would improve the optical signal-to-noise ratio (OSNR), thus the power penalty was reduced. However, further increase in signal power would cause excess amount of fiber nonlinear effects, which severely degraded the performance. As the signal power increased, RZ signal curve kept almost constant, showing negligible penalty due to fiber nonlinearities. In contrast, NRZ signal degraded quickly. To conclude, the RZ signal has a better performance than the NRZ signal in terms of receiver sensitivity and nonlinearity tolerance.

3.3 RZ-FSK Transmitter Design

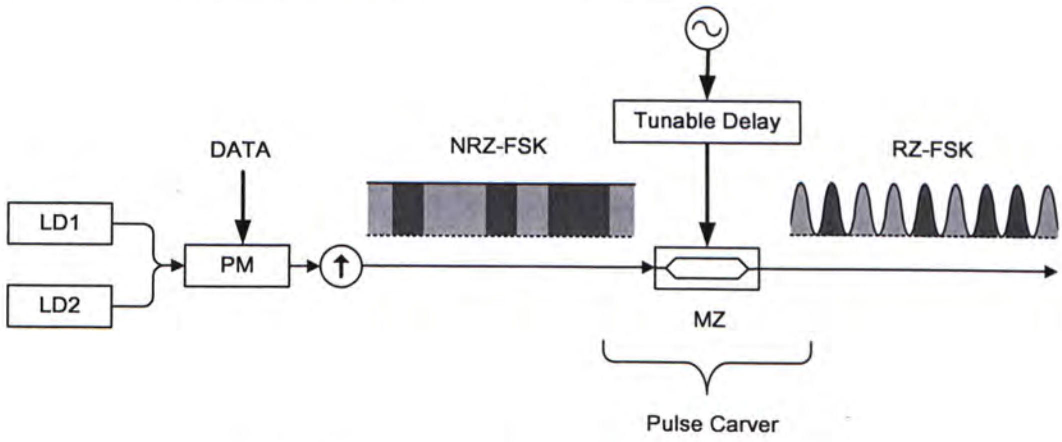


Fig. 3.4 Transmitter design for RZ-FSK format.

To generate the new modulation format RZ-FSK, we propose a new transmitter design which can be divided into two parts, NRZ-FSK transmitter and pulse carver, as shown in Fig. 3.4. The NRZ-FSK transmitter is exactly the same as our proposed optical FSK transmitter based on polarization modulation. Details can be found in part 2.2 of this thesis. The NRZ-FSK signal generated is fed into a MZ optical intensity modulator, driven by a sinusoidal electrical signal from a local oscillator. The frequency of the local oscillator is the same as the data rate. A constant intensity NRZ-FSK signal is carved into a pulse train by the MZ modulator while keeps the frequency information unchanged, generating a 50% duty cycle RZ-FSK signal. Attention has to be paid to the timing alignment between the optical NRZ-FSK signal and the electrical clock signal. The peak of the clock signal (maximum transmission point of MZ modulator) has to be optimized to appear at the middle of each bit. Detuning from the middle may introduce power penalty, just the same as the cases of pulse carving of ASK or DPSK signals [22]. Fig. 3.5 shows the waveforms of each wavelength and the resultant signal of NRZ-FSK and RZ-FSK.

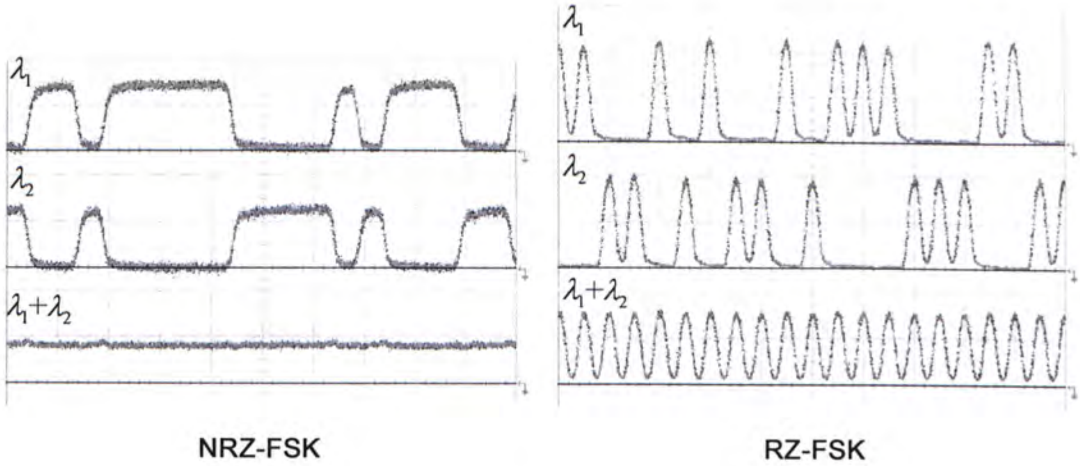


Fig. 3.5 Waveforms of NRZ-FSK and 50% duty cycle RZ-FSK signal (including individual wavelength). (Time scale: 200ps/div)

3.4 Performance Comparison

In order to investigate the performance of the newly proposed RZ-FSK modulation format, we have compared RZ-FSK with NRZ-FSK in three aspects, back-to-back performance, chromatic dispersion tolerance and fiber nonlinearity tolerance. The NRZ-FSK transmitter used is our proposed transmitter based on polarization modulation. Thus, the only difference between the two transmitters is the pulse carver, and we could make sure that we are comparing the modulation formats, but not the transmitter designs. Besides, we carried out experiments for back-to-back performance and chromatic dispersion tolerance investigation, while simulations for fiber nonlinearity tolerance. The reason is that the highest optical power supported in our laboratory is not high enough to distinguish their tolerances against fiber nonlinearity. The results will be presented in the following sections.

3.4.1 Back-to-back performance

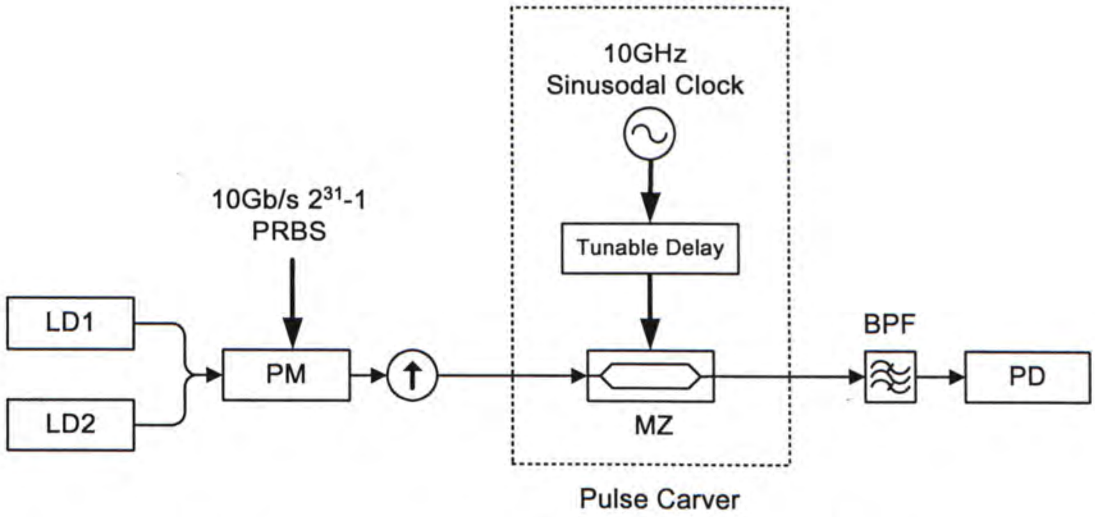


Fig. 3.6 Experimental setup for investigation of back-to-back performance.

The experimental setup is shown in Fig. 3.6. Two CW light launched from two DFB lasers (1553 nm and 1553.6 nm) were combined and fed into an optical phase modulator followed by a polarizer for NRZ-FSK modulation. The data pattern used was 2^{31}-1 PRBS. The pulse carver was used only for RZ-FSK generation. The tunable delay was optimized as stated before. We passed the output signal into an optical bandpass filter (BPF) and followed by a photodiode (PD) for back-to-back detection. The center of the filter passband was set to 1553 nm and its 3-dB bandwidth was 0.2nm.

We have compared the bit error rate (BER) performances of the NRZ-FSK and RZ-FSK signals, as shown in Fig. 3.7. As what we have expected, the receiver sensitivity of the RZ-FSK signal was about 2.5-dB lower than that of the NRZ-FSK signal. It was because the peak power of the RZ-FSK signal is higher than that of the NRZ-FSK signal at the same average received optical power. Thus, RZ-FSK has shown receiver sensitivity advantage over NRZ-FSK in back-to-back case.

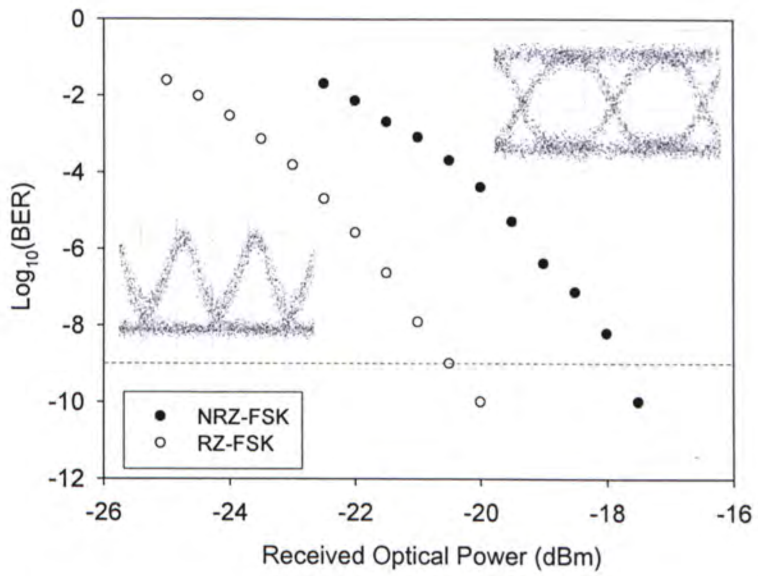


Fig. 3.7 Back-to-back BER of 10 Gb/s demodulated NRZ-FSK and RZ-FSK. Insets are the corresponding eye diagrams.

3.4.2 Chromatic dispersion tolerance

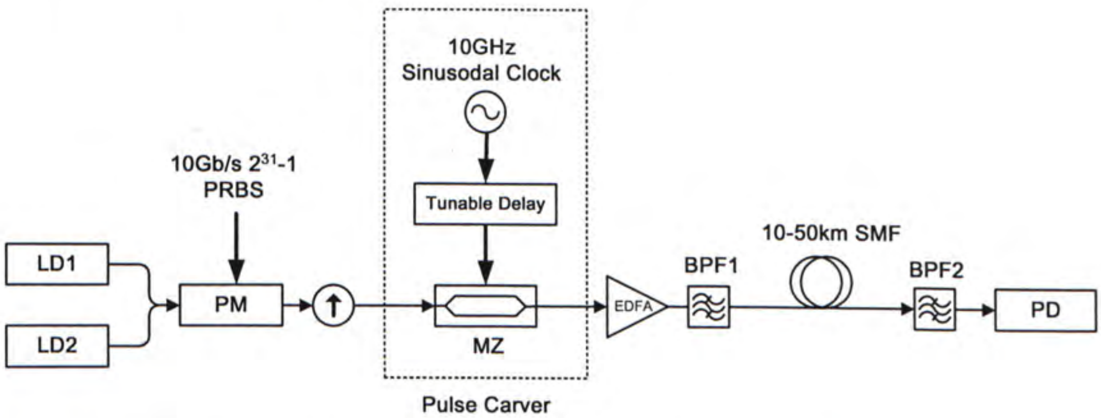


Fig. 3.8 Experimental setup for investigation of chromatic dispersion tolerance.

The transmitter design in this experiment was the same as the previous one. At the output, the signal was amplified by an EDFA and then passed through BPF1 (center wavelength was 1553.3 nm and 3-dB bandwidth was 0.8 nm) for ASE suppression. The signal (optical power about 0 dBm) was then transmitted through a piece of single mode fiber (SMF) without any chromatic dispersion compensation. The receiver was the same as the previous one.

To compare, we increased the length of the SMF from 10 km to 50 km in 10-km step and measured their receiver sensitivity penalties due to chromatic dispersion. The result is shown in Fig. 3.9. Since RZ-FSK has some guard time between adjacent bits, we expected that RZ-FSK would show higher tolerance against chromatic dispersion. This expectation is proved by the experiment. For 1-dB receiver sensitivity penalty tolerance, the transmission distance of RZ-FSK signal was about 30 km, which was three times of that of NRZ-FSK signal. We may observe the difference more clearly by comparing their eye diagrams. Fig. 3.10 shows their eye diagrams after 20-km and 50-km transmission. After 20-km transmission, the eye diagram of the RZ-FSK signal was very clear but that of the NRZ-FSK signal started to degrade. After 50-km transmission, the eye diagram of the NRZ-FSK signal was nearly closed, while that of the RZ-FSK signal still maintained a good eye opening.

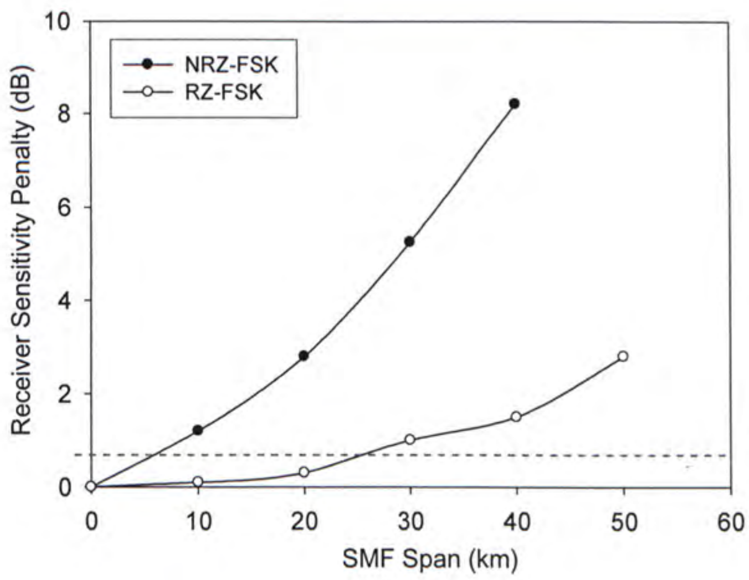


Fig. 3.9 Receiver sensitivity penalty due to chromatic dispersion

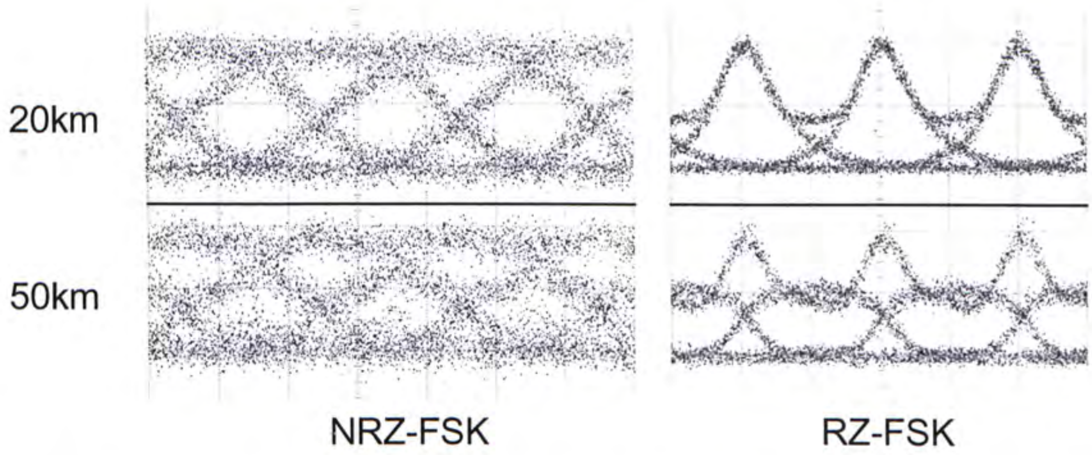


Fig. 3.10 Eye diagrams of NRZ-FSK and RZ-FSK signals degraded by chromatic dispersion. (Time scale: 50ps/div)

3.4.3 Fiber nonlinearity tolerance

We used OptSim® as our simulation software for fiber nonlinearity tolerance investigation. We have done simulation for SPM tolerance. In SPM simulation, we increased the input optical power of FSK signal for single channel transmission to see how much penalty was introduced by such increase in power. Besides, the NRZ-FSK transmitter we used was based on complementary intensity modulation because OptSim® does not support polarization modulation in phase modulator.

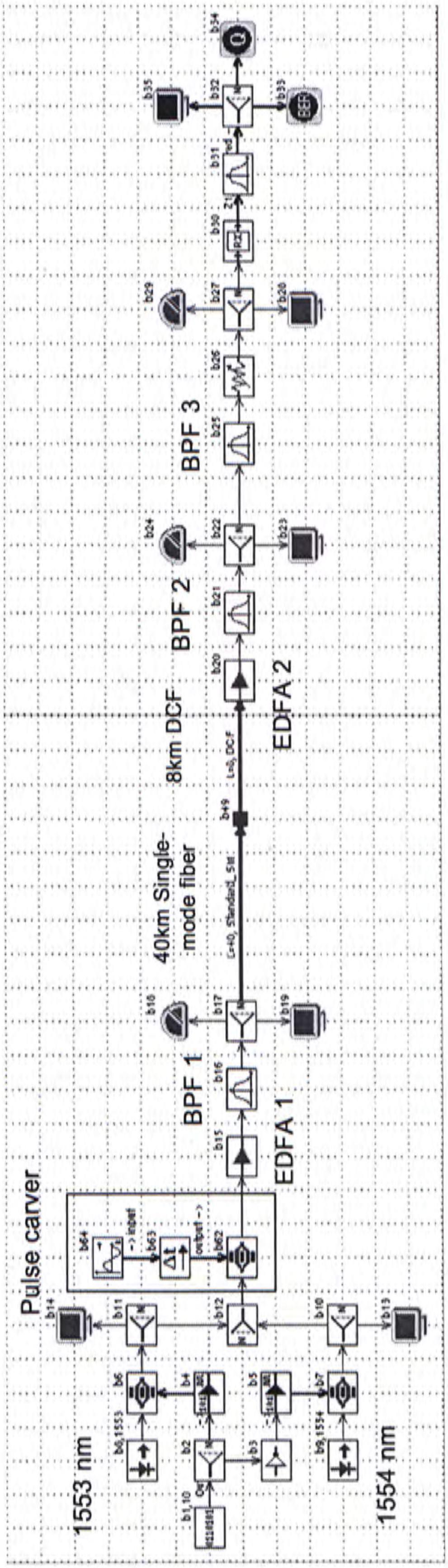


Fig. 3.11
Simulation setup of
SPM investigation

Fig. 3.11 shows the simulation setup for SPM investigation. Two CW light (1553 nm and 1554 nm) were intensity modulated by complementary NRZ data and then combined to form NRZ-FSK signal. Pulse carver was used for the generation of RZ-FSK signals. The signals were then amplified by EDFA1 and filtered by BPF1 (center wavelength was 1553.5 nm and 3-dB bandwidth was 1 nm). The transmission medium was 40-km SMF and its chromatic dispersion was completely compensated by a piece of 8-km DCF. After the transmission, the Q value was measured. We increased the input optical power of FSK signal from 5 dBm to 25 dBm and found the corresponding Q values to see how SPM affects both the NRZ-FSK and the RZ-FSK signals. Fig. 3.12 depicts the results. It is shown that the RZ-FSK signal outperformed the NRZ-FSK signal at all input optical powers. The Q degradation caused by further increase in input power is much larger in NRZ-FSK signal than RZ-FSK signal, showing that RZ-FSK signal has higher tolerance to SPM degradation.

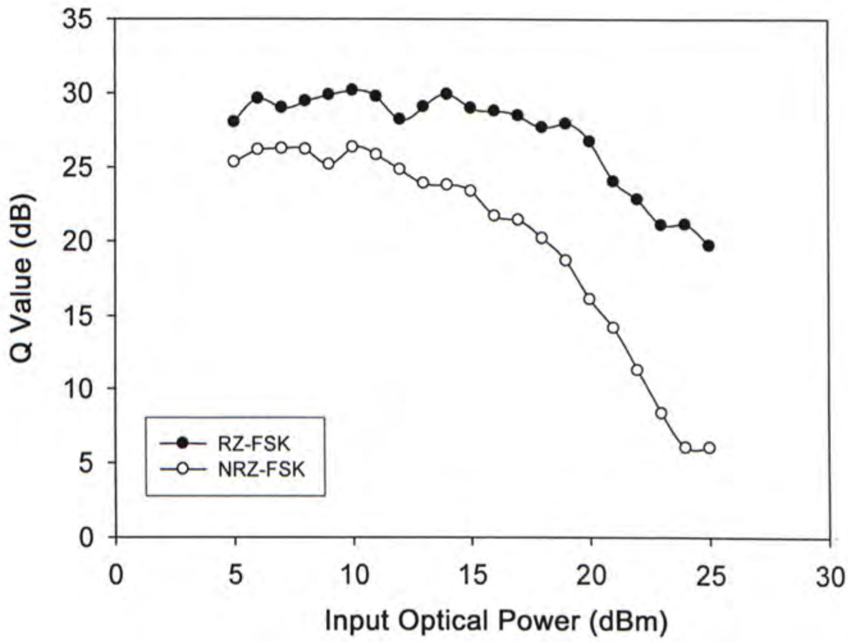


Fig. 3.12 Q value degradation due to SPM for NRZ-FSK and RZ-FSK.

3.5 Summary

We have proposed a new modulation format RZ-FSK, which can be generated by pulse carving of conventional NRZ-FSK signal, to improve the performance and impairment tolerance. We have shown from experiments that the RZ-FSK signal has better receiver sensitivity and higher tolerance to chromatic dispersion than the NRZ-FSK signal. For fiber nonlinearity, the RZ-FSK signal performs better than the NRZ-FSK signal under the influence of SPM. Therefore, RZ-FSK can be considered as a promising candidate as the modulation format in optical transmission system.

4 A Novel Optical Transmitter for High-Speed Differential Phase Shift Keying/ Inverse Return-to-zero (DPSK/Inv-RZ) Orthogonally Modulated Signals

4.1 Introduction

Orthogonal modulation has recently aroused much attention for its effectiveness in improving the spectral efficiency of the optical carrier. One common example is the combination of amplitude shift keying (ASK) and differential phase shift keying (DPSK) signals [23]. Another combination of inverse return-to-zero (Inv-RZ) with DPSK [24] or with differential quadrature phase shift keying (DQPSK) [25] has been recently proposed to achieve double or triple spectral efficiency, respectively. However, their Inv-RZ transmitter was achieved by modulating the optical pulses from a mode-locked laser diode (MLLD), via an optical intensity modulator, followed by cross-gain modulation (XGM) in a semiconductor optical amplifier (SOA) for intensity inversion. In addition to the complicated setup of the transmitter, the major drawbacks of this scheme are relatively large pulse width (long tail) of the generated Inv-RZ pulses and limited operation speed (< 10Gb/s) due to the slow carrier recovery time of SOA. The detail will be discussed in part 2. In this chapter, we propose and demonstrate a simple and effective optical transmitter for generation of high-speed DPSK/Inv-RZ orthogonally modulated signals using a dual drive Mach-Zehnder Interferometric modulator (DD-MZI) and an optical phase modulator. A 10-Gb/s DPSK signal has been successfully superimposed on a 10-Gb/s Inv-RZ signal and the performance has been experimentally characterized. This proposed scheme greatly simplifies the DPSK/Inv-RZ transmitter design and thus is very practical and cost-effective.

4.2 Previous Scheme

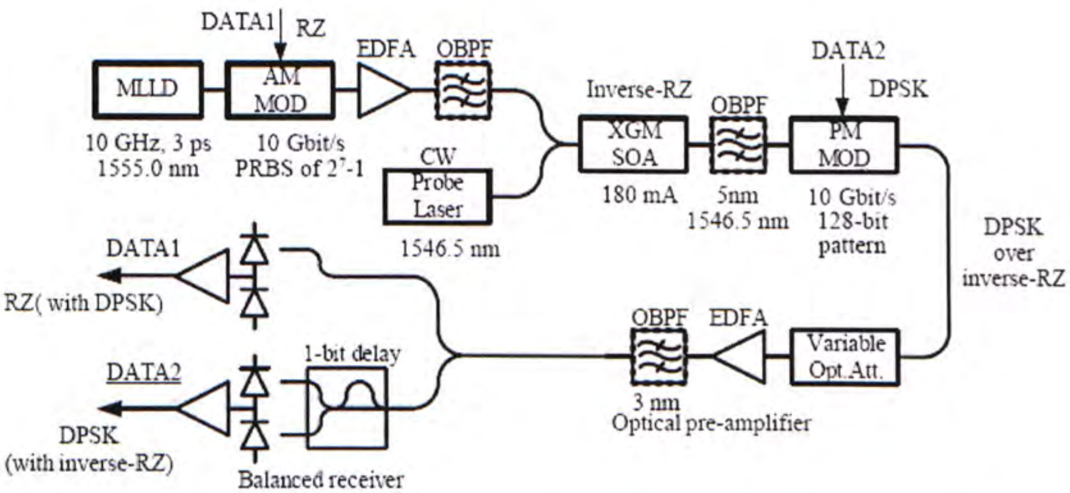


Fig. 4.1 Previous scheme of DPSK/Inv-RZ signal generation. (Extracted from [24])

In [24], a method based on XGM in SOA was proposed to generate DPSK/Inv-RZ signal (Fig. 4.1). 10 GHz, 3 ps optical pulse train from a MLLD was modulated by 10 Gb/s PRBS data via an optical intensity modulator for RZ modulation. For inverse-RZ generation, XGM in a SOA was adopted by injecting CW probe and the

RZ pulses. Optical band-pass filter was employed to select the converted Inv-RZ optical pulses. Then, DPSK modulation with another data was superimposed onto the Inv-RZ signal. Fig. 4.2 shows the eye diagrams of detected signal of (a) DPSK with Inv-RZ, (b) DPSK without Inv-RZ (c) Inv-RZ with DPSK, and (d) Inv-RZ without DPSK. Note that for (c) and (d), the polarity of Inv-RZ is inversed back to RZ by single-end direct detection.

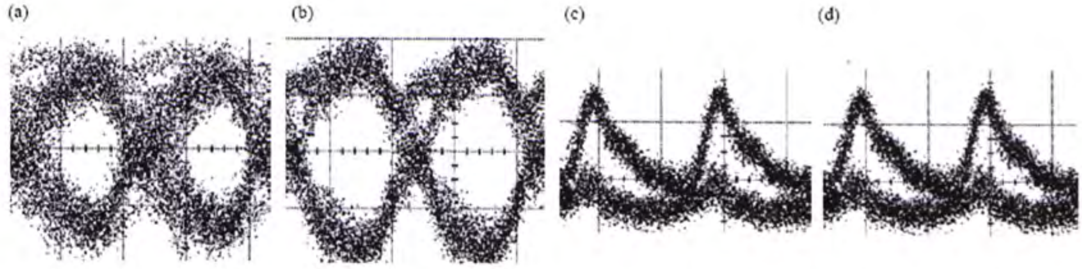


Fig. 4.2 Eye diagrams of detected signals. (Time scale: 50ps/div) (a) DPSK with Inv-RZ, (b) DPSK without Inv-RZ, (c) Inv-RZ with DPSK, (d) Inv-RZ without DPSK. (Extracted from [24])

From Fig. 4.2 (c) and (d), we observed that the tail of the RZ pulse was very long, lasting for the whole bit. As stated above, the reason is SOA's limited carrier recovery time could not support such high speed operation. Such long tail would severely degrade the DPSK signal, which can be identified from Fig. 4.2 (a) and (b). They found out that the power penalty introduced by inverse-RZ to DPSK was 5 dB. Besides, to generate an inverse-RZ signal, a pulse source, an amplitude modulator and a SOA are necessary. Such high cost hinders this scheme to be a practical approach.

4.3 Proposed Transmitter Design

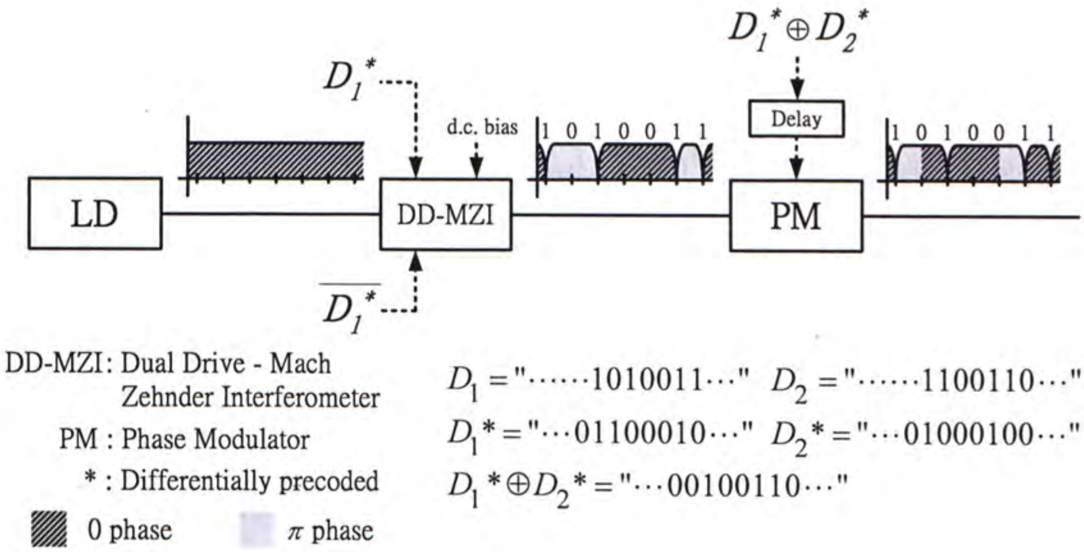


Fig. 4.3 Proposed DPSK/Inv-RZ optical transmitter and operation principle

Fig. 4.3 illustrates the configuration and operation principle of the proposed DPSK/Inv-RZ transmitter. A continuous-wave (CW) light beam from a DFB laser diode is fed into a dual-drive Mach-Zehnder Interferometric modulator (DD-MZI), which is operated in a push-pull configuration and is modulated by a differential pair of differentially pre-coded NRZ data signals (D_1^* and $\overline{D_1^*}$, where "*" denotes differentially pre-coded). In this way, a DPSK signal with intensity dips at the phase transitions is generated. Note that the intensity dips exactly represent the original data D_1 in the dark pulse waveform. Consequently, this resultant intensity waveform is, in principle, equivalent to an Inv-RZ signal. This novel Inv-RZ signal generation scheme is very simple and practical as it only requires a single stage of DD-MZI, thus greatly reduces the complexity of the Inv-RZ transmitter, as compared with the previous approaches. The width and depth of the intensity dips depend on the response of the DD-MZI as well as the rising and falling times of the driving electrical data signals.

Another independent differentially pre-coded data signal D_2^*, can be encoded onto the phase of the Inv-RZ signal, via an optical phase modulator (PM), to realize an orthogonally modulated signal with two bits per symbol. However, the original phase of the Inv-RZ signal contains the phase information of D_1^*, thus D_2^* cannot be simply modulated to it. To re-write the phase information of the Inv-RZ signal, $D_1^* \oplus D_2^*$, instead of D_2^*, is applied to the PM, where $\oplus$ stands for exclusive-OR (XOR) logic operation. Using the fact that $D_1^* \oplus D_1^* \oplus D_2^* = D_2^*$, the phase information is rewritten and only D_2^* remains in the phase. As a result, a DPSK/Inv-RZ orthogonally modulated signal is generated at the output of PM, with data D_1 encoded in intensity and data D_2^* in phase. It should be noted that the alignment between the two electrical data signals (D_1^* and D_2^*) is very crucial. Any timing misalignment between them may induce power penalty to D_2^*, which is in DPSK format. Nevertheless, the Inv-RZ signal (D_1) should be unaffected by such timing misalignment, as the phase re-writing process for D_2^* does not alter any intensity information (D_1).

Demodulation of this DPSK/Inv-RZ signal can be achieved by simply splitting the power of the received signal into two parts. One of them is fed into a photodiode for direct Inv-RZ detection, while the other one is fed into an optical delay interferometer (DI), followed by a photodiode for DPSK demodulation and detection.

4.4 Experiment and Results

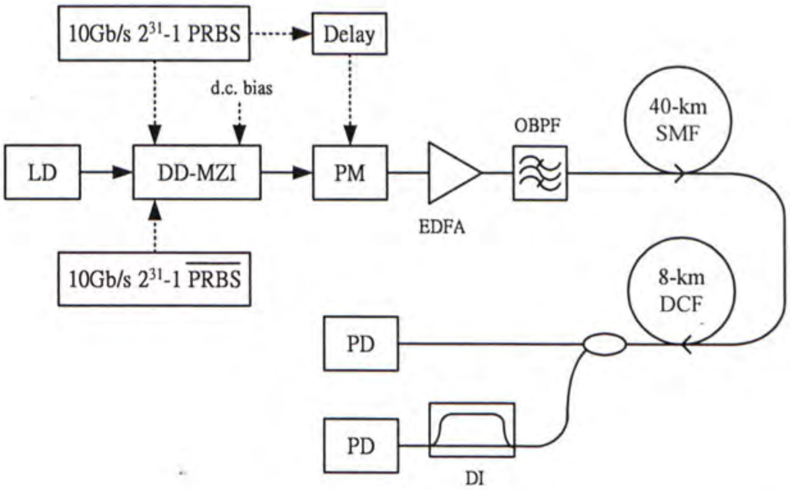


Fig. 4.4 Experimental setup. DD-MZI: dual-drive Mach-Zehnder interferometric modulator, PM: optical phase modulator, OBPF: optical bandpass filter, PD: photodiode, DCF: dispersion-compensating fiber, DI: delay interferometer

We have experimentally demonstrated the proposed optical transmitter for DPSK/Inv-RZ signals at 10-Gb/s and also characterized the performance, using the experiment setup shown in Fig. 4.4. A CW light beam at 1547 nm generated by a DFB laser was fed into a DD-MZI modulated by a differential pair of 10-Gb/s 2^{31}-1 NRZ pseudorandom binary sequence (PRBS). The output Inv-RZ signal was then fed into an optical PM, where a delayed version of the original PRBS was applied for phase re-writing. After the re-writing, the phase information of the output signal was the logic XOR result between the original PRBS and its time-delayed PRBS. As the logic XOR output of the two PRBSs with non-zero relative shift is also a PRBS, thus the bit error rate (BER) of the re-written phase information can be measured at the receiver. To further demonstrate the proper operation of our proposed transmitter, we set the data patterns and observed the waveforms of the signal at different positions, as shown in Fig. 4.5. The data set used was the same as that shown in Fig. 4.3. The results proved that the phase re-writing was successful.

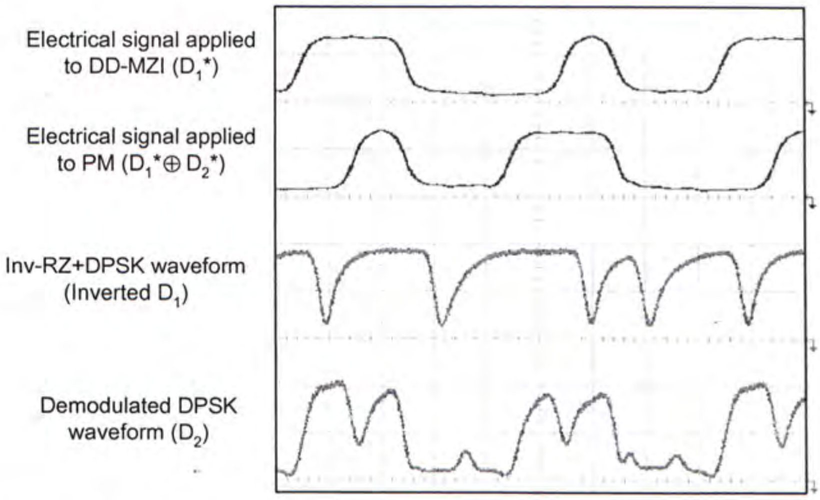


Fig. 4.5 Measured waveforms of the input electrical data signals and the received signals. Data sequences are the same as that depicted in Fig. 4.3. (Time scale: 100ps/div)

Fig. 4.6 shows the eye diagrams of (a) the generated DPSK/Inv-RZ signal (D_2^* on D_1), (b) the demodulated DPSK signal without Inv-RZ encoding (D_2^* without D_1) and (c) demodulated DPSK signal with Inv-RZ encoding (D_2^* with D_1). It can be seen that the width of the dark pulses of the Inv-RZ signal is much smaller than that reported in [24, 25]. Moreover, clear eye openings are observed in both the demodulated DPSK signals with and without Inv-RZ encoding.

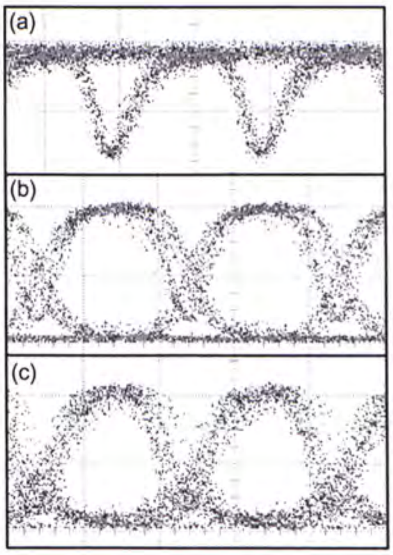


Fig. 4.6 Eye diagrams of generated signals. All three cases are measured in back-to-back case. (Time scale: 50ps/div) (a) generated DPSK/Inv-RZ signal, (b) demodulated DPSK with Inv-RZ, (c) demodulated DPSK without Inv-RZ.

The generated 10-Gb/s DPSK/Inv-RZ signal was then amplified by an erbium-doped fiber amplifier (EDFA) and filtered by an optical bandpass filter (OBPF) with a 3-dB bandwidth of 0.8 nm to suppress the excessive amplified spontaneous emission (ASE). The amplified signal (at about 0 dBm) was transmitted over a piece of 40-km standard single-mode fiber (SMF) and was completely dispersion-compensated by a piece of 8-km dispersion-compensating fiber (DCF). At the receiver, the signal was split into two paths, one for Inv-RZ detection and the other for DPSK demodulation and detection. Fig. 4.7 shows the BER characteristics of the detected signals under different cases. The four BER curves of the Inv-RZ signal show that there is negligible power penalty introduced by the additional phase modulation, via the PM. The other four curves for the DPSK signal indicate that the DPSK signal suffers from about 1.4-dB power penalty, which is induced by the non-uniform intensity of the dark pulses of the Inv-RZ signal as well as the imperfect phase rewriting process.

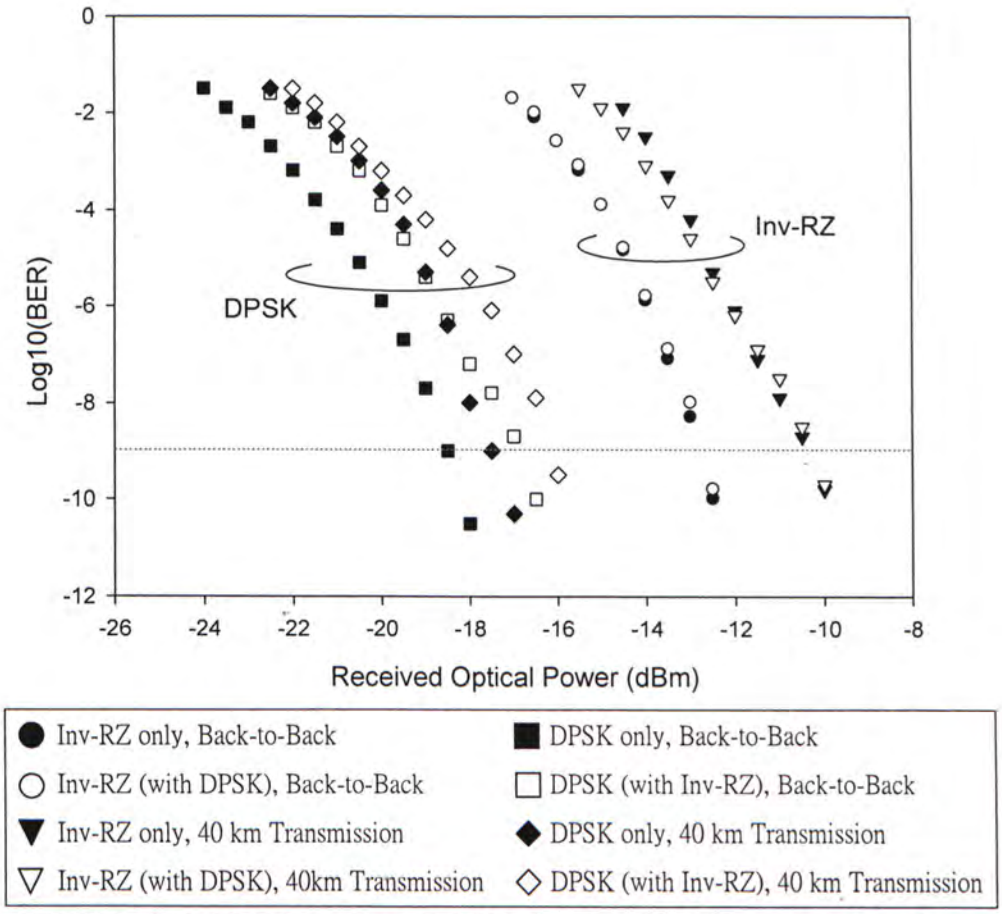


Fig. 4.7 BER of 10-Gb/s Inv-RZ and DPSK signals with/without orthogonal modulation under 40 km transmission or back-to-back.

Fig. 4.8 shows the power penalty induced to the DPSK signal by timing misalignment between the two driving electrical data signals. We adjusted their relative delay by an electrical delay line and measured the corresponding receiver sensitivity to achieve a BER of 10^{-9}. The tolerance for 1-dB penalty is about 35 ps, from -20 ps to 15 ps, which is larger than 20 ps reported in [25]. The slight asymmetry can be attributed to the asymmetric intensity profile of the dark pulses in the Inv-RZ signal. The enhanced tolerance against timing misalignment can be attributed to the much narrower dark pulses of the Inv-RZ signal generated by our proposed transmitter.

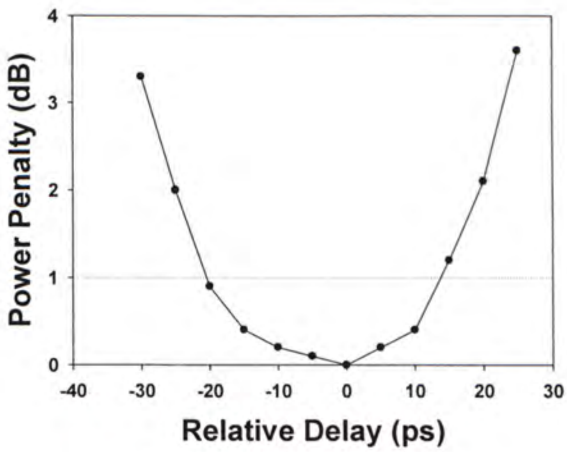


Fig. 4.8 Power penalty induced to the DPSK signal due to timing misalignment between the two driving electrical data signals, normalized to the case without timing misalignment

4.5 Conclusion

We have proposed and experimentally demonstrated a simple and novel optical transmitter for superimposing high-speed DPSK signal over an Inv-RZ signal generated by DD-MZI. We experimentally determined that negligible power penalty is induced by the DPSK signal to the Inv-RZ signal while about 1.4-dB penalty by the Inv-RZ signal to the DPSK signal. Compared with previous one, our scheme is simpler but can achieve much better performance. We have also achieved a timing misalignment tolerance up to 35% of the bit slot, for 1-dB power penalty.

5 Summary

5.1 Thesis Summary

The objectives of this thesis are to provide more flexible, practical and simple transmitter designs for FSK and DPSK/Inv-RZ modulation formats, and improve FSK modulation format by proposing the RZ-FSK modulation format.

Chapter 1 introduced some background knowledge about FSK signal, modulation format and orthogonal modulation. Details about optical FSK applications in optical packet switching network and WDM-PON were also given.

Five previously proposed FSK transmitters were discussed and compared in details in chapter 2. Apart from that, we proposed and experimentally demonstrated a novel high-speed optical FSK transmitter based on polarization modulation, which featured high flexibility. The performance of the transmitter was further experimentally characterized.

In chapter 3, we proposed a new modulation format RZ-FSK based on conventional FSK format for its potential of high tolerance to chromatic dispersion and fiber nonlinearity. Experiments and simulations were carried out and proved that the

RZ-FSK signal performs better than the NRZ-FSK signal.

A novel proposed transmitter was described in chapter 4 to generate DPSK / Inverse-RZ orthogonally modulated signal. The transmitter comprises a dual-drive Mach-Zehnder intensity modulator and an optical phase modulator. Compared to the previous scheme, this design has lower complexity and offers better performance. Its performance was experimentally investigated.

5.2 Future Work

In chapter 2, we have proposed a new high-speed optical FSK transmitter. It shows high flexibility among all the FSK transmitters. However, since it requires polarization modulation, the requirement for the polarization control is high. In the other words, it may not as stable as other schemes and may require precise polarization control. To improve this aspect, we expect to figure out some methods to turn the proposed transmitter into polarization insensitive, or at least reduce the polarization mismatching penalty.

We have investigated the degradation induced by fiber nonlinearities to NRZ-FSK and RZ-FSK signals in chapter 3. However, due to hardware limitation, we obtained the data by simulations only and were not able to perform actual experiments. Experimental investigation should be done in the future. Besides, since a pulse carver is used to carve the NRZ-FSK signal to the RZ-FSK signal, any timing misalignment between the FSK data and the pulse carver would introduce penalty. More analysis would be carried out to characterize such misalignment penalty and the performance comparison with DPSK signals would also worth investigation.

List of Publications

- S. S. Pun, C.K. Chan, and L. K. Chen, "A novel optical frequency shift keying transmitter based on polarization modulation," paper JWA43, in *Proc. Optical Fiber Communication Conf. (OFC'05)*, Anaheim, California, USA, 2005.

- S. S. Pun, C. K. Chan, and L. K. Chen, "A novel optical frequency shift keying transmitter based on polarization modulation," *IEEE Photonics Technology Letters*, Vol. 17, no. 7, pp. 1528-1530, 2005.

- S. S. Pun, C. K. Chan, and L. K. Chen, "Demonstration of a novel optical transmitter for high-speed differential-phase-shift-keying/Inverse-return-to-zero (DPSK/Inv-RZ) orthogonally modulated signals," submitted to *IEEE Photonics Technology Letters*.

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