Applications of Optical Orthogonal Modulation Schemes in Optical Networks

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Abstract

Recently, optical orthogonal modulation has attracted much interest in optical systems. More than one data channels, each of which is modulated in a different dimension such as optical intensity, optical frequency or optical phase, can be transmitted simultaneously on a single wavelength. One of the feasible approaches is to modulate a relatively low-speed optical amplitude-shift-keying (ASK) data stream on an optical differential phase-shift-keying (DPSK) high-speed optical signal, which demonstrates constant intensity characteristics. This finds applications to carry the necessary supervisory or optical label information, which is usually of Mb/s, in high-speed optical transmission systems to facilitate network monitoring and control. In addition, the same technique can also be applied to optical label-switched networks, where the high-speed optical packet payload is optical DPSK-modulated while the lower-speed labels are optical ASK-modulated. The optical label can also be swapped all-optically to update the label information for next-hop routing.

In this thesis, we investigate, both numerically and experimentally, the performance of the optical orthogonal modulation scheme to carry relatively-low speed (<2.5-Gb/s) ASK signals on a high-speed (10-Gb/s) optical DPSK data stream. Several design optimization and trade-offs, such as the bit rates and the optimal extinction ratios of the ASK signal, etc., have been considered and investigated. The goal is to optimize the system parameters and achieve minimal degradation to each of the orthogonal channels on the same wavelength. On the other hand, we have also studied and experimentally demonstrate the all-optical label swapping operation of the optical ASK labels on the high-speed optical DPSK packet payload. All-optical label erasure and renewal have been successfully demonstrated, and the performances of both the transmission, as well as the all-optical swapping operation, have been evaluated.

摘要

近來光正交調製成爲光通信系統研究的一個焦點。採用這一技術，以不同的光調製方式如強度、頻率或相位調製的多個數據信道可以在同一波長上同時傳輸。其中一種可行的方案是將低速率的幅移鍵控（amplitude-shift-keying (ASK)）數據調製在高速的差分相移鍵控（differential phase-shift-keying (DPSK)）光信號上。這一方式可應用于負載高速光傳輸系統中監測和控制所需的管理信息（通常Mb/s）。此外正交調製也可以應用到光標簽交換（optical label-switched）網絡中，將ASK調製的低速光標簽加載到DPSK調製的高速光包（packet）載荷上。光標簽的交換和更新全部在光層進行。

本論文用數學和實驗的方法對低速（<2.5-Gb/s）ASK信號和高速（10-Gb/s）DPSK信號正交光調製的性能進行了研究。考察不同ASK數據速率和調製深度對系統的影響，我們得到了系統最優化的條件。在最優化之後系統可以使正交調製的每個信道都達到最小的損耗。另外我們也通過實驗研究了在DPSK載荷上使用ASK光標簽進行全光交換，成功地實現了光標簽的擦除和更新。實驗結果對DPSK/ASK正交調製用於全光交換的傳輸和交換性能進行了評估。

Contents

Chapter 1: Introduction

Communication is one of the basic requirements in human society. Different kinds of media are used to carry information. Using light, by means of smoke, fire, flag, mirror or lamp, was an immemorial way for communication in the old days, but their effective bit rates were very low and the transmission distance between intermediate relay stations was very limited. In the 1830s, telegraph came along and electrical communication replaced the use of light. The bit rate-distance (BL) product increased to 100(Mb/s)-km and was limited to such value due to fundamental limitations in the mature electrical communication systems. The appearance of laser source and high diaphaneity glass fiber pushed optical communication to a new acme. A large amount of information could be transmitted at the speed of $2\times10^{8}m/s$ through tiny silica tunnels. In 25-year time, the BL product had increased seven orders. There were four remarkable generations in lightwave systems. The first three generations used lasers at the wavelength 0.8μm, 1.3μm and 1.55μm respectively. By using optical amplification and wavelength-division multiplexing (WDM) in the fourth generation, the system capacity doubled every 6 months and achieved 10Tb/s operation by the beginning of the 21st century. The next generation will be emphasized on increasing the system capacity by using more channels, and increasing the bit rate of each channel. At the same time, with increasing system complexity, how to switch and manage the high speed information in the optical layer becomes a critical issue to resolve the bottle-neck problem in practical optical networks.

1.1. Modulation Formats in Optical Communication Systems

Similar to electronic systems, optical communication systems use three kinds of basic modulation formats known as amplitude-shift keying (ASK), phase-shift keying (PSK), and frequency-shift keying (FSK) [1]. Fig 1.1 shows the bit patterns for these modulation schemes.

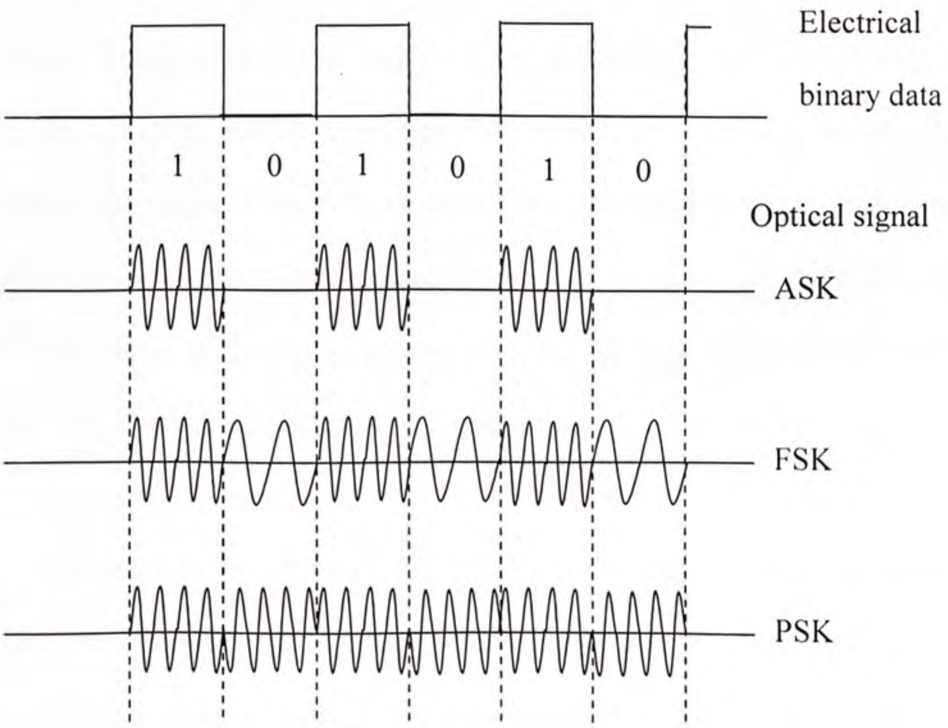


Fig 1.1 Bit pattern for ASK, FSK, PSK format

1.1.1 Optical ASK Format

The electric field of an optical ASK signal can be expressed as:

$$E_s(t) = A_s(t)\cos[\omega_0 t + \varphi_s(t)]$$

where ω_0, φ_s are kept constant and A_s is the amplitude modulation function.

The ASK format is often called on-off keying (OOK) because the amplitude is set to zero when transmitting the bit "0", in most practical cases. Nowadays ASK is the most commonly used modulation format in practical optical communication systems because of its system simplicity. There are two kinds of optical ASK modulation technologies, direct modulation and external modulation. In direct modulation systems, the optical bit stream is generated by directly modulating a semiconductor laser diode at the transmission side. However, the induced frequency chirp severely degrades the system performance, especially at high bit rates, say > 10 Gb/s. Thus external modulation is usually employed, instead, for high speed signals. $LiNbO_3$ waveguide in Mach-Zehnder (MZ) configuration is a commonly used optical intensity external modulator. It can achieve 20 dB extinction ratio (ER), which is the ratio of the on-level to the off-level, and it has a high modulation speed of up to 75 GHz. Other modulators such as polymeric electro-optic MZ modulator and electro-absorption (EA) modulator are also commonly used. Fig 1.2 shows the configuration of an intensity-modulated/direct-detection (IM/DD) system with external modulation. The light come from the continuous wave (CW) laser is modulated at the MZ modulator by an electrical data stream. After transmission, the optical ASK signal is detected by a photo diode.

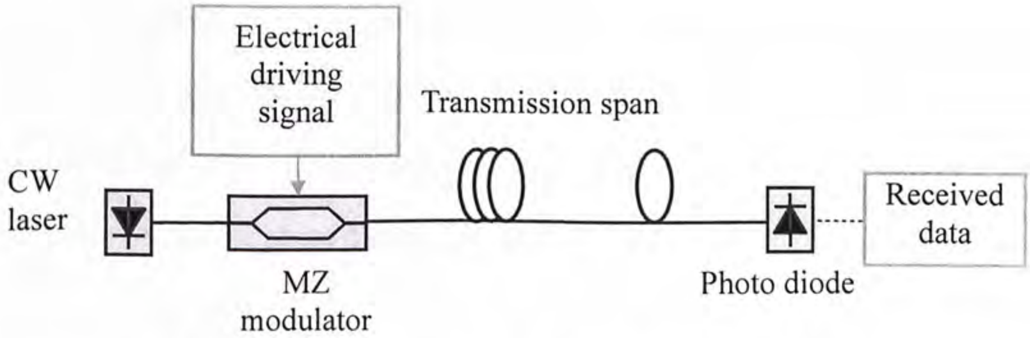


Fig 1.2 IM/DD system with external modulation

There are many advantages of using ASK modulation. Besides the structural simplicity and easy realization, the extinction ratio of ASK signal can be easily adjusted, which makes orthogonal modulation (to be discussed in section 1.1.4) on ASK signal possible to facilitate label processing functions.

1.1.2 Optical FSK Format

To obtain the optical FSK signal: $E_s(t) = A_s \cos[(\omega_0 \pm \Delta\omega)t + \varphi_s]$, the two complementarily modulated optical frequencies are generated. Direct modulation can be done by changing the operation current of the semiconductor lasers. The output signal has constant intensity. Also we can use external modulation to achieve the optical FSK modulation. Fig 1.3 shows one of the external FSK modulation schemes. Two CW laser sources are employed, with the central wavelength λ_1 and λ_2, respectively. λ_1 and λ_2 should be carefully chosen, close enough that the coherence is guaranteed. At the same time there should be enough spacing between λ_1 and λ_2 so that the optical filter at the receiver can filter out one of the intensity modulated signal. The two intensity modulators are driven by the electrical signal DATA and the complementary signal: $\overline{DATA}$, respectively. An optical delay ensures that the signals at the upper and the lower arms arrive at the coupler simultaneously and cancel each other. Thus the constant intensity optical FSK (OFSK) signal is obtained. At the receiver side, an optical filter is needed to filter out one of the frequencies for demodulation before the photo diode.

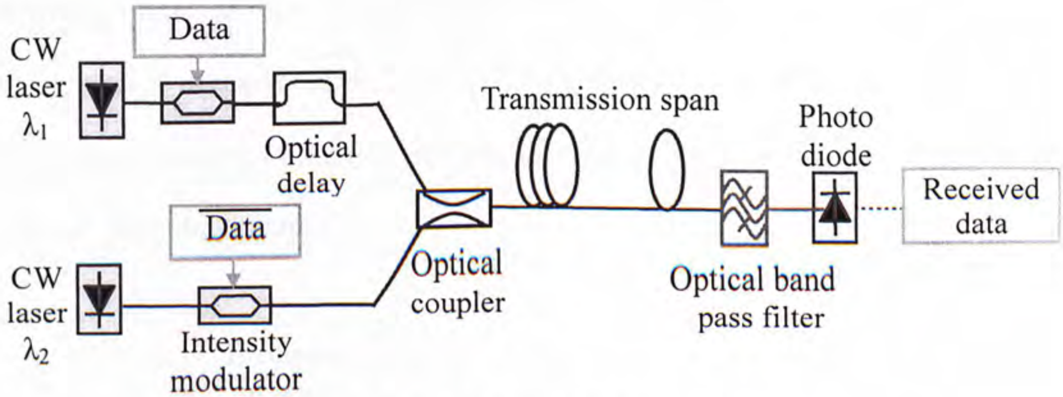


Fig 1.3 Optical FSK modulation system

There are many other ways to realize OFSK. Unlike optical ASK and PSK modulation, optical FSK has not yet had a mature, integrated modulation module. Developing compact, cost-effective and stable OFSK modulation module is a research topic nowadays.

1.1.3 Optical PSK Format

Compared with optical FSK, the modulator structure of optical PSK is much simpler. A single $LiNbO_3$ waveguide can be used. Different optical phase shifts are induced to the optical carrier according to the data pattern. To extract the phase information without vagueness at the receiver, the phase of the optical carrier should be stable, which poses a stringent requirement on the tolerable linewidth of the transmitter laser. By employing differential phase-shift keying (DPSK), this requirement can be relaxed in such a way that the carrier phase could be stable over a duration of two bits. A typical optical DPSK modulation system is shown in Fig 1.4. In DPSK format, the output bit stream is the interferometric result of two neighboring bits of the original PSK signal. Therefore an optical delay interferometer is necessary at the receiver. The polarization controller (PC) is used to align the signal with the principle axis possessing maximum modulation response in the optical phase modulator.

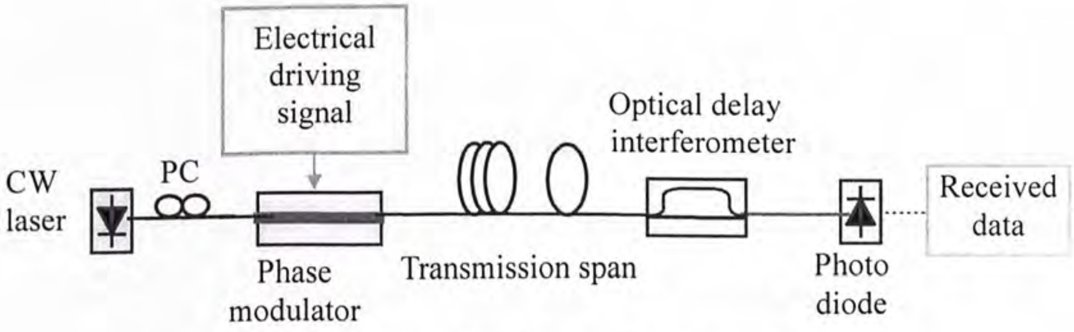


Fig 1.4 Optical DPSK modulation system

Conventionally, the transmission bit rate was relatively low. To produce a delay of one bit period, the delay arm of the optical interferometer was so long that it was not only impractical to implement but also the temperature stability was poor. Recent researches have found that optical phase modulation, especially DPSK, is more robust than ASK in cases of high bit rate, high power channels and optical packet switched networks [2]. Both simulation and experimental demonstrations showed that the constant channel power of DPSK systems suffered less from fiber nonlinearities, resulting in better system performance results. These aroused great attention of employing optical DPSK format for high speed payload carrier. Using the constant power characteristic, we can develop an orthogonal modulation scheme in combination with ASK signal.

1.1.4 Optical Orthogonal Modulation

From the characteristics of the basic modulation schemes, we can construct new modulation schemes by combining optical PSK or optical FSK with optical ASK. Since both PSK and FSK have constant intensity, intensity modulation can be added simultaneously on the same wavelength. Fig 1.5 illustrates one example of an orthogonal modulation signal employing ASK label on the optical PSK or optical FSK packet payload. The shaded bits and white bits in the packet payload represent different optical phases. In this thesis, we describe the orthogonal modulation as payload/label. For example, DPSK/ASK orthogonal modulation means we use the DPSK modulation for the payload, and the ASK for the label. Normally, the label has lower bit rate than the payload.

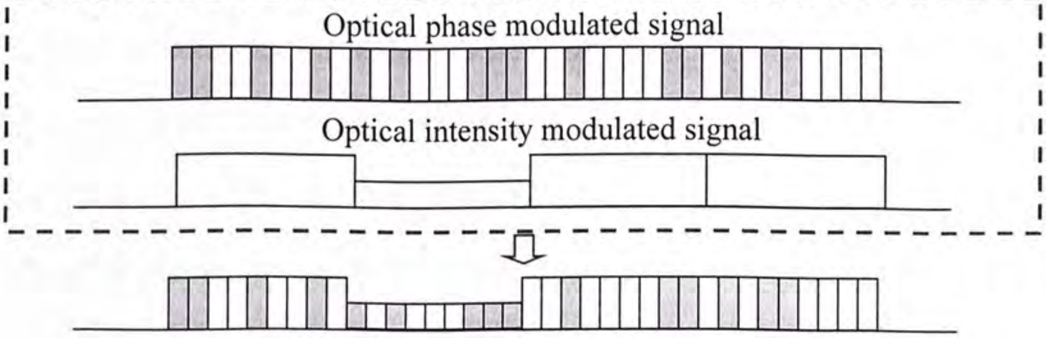


Fig 1.5 PSK/ASK optical orthogonal modulated signal

The low-bit-rate label can be used to carry the control signal. There are many applications that can make use of orthogonal modulation schemes, such as supervisory information dissemination and optical label swapping. The background of these two applications will be discussed in the following sections.

1.2. All-Optical Packet Switching

In today's telecommunication networks, packet-based data traffic is growing rapidly and is expected to overtake the circuit-switched traffic. It is considered to be more efficient to carry IP packets directly over WDM channels in data transport networks, avoiding using synchronous digital hierarchy (SDH) or asynchronous transmission mode (ATM) as the intermediate layers. With the growth of the traffic and the network complexity, how to distinguish and forward individual data streams in the middle network nodes becomes the bottleneck problem of today's optical communication networks. Compatible with wavelength division multiplexed (WDM) transmission, packet routing and forwarding operations at terabit/s should be supported in next generation all-optical Internet Protocol (IP) routing networks. In addition to the speed requirement, most of the packets are of small size (50% of them are less than 522bytes) and of various types of protocols. New technologies which can handle routing and forwarding of small packets at Giga-packets/s or above with low latency while supporting updated IP routing protocols such as Multiprotocol Label Swapping (MPLS) [3] are desirable. All-Optical Label Swapping (AOLS) is a suitable candidate. The packet-by-packet routing and forwarding functions of MPLS can be implemented directly in the optical layer. Fig 1.6 illustrates an optical AOLS core network.

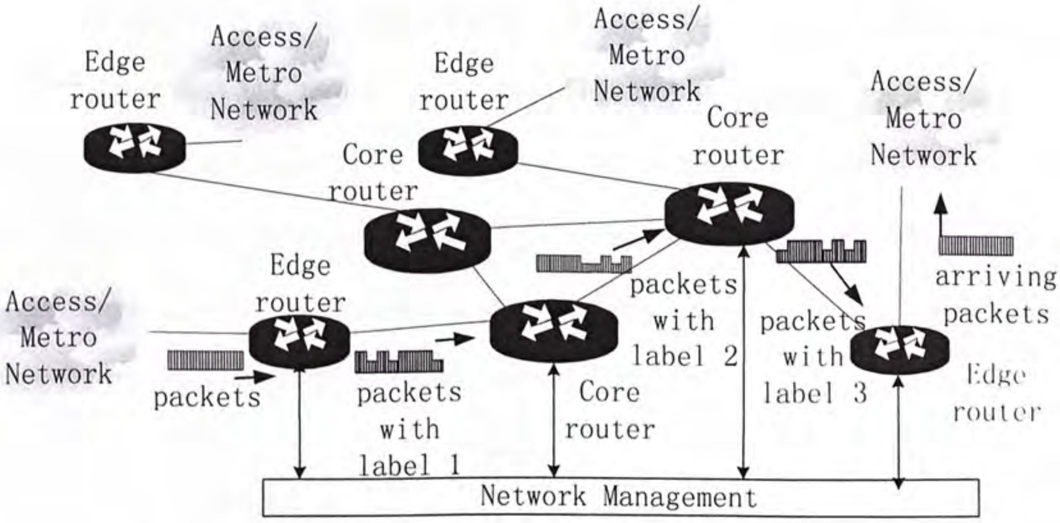


Fig 1.6 All-Optical labeling swapping in IP-Over-WDM network

At an ingress router IP packets enter the core network and are labeled there. In addition to the wavelength label, a second level optical label is necessary for provisioning, maintaining, and restoring switched light-paths. Packet forwarding and label updating are done at the core router in each hop according to this second-level optical label. When exiting from an egress router, the label is removed. Several technologies for packet swapping and forwarding at core routers have been proposed [4, 5, 6, 7].

1.2.1 AOLS Using Subcarrier Labels

All-optical label swapping with wavelength conversion and subcarrier multiplexed (SCM) addressing for WDM-IP networks [5] was first demonstrated in 1999 by D. J. Blumenthal, University of California at Santa Barbara. Based on cascaded semiconductor optical amplifiers, this module performed the functions of payload 2R regeneration, double sideband subcarrier label removal and rewriting. Other modules such as fiber-loop-mirror (FLM) [4], fiber bragg grating filter (FBG) [6] and Lyot-Sagnac filter [7] etc. were employed to realize the label regeneration. Fig 1.7 explains the theoretical setup of the subcarrier multiplexed AOLS. Label information is carried on out-of-band subcarriers. By employing accurate band-pass filters, the label information can be extracted and renewed.

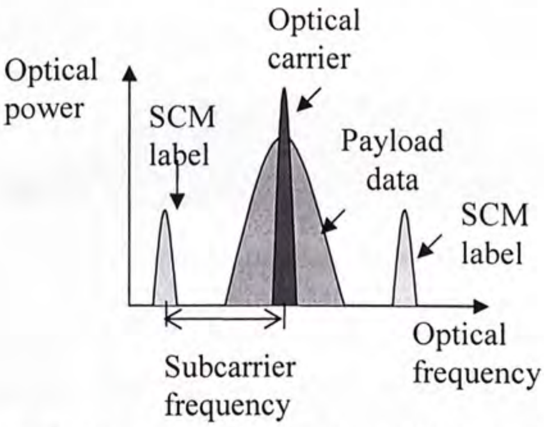


Fig 1.7 Subcarrier multiplexed (SCM) optical label

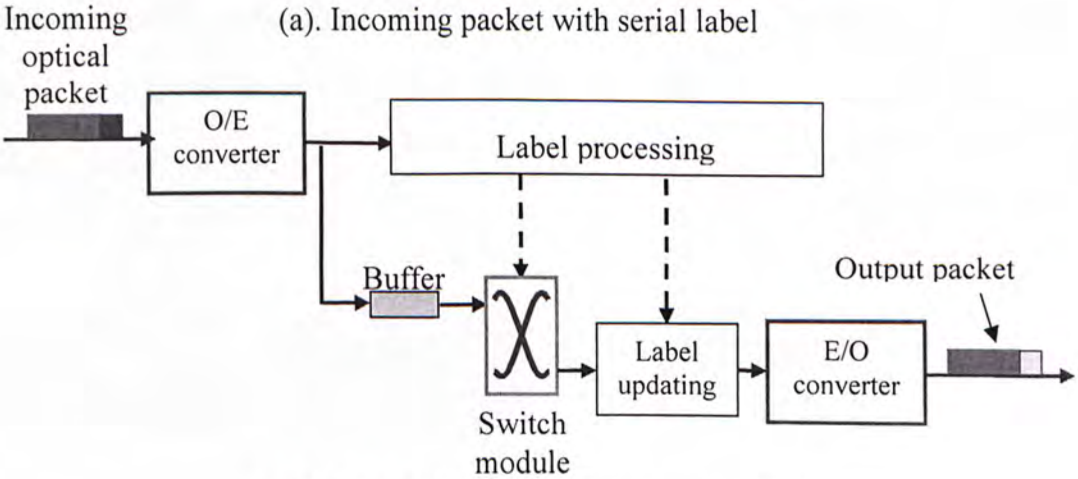
To relax the strict requirement on the filter used to filter out the subcarrier sidebands, optical subcarrier labeling schemes employing single-sideband were demonstrated [8, 9, 10]. Subcarrier multiplexed AOLS has some draw-backs: the payload suffers from the side-band label signal; the label regeneration module is complicated and is not cost-effective.

1.2.2 Serial Labels

Serial label is originally used in electrical IP packet switching networks. A few bits are attached to the packet header so as to carry the label information.

Intermediate network nodes only need to process this header to decide the output port for this packet. The original optical bit serial label swapping is shown in Fig 1.8. The label is placed ahead of the payload (Fig 1.8 (a)). Optical/Electrical (O/E) converters were used to convert the optical packets to electrical ones. The data transparency was sacrificed in this scheme. Meanwhile, in optical systems, the bit rate is of several orders higher. So this serial label scheme would encounter processing speed problem at the electrical modules.

(a). Incoming packet with serial label



(b). Optical label swapping using serial label

Fig 1.8 Optical packet swapping employing serial label and O/E/O conversions

Several optical bit serial labeling swapping schemes have been demonstrated. Some of them employed differential phase-shift keying encoded labels [11, 12]. Although the label could be easily extracted, the label processing speed was still at 10-Gb/s, which was too high to be cost-effective. Header recognition using phase coded superstructured fiber bragg gratings [13] and label swapping together with wavelength conversion of multiple WDM channels at 10 Gb/s using PPLN waveguides as λ-shifters [14] have been investigated. These schemes required synchronous header removal and insertion when updating the label, which was not practical in packet by packet swapping.

1.2.3 Orthogonal Modulated Labels

Orthogonal modulation schemes carry two in band signal streams at the same time. This feature enables labeling swapping on the optical layer by regarding one of the streams as the label and the other one as the payload. Compared with other labeling schemes, orthogonal modulation has simpler configuration and higher flexibility. Fig 1.9 shows the demonstration of orthogonal modulation used in all-optical label swapping.

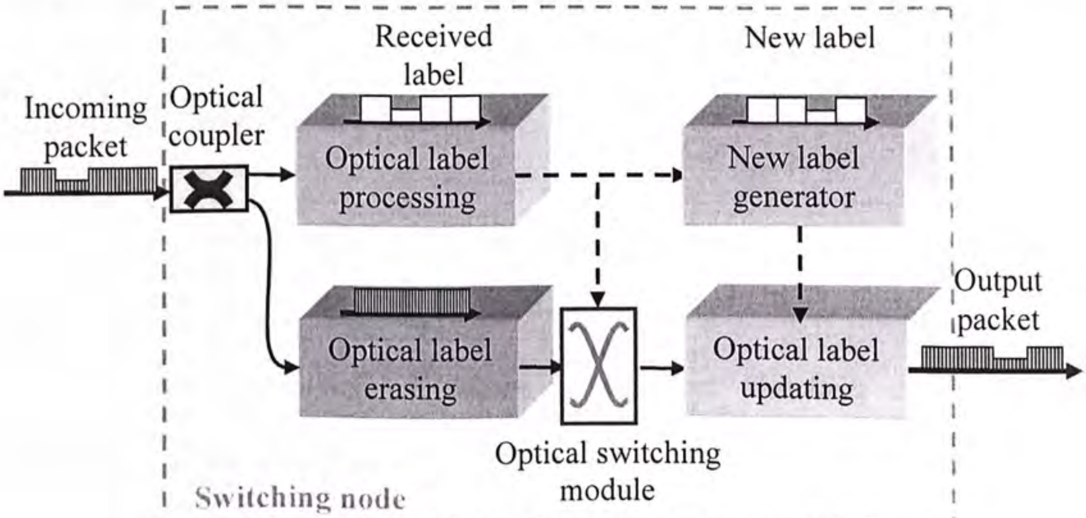


Fig 1.9 All-optical label swapping using orthogonal modulation scheme

The incoming packets are split into two arms at the switching node, one for label processing and the other for payload forwarding. The packets are switched in the optical layer so that the transparency is guaranteed. Multi-protocol transmission can be supported without any additional components. Lower bit rate label is usually applied without the strict limitation on the bit length, thus avoids using high speed electrical components for label processing. We will go into further details in chapter 2 and chapter 3 about the proposed realization of label swapping using orthogonal modulation.

1.3. Optical Supervisory Control

To facilitate the network management, supervisory schemes are required to monitor the working status and performance of all network elements. There are mainly three kinds of supervisory control in different purposes: the optical cross-connect (OXC) supervisory schemes, the optical amplifier supervisory schemes and the system supervisory schemes.

1.3.1 OXC Supervisory Schemes

Optical cross-connects (OXC's) route wavelength channels from various sources to their own destinations according to the higher layer routing setting. To avoid the possible component failure or incorrect switching caused by the malfunction of the optical switches, optical supervisory control is used in the OXC's to detect the routing failure in the optical layer. There are several proposed OXC supervisory schemes employing pilot tone [15, 16]. Fig 1.10 illustrates the configuration of the scheme in [15].

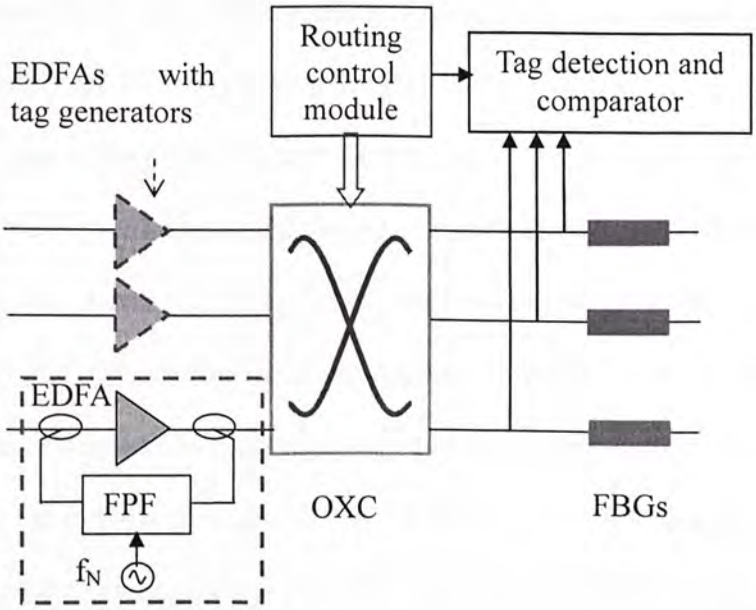


Fig 1.10 OXC supervisory schemes using frequency pilot tone

The input fiber was assigned a unique identification (ID) by adding a frequency tag on the unused amplified spontaneous emission (ASE) of the erbium-doped fiber amplifier (EDFA). By changing the modulation frequency f_i (i=1, 2, 3…N) of the scanning Fabry-Perot filter (FPF), unique tags were obtained for each input fiber. The tags were detected at the output ports and compared with the switch-setting information stored in the routing control module. Thus failures or mis-routing could be detected immediately. The routing ID could be removed [16] to support scalable optical-path supervision.

1.3.2 Optical Amplifier Supervisory Schemes

In the WDM transmission links, multiple inline optical amplifiers are used to improve the transmission span and signal quality. The optical amplifier supervisory schemes are used to identify the degraded or failed optical amplifiers in the optical layer. The basic idea is to allocate a special ID to each optical amplifier in the transmission line. When the optical signals pass though an amplifier, the ID information together with the healthy status of this optical amplifier is added. At the receiving side, the status of all optical amplifiers in the path can be monitored. Previous proposed schemes include modulating a pump laser or the amplified spontaneous emission (ASE) with telemetry signal [17,18] at the optical amplifier, using optical time-domain reflectometry (OTDR) [19,20], passive surveillance schemes using fiber bragg gratings with ASE [21,22] and optical feedback loop with unique loop length for each EDFA [23], etc. Optical amplifier supervisory schemes provide efficient ways to monitor the transmission span between two network nodes.

1.3.3 Optical Supervisory Schemes for Transmission Networks

The supervisory schemes for optical amplifiers and OXC's are mostly designed for single network module or component. In order to achieve more complicated network management functions, another kind of supervisory schemes is needed to disseminate the network information between the major router nodes so that unique operation, administration, and maintenance (OAM) functions required in WDM networks can be realized. Previously proposed approaches include using a separate control channel [24] and optical subcarriers [25, 26, 27, 28].

Using a dedicated physical channel link for monitoring may not possible due to the limited available resources. Employing a separate WDM channel may complicate the system design and require dedicated transceiver. Subcarrier modulation provides transparency supervisory information dissemination, but there are still some shortages. Cross talk occurs between the subcarrier signal and the line signal, thus limits the subcarrier modulation index to a few percentage points to maintain an acceptable SNR penalty (less than 1 dB). Moreover, accurate optical band-pass filters (BPFs) are required in each inline node to extract or insert the supervisory signal.

Instead of using a separate wavelength or subcarrier channel, we may employ an orthogonal modulation scheme in which the relatively low-speed supervisory data can be superimposed onto the high-speed payload data. In this way, we can save the network resources and can keep the complexity of the transmission nodes low.

1.4. Thesis Organization

This chapter gives a general introduction on optical modulation formats and the background of the applications that we will discuss in this thesis. Chapter 2 studies the previous researches in optical orthogonal modulation. The optical DPSK/ASK orthogonal modulation scheme will be proposed in Chapter 3. Numerical simulation, experimental demonstration and characterization of the proposed scheme will be presented to evaluate the performance. Chapter 4 gives the conclusions of this thesis.

Chapter 2:

Previous Studies on Optical Orthogonal Modulation

We have discussed the basic modulation formats in chapter 1. With the characteristics of these formats taken into consideration, the possible orthogonal modulation schemes are ASK/DPSK, DPSK/ASK, ASK/FSK and FSK/ASK. Several applications using optical orthogonal modulations have been demonstrated.

2.1. Orthogonal Modulation Used in STARNET

STARNET [29] was a broadband optical WDM local area network (LAN) which could support traffic with a wide range of speed and continuity characteristics. At the Optical Communications Research Laboratory (OCRL) of Stanford University, a packet-switched STARNET computer interface had been designed and implemented with the average transmit and receive throughputs of 685 Mb/s and 571 Mb/s, respectively. OCRL had already demonstrated several combined modulation techniques such as frequency shift-keying and amplitude shift-keying (FSK/ASK) [30], phase shift-keying and amplitude shift-keying (PSK/ASK) [31], and differential phase shift-keying and amplitude shift-keying (DPSK/ASK) [32]. The combined ASK/DPSK modulation had the receiver sensitivity better than -32 dBm. Although the orthogonal modulation schemes used in STARNET were at low bit rate and the diameter of the network was small (about 5km), the successful demonstration of carrying two optical signals simultaneously showed its advantages in the simplicity of the network nodes and good receiver sensitivities of both of the orthogonally modulated signals.

2.2. AOLS in IP-over-WDM Networks Employing Orthogonal Modulation

In chapter 1 we described several previously proposed labeling schemes used in AOLS. Employing orthogonal modulation label is an important and promising way. Without limitation on the label length, advanced routing and traffic engineering and more comprehensive network architectures requiring multiple addressing levels for Quality-of-Service (QoS) can be supported.

2.2.1 DPSK Labels on ASK Payload

Two-level optical labeling in IP-over-WDM networks was first proposed in ECOC 2001 by Ton Koonen, IST project STOLAS [33]. The label information was DPSK modulated on the phase, and the payload was modulated on the intensity of the carrier [33, 34]. Transmission performance and wavelength conversion were investigated by Nan Chi at Technical University of Denmark later on [35, 36, 37]. The configuration of the transmitter of the proposed ASK/DPSK scheme is shown in Fig 2.1 [33].

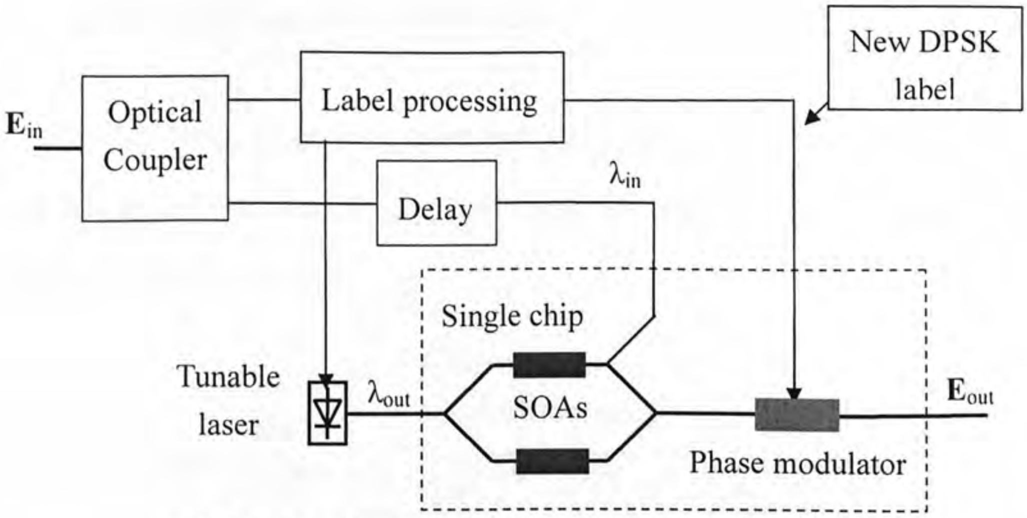


Fig 2.1 Two-level optical label swapper using DPSK/ASK orthogonal modulation

The optical label swapping was accomplished at core routers. The incoming packet payload was at 10 Gbit/s and the DPSK label information was at 155 Mbit/s. An optical coupler spit the incoming optical packet into two streams, one for label processing and the other for packet swapping and forwarding. The label processing unit decoded the DPSK signal, and used this information to decide which wavelength to swap to for the next hop, and then generated a new label to be encoded by the optical phase modulator. By using a fast tunable laser and a Mach Zehnder Interferometer (MZI) with semiconductor optical amplifiers (SOAs) in both arms, wavelength swapping was realized. The cross-phase modulation in the SOAs transferred the payload intensity modulation from the incoming wavelength to the outgoing wavelength set by the tunable laser. The DPSK label was removed in the MZI. New label was added in the subsequent phase modulator. In this scheme, the intensity modulation and phase modulation were integrated onto a single chip.

2.2.2 FSK Labels on ASK Payload

Besides DPSK label, FSK label (Fig 2.2) [34] could also be employed. The optical phase modulator was unnecessary, but it required that the tunable laser diode could be efficiently FSK modulated.

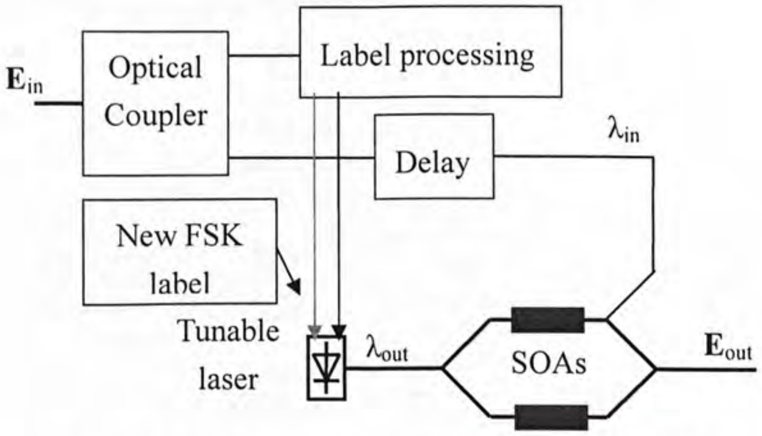


Fig 2.2 Two-level optical label swapper using ASK/FSK orthogonal modulation

Transmission and wavelength swapping performance of both ASK/DPSK and ASK/FSK schemes were evaluated by simulation [34, 35]. Parameters such as fiber span, extinction ratio, coupling ratio and laser linewidth were considered. It was found that the self phase modulation of the ASK payload due to the fiber nonlinear effect would give rise to phase noise on the DPSK label. On the other hand, the phase noise could be converted into the intensity fluctuation of payload through fiber dispersion. Therefore an optimum extinction ratio (ER) should be maintained. Simulation result showed that compared with the ASK/FSK system, the performance of the ASK/DPSK system was significantly more sensitive to the laser extinction ratio, while the overall receiver sensitivities of these two systems were similar.

2.2.3 Experimental Result of ASK/DPSK Label Swapping

Experimental research of ASK/DPSK label swapping was carried out in [36,37]. The 10-Gb/s ASK payload and 2.5-Gb/s DPSK label were transmitted simultaneously over an 80-km nonzero dispersion-shifted fiber (NZDSF) with less than 1-dB power penalty. The transmission experiment setup is shown in Fig 2.3.

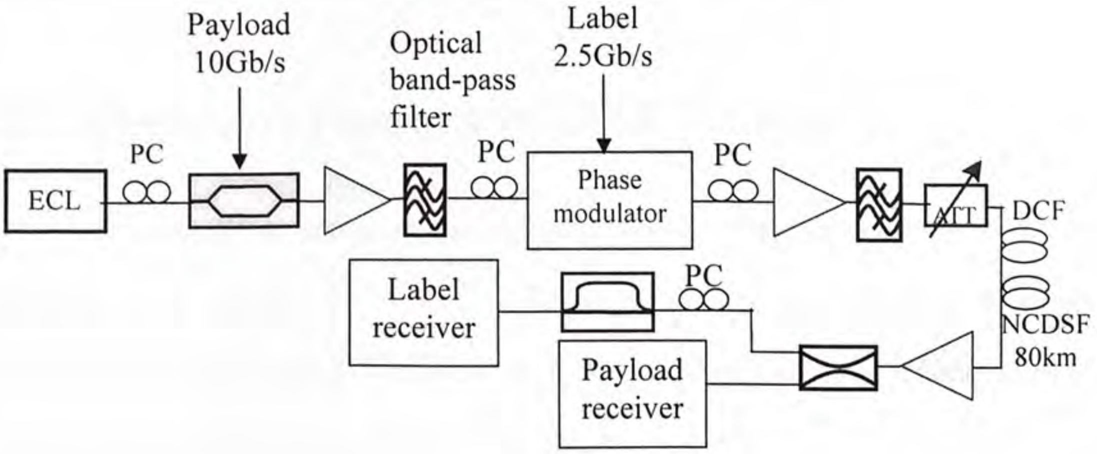


Fig 2.3 Experimental demonstration of ASK/DPSK orthogonal modulation

A 1555.7 nm external cavity laser (ECL) was used as the light source. The 10-Gb/s payload and the 2.5-Gb/s label were modulated by a Mach–Zehnder modulator (MZM) and the subsequent phase modulator respectively. An optical delay interferometer with one bit delay was used to recover the label signal at the receiver. The transmission span was 80-km nonzero dispersion-shifted fiber (NZDSF), with a matching length of dispersion compensation fiber (DCF) to fully compensate the chromatic dispersion in the NZDSF. A tradeoff between the extinction ratio (ER) requirements for the payload and the label was observed. The ER of intensity modulation was about 3 dB in transmission and wavelength conversion. About 1-dB power penalty was observed after transmission. Compared to 50-km SMF fiber span transmission [36], using NZDSF improved the performance by about 5 dB [37]. The wavelength conversion was realized by using four-wave mixing (FWM) in fibers. Unlike previous schemes which removed and updated the label signal, this one converted the wavelength while keeping the DPSK label unaltered.

2.3. Quaternary Optical ASK-DPSK Modulation

An ASK-DPSK optical modulation scheme with direct detection (ASK-DPSK/DD) [38] was proposed in 2003 by Michael Ohm in University of Stuttgart. This scheme was designed for high speed communication by carrying two bits in one symbol. The modulator configuration is illustrated in Fig 2.4.

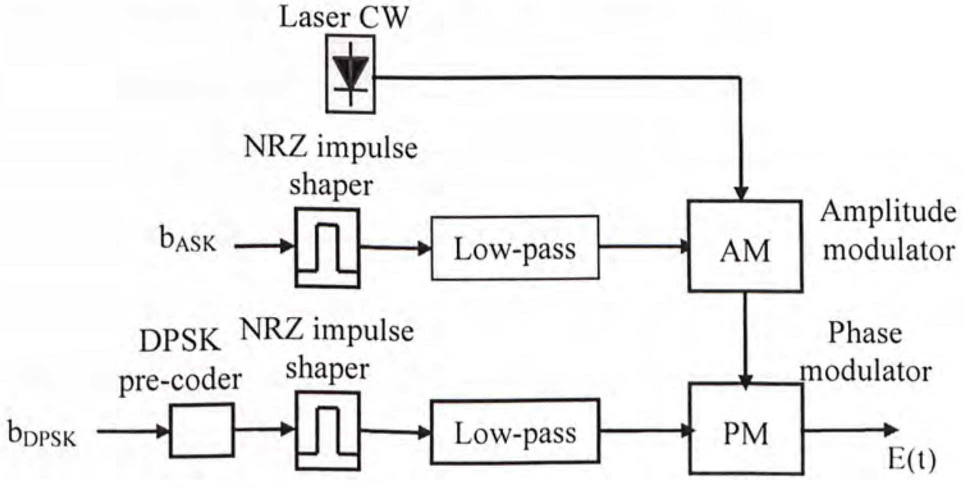


Fig 2.4 ASK-DPSK modulator configuration

Direct detections of both ASK and DPSK signal were used in the receiving part. For

DPSK signal, balanced detection improved the sensitivity. System performance of 80-Gb/s ASK-DPSK/DD, in which both the ASK signal and the DPSK signal were at the bit rate of 40 Gb/s respectively, had been investigated numerically. It showed that this scheme could double the spectral efficiency by adding only moderate complexity, compared to intensity modulation with direct detection (IM/DD).

2.4. Conclusion

In this chapter we introduced the previous studies in optical orthogonal modulation. As ASK format was commonly used in WDM networks, these proposed schemes all used ASK as the high speed payload. Numerical and experimental investigations had been carried out to measure the performance of the modulation schemes. Among the observed tradeoffs, the extinction ratio was a key parameter that affected the system performance. Simulation results and experimental demonstrations illustrated that an optimized operation condition could be obtained. The transmission performance met the practical requirements. The routing nodes would be much simpler compared to other labeling schemes such as serial labeling and subcarrier labeling. However, there were still some shortcomings. DPSK signal would be affected by the rapid amplitude fluctuations due to the comparably high extinction ratio of the ASK payload. To match with the lower bit rate of the label, the delay line would be so long that the DPSK label demodulator had poor temperature stability. Meanwhile, the dispersion effect would greatly degrade ASK payload performance, thus careful dispersion compensation was necessary.

Chapter 3:

Optical DPSK/ASK Orthogonal Modulation Scheme

3.1. Motivation

As we have seen in chapter 1, optical network is the trend of communication networks. AOLS is suitable to solve the bottle-neck problem existing in the information switching. Among the labeling schemes, using an in-band orthogonal modulated label has more advantages. Previous optical orthogonal modulation schemes employed DPSK format as the low speed label. However, it required more complicated label transmitter circuits at each router node and it was not practical to implement relatively low-speed optical DPSK demodulators. Since optical DPSK has recently attracted much interest for WDM systems because of its high robustness in the presence of fiber nonlinearities, we come up with the idea of using DPSK format as the high speed payload. The constant intensity of DPSK payload can improve the system performance in means of dispersion, and it facilitates the addition or extraction of the ASK label information. By using DPSK format for high speed payload, the demodulator will be more simple and stable. On the other hand, using DPSK can suppress the Cross-Gain modulation in SOA compared to ASK modulation format. The cross-gain modulation effect is due to the relatively low saturation energy and the gain recovery time in the SOA comparable with the bit period. DPSK modulation format has constant intensity, so that it is immune to crosstalk caused by the cross-gain modulation effect theoretically. This was also proved by experiments [39].

Inspired with these advantages, we proposed our DPSK/ASK modulation scheme for all-optical label swapping and supervisory information dissemination and investigated both numerically and experimentally the optimized operation conditions for such orthogonal modulation. In addition, label swapping, including label adding and removing, was also successfully demonstrated.

3.2. Proposed Optical DPSK/ASK Orthogonal Modulation Scheme

In this chapter, we propose to employ a simple scheme using DPSK/ASK orthogonal modulation, where the high-speed payload data are encoded in the optical DPSK format while the label information is directly intensity (ASK) modulated onto the constant intensity profile of the payload. This scheme can be applied as a supervisory control method or labeling swapping technology. It is flexible because the bit rate and the extinction ratio of the ASK signal can be adjusted to fit different application requirements of the control information.

As the ASK label data is usually of much lower bit rate (<2.5-Gb/s), the high–speed (~10-Gb/s) optical DPSK payload signal may suffer from slow amplitude fluctuation. One feasible solution is to reduce and optimize the extinction ratio of the ASK signal in such a way that both the high-speed optical DPSK payload signal and the low-speed ASK signal can still achieve error-free performance with minimal induced power penalty to each other. As the ASK signal is at low bit-rate and thus its intrinsic low receiver sensitivity can provide large tolerance to its degraded extinction ratio. We assume the high-speed optical DPSK signal is operating at 10-Gb/s and its performance is examined in the presence of the ASK signal under different bit rates and extinction ratios.

3.3. DPSK/ASK Orthogonal Modulation Modules

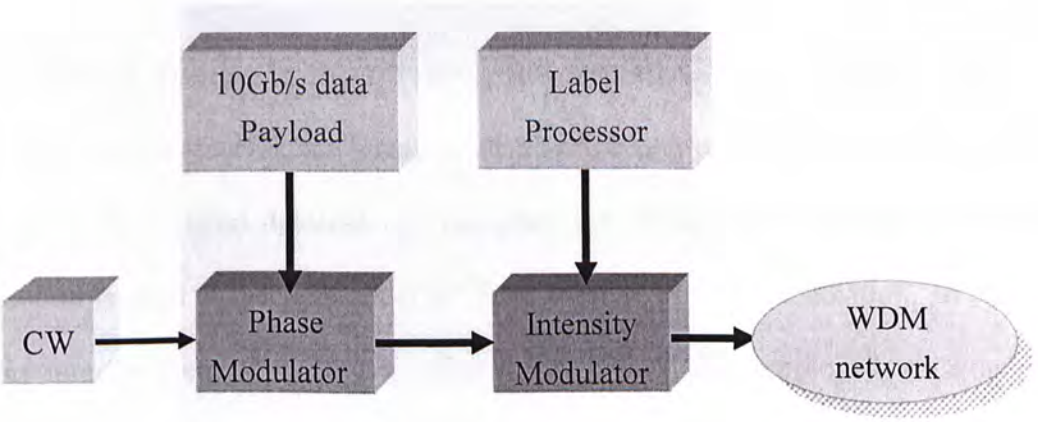


Fig 3.1 ASK/DPSK Transmitter

Fig 3.1 shows the block diagram of the DPSK/ASK transmitter. An optical phase modulator and an optical intensity modulator are employed. The CW light is first modulated with the 10-Gb/s payload data in optical DPSK format, via the optical phase modulator. The resultant payload signal, which exhibits a constant intensity profile, will then be modulated with the lower-speed ASK data via the optical intensity modulator. As a result, both the high-speed payload and the label can be transmitted over the WDM network simultaneously.

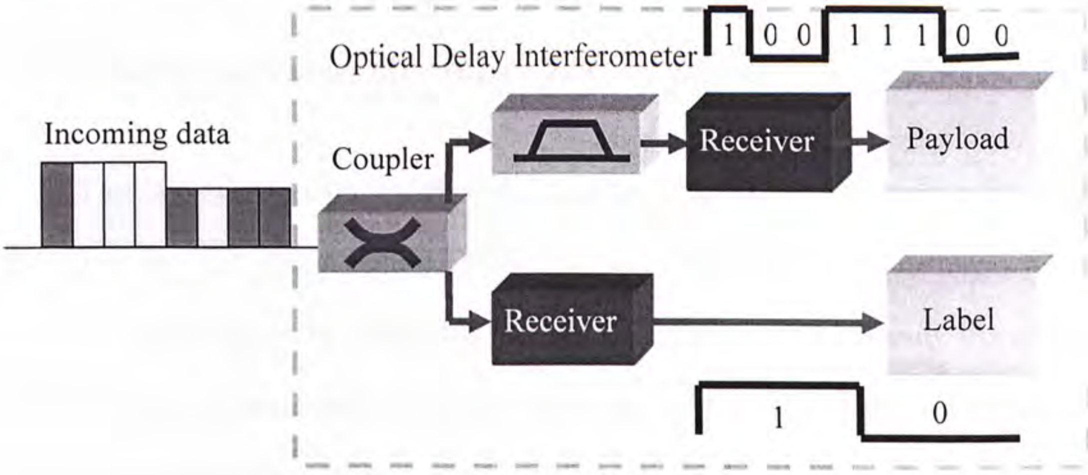


Fig 3.2 Demodulation and reception block

A block diagram in Fig 3.2 shows how the orthogonally modulated signal is decoded. At the receiver, the incoming data is split into two arms by a coupler. One for ASK label signal detected and the other for DPSK payload reception. Direct detection is used at the ASK receiver. For DPSK payload demodulation, an optical delay interferometer with the arm delay of one bit period is employed. An example of data decoding is shown in Fig 3.2. The one bits and zero bits in the incoming payload data have a phase difference π. The envelope of the incoming data is the slow ASK signal. The corresponding electrical signals are obtained at the receivers.

3.4. Numerical Simulations

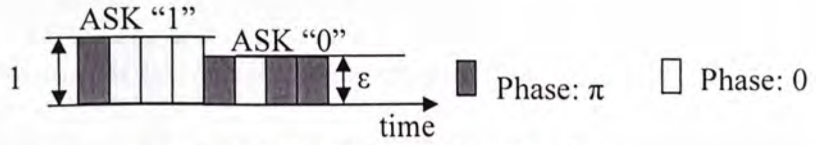
In this section, we study the mathematical model of the DPSK/ASK orthogonal modulation format. Moreover, we have performed simulation using a commercial simulation software, OptSIM^{TM} to investigate and optimize the performance of such orthogonal modulation scheme under different operating conditions.

3.4.1 Mathematical Model of DPSK/ASK Signal

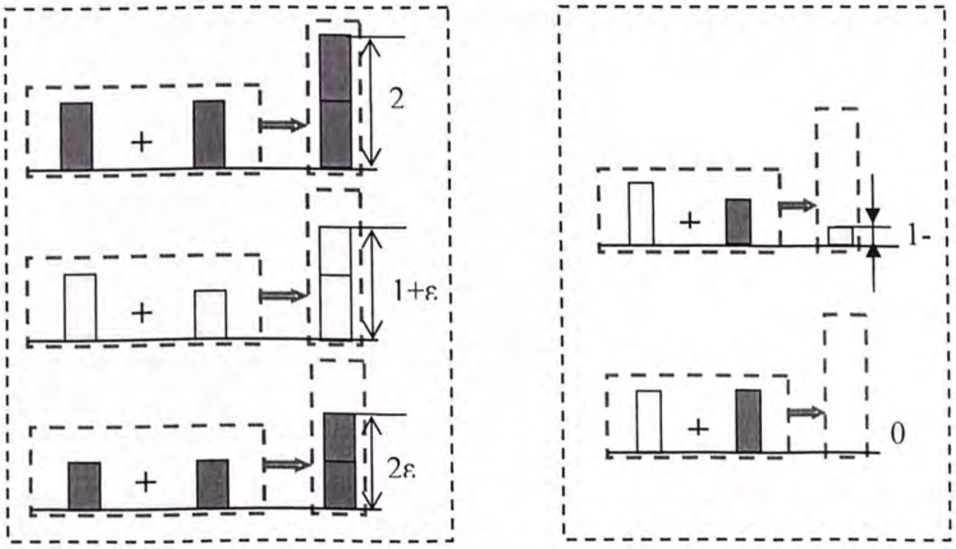
The low-speed ASK signal will definitely degrade the signal-to-noise ratio (SNR) of the high-speed optical DPSK payload. Therefore, the extinction ratio of the ASK signal has to be controlled so as to limit the possible intensity fluctuation induced to the constant intensity profile of the optical DPSK payload, which may, in turn, induce the system degradation. On the other hand, in order to ensure that the ASK signal can be detected by an ordinary optical receiver, the extinction ratio of the ASK signal should be large enough. Assume that the DPSK data is 10 Gb/s, and the ASK data bit rate is (10/k) Gb/s, where k is a positive non-zero integer. Equation (1) expresses the DPSK/ASK orthogonal modulation signal, $S(t)$, with a finite ASK extinction ratio [$-10\log_{10}(\varepsilon)$] $(0<\varepsilon<1)$, where ε is defined as the optical power ratio of the zero level to the one-level of the ASK signal after being superimposed onto the high-speed optical DPSK payload.

$$S(t)=\sum_{n=-\infty}^{+\infty}\left\{[\varepsilon+(1-\varepsilon)q_{s,n}g_s(t-nT_s)]\cdot\sum_{m=1}^{k}\exp[i\cdot\pi\cdot q_{d,kn+m}g_d(t-(kn+m)T_d)]\right\} \tag{1}$$

where $q_{s,n}$ and $q_{d,n}$ are the n^{th} bit value of the ASK data and the optical DPSK payload, respectively; T_s and T_d are their respective bit periods while $g_s(\cdot)$ and $g_d(\cdot)$ are their respective pulse shapes. The ASK pulse shape, $g_s(\cdot)$, is assumed to be non-return-to-zero (NRZ). The intensity level of the optical DPSK payload is normalized to 1. Fig 3.3 illustrates the possible interferometric output intensity level of the received DPSK signal. For convenience, we suppose that in the incoming data (Fig 3.3(a)) the one bits are with π phase and the zero ones are with 0 phase. For the ASK envelope, the intensity of bit "1" is normalized to 1, and for the "0" bit is ε, as shown in Fig 3.3(a). The interferometric result of the two adjacent bits is the DPSK output. As described in Fig 3.3 (b) and (c), there are five possible intensity levels of the output signal, assuming no noise is present. Because of the degradation caused by the ASK modulation index, the smallest output intensity level is 2ε for an output bit "1" and (1-ε) for an output bit "0".



(a) DPSK/ASK modulated packet



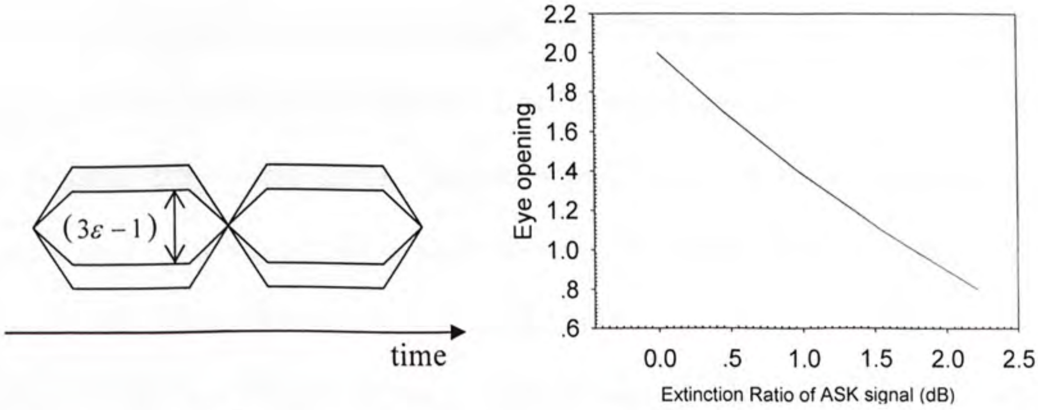
(b) Output "1" (c) Output "0"

Fig 3.3 Possible intensity levels of the demodulated output of the optical DPSK payload.

10Gb/s Data q_d	ASK Data $q_{s,n}, q_{s,n+1}$	Intensity level of the demodulated optical DPSK payload
0	1,1	2
	1,0 and 0,1	$1+\varepsilon$
	0,0	2ε
1	0,1 and 1,0	$1-\varepsilon$
	0,0 and 1,1	0

Table 1

Table 1 lists the possible cases and the intensity levels of the demodulated output of the optical DPSK payload.From Table 1, it can be deduced that the worst case eye-opening of the demodulated optical DPSK payload is (3ε-1), as illustrated in Fig 3.4(a). Fig 3.4(b) shows the relation of the eye-opening of the demodulated optical DPSK payload against different values of the ASK extinction ratio of the label.



(a) (b)

Fig 3.4 (a) Definition of eye opening;
(b) The eye-opening of the 10-Gb/s optical DPSK payload vs the ASK extinction

3.4.2 Simulation Model

We have used a commercial simulation software, OptSIM^{TM}, to investigate and optimize the performance of the proposed DPSK/ASK orthogonal modulation scheme under different operating conditions.

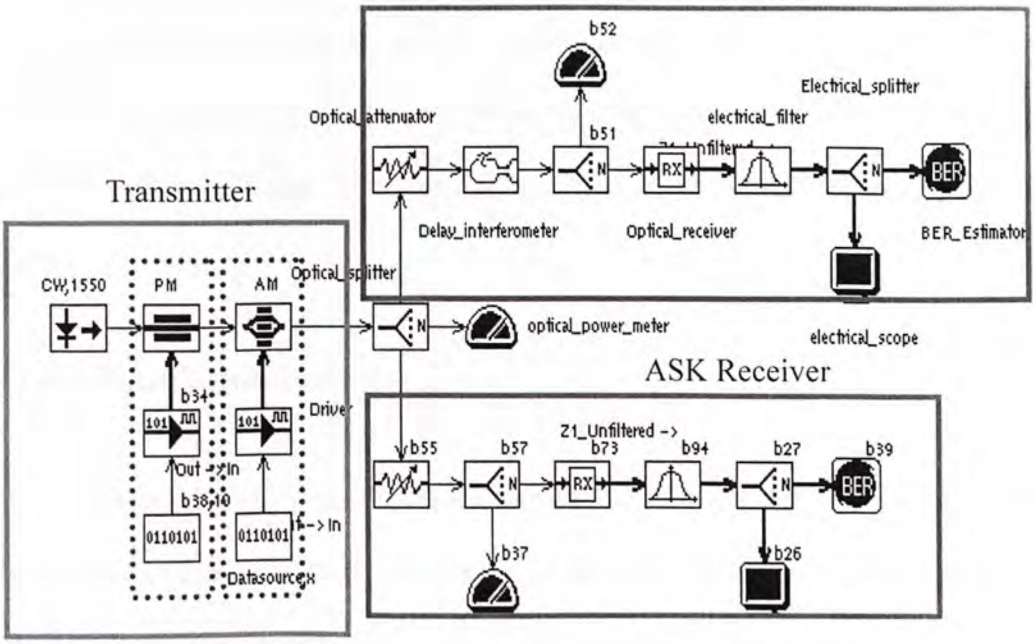


Fig 3.5 Simulation model

Fig 3.5 shows the simulation model. The CW light at 1550nm was modulated by an optical phase modulator with the 10-Gb/s pseudo-random bit sequence (PRBS) to generate the optical DPSK payload signal. It was then modulated with a lower-speed ASK signal, via a Mach-Zehnder modulator (MZM), whose driving voltage was controlled by the modulator driver. By appropriately setting the driving voltage levels for "1" and "0" bits, different extinction ratios for the ASK signal could be achieved. The resultant DPSK/ASK orthogonal modulated signal was then split into two streams. For the upper arm, the DPSK signal was demodulated by a 100-ps delay-interferometer and was detected by a high speed receiver, followed by a 10-Gb/s Bessel filter before measuring the bit error rate (BER). At the lower arm, the ASK signal was directly detected by an optical PIN receiver, followed by a RF Bessel filter before measuring the BER. The bandwidth of the Bessel filter was chosen to match the bit-rate of the ASK signal so as to limit the receiver noise. The optical powers of the signals at both arms were adjusted, via the optical attenuators, for BER measurements. All components were assumed to be ideal that no insertion loss and noise induced. The couplers also had no power split loss for each output port.

3.4.3 Simulation Results

We have performed the simulation of the DPSK/ASK signal when the ASK data was at three different bit rates: 622-Mb/s, 1.244-Gb/s and 2.488-Gb/s. NRZ pulse shape was used for both ASK and DPSK modulations. The receiver sensitivities (at BER=10^{-9}) of both the 10-Gb/s optical DPSK payload and the ASK signal were obtained, under different extinction ratios (ER) of the ASK signal. The results are shown in Fig 3.6.

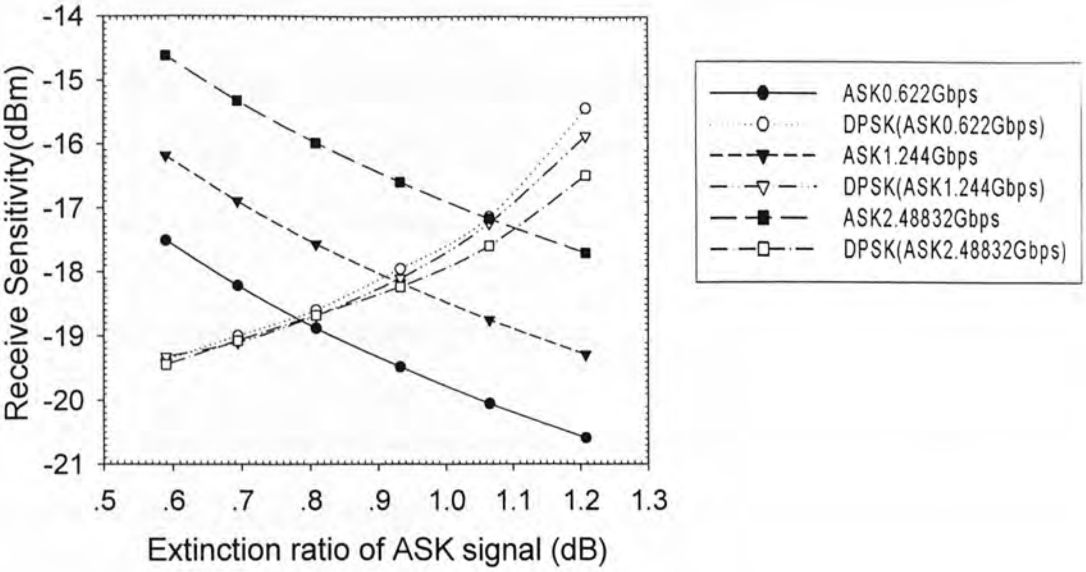


Fig 3.6: Simulation results: receiver sensitivities of the 10-Gb/s optical DPSK signal with the ASK signal at various bit-rates against different ASK extinction ratios [$-10\log_{10}(\varepsilon)$].

With the increase of the ER, the receiver sensitivity of the optical DPSK payload decreased, due to the increased intensity fluctuation, while that of the ASK signal increased. At different bit rates of the ASK signal, its receiver sensitivity curves were spaced apart, about 1.5-dB difference was observed between two adjacent curves. It was due to the fact that the receiver noise had been limited by the matched receiver filter. Higher bit rate resulted in higher required minimum received power to achieve the BER=10^{-9}. On the contrary, the variations of optical DPSK signal sensitivity were small under different bit rates of ASK signal. There existed a cross-point for each DPSK-ASK curve pair, where the receiver sensitivities for both the optical DPSK signal and the ASK signal were at the minimum simultaneously. The corresponding value of the ASK extinction ratio was chosen as the optimum

ASK extinction ratio. At higher bit rates, the optimum ASK extinction ratio would be larger. According to different application requirements on the sensitivities of payload and control information, we could adjust the operation condition by using the proper ASK bit rate and extinction ratio.

3.5. Experimental Demonstration

To evaluate the real performance of our modulation scheme, experiments have been established. The results suggested that it is a promising scheme for transmitting in-band control information together with the high speed payload.

3.5.1 Experimental Setup

Fig 3.7 shows the experimental setup which is similar to the simulation model which was presented in section 3.2.

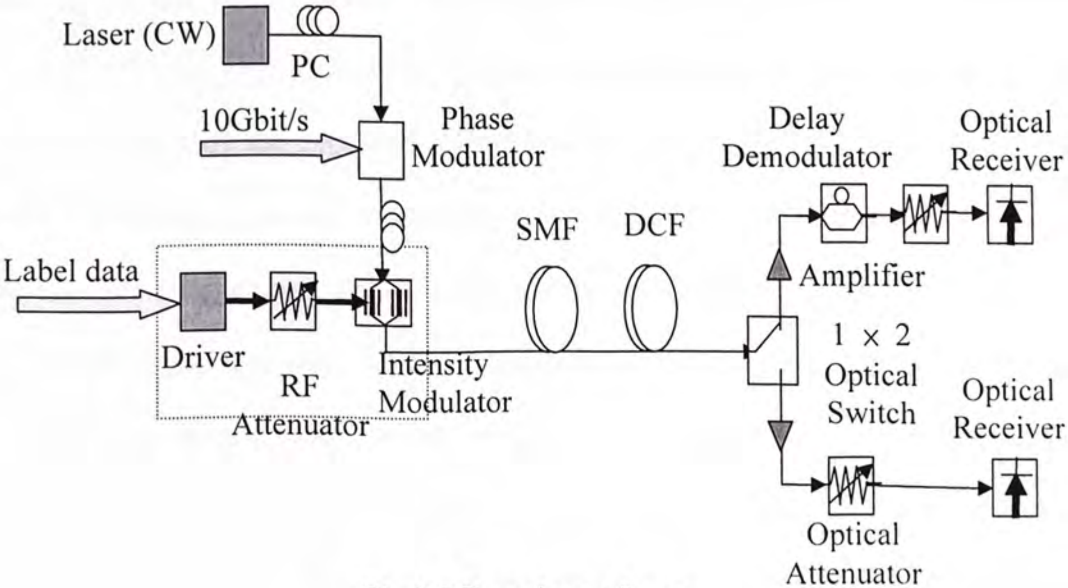


Fig 3.7 Experiment Setup

A 1550nm CW laser was used as the light source. Two polarization controllers (PC) were used to align the polarization of the carrier with the principle axis possessing maximum modulation response in the optical phase modulator (PM) and the optical intensity modulator. The PM was driven by a 10-Gb/s NRZ 2^{31}-1 pseudo random binary sequence (PRBS), while the optical intensity modulator was driven by a lower bit-rate NRZ 2^{31}-1 PRBS. From the simulation results in section 3.3, the range for ASK extinction ratio (ER) was about 1-2dB. To achieve such a small value of ER, an electrical tunable attenuator was used to adjust the driving voltage level of the ASK signal. The resultant DPSK/ASK optical signal was then fed into a piece of standard single mode fiber (SMF) for the transmission experiment (to be presented in section 3.6). To minimize the possible phase-to-intensity conversion induced by the fiber chromatic dispersion, a piece of dispersion compensating fiber (DCF) was also used. At the receiving side, the orthogonal modulated signal was fed into two receiver circuits, one for optical DPSK demodulation via a delay-interferometer with the arm delay of 94 ps, while the other one for direct detection of the optical ASK signal. To simplify the experiment setup and save the equipment, DPSK signal and ASK signal were measured separately, while keeping the same operation conditions for each sampling point. A 40-Gb/s optical PIN photon diode was used for both ASK and DPSK signal receiving. Matching low-pass filters were used to limit the receiver noise. If only intensity modulation (ASK) was performed, its receiver sensitivity (at BER=10^{-9}, 2.5-Gb/s) was measured to be -26 dBm. Similarly, when there was optical DPSK signal only, its receiver sensitivity (at BER=10^{-9}, 10-Gb/s) was measured to be -21.4 dBm.

3.5.2 Experimental Results

A proper operation bias of the intensity modulator was fixed. By changing the value of the electrical tunable attenuator, different extinction ratios were achieved. The range of the extinction ratio should be 1-2 dB referring to the simulation result. Fig 3.8 shows the experimental results of the receiver sensitivities of both the 10-Gb/s DPSK payload signal and the ASK signal under different ASK extinction ratios and different ASK bit rates. All receiver sensitivities were measured just before the receiver, at BER 10^{-9}.

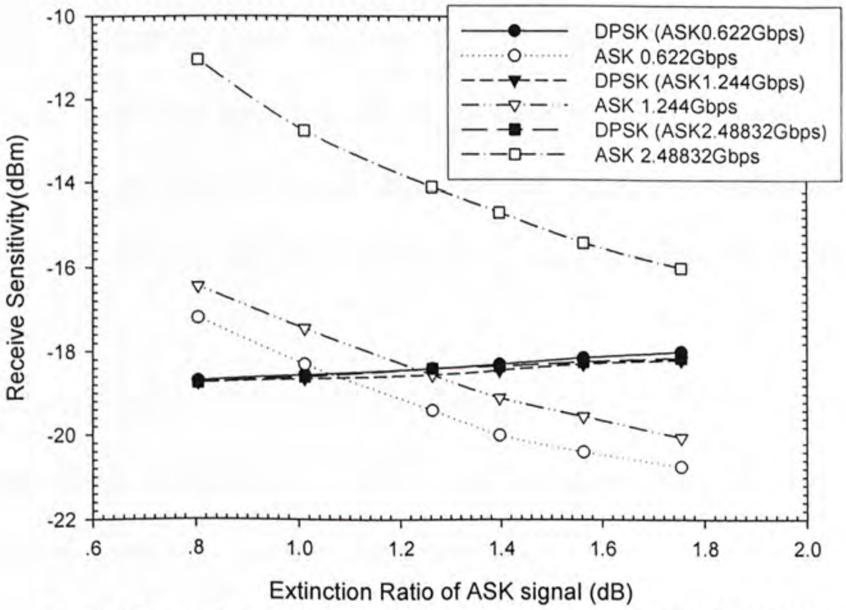


Fig 3.8 Experimental results: receiver sensitivity of the 10-Gb/s optical DPSK signal with the ASK signal at various bit-rates against different ASK extinction ratios [$-10\log_{10}(\varepsilon)$]

The trend of the curves agreed well with the simulation results presented in section 3.2.3. With the increase of the extinction ratio, the receiver sensitivities of

ASK signal increased, while those of DPSK signal decreased. As expected, cross points of DPSK curves and ASK curves were obtained. For different ASK bit rate, the cross point was different. Higher ASK bit rate required higher ER to achieve comparable performance with DPSK payload. When the ASK signal was at 622-Mb/s and 1.244-Gb/s, the receiver sensitivities were less than -18 dBm for both the 10-Gb/s optical DPSK payload and the ASK signal at their respective optimum ASK extinction ratios. When the bit rate of the ASK signal increased to 2.5-Gb/s, the phase noise induced by the optical DPSK signal became grievous and thus further degraded the system performance. On the other hand, DPSK signal was not affected by ASK bit rate because the intensity fluctuation was relatively slow and mild. However, the DPSK signal was very sensitive to the extinction ratio of the ASK signal. In our experiment, great degradation of DPSK signal sensitivity was observed while the extinction ratio of the intensity modulator drifted with temperature. To maintain an accurate result, the temperature should be maintained constant.

Fig 3.9 shows the eye diagrams of the received 622-Mb/s ASK signal, the corresponding demodulated 10-Gb/s DPSK signal and the waveform of the orthogonal modulated signal on the transmission fiber.

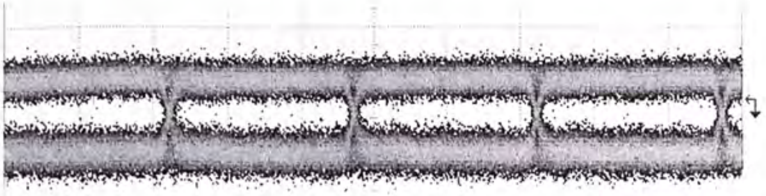


Fig 3.9 (a) Received ASK (622-Mb/s) eye diagram (640ps/div)

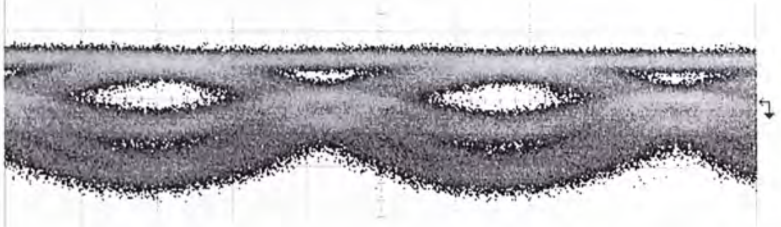


Fig 3.9 (b) Received demodulated 10-Gb/s DPSK eye diagram (25ps/div)

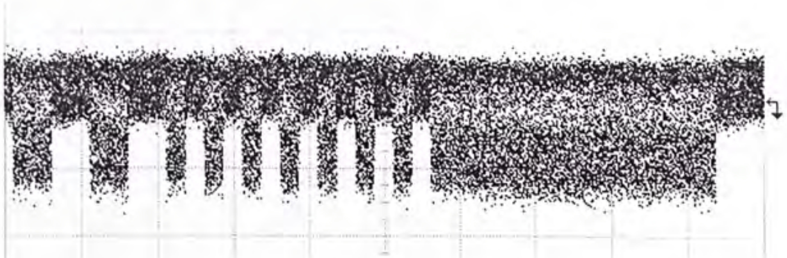


Fig 3.9 (c) Waveform of the orthogonal modulated signal on transmission fiber (1.6ns/div)

All the diagrams were inverted because there was an inverting electrical amplifier at the optical receiving module. Clear eye opening was observed of the received ASK signal (Fig 3.9 (a)). For the DPSK payload, the eye opening (Fig 3.9(b)) shows that the degradation caused by ASK modulation was acceptable. Fig 3.9 (c) shows the waveform of DPSK/ASK signal. The ASK signal was embedded as envelope of the high speed DPSK signal. Higher extinction ratio (about 3.7 dB) was chosen to show the amplitude fluctuation more clearly.

3.6. Transmission Experiment

We have also performed the transmission experiment for the DPSK/ASK signal over a 40-km standard single mode fiber (SMF). A piece of 8-km dispersion compensating fiber (DCF) was used to compensate the fiber chromatic dispersion. The bit rate of the ASK signal was chosen to be 1.244-Gb/s while that of the optical DPSK payload was 10-Gb/s. The optimal ASK extinction ratio (~1.3 dB) was chosen. BER performance of the optical DPSK data and the ASK data after transmission are depicted in Fig 3.10 and Fig 3.11, respectively.

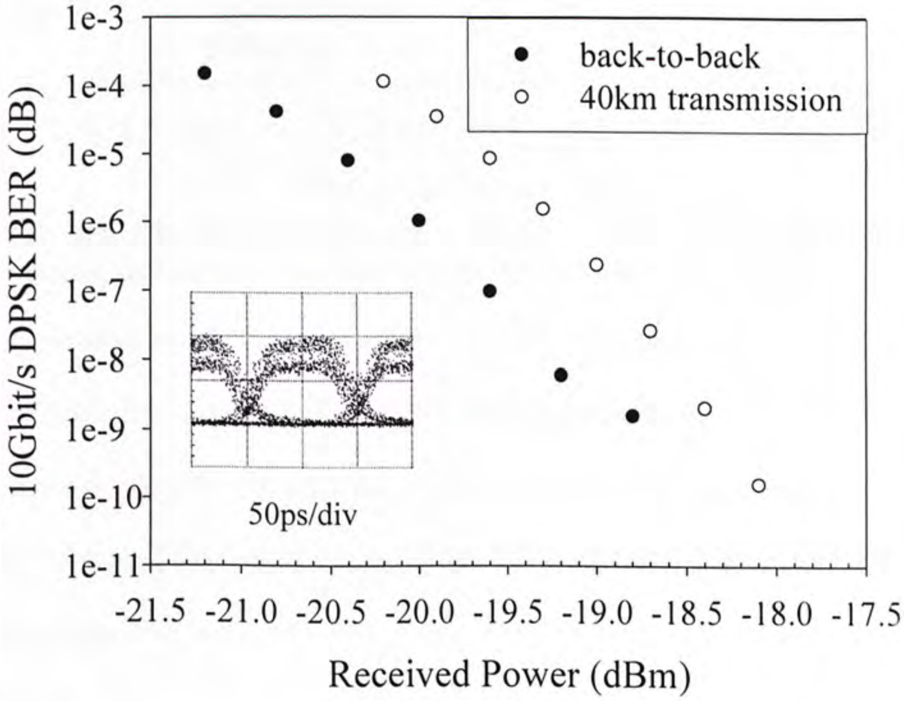


Fig 3.10 Transmission performance of 10-Gb/s DPSK signal on DPSK/ASK orthogonal modulation. Inset shows the detected DPSK waveform

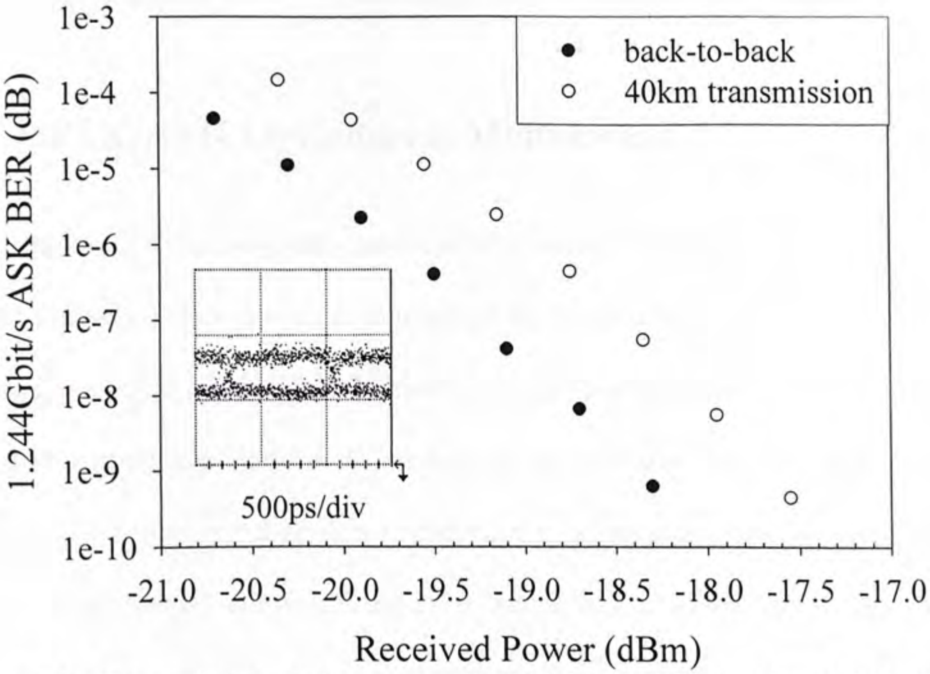


Fig 3.11 Transmission performance of 1.244-Gb/s ASK signal on DPSK/ASK orthogonal modulation. Inset shows the detected ASK waveform.

The receiver sensitivities (at BER=10^{-9}) for both signals were measured and the power penalties were 0.7 dB for the ASK signal and 0.45 dB for the optical DPSK payload, respectively, after the transmission. Clear eye opening, shown in the insets, was obtained for both the 1.244-Gb/s ASK and 10-Gb/s optical DPSK signal. The power penalties were less than 1 dB, which would be acceptable in one-hop transmission.

A scheme using balanced detection for DPSK payload [40] was proposed in ECOC'03. By employing balanced detection, the DPSK receiver sensitivity and the tolerance of DPSK receiver to packet power fluctuations were improved. Higher extinction ratio for ASK would be feasible because of the 3 dB increase of DPSK receiver sensitivity.

3.7. Supervisory Information Dissemination Using DPSK/ASK Orthogonal Modulation

Since this orthogonal modulation scheme carries two data streams simultaneously, it is appropriate to transmit the control information together with the payload in optical layer. Optical supervisory (SV) information dissemination is one of the important applications. Compared to the previous schemes such as separate channel, pilot tone or subcarrier modulation, it is more practical and cost effective. First, no additional control channel is needed. The label length has no strict limitations compared to pilot tone, thus more information can be carried. More complicated system functions, for example the quality of service (QoS), can be supported by employing longer supervisory signal. Moreover, the orthogonal modulation avoids the complex filter modules needed in subcarrier schemes. The modulation and demodulation configuration is much simpler and can be integrated. By employing the high speed constant intensity DPSK payload, we can get better transmission performance.

Using this DPSK/ASK modulation scheme in the all-optical label swapping is another main application. Besides the advantages we mentioned in SV information dissemination, the ASK label signal can be easily added and removed. Transparent swapping can be realized in optical layer with low switching latency. To evaluate the swapping performance, experiment had been demonstrated.

3.8. Label Swapping Experiment and Results

We have demonstrated a two hop optical label swapping to measure the switching performance. Simple label updating configuration, high flexibility and low power penalty for both payload and label make the scheme attractive to be used practically. Fig 3.12 illustrates the block figure of the swapping system setup. The packet enters the edge router, where the ASK label is added. Then the resultant signal arrives at the core router for swapping. Label removing and updating is performed at the core routers. The new label is used to control the next switch.

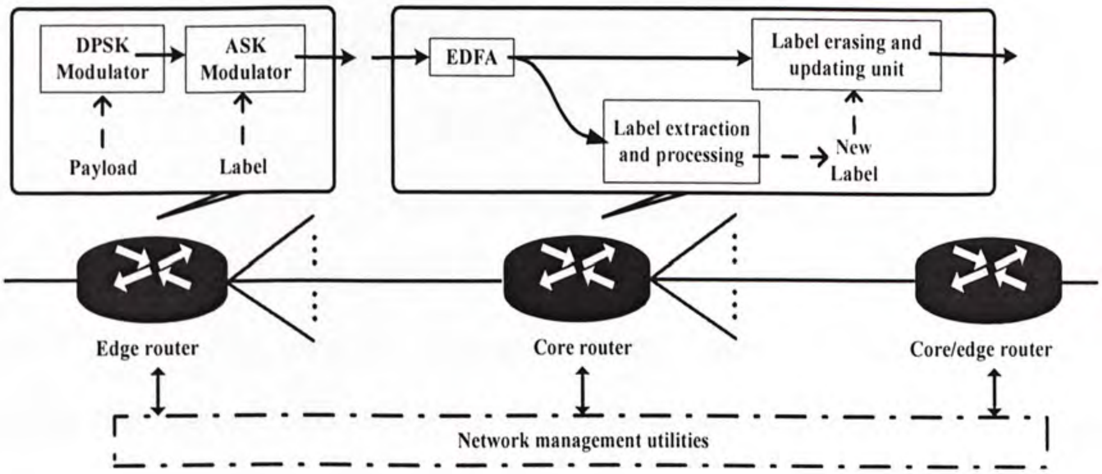


Fig 3.12 Two hop optical label swapping

3.8.1 Experiment Setup

We used the nonlinearity of SOA to remove the ASK label. Fig 3.13 shows the experimental setup.

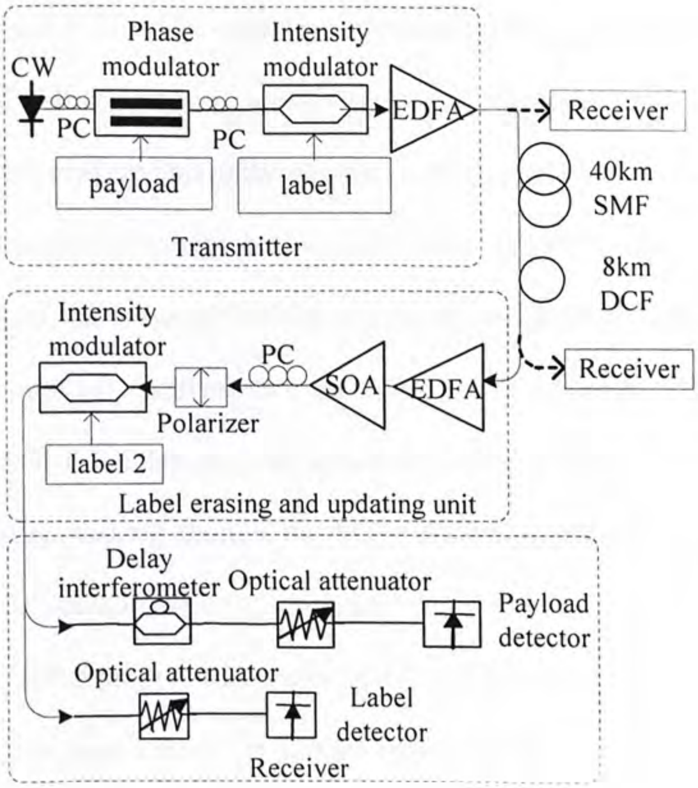
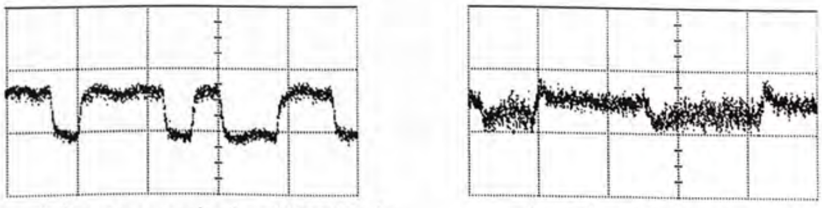
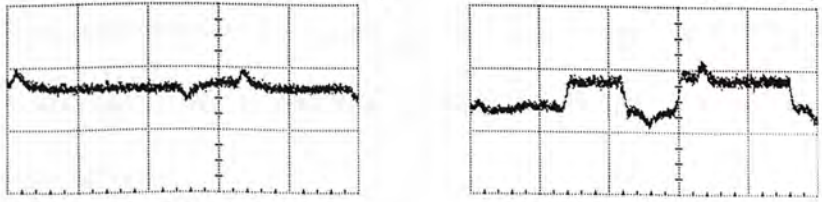


Fig 3.13 Label swapping experiment setup

A 1550nm CW laser was used as the light source. Two polarization controllers (PC) were used to align the polarization of the carrier with the principle axis possessing maximum modulation response at the optical phase modulator (PM) and the optical intensity modulator (IM). The PM was driven by a 10-Gb/s NRZ 2^{31}-1 pseudo random binary sequence (PRBS), while the optical intensity modulator was driven by 1.244-Gb/s NRZ 2^{31}-1 PRBS. An optimized ASK extinction ratio (~1.3 dB) was chosen to get error-free operation for both payload and label. The resultant DPSK/ASK optical signal was then fed into a 40-km-long standard single mode fiber (SMF) for transmission. A piece of 8-km dispersion compensating fiber (DCF) was used to minimize the phase-to-intensity conversion induced by the fiber chromatic dispersion. At the receiving side the optical DPSK payload was demodulation via a 103.5-ps-delay-interferometer (DI), while the ASK label was direct detected. All the receiver sensitivities were measured just before entering the receiver. In label erasing and updating unit (LEU), an SOA was used to saturate the intensity so that the difference between the mark and the space level of the label could be reduced. Because of TE/TM asymmetry in effective indices, confinement factors, etc, nonlinear birefringence evolution would occur in SOA. The state of polarization (SOP) of mark and the space level would rotate for a different angle respectively after passing though the SOA. By tuning the following polarization controller (PC), a certain angle in which both level had the same output power could be found. The following polarizer was tuned to align with that certain angle, so the residual intensity modulation was further removed. The optical power entering the SOA was 3 dBm and the output power from the LEU was about 4 dBm, which indicated that the LEU could also serve as the power booster for next-hop transmission. The waveforms of ASK label removing and updating are shown in Fig 3.14.



a. After transmission(2ns/div) b. After SOA (1ns/div)



c. After polarizer (1ns/div) d. Updated label (1ns/div)

Fig 3.14 ASK Label waveform in label removing and updating unit

Fig 3.14(a) shows the received ASK label signal after transmission. After saturating the signal in the SOA (Fig 3.14(b)), the difference between the mark level and the space level was greatly reduced, but it couldn't be completely cleared up. At the same time the noise was amplified. If we only used the SOA to remove the label, then directly added a new label on it, the signal degradation for the next hop transmission would be serious. By adjusting the polarization controller and the polarizer, the same output power of the mark level and the space level was obtained (Fig 3.14(c)), leaving only the residual edges. The amplified noise was also restricted to an acceptable level. In this way, we got the label-erased signal. A new label was added as shown in Fig 3.14(d). We used the complementary pattern of the original label. For comparison, we still employed the original extinction ratio (about 1.3 dB) for the new label. The effect of the residual edges was little from the experiment results, which will be discussed in next section.

3.8.2 Experiment Results

We have measured the back-to-back performance, the 40-km transmission performance and the label erasing and updating performance of both the label and the payload. The results are shown in Fig 3.15 and Fig 3.16, for DPSK payload and for ASK label respectively. The inset of Fig 3.15 shows the eye-diagram of the DPSK payload after label erasing. All the received optical powers were measured just before the receiver.

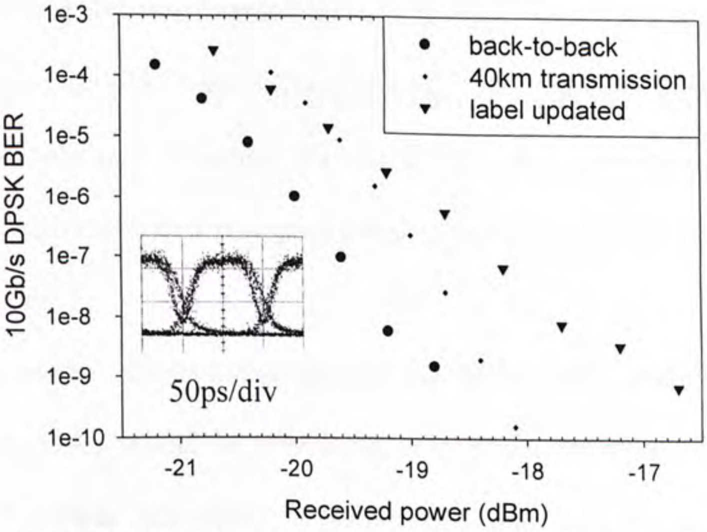


Fig 3.15 BER measurements of DPSK payload signal,
Inset: DPSK eye-diagram after label removing (50ps/div).

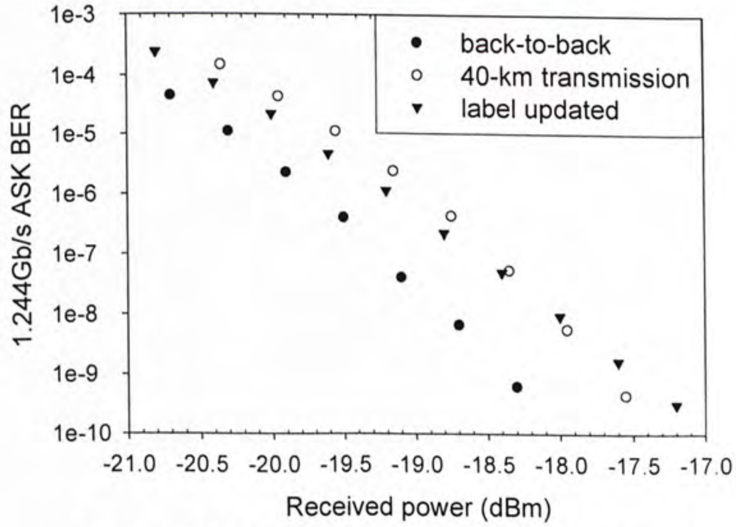


Fig 3.16 BER measurements of ASK label signal

The receiver sensitivities (at BER=10^{-9}) for both signals were measured and the power penalties were 0.45 dB and 0.8 dB for DPSK payload and ASK label transmission respectively. Clear eye opening, shown in the inset of Fig 3.15, was obtained for 10-Gb/s optical DPSK signal after the label erasing. And the power penalty of 1.4 dB for the optical DPSK payload and less than 0.2 dB for the ASK label was induced by label removing and adding. Since the label erasing and updating induced smaller penalty for the ASK label than the DPSK payload, we could employ balanced detection for the DPSK signal to improve the system performance. With this small swapping penalty, more hops between swapping nodes could be obtained.

The experimental results suggested that the DPSK/ASK orthogonal modulation scheme we proposed would be promising in optical label swapping, owing to its simplicity of system structure, flexibility of label bit rate and low penalty performance in transmission and label swapping.

Chapter 4: Conclusion

4.1. Thesis Summary

In this paper, new schemes using DPSK/ASK and FSK/ASK orthogonal modulation for in-band control information dissemination have been presented. By superimposing the lower-speed ASK data onto the constant intensity profile of the high-speed optical DPSK or FSK payload, the ASK information can be disseminated without requiring an extra dedicated control channel. The characteristics of the scheme have been studied and characterized both numerically and experimentally. It is found that the ASK data has good performance when the bit rate is below 1.244 Gb/s and when operating at the optimum ASK extinction ratio. The results suggest that the DPSK/ASK orthogonal modulation scheme is a feasible solution for supervisory dissemination in WDM networks. In addition, these schemes can be used for all-optical labeling swapping. Successful experiment demonstrations of label removal and updating show the advantages of these orthogonal modulation schemes:

- The modulation and receiving configuration is simple. The edge routers and core routers can be more compact and inexpensive.
- DPSK payload has better transmission performance because of the higher tolerance of fiber nonlinearities.
- The supervisory information or the label is carried in band, no additional

channel is needed. Bandwidth efficiency is greatly improved.

- Labeling swapping is carried out on optical layer. Transparency and switching speed are guaranteed.
- The length and bit rate of the label are more flexible than former schemes. In individual applications we can have the optimum plot.

4.2. Future Work

This DPSK/ASK orthogonal scheme still needs improvement before being employed in practical applications. How to keep a constant ASK modulation extinction ratio is the most important problem to be solved. The system degradation caused by dispersion under different ASK operation condition is another issue to be studied. The result will lead to solutions to increase the bit rate of the label or supervisory signal.

List of Publications

1 Y. Yang, C.K. Chan, L.K. Chen; "System Characterization of Optical ASK/DPSK Orthogonal Modulation for Supervisory Information Dissemination", *Asia Pacific Optical Communications and Wireless Communication Conference, APOC,* Paper 5281-69, Wuhan, China PRC, Nov. 2003.

2 N. Deng, Y. Yang, C.K. Chan, L.K. Chen, W. Hung; "All-Optical OOK Label Swapping on OFSK Payload in Optical Packet Networks", *IEEE/OSA Optical Fiber Communication Conference, OFC 2004,* Paper FO5, Los Angeles, USA, Feb. 2004.

3 N. Deng, Y. Yang, C.K. Chan, W. Hung, L.K. Chen; "Intensity-Modulated Labeling and All-Optical Label Swapping on Angle-Modulated Optical Packets", *IEEE Photonics Technology Letters,* vol. 16, no. 4, pp.1218-1220. Apr. 2004.

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