INVESTIGATION OF OTDM DEMULTIPLEXING AND HYBRID TECHNIQUES

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CERTIFICATE

I, Sneh Lata, hereby certify that the work which is being presented in this dissertation entitled **"INVESTIGATION OF OTDM DEMULTIPLEXING AND HYBRID TECHNIQUES"** by me in partial fulfillment of the requirements for the award of degree of Master of Engineering in Electronics and Communication Engineering from Thapar University, Patiala, is an authentic record of my own work carried out under the supervision of **Dr. R. S. Kaler** and refers other researcher's works which are duly listed in the reference section.

The matter presented in this dissertation has not been submitted in any other university/Institute for the award of any other degree.

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ABSTRACT

Optical fiber communication provides transmission of light and thus information over long distances. Optical fibers offer huge data transmission capacity. There are several multiplexing techniques used for optical fiber communication including FDM (frequency division multiplexing), TDM (Time Division Multiplexing) and WDM (Wavelength Division Multiplexing). OTDM (Optical Time Division Multiplexing) is a powerful multiplexing technique that provides very high capacity of data transmission over optical fibers. In OTDM networks, several lower bit-rate optical streams are time-multiplexed to generate a high bit-rate data stream. Likewise, at the receiver side of the system, the high bit-rate optical signal is time demultiplexed to several lower bit-rate signals. The most critical element of the OTDM system is the demultiplexer. So far, different demultiplexing schemes have been proposed for the demultiplexing of OTDM signals including various optical gate switches and other methods. A good demultiplexer design is essential for receiving error-free signal with efficient bit error rate (BER) performance and to decrease the cross-talk between the channels. One method for achieving the efficient demultiplexing system is to use optical gating using different types of modulators arranged in different configurations. Efficient demultiplexing can also be attained by utilizing hybrid OTDM system. Using hybrid OTDM networks helps in reducing the crosstalk between the adjacent channels thereby improving the overall system performance. The main objective of this dissertation is to investigate and propose OTDM demultiplexing and hybrid architectures for enhanced and error-free performance.

Firstly, 160 Gb/s OTDM DQPSK system with optical gating using mach-zehnder modulator and clock recovery is analyzed. Secondly, serial-to-parallel conversion of optical time division multiplexed (OTDM) data tributaries into wavelength division multiplexed (WDM) channels from 160 Gbit/s to 4x40 Gbit/s using four-wave mixing (FWM) in highly non-linear fiber (HNLF) followed by a single electro-absorption modulator based optical gate. Thirdly, a 160 Gb/s hybrid optical time-division multiplexing (OTDM) system is demonstrated which contains hybrid modulation formats of on-off keying (OOK) and differential phase shift keying (DPSK) and its demultiplexing performance is investigated using a mach-zehnder modulator.

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LIST OF ABBREVIATIONS

AWG	Arrayed Waveguide Grating
BER	Bit Error Rate
DPSK	Differential Phase Shift Keying
DQPSK	Differential Quadrature Phase Shift Keying
DWDM	Dense Wavelength Division Multiplexing
EAM	Electroabsorption Modulator
EDFA	Erbium Doped Fiber Amplifier
ETDM	Electrical Time Division Multiplexing
E/O	Electrical-to-Optical
FBG	Fiber Bragg Grating
FWM	Four Wave Mixing
HNLF	Highly Non-Linear Fiber
LO	Local Oscillator
MZM	Mach-Zehnder Modulator
NOLM	Non-linear Optical Loop Mirror
NRZ	Non-return-to-zero
OBPF	Optical Band-pass Filter
OOK	On-off Keying
OSNR	Optical signal-to-noise Ratio
OTDM	Optical Time Division Multiplexing
O/E	Optical-to-Electrical
PC	Polarization Controller
PLL	Phase Locked Loop
QAM	Quadrature Amplitude Modulation
Q-factor	Quality Factor
RC	Resistance-Capacitance
RMS	Root Mean Square
RZ	Return-to-zero
SMF	Single Mode Fiber

SMZ	Symmetrical Mach-zehnder
SOA	Semi-conductor Optical Amplifier
SDH	Synchronous Digital Hierarchy
TW-EAM	Traveling-wave Electro-absorption Modulator
UNI	Ultrafast Non-linear Interferometer
VOA	Variable Optical Attenuator
XPM	Cross Phase Modulation

CHAPTER 1

INTRODUCTION

1.1 Introduction

Optical Fiber system plays a significant role in communication system. The optical carrier frequency has very great potential transmission bandwidth than metallic cable systems. Invention of various multiplexing technology empowered very high capacity optical fiber communication networks that provides transmission over thousands of kilometres without using any electronic repeaters [1]. The progress of optical components has focussed on the configuration of complex point-to-point capacity systems as a means for the required data traffic transportation. Combining the probable limitations in electronics and advances in optical technology, it has been acknowledged that there may be gains in employing reconfigurable optical transmission systems. Optical technology plays an imperative role in the reduction of the requirement of the electronic processing by routing the groomed traffic in the optical domain direct to the target in order to avoid the need for large electronic processors at intermediate network positions [2]. There is an increasing demand for expanded transmission capacity. This rising demand can be met by using OTDM technique. In OTDM, a data stream of high bit rate is constructed directly by time-division multiplexing various optical streams of lower bit rate [3]. At the receiver terminal, demultiplexing of the very high bit-rate optical signal to several lower bit-rate signals is performed before detection and conversion into the electrical field. The time-division multiplexing is a completely digital technique and hence it is compatible with the idea of an all-digital network which combines switching and transmission. Further, OTDM offers system design flexibility, including the probability of adaptable bandwidth allocation into different baseband channels and also the likelihood of simple system hardware where only a single transmitter laser is needed for all the channels. Increasing demands for capacity have initiated the development of high-speed optical shared media systems. Very high-speed optical OTDM systems having single wavelength channel rates in excess of 100 Gb/s, offer simple organization and control, the capacity to provide truly flexible bandwidth on demand service, packet switching, and scalability in the number of users [4]. At present time, the major research work on ultrafast optical networks has been dedicated to device technology demonstrations such as all-optical logic at OTDM rates [5], high repetition rate short optical pulse sources [6], self-synchronization methods [7], wavelength conversion [8], and long-haul transmission using ultra-short pulses [9].

1.2 Background

Increasing demand for expanded transmission capacity has led to the advancement in ultra-high bit-rate light wave systems. These growing demands have led to increased interest in multi Gigabit-per-second pulse code modulated (PCM) systems, and have highlighted the need for wide-band and high-speed electronics in light wave transmission and receiving systems. So far, it has commonly been probable to meet these needs with high-speed Si and GaAs circuits, but at Gbit/s bit rates, it becomes even more challenging to develop the necessary digital electronic circuits. One method to get rid of this electronic speed restriction is to extend the recognized techniques of electrical multiplexing into the optical field. The two main methodologies to optical multiplexing are optical wavelength or frequency-division [11, 12, respectively] multiplexing and time-division multiplexing [13, 14]. For the first time, OTDM system transmission was successfully demonstrated in 1988 (Bell Laboratory). Ever since, the bit rate for single wavelength channel OTDM system operation has undergone remarkable advancement. The initial OTDM transmission experiment of 100 Gb/s was testified in 1993 over a fiber distance of 36 km [15]. Since then, there has been large development in the direction of much higher bit rates for OTDM transmission technique and much longer communication networks. In recent times, OTDM transmission technology prospered in the transmission of a TDM bit rate of 160 Gb/s over a record fiber link of 4320 km and of 2.4 Tb/s over a fiber length of 160 km [16]. The past has observed that OTDM will be substituted by ETDM as soon as electrical signal processing becomes accessible at the required TDM data rate. Therefore, OTDM transmission technology is often considered to be an interim technique to examine the feasibility of very high-speed data transmission in fibers.

1.3 Motivation

Features which make OTDM very attractive as a future network technology are:

- Provides easy access to high line rates (100 Gb/s and greater).
- Tributary data rates at any desired degree of granularity and compatible with existing technologies like SDH.
- Greatly simplified dispersion management (due to single wavelength transmission).
- OTDM is able to get along with WDM. For point-to-point applications, it can be used to enhance the WDM channels data rate in order to decrease the overall complexity of the system. OTDM also helps in improving the spectral efficiency for WDM system.
- OTDM transmission network may deliver a really high-speed low-latency data link with maximum parallelism offering applications in the areas of both distributed computing industry and scientific data acquisition.

1.4 Optical Networking

An optical network is a system that connects computers (or other devices which can produce or store data in electronic form) using optical fibers. To enable data communication, an optical system also consist of other optical devices to generate optical (electrical) signals from electrical (optical, respectively) data, to restore optical signals after transmission through fibers, and to direct optical signals through the network. Basically, optical networks are those networks in which the principal physical layer technology for transport is optical fiber. The optical networks can be opaque or all-optical, and can be single-wavelength or based on dense wavelength division multiplexing (DWDM).

Optical fiber networks are used due to their possibly unlimited capabilities, as given below [10]:

- large bandwidth (over 50 Tbps),
- little signal attenuation (as low as 0.2 dB/km), and hence offers transmission over long distances without requiring any repeaters,
- immunity to electromagnetic interference,

- high signal security and hence difficult to eavesdrop because of no electromagnetic radiation,
- no crosstalk and interferences between fibers in the same cable,
- low signal distortion, hence appropriate for transmitting digital information,
- need low power,
- low material usage, small space requirement, light weight, cost-effective, non-flammable
- high electrical resistance, hence harmless to use near high-voltage equipment or between different earth potential areas.

1.5 Time Division Multiplexing

In a basic time-division multiplexed system, a set of data streams with low-bit-rate, each having a stable and pre-defined bit rate is combined into a single high-speed bit stream which can be communicated over a single channel. This method has numerous applications. The main motive to use TDM is to take benefit of current transmission links. It would be very costly to assign a costly physical channel to each low-bit-rate stream (say, a complete optical fiber transmission line) which is extended over a longer distance [17]. Fig.1.1 shows three sources, each having 64 Kbps of data that is to be transmitted to every user at receiver side. The high-bit-rate channel can be distributed into a sequence of time slots, and these time slots can be utilized by the three sources alternately. Thus complete data of all the three sources can be transmitted through the single, shared channel. Clearly, at the receiver terminal of the channel, the process must be inverted (i.e., the system should split the 192 Kbps multiplexed data signal again into the original three 64 Kbps data streams, which can then be delivered to three different users). This reverse procedure is known as demultiplexing.

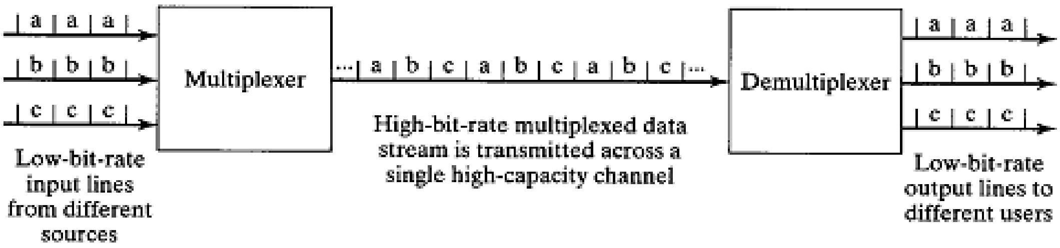


Fig.1.1. Basic time division multiplexing [17]

Table 1.1 Comparison between ETDM and OTDM [6]

ETDM	OTDM
• Electrical Time Division Multiplexing	• Optical Time Division Multiplexing
• Transmission medium- electrical e.g. copper cable	• Transmission medium- optical fiber cables
• Inter-symbol Interference (ISI)- high	• Inter-symbol Interference (ISI)- low
• Data rate- low	• Data rate- high
• Rx sensitivity- less sensitive	• Rx sensitivity- can yield ~1db better absolute sensitivities than ETDM
• Operating speed- limited	• Operating speed- high (> 100 Gb/s)
• Security- Less (due to electromagnetic radiation)	• Security- High

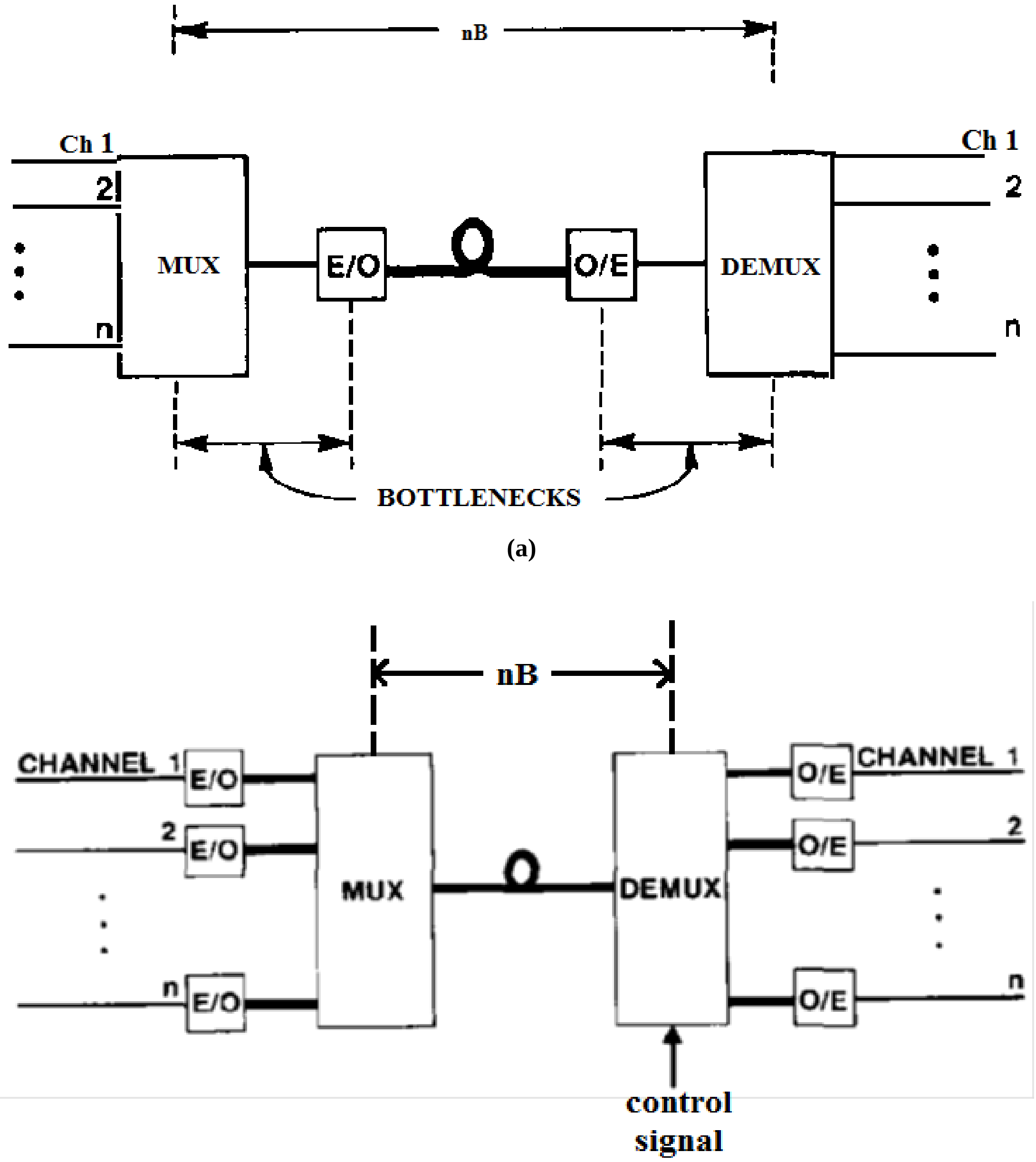
1.6 Optical Time Division Multiplexing

Basic Principle

The basic principle of time-division multiplexing and demultiplexing involves allocation of a series of time slots to all the baseband data streams on the multiplexed channel. Optical time division multiplexing (OTDM) is a scalable and powerful technique for investigating high-speed data transmission systems, associated signal processing and monitoring techniques at serial data rates far away from the bandwidth limitation of electronics. The OTDM system is basically compatible with present multi-level quadrature-amplitude modulation setups and digital coherent detection. As compared to the wavelength division multiplexing (WDM), only single wavelength (color) of light is used. An OTDM system includes a multiplexer at the transmission side and a demultiplexer at the receiving side. A multiplexer (MUX) bring together the bit stream with higher bit-rate from the baseband streams, whereas a demultiplexer (DEMUX) rebuilds bit streams at the basic lower bit rate by bit separation in the multiplexed stream. Fig.1.2 shows the similarities and dissimilarities between electrically and optically time multiplexed lightwave networks. In the figure, thick lines represent optical (fiber) signal paths whereas thin lines represent electrical signal paths. Multiplexing is performed in the electrical domain, before the electrical-to-optical (E/O) conversion in an electrically time-multiplexed network as shown in Fig. l (a) and demultiplexing is performed after the optical-to-electrical (O/E) conversion. For n number of baseband channels, every channel having bit rate B, the bit rate of the multiplexed channel is nB. Electronic bottlenecks potentially take place in the multiplexer and in the E/O and O/E converter and demultiplexer, where the electronics need to work at the complete multiplexed bit rate. The restrictions arise from 1) speed restrictions of digital integrated circuitry, 2) speed restrictions due to linear amplifiers with high-power and low-noise which are used to drive the laser or modulator in the E/O and O/E converter, 3) restricted modulation bandwidths of modulators and lasers, and 4) the receiver sensitivity provided by an avalanche photodiode lowers by more than 3 dB for each octave rise in the bandwidth of the receiver [18]. Such problems have so far restricted the maximum bit rate for electrically multiplexed systems to 10 Gbit/s [19]-[21].

In the optical multiplexed network, as shown in Fig. l (b), the electronic bottlenecks can be eliminated by shifting the transmitters and receivers (i.e., the E/O and O/E converters) into the baseband channels. After the E/O conversion, Multiplexing is performed and demultiplexing is done prior to the O/E conversion. All electronics related with the signal processing work only at the bit rate of the baseband. The process of time-multiplexing several lower bit rate baseband channels on a higher bit-rate channel can be distributed into these three sub processes: sampling, timing, and combining [13]-[14]. Sampling gives samples of the arriving baseband data signal, in order to identify every incoming bit value. The timing function makes sure that samples are obtainable at the accurate time slots on the multiplexed channel.

The combining process gathers all the sampled baseband data streams to produce the multiplexed data stream with higher bit-rate as shown in Fig.1.3 In higher data rate electrically multiplexed systems, it is suitable to sample all input data streams by using short sampling pulses that are scheduled to match to the correct time slots on the multiplexed data stream [19]-[21].



(a)

(b)

Fig.1.2. Basic Structures of (a) electrical and (b) optically time-division multiplexed lightwave systems [3]

1.7 Key Components for OTDM

1. Transmitter
    - Ultra short optical pulse generation
    - Modulation format (OOK, DQPSK, DPSK, M-ARY QAM)
2. Transmission channel
    - Dispersion-managed fiber for ultra-short pulse propagation
3. Receiver

- Optical clock extraction
- OTDM demultiplexing

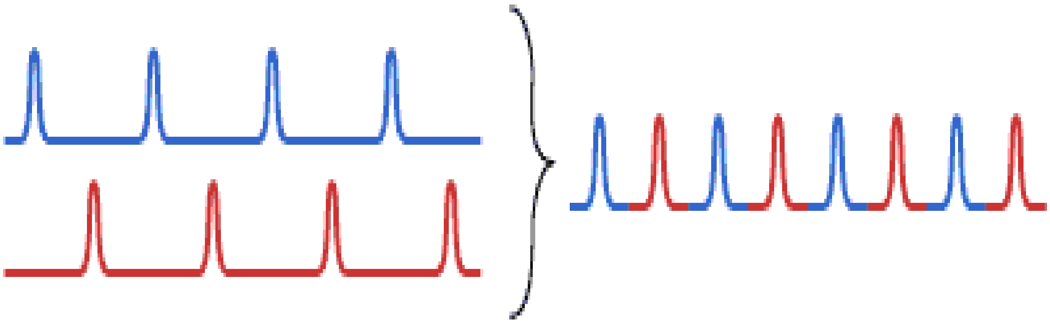


Fig.1.3. Higher bit rate multiplexed data streams

1.8 System Composition

Optical time division multiplexing communication system is mainly composed of the light emitting part, transmission and receiving part.

1.8.1 The Transmitting Part

It mainly consists of the ultra-narrow pulse light source and the optical time division multiplexer. Sources with high repetition frequency and ultra-short optical pulse source species includes erbium doped fiber ring laser, active mode-locking Semiconductor laser, semiconductor ultra-short pulse source, ultra-short optical pulse sources. The pulse width of the signal to be multiplexed should be less, and it should have a high extinction ratio (up to 30dB), and the pulse time jitter total RMS values should not be greater than the channel time slot of the 1/14. This is because the rectangular pulse shape is not ideal, but as Gauss pulse, time jitter between the signal source with the clock jitter can cause the strength of demultiplexing, the strength of the signal jitter error increase [22]. In the transmitter part of OTDM system, various optical pulses, termed as tributaries, initiating from same laser source (similar central wavelength), are independently encrypted by electrically produced data signals. The tributaries are bit interleaved serially because of the low duty cycle of their pulses so as to form serial OTDM data signal having high speed. After providing delay to all the channels, now all the signals are multiplexed using a multiplexer. After that the multiplexed data is transmitted through an optical fiber as shown in the Fig.1.4 below. OTDM multiplexed data can be transmitted over different types of optical fibers available for different lengths according to the transmission requirements. After performing the complete signal processing, now multiplexed data transmitted over the fiber reaches the receiver terminal where demultiplexing and further data processing is performed.

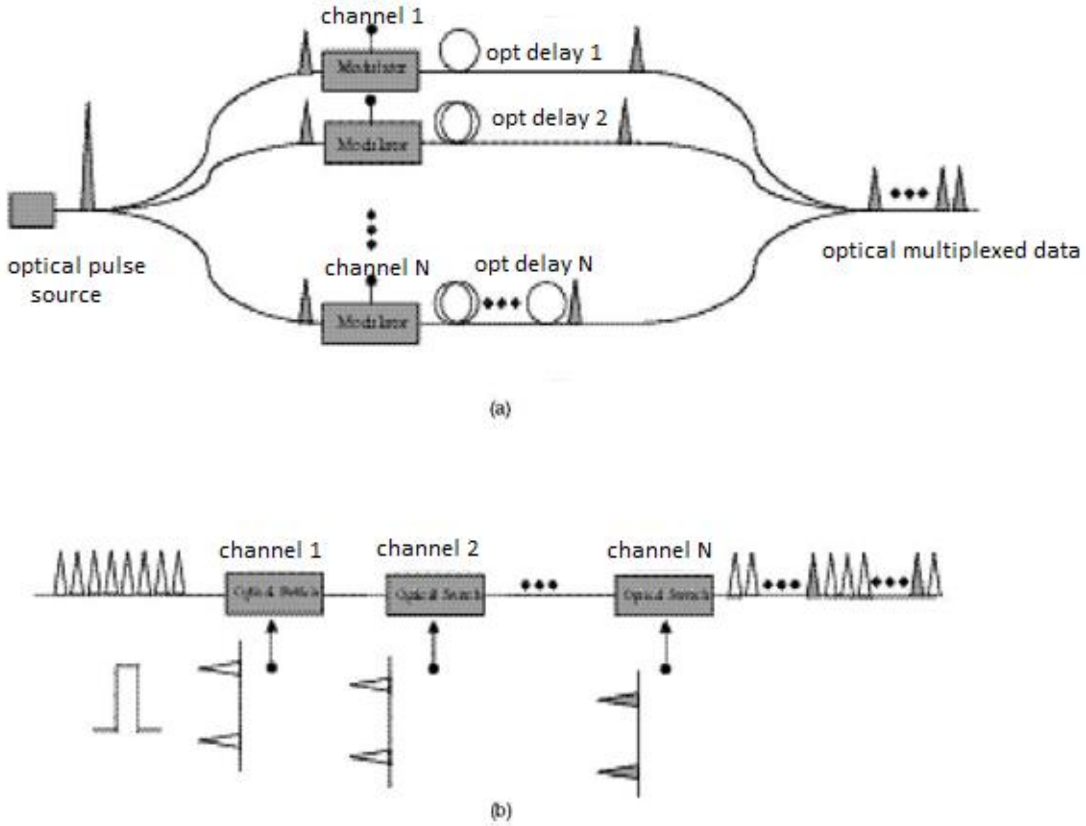


Fig.1.4. OTDM transmitter; (a) modulation, optical delay and multiplexing of signals (b) transmission of multiplexed channels

1.8.2 The Receiving Part

The receiving part includes demultiplexer, optical clock extraction and low-speed optical receiver. Optical clock extraction must be extracted from the high bit rate optical pulses in pulse low light, for example 10GHz clock signal extraction from 160Gbit/s light pulse. For the extracted clock pulse acting as the control pulses to a demultiplexer, the pulse width should be narrow and therefore, the time jitter clock pulse and the phase noise should be as low as possible. In order to make sure about the stability of the clock pulse, peak power should enable the pulse extraction properties and polarization structure. To come across these requirements, all-optical clock extraction methodology has the mode-locked erbium-doped fiber laser, phase-locked loop (PLL) and mode-locked semiconductor laser.

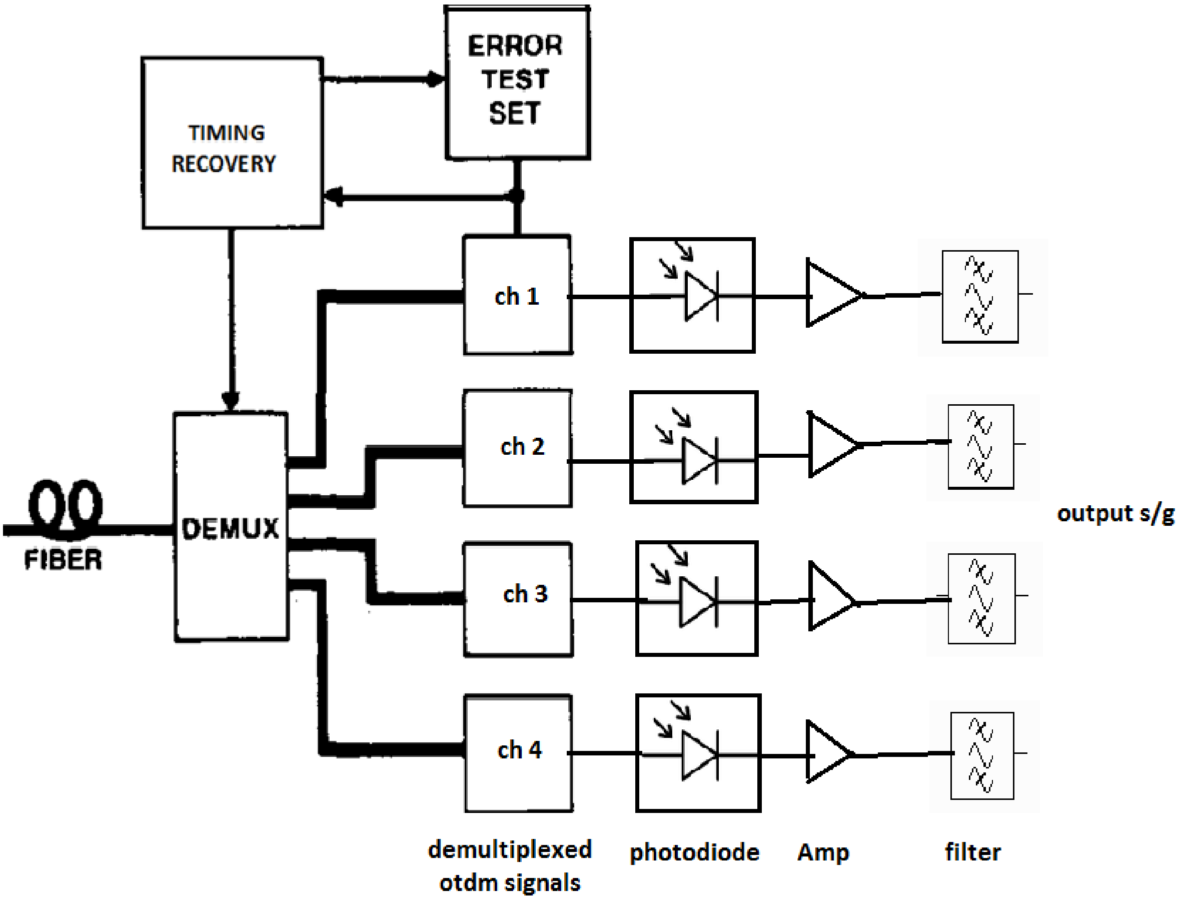


Fig.1.5. Basic Schematic of OTDM receiver

Optical demultiplexer system coincides with the optical multiplexer system so that the demultiplexer can synchronously output optical pulse signal having low bit rate, for example, when the clock pulse is about 10GHz, the optical demultiplexer is separated from the 10Gbit/s signal from the 160Gbit/s signal, the same 16 optical demultiplexing device can produce 16 groups of 10Gbit/s signals. Optical demultiplexer includes optical Kerr switch, optical modulator switch, four wave mixing (FWM) switch, nonlinear optical loop mirror (NOLM), cross phase modulation (XPM) switching etc. [22]. A serious issue in OTDM is the capability to decompose the high-speed signal down to the lower speed tributaries. OTDM receiver consists of demultiplexer and timing recovery unit as shown in the Fig.1.5. After transmission of modulated, multiplexed and time interleaved signal, it is finally retrieved at the receiver side at different time intervals. Firstly, the incoming multiplexed signal will be demultiplexed using a demultiplexer and then it is demodulated at different time slots. Various techniques for demultiplexing in OTDM networks has been proposed including optical gating using modulators, amplifiers etc. One such technique includes all-optical gates based upon semi-conductor optical amplifier (SOA) for high-speed processing. In this method, semi-conductor optical amplifiers are the building blocks for the generation of all optical gates for wavelength conversion and OTDM demultiplexers. Simple gating can be implemented using four-wave mixing and cross-gain modulation to the interferometric gates using the cross phase modulation. These gates provide high-efficiency for high speed signal processing. These gates can operate at bit rates in excess of 100 Gb/s [23].

Another technique for OTDM demultiplexing to lower bit rate signals is based on four-wave mixing (FWM) into highly non-linear fiber (HNLF). An all-optical tunable delay can be implemented to select the desired OTDM channel. Both demultiplexing and optical delay can be realized in single HNLF thereby reducing the component count [24]. Subsequently, fiber technologies have a most important benefit over semiconductor techniques as SOAs are usually limited by relatively slow relaxation time. However, in comparison to fiber based techniques, devices based on fibers offers the advantage of ease of integration and compactness. Latest developments in semi-conductor technology have resulted in a dramatic increment in the speed of demultiplexing.

Successful demultiplexing can also be achieved using all-optical symmetric Mach–Zehnder (SMZ) switching based optical switch. This technique uses symmetric mach-zehnder interferometer to generate an optical switching window to demultiplex different OTDM channels. Apart from using these techniques, there is another technique available to implement OTDM demultiplexing which includes optical gating using different modulators e.g. electro-absorption modulator (EAM), mach-zehnder modulator (MZM) or the combination of both.

Moreover, other system configurations can also be employed to achieve more efficient and error-free OTDM demultiplexing. These include hybrid OTDM schemes including use of wavelength division multiplexing (WDM) along with OTDM architecture in order to get the advantages of both the techniques by combining their features. Other techniques for error free demultiplexing may use a technique including polarized OTDM channels can also be used. In hybrid modulation system, different OTDM channels can be modulated by using different modulation schemes e.g. OOK, DPSK, QAM, DQPSK in order to reduce the adjacent channel crosstalk at the receiver thereby enhancing the demultiplexing performance. In the former case, the different OTDM channels are polarization multiplexed i.e. different channels have different polarization angles of their beams. This provides ease for the transmission of the signals and enhanced demultiplexing is achieved due to the reduction of the adjacent channel crosstalk. So, using different enhanced demultiplexing techniques, OTDM networks can be made more advanced providing error free data transmission and increased capacity of the system. Another significant enabling technology for high-speed OTDM systems is the clock extraction function. To implement signal processing synchronously, a highly stable recovered clock (electrical or optical) component with low amplitude noise and phase is necessary. For OTDM networks, operating at data rates beyond electronic capacities, depending on the nature of application, two recovered clock frequencies may be needed. In the case of demultiplexing at the receiver terminal or add/drop multiplexing at a network port, a recovered clock component at sub-harmonic frequencies is required whereas for in-line 3R (retiming, reshaping and re-amplification) signal processing, a recovered clock component which is identical to the original OTDM line rate is more anticipated.

1.9 Objectives of Dissertation

1. To propose enhanced demultiplexing performance of OTDM system using optical gating using modulators.
2. To investigate the performance of hybrid OTDM system using OTDM to WDM trans-multiplexing.
3. To propose a hybrid OTDM system to reduce adjacent channel crosstalk.

1.10 Organization of Dissertation

Chapter 2 represents the literature survey about the topic of the dissertation. The first step to start the dissertation is to study the papers that have been already published by other researchers. Paper associated to this work are selected and studied. Literature review makes it easier to perform this work and meet the objectives.

Chapter 3 presents the 160 Gb/s OTDM DQPSK system demultiplexing using cascaded mach-zehnder modulators.

Chapter 4 investigates the performance of the OTDM-to-WDM conversion based upon FWM and time gating.

Chapter 5 presents a 160 Gb/s hybrid optical time-division multiplexing (OTDM) system containing hybrid modulation techniques of on-off keying (OOK) and differential phase shift keying (DPSK) and its demultiplexing.

Chapter 6 consist of the conclusion and future scope of the proposed work.

CHAPTER 2

LITERATURE SURVEY

With the ever-growing demand for larger capacity and higher speed brought about by rapid data growth, interest in OTDM has been increasing rapidly in recent years as depicted in this chapter. Demultiplexing plays a critical role to enhance the OTDM system performance. The literature survey of OTDM systems by various researchers is in past years is shown below:

Feiste U. *et al.* [25] investigated the first 160 Gbps return-to-zero (RZ) transmission on field-installed G.652 standard fiber. The basic principle used for the transmission was the optical time division multiplexing (OTDM) system. At the receiver side, a 160 Gbit/s to 40 Gbit/s OTDM demultiplexer following 40 Gbps electrical signal processing (ETDM) is performed. The comparison of the results of proposed setup with 160 Gbit/s to 10 Gbit/s OTDM demultiplexing experiments is done. The OTDM demultiplexer was designed using cross phase modulation (XPM) in a semiconductor optical amplifier (SOA).

Scott A. Hamilton *et al.* [26] demonstrated ultra-high speed slotted optical time-division multiplexed (OTDM) systems as a promising means of using a very efficient next generation packet-switched all-optical network. This type of set-up is capable of offering simple network organization, self-routing of packets, the capability to support adjustable quality-of-service, the usage of digital regeneration, encryption and buffering, scalability in the number of users. Boolean logic gate and all-optical switch implementations by using ultrafast non-linear interferometers (UNIs) which are capable of pattern-independent, stable process at excess speeds of 100 Gbps are revised. The ability beyond logic demonstrations and switching provided by the UNI to consist system-level tasks for example address comparison, packet synchronization, and rate conversion was depleted. These progressive all-optical signal processing abilities were used to determine test bed for a slotted OTDM multi-access system working at 112.5 Gb/s line rates using integral scalability in the system line rates and the number of consumers. It was reported that the long-haul distance of proposed OTDM network can be extended much greater than 100 km using the long-haul transmission of short optical pulse streams in fiber cable and all-optical 3R regeneration as a economical means.

Jie Li *et al*. [27] reported a vigorous and simple all-optical optical time-division demultiplexing method using cross-phase modulation (XPM)-induced wavelength shifting in 100 m highly non-linear fiber (HNLF) using following optical filtering. All-optical demultiplexing of data from 160 Gb/s to 10 Gb/s with 2.8 ps switching window has been successfully demonstrated. Since the wavelength shifting induced by XPM is directed using the trailing or leading edge of the switching pulse, the switching window of this demultiplexing scheme is less than the switching pulsewidth. This demultiplexer is able to demultiplex OTDM data at bit rates greater than 500 Gbps by consuming the full strength of the 2.4-ps switching pulses.

Martin M. Strasse *et al*. [28] analysed experimentally and theoretically the comparable performance of electrical time-division demultiplexing (ETDM) and optical time-division demultiplexing (OTDM) and beat-noise restricted return-to-zero signal recognition by receivers were theoretically and experimentally confirmed. OTDM receivers offer a small sensitivity advantage, mainly autonomous of parameters such as the receiver's optical filter bandwidth or center frequency. The OTDM sensitivity benefit is caused due to reduced inter-symbol-interference characteristics of the OTDM receiver, along with the suppression of beat noise by the time demultiplexing window. The latter effect can be caught by prolonged expressions for the beat-noise alterations represented in this letter.

Huang Z. *et al.* [29] investigated the aspects of switching and transmission of an optical signal involving individual OTDM channels having unequal amplitudes with in-line non-linear fiber loop mirrors in a dispersion-managed link. It was shown that amplitude differences from channel-to-channel in OTDM data streams have a strong influence on the switching performance of different channels into a 2R regenerator. The optical signals in different channels involve either suppression or increase in the amplitude noise subject to the inter-channel difference in amplitude. Channel uniformity should be controlled properly in the OTDM transmitters so as to provide stable long-haul transmission in the 2R-regenerated networks.

Yabin Ye *et al*. [30] proposed the idea of OTDM light trail systems. Present Ethernet switches can only work at most 10 Gb/s due to the restriction of the electrical port speed. OTDM technology can be exploited in order to perform 100 Gb/s Ethernet switching. OTDM light path networks are capable of 100 Gbps Ethernet switching but more modulators are required to be used in the transmitters and in the super light path, only source node to downstream nodes connection can be realized. Light trail network principle permits intermediate ports to use the light trail using the OTDM technology. Using this technique, 100 Gb/s line speed can be attained without increasing the number of modulators at the transmitter side or the port speed. Here, node architecture was proposed for the OTDM light trail network and four ways of time slots assignment are categorized. Numerical simulation proved that the capability of usual light trail systems can be increased successfully by employing OTDM light trail networks. The OTDM light trail network provided cost effective and better performance as compared to the OTDM light path networks.

Ghassemlooy Z. *et al*. [31] proposed an all-optical symmetric Mach–Zehnder (SMZ) switching based optical switch. To avoid the bottleneck caused by optoelectronic conversion in all-optical high-speed time division multiplexed (OTDM) routers, it is desired to perform switching, data routing, synchronization and recovery of clock signal in the optical domain. A 1x2 OTDM router was designed using the proposed switch as a building block for asynchronous OTDM packet routing. The address recognition, clock extraction and payload routing were performed in the optical domain. Simulation results and numerical results show that the address recognition, clock recovery and payload routing were possible with small extents of crosstalk. The results of simulation for 1x2 router for bit error rate (BER) performance was also presented. The receiver sensitivity noticed for a BER of 10^{-9} is -26 dB in comparison to the baseline detection without using a -38 dB router. The suggested router shows high potential to be used in ultrahigh-speed OTDM systems.

Paulo J. Almeida *et al*. [32] theoretically and experimentally presented an add-drop time-division multiplexer which is able to provide high-extinction-ratio. The proposed approach depends on the conversion of optical signals from time to frequency domain and also on the switching of linearly chirped optical pulse streams. By transforming a 40 Gb/s optical time-division multiplexing (OTDM) signal into 4×10 Gbps wavelength-division multiplexing (WDM) signals and employing fiber Bragg gratings (FBG) for the frequency-domain add–drop multiplexing, an error-free process for the dropped, and added channels and a timeslot suppression ratio of 30 dB in excess were attained. Further conversion from WDM-to-TDM signal was performed to transform the resultant signal back to the time domain. This was also shown that more complicated filtering functions without requiring any additional synchronization of the tributary channels can be designed by simultaneously operating on multiple channels by cascading gratings.

Hsu-Feng Chou *et al.* [33] demonstrated the scheme and performance of several elements based upon traveling-wave electro-absorption modulators (TW-EAMs) in wavelength-division-multiplexing (WDM) and optical time-division-multiplexing (OTDM) systems. The integration of traveling-wave (TW) electrode scheme into the electro-absorption modulators (EAMs) provides a relief to the resistance–capacitance (RC) bandwidth restriction common to lumped components thereby facilitating greater operating speed without shortening the device. Hence, high-speed operation can be joined with essential modulator features such as extinction ratio and modulation efficiency. Although important modulation bandwidth has been attained, a less recognized feature is that the TW electrode also delivers an additional dimension for enhancing and enabling functionalities beyond the broadband modulation. This new dimension initiates from the distributed influence of the TW scheme and its collaborations with typical EAM properties. In this paper, such developments in current years with particular applications for optical signal processing in WDM and OTDM systems were analysed. The discussed functionalities consist of a number of optical gating procedures for regenerative wavelength conversions for WDM, OTDM and clock recovery.

Xiao-Ping Xie *et al.* [34] analysed the polarization dependence of demultiplexer based on four-wave mixing (FWM) in semi-conductor optical amplifier (SOA) for optical time division multiplexing (OTDM) system. The polarization states of OTDM data streams and the control pulses plays a significant role in the optical time demultiplexing procedure as it can impact the bit-error rate (BER) performance of the

OTDM system. This work demonstrated the influence of the polarization states of the light on the four-wave mixing of a SOA by using a simulation approach using OptiSystem simulation tool and studied the bit error rate performance of 100Gbit/s OTDM systems for time demultiplexing. It was observed that for OTDM systems, the Q-factor or the BER depends on the misalignment angle θ between the polarization states of the OTDM data pulses and the control pulses. As the misalignment angle θ increases, the BER performance (or Q-factor) and the optical power of resultant FWM component for OTDM system was degraded. The results show that for the linearly polarized lights, the reduction in Q-factor and increment in BER are made easily with θ changing its value from 0^0 to 75^0 whereas it becomes rapid when θ goes beyond 75^0. Although the best BER system performance is achieved for zero misalignment i.e. $\theta = 0^0$, the BER performance can still tolerate some misalignment upto $20^{0.}$ This is helpful in providing applications for optical-time demultiplexing based on SOA and for the engineering designs. From the simulation results for $\theta = 0^0$, the best system bit error rate of 1.25×10^{-12} and the value of maximum Q-factor equal to 6.9 was obtained.

Ming Chen *et al.* [35] demonstrated experimentally the demultiplexing for OTDM system exploiting two concatenated electro-absorption modulators (EAMs). OTDM signal of 80 Gbps was successfully demultiplexed to base rates of 20 Gbps and 10 Gbps using the pair of EAMs, respectively. Simultaneous clock recovery and demultiplexing was done by using the two EAMs in combination with a 10 GHz clock extraction module built using phase-locked loop is bring together to extract the clock from the 80Gbit/s OTDM signal. The EAMs-PLL module was presented for 10GHz clock recovery from 80 Gbps optical time division multiplexing signal. Error-free performance was achieved. The demultilplexing and clock extraction element can further be extended to ultra-high speed OTDM systems.

Jing Xu *et al.* [36] compared the power consumption between point-to-point optical time division multiplexing (OTDM) systems and wavelength division multiplexing (WDM) systems. The benefits and drawbacks of the WDM and OTDM systems were emphasized from an energy efficiency perspective. On investigation, it is found that the topology of the OTDM demultiplexing component should be cautiously selected so as to be comparable to WDM systems in power consumption feature and enhanced and adjustments were to be made between power consumption and speed using state-of-the-art switching techniques. Mainly the power intake of the laser sources in the WDM system and that of the demultiplexing elements in the OTDM structure were compared. To be analogous to the power intake of a WDM system, state-of-the-art demultiplexing units in OTDM networks still require improvement either in switching performance or energy efficiency. Additional investigations were conducted to explore the effect from transmission impairments along with the use of novel technologies.

Nhan D. Nguyen *et al.* [37] presented the demultiplexing and demodulation of 320Gbps OTDM-DQPSK system by either conventional, that is demultiplexing and then detection, or coherent detections using the local oscillator working in pulsed sequence. In a homodyne coherent receiver, a continuous-wave local oscillator (LO) may be interchanged by a short-pulse laser source allowing simultaneous demultiplexing and detection of the multiplexed channels of the ultra-high speed phase modulated OTDM signals. Atleast 5 dB improvement was indicated in the receiver sensitivity by Simulated results over the conventional method by using the pulsed LO coherent receiver. Furthermore, the simplified OTDM receiver configuration using the coherent detection permits a practicability of incorporation of ultra-high speed OTDM technique into compact WDM network for ultra-high capacity optical set-ups.

Yugnanda Malhotra *et al.* [38] demonstrated optical time division multiplexing using MZI switching at 160 Gb/s. Various low speed pulse streams can be multiplexed to generate one data stream of high-speed by using OTDM technique, so that data by each input channel is transmitted in the allotted time slot. A fast multiplexer switch was used to perform the simulation. At the termination of the TDM link, different data streams were routed by using a demultiplexer switch and the demux was implemented using MZI switch as it included a semi-conductor optical amplifier (SOA) and also an optical coupler. The channel presented the simulation of a four channel OTDM at 40 Gb/s and investigated the effect of the pulse width, signal power and control signal power on bit error rate. The mux and demux utilizing the MZI switch sustain the delay between adjacent channels and provide high temperature stability as these are hybrid integrated on the MZI switch.

Khider I *et al.* [39] presented the Spectrum compression depending on filters for the improvement of bandwidth efficiency and experimentally demonstrated for 40 Gb/s OTDM system. Even after 100 km transmission, demultiplexing and clock recovery can be executed successfully, and the improvement in data rate-to-bandwidth ratio has also been realized. Compatibility of AWGs (arrayed waveguide gratings) in WDM networks can be utilized to highly improve the communication capability for WDM and OTDM systems. The filter-based spectral compression was successfully demonstrated and the bandwidth efficiency is significantly improved.

Nan Jia *et al*. [40] demonstrated the performance of system including simultaneous clock enhancing and demultiplexing by utilizing two bidirectionally activated electroabsorption modulators (EAMs). The suggested system was experimentally tested in a 160 Gb/s 100 km transmission system. The clock component of 10 GHz was enhanced before launching it into the clock recovery module. The extracted 10 GHz clock component was presented with low timing jitter (300 fs) and error-free signal transmission was achieved with the power penalty of 0.9 dB. The proposed setup has advantages of simultaneously enhancing the base clock component and demultiplexing. The experimental results represented that the bidirectionally functioned EAM could improve the proportion of clock component of 10 GHz and thereby making it easier to retrieve 10 GHz clock. The recovered clock component was presented with excellent stability and low timing jitter.

Hung Nguyen Tan *et al.* [41] proposed and demonstrated a reconfigurable optical time-division multiplexing (OTDM) to wavelength division multiplexing (WDM) format conversion providing complete flexibility in terms of wavelength allocation and channel spacing. The system comprised of a multiwavelength pulse compressor based on Raman amplification and a sampling gate. Four conventionally produced WDM pulse trains of 10 GHz were compressed to around 2.5 ps at the same time and, then multiwavelength sampling of a 40 Gb/s 3.49 ps OTDM signal was performed. All the four 10 Gb/s tributaries were simultaneously extracted to WDM channels in WDM grid with tunable channel spacing. OTDM tributaries can be easily mapped onto any chosen wavelength order by controlling time delays between the WDM clock channels, which is also termed as wavelength and time-selective function. The reconfigurable functions can be obtained independently on the incoming OTDM signal by simply setting respective parameters of the WDM synchronous pulse trains at the terminals. It is also important for the good overall performance obtained for all demultiplexed channels. Power penalties lower than 1.9 and 2.1 dB are achieved with slight penalty deviations, 0.3 and 0.5 dB, between channels as the conversion of OTDM tributaries to WDM grid takes place with channel spacing of 400 and 200 GHz, respectively.

Jing Xu *et al*. [42] demonstrated for the first time OTDM-DPSK demultiplexing for 80 to 40 Gb/s utilizing a single SOA supported by offset-filtering. Error free performance was accomplished with an average power penalty of 5.5 dB. Apart from high stability, low switching power as well as probability of integration, this particular arrangement is essentially robust to the patterning effects in the SOA. Further, the BER performance is likely to be upgraded by applying shorter pump and/or probe pulses.

Sanmukh Kaur *et al.* [43] investigated the performance of non-return-to-zero (NRZ) and return-to-zero (RZ) modulated signals in all optical time demultiplexing of an OTDM channel using a symmetric semi-conductor amplifier mach-zehnder interferometer (SOA-MZI) as a demultiplexing switch at data rates upto 160 Gbit/s. Firstly, the effect of control signal power, input signal power and pattern length on bit error rate and extinction ratio of demultiplexed channel for RZ and NRZ modulated signals at different bit rates was investigated. Secondly, demultiplexing of OTDM signal to base rate from 160 Gbit/s to 40 Gbit/s was demonstrated successfully providing error-free performance for both modulation formats. In the case of demultiplexing for 40-10 Gb/s and 80-20 Gb/s, error-free performance was achieved with a low bit error rate of the order of 10^{-94} for both the cases. For the similar bit error rate performance at 120-30 Gb/s, RZ signals need 4dBm more input power than the NRZ signal case. For the NRZ case, demultiplexed channel offers 3 dB to 5 dB more extinction at different data rates.

Table2.1 Literature survey of OTDM systems in past few years.

TYPE	AUTHOR	WORKDONE	RESULT
Demultiplexing Based on optical Switching	Z. Ghassemlooy *et al*.	An all-optical symmetric Mach–Zehnder (SMZ) switching based optical switch is proposed and a 1x2 OTDM router was designed using the proposed switch as a building block for asynchronous OTDM packet routing.	The receiver sensitivity noticed for a BER of 10^{-9} is -26 dB in comparison to the baseline detection without using a -38 dB router
	Ming Chen *et al.*	OTDM signal of 80 Gbps was successfully demultiplexed to base rates of 20 Gbps and 10 Gbps using the pair of EAMs.	The optimized switching window obtained was about 6 ps with a suppression ratio of better than 23dB.
	Yugnanda Malhotra *et al.*	160 Gb/s optical time division multiplexing using MZI switching was demonstrated.	Mux and demux utilizing MZI switch sustain delay between adjacent channels and provided high temperature stability.
	Nan Jia *et al*.	The performance of 160 Gb/s 100 km OTDM transmission system including simultaneous clock enhancing and demultiplexing by utilizing two bidirectionally activated electroabsorption modulators (EAMs) was demonstrated.	bidirectionally functioned EAM could improve the proportion of clock component of 10 GHz and thereby making it easier to retrieve 10 GHz clock with excellent stability and low

			timing jitter.
	Sanmukh Kaur *et al.*	The performance of NRZ and RZ modulated signals in all optical time demultiplexing of an 160 Gbit/s OTDM channel using a symmetric semi-conductor amplifier mach-zehnder interferometer (SOA-MZI) as a demultiplexing switch was investigated.	For the NRZ case, demultiplexed channel offers 3 dB to 5 dB more extinction at different data rates.
Demultiplexing using XPM	U.Feiste *et al.*	The first 160 Gbps return-to-zero (RZ) transmission on field-installed G.652 standard fiber was investigated.	For a bit rate of 160 Gbit/s, a receiver sensitivity (BER = $l0^9$) of -22.4dBm and -20.7dBm at a base rate of 10 and 40 Gbit/s was achieved, respectively.
	Jie Li *et al.*	A vigorous and simple 160 Gb/s all-optical optical time-division demultiplexing method using cross-phase modulation (XPM)-induced wavelength shifting in 100 m highly non-linear fiber (HNLF) using following optical filtering was investigated.	All-optical demultiplexing of data from 160 Gb/s to 10 Gb/s with 2.8 ps switching window was successfully demonstrated. The measured receiver sensitivities were between 32 and 34.2 dBm.
OTDM comparison	Martin M. Strasse *et al.*	Experimentally and theoretically compared the performance of ETDM and OTDM	OTDM receivers offer a small sensitivity advantage due to reduced ISI.
	Jing Xu *et al.*	The power consumption between point-to-point OTDM systems and WDM systems was compared.	Demultiplexing units in OTDM networks still require improvement either in switching performance or energy

			efficiency.
Conversion techniques	Paulo J. Almeida *et al*.	Transformation of 40 Gb/s OTDM signal into 4×10 Gbps WDM signals and employing FBG for the frequency-domain add–drop multiplexing.	An error-free process for the dropped, and added channels and a timeslot suppression ratio of 30 dB in excess were attained.
	Hung Nguyen Tan *et al.*	OTDM to WDM format conversion providing complete flexibility in terms of wavelength allocation and channel spacing was demonstrated.	Power penalties lower than 1.9 and 2.1 dB were achieved with slight penalty deviations, 0.3 and 0.5 dB, between channels.
Demultiplexing using SOA	Xiao-Ping Xie *et al.*	The polarization dependence of demultiplexer based on FWM in SOA for OTDM system was analysed.	For the linearly polarized lights, the reduction in Q-factor and increment in BER were made easily by changing θ.
	Jing Xu *et al.*	For the first time OTDM-DPSK demultiplexing for 80 to 40 Gb/s utilizing a single SOA supported by offset-filtering was demonstrated.	Significant cross-talk from the non-target channel was observed, which explains the large power penalty for 80 Gb/s demultiplexing and the observable error-floor.

CHAPTER 3

160 Gb/s OTDM DQPSK SYSTEM DEMULTIPLEXING USING CASCADED MACH-ZEHNDER MODULATORS

In this chapter, 160 Gb/s OTDM DQPSK system with optical gating using mach-zehnder modulator and clock recovery is analyzed. Error free transmission is achieved over 120 km fiber link. Basically, four tributaries are DQPSK modulated and time-division multiplexed. At the receiver side, a clock extraction circuit is employed. The 160 Gb/s data signal is split into two parts, one is utilized for clock recovery while another is used for further demultiplexing. The cascaded mach-zehnder modulators are used to produce short optical gate pulses. The two Mach-zehnder modulators help in the extraction of low timing jitter clock and hence error-free transmission is realized. Highly improved performance with low power penalty is obtained.

3.1 Introduction

The growth of optical components has focussed on the configuration of higher point-to-point capacity networks as a simple source to transport the essential data traffic. Relating the advances in optical technology and possible restrictions in electronics, it has been known that there may be benefits in using reconfigurable optical transmission systems [2]. There are several multiplexing techniques used for optical fiber communication including FDM (frequency division multiplexing), TDM (Time Division Multiplexing) and WDM (Wavelength Division Multiplexing). Very high speed optical time division multiplexing (OTDM) systems play significant role to satisfy increasing demand for high capacity optical systems. OTDM system provides bit rates upto 1.28 Tbit/s. Optical signals having steady pulse separation are time-division-multiplexed in order to reduce crosstalk among adjacent data pulses on demultiplexing and to diminish the timing jitter [43]. The main principle of optical time division multiplexing and demultiplexing includes allocating time slots to all baseband data streams. A multiplexer bring together the bit stream having higher bit rate from the baseband streams at the actual lower bit rate by splitting bits in the multiplexed stream. The demultiplexer plays most critical part in an OTDM system. Most of the photons from every incoming bit should be transmitted to the suitable O/E converter in order to have good system sensitivity. Demultiplexing is considered as one of the fundamental technologies in OTDM systems and it can be implemented based on ultrafast non-linear interferometer (UNI) [15], non-linear optical loop mirror (NOLM) [44], or by using a Mach-zehnder interferometer (MZI) [45] based upon semiconductor optical amplifiers (SOAs). Successful demultiplexing also depends on correct timing recovery [3]. For 160 Gb/s OTDM system, a simple method of demultiplexing is using electro-optical on-off gates based on electro-absorption modulators (EAM) [44] or mach-zehnder modulator (MZM).

Volkan Kaman et al. [47] investigated the use of a single electro-absorption modulator (EAM) to simultaneously demultiplex and identify a single channel from a bit-interleaved data signal such that the other channel is left unaffected.

Nan Jia et al. [40] demonstrated a method for executing optical time-division demultiplexing and simultaneous clock enhancing using two bidirectionally operated electroabsorption modulators (EAMs). The system performance is tested experimentally in a 160 Gb/s 100 km transmission network. The result of the proposed scheme shows that by using the two EAMs, it becomes easy to recover 10 GHz clock and the recovered clock is presented with low timing jitter. The switching windows can be reduced further more by utilizing more than one EAM modulator, permitting simple advancements as the data rate improves.

Using cascaded electro-absorption modulator results in large loss causing signal to noise ratio (SNR) degradation and temperature feedback control is required. However, the advantage of low insertion loss can be realized by using two cascaded MZMs as compared to the system using EAM.

In this chapter, two cascaded MZMs are used as optical gate producing a gate pulse of high quality to enable 4:1 demultiplexing of 160 Gb/s signals and comparatively enhanced bit error rate performance is achieved. The chapter is organised as follows: section 1.2 includes theoretical Analysis of cascaded mach-zehnder modulators, section 1.3 describes in detail the simulation setup for the generation of optical gating using MZM and its results, and section 1.4 concludes the paper.

3.2 Theoretical Analysis

In OTDM system, several demultiplexing techniques can be used including Four Wave Mixing, optical gating by using different optical modulators and also by implementing different clock extraction techniques. Simultaneous clock recovery and demultiplexing can be employed using electro-absorption modulator, mach-zehnder modulator and/or combination of both. The proposed system uses two cascaded mach-zehnder modulators with a clock recovery circuit in order to obtain an ultra-low timing-jitter clock recovery with the capability of simultaneous time-division demultiplexing. Basically, a mach-zehnder modulator multiplexes two sets of electrical signals in the time domain such that these two signals modulate the CW light passing through the modulator.

The output electric field of an MZ modulator is expressed in equation (3.1) [48]

$$E_o = E_i/2\ \{e^{j\phi}{}_1 + \Upsilon e^{j\phi}{}_2\} \qquad (3.1)$$

Where, E_o is the incoming electric field that undergoes a phase change in each arm of an MZ modulator and Υ is the scaling factor whose value lies from zero to one that accounts for an asymmetric device, and ϕ_1 and ϕ_2 are phase changes in arm1 and arm2, respectively. The scaling factor, $\Upsilon<1$, if the splitting/combining ratios of MZM are not exactly 50/50, or the losses in the two arms are different. The splitting ratio can easily be extracted by measuring the dc extinction ratio ($\mathcal{E}$) which is the ratio of maximum to minimum optical output intensity [48].

$$\Upsilon = (\mathcal{E}^{1/2} - 1)\ (\mathcal{E}^{1/2} + 1) \qquad (3.2)$$

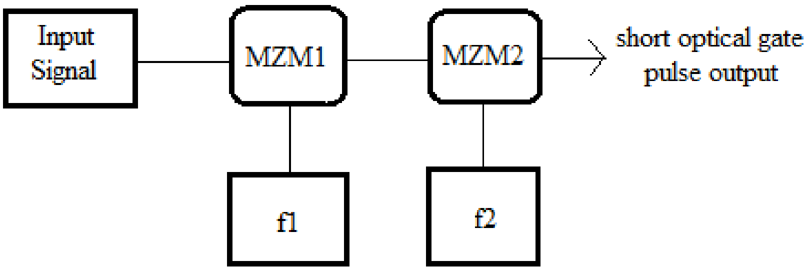


Fig.3.1. Optical gating using cascaded Mach-zehnder modulators

Here, two cascaded mach-zehnder modulators are used such that MZM1 produces spectral lines parted by a frequency f_1 [49]. Then, MZM2 re-modulates these seeding components with a frequency f_2 as shown in Fig.3.1. RF power and DC bias in both MZMs are adjusted so as to obtain same amplitude and phase and additional sidebands are highly suppressed.

3.3. Simulation and Results

The simulation arrangement for 160 Gb/s OTDM DQPSK system employing Mach-zehnder modulator with simultaneous clock recovery is shown in Fig.3.2. The performance of 160-Gb/s demultiplexer using the cascaded MZM is measured using this arrangement. The transmitter consists of a narrow pulse source emitting pulses of 40GHz repetition rate with center frequency 193.1 x 10^{12} Hz and T_{FWHM}= 0.5 s. Then the four channels are DQPSK modulated and time delay is provided to these channels in order to implement time-division multiplexing. The DQPSK technique provides double bit rate as it transmits two bits per symbol.

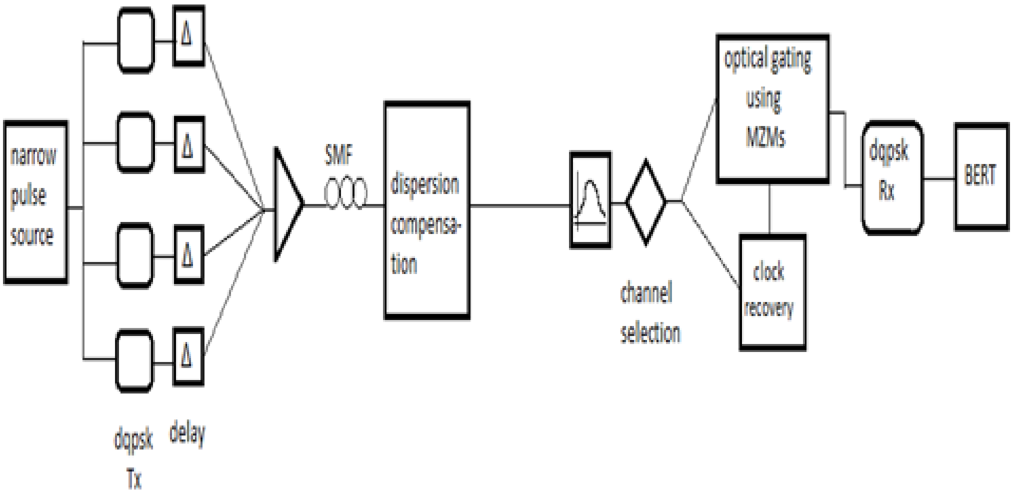


Fig.3.2. Setup for 160 Gb/s OTDM DQPSK Tx and Rx using MZM and clock recovery

As data rate increase, OOK-NRZ or RZ modulation formats becomes inefficient from bandwidth point of view. DQPSK enables high spectral efficiency and hence can be implemented in ultra-long haul transmission. Fig.3.3 shows the transmission channel waveforms for four different channels.

These four signals are transmitted on a 120 km SMF (single mode fiber). The channel consists of dispersion compensation circuit to combat the effect of dispersion losses encountered in the optical fiber. Then the signal is filtered with a bandpass optical filter (BPF) having bandwidth of 200 GHz. The receiver section includes a channel selector, optical gate with simultaneous clock recovery and DQPSK receiver. The OTDM tributaries can be selected orderly by using a channel selector before optical gating and clock recovery.

Table 3.1 Parameters used

Parameters	**Value**
FWHM	0.5 s
Time Window	12.8×10^{-9} s
Center Frequency	193.1×10^{12} Hz
Laser Source Parameters	**Value**
Pulse shape	Gaussian
Emission Frequency	193.1×10^{12} Hz
Peak Power	1 mW
MZM parameter	**Value**
Extinction ratio	30 dB

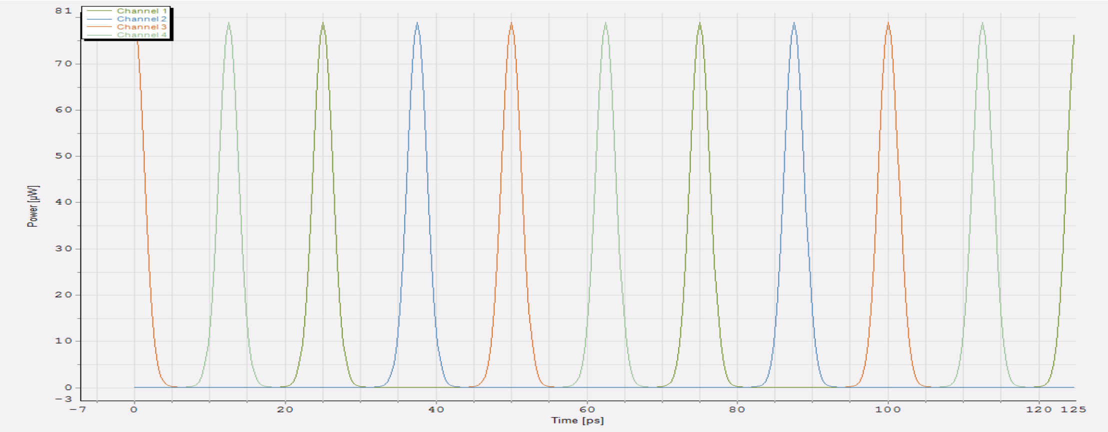


Fig.3.3. Transmission channel waveforms

The 160 Gb/s data signal is divided into two branches using a 3 dB coupler, one is utilized for clock recovery while another is for further demultiplexing. The incoming signal is provided in a clock recovery circuit generating two clock signals of 20 GHz and 40 GHz. These clock signals are input to the two cascaded mach-zehnder modulators with incoming signal as the other input. After providing both the inputs to first mach-zehnder modulator, a short optical gate output can be obtained but enhanced output can be achieved after passing the signal through second mech-zehnder modulator.

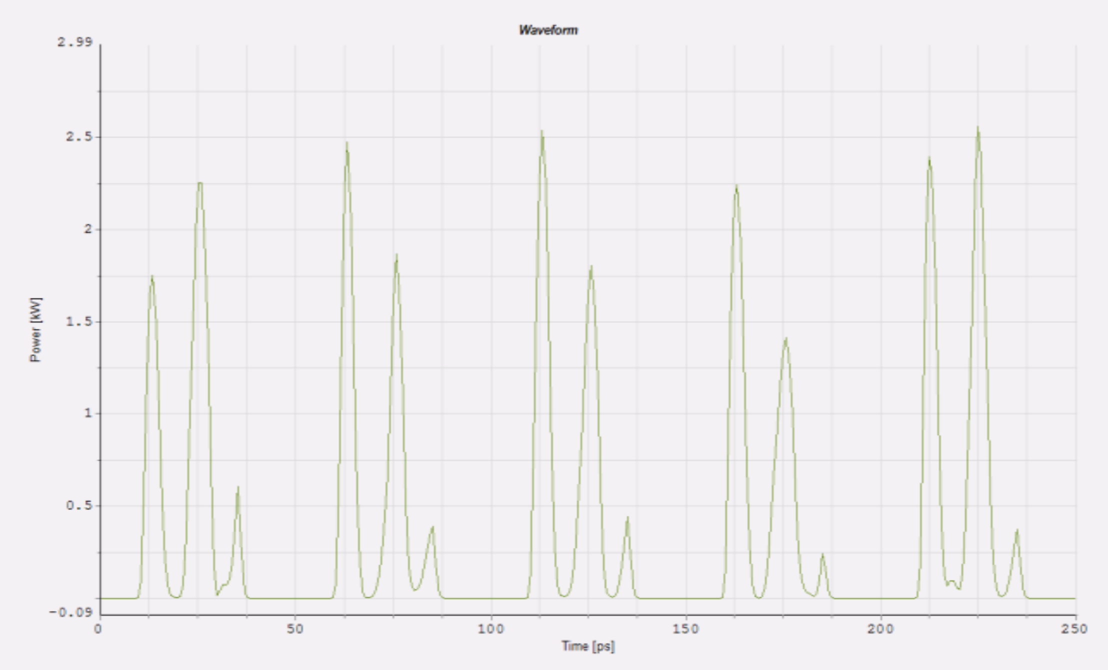


Fig.3.4. Output after MZM1

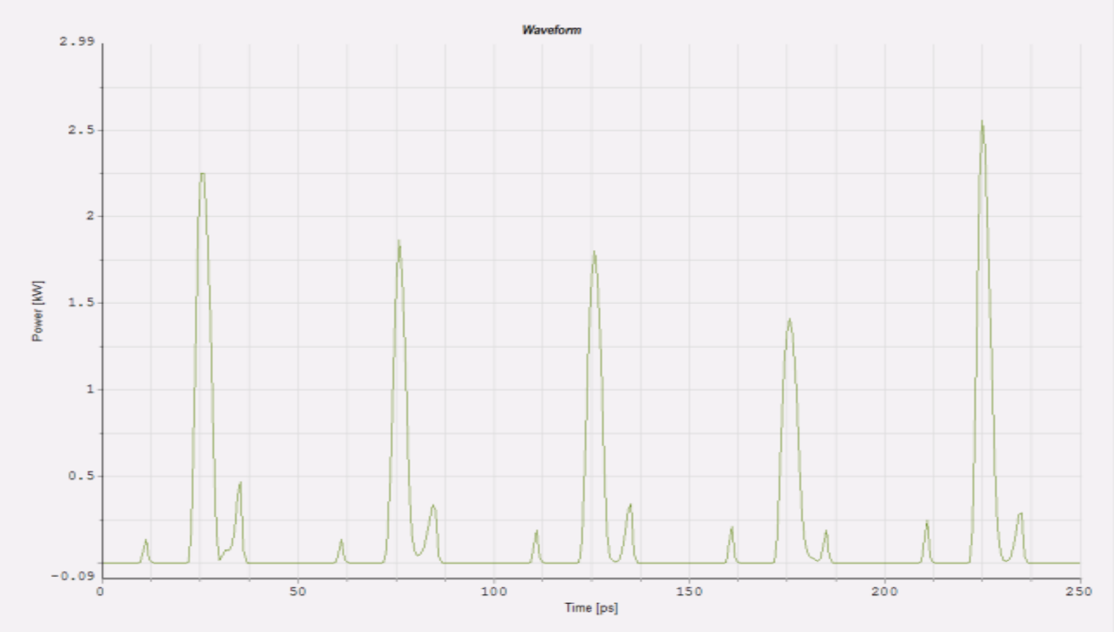
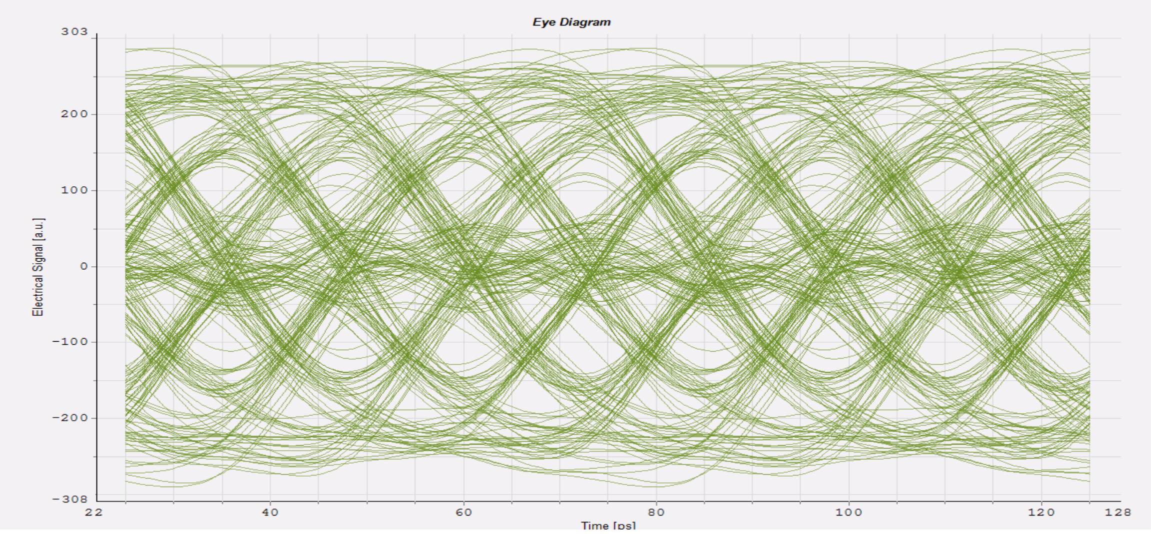
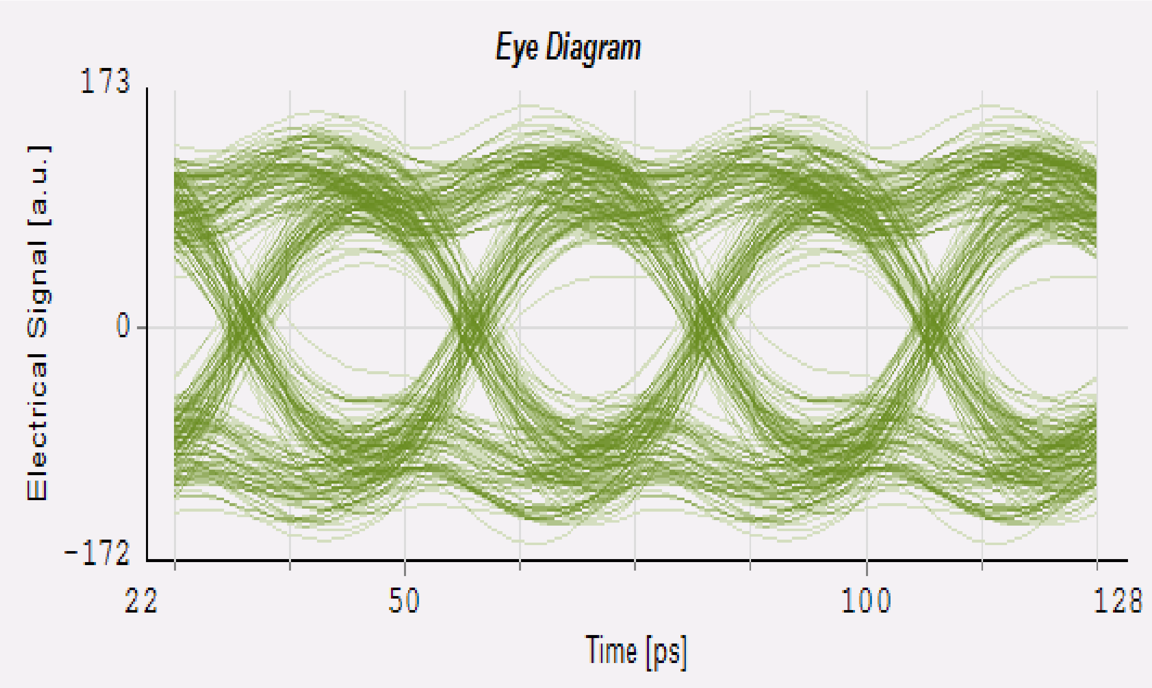


Fig.3.5. Output after MZM2

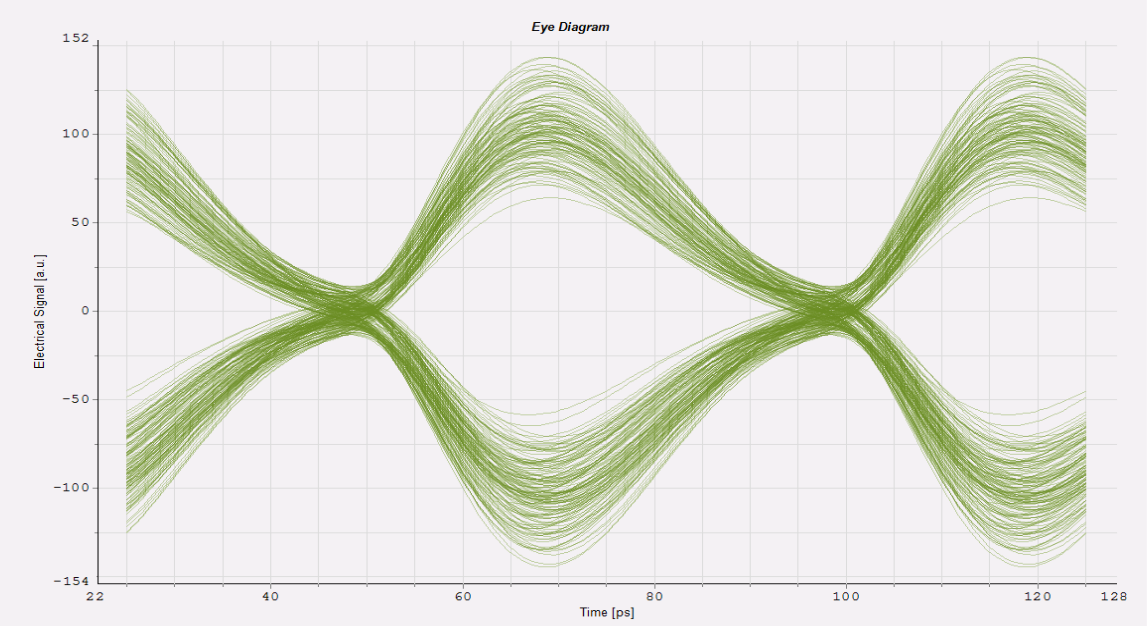
The selected channel after this optical gate is shown in figures 3.4 and 3.5. Fig 3.4 shows the output of first mach-zehnder modulator and Fig.3.5 shows the output of second mach-zehnder modulator. The extinction ratio of mach-zehnder modulator is 30 dB. Hence we obtain an optimized window generation after using the two cascaded mach-zehnder modulators. MZM 1 generates a switching window of approximately 25 ps and MZM 2 provides an optimized shortened switching window of approximately 6ps at the repetition rate of 40 GHz.



(a)



(b)



(c)

Fig. 3.6 Eye diagrams

Finally the output signal can be obtained using DQPSK Rx. The eye diagram for back to back system (i.e. the system without using clock recovery and optical gating) and the system with using MZM is presented in Fig.6. Fig 6(a) represents the eye diagram for the simple configuration of the OTDM system in which no optical dating using the mach-zehnder modulator is used, Fig.6(b) and (c) represents the eye diagrams for the cases of demultiplexing using optical gating using single MZM and two cascaded MZMs, respectively. It can be clearly observed by comparing the eye diagrams for the different cases that an improved eye-diagram can be achieved for the case of single MZM as compared to the system without using any optical gating and further, it can be shown that more enhanced and open eye diagram is achieved for the system architecture using more than one mach-zehnder modulator i.e. using cascaded modulators.

The bit error rate performance for demultiplexing is estimated by using a bit error rate tester (BERT). Fig 3.7 shows the BER vs. OSNR graph. It represents the averaged bit error rate measurement of the 160 Gb/s DQPSK OTDM system after transmission for demultiplexed tributaries against optical signal-to-noise ratio.

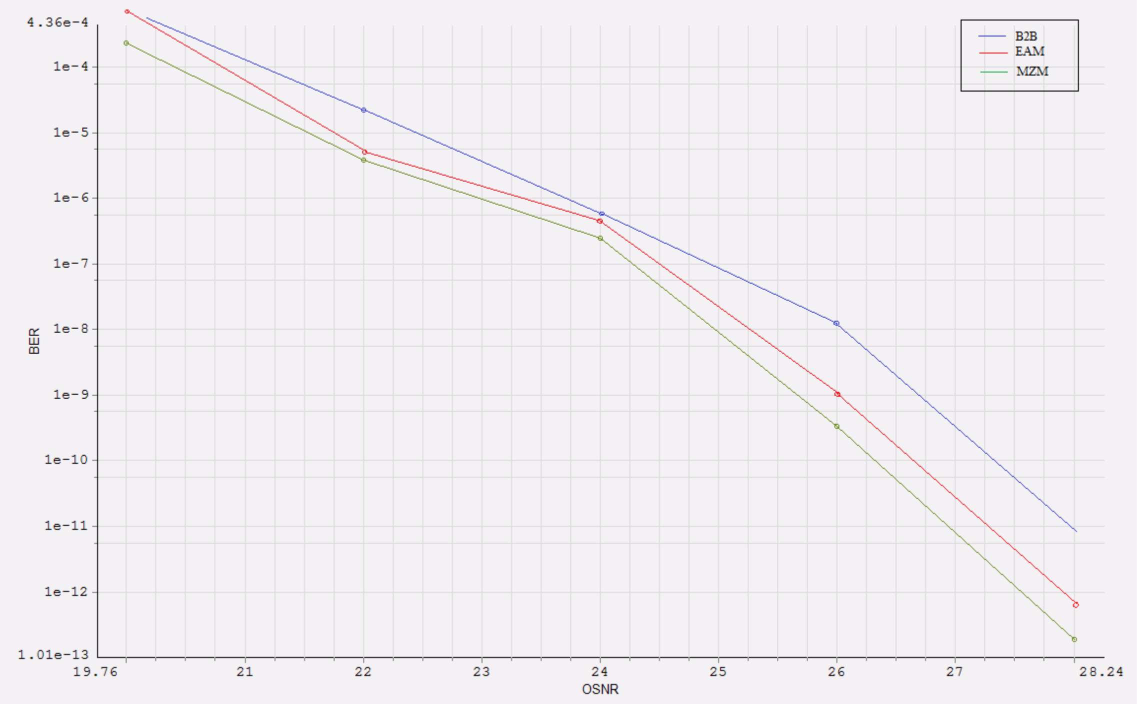


Fig.3.7. BER vs. OSNR graph

This figure compares the back to back system performance with the system using the optical gating and clock recovery system for the cases of electro-absorption modulator and mach-zehnder modulator. It can be clearly observed from the figure that highly improved bit error rate performance is achieved after employing the clock recovery circuit and the optical gating using mach-zehnder modulators.

Fig.3.8 shows the BER performance for the demultiplexing using single MZM and cascaded MZM. In case of the 160 Gb/s OTDM system using single mach-zehnder modulator for optical gating, 40 GHz clock recovered from the clock recovery circuit is applied to the mach-zehnder modulator with the incoming data signal being the another input to the modulator.

BER vs OSNR plot displays that the bit error rate performance for the case of optical gating using cascaded mach-zehnder modulator is improved as compared to the demultiplexing using single modulator. The switching window obtained using two cascaded mach-zehnder modulators is more optimized and offers lesser amount of adjacent channel crosstalk.

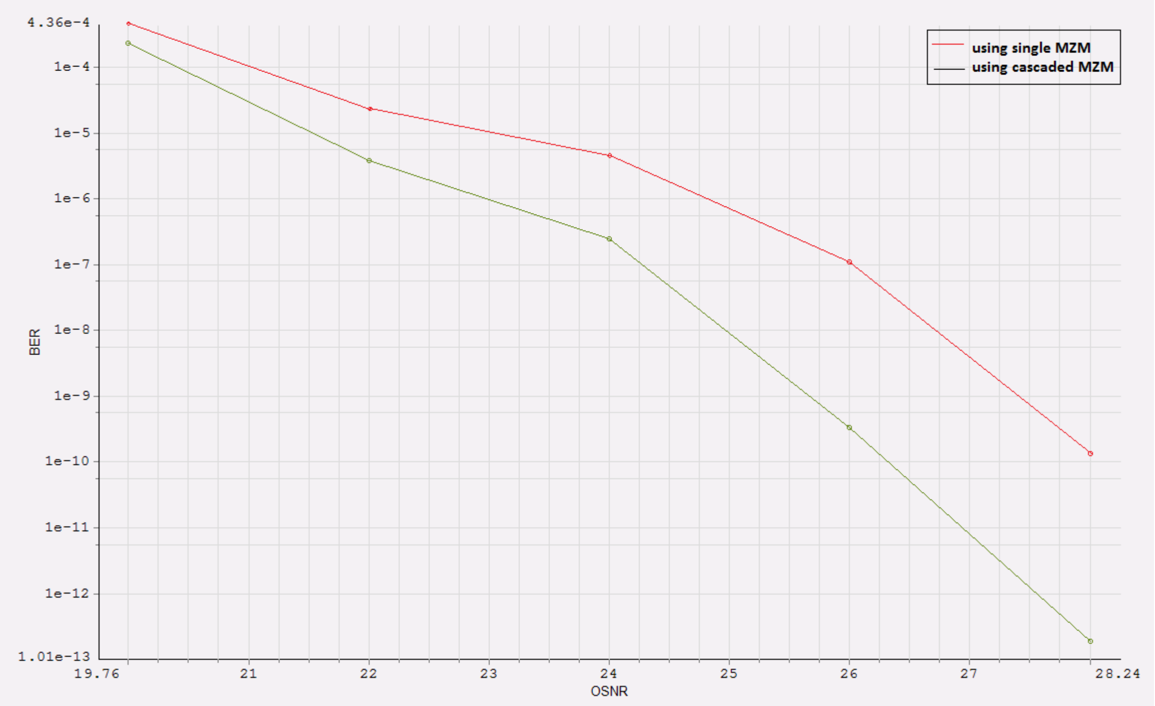


Fig.3.8. BER vs. OSNR for single and cascaded MZM

3.4 Conclusion

This chapter presents the utilization of two cascaded mach-zehnder modulators with clock recovery circuit for improved OTDM receiver by generating short optical pulses. This technique is successfully demonstrated for 160 Gb/s OTDM DQPSK system showing error-free transmission with power penalty less than 1 dB. The simulation results show that the clock component can be enhanced using MZ modulator in order to make clock recovery easier.

CHAPTER 4

OTDM-TO-WDM CONVERSION BASED ON FWM AND TIME GATING

This chapter presents the serial-to-parallel transformation of optical time division multiplexed (OTDM) data tributaries into wavelength division multiplexed (WDM) channels from 160 Gbit/s to 4x40 Gbit/s by using four-wave mixing (FWM) in highly non-linear fiber (HNLF) following an optical gate based on single electro-absorption modulator. The FWM is implemented by using pump pulses. The complete simultaneous error-free demultiplexing of a 160-Gb/s OTDM data stream to 4x40-Gb/s WDM channels is successfully demonstrated thereby achieving an error-free performance.

4.1 Introduction

Rising demands to increase capacity have led to the growth of high-speed optical shared media networks. Multiplexing techniques like optical time division multiplexing (OTDM) and wavelength division multiplexing (WDM) can propose broad bandwidths in addition to the ability to provide remote signal processing [50]. The Optical time division multiplexing (OTDM) is a simple technique providing high-speed data generation beyond the bandwidth limitation of electronics. In OTDM signal, various optical pulse streams, termed as tributaries (originated from the identical laser i.e. having same wavelength), are independently encoded by electrically produced data signals. These tributaries with low duty cycle pulses are serially bit interleaved in order to form the OTDM signal [51]. Optical networks may profit from a combined arrangement of WDM (wavelength-division multiplexing) and TDM (time-division multiplexing) in terms of growing transmission capacity, decreasing power consumption, and making the network management simple [52]. In the case of WDM (wavelength division multiplexing), an optical channel is allocated to each electrical data stream with its own central wavelength and each produced from a different laser. In comparison to OTDM, WDM channels can overlap in the time domain (parallel to each other) and these channels can be selected by optical filtering at the receiver side. At the receiving end in OTDM systems, the tributaries are conventionally demultiplexed in distinct high-speed switches. Therefore, power consumption and complexity of the receiver essentially scale with the number of OTDM tributaries. In order to combat this problem, various demultiplexing techniques for the tributaries in a single switch by serial-to-parallel conversion have been proposed [53]–[55]. One of such technique is OTDM to WDM conversion. Different techniques can be used for this.

Rui Morais et al. [56] demonstrated the conversion of wavelength using side filtering of SPM broadened spectrum in highly non-linear fiber (HNLF), following optical gate based on a single EAM. OTDM-to-WDM transformation from 128.1Gbit/s to 3×42.7Gbit/s is realized. To perform the wavelength conversion, the OTDM signal was passed through a commercial HNLF. After spectral broadening due to SPM in the HNLF, two tunable filters are used to perform side filtering. The results of BER measurement present a maximum of 2dB penalty for the central channel at a BER of 10^{-9} and no error floor.

But the system configuration utilized is somewhat complex and also simultaneous trans-multiplexing is not achieved. Hence in order to attain simultaneous OTDM-to-WDM transformation, a technique called Four-wave mixing can be used.

In this chapter, conversion of several 40 Gb/s tributaries of a 4 × 40 Gb/s OTDM signal onto a WDM grid using four wave mixing (FWM) and time gating is described. The basic approach used here is to reproduce the original OTDM signal to four separate wavelengths. This involves FWM (four-wave mixing) based phase modulation which takes place between the data pulses and linearly chirped pump pulses [57]. Using this method, the time information of the time-division multiplexed signal is represented on the power spectrum of the idler which is produced in the FWM procedure thereby transforming the time-interleaved OTDM tributaries to various wavelengths.

This chapter is organised as follows: section 4.2 includes theoretical analysis of four wave mixing and how wavelength conversion is carried out using this technique, section 4.3 includes simulation setup of the proposed scheme and corresponding results, and finally section 4.4 provides the conclusion of the chapter.

4.2 Theoretical Analysis

The basic principle used here for Time-Division Multiplexing to Frequency-Division Multiplexing is four-wave mixing. The operation of phase-modulation must occur at the base rate of the tributaries, so as to map individual pulse of a tributary to the particular DWDM wavelength. In this chapter, the operation performed is at a base rate of 40 GHz. A Gaussian pulse having full-width at half maximum width (FWHM) of 1.5 ps is implemented for 160 Gbit/s data. Phase-modulation by a parametric process such as FWM is required to generate the required linear chirp over such a relatively large time span requires. Fig.4.1 shows the basic concept of OTDM to WDM conversion using four-wave mixing. Basically, FWM is a non-linear effect rising from a third-order optical nonlinearity. This can take place if at least two different frequency components are transmitted simultaneously in a non-linear medium, for example an optical fiber. Supposing only two input signals with frequencies, ν_1 and ν_2 (with $\nu_2 > \nu_1$), then at the difference frequency, a refractive index modulation will take place resulting in two additional frequency components [58].

To achieve high chirp rate, the phase modulation can be implemented via FWM. In FWM process, the conversion of signal to an idler $E_i(t)$ takes place which combines the phases of both signal and pump as shown in equation (4.1).[43]

$$E_i(t) \propto E_p^2(t)E_s^*(t) \qquad (4.1)$$

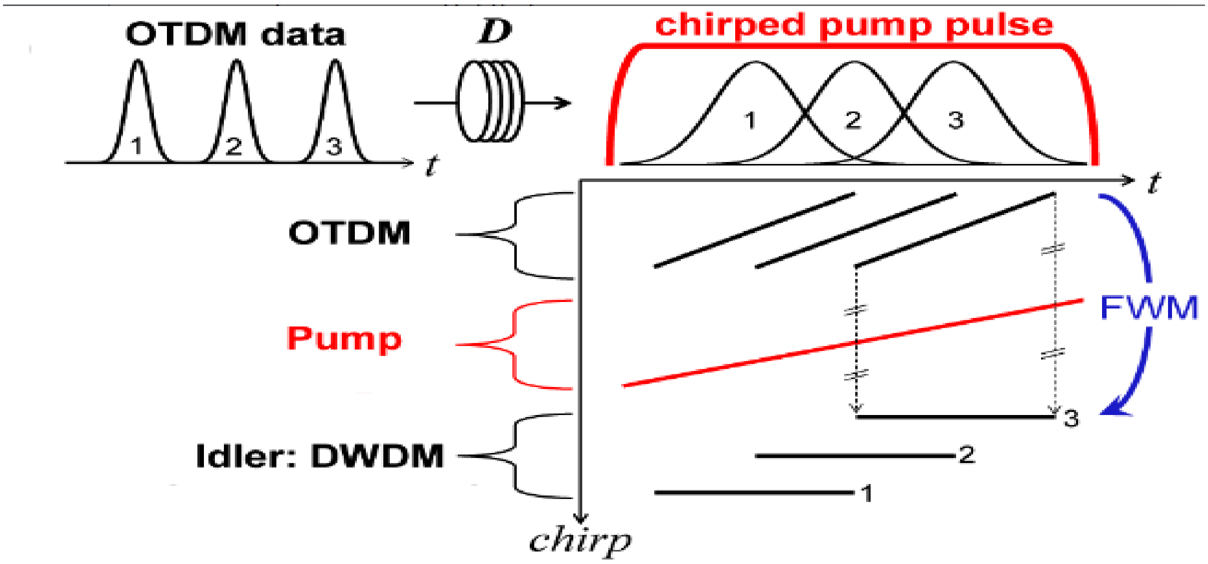


Fig.4.1. Basic principle of OTDM to WDM conversion using FWM

FWM is a phase-sensitive method (i.e., the interaction depends on the relative phases of all beams), its effect can efficiently accumulate over longer distances e.g. in a fiber, only if a phase-matching condition is satisfied.

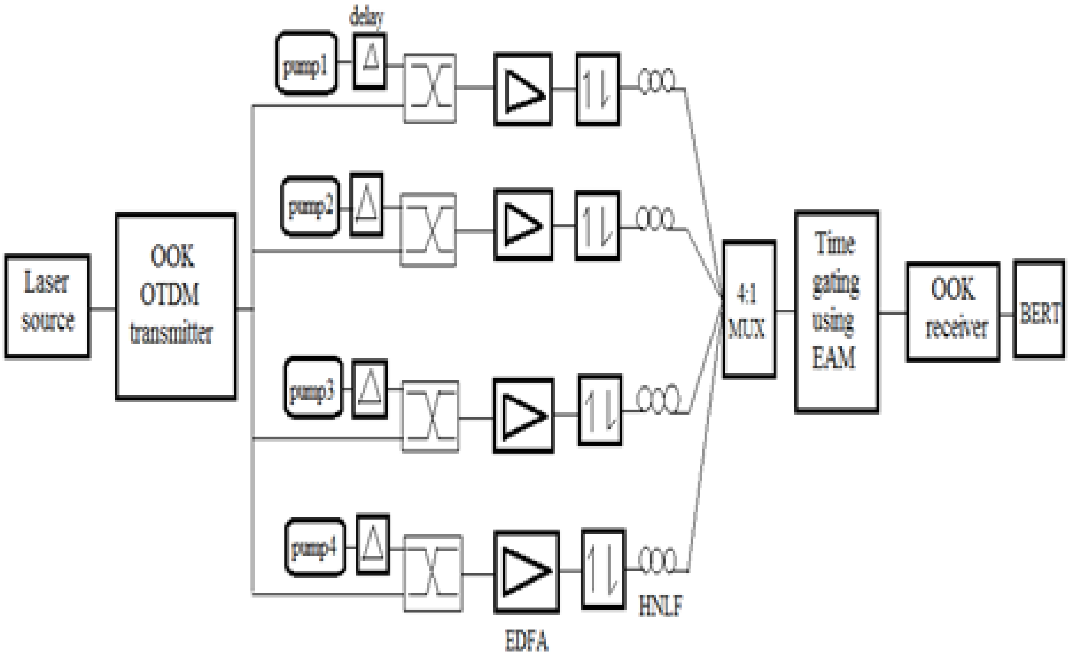


Fig.4.2. Setup for OTDM-to-WDM conversion using FWM, EDFA: erbium-doped fiber amplifier, HNLF: highly non-linear fiber, BERT: bit error rate tester, EAM: electro-absorption modulator

4.3 Simulation and Results

The experimental setup of the OTDM-to-WDM converter is shown in Fig.4.2. A CW laser is used with optical frequency $193.1 x 10^{12}$ Hz and launch power 1 mW at a repetition rate of 40 Gb/s. The pulses are OOK (ON-OFF keying) modulated and then time-interleaved in four different channels in order to generate the time-division multiplexed signal. An OTDM signal of 160 Gbps is transformed into four 40 Gb/s WDM channels. Here, pulsed pump lasers are used to sample the input signal into four separate channels at 40 Gbps each and then amplified using EDFA amplifier and resampled to modify the sample rate and center frequency of the sampled band signals and/or changes the spectral width of the noise bins. Four different pump signals at wavelengths 1578 nm, 1561 nm, 1545 nm and 152 nm are used for channels from 1 to 4 respectively.

Then, every channel (OTDM plus pump as shown in Fig.4.3.) is fed into a fiber of 10 km length. FWM takes place within the fiber and produces the required output frequency of each channel. The WDM channels are then multiplexed to show the WDM spectrum as shown in Fig.4.4.

Parameters	**Values**
Launch Power	1 Mw
OTDM optical frequency	$193.1x10^{12}$ Hz
OTDM pulse width	$1.5x10^{-12}$ s
Pump pulse width	$1.5x10^{-12}$ s
Channel spacing	$4x10^{12}$
WDM ch1 frequency	$196.1x10^{12}$ Hz
WDM ch2 frequency	$194.1x10^{12}$ Hz
WDM ch3 frequency	$192.1x10^{12}$ Hz
WDM ch4 frequency	$190.1x10^{12}$ Hz

Table 4.1 Parameters used and their value

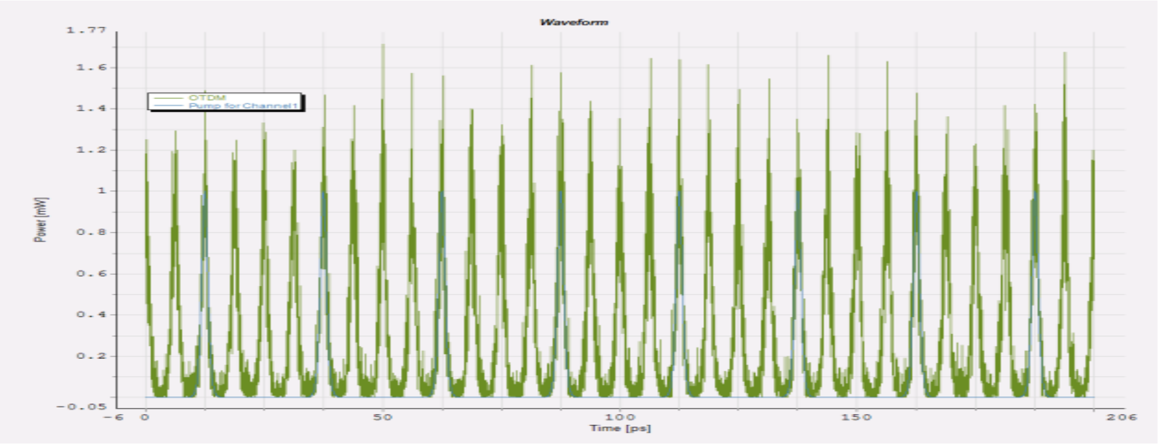


Fig.4.3. OTDM and pump pulse

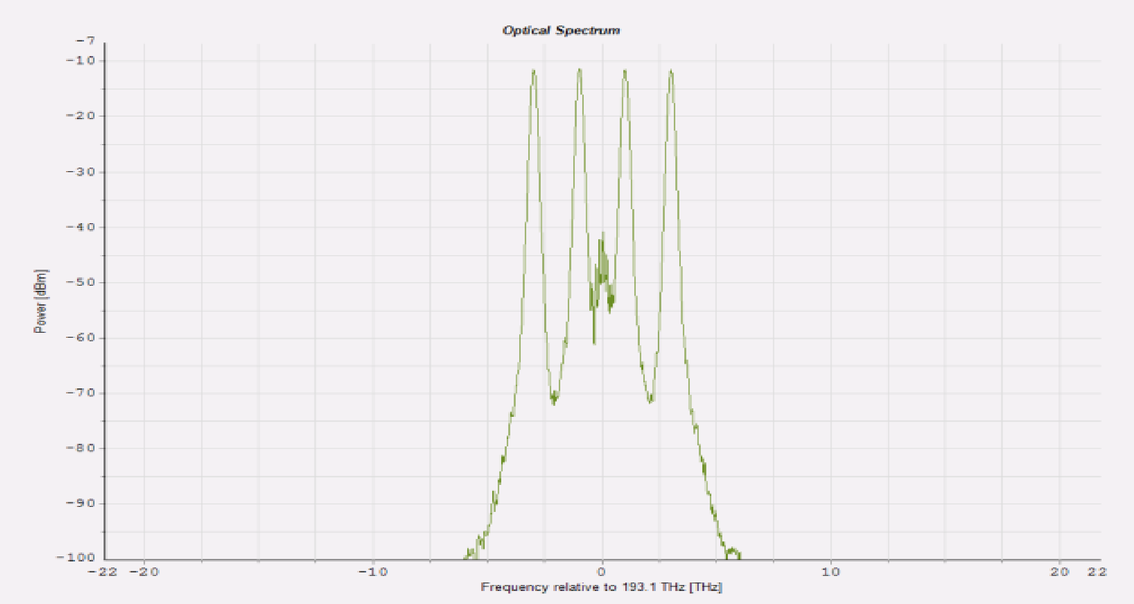
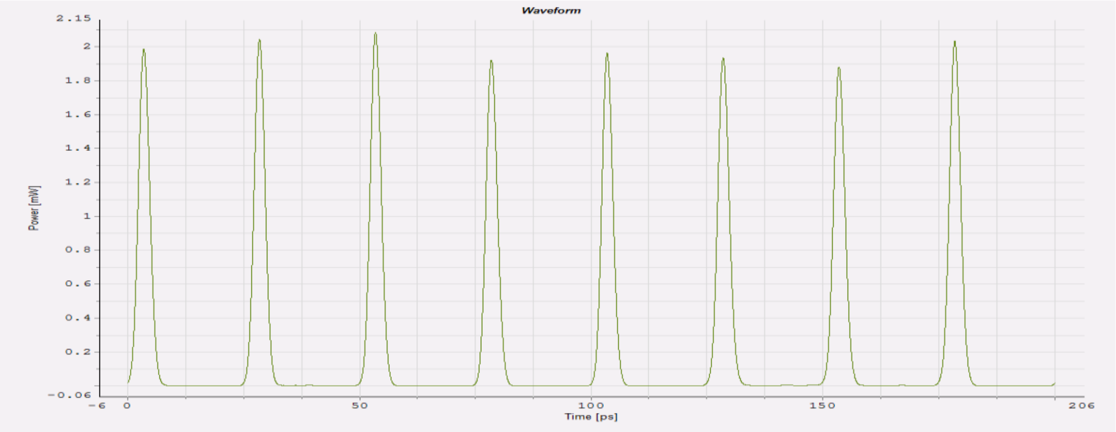
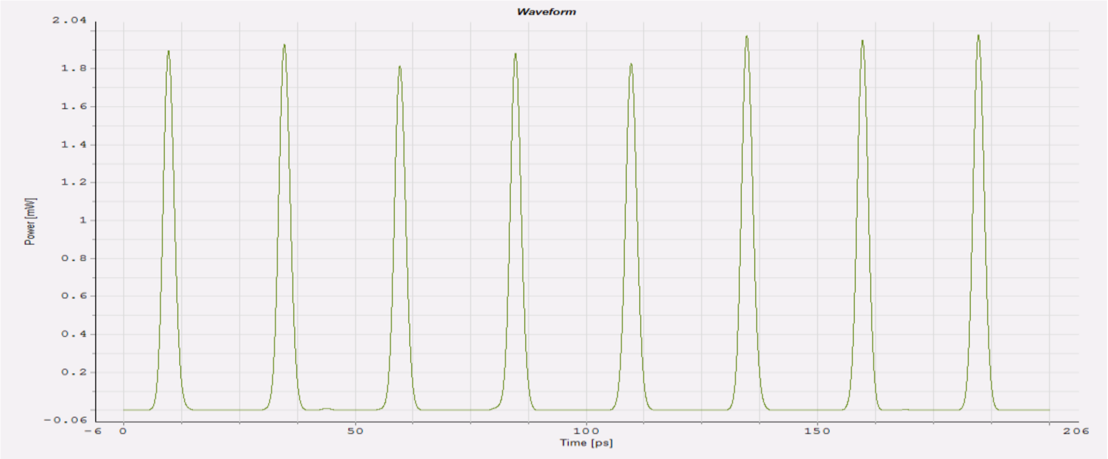


Fig.4.4. Multiplexed WDM channels

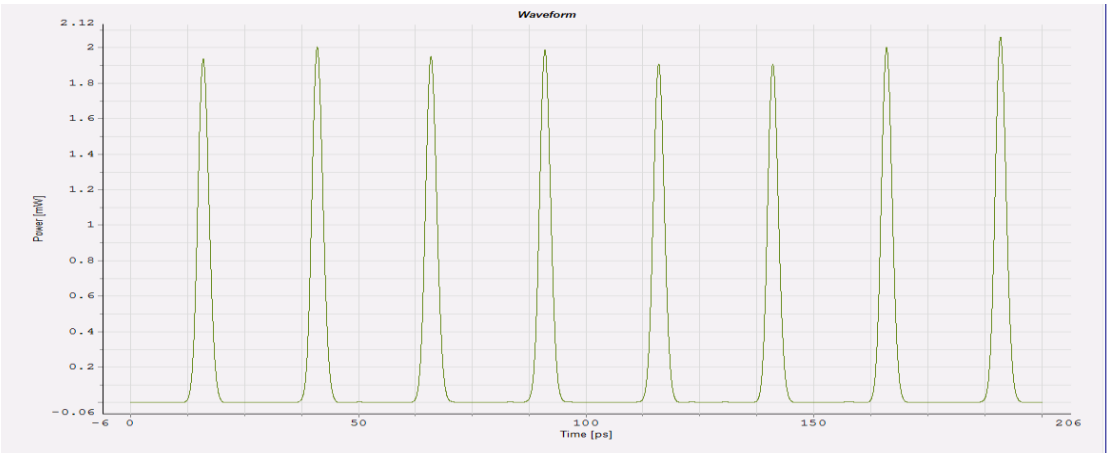
Fig.4.5 (a, b, c, d), (e) Shows the demultiplexed WDM channels to show individual and combined time traces, respectively. After trans-multiplexing, now the WDM signals are forwarded to the receiver side. The optical gate used is based on Electro-Absorption Modulator (EAM) at 40 Gb/s. After gating, filtering of the resultant WDM signal is done and it is fed to the OOK receiver and further to Bit-error rate tester (BERT) to determine the BER performance of the system.



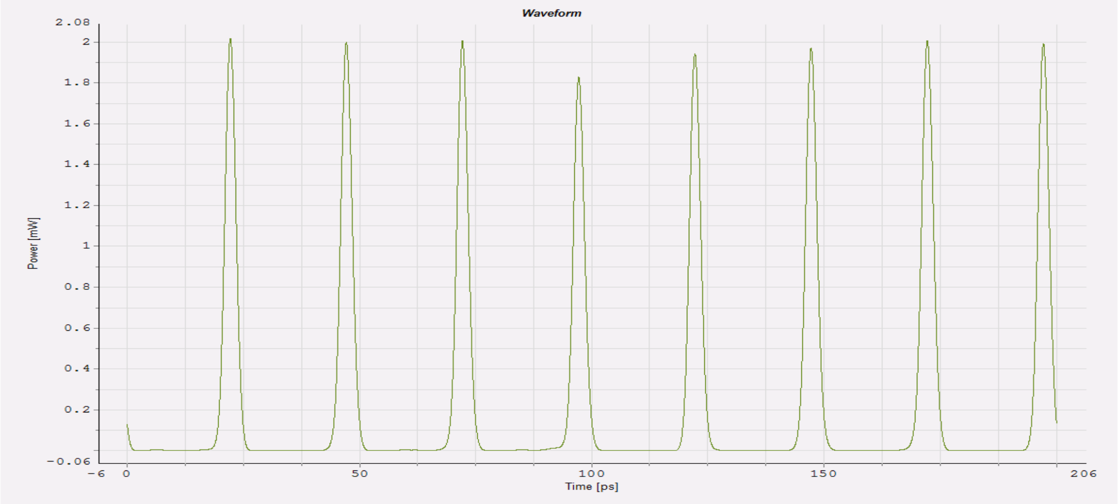
(a) Channel 1



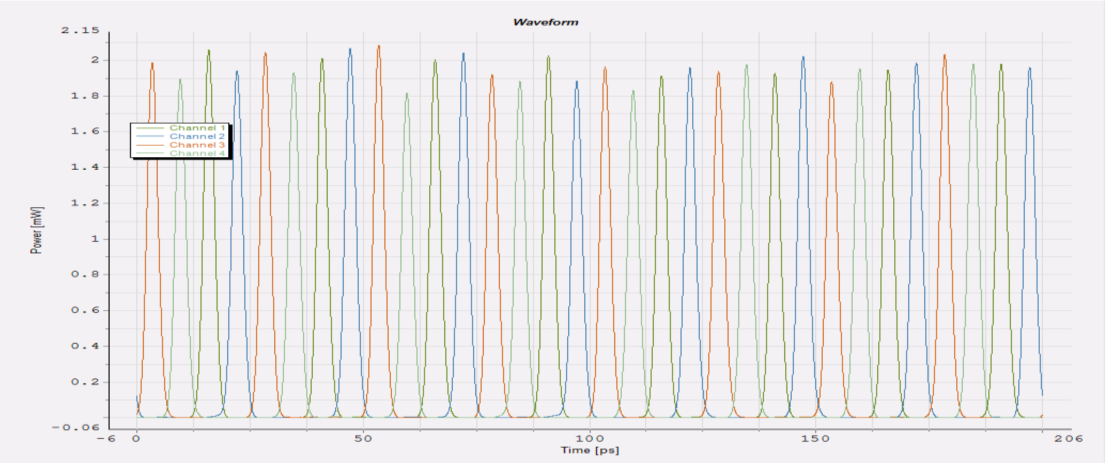
(b) Channel 2



(c) Channel 3



(d) Channel 4



(e)

Fig.4.5 Demultiplexed and Combined WDM Channels

Fig.4.6 represents the optical spectrum of four WDM channels. For simultaneous mapping and fine equalization, the pump pulse should have the width of the tributary bit slot and there should be no interference between the neighbouring pump pulses. After optical gating and demultiplexing, the finally received WDM signal with different wavelengths is shown in Fig.4.7.

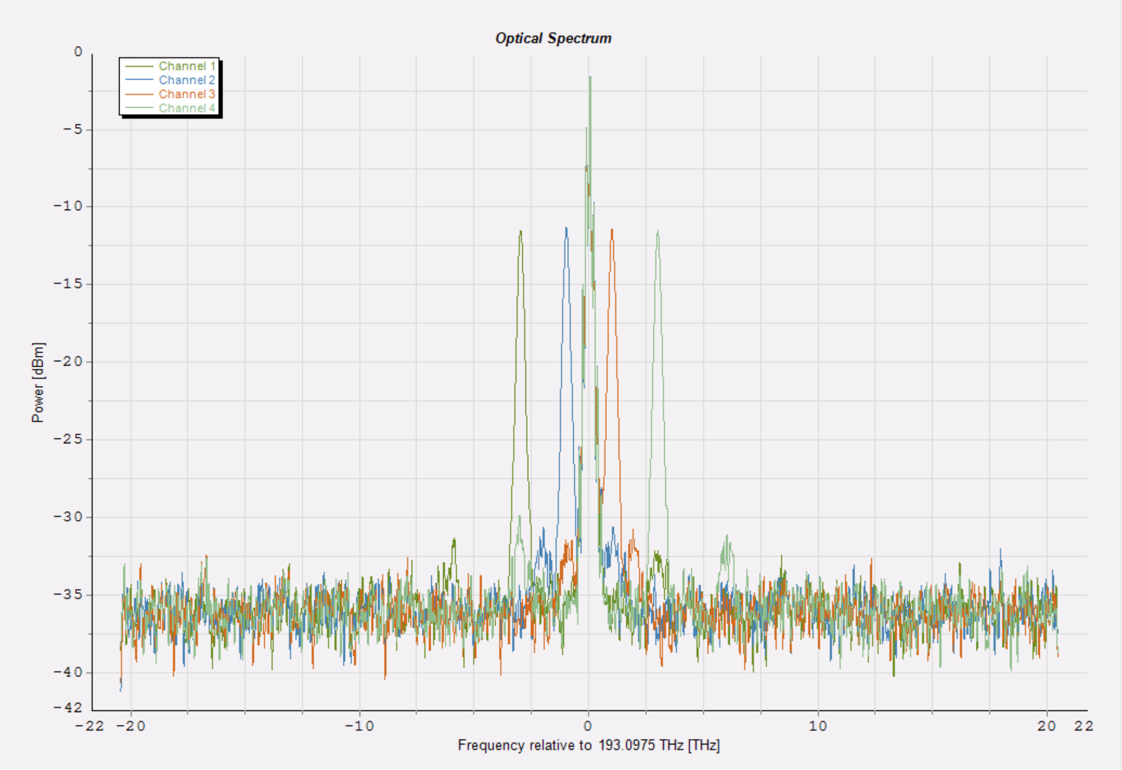


Fig.4.6. Optical spectra of demultiplexed WDM channels

It can be realized that successful mapping of the tributaries to different wavelengths is performed i.e. at 1529nm, 1545nm, 1561nm and 1578nm respectively. These wavelength channels can be obtained using the narrow channel spacing and the optical gating. Four different tributaries are extracted using optical gating via electro-absorption modulator and a 0.3 nm OBPF and the corresponding bit error rate curves are shown in Fig.4.8. It shows the bit error rate performance of different WDM channels w.r.t. the power. At the demultiplexer, the correct wavelength allocation can be achieved by simply altering the relative time delay among OTDM signal and the pump signal. Error free performance is reached for all the channels. Fig.4.8 also compares the BER vs power for B2B case along with different channels.

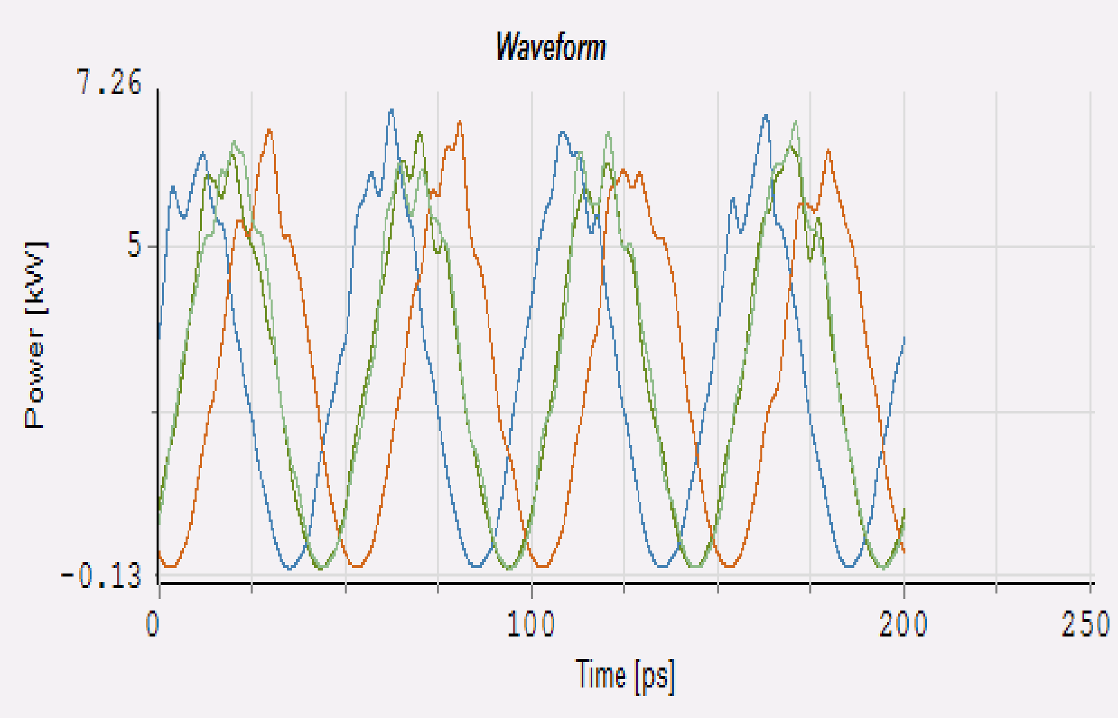


Fig.4.7. Received WDM waveforms at the output

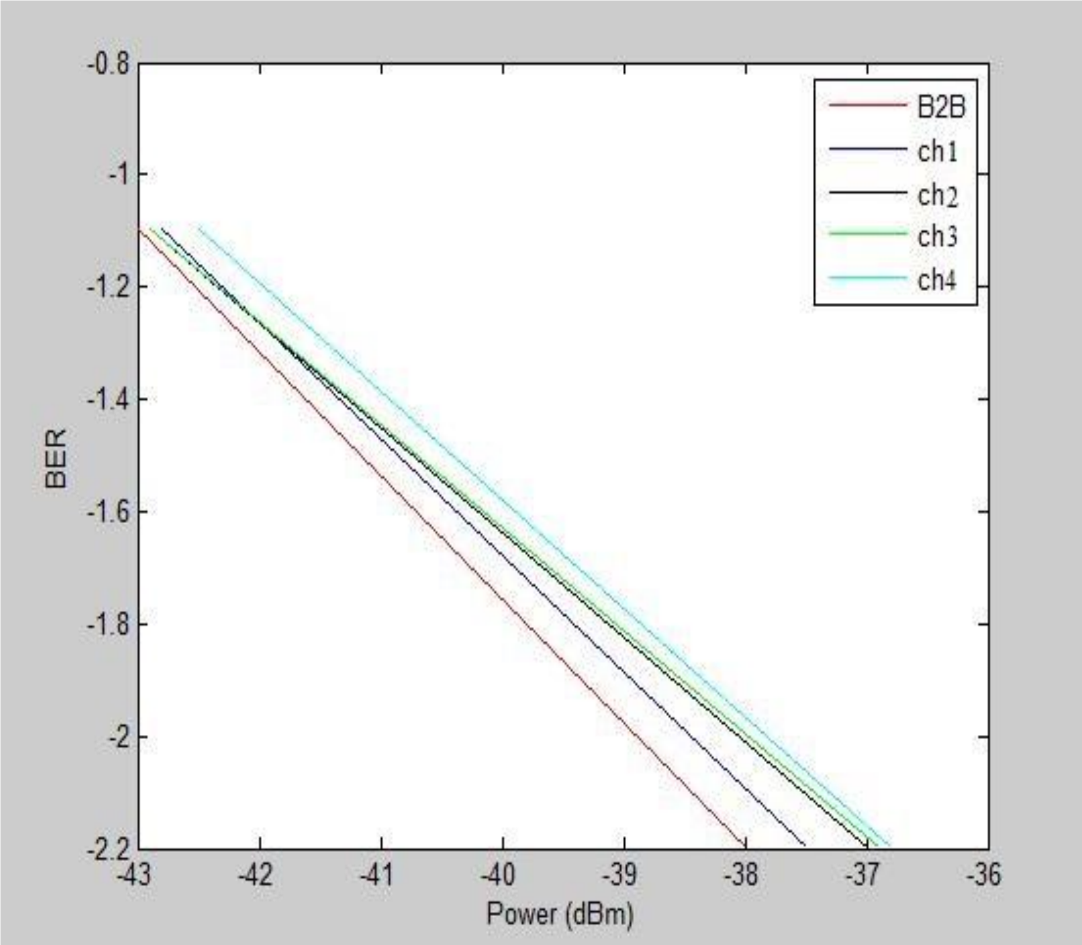


Fig.4.8. BER curves of the four tributaries and for the B2B case

4.4 Conclusion

This chapter has presented the utilization of FWM and time gating for 160 Gb/s OTDM to 4x40 Gb/s WDM conversion. This technique depends on the time-to-frequency mapping which is realized using FWM process between the dispersed OTDM signal and the linearly chirped pump pulses. It was successfully realized for OOK OTDM system featuring simultaneous conversion of four tributaries to WDM channels using this technique. Error-free performance with low penalty is achieved. This OTDM-to-WDM transmultiplexing method can provide an important decrease in the OTDM receiver complexity.

CHAPTER 5

HIGH SPEED HYBRID OOK/DPSK OTDM SYSTEM WITH ENHANCED DEMULTIPLEXING USING MZM

A 160 Gb/s hybrid optical time-division multiplexing (OTDM) system is demonstrated that consists of hybrid modulation formats of on-off keying (OOK) and differential phase shift keying (DPSK) and its demultiplexing performance is investigated using a mach-zehnder modulator. Hybrid OTDM system offers very less signal degradation because of probable crosstalk among adjacent channels as compared to the conventional OTDM system. Here 160 Gb/s to 40 Gb/s hybrid OTDM demultiplexing is realized successfully. A comparatively wide switching window can be obtained for the hybrid OTDM system that cannot be achieved utilizing conventional OTDM system. Timing misalignment tolerance can be significantly enhanced for hybrid structure.

5.1 Introduction

Optical time-division multiplexing (OTDM) is a promising technique for improving the capacity of the optical transmission networks [59]. So far, various techniques have been demonstrated to enhance the capacity of optical time division multiplexing systems. In order to increase the capacity even further, hybrid OTDM system can be realized. Basically, the hybrid OTDM consists of different modulation for different channels e.g. all the odd channels are intensity modulated whereas all the even channels are phase modulated in order to reduce the signal distortion at the receiver side. Using these two unlike modulation schemes, the deterioration in performance caused by crosstalk among adjacent channels in a hybrid OTDM is much less than that in a conventional OTDM signal with homogeneous modulation schemes [60]. In general, a 160Gb/s (or 40Gb/s) OTDM signal can be simply demultiplexed to its base rate 40 Gb/s (or 10 Gb/s) [61,62]. The performance of the demultiplexing unit can be significantly improved and relaxation in the need for the control circuit can be achieved. For demultiplexing operation, a number of optical switching techniques have been applied, comprising four-wave mixing in non-linear fibers [63], non-linear optical loop mirrors (NOLMs) [64, 65], Mach-Zehnder interferometers with SOAs [66] and using cascaded modulators.

S. Ferber et al. [67] demonstrated the comparison between DPSK and OOK modulation system. 160 Gbit/s single polarization OTDM transmission over dispersion-managed SLA 3x80 km fiber using OOK and DPSK modulation. The influence of the fiber input power is theoretically and experimentally investigated. This demonstration revealed a significant advantage for DPSK modulation.

Ning Deng et al. [68] examined the performance of a novel hybrid 84.88 to 10.61 Gb/s optical time-division multiplexing (OTDM) methodology containing hybrid modulation setups of RZ on–off keying (OOK) and RZ differential-phase-shift keying (DPSK) and its demultiplexing using a commercial EAM operated at normal conditions to generate a switching window. Experimental results showed that somewhat wide switching window can be achieved which is not obtained in case of conventional OTDM.

The benefit of hybrid OTDM can be more noteworthy in ultrahigh-speed (160 Gb/s) OTDM demultiplexing, where the performance is more sensitive to timing drift or timing jitter of the switching window This hybrid OOK/DPSK OTDM system is further realized here in this paper for higher bit rate and demultiplexing can be carried out using cascaded mach-zehnder modulator for enhanced performance and optimized switching window.

The chapter is organised as follows: section 2 includes theoretical analysis of the hybrid OOK/DPSK OTDM system and demultiplexing by generating the switching window, section 3 includes simulation setup of the proposed hybrid scheme and results including the bit error rate performances of the hybrid and conventional system, and finally section 4 concludes the chapter.

5.2 Theoretical Analysis

Fig.5.1 represents the hybrid format and the 4:1 high-speed hybrid OTDM signal demultiplexing. Either RZ-OOK or RZ-DPSK formats are employed in all the channels in case of a conventional OTDM signal. Here, in this proposed hybrid OTDM scheme, every odd channel is in RZ-DPSK format while every even channel is in RZ-OOK format, as illustrated in Fig. 5.1(a). In this hybrid system, the RZ-OOK channels are time-interleaved with the RZ-DPSK channels. Fig. 5.1(b) represents the 8:1 demultiplexing of an RZ-OOK channel where the switching window covers not only the desired demultiplexed channel but also some part of its two nearby channels. In a conventional OOK OTDM signal including all channels in RZ-OOK formats, this type of demultiplexing would cause severe crosstalk from adjacent channels and may severely weakens the target demultiplexed channel. However, for an OOK channel in the proposed hybrid OTDM signal, adjacent channel crosstalk is part of the adjacent DPSK bits, having the same extent of power for either DPSK "1" or "0". This is same as adding a small amount of constant power to the desired OOK channel, which may change the detection threshold but will not make wrong detection due to crosstalk from neighbouring channels. Similarly, for a DPSK channel in a hybrid OTDM system, the demultiplexing will gate portion of the neighbouring OOK bits. However, after DPSK demodulation, the gated portion of the OOK bit will interfere destructively with its previous bit.

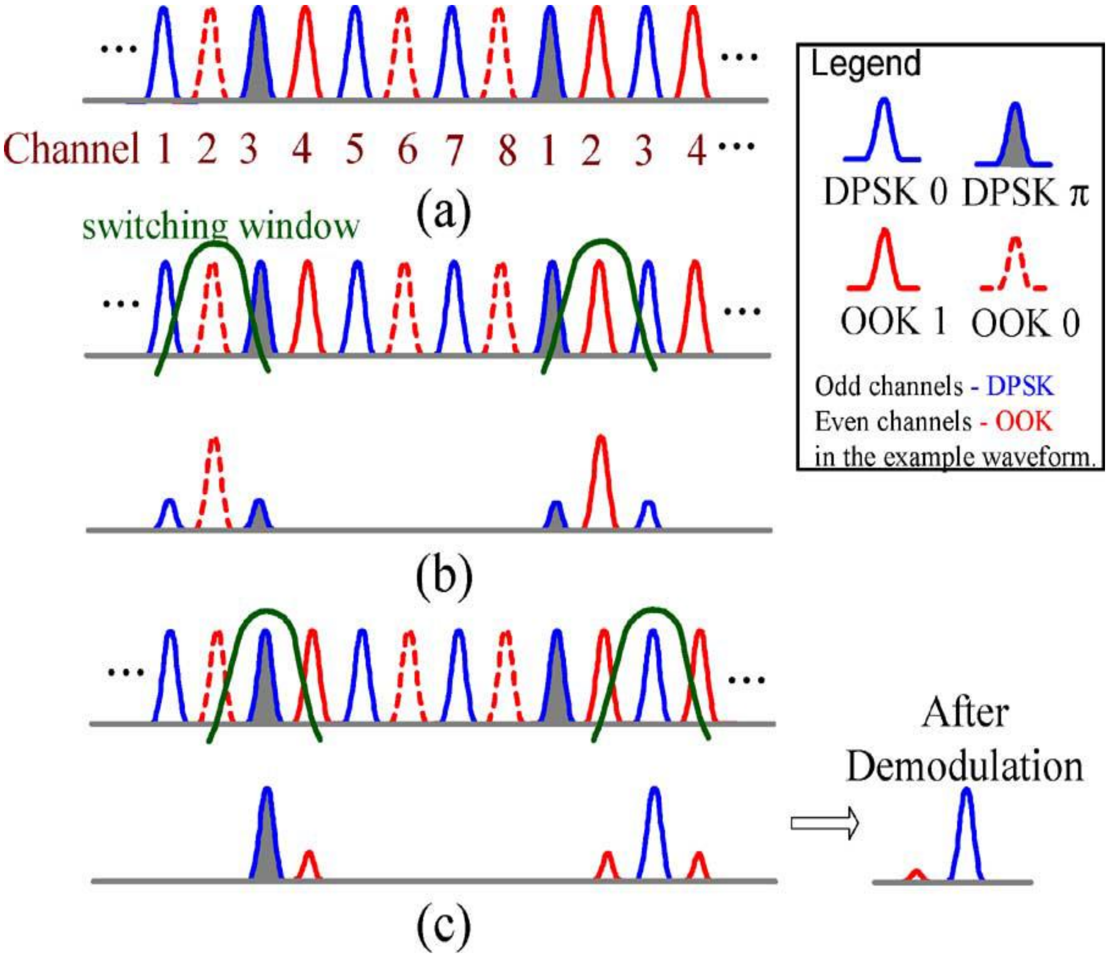


Fig.5.1. (a) Hybrid OTDM signal scheme (b) OOK channel demultiplexing (c) DPSK channel demultiplexing. [68]

In other words, the gated power of the OOK bit will vanish or become as low as a quarter of its actual power, subject to whether its two consecutive bits are similar or not. Hence, the DPSK channel demodulation procedure can significantly improve the crosstalk from the adjacent OOK channels, in comparison to the demultiplexing of a conventional RZ-DPSK OTDM format [68].

5.3 Simulation and Results

Fig.5.2 presents the simulation arrangement of the 160 to 40 Gb/s hybrid OTDM system. A continuous laser source generating 40 GHz pulse train (1.5-ps full-width at half-maximum (FWHM) peak-to-floor extinction ratio 20 dB) is first parted into two branches. After that, the phase modulation and intensity modulation of the two pulse trains is performed, respectively. A tunable optical delay line (ODL) is used to adjust the OOK signal to provide a delay of 6.2 ps w.r.t. the DPSK signal. To insure same peak power and polarization for both the branches, a variable optical attenuator (VOA) and polarization controller (PC) are used. Fig.5.3 shows the transmitted OOK/DPSK hybrid signal propagated in 80 km single mode fiber. After modulating and interleaving the signals, the interleaved OOK/DPSK signal is 1:2 time-multiplexed to generate 160 Gb/s hybrid OTDM signal as presented in Fig. 5.4(a).

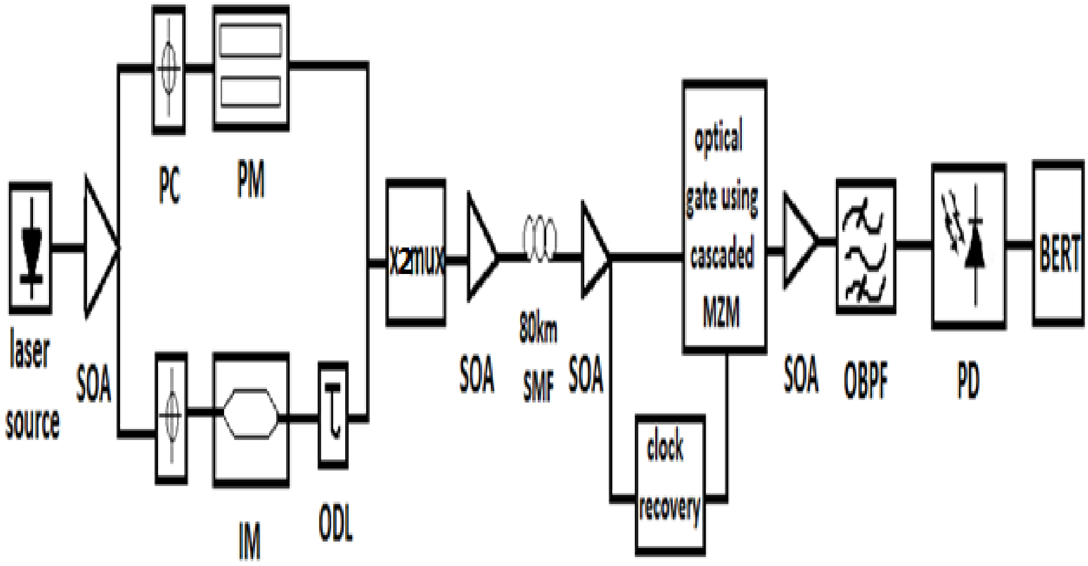


Fig.5.2. Simulation setup (SOA is semi-conductor optical amplifier; PM is phase modulator; PC is polarization controller; IM is intensity modulator; ODL is optical delay line; OBPF is optical bandpass filter; BERT is bit error rate tester; PD is photo diode)

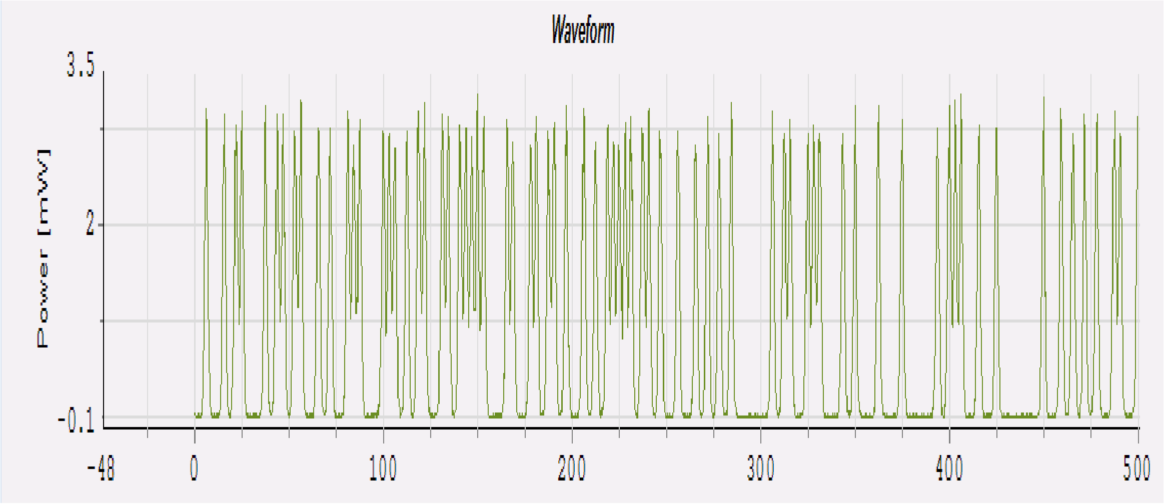
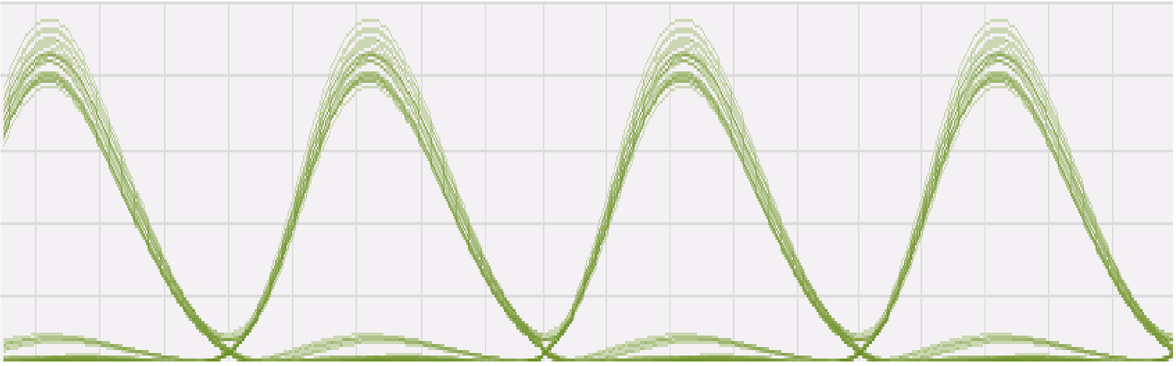
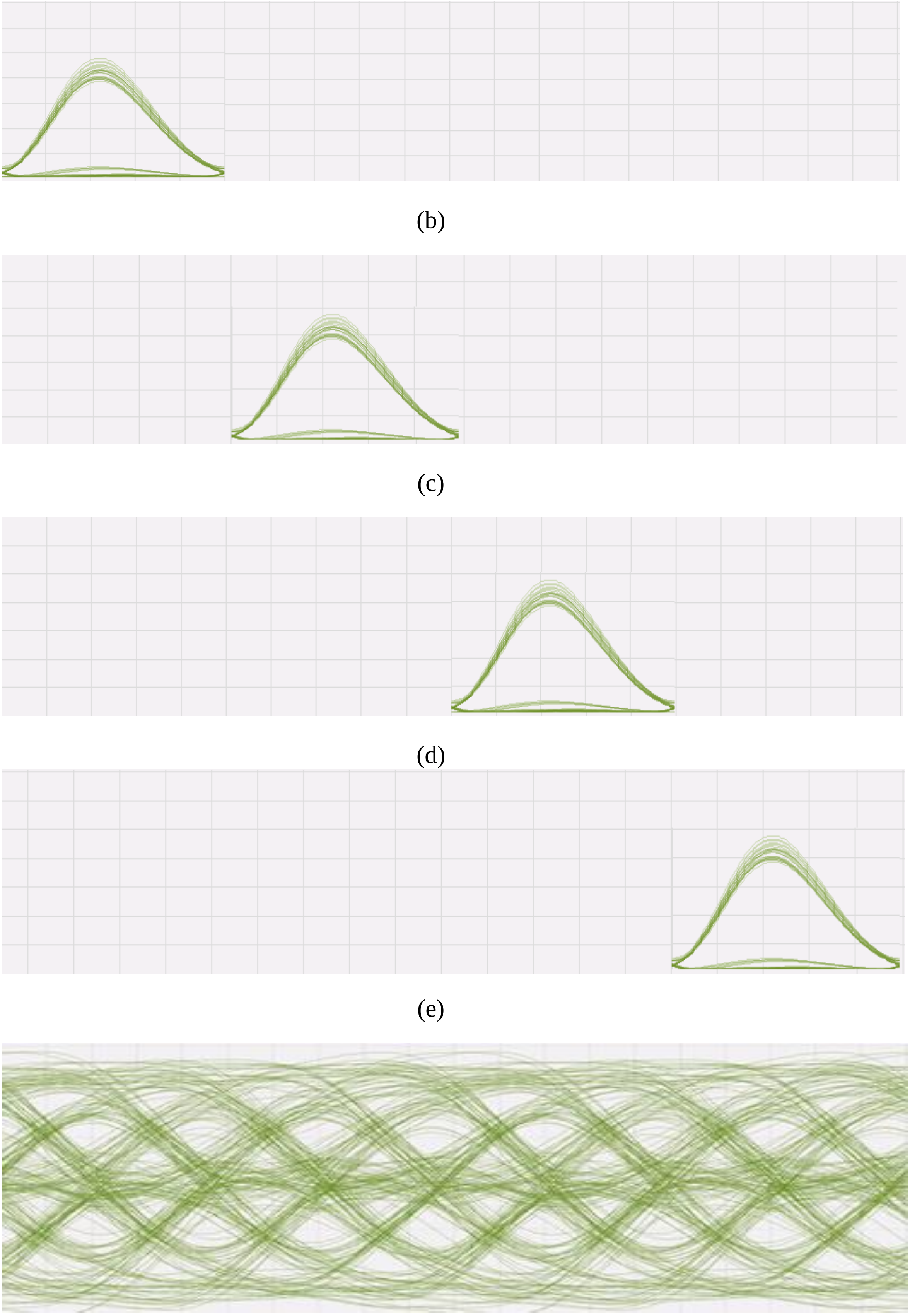


Fig.5.3. Transmitted signal

After amplifying the signal using a SOA (semi-conductor optical amplifier), the signal is passed to the optical gate which generates the required switching window. The optical gate basically consists of two cascaded mach-zehnder modulators driven by two clock pulses of 20 and 40 GHz respectively. The clock signals are extracted using clock recovery circuit. The switching window generated by the optical gate is around 8 ps. The detection of the demultiplexed RZ-OOK channels is done directly whereas the RZ-DPSK channels are firstly demodulated using a delay interferometer (DI) before detection. Fig. 5.4(b)–(e) represents the four demultiplexed OOK channels from the 160 Gb/s hybrid OTDM signal. Fig 5.4(f) represents the 160 Gb/s conventional OOK OTDM system. From this eye diagram this could be clearly analysed that for the conventional homogeneous OTDM system, the crosstalk among neighbouring channels is present.



(a)



(b)

(c)

(d)

(e)

(f)

Fig.5.4. (a) Hybrid OTDM signal (b)-(e) Demultiplexed channels (f) Conventional OOK OTDM system

On the other hand, employing the suggested hybrid OTDM, the eye diagrams of the demultiplexed and demodulated channels are clearly open, as shown in Fig. 5.4. Hence improved tolerance to the crosstalk among adjacent channels can be achieved by implementing hybrid OTDM signals. The BER of the eight 40 Gb/s demultiplexed channels from the hybrid OTDM signal is measured as shown in Fig. 5.5. All the channels achieve error-free detection.

From the bit error rate performances, slight enhanced receiver sensitivity can be observed for DPSK channels than OOK channels. Fig 5.6 Shows the BER vs. optical signal-to-noise ratio (OSNR) for conventional DPSK OTDM system and conventional DPSK OTDM system. The comparison between the bit error rate performances clearly shows that the performance is enhanced for the former case.

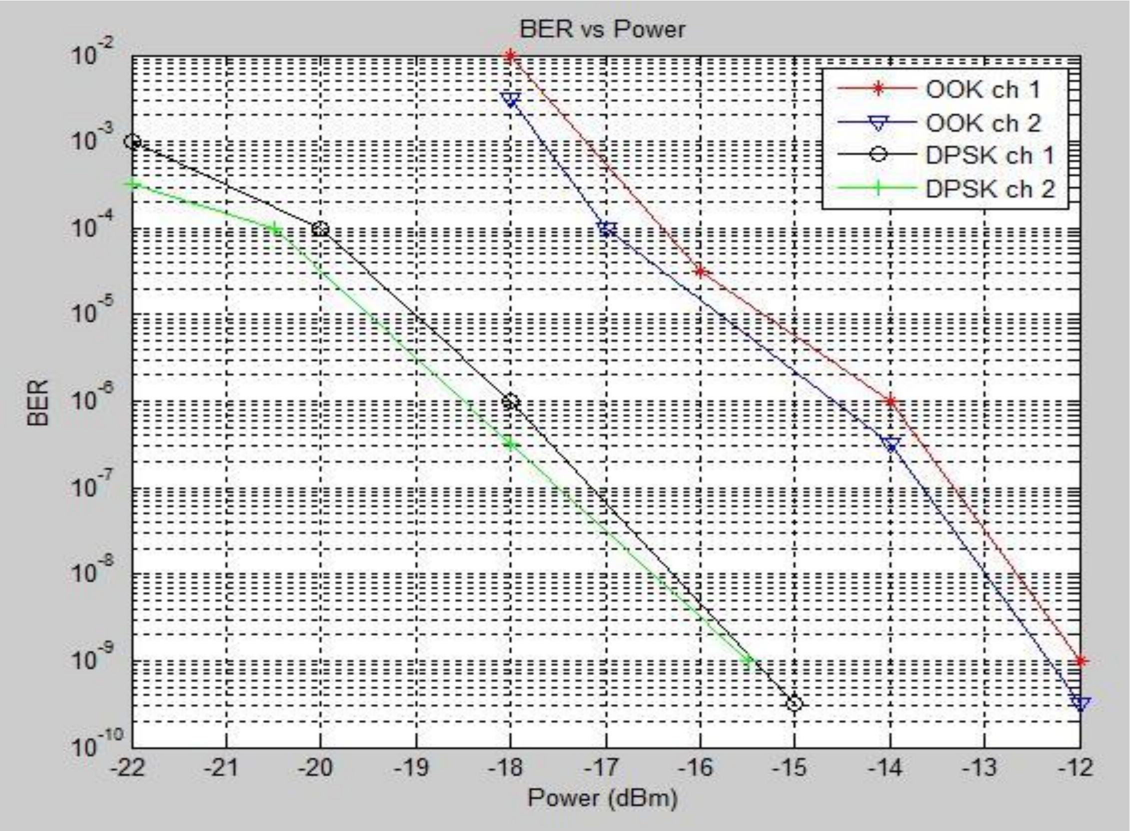


Fig.5.5. BER vs. Power

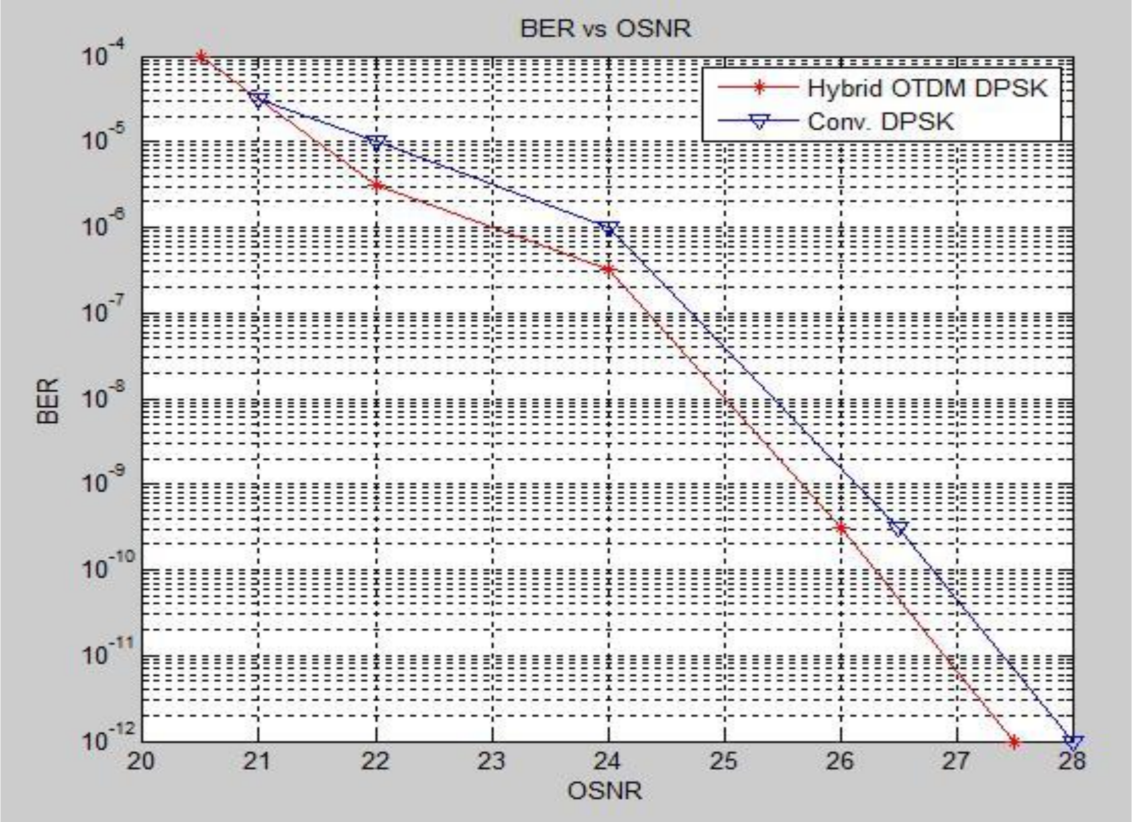


Fig.5.6. BER vs. OSNR

5.4 Conclusion

In this chapter, 160 Gb/s hybrid OOK/OTDM system is successfully demonstrated. The simulation result shows that the proposed system offers enhanced demultiplexing performance as compared to the conventional homogeneous OTDM system. The performance of the system demultiplexing depends on the timing misalignment of the switching window. Ultrahigh-speed OTDM demultiplexing is performed using mach-zehnder modulator. Enhanced bit error rate ($<10^{-9}$) is obtained. The performance is more sensitive to timing jitter or timing drift of the switching window, the hybrid OTDM system plays significant role in error free data transmission and MZM provides an optimized switching window.

CHAPTER 6

CONCLUSIONS, RECOMMENDATIONS AND FUTURE SCOPE

6.1 Conclusions

This chapter presents the summary of investigation done in this dissertation. Firstly, conclusions are drawn from this research, after that the recommendations have been provided on the basis of the conclusions and further suggestions for future research are deliberated. The key results attained in this dissertation are summarized below

1. The utilization of two cascaded mach-zehnder modulators with clock recovery circuit for improved OTDM receiver by generating short optical pulses is proposed. This technique is successfully demonstrated for 160 Gb/s OTDM DQPSK system showing error-free transmission with power penalty less than 1 dB. Error free transmission is achieved over 120 km fiber link. On the receiver side, a clock recovery circuit is employed. The 160 Gb/s data is split into two parts, first is utilized for clock extraction while another for further demultiplexing. Two cascaded MZMs are used to produce short optical gate pulses. The two Mach-zehnder modulators help in the extraction of low timing jitter clock and hence error free transmission is realized. The simulation results show that the clock component can be enhanced using MZ modulator in order to make clock recovery easier. The bit error rate performances are compared for different cases. Firstly, BER vs OSNR plot for three cases namely system without using optical gating, system with employing optical gating using EAM and using MZM, respectively. It is found that more improved performance is obtained for the case of demultiplexing using optical gating using cascaded MZM as compared to using EAM. Another plot for BER vs OSNR represents the comparison of bit error rate performance for demultiplexing using single and cascaded mach-zehnder modulator.

   The use of MZM is recommended over electro-absorption modulator as the former offers low insertion loss. Moreover, using cascaded mach-zehnder modulator instead of single modulator provides more enhanced results.

2. Serial-to-parallel conversion of optical time division multiplexed (OTDM) data tributaries into wavelength division multiplexed (WDM) channels from 160 Gbit/s to 4x40 Gbit/s using four-wave mixing (FWM) in highly non-linear fiber (HNLF) followed by a single electro-absorption modulator based optical gate is demonstrated. The mentioned method is based upon the mapping of time-to-frequency which is realized utilizing an FWM procedure between the linearly chirped pump pulses and the dispersed OTDM signal. This technique was successfully demonstrated for OOK OTDM system featuring simultaneous conversion of four tributaries to WDM channels. A low power penalty error-free performance is achieved.

3. 160 Gb/s hybrid OOK/OTDM system is successfully demonstrated. The simulation result shows that the proposed system offers enhanced demultiplexing performance as compared to the conventional homogeneous OTDM system. The performance of the system demultiplexing depends on the timing misalignment of the switching window. Ultrahigh-speed OTDM demultiplexing is performed using mach-zehnder modulator. Enhanced bit error rate ($<10^{-9}$) is obtained. More sensitive performance to timing jitter or timing drift of the switching window is realized.

6.2 Recommendations

1. The use of MZM is recommended over electro-absorption modulator as the former offers low insertion loss. Moreover, using cascaded mach-zehnder modulator instead of single modulator provides more enhanced results.
2. This OTDM-to-WDM transmultiplexing is recommended as it can provide a significant decrease in the OTDM receiver complexity. Also, modulation techniques other than OOK can be used for modulating different OTDM channels (e.g. DPSK, QAM etc.) or we can say that phase modulated signals can also be used because the FWM offers phase preserving properties.
3. The hybrid OTDM system plays significant role in error free data transmission and MZM provides an optimized switching window. Increasing the bit rate of the system requires more optimized switching window so as to avoid crosstalk

among the adjacent channels. So mach-zehnder modulator is recommended for enhanced demultiplexing of higher data rate OTDM channels.

6.3 Future Scope

During the progression of this dissertation, several avenues for continuing this study became evident. The issues that were considered worthwhile are summarized below

- In this dissertation, the polarization effects have not been taken into account. Simulation studies can be carried out for same architectures while taking into account the polarization effects.

- The comparison of different switching techniques can be done on the basis of simulation results and based on their performance, it can be concluded that which switching technique is best.

- Hybrid techniques other than OOK and DPSK can be utilized to analyse the OTDM system for higher bit rates and their demultiplexing performance can be demonstrated.

- OTDM transmission can be realized over longer distances. However, over longer distances, the pulse transmission may suffer from transmission impairments caused due to long-term PMD (polarization mode dispersion) variation and higher order PMD. Signal processing techniques, for instance time-domain OFT and reduction of bandwidth by using multi-level RZ-QAM are expected to overcome this type of limitations and obtain Tbit/s propagation over 500-1000 km.

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