The Hong Kong Polytechnic University

Department of Electronic and Information Engineering

Wavelength Division Multiplexed Passive Optical Networks

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A Thesis Submitted in Partial Fulfillment

of the Requirements for the Degree of

Master of Philosophy

Dec 2012

Certificate of Originality

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Name of student: DONG Tian

Abstract

Optical fiber transmission technology has been used widely and has been playing a more and more important role in today's telecommunication networks. As a transmission medium, optical fiber offers many advantages comparing with other alternatives, such as broad bandwidth and low attenuation. This enables large data capacity over an extremely long transmission distance. It has been the main medium of signal transmission for long haul networks and from the beginning of this century, significant amount of research work has also been carried out in using optical communication technology for optical access networks as the best solution for the "last-mile" connectivity.

Wavelength division multiplexing passive optical network (WDM-PON) is a promising candidate for the next generation optical access networks. In this thesis, several interesting WDM-PON schemes are proposed and investigated to solve some research challenges in WDM-PON system, which are colorless ONU, Rayleigh backscattering, and dual independent service data transmission.

Subcarrier multiplexed WDM-PON system is studied. The system uses subcarrier multiplexed single sideband (SSB) modulation for downlink data transmission and

RSOA re-modulation of baseband data for uplink data transmission to realize a bidirectional PON system. The scheme reduces the effect of RB and since self-heterodyne coherent detection can be realized, high order modulation can be employed to further increase the data rate and dispersion equalization can be easily realized. The use of a high frequency subcarrier also allows direct detection to be employed for uplink data detection without the need for optical and electrical filtering at the OLT. Using the proposed system, a 2.5Gb/s bidirectional WDM PON system with RSOA re-modulation is demonstrated experimentally.

OFDM-WDM-PON system is investigated. In this scheme, a WDM PON system using direct detected OFDM for downlink signal transmission is studied experimentally. Single sideband modulated OFDM signal with a guardband at the baseband is used to simplify direct detection of the OFDM signal at the ONU. The guardband portion of the downlink signal is used by an RSOA for baseband signal re-modulation. The use of OFDM for uplink signal transmission allows high data rate to be realized for limited RSOA bandwidth. Using the proposed system, 40Gb/s downlink signal transmission and 10Gb/s uplink transmission for a WDM PON system are demonstrated.

Pol-MUX WDM-PON system is evaluated through simulation. The downlink is a Pol-MUX signal with two orthogonally single-sideband (SSB) signals with different local oscillator (LO). One upper-sideband (USB) is used as wired service, the other lower-sideband (LSB) is used as wireless service. This configuration can overcome the CD and RB effect and eliminate undesirable beat frequency of dual service signals to maximize RF spectrum utilization. It avoids the complex polarization de-multiplexing at the ONUs and enables a scalable receiver frontend without additional filters. By using the proposed system, 10Gbps downlink transmission with scalable ONUs for a dual service WDM-PON system is demonstrated through simulation.

List of Publications

JOURNALS:

[1] Tian Dong, Yuan Bao, Yu Ji, Alan Pak Tao Lau, Zhaohui Li, Chao Lu, "Bidirectional hybrid OFDM-WDM-PON system for 40 Gb/s downlink and 10 Gb/s uplink transmission using RSOA remodulation," *IEEE Photon. Technol. Lett.*, Vol.24, pp.2024-2026, Nov. 2012.

CONFERENCES:

[2] Tian Dong, Chao Lu, Yu Ji, Alan Pak Tao Lau, "WDM-PON System based on Subcarrier Multiplexed Single Sideband Modulation," OECC2012, Busan, Korea.

Acknowledgement

I would like to express my most sincere gratitude to all those who gave me the possibility to complete this thesis. I want to thank the Department of Electronic and Information Engineering of The Hong Kong Polytechnic University for giving me permission to commence this thesis in the first instance, to do the necessary research work and to use departmental resources.

I would like to express my deepest gratitude to my thesis supervisor, Prof. Lu Chao, for his inspirational guidance, stimulating suggestions and longtime encouragement, helped me in all the time of research for writing of this thesis. In my research life, he taught me not only the methodology and skills, but also guide me to be explorer, innovator. Moreover, his profound knowledge in optical communications opens a huge door for me and leads me to a dream world.

It is my pleasure to study in Optical Communications Laboratory in the Department of Electronic and Information Engineering. I have learnt much from members there. I would like to express my sincere thanks to Dr. Alan Pak Tao Lau, Dr. Yang Yanfu, Dr. Yan Shuangyi, Mr. Wang Dawei, Ms. Ji Yu, Mr. Gao Yuliang, Mr. Wen Xuan.

This thesis is dedicated to my dearest families for their upbringing.

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Chapter 1

Introduction

1.1 Optical access networks

Access network is the network which connects the Central Office (CO) to the end users. It is often referred to as the "last-mile" networks. In recent years, it is also called the "first-mile" networks [1]-[2], because for multiple service providers with multiple services, the access network is the first step to broadcast message to end users. This clearly reflects the importance of access networks in telecommunication networks.

The most expensive part of an access network is the "last-mile", because the number of end users need to be accessed is often very large. The provision of the "last-mile" connectivity can be through twisted copper pairs, coaxial cable and microwave link. However, these transmission media often have large attenuation, limited bandwidth and significant amount of noise and cross-talk. These limit the data transmission rate, number of users and transmission range.

Optical fiber transmission technology has been used widely and has been playing a more and more important role in today's telecommunication networks. As a transmission medium, optical fiber offers many advantages comparing with other alternatives, such as broad bandwidth and low attenuation. This enables large data capacity over an extremely long transmission distance. It has been the main medium of signal transmission for long haul networks and from the beginning of this century, significant amount of research work has been carried out in using optical communication technology for optical access networks as the best solution for the "last-mile" connectivity.

1.2 Increasing bandwidth demand

With the rapid development of the Internet, many new services with rich feature are being created and many of them are becoming very popular worldwide. Since many of them have become an important part of our life, our expectations for quality of experience (QoE) have also grown rapidly. The rapid growth of peer-to-peer (P2P), high-definition television (HDTV), 3D television (3DTV) [3]-[4], and cloud computing has produced a very huge bandwidth demand.

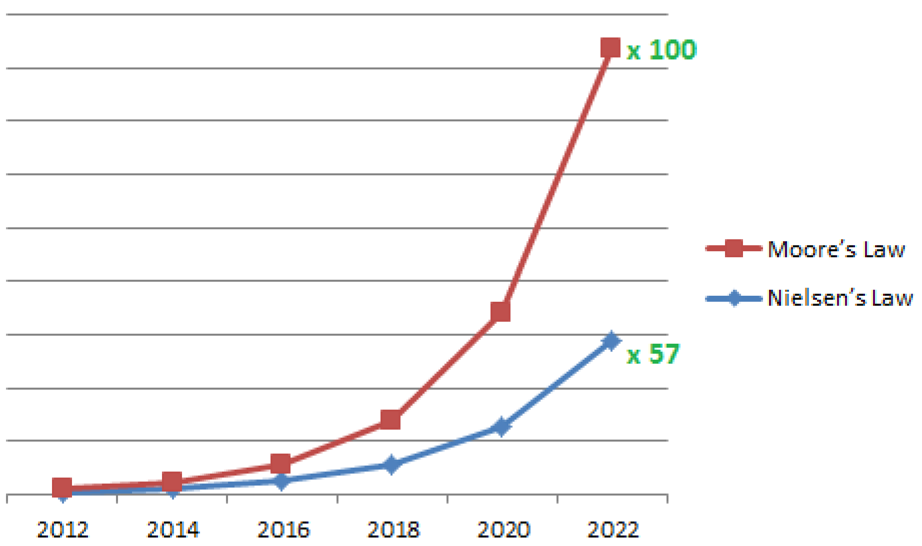

Fig.1.1 Available bandwidth vs. demand bandwidth

The relationship between available bandwidth and bandwidth demand is shown in Fig.1.1. According to the famous Moore's Law[5], "the number of transistors on integrated circuits doubles every 18 months" In Nielsen's Law of Internet Bandwidth, it has been predicted that "a high-end user's connection speed grows by 50% per year"[6]. This can be used to predict the increase in bandwidth demand of optical access networks. The annual growth rate of the bandwidth abide by Nielsen's Law is 50% and the annual growth of the computer power abide by Moore's Law is around 60%. The increase in bandwidth is slower than the increase in computer power. It is inevitable that solution has to be found to increase the available bandwidth to match the growth of the computational power.

This means there is a huge challenge to access networks. Comparing with coaxial cable, twisted copper pair and microwave, optical fiber is considered to be the most desirable access media and optical access networks are the most promising candidates for solving the issue of the "last mile" bandwidth demand.

1.3 PON systems overview

The basic model for an optical access network is the "FTTx" model, which means in "Fiber to the x" [7]. "x" can be different according to the deployment of optical fiber in the optical access networks. "x = H = Home", "x = C = Curb", "x = N =

Neighborhood", "x = P = Premises", "x = B = Business", "x = O = Office", etc. These models are shown in Fig.1.2.

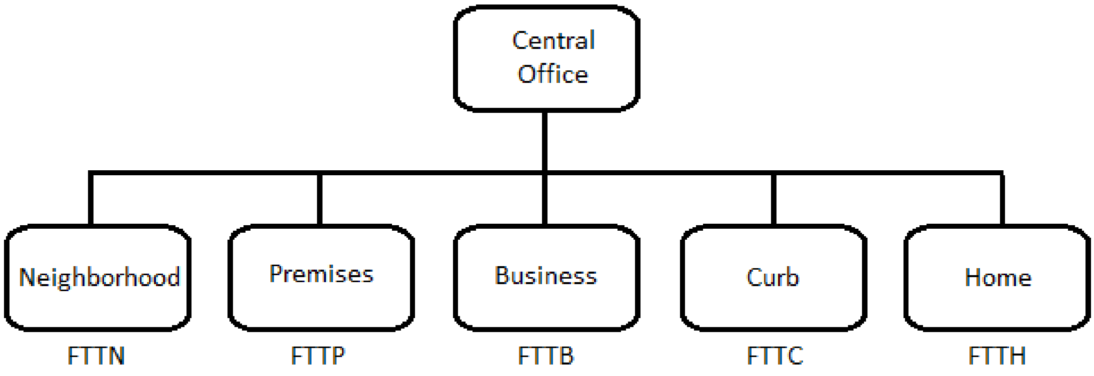

Fig.1.2 "FTTx" concepts in optical access networks

1.3.1 PON types

APON and BPON represent Asynchronous Transfer Mode PON and Broadband PON. These two types of PON are based on Asynchronous Transfer Mode (ATM) technology. There are two wavelengths of 1550nm and 1490nm for downlink transmission, and one wavelength of 1490nm for uplink transmission. These are defined in ITU-T G.983 standard [8]. Since ATM has largely disappeared, APON and BPON are no longer used.

GPON, EPON, and GEPON represent Gigabit PON, Ethernet PON, and Gigabit Ethernet PON. These types of PON are evolving from APON and BPON. GPON is using the same wavelength setting as BPON. It shares up to 2.5Gbps bandwidth among up to 32 users and it is defined in ITU-T G.984 standard [9]. EPON encapsulates all the data in a frame structure similar to Ethernet frames. 1550nm is used for downlink transmission, and 1310nm is used for uplink transmission. It shares the 1.25Gbps bandwidth among end users, while GEPON increases the data rate to 2.5Gbps.

GPON and EPON are currently the major alternative technologies used in optical access networks. Researchers around the world are studying alternatives for optical access network beyond GPON and EPON, such as the ten gigabit passive optical network (XG-PON) for up to 10Gbps optical access networks [10] and Next Generation PON (NG-PON) for up to 40Gbps ~ 100Gbps optical access networks.

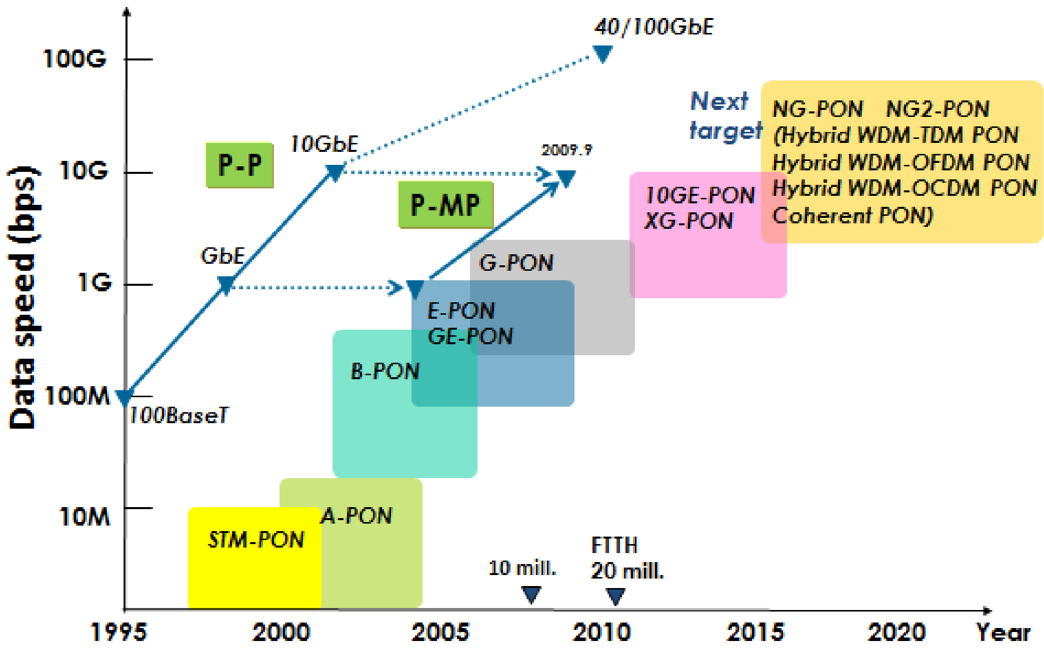

Fig.1.3 PON system deployment scenario

1.3.2 PON architectures

There are many kinds of PON topologies [11], which are adapted to different applications. The most commonly used is the “Tree topology”. In addition, there are “Ring topology”, “Bus topology”, and “Tree with redundant trunk topology”. These topologies are showed in Fig.1.4.

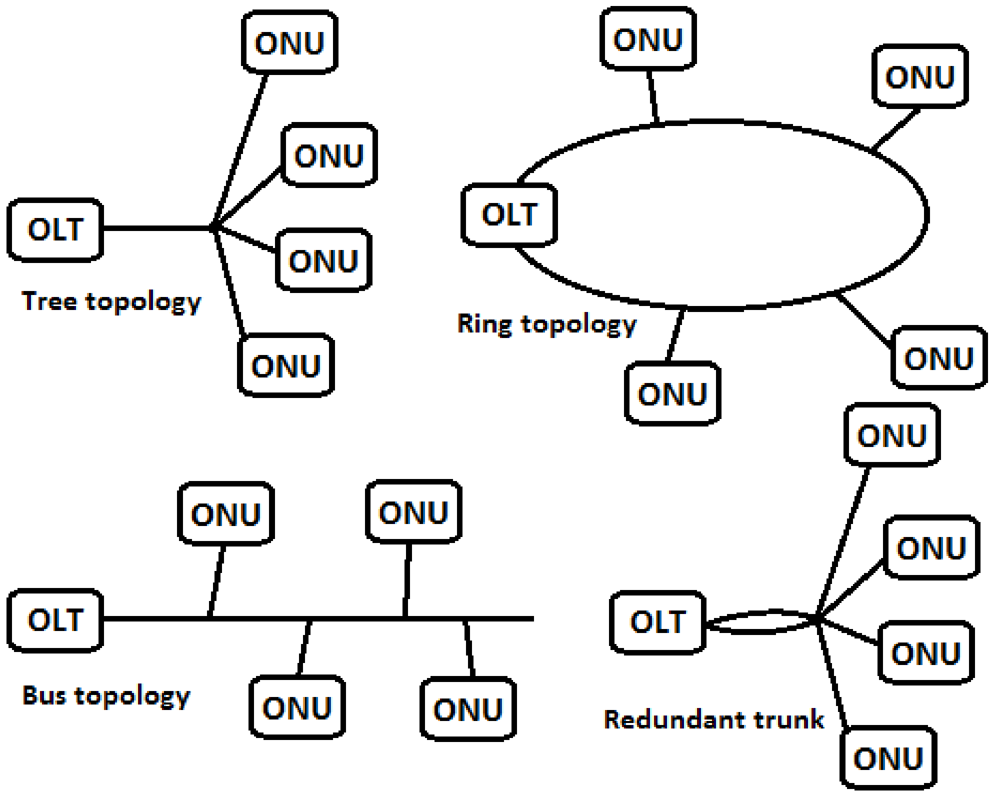

Fig.1.4 PON Topologies

A typical architecture of the passive optical network (PON) is showed in Fig.1.5. The PON network consists of three main parts: central office (CO), optical distribution network (ODN) and optical networks unit (ONU).

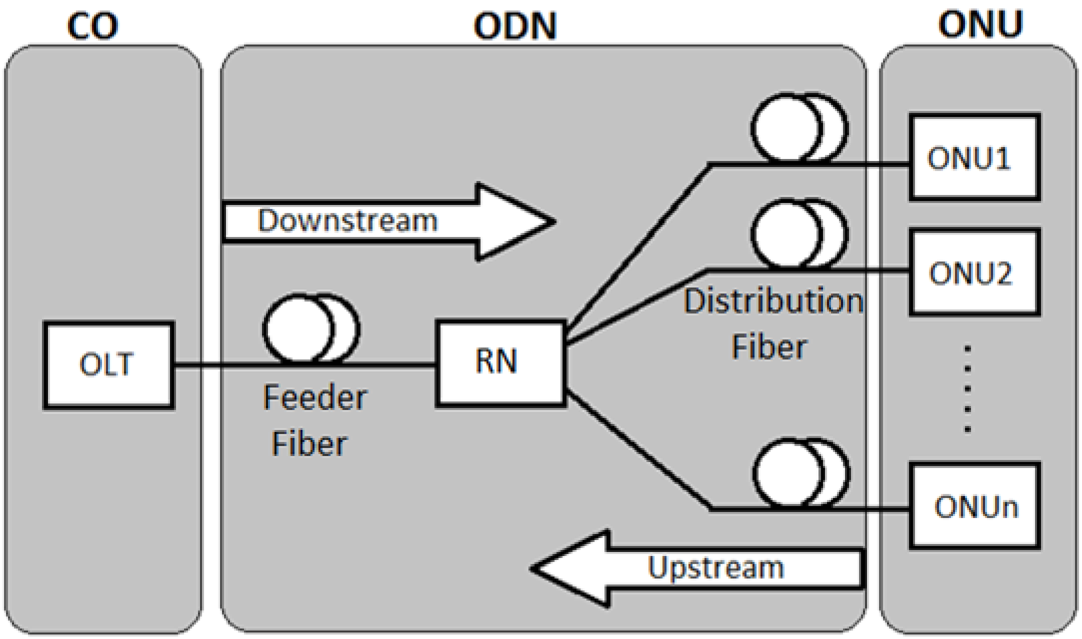

Fig.1.5 The architecture of a passive optical network

In a basic PON transmission system [12], the CO is controlled and operated by the network service, it is far away from end-users, generally more than 20 km, and send out the downlink data to the networks. The core part of CO is the optical line terminal (OLT), which works as the transmitter, modulate the downlink data and send the data out to the feeder fiber. Besides, the CO has its receiver frond-end, which is used to receive the uplink data come from the ONUs, ensure the communication between the OLT and the ONUs can be processed smoothly. Sometimes, encryption is needed to ensure privacy.

The ODN consists of three parts, the feeder fiber, the remote node (RN), and the distribution fibers. In the downlink transmission, the OLT broadcasts the downlink data to all ONUs thought a long feeder fiber, the RN is typically a passive device and will deliver the data to each ONU via different distribution fiber; In the uplink transmission, each ONU sends different uplink data to the RN through distribution fibers, the RN combines the data together, and deliver the uplink data to the OLT through the feeder fiber.

The RN is shared by all ONUs in PON systems, so it is often placed near to the ONUs, to make sure the required length of distribution fibers is much less than the length of the feeder fiber. Such a configuration can significantly reduce the network deployment cost. The other important feature is the RN in a PON system is all passive, which means only the passive components are used such as passive splitters and passive connectors. Comparing with an active RN with amplifiers and regenerators, a passive RN reduces the cost of deployment as well as the cost of maintenance.

At the CO the uplink data from different ONUs will be received by the same OLT, medium access control (MAC) is thus necessary. Commonly used multiple access schemes are time division multiple access (TDMA) and wavelength division multiple access (WDMA). Using these, different PON architecture can be realized, namely time division multiplexed passive optical network (TDM-PON) and wavelength division multiplexed passive optical network (WDM-PON).

1.4 Major contributions of the thesis

In this thesis, some important issues of WDM-PON systems are studied. These include the reduction of Rayleigh Backscattering (RB) effect in bidirectional WDM-PON systems, reduction of the complexity of ONUs using commercial low cost reflective semiconductor amplifier (RSOA), and the simultaneous provision of dual services data using polarization multiplexing to achieve scalable ONUs without polarization de-multiplexing and optical filter. Three WDM-PON systems are demonstrated, the first is a subcarrier multiplexing WDM-PON system, the second is an orthogonal frequency-division-multiplexing (OFDM) WDM-PON system, the third is a polarization multiplexing (Pol-MUX) WDM-PON system, these systems can provide a variety of optical data format for transmission, from OOK to 64QAM, and from single service to dual services. The following sections will describe the details of these contributions.

1.4.1 Reducing Rayleigh Backscattering

A novel scheme was proposed and demonstrated to reduce Rayleigh Backscattering effect in WDM-PON systems. In a single feeder fiber WDM-PON system, downlink data is modulated with signal sideband (SSB) modulation onto a subcarrier instead of modulation at the baseband, so that there is a guard-band at the baseband. In the re-modulation process, optical carrier with this guard-band is regarded as a centralized light source, and can be modulated at the baseband. Because the downlink and uplink data occupies different portion of the optical spectrum, RB noise will not affect each other at all, the system tolerance to RB is substantially enhanced. Moreover, this is achieved without increasing the system cost and complexity comparing with many other alternative schemes. For example, only one light source at the OLT, the ONU remains colorless. No filter, delay-interferometer (DI) or interleaver is necessary to filter out unwanted optical carriers.

This scheme was applied to three WDM-PON systems. The first is a WDM-PON system based on subcarrier multiplexed single sideband modulation, this system reduces the effect of RB and allows self-heterodyne signal detection at the OLT for high order modulation format and chromatic dispersion (CD) equalization. The second is a bidirectional hybrid orthogonal frequency-division-multiplexing wavelength-division-multiplexing passive optical network (OFDM-WDM-PON) system. This system uses OFDM signals occupying different portions of the available signal spectrum for uplink and downlink signal transmission to reduce the effect of RB, CD and power fading. 40 Gb/s downlink signal transmission based on single sideband modulated (SSB) OFDM signal and 10Gb/s uplink signal transmission using re-modulation of a reflective semiconductor-optical-amplifier (RSOA) is achieved. The third is a polarization multiplexing (Pol-MUX) WDM-PON system. This system can provide dual services with two independent data streams, one data stream can be used to provide Point-to-Point (P2P) service, the other data stream can be used for broadcast or wireless service, and it reduces the effect of RB. A depolarized light source is used for polarization-sensitive RSOA re-modulation, the ONU can be scalable to meet demand of different users by using different bandwidth receiver frontend, and no polarization de-multiplexing system is need at the ONUs.

1.4.2 Low cost and low complexity colorless ONUs

The most cost sensitive part of a PON system is the cost of ONUs, because each end-user needs an ONU and the service providers often have to bear its cost. In a WDM PON system in order to keep the inventory low, all the ONUs have to be wavelength insensitive, i.e. they have to be colorless. Remodulation using centralized light sources has been an effective scheme for realizing colorless ONUs. One of the re-modulation schemes is based on the use of reflective semiconductor optical amplifiers (RSOA). It is one of the most promising candidates for the next generation WDM PON optical access network. The RSOA is a modulator as well as an amplifier. Low cost packaging can be used to manufacture it at very low cost. It can be used to remodulate downstream signal for upstream signal transmission. However, the modulation bandwidth of a RSOA is only about 1.5 GHz, which can not meet the bandwidth needs for optical access networks nowadays. An OFDM based scheme has been proposed to use commercial cost effective RSOAs as colorless ONUs to achieve up to 10Gbps high speed data transmission in the bidirectional WDM-PON systems.

1.4.3 Simultaneously providing dual services

Novel schemes are proposed and demonstrated to provide simultaneously dual services using polarization multiplexing (Pol-MUX) technology for achieving scalable ONUs without polarization de-multiplexing and optical filter. Pol-MUX technology can generate and transmit two independent data streams in two uncorrelated orthogonally polarized beams. One data stream can be used to provide Point-to-Point (P2P) service; the other data stream can be used to provide broadcast or wireless service. However, polarization de-multiplexing process in the ONUs is complicate and costly, this has limited it use at the ONU.

Here a Pol-MUX technique combined with SSB modulation is proposed. The downlink is a Pol-MUX signal with two orthogonally single-sideband (SSB) signals with different local oscillator (LO). One upper-sideband (USB) is used as wired service, the other lower-sideband (LSB) is used as wireless service. This configuration can overcome the CD and RB effect and eliminate undesirable beat frequency of dual services signals to maximize RF spectrum utilization. It can also avoid the complex polarization de-multiplexing to simplify the ONUs structure and allow a scalable receiver frontend without additional filters be realized.

1.5 Outline of the thesis

This thesis has 6 chapters. The remaining chapters of the thesis are organized as follows:

Chapter 2 gives an overview of bidirectional WDM-PONs. It reviews the WDM-PON architectures and the benefits of using WDM-PON. Then some research challenges of the WDM-PON are discussed, such as colorless ONU, Rayleigh backscattering in WDM-PON system, and dual service data transmission in a PON system.

Chapter 3 reviews previously proposed WDM-PON systems using signal re-modulation schemes, and previously proposed WDM-PON systems for Rayleigh backscattering reduction. A WDM-PON system based on subcarrier multiplexed Single Sideband Modulation is then proposed. The operation principles are explained and experimental demonstrations are described. This chapter also discusses some key issues in this scheme, such as the effect of limited RSOA bandwidth and RSOA saturation level as well as possible way for increasing data rate and improving receiver sensitivity.

Chapter 4 reviews previously proposed OFDM-PON systems, and previously demonstrated RSOA re-modulation schemes. A bidirectional hybrid OFDM-WDM-PON system for 40Gb/s downlink and 10Gb/s uplink transmission using RSOA re-modulation is then described. The operation principles are explained and the experimental results are discussed. This chapter also discusses some key issues in this scheme, such as comparison with similar schemes, comparison between DSB and SSB, different OFDM modulation formats and modulators, CSR design, LO frequency design, reversed signals substitution, pre-emphasis algorithm and some other limiting factors.

Chapter 5 reviews previously proposed WDM-PON systems that can simultaneously provide dual service. A novel Pol-MUX WDM-PON architecture for simultaneously providing dual services to achieve scalable ONUs without polarization de-multiplexing and any optical filter is then described. The operation principles are explained and simulations results are discussed. This chapter also discusses some key issues in this scheme, such as LO frequency design, scalable receiver front-end design, and some differences between realistic situations and simulation results.

Chapter 6 gives a summary of this thesis and suggests possible future work.

Chapter 2

WDM-PON systems

2.1 Introduction

The optical access networks can be divided into two categories according to the components used in the RN [13]. If the RN uses active components, such as active switch, amplifier and regenerator, it is called as active optical network (AON). If the RN only uses passive components, such as passive divider and passive switch, it is called a passive optical network (PON). The most important advantage of a PON is that no power supply is required at the RN. In addition, deployment and maintenance of PON can be easier than AON. So PON is more attractive than AON and is the most promising candidate for optical access networks.

Time division multiplexing technology is very popular and widely used in passive optical network [14]. Many standards such as APON, BPON, and GPON use the TDM-PON schemes. The end-users can share the bandwidth of a PON system in the time domain according to the time slots used at the OLT. However, this configuration has some disadvantages, for example, the sharing of bandwidth of a PON by many ONUs limits the transmission capacity of each end user. In addition the receiver at the OLT needs to operate at burst mode. Since data transmitted by an OLT will be received by all the ONUs, the security is also compromised.

Using wavelength division multiplexing technology in access networks were conceived in the late 1980s [15]. In a WDM-PON, the ONUs use different wavelengths for connection with the OLT, instead of sharing a single wavelength in the time domain. This scheme can avoid many shortcomings in the TDM-PON, such as the limited bandwidth per user due to sharing of bandwidth in the time domain, the presence of eavesdropping that may compromise security, and the difficulty in network upgrading. The main challenge of WDM-PON systems for practical implementation is its high cost and complexity, for example the need of additional light sources to generate optical carrier on different wavelength, the requirement of incorporating WDM MUX/DMUX in the current generation TDM-PON for upgrading. These however, can be overcome through the continue effort in optical component system integration. Due to its ability to significantly increase the system capacity and its ability as a complementary technique of TDM-PON, WDM-PON has attracted much research attention in recent years as a promising solution for future broadband optical access networks [16].

2.2 WDM-PON architectures

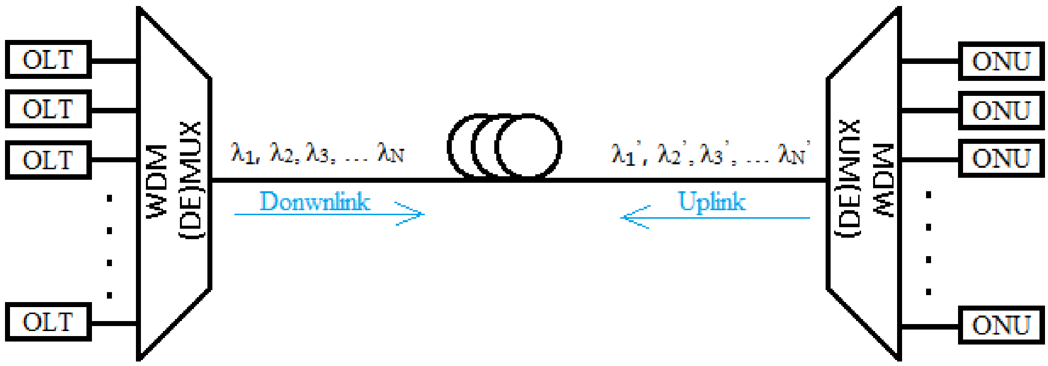

Fig.2.1 WDM-PON architecture

Fig.2.1 shows a typical WDM-PON architecture. It is consisting of CO, ODN, and ONUs as in a typical PON system. Instead of a single transmitter and receiver as in a TDM-PON, the OLT at CO has many transmitters and receivers. Each connects to one ONU using a separate wavelength carrier. This means, if the number of ONUs is m, it needs m separate optical carriers with m different wavelengths.

The key components in a WDM-PON system are the WDM multiplexer and demultiplexer. They replace the power splitter in a TDM-PON. The WDM multiplexer and demultiplexer are typically made of array waveguide gratings (AWG). The WDM multiplexer and demultiplexer combine and split signals with different wavelengths, and routes different wavelengths to specific destinations.

Because the OLT and the ONUs communicate with different wavelengths, it provides many parallel peer to peer connections. There is no need for P2MP MAC. The transmission data rate per end user is not limited by the number of sharing users in the PON system. This enables the number of users and data rate per user to be significantly increased.

2.3 Research challenges of WDM-PON

The WDM-PON architecture is not complicated at first sight. It is similar to TDM-PON by replacing passive splitter with WDM multiplexer and demultiplexer.

By removing the need for bandwidth sharing, it may significantly increase the number of user and bandwidth per user supported by the access network. However, in order to use it in practical network systems, a number of research challenges need to be overcome, such as colorless ONUs, Rayleigh backscattering and provision of different services simultaneously over the same network.

2.3.1 Colorless ONU

In a bidirectional WDM-PON system, both the OLT and the ONU need an optical carrier for data transmission. Wavelength specific light sources can be used at the OLT since it is in a controlled environment and maintenance can be easy. However, at the ONU, the challenge for light source selection is much greater since variation in operational environment can be significant and maintain the inventory can be expensive. As a result, how to achieve a cost effective ONU becomes the most important research challenge in WDM-PON.

The easiest way is to use a wavelength specific light source in each ONU, such as a distributed feedback (DFB) laser. However, the wavelength of the DFB laser needs to be carefully controlled. For example, the wavelength will drift with aging and it is also affected by the change of temperature. One solution is to use a thermo electric cooler (TEC) with each DFB laser, it can keep the temperature stable, so that the wavelength of the DFB laser will be stable. The so called colored ONUs use light source working at different wavelengths, such a device in each ONU will greatly increase the system cost and complexity.

To replace a colored ONU, much research has been focused on the possibility of using colorless ONUs. Here, all the ONUs will be the same if they are colorless. Wavelength of an ONU is defined by the OLT through a control signal or a centrally supplied light source. The use of colorless ONU can effectively reduce the system cost. The simplest way to implement a colorless ONU is the use of a tunable laser at the ONU. However, a tunable laser is still expensive. Although some possible ways to implement low cost tunable lasers have been proposed [17], it will be a long time before it can be cost effective for PON systems.

The colorless ONUs can also be realized by spectrum slicing technique. This scheme uses a broadband light source such as a light emitting diode (LED) [18] at each of the ONU. When it comes to the RN, it will be sliced into different wavelength carriers and routed to the OLT. The main challenges are the limited signal power due to spectral slicing and limited modulation speed of the LED (typically less than 200Mbps). If an EAM is used with the broadband LED or ASE source, cost will be high. In addition, intensity noise due to spectral slicing and dispersion due to broad optical spectrum can also be a concern.

Another possible solution for colorless ONU is to use injection locking of Fabry-Perot

(FP) laser. The longitudinal mode of a FP laser can be injection locked using either a spectral sliced ASE source from the OLT [19] or it can be locked with a coherent light source from the OLT [20]. The former may only enable limited data rate due to intensity noise while the latter is an expensive option. Injection locking of a low reflectivity FP laser has also been studied [21].

An attractive solution to achieve colorless ONUs is the use of centralized light sources (CLS) at the OLT. This scheme offers a simple way for wavelength management and maintenance. Typical schemes are the carrier distributed schemes and the re-modulation schemes. In the carrier distributed scheme, an additional light source is used to distribute an optical carrier for each ONU for the uplink modulation; in the re-modulation scheme, the downlink signal is reused or partly reused for uplink modulation. The most popular modulator is the reflective semiconductor optical amplifier (RSOA) and Reflective Electro-absorption modulator (REAM) [22].

2.3.2 Rayleigh Backscattering in WDM-PON

Rayleigh scattering "is the elastic scattering of light or other electromagnetic radiation by particles much smaller than the wavelength of the light" [23], which is discovered by British physicist Lord Rayleigh. In an optical communication system, when a light is transmitting in an optical fiber, some of the light will be scattered and reflected back to input direction, which is called Rayleigh backscattering (RB).

If an optical signal is launched into a length of fiber, the expectation of RB intensity can be represented as,

$$\mathrm{E}(I_{RB}) = I_s \alpha_s S(1 - e^{-2\alpha L})/2\alpha$$

where the symbols I_s, α_s, S, α, L are input signal intensity, Rayleigh scattering attenuation coefficient, recapture factor, fiber attenuation coefficient and fiber length (km) respectively [24].

In one feeder fiber bidirectional WDM-PON system, using the carrier distributed scheme or the re-modulation scheme will always generate RB in transmission, which is unavoidable. If the PON architecture is not well designed, the RB will become a strong noise and degrade the system performance in long distance and high speed transmission system. For example, in downlink transmission, the RB of uplink signal transmit in the same direction as the downlink signal, so the received downlink signal contains the RB of the uplink signal. Although the power is not very strong, the downlink signal is also very weak after long distance transmission, due to signal beating and crosstalk, RB will seriously affect the system performance, especially in high data rate and long reach PON systems. This situation will also occur in the uplink transmission.

The research challenge is reducing the effect of RB by careful design of the system configurations. Using dual fiber to transmit uplink and downlink signal separately is not a good practical solution, because the fiber deployment cost is doubled. Some schemes have been proposed to reduce the RB effect typically with increased system complexity. More solutions need to be studied in the future.

2.3.3 Dual service data transmission in WDM-PON

In many WDM PON systems, dual services may need to be provided. The two data services are independent and transmitted in the same channel [25]. Some schemes have been proposed to provide simultaneously dual services, however most suffer from performance degradations, such as the inter channel interference between dual service signals, the limited data rate, the need of extra light source and narrow band-pass filters and the undesirable beat noise. The two independent data need to share a single wavelength in a WDM-PON. How to use one channel and one wavelength to simultaneously transmit two different data streams is a great research challenge.

Chapter 3

Subcarrier Multiplexed WDM-PON system

3.1 Introduction

Wavelength division multiplexed passive optical network (WDM-PON) is an attractive solution to meet the ever increasing bandwidth demand of internet users. Signal re-modulation using centralized optical carriers enables the realization of colorless ONUs for WDM-PON systems and at the same time allows the uplink and downlink of the PON system to share a single optical carrier. Many WDM-PON system architectures based on this approach have been proposed and demonstrated. RSOA is typically used for re-modulation of the uplink data [26].

Although it is possible to modulate both the uplink and downlink using baseband modulation, careful selection of modulation format is necessary to reduce crosstalk between the uplink and downlink data. For example, DPSK can be used for downlink transmission and RSOA is used for uplink data transmission using OOK. However, phase to intensity noise conversion caused by the phase modulation may affect the performance of the uplink data transmission [27]. Alternatively, downlink OOK modulation using limited extinction ratio and uplink transmission using DPSK may be employed with power penalty caused by the limited extinction ratio. Additional challenges that may affect the PON signal transmission are chromatic dispersion (CD) penalty with increased data rate and Rayleigh backscattering (RB) caused by downlink signal to the uplink data transmission. Various techniques have been proposed to address these limitations typically with increased system complexity [28].

An attractive alternative is to use subcarrier multiplexing to separate the uplink and the downlink signals [29]. In order to reduce the effect of fading associated with dispersion, single-sideband (SSB) modulation should be used [30].

In this chapter, a WDM-PON system using subcarrier multiplexed single sideband (SSB) modulation for downlink data transmission and RSOA re-modulation of baseband data for uplink data transmission is proposed to realize a bidirectional PON system. Experimental result at 2.5Gbit/s has been demonstrated. The scheme reduces the effect of RB and since self-heterodyne coherent detection can be realized, high order modulation can be employed to further increase the data rate and dispersion equalization can be easily realized. The use of a high frequency subcarrier also allows direct detection to be employed for uplink data detection without the need for optical and electrical filtering at the OLT.

3.2 Previous WDM-PON systems with signal re-modulation schemes

In a WDM-PON system, there are many methods to generate upstream data. Such as the carrier distributed scheme and the signal re-modulation schemes.

In the carrier-distributed scheme, the OLT needs at least two light sources, one is used for the downlink data transmission, the other is distributed from the OLT to each of the ONUs for uplink data transmission, which means that the OLT provides the light source to the ONU for uplink data transmission remotely. The most serious problem of this scheme is the significant increase in system cost due to extra light sources needed. Although incoherent broadband amplified spontaneous emission (ASE) light can be used at the OLT to reduce the system complexity, the available optical signal power at the ONU will be very low. Intensity noise and dispersion penalty as a result of spectral slicing will also limit data transmission rate.

In the re-modulation scheme, the downstream light or some part of it can be reused as the upstream carrier by the upstream signal for data transmission without the need for other light source at the ONUs [31]-[34]. This scheme has many advantages, such as the ease of wavelength management. Much research has been focused on the signal re-modulation schemes, and it is one of the most promising candidates for next generation optical access networks.

Several re-modulation schemes have been proposed, such as downstream differential phase shift keying (DPSK) and upstream on off keying (OOK), downstream inverse return-to-zero (IRZ) and upstream OOK, downstream DPSK and upstream DPSK, downstream OOK and upstream DPSK, etc. However, each approach has its limitation, such as poor chromatic dispersion performance, the need for synchronization and limited data transmission rate.

3.2.1 Downstream DPSK and upstream OOK scheme

In this scheme, as showed in Fig.3.1 [35], the downstream data is modulated by a phase modulator (PM) at the OLT, after downlink data transmission through the optical fiber, it is detected at the ONU by an optical delay interferometer (ODI) based DPSK demodulator followed by an optical receiver. The upstream data is used to modulate part of the received optical signal using a Mach-Zehnder modulator (MZM). At the OLT, the upstream data is received by a direct detection optical receiver.

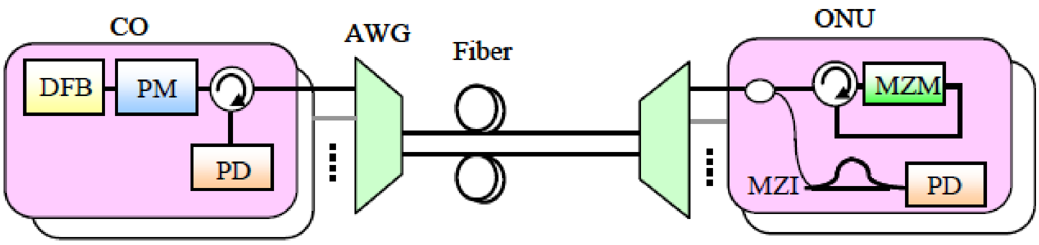

Fig.3.1 Downstream DPSK and upstream OOK scheme [35]

The downstream signal is phase modulated using a phase modulator. The optical power is constant. When part of the signal is remodulated using OOK format at the ONU, the signal should not be affected by the downstream signal if there is no fiber chromatic dispersion. However, fiber dispersion will cause phase to amplitude conversion and the amplitude of the downstream optical carrier is no longer constant. This will affect the performance of the upstream signal remodulation in the OOK format. The scheme proposed the use of a reduced modulation index (RMI) DPSK signal to reduce the CD impact for upstream remodulation. In addition, optical carrier chirp caused by downstream phase modulation will also introduce penalty to upstream remodulation signal since the amplitude of the optical carrier is no longer constant but a function of the downstream signal.

3.2.2 Downstream IRZ and upstream OOK scheme

In this scheme, as showed in Fig.3.2 [32], the downstream data is modulated using inverse-return-to-zero (IRZ) format by a RZ-shaped RF signal. After optical transmission link, the optical signal is distributed to different ONUs at the remote node. At the ONU, the received signal is divided into two portions, one portion is transmitted into an optical receiver, and the other portion of the downstream optical signal is remodulated by an MZM for upstream OOK modulation. When the upstream signal is transmitted back to the OLT, the signal is received by a direct detection receiver.

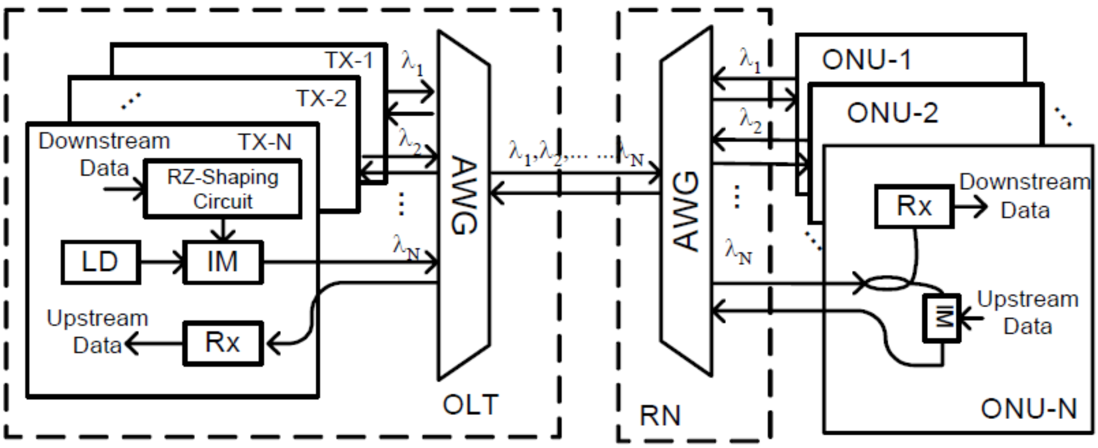

Fig.3.2 Downstream IRZ and upstream OOK scheme [32]

The IRZ transmitter consists of a MZM driven by a RZ-shaped RF electrical driving signal generated by adding a RF clock signal to the NRZ data. When the DC bias of the MZ modulator is set at the quadrature point, the modulated optical signal is an IRZ signal. Therefore, there is always optical power at both the zero state and the one state. Such a signal can be re-modulated with OOK format at the ONUs. This scheme does not need to erase the downstream data, so that the optical carrier can be modulated with high extinction ratio (ER) at the OLT.

3.2.3 Downstream DPSK and upstream DPSK scheme

In this scheme, as showed in Fig.3.3 [33], the downstream data is modulated by a LiNbO3 phase modulator (PM) at the central office. Then it is transmitted through an isolator and a 10km single mode optical fiber link. The signal passes through a circulator and is divided by an optical coupler. One portion of the signal is received by an optical delayed interferometer (ODI) based DPSK receiver at the ONU. The other portion is used for re-modulation of the downstream optical carrier with the upstream data, some pre-coding is necessary in this step. The upstream data can be received by a standard DPSK receiver at the OLT.

Synchronization is very important to align the downstream data with the upstream modulation signal in this scheme. Electrical delay line and electrical buffers are necessary and can be used to control the time delay.

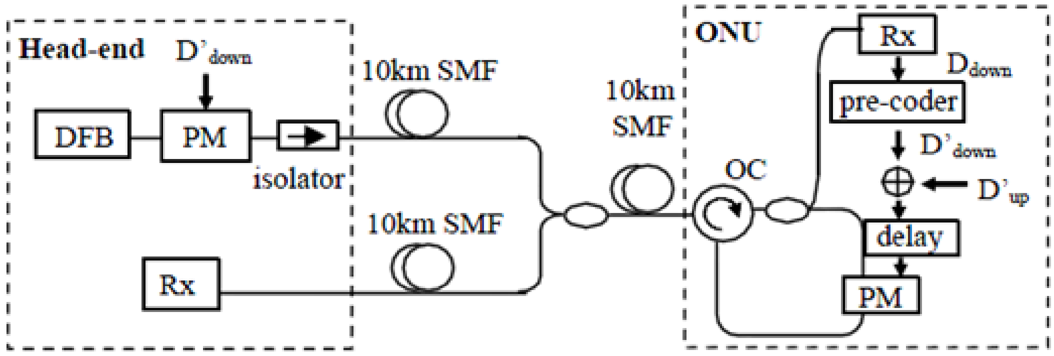

Fig.3.3 Downstream DPSK and upstream DPSK scheme [33]

3.2.4 Downstream OOK and upstream DPSK scheme

In this scheme, as shown in Fig.3.4 [34], the downstream data is modulated by a MZM using low extinction ratio (ER) OOK format at the OLT. After transmission down a single mode fiber transmission link of the WDM PON, one portion of the signal is detected by an optical receiver at the ONU, the other portion is remodulated by a phase modulator with DPSK upstream data. When upstream data arrives at the OLT, it is received by a standard DPSK receiver.

Low extinction ratio will affect transmission performance of the downstream data. Careful selection of extinction ratio is necessary to balance between the uplink and downlink signal transmission performance.

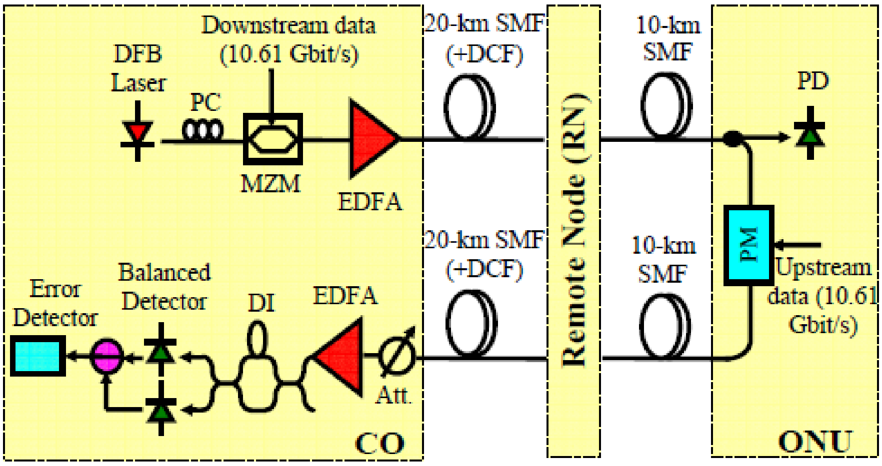

Fig.3.4 Downstream OOK and upstream DPSK scheme [34]

3.3 WDM-PON systems for reducing Rayleigh Backscattering

When light travels in the optical fiber, some part of light is scattered and reflected back, this phenomenon is called Rayleigh backscattering (RB). This light is in the opposite direction of the original light, and will generate interferometric noise in single feeder fiber bidirectional PON systems. This will degrade the system transmission performance.

The easiest way to avoid RB noise is using dual fiber for transmission uplink and downlink signal separately. However, this method will increase the system complexity and cost. How to reduce the RB noise in a one feeder fiber bidirectional PON system is a challenging problem for researchers.

Several schemes for reducing RB have been proposed, such as reducing RB based on in-band optical filtering, reducing RB based on micro-ring modulators, and reducing RB based on SSB-CS modulation, etc. These schemes reduce RB noise but typically with increased system complexity.

3.3.1 Reducing RB based on in-band optical filtering

This scheme reduces the RB noise by using in-band optical filtering in the carrier distributed WDM-PON system. Instead of using conventional on-off keying (OOK) modulation format, the differential phase-shift keying (DPSK) modulation format is used at the ONU. At the OLT an optical notch filter helps to suppress effectively the carrier RB.

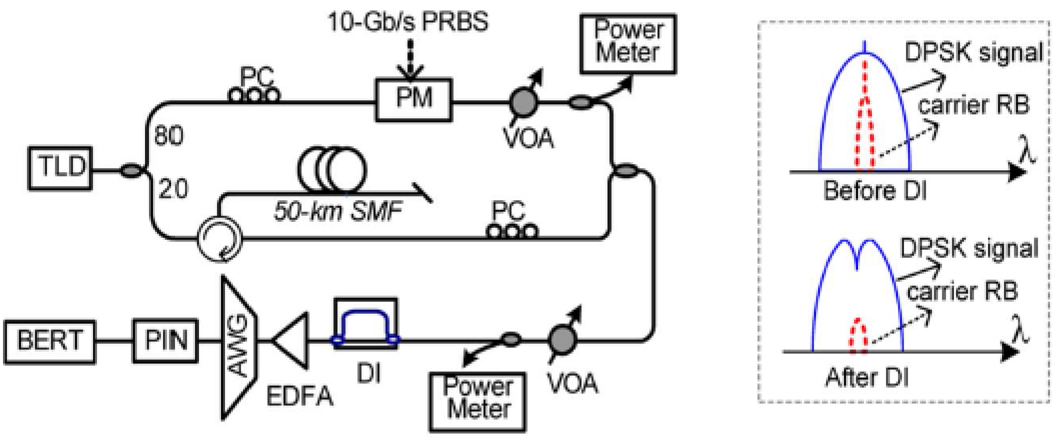

Fig.3.5 Reducing RB based on in-band optical filtering [36]

As showed in Fig.3.5 [36], the DPSK signal and carrier RB with 50km SMF transmission are combined together, a VOA, power meter, DI and EDFA are used before the AWG. The carrier RB is the dominant noise in the system, the power of carrier RB before and after DI is measured, the result shows the carrier RB can be suppressed by up to 19dB using the notch filter. 10Gbps upstream signal is experimental demonstrated, and less than 2.5dB power penalty after 60km transmission was realized.

3.3.2 Reducing RB based on SSB-CS modulation

This scheme uses a single sideband carrier suppressed (SSB-CS) signal modulation at the ONU. It is achieved by an integrated dual parallel Mach-Zehnder modulator (DPMZM). After SSB-CS modulation, the uplink signal and downlink signal are at different wavelengths. This effectively reduces the spectral overlap between the RB noises and uplink signal.

This scheme [30] can efficiently reduce the system performance degradation due to RB comparing with system using conventional NRZ signal. However, the use of a SSB modulator at the ONU may not be a viable option since comparing with OLT, its operational environment can change significantly.

3.3.3 Reducing RB based on micro-ring modulators

Cascaded silicon micro-ring modulators at the OLT are used as the downlink modulators. It can achieve wavelength selective modulation. The OLT can generate a SSB downlink signal with a carrier for uplink re-modulation. The ONU modulate the uplink data on the clean carrier distributed from the OLT, so that it can reduce the RB noise effect [37].

However, stable narrow band filter is needed at the ONU. Besides, polarization adjustment and differential delay due to propagation delay will also increase the system complexity.

3.4 WDM-PON System based on Subcarrier Multiplexed Single Sideband Modulation

Here a WDM PON system based on single sideband (SSB) modulated subcarrier multiplexed signal for downlink data transmission is studied experimentally. The scheme reduces the effect of Rayleigh backscattering (RB) for improved system performance.

3.4.1 Proposed system architecture

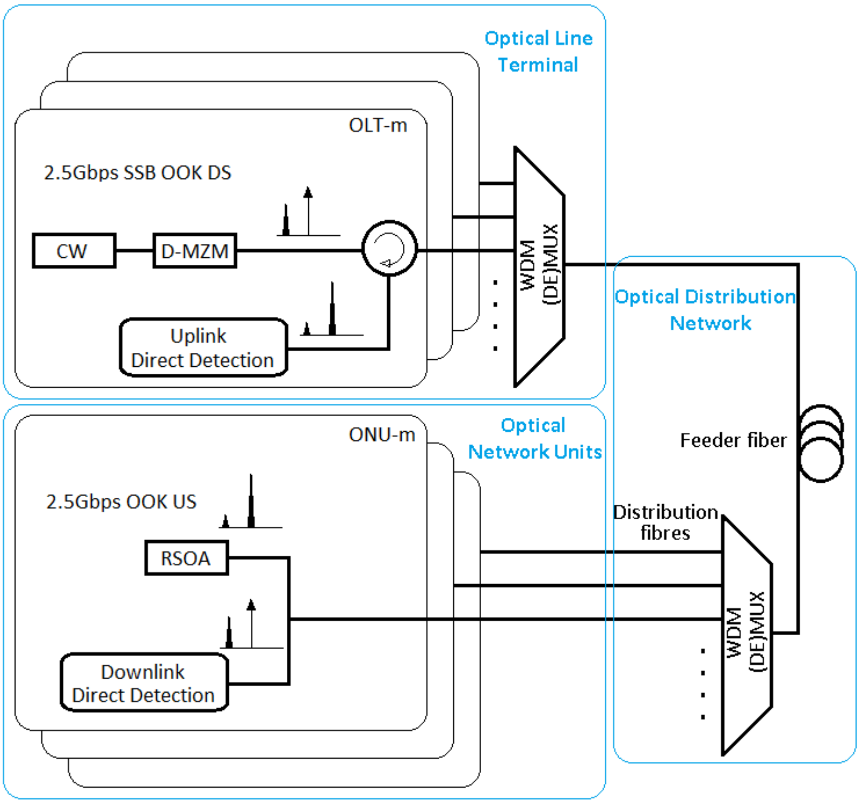

Fig.3.6 Architecture of proposed subcarrier multiplexed WDM-PON system

Fig.3.6 shows the architecture of the proposed bidirectional subcarrier multiplexed WDM-PON system. There are m channels for optical line terminal (OLT) and m channels optical network units (ONU). In each OLT, the optical carrier is modulated by a dual-electrode Mach–Zehnder modulator (MZM) for generating a SSB downlink signal. The power fading effect due to chromatic dispersion (CD) can be overcome by SSB modulation format. After transmission through the optical distribution network (ODN), which consists of a feeder fiber, a demultiplexer, and distribution fibers, the signal is split into two portions. One portion is used for direct detecting the downlink single sideband signal; the other portion is used for generating the uplink signal by RSOA re-modulation of the optical carrier. For uplink signal transmission, baseband modulation with direct detection is chosen at the OLT. The scheme also allows self-heterodyne signal detection at the ONU for high order modulation and chromatic dispersion (CD) equalization.

The system architecture offers following advantages:

1) The use of SSB signal for downlink transmission can reduce the power fading effect due to CD for downlink transmission.

2) The downlink and uplink signals are modulated onto different frequencies. The downlink signal is on one SSB subcarrier, while the uplink signal is on the optical carrier. Such a configuration can help to reduce the interference between the RB of downlink signal and uplink signal, and the interference between the RB of uplink signal and downlink signal to reduce the degradation effect of RB in the entire PON systems and to increase the receiver sensitivity for both downlink and uplink transmission.

3) The use of commercial RSOA in the ONU helps to reduce the need for additional light sources at the ONU. There is no need for any optical filter in the system for separating the optical sideband subcarrier and the optical carrier.

4) This scheme allows self-heterodyne coherent signal detection at the ONU, and self-homodyne coherent signal detection at the OLT. So a variety of coherent DSP algorithm can be employed in the system. This will help to significantly increase the system performance and adaptability.

3.4.2 Experimental demonstration

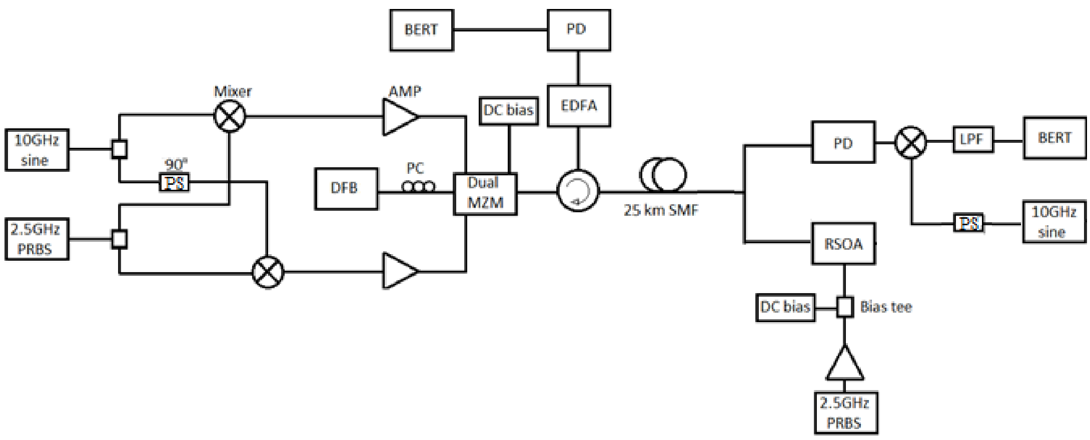

Fig.3.7 Experimental setup of proposed subcarrier multiplexed WDM-PON

Fig.3.7 shows the experimental setup. For downlink data transmission at the OLT, a CW signal from a DFB laser is modulated by a dual-electrode Mach–Zehnder modulator (MZM) to generate the single sideband subcarrier multiplexed signal (SSB). A 2.5Gbps 2^{15}-1 PRBS data is mixed with two 90◦ phase shifted 10GHz sinusoidal RF signal to generate two modulated subcarrier signals. The mixer bandwidth is from 3.4GHz to 15GHz, so there is no need for a band-pass filter to filter out the baseband frequency. The modulator biased at the quadrature point (V_{bias}=1.05V) is driven by these two RF subcarrier signals. The generated SSB signal has 10GHz spacing from the un-modulated optical carrier, and is 15dB lower than the carrier.

At the ONU, the SSB signal is directly detected by a photodetector (PD). It is essentially a self-heterodyne detection system generating a 10GHz beating signal between the SSB signal and the optical carrier. Since optical field information is maintained, coherent DSP detection algorithm can be employed for data detection. This offers the potential for using high order modulation formats for downlink data transmission for simplicity. In the experiment we mixed this beating signal with the same 10GHz sinusoidal RF signal for down conversion to the baseband to enable baseband data detection. After a low-pass filter, it can be measured by the BERT.

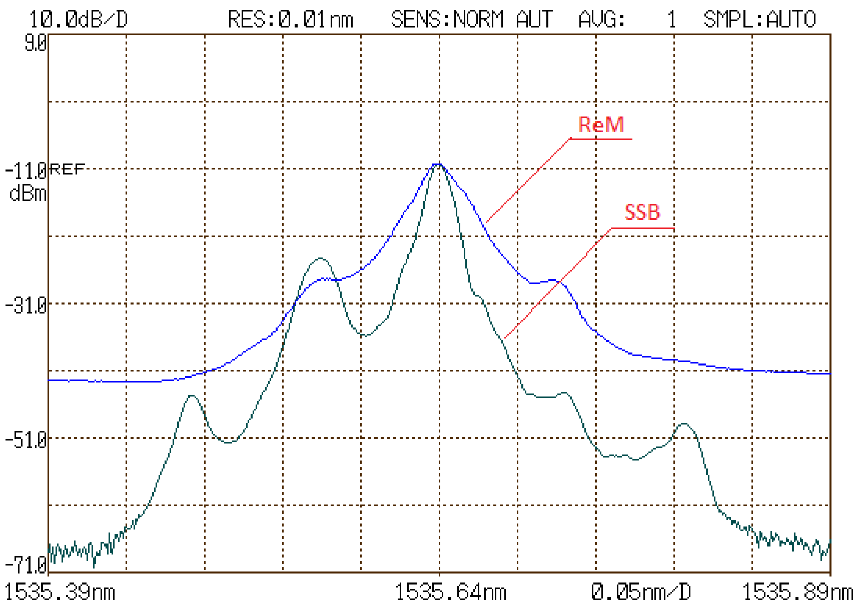

Fig.3.8 Measured optical spectrum

For the uplink transmission, the downlink light is used as the centralized optical carrier and is injected into an RSOA. The RSOA is driven by 2.5Gbps 2^{15}-1 PRBS data and with maximum bias current (I_{bias}=60mA). When the sideband subcarrier signal is more than 10GHz away from the optical carrier, the downlink signal is suppressed almost completely because the limited response speed of the RSOA. The re-modulated optical spectrum is showed in Fig.3.8, "SSB" represents the optical spectrum of single sideband downstream signal, and "ReM" represents the optical spectrum of RSOA re-modulated upstream signal. This feature allows the re-modulated uplink data to be directly detected by a direct detection optical receiver at the OLT without the need to use optical or electric filter to remove the subcarrier signal first. Similar receiver sensitivity performance can be achieved as that using CW seeded re-modulation scheme.

3.4.3 Experiment results

Fig.3.9 shows the measured BER performance for both uplink and downlink signal transmission with back to back (B2B) and 25km SMF fiber transmission at 1535nm. “US-B2B” represents upstream back to back, “US-25km” represents upstream 25km SMF transmission, “DS-B2B” represents downstream back to back, and “DS-25 km” represents downstream 25km SMF transmission. On-Off key (OOK) is used for both uplink re-modulation and downlink subcarrier modulation, 2.5Gbps and 2^{15}-1 PRBS data is used for uplink and downlink measurement.

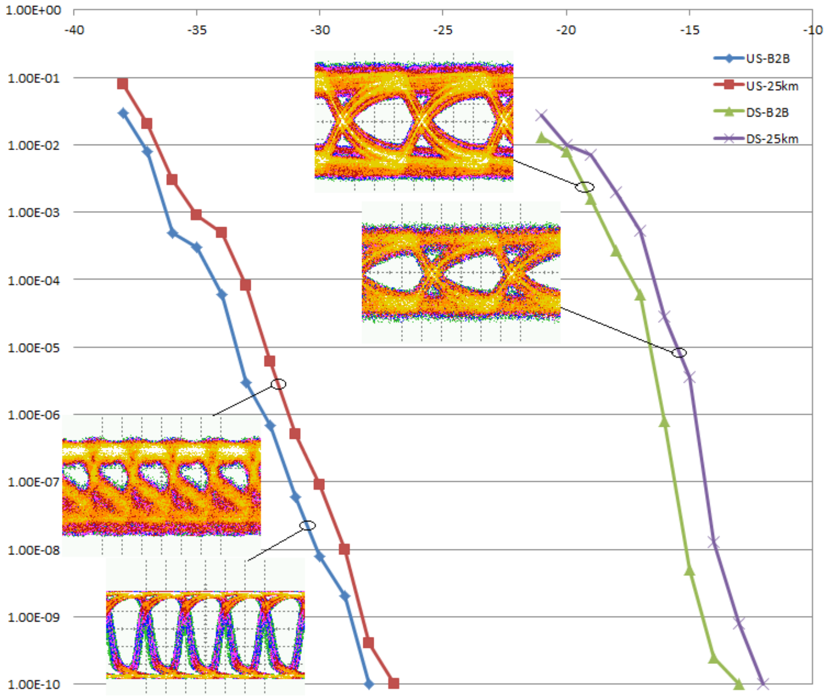

Fig.3.9 BER performances and eye diagram

The results show that the receiver sensitivity achieved for downlink SSB signal is -18.8dBm at 1×10^{-3}, with approximately 1dB penalty after 25km SMF transmission. The eye diagram shows good system performance. For uplink signal, an erbium doped fiber amplifier (EDFA) (gain=28dB, NF=5dB) is used before the PD as a pre-amplifier, and data is directly detected without any filter, the receiver sensitivity of RSOA re-modulated signal can reach -36.5dBm at 1×10^{-3}, with approximately 1dB penalty after 25km SMF transmission

3.5 Discussions

In this section, a more detailed look at the proposed subcarrier multiplexed WDM-PON system is presented. The evaluation of RSOA bandwidth and possible ways to increase data rate of the system are discussed.

3.5.1 RSOA bandwidth evaluation

A key component of the proposed system is the reflective semiconductor optical amplifiers (RSOA) [38]. It is a modulator as well as an amplifier for remodulating the downstream signal for upstream data transmission.

In the experiment, the used RSOA is a 1.55μm reflective semiconductor optical amplifier (RSOA) by Centre for Integrated Photonics (CIP). The model is CIP-SOA-R-OEC-1550.

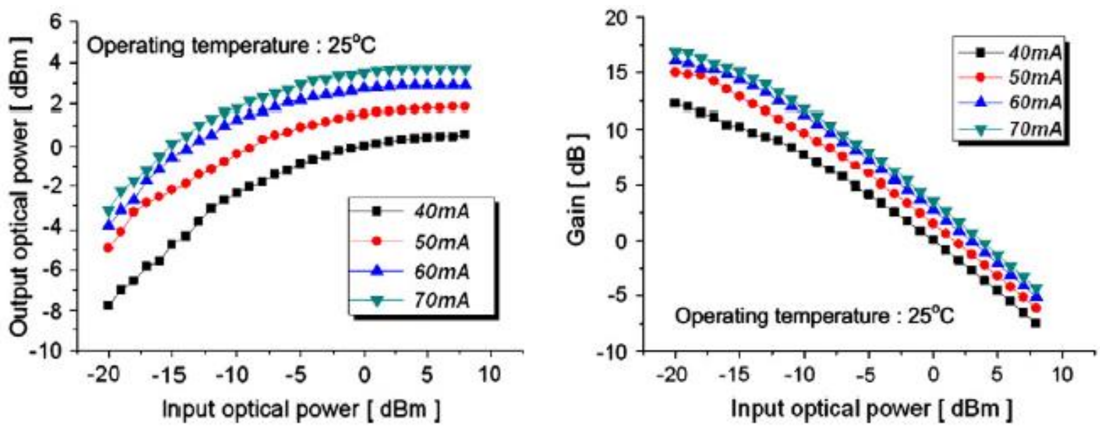

Fig.3.10 Gain saturation character of RSOA [39]

The gain saturation of the RSOA is very useful in the re-modulation schemes, it helps to erase the downstream data and rewrite upstream data in the same optical carrier. As the injected optical power increasing, the optical gain in the RSOA output decreases, as shown in Fig.3.10 [39].

The RSOA used has only 1.5GHz electrical bandwidth [40]. To assess its potential for further system performance improvement, its characteristics were evaluated. The RSOA is injected with a continuous waveform (CW) light source. It is then modulated with (non-return to zero) NRZ signals at different clock frequencies, from 1GHz to 4GHz. The signals were amplified by a 10Gbps optical modulator driver (JDS Uniphase, H301-1110) amplifier with peak to peak voltage up to 7V. The results are showed in Fig.3.13.

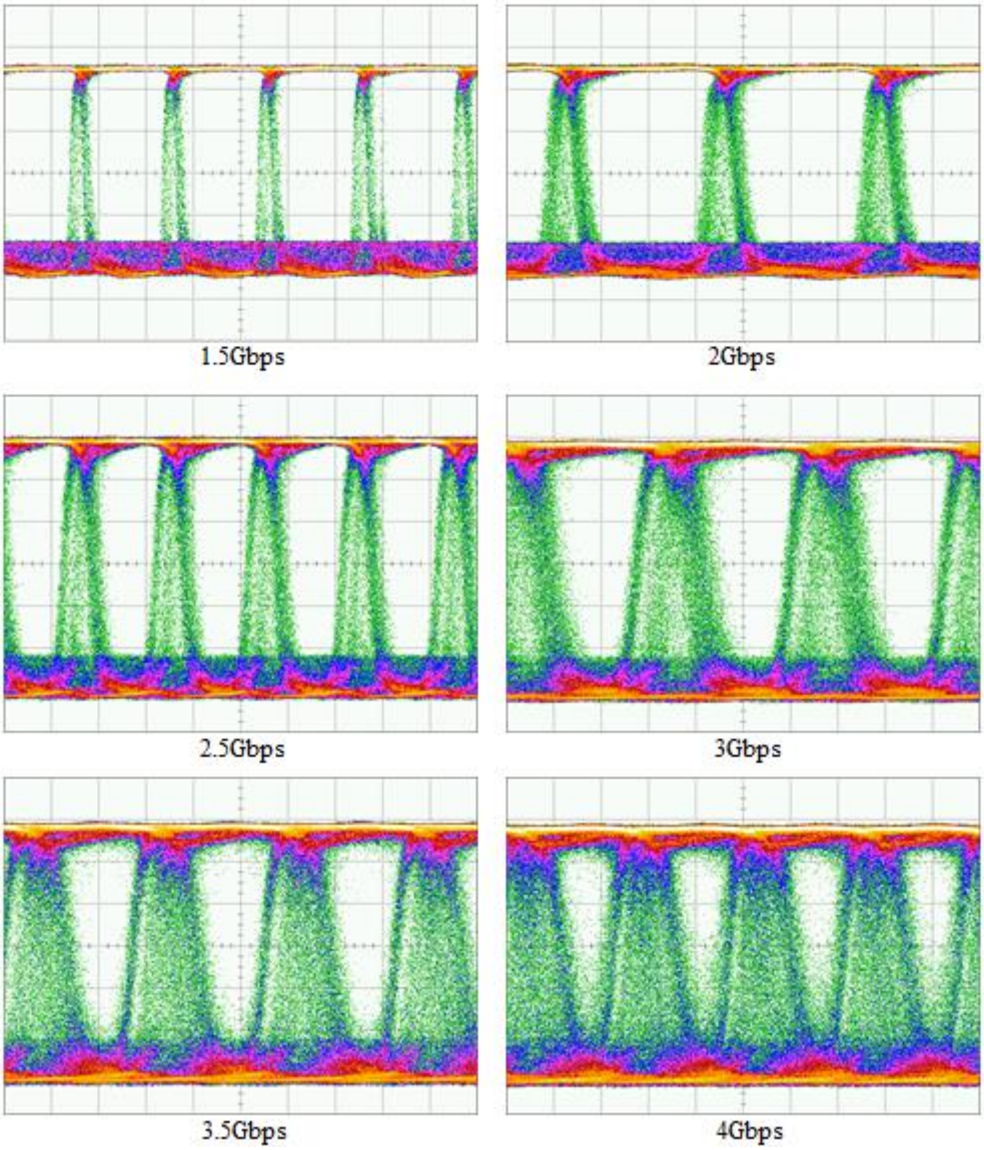

Fig.3.11 RSOA modulation eye diagram from 1.5Gbps to 4Gbps

From the results in Fig.3.11, the RSOA modulation eye diagram becomes worse as the modulation frequency increases. The back to back (B2B) bit error rate (BER) at 2.5Gbps, 3Gbps, 3.5Gbps, and 4Gbps is showed in Fig.3.12. It indicates that when the modulation data rate increases beyond certain value, the RSOA modulation performance degrades.

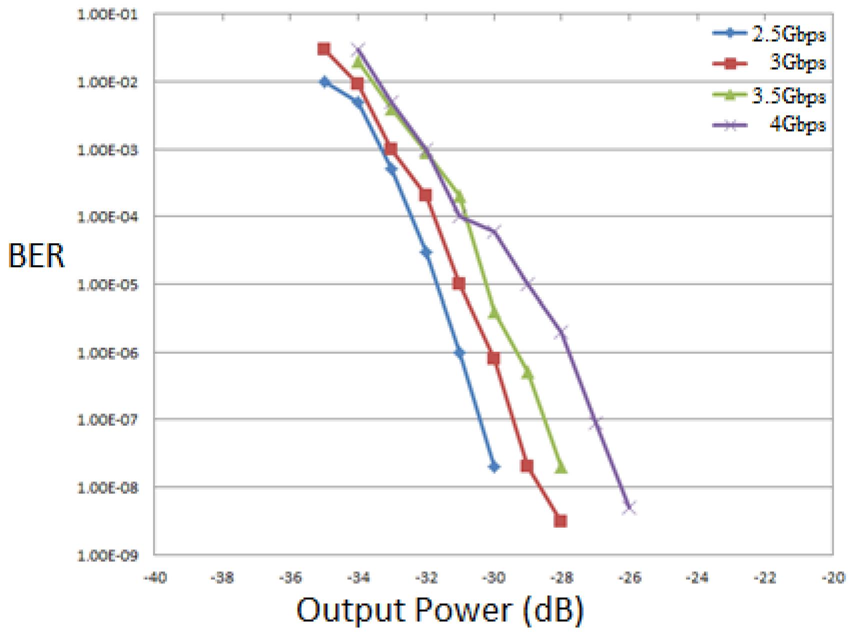

Fig.3.12 BER of RSOA B2B modulation from 2.5Gbps to 4Gbps

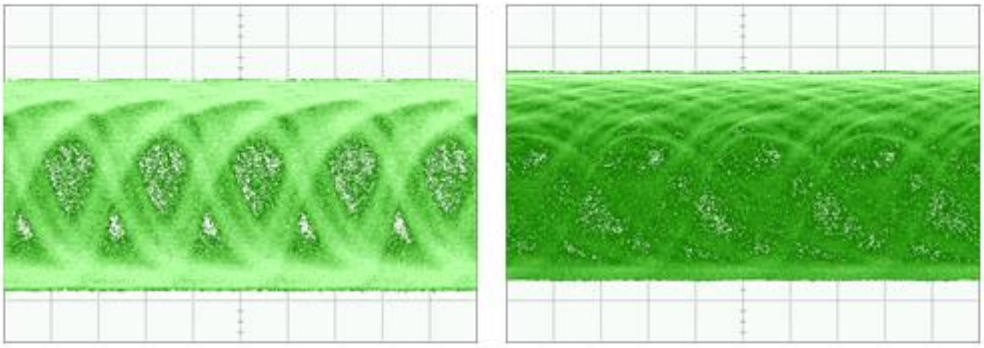

Fig.3.13 RSOA modulation eye diagram with 5Gbps and 8Gbps

Fig.3.13 shows RSOA modulation eye diagram with 5Gbps and 8Gbps, it is clear that the system performance decreased rapidly after 4Gbps, the best B2B BER performance of 5Gbps RSOA modulation can only achieve 1×10^{-3}, and the best B2B BER performance of 8Gbps RSOA modulation can only achieve 1×10^{-1}.

3.5.2 Further increase of data rate

With limited RSOA bandwidth, the data rate can only be increased through the use of higher order modulation format. Some preliminary investigations have been carried out.

The modulation bandwidth of the RSOA is about 1.5GHz. The data rate achieved is less than 4Gbps. To increase data rate without increasing modulation speed, higher order modulation formats must be used. These include 4-ary pulse amplitude modulated (4-PAM) signal, quadrature phase shift keying (QPSK) signal, or orthogonal frequency-division-multiplexing (OFDM) signal with high order modulation per subcarrier.

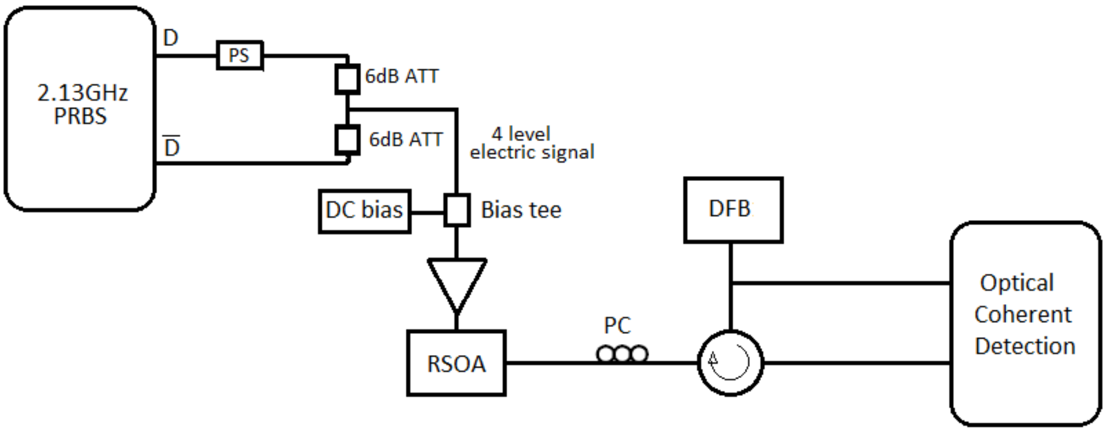

Fig.3.14 Experimental setup of QPSK modulation using RSOA

Fig.3.14 shows the experimental setup of for studying QPSK modulation using RSOA. The PRBS data source is driven by 2.13GHz clock, the DATA and reversed DATA are delayed several symbols and combined together. Each arm needs a 6dB attenuator to reject the reflected signal in order to increase the quality of four-level electric signal. The signal is detected by an optical coherent receiver with homodyne detection. Fig.3.15 shows a 2.13Gbps QPSK received signal modulated by RSOA, a clear received signal distributions can be recovered by advance DSP algorithm.

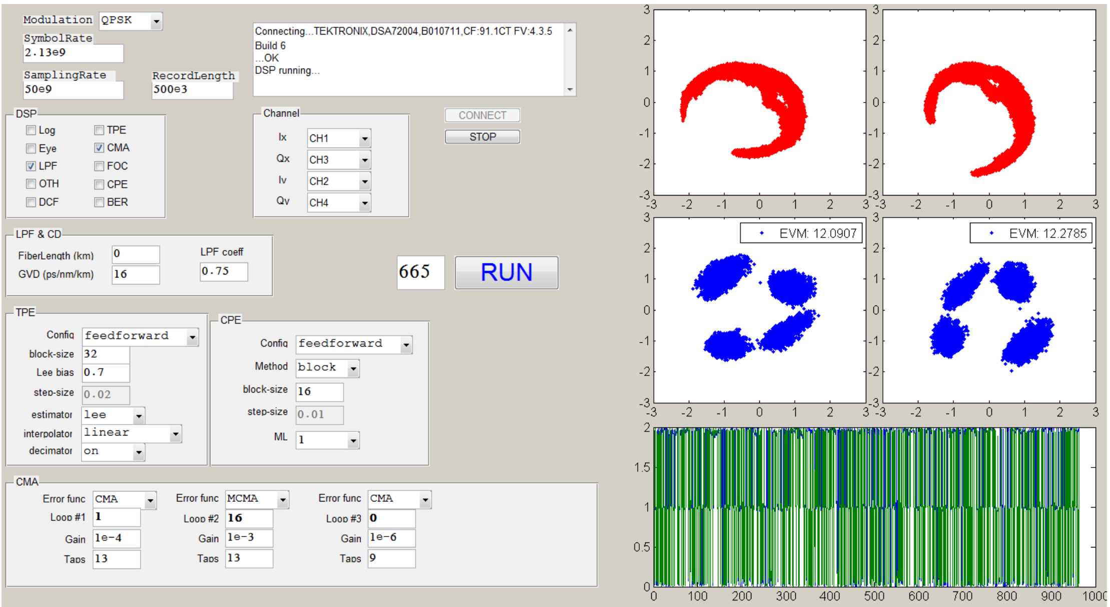

Fig.3.15 QPSK constellations using RSOA modulation

3.5.3 Overcome power fading with SSB modulation

In this work, a dual-electrode Mach–Zehnder modulator (MZM) is used to generate downlink signal in the OLT, which can be treated as two parallel phase modulators (PM). If the a continuous-wave (CW) signal is used, the optical field of the modulated output signal can be represented by

$$E(t) = \frac{A}{2}\{\cos(\omega_c t + \alpha\pi + \beta\pi\cos\omega_{rf} t) + \cos(\omega_c t + \beta\pi\cos[\,\omega_{rf} t + \theta])\}$$

where the symbols A, ω_c, α, β, ω_{rf}, θ, are amplitude of the input signal, angular frequency of the input signal, normalized bias voltage, normalized amplitude of the RF signal, angular frequency of the RF signal, phase difference between two RF signals respectively.

When phase difference $\theta = \pi$, dc voltage biases at the quadrature point $\alpha = \pi/2$, a DSB signal is generated, the power spectral density (PSD) can be simplified and represented by

$$S_E(\omega) = \frac{\pi A^2}{4}[J_0^2(\alpha\pi)\delta\{\omega + \omega_c\}$$
$$+J_1^2(\alpha\pi)\delta\{\omega + (\omega_c - \omega_{rf})\}$$
$$+J_1^2(\alpha\pi)\delta\{\omega + (\omega_c + \omega_{rf})\}]$$

where δ{} is a delta function, J_0 and J_1 are the 0th and 1st order Bessel functions respectively. It contains an optical carrier at ω_c, a LSB subcarrier at ω_c - ω_{rf} and a USB subcarrier at ω_c + ω_{rf}.

However, both LSB and USB will generate new components at frequency ω_c + ω_{rf} and ω_c - ω_{rf} by beating with the optical carrier, and the phase of signals at different frequencies will change in different rates after a length of fiber transmission according to the chromatic dispersion properties. As a result, the RF power P_{rf} will be in direct proportion to the resultant phase of the composite signal at the same spectral frequency, which can be represented by

$$P_{rf} \propto \cos[\frac{\pi LD}{c}\lambda_c^2 f_{rf}^2]$$

where the symbols L, D, c, λ_c, f_{rf}, are fiber length, dispersion parameter, optical carrier wavelength, RF frequency respectively [41].

The phase difference of the composite RF signal will cause the power fading effect, a complete cancellation will even happen when the phase difference is π. If a SSB signal is generated, it contains only one sideband with an optical carrier, so that the beating signal of one sideband will not impact the other. This explains why SSB modulation format can overcome the power fading effect.

3.6 Summary

In this chapter, some previously proposed WDM-PON systems with signal re-modulation schemes are reviewed. Previous work on WDM-PON systems for reducing Rayleigh Backscattering is discussed. WDM PON system architecture based on SSB subcarrier multiplexed downlink transmission and baseband re-modulation at the ONU using an RSOA is studied experimentally. The scheme enables the maintenance of field information, thus allows downlink signal transmission using high order modulation formats and easy dispersion equalization at the electrical domain. The scheme also enables the effect of RB to be reduced. RSOA re-modulated data can be directly detected without the need for any optical or electrical filter. Receiver sensitivity of 2.5Gbps data at -18.8dBm for downlink and -36.5dBm for uplink at BER of 1×10^{-3}, with 1dB penalty after 25km transmission has been realized. Much higher data rate using higher order modulation and self-coherent detection can be expected for uplink data transmission in the near future.

Chapter 4

OFDM-WDM-PON system

4.1 Introduction

In previous chapters, carrier remodulation based WDM-PON systems are reviewed and it was shown that SSB subcarrier multiplexed downlink transmission and baseband re-modulation at the ONU using an RSOA offers simple system architecture and reasonably good system performance. However, further increase of data rate is limited by RSOA modulation bandwidth. Generating high order modulation format such as QPSK signal through driving RSOA directly was proven to be difficult and will also introduce certain amount of performance degradation.

Orthogonal frequency-division-multiplexing (OFDM) enables superior tolerance to CD and allows flexible bandwidth allocation to PON users and can provide good tradeoff between data transmission rate and system reach. It is one of the most promising candidates for the next generation optical access networks [42]-[45]. 10Gb/s data OFDM transmission using reflective semiconductor-optical-amplifier (RSOA) re-modulation of injected CW light has been demonstrated [46], and simulation study has demonstrated the effectiveness of using 10Gb/s OFDM signal for high speed bi-directional signal transmission in a WDM PON system with upper sideband (USB) for downlink transmission and lower sideband (LSB) for uplink transmission [47]-[48].

In this chapter, the experimental study of a WDM PON system using direct detected

OFDM for downlink signal transmission is described. Single sideband modulated OFDM signal with a guardband at the baseband is used to simplify direct detection of the OFDM signal at the ONU. The guardband portion of the downlink signal is used by an RSOA for baseband signal re-modulation. The use of OFDM for uplink signal transmission allows high data rate to be realized for limited RSOA bandwidth. Using the proposed system, 40Gb/s downlink signal transmission and 10Gb/s uplink transmission for a WDM PON system is demonstrated.

4.2 Bidirectional hybrid OFDM-WDM-PON system for 40 Gb/s downlink and 10 Gb/s uplink transmission using RSOA re-modulation

A bidirectional hybrid orthogonal frequency-division-multiplexing wavelength-division-multiplexing passive optical network (OFDM-WDM-PON) system is studied. The proposed scheme uses OFDM signals occupying different portion of the available signal spectrum for uplink and downlink signal transmission to reduce the effect of Rayleigh backscattering (RB), chromatic dispersion (CD) and power fading. 40 Gb/s downlink signal transmission based on single sideband modulated (SSB) OFDM signal and 10Gb/s uplink signal transmission using re-modulation of a reflective semiconductor-optical-amplifier (RSOA) are realized.

4.2.1 Proposed system architecture

Fig.4.1 shows the proposed bidirectional hybrid OFDM WDM PON system architecture. In each optical line terminal (OLT), the optical carrier is modulated by an intensity modulator (IM) with up converted OFDM signals, DSB signal is generated. To reduce the power fading effect, an optical filter is used to filter out one sideband to produce a SSB signal. After a WDM multiplexer/demultiplexer and transmission through the optical distribution network (ODN), which consists of 20km SMF feeder fiber, a WDM multiplexer/demultiplexer and one distribution fiber, the signal is split into two portions. One portion is used for direct detection of the single sideband OFDM downlink signal; the other portion is used for generating the uplink signal by RSOA re-modulation of the optical carrier. A few options are available for uplink signal transmission: baseband modulation with direct detection at the OLT; baseband modulation with coherent detection at the OLT and OFDM. OFDM is used here to enable the use of high order modulation due to limited RSOA bandwidth.

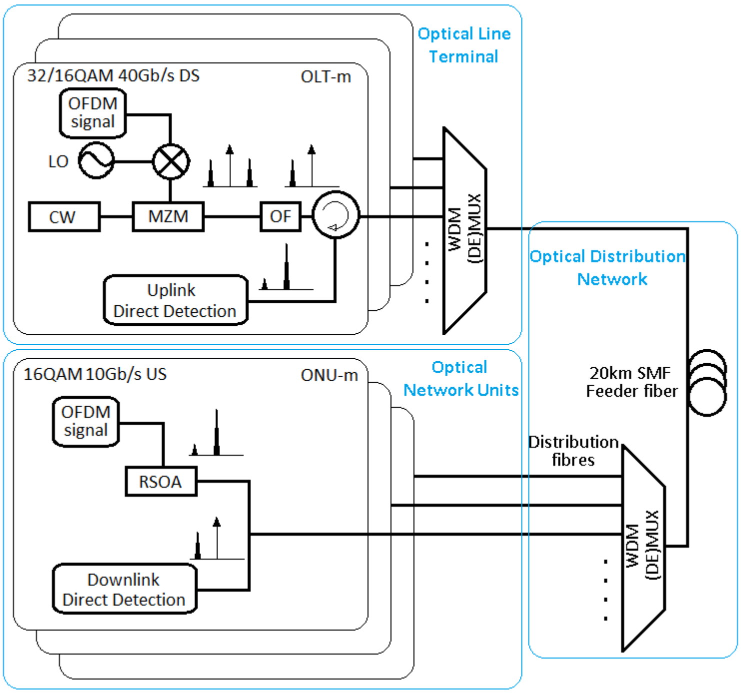

Fig.4.1 Architecture of proposed hybrid OFDM-WDM-PON system

4.2.2 Advantages of the proposed system

The system architecture offers following advantages:

1) SSB signal is used for the downlink transmission. It can reduce the power fading effect due to CD for downlink transmission. In particular for high data rate downlink transmission up to 40Gbps, and transmission more than 20km in standard single mode fiber (SSMF), the system performance degradation is very serious. Such a configuration can significantly increase the downlink receiver sensitivity.

2) The downlink and uplink signals are modulated onto different frequencies. The downlink OFDM signal is modulated on the lower sideband (LSB) of the SSB

subcarrier, while the uplink OFDM signal is modulated on the guardband of the optical carrier at the baseband, the frequency spacing between uplink and downlink data is 12GHz, which depends on the frequency selection of the local oscillator (LO). Such a configuration can reduce the interference between the RB of downlink signal and uplink signal, and reduce the interference the interference between the RB of uplink signal and downlink signal. The degradation effect of RB in the entire bidirectional transmission of the WDM-PON system is reduced as a result. Such a configuration can increase the receiver sensitivity for both downlink and uplink transmission, and ensure good system performance.

3) The scheme allows the use of the commercial RSOA at the ONU. The electric bandwidth of the RSOA is only 1.5GHz, the use of OFDM signals to modulate the bandwidth limited RSOA with high order modulation format can increase spectral efficiency and transmission bit rate. A 10Gbps 16QAM OFDM signal generated by the AWG with 1/32 CP and 512-point FFT is used, the total signal bandwidth is 2.58GHz, in section 3.4.3 RSOA performance was evaluated, and it was shown that binary modulation up to 4Gbps for the RSOA can be achieved with 16QAM modulation per subcarrier, a 10Gbps uplink transmission with the RSOA can be achieved.

4) No additional light sources at the ONU are needed. No optical filter is required in the system for separating the optical sideband subcarrier and the guardband optical

carrier. All these enable the realization of a low cost and low complexity OFDM-WDM PON system with easy wavelength management and easy deployment and operation.

5) This scheme allows self-heterodyne coherent signal detection at the ONU, and self-homodyne coherent signal detection at the OLT. A variety of coherent DSP algorithm can be employed in the system, which will help to significantly increase the system performance and adaptability.

4.2.3 Experimental demonstration

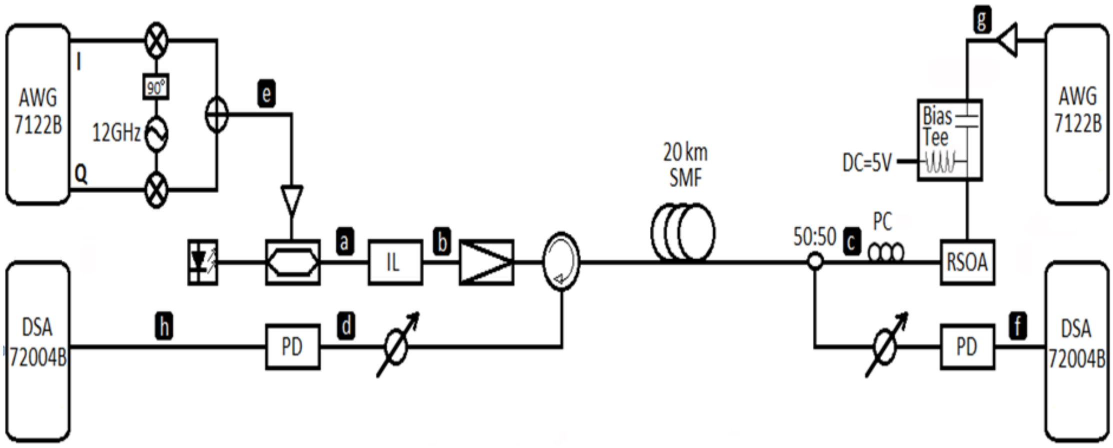

Fig.4.2 Experiment setup of proposed hybrid OFDM-WDM-PON system

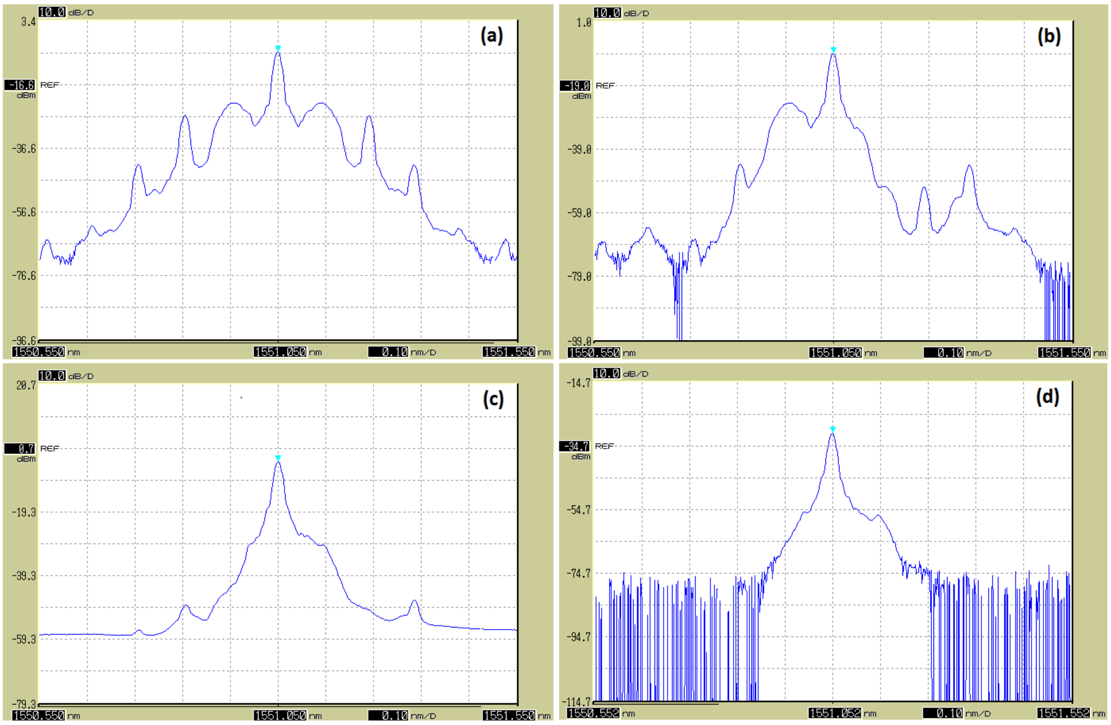

Fig.4.3 Optical spectra of proposed hybrid OFDM-WDM-PON system

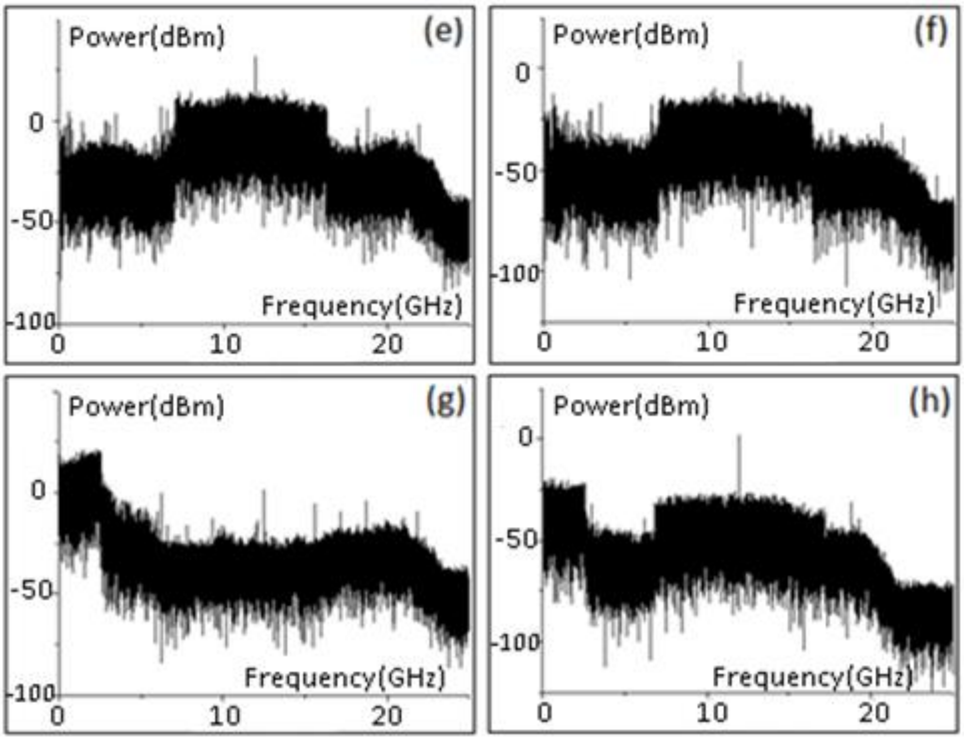

Fig.4.4 RF PSD of proposed hybrid OFDM-WDM-PON system

Fig.4.2 shows the experiment setup of the proposed hybrid OFDM-WDM-PON system. The optical spectra at different points of the system are given in Fig.4.3. The RF power spectral densities (PSD) of electrical signals at different points of the system are shown in Fig.4.4. In the experiment, a centralized lightwave (CW) at 1551.05nm is used for signal transmission. An arbitrary waveform generator (Tektronix AWG7122B) with 12GS/s sampling rate is used to generate the OFDM signals. The downstream signal is 32QAM/16QAM mixed modulation formats OFDM signal. The FFT size is 512 and 1/32 of cyclic prefix (CP) is applied, the total bit rate is 40.16Gbps. The baseband signal is up converted to 12GHz RF frequency by an IQ mixer (Marki IQB0618LK) and the total signal bandwidth is 9.3GHz. The signal is amplified by a broadband modulator driver amplifier (SHF810) and then used to modulate an 18GHz intensity modulator (IM, Covega mach-20). An interleaver (IL, 25-50GHz Optoplex) is then used to filter out the USB of the optical signal to generate the SSB optical OFDM signal. The carrier to sideband ratio (CSR) of the generated signal is 15dB. The downlink signals are amplified by an EDFA (NF=4.5) to 6dBm and transmitted through 20km single mode fiber (SMF).

The received SSB OFDM signal is split by a 50:50 coupler at the ONU. One portion of the signal is used for direct detection by a 20 GHz linear PIN receiver (Discovery, DSC-R401HG, sensitivity=-15dBm) after a variable optical attenuator (VOA) and then sampled by a 50GS/s real-time scope (Tektronix DSA72004B). Recovery of the constellation diagram and bit error rate (BER) evaluation are carried out through offline digital signal processing (DSP). The other portion of the signal (-5dBm) is injected into a 1.5GHz bandwidth RSOA (CIP-SOA-R-OEC-1550) and is modulated by a 10Gbps 16QAM OFDM signal generated by the AWG with 1/32 CP and 512-point FFT, and amplified by a linear modulator driver amplifier (TriQuint, TGA4823-2-SM) after a bias tee (bias current = 72mA). The total signal bandwidth is 2.58GHz and the output of the RSOA is about 7dBm. The residue LSB is reduced by adjusting saturation level of the RSOA. After transmission through the same 20km SMF, the uplink signal passes through a circulator and a VOA and directly detected by a 9GHz PIN receiver (EMCORE R2860E, sensitivity=-20dBm) followed by offline DSP to recover the uplink data.

4.2.4 Experiment results

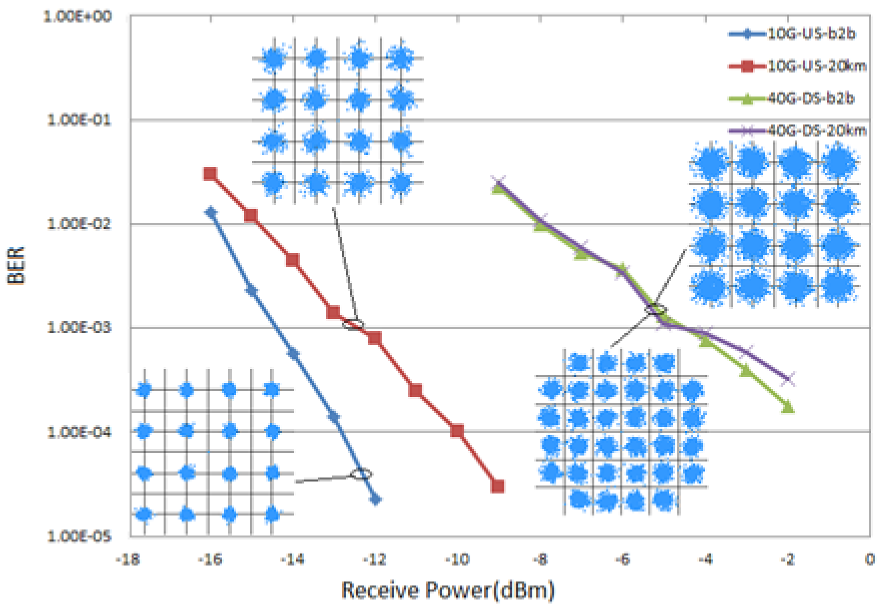

Fig.4.5 BER and received signal distributions

Fig.4.5 shows the measured BER and received signal distributions for both uplink and downlink signals for back-to-back (b2b) and 20km SMF transmission. The downlink 40Gbps signals with 16QAM and 32QAM mixed constellation can achieve a BER performance better than 1.8×10^{-4} and the 20km transmission curve is very close to that of b2b. Therefore, the dispersion and power fading penalty is almost negligible in 20km SSB transmission. The uplink 10Gbps 16-QAM signals can achieve -14.5dBm receiver sensitivity at BER of 1×10^{-3} and there is a penalty of about 2dB after 20km transmission due to dispersion and non-ideal modulation characteristics of the RSOA [49].

4.3 Discussions

In this section, a more detailed look at the proposed OFDM-WDM-PON system is given. The comparison between the proposed scheme and other similar schemes, comparison between DSB and SSB performance and evaluation of OFDM modulation performance are described. The effect of pre-emphasis, carrier to sideband ratio (CSR), local oscillator (LO) frequency and OFDM modulation format are discussed.

4.3.1 Advantages of the scheme comparing with previously proposed schemes

Similar concept and simulation demonstration of optical SSB for the reduction of

Rayleigh backscattering was given in reference [48]. In the work, upper sideband (USB) was used for downlink signal transmission while lower sideband (LSB) was used for uplink signal transmission. To realize this, four different bandpass filters (BPFs) are needed, two at the OLT, the other two at the ONU. Reflective EAM at the ONU was used since high modulation frequency for uplink transmission was necessary. This implies high cost, as show in Fig.4.6.

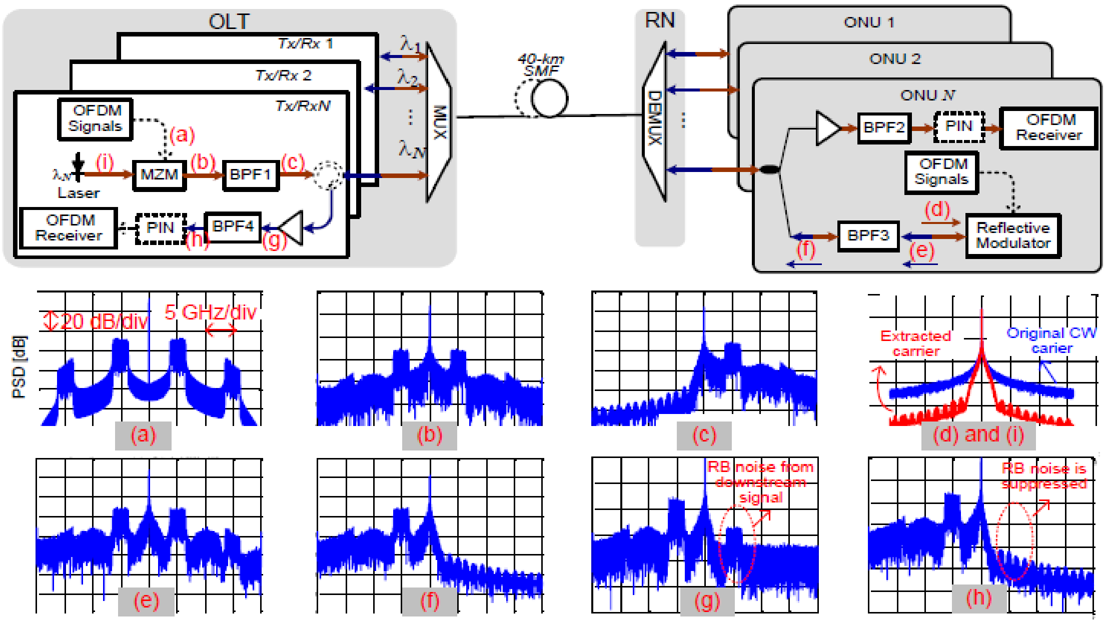

Fig.4.6 Similar architecture with proposed OFDM-WDM PON [48]

In the architecture studied in the chapter, single sideband (SSB) OFDM signal with a guardband at the baseband was used for downlink signal transmission. This enables direct detection of the OFDM signal at the ONU. Only one BPF at OLT is needed to generate the SSB signal. At the ONU, the guardband was used by the reflective semiconductor optical amplifier (RSOA) for baseband signal re-modulation. An

RSOA is a much simpler device since TOSA packaging like that used for an uncooled laser can be employed. It can be used since modulation is at the baseband and not at the passband as proposed in [48]. Although it will suffer dispersion penalty, such a configuration enables a more cost-effective ONU. A bandwidth limited RSOA (1.5GHz bandwidth) can be used as the uplink modulator with 16QAM OFDM signals at 10Gb/s. To realize this, pre-emphasis was employed to overcome the bandwidth limitation and non-ideal modulation characteristics of the RSOA. To obtain optimal system performance, carrier suppression ratio (CSR) of the downlink SSB signal needs to be adjusted to balance uplink and downlink bidirectional transmission performance. A 40Gb/s downlink signal transmission, with 32QAM/16QAM mixed OFDM signal taking into consideration the non-ideal component performance is demonstrated; while in [48], bidirectional transmission of 10Gb/s 16-QAM OFDM signal was only demonstrated through simulations by assuming ideal component performance.

4.3.2 OFDM modulation performance evaluation

In the proposed bidirectional hybrid OFDM-WDM-PON system, the downlink and uplink need to use different modulators. For the uplink, it is preferable to use an RSOA for low cost ONU implementation. While for the downlink, there are several options. These include Mach-Zehnder (MZ) modulator with DSB modulation, MZ modulator with SSB modulation, externally modulated laser (EML) with DSB modulation, and directly modulated laser (DML) with baseband (BB) modulation. Here modulation performances of them are compared to show why MZ modulator with SSB modulation was used in system implementation.

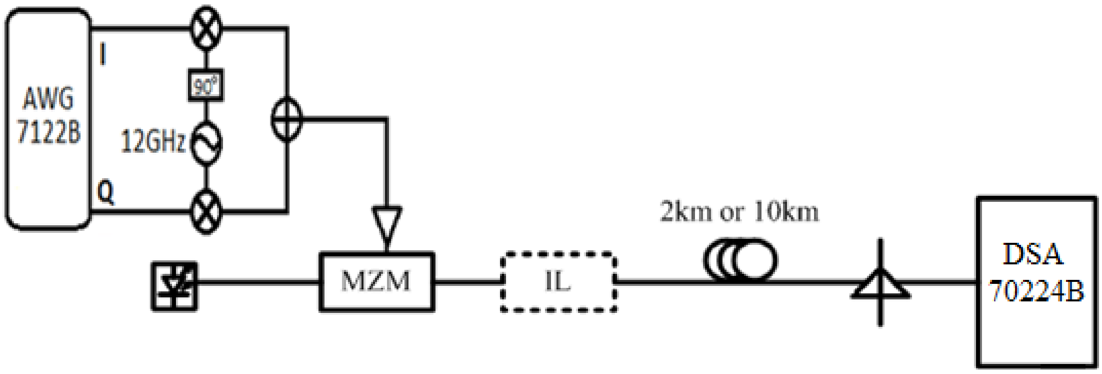

Fig.4.7 Experiment setup of OFDM modulation

The experimental setup is shown in Fig.4.7. An arbitrary waveform generator (Tektronix AWG7122B) (12Gs/s sampling rate) is used to generate the OFDM signals. Both 16QAM and 64QAM are used as modulation format and the total bit rate is 40-Gb/s. Then the baseband OFDM signal is up-converted to 12 GHz RF frequency by an IQ mixer. The amplified OFDM signal is then used to drive the MZM and the DC bias is set at the quadrature point. An interleaver (IL) is used to generate single sideband (SSB) for comparison. In addition, in the experiment the electrical amplifier is not a linear amplifier and if a linear electrical amplifier is used, the performance will be improved.

1) Using MZM with DSB modulation

40Gbit optical double sideband (DSB) transmission was used and signal to carrier (SCR) is -20dB, local oscillator frequency (LO) is 12GHz and 5dBm optical signal at 1551nm was launched into the single mode fiber. V_{pp} is 4V for the amplified electrical signal. The optical spectrum is shown in Fig.4.15, and the signal to carrier ratio is about -20dB. The OFDM signals are detected by a 20 GHz Linear PIN + TIA optical receiver. The measured BER results for BTB, 2km and 10km are shown in Fig.4.8. The power penalty induced by 2km fiber dispersion can be negligible at BER=1×10^{-3} and the penalty for 10km transmission at BER=1×10^{-3} is about 3.3 dB due to the power fading.

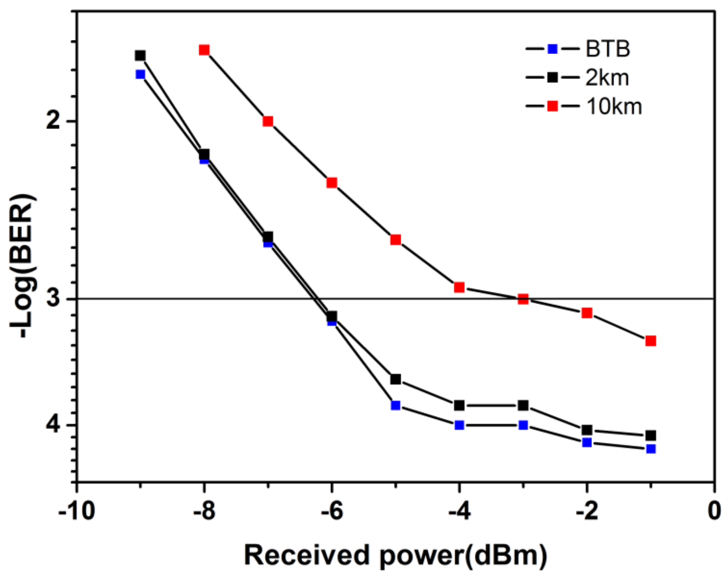

Fig.4.8 BER of MZM with DSB modulation

2) Using MZM with SSB modulation

For 40Gbps single sideband (SSB) transmission, the operational condition is the same.

The OFDM signals are received by a 20 GHz Linear PIN + TIA optical receiver. The measured BER results for BTB, 2km and 10km are shown in Fig.4.9. The power penalties induced by 2km fiber and 10 km dispersion are much smaller for BER= 1×10^{-3}.

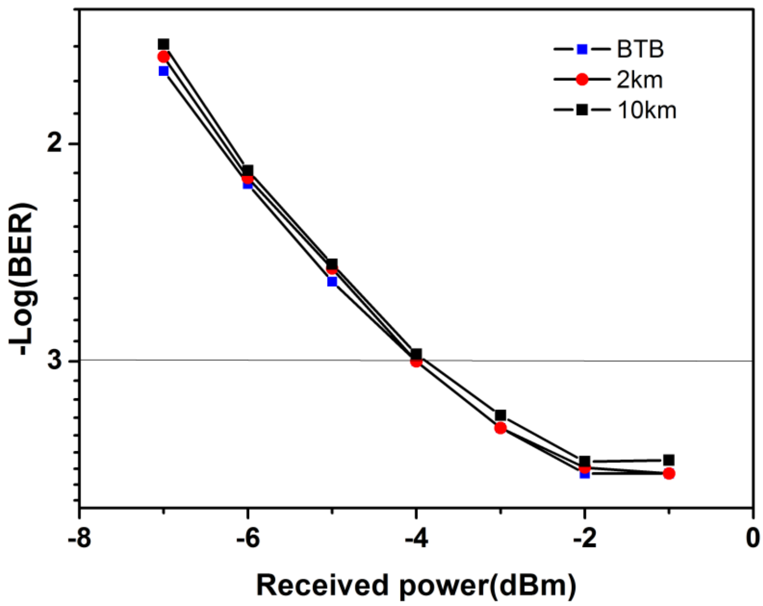

Fig.4.9 BER of MZM with SSB modulation

3) Using EML with DSB modulation

An EML is used here instead of the CW laser and MZM as in previous cases. The optical power from the EML is 0dBm. The data is 40Gbps DSB modulation. The OFDM signals are received by a 20 GHz Linear PIN + TIA optical receiver. The measured BER results for BTB and 2km are shown in Fig.4.10. The power penalty induced by 2km fiber dispersion is very small at BER= 1×10^{-3}. However, after the 10 km transmission, the BER is 1×10^{-2} with the received power of -3dBm due to the power fading.

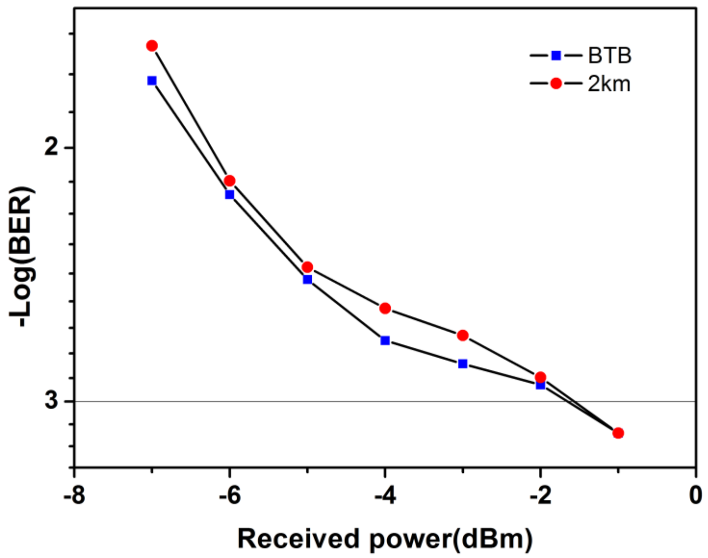

Fig.4.10 BER of EML with DSB modulation

4) Using DML with base band modulation.

The bandwidth of DML is 10GHz and the optical output power is 6dBm. It is modulated with 20Gbps data. In the experiment, the OFDM signal is transmitted in baseband. The OFDM signals are received by a 20 GHz Linear PIN + TIA optical receiver. Fig.4.11 shows the measured BER results and the penalty for 2km transmission at 1×10^{-3} is 1dB. After 10km transmission, the BER is 6×10^{-2} due to power fading induced by chirp of the direct modulated laser.

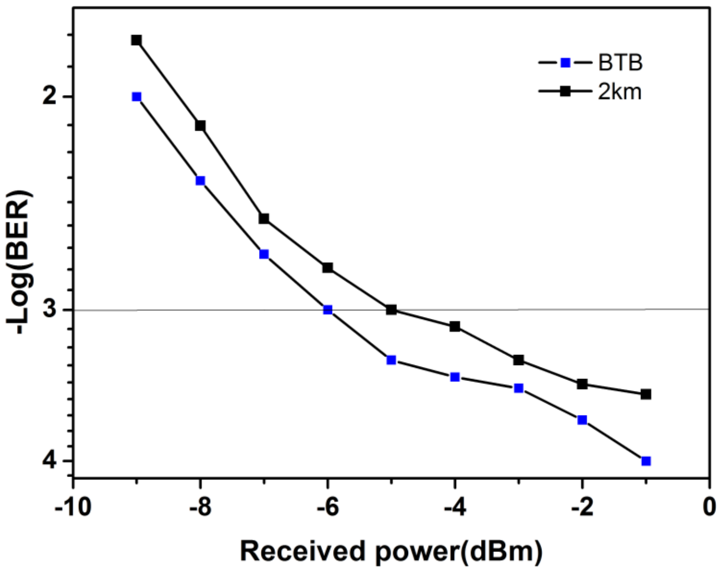

Fig.4.11 BER of DML with BB modulation

The output optical power for EML is 0dBm which is lower than the other two. The dynamic extinction ratio of EML (9dB) is the main factor affecting the performance. The chirp of DML is the main limiting factor since the penalty between BTB and 2km is 1dB.The bandwidth of DML (10GHz) is also a limiting factor for high speed transmission.

As a result MZM is used as downlink modulator, and SSB modulation was selected to transmit the signal over 20km optical fiber. The results above show that DSB transmission will suffer from power penalty as a result of fiber dispersion induced power fading. SSB transmission can combat the power fading, but an additional optical filter is required for the OFDM transmitters. When operating at back-to-back DSB OFDM transmission has higher sensitivity than that of SSB. After 10km transmission, however, SSB transmission will have higher sensitivity than that of

DSB due to power fading effect for DSB.

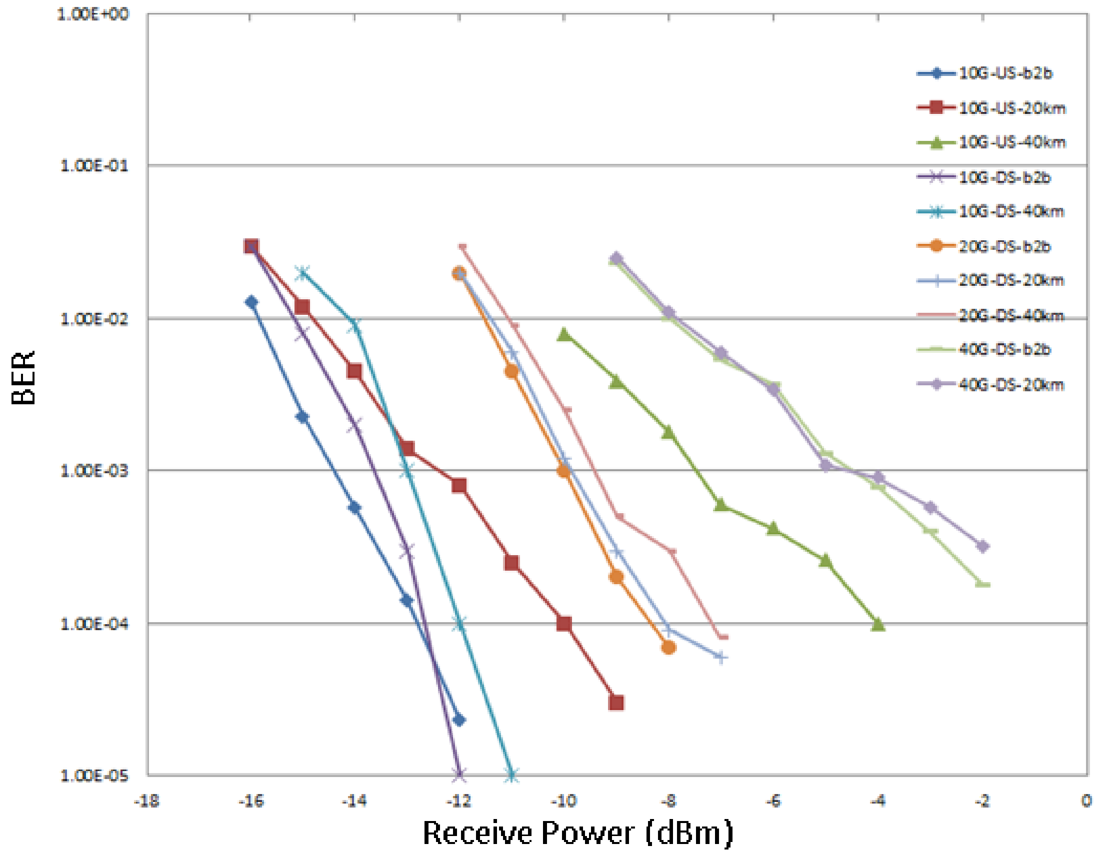

Fig.4.12 Different downstream receiver sensitivity

Fig.4.12 shows different downstream receiver sensitivity curves at 10Gbps, 20Gbps and 40Gbps data rate with b2b and transmission after 20km and 40km SMF. It can be seen that the receiver sensitivity of 10Gbps data rate is about 4dB better than that of 20Gbps data rate, and is about 8dB better than that of 20Gbps data rate.

4.3.3 Comparison of DSB and SSB modulation

It is well known that double sideband modulation (DSB) will result in fading that can significantly limit system performance. For the OFDM signal (40Gb/s 32QAM/16QAM mixed OFDM signal), experimental results show that BER is significantly above the FEC limit after 20km downstream transmission if DSB modulation is used. Experimental results show that the BER curve of 20km transmission is very close to back to back transmission with SSB signals, the power fading penalty caused by dispersion is almost negligible.

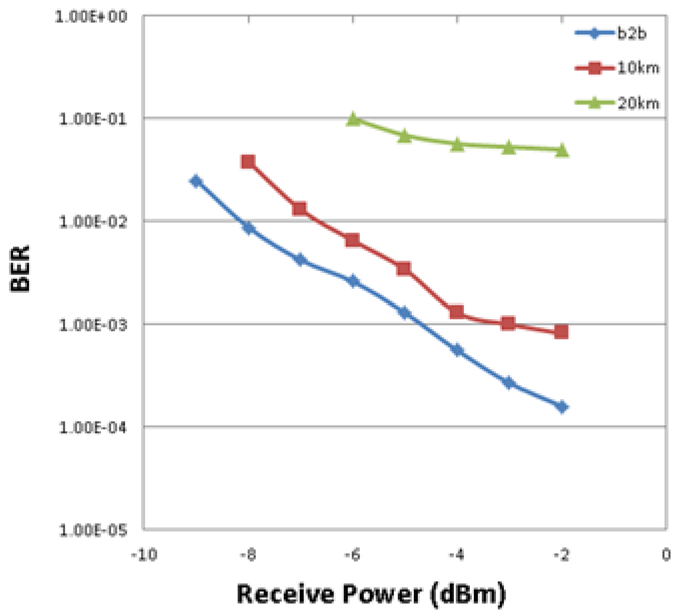

Fig.4.13 BER of DSB OFDM signals with b2b, 10km and 20km transmission

The measured BER results of 40Gb/s downstream DSB OFDM signals for b2b, 10km and 20km transmission are shown below, the performance comparison of DSB and SSB is presented in Fig.4.13 to show the advantage of optical SSB scheme. The RF power spectral density of DSB OFDM signals after 20km transmission is shown in Fig.4.14. Fading is apparent from the spectrum which explains the degraded transmission performance.

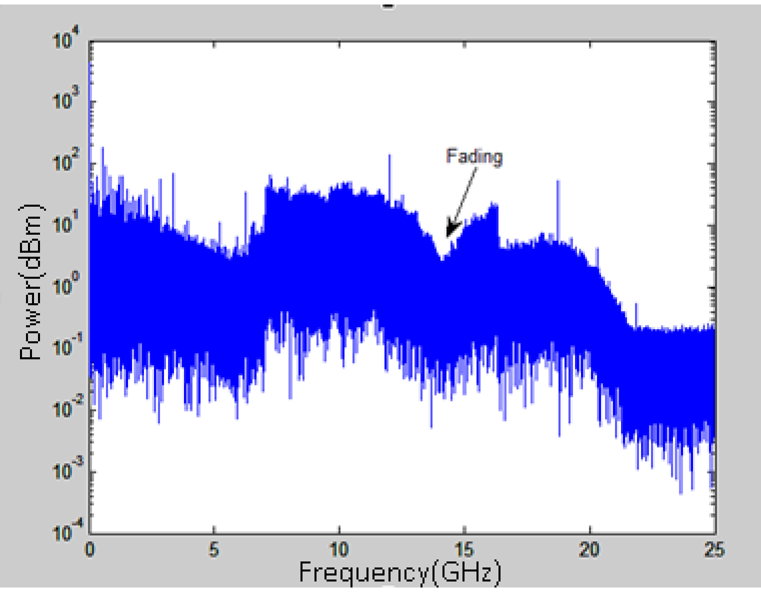

Fig.4.14 RF PSD of DSB OFDM signals after 20km transmission

The downlink used SSB signal which can significantly reduce the effect of power fading caused by chromatic dispersion; while the uplink used RSOA to modulate a baseband signal, it is a double sideband signal and due to chirp introduced by the RSOA modulation and its limited bandwidth chromatic dispersion will degrade the system performance after 20 km transmission. So, there is negligible penalty for the downlink transmission when comparing the results for b2b and 20 km of fiber transmission, but there is about 3dB penalty for the uplink transmission.

4.3.4 CSR design

The carrier to sideband ratio (CSR) of the downlink DSB OFDM signal is affected by the bias voltage of the IM. The downlink receiver sensitivity decreases with the increase of CSR due to reduced modulation index, while the uplink receiver sensitivity increases with reduced crosstalk. The downlink receiver sensitivity increases with reduced CSR value while the uplink receiver sensitivity decreases.

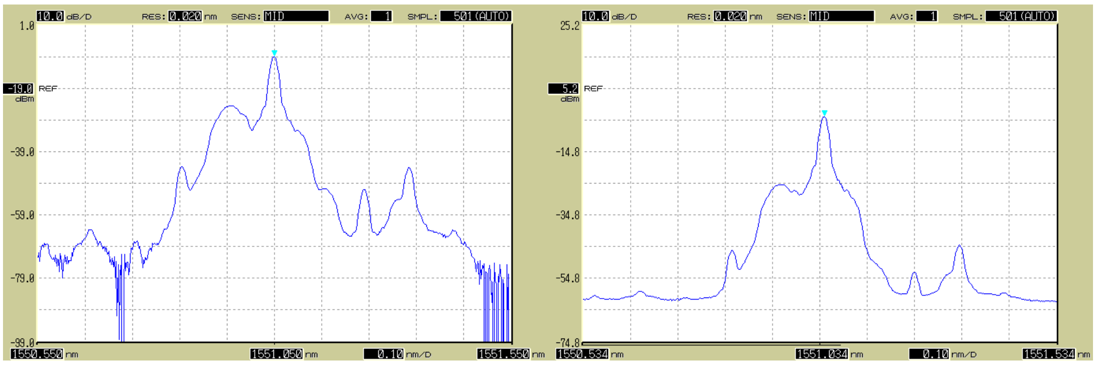

Fig.4.15 DS signal with 15dB and 20dB CSR

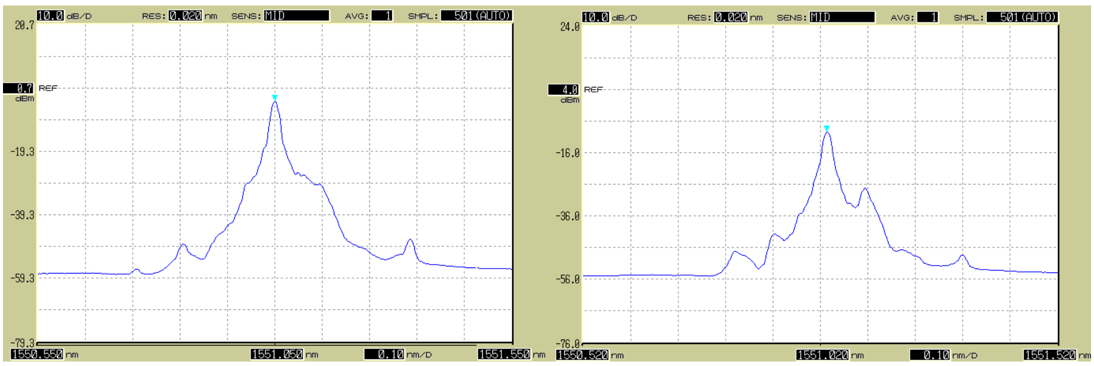

Fig.4.16 US signal with 15dB and 10dB CSR

Fig.4.15 shows the filtered optical spectrums of downstream SSB signal with 15dB and 20dB CSR of downlink DSB modulation. The CSR of 15dB is better than that of 20dB due to the different modulation index on the LSB. Fig.4.16 shows the RSOA re-modulation optical spectra of upstream BB signal with 15dB and 10dB CSR of downlink DSB modulation. The CSR of 15dB is better than that of 10dB due to the different intermodulation on the carrier and crosstalk.

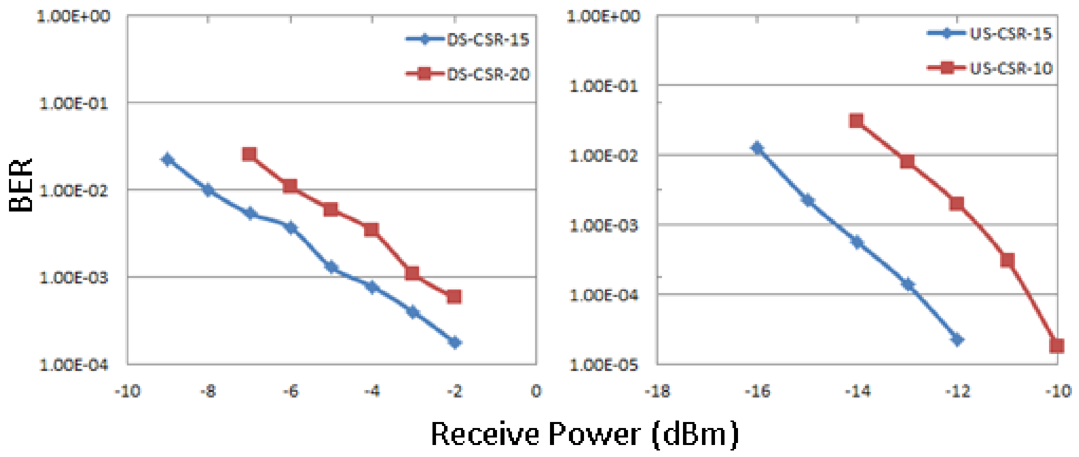

Fig.4.17 US and DS BER with different CSR

Fig.4.17 shows the measured downstream and upstream BER with different CSR of downlink DSB modulation. It shows the BER of 15dB CSR is about 2dB better than that of 20dB CSR for the downstream signal, while the BER of 15dB CSR is about 2.5dB better than that of 10dB CSR for the upstream signal. After some optimization, it is found that a CSR of 15dB achieves the best trade-off between uplink and downlink performance and the best overall bidirectional transmission performance in our proposed OFDM-WDM-PON system.

4.3.5 LO frequency design

The selection of LO frequency will also affect the system performance. If the LO frequency is too low, it is difficult for filter to filter the DSB signal to obtain a SSB signal. It will also reduce the guardband. This will have two implications. The beating signal will affect the performance of the direct detected OFDM signal. The available bandwidth for RSOA re-modulation will also reduce. If the LO frequency is two high, it will increase the demand of component bandwidth, which will increase the system cost.

The signal is up-converted by the IQ mixer. In the experiment, An IQ mixer with LO frequency from 6.0 to 18.0 GHz was used. BER performance of downlink DSB OFDM signal with different LO frequencies 14GHz, 12GHz, and 10GHz are used. It shows these LO frequencies can achieve the same BER performance, and they also have no impact for uplink signal transmission, because electrical spectra are not overlapped with each other. However, when DSB signal is filtered to obtain the SSB signal, the bandwidth of the interleaver limits the SSB signal quality. The filtered SSB signal is degraded by more than 1dB for 10GHz LO frequency, as shown in Fig.4.18, and the LO frequencies larger than 12GHz do not have such a filtering problem. After some optimization, 12GHz LO was chosen which is suitable for the system configuration, especially the interleaver filter.

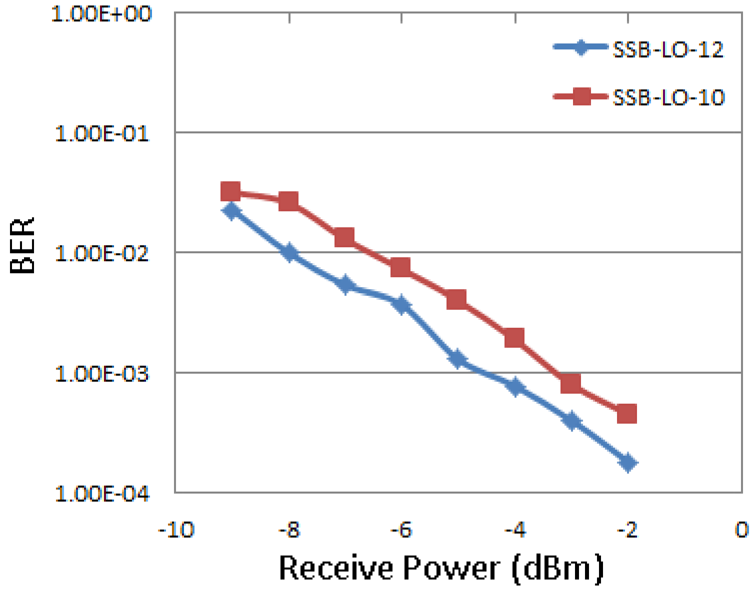

Fig.4.18 BER of SSB signal with 12GHz and 10GHz LO

4.3.6 Effect of pre-emphasis

Pre-emphasis is used at both downlink and uplink to optimize the performance of the OFDM signal. It adjusts the power of each subcarrier to balance the SNR performance among the subcarriers so that the overall BER performance is optimized. It is found the scheme can improve the system BER performance especially for the uplink signal transmission. Fig.4.19 shows the SNR for different OFDM subcarriers of the uplink RSOA re-modulated signal with and without pre-emphasis. The blue curve replaces the SNR of OFDM subcarriers without using pre-emphasis, and the red curve replaces the SNR of OFDM subcarriers with pre-emphasis. After using pre-emphasis, the SNRs close to each other for all the subcarriers.

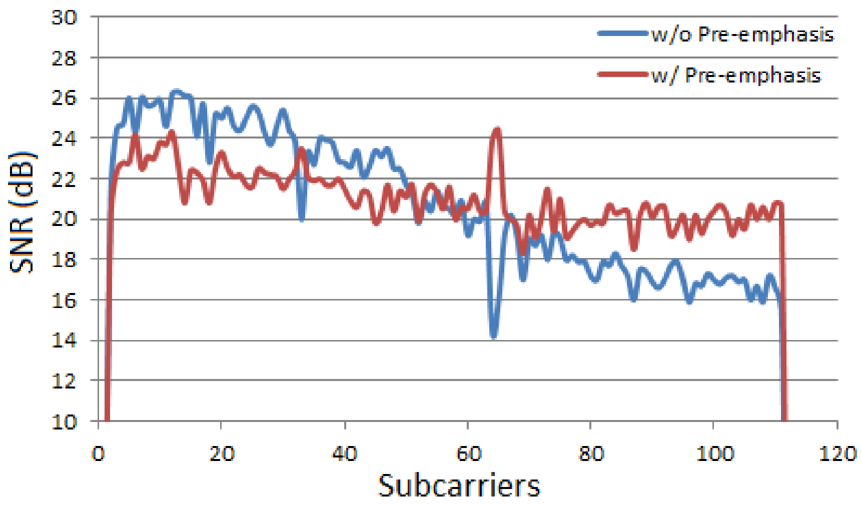

Fig.4.19 SNR with and without pre-emphasis

Due to the limited bandwidth of the RSOA and interference of the downstream signal, the SNR of the high frequency subcarriers decreases very fast (for subcarrier frequency higher than 2GHz). In this case, pre-emphasis is very effective in slowing the downward trend of subcarriers SNR for improving the overall BER performance of the system.

4.3.7 OFDM modulation format

The downlink OFDM signals use a 32QAM and 16QAM mixed modulation format. Because the performance of up-conversion with downlink OFDM signal is degraded by the IQ mixer. Marki double balanced mixer IQB0618LK was used, the IF frequency range is from DC to 5.0 GHz. The component parameter can meet the experiment requirements. However, the SNR between low frequency and high frequency is different after the up-conversion, which is limited by the device response. The subcarriers corresponding to low frequency OFDM signal at baseband have a larger SNR after the up-conversion, while the subcarriers corresponding to high frequency OFDM signal at baseband have a smaller SNR after the up-conversion.

In the experiment, the SNR of each OFDM subcarriers are different because the unbalanced up-conversion process, even though pre-emphasis was used to balance the SNR of each subcarrier, there are still some differences in the performance. If only 16QAM modulation format is used in the downlink, the bandwidth of the IQ mixer does not allow 40Gbps data rate to be realized, if 32QAM modulation format is used alone in the downlink, the back-to-back BER performance can not achieve 1×10^{-4}. So 32QAM and 16QAM mixed modulation format was used. 32QAM modulation format is used for the low frequency OFDM signal, and 16QAM is used for the high frequency OFDM signal, as shown in Fig.4.20. Such a configuration can help to achieve a better BER performance while utilizing the full bandwidth of the components.

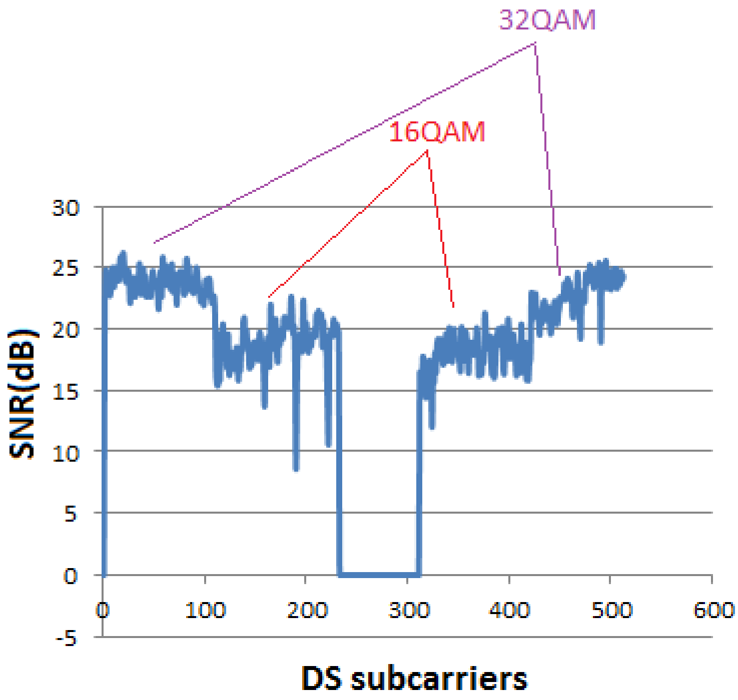

Fig.4.20 Different modulation format according to different SNR

4.4 Summary

In this chapter, experimentally investigation is carried out on a bidirectional hybrid OFDM-WDM-PON system based on subcarrier-multiplexing SSB for downlink transmission and RSOA re-modulation for uplink transmission. This scheme offers a good solution for overcoming RB, CD and power fading to realize a cost-effective configuration with optimized transmission data rate and BER performance. The experimental results show that downlink SSB signal transmission can achieve a BER performance of 1.8×10^{-4}. There is almost no penalty after 20km transmission. RSOA re-modulation with OFDM signal can easily achieve 10Gbps data rate with direct detection. Coherent detection can be used at the OLT to further increase the receiver sensitivity and reduce the dispersion penalty in the uplink transmission.

Chapter 5

Pol-MUX WDM-PON system

5.1 Introduction

In single feeder fiber WDM-PON system, providing dual services with two independent data streams is very attractive and has been studied extensively [50]. One of the data stream can be used for Point-to-Point (P2P) or wired service; and the other data stream can be used for broadcast or wireless service. Simultaneous generation of wired signal using baseband (BB) and wireless signal using radio-frequency (RF) is the most extensively investigated architecture[50-55]. However, these schemes suffer from degradations due to: 1) chromatic dispersion (CD); 2) inter-channel interference between dual service signals; 3) limited modulation format and data rate; 4) they also need extra light source and narrow band-pass filters (BPF).

Polarization multiplexing (Pol-MUX) technique is an attractive candidate for dual services PON system [56]. Generation and transmission of two independent data streams in two uncorrelated orthogonally polarized beams have been demonstrated. However, the main challenge is polarization de-multiplexing process at the ONUs. Although cost-effective automatic polarization de-multiplexing system have been demonstrated in [57], it is still too complicated to be used in cost sensitive ONUs..

Another challenge is the Rayleigh backscattering (RB) in dual services bidirectional PON systems, because downlink and uplink signals are modulated onto the same frequencies. Various techniques have been proposed and demonstrated [58-59], but no schemes are suitable for a dual services bidirectional PON systems specially.

In this chapter, a novel WDM PON system for providing dual services is studied through simulation. The downlink of the system is a Pol-MUX signal with two orthogonally single-sideband (SSB) signals with different local oscillators (LO). One upper-sideband (USB) is used as wired service, the other lower-sideband (LSB) is used as wireless service. This configuration can overcome the CD and RB effect, eliminate undesirable beat frequency of dual service signals to maximize RF spectrum utilization, avoid the complex polarization de-multiplexing, simplify the ONUs structure and achieve a scalable receiver frontend without additional filters. Besides there is a guardband consists of two uncorrelated orthogonally polarized carriers, which provides a depolarized light source for re-modulation by a polarization-sensitive RSOA. Using the proposed system, a 10Gbps downlink transmission with scalable ONUs and 2.5Gbps uplink transmission with RSOA re-modulation for a dual services bidirectional WDM-PON system is demonstrated through simulation.

5.2 Previous WDM-PON systems with dual services

Several schemes for PON systems for providing simultaneously dual services have been proposed, such as providing dual services based on BB and RF signals, providing dual services based on 60 GHz RoF system and providing dual services with reducing RB effect, etc. These schemes typically need a very large bandwidth modulator for radio over fiber signal and some extra light sources or bandpass filters.

5.2.1 Providing dual services based on BB and RF signals

In the scheme as shown in Fig.5.1 [51], one data stream at 10Gbps is modulated at the baseband using OOK signal and another data stream at 155Mbps is modulated with DPSK and then up-converted by a 60GHz RF signal. The two signals are amplified and then used to modulate an electro absorption modulator (EAM). The signal is transmitted through 40km dispersion shifted fiber (DSF). In the receiver front-end, the signal is detected by a large bandwidth PD, the received electrical signal is divided by a power splitter. After amplification and filtering, the OOK signal and DPSK signal can be received separately. The main system performance degradation of this scheme is caused by the nonlinearity of the EAM as reported by the authors.

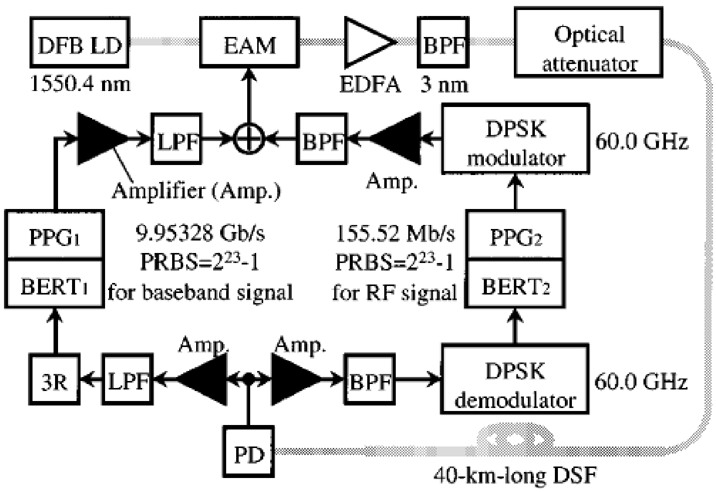

Fig.5.1 Dual services based on BB and RF signals [51]

5.2.2 Providing dual services based on 60 GHz RoF system

In this scheme, the WDM-RoF-PON architecture as showed in Fig.5.2 [54] is used to provide wired and wireless services for both downlink and uplink. For the downlink transmission, 2.5Gbps OFDM signals with QPSK modulation format are used for both wireless and wire-line channels, and for the uplink transmission, the downlink wavelength is reused by OOK modulation. An interleaver (IL) is used to separate the wireless and wire-line channels. The wired channel and wireless channel are designed independently, so it is very flexible for system deployment and upgrade, and is suitable for different applications. The results for B2B, 20km and 50km transmission are also showed by the authors.

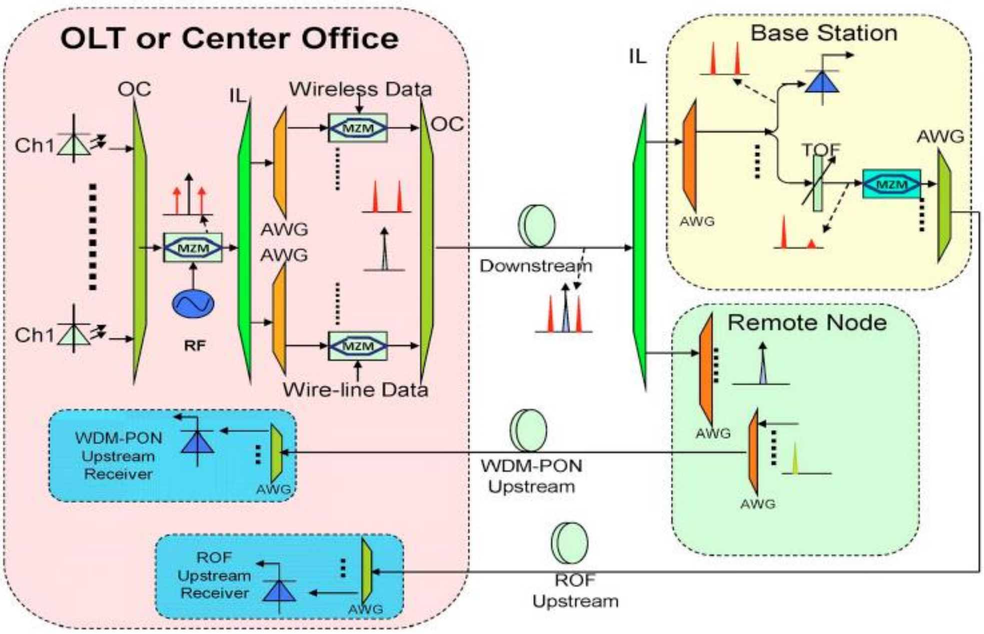

Fig.5.2 Dual services based on 60 GHz RoF system [54]

5.2.3 Providing dual services with reducing RB

This scheme provides dual services with reduced RB effect with a DWDM-TDM PON system. In the remote node (RN), each light source is modulated, and become two continuous wave carriers. One is used for wired channel and the other for wireless channel. The ONU modulates the two optical carriers for uplink transmission, besides, one semiconductor optical amplifier (SOA) is used for increasing the output power at the ONUs. The Fig.5.3 [55] shows the optical wavelength is used in the whole system, the optical spectrum does not overlap with each other for uplink signal and downlink RB and for downlink signal and uplink RB. The experiment results also show this scheme can effectively reduce the RB effect.

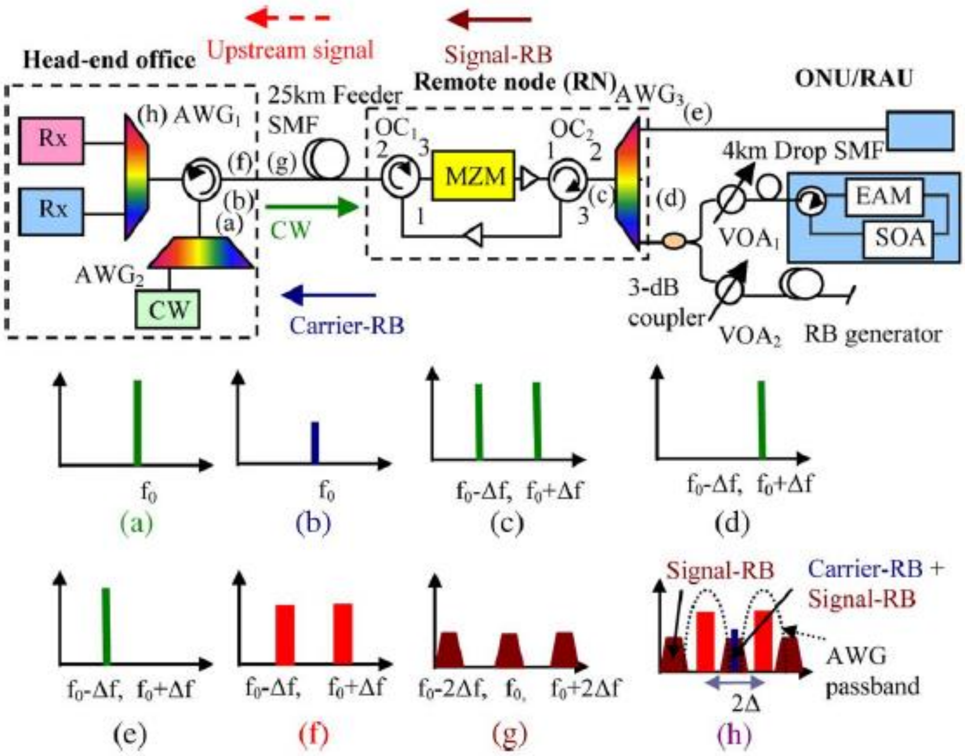

Fig.5.3 Dual services with reducing RB [55]

5.3 A novel Pol-MUX WDM-PON architecture for simultaneously providing dual services

A novel Pol-MUX WDM-PON architecture for simultaneously providing dual services achieving scalable ONUs without polarization de-multiplexing and optical filters is demonstrated through simulation. The proposed scheme uses two SSB signals up-converted by different LOs on two different side of the optical carrier. These two signals also have the orthogonally polarization. This scheme can reduce the effect of RB and CD. It also helps to eliminate ISI and different frequency beating noise. The ONU structure is very simple, no complex polarization de-multiplexing and filters is need. It can be used for receiving dual services or only receiving the broadcast data with a more economy low bandwidth receiver front-end. A 10Gbps downlink transmission with 5Gbps wireless data and 5Gbps wired data is demonstrated through simulation successfully, with very clear received eye diagrams.

5.3.1 Proposed system architecture

Fig.5.4 shows the proposed bidirectional Pol-MUX WDM-PON system architecture. In each OLT, the optical carrier is split by a 50:50 coupler. One portion is used to generate SSB P2P signals with LSB before multiplexer1 (MUX1). The other portion is used to generate SSB broadcast signals with USB after MUX2. The two downlink signals are adjusted to have orthogonally polarization. The data signals are de-correlated by an optical delay line and then combined by a polarization beam combiner (PBC). After transmission through 20km single-mode fiber (SMF) and a demultiplexer, the downlink signal can be received by two kinds of ONUs with different bandwidth. ONU1 has a low bandwidth PIN receiver, which only receives the broadcast data; ONU2 has a high bandwidth PIN receiver, which can receive the broadcast and P2P data at the same time. Each ONU re-modulates the downlink signals directly by a polarization-sensitive RSOA on the gaurdband.

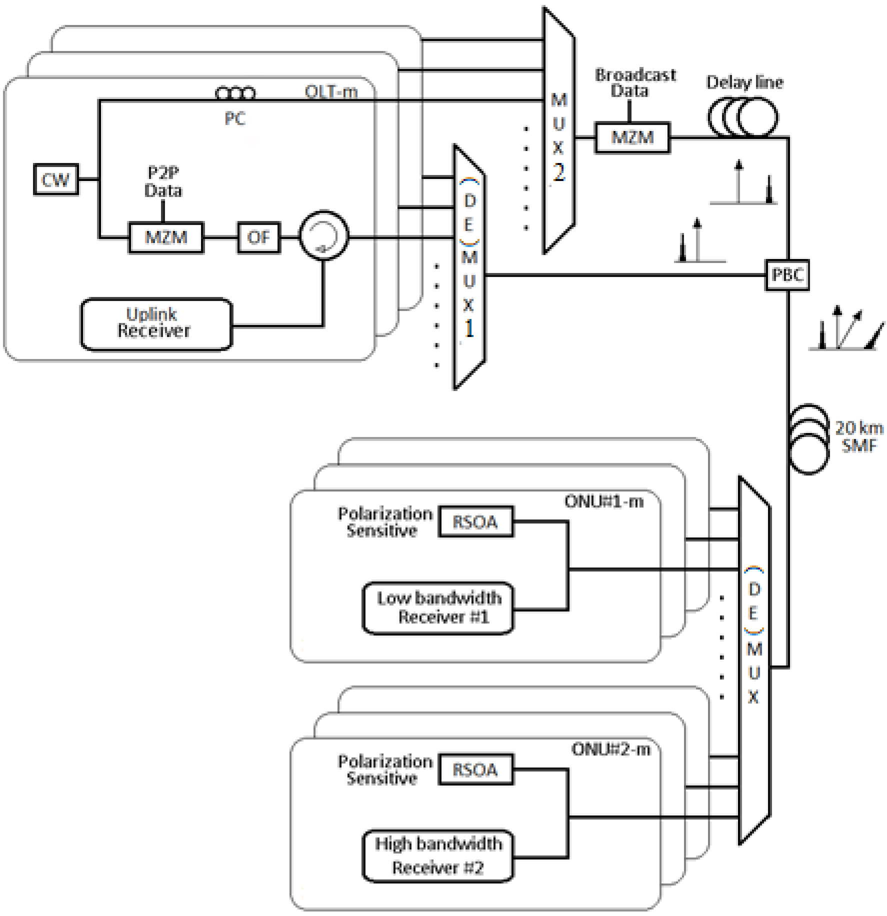

Fig.5.4 Architecture of proposed Pol-MUX WDM-PON system

5.3.2 Advantages of the proposed system

The system architecture offers following advantages:

1) SSB signal is used for downlink transmission. This can help to reduce the power fading effect due to CD for downlink transmission. Such a configuration can increase the downlink receiver sensitivity significantly.

2) The two independent data can provide dual services at the same time. There is no overlay between the two data in the RF spectrum or the optical spectrum. The use of orthogonally polarization for the two channels with different up-converted LO frequencies will reduce the interference between two data streams. This help to increase the system performance.

3) The two independent downlink signals and uplink signal are modulated onto different frequencies. The downlink wireless signal is modulated on the lower sideband (LSB) of the SSB subcarrier, the downlink wired signal is modulated on the upper sideband (USB) of the SSB subcarrier, and the uplink OFDM signal is modulated on the guardband of the optical carrier at the baseband. The frequency spacing between uplink and downlink data is variable according to the frequency selection of the local oscillator (LO). Such a configuration can reduce the interference between the RB and the signal transmitted, so as to reduce the RB effect in the entire bidirectional transmission PON system. Such a configuration can increase the receiver

sensitivity for both downlink and uplink transmission.

4) No additional light source is used at both OLT and ONU to distribute the optical carrier, no polarization de-multiplexing system is need at the ONU, and no narrow bandpass filter is need to separate the optical carrier and two sideband as well. The two independent data streams can be received using different bandwidth receiver frontends for different needs. Such a configuration can meet demands of different users and increase the system adaptability for realizing a low cost and low complexity WDM-PON system.

5) This scheme support coherent signal detection at both the ONU and the OLT, so a variety of coherent DSP algorithm can be employed in the system, which will help to significantly increase the system performance and adaptability.

5.3.3 Simulation demonstration

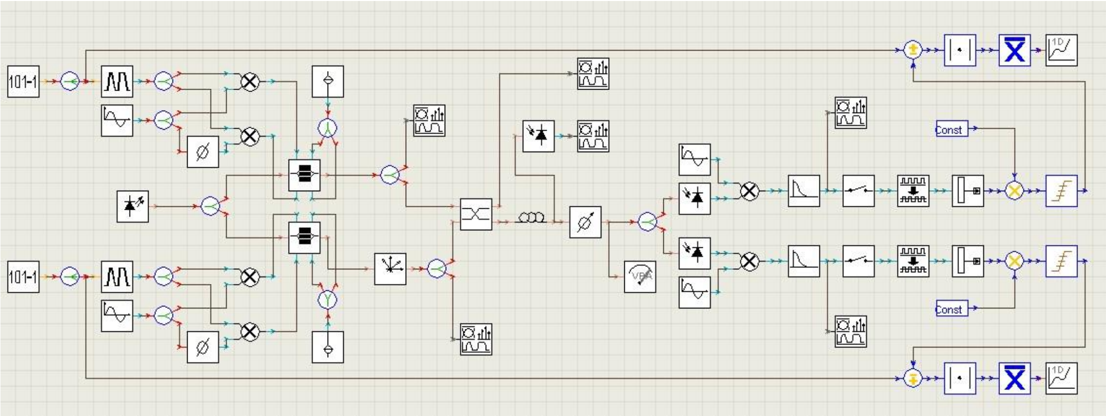

Fig.5.5 Simulation setup of proposed Pol-MUX WDM-PON system

Fig.5.5 shows the simulation setup of the proposed Pol-MUX WDM-PON system. In the simulation, VPIphotonics8.0 is used as the simulation software.

A centralized lightwave (CW) at 193.1THz is used as the optical carrier. This carrier is equally divided by a 3dB coupler into two optical carriers. These two carriers are modulated by two DP-MZMs, which are biased at π/2 and 3π/2 respectively. Each modulator are driven by a 5Gbps OOK signal with different up-converted LO frequencies, one is 10GHz and used for broadcast channel, the other is 20GHz and used for P2P channel. Fig.5.6 shows the optical spectra of two independent downlink signals. The broadcast data is modulated on the LSB with a guardband, while the P2P data is modulated on the USB with a guardband. The two channels are multiplexed with orthogonal polarizations and become the transmitted downlink signal. The total bit rate of the downlink signal is 10Gbps. Fig.5.7 shows the optical spectrum of transmitted downlink signal after Pol-MUX, the two independent data streams are distributed on different sides of the carrier.

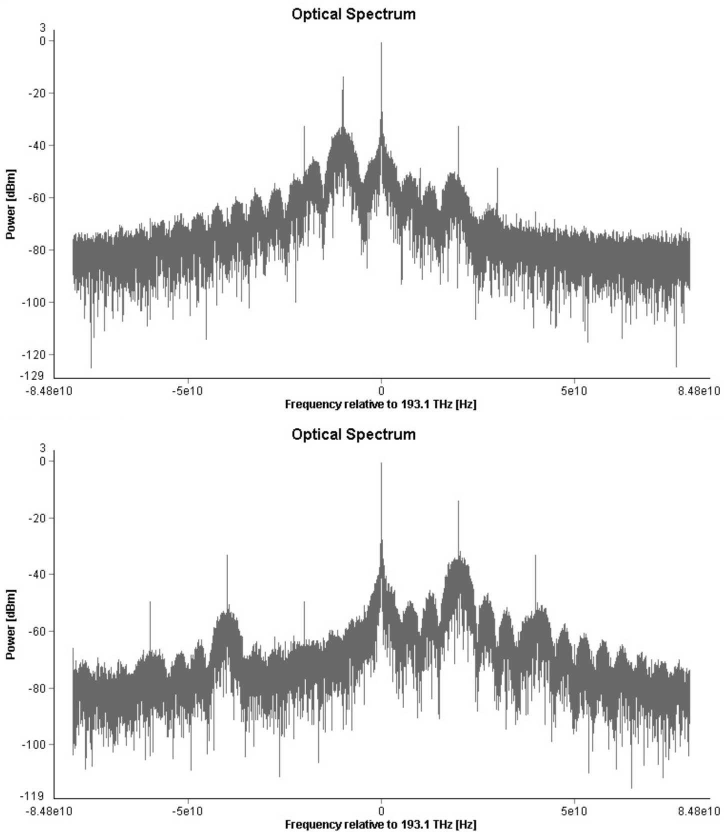

Fig.5.6 Optical spectrum of two independent downlink signals

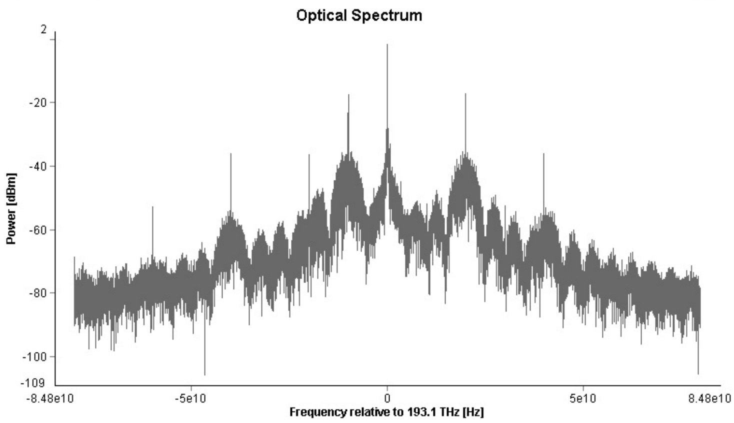

Fig.5.7 Optical spectrum of transmitted downlink signal after Pol-MUX

At the ONU, the downlink signal is divided by a 3dB coupler. One portion of the signal is direct detected by a PIN receiver and mixed with a 10GHz LO. The frequency of the LO is the same as the LO for up-converting the broadcast channel. Carrier phase is locked to the electrical carrier of the signal. It can down-convert the broadcast data to the baseband. The other portion of the signal is direct detected by another PIN receiver and mixed with a 20GHz LO, the frequency is the same as the LO of P2P channel in up-converted process. Its phase is locked to the electrical carrier signal. It can down-convert the P2P data to the baseband. After the down conversion process, the signals for broadcast and P2P channels are filtered by two lowpass filters, A 4 order Gaussian filter with 3.75GHz bandwidth has been chosen in the simulation. The BER is then calculated for each individual data stream.

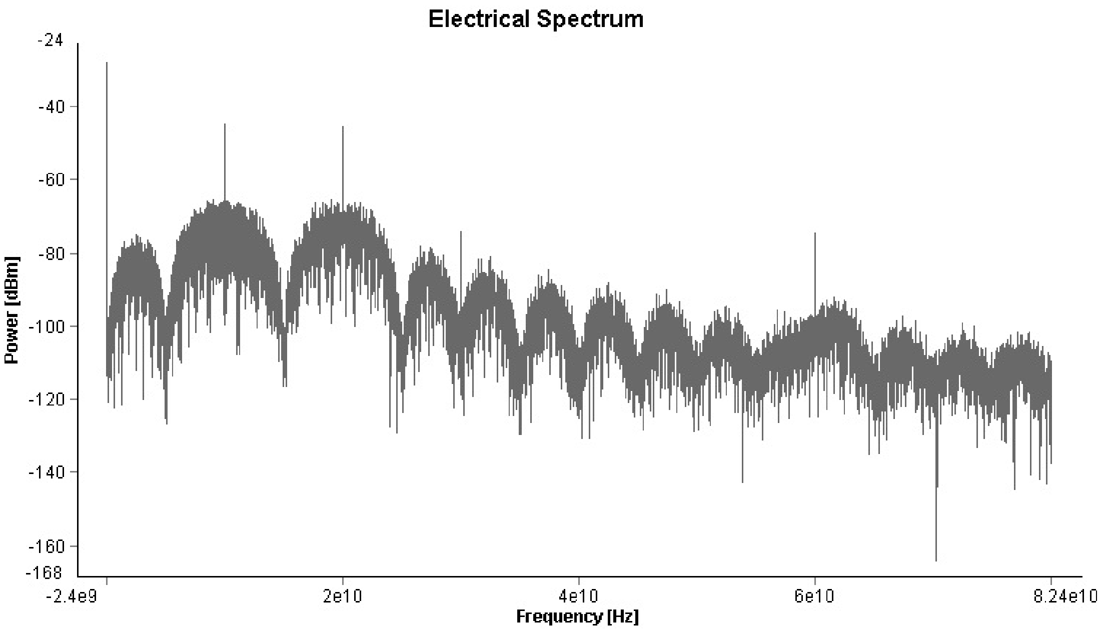

Fig.5.8 Electrical spectrum of received downlink signal

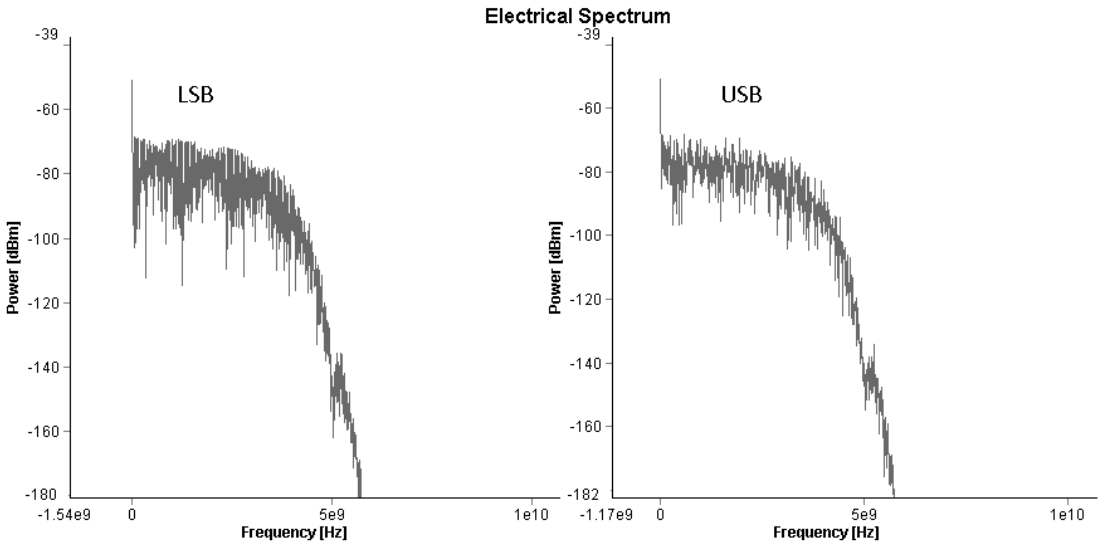

Fig.5.9 Electrical spectrum of the down-converted signals

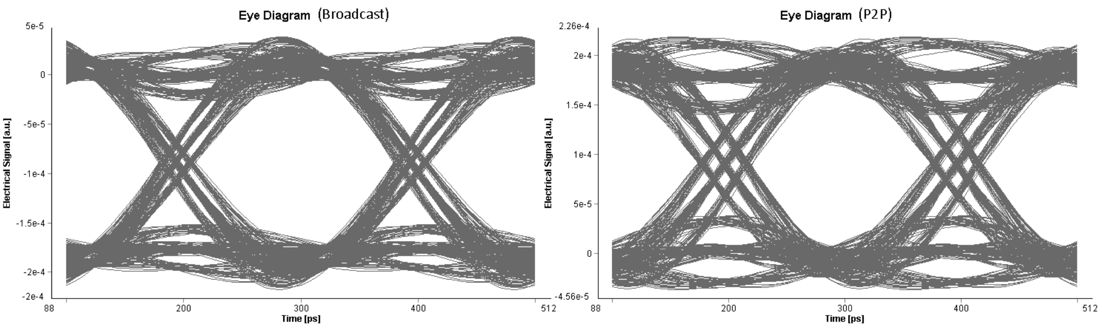

Fig.5.10 Eye diagram of the received signals

Fig.5.8 shows the electrical spectrum of received downlink signal before down conversion. Fig.5.9 shows the electrical spectrum of received broadcast and P2P signals after down conversion with different LO frequencies. The left figure is down-converted signal with LO frequency of 10GHz and the right figure is down-converted signal with LO frequency of 20GHz. The eye diagrams of received signals are shown in Fig.5.10. Good system performance is expected.

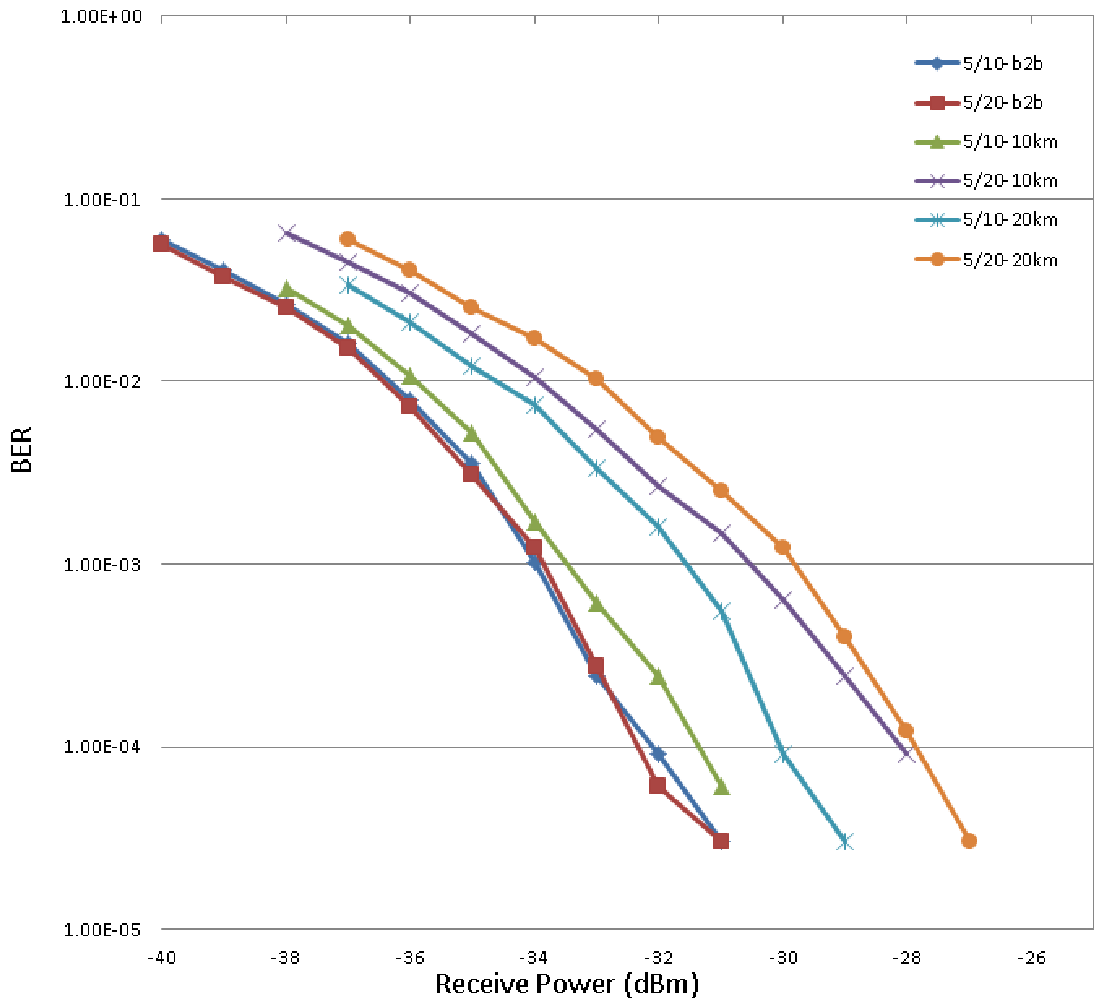

Fig.5.11 BER curves of proposed system with different transmission distance

The BER of back-to-back, 10km SMF fiber transmission and 20km SMF fiber transmission are measured to study the system performance for different transmission distance. A length of single mode fiber (SMF) and an attenuator is used between the transmitter and receiver to adjust the transmission length and received signal power. The standard parameters as those of Corning SMF-28 optical fiber at 1550nm is used for simulation [60]. In the simulation process, it was found that chromatic dispersion (CD) and polarization mode dispersion (PMD) are the main factors affecting the performance of the system after transmission. The BER of the data stream with higher subcarrier frequency will increase faster than the BER of data stream with lower subcarrier frequency with the increase of transmission distance. If CD and PMD parameters are turn off in the simulation, the system performance will have almost no degradation after 20km transmission.

As shown in Fig.5.11, 5/10-b2b and 5/20-b2b are the BER curves of 5Gbps OOK signal with 10GHz and 20GHz LO frequencies for back to back transmission. It is clear that the two data streams have similar BER performance without signal transmission. -34dBm receiver sensitivity can be obtained at BER=1×10^{-3}. 5/10-10km and 5/20-10km are the BER curves of 5Gbps OOK signal with 10GHz and 20GHz LO frequencies for 10km transmission. The BER of P2P data stream is worse than the BER of broadcast data stream. There is about 3dB power penalty. 5/10-20km and 5/20-20km are the BER curves of 5Gbps OOK signal with 10GHz and 20GHz LO frequencies for 20km transmission. It was found the difference in BER between P2P data stream and broadcast stream is about 2dB at BER=1×10^{-3}.

5.4 Discussions

In this work, only simulation results were shown due to the availability of key devices for experimental studies. In the simulation setup, only downlink transmission was shown because the uplink transmission is almost the same as previous schemes presented in early chapters. For example, if a RSOA is used to re-modulate the uplink signal on the guardband, a 2.5Gbps data transmission can easily be achieved.

5.4.1 LO frequency design

For the modulation of the two independent downlink data, the data rate and up-conversion LO frequency should be careful designed. The setup shown is for 5Gbps data for both broadcast and P2P data. Up-conversion frequencies are set at 10GHz and 20GHz. In practical applications, the frequency can be varied according to different demands. For example, if 2.5Gbps is used for broadcast data and 10Gbps is used for P2P data, up-conversion frequencies can be set at 7.5GHz and 20GHz. In selecting the frequencies, it is essential to avoid the spectrum overlap among the broadcast downlink data, P2P downlink data, and uplink data. Such a setup will greatly increase the flexibility and adaptability of the optical access networks system, and allow us to design solutions for different end-users.

The system above has also been simulated using VPI. Fig.5.12 shows the optical spectrum of the 12.5Gbps downlink transmitted signal after Pol-MUX. 2.5Gbps is used as broadcast data stream and 10Gbps is used as P2P data stream. Fig.5.13 shows the electrical spectrum of received 12.5Gbps downlink signal.

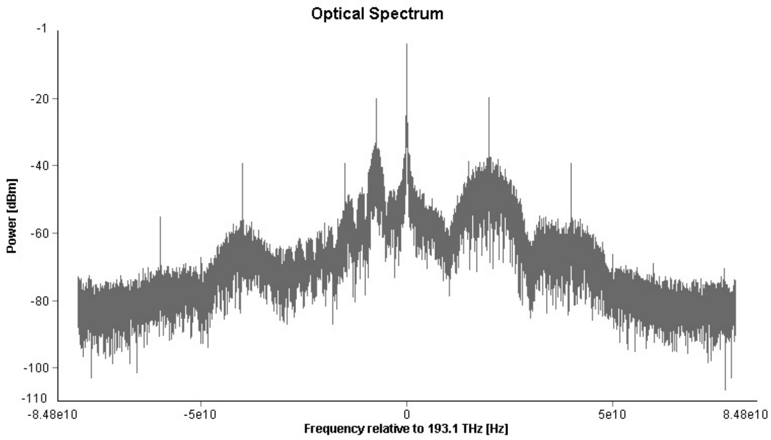

Fig.5.12 Optical spectrum of 12.5Gbps downlink transmitted signal

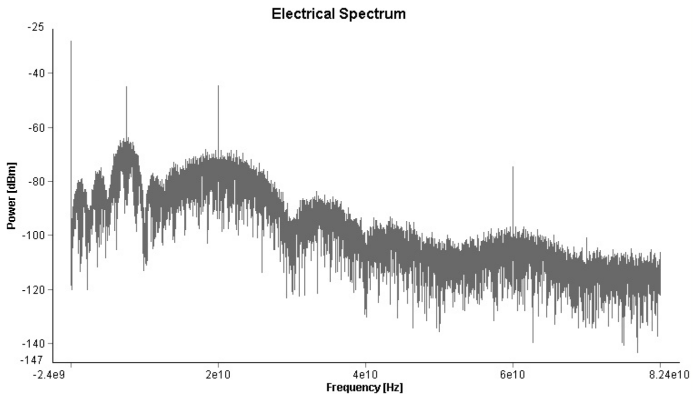

Fig.5.13 Electrical spectrum of 12.5Gbps received downlink signal

Fig.5.14 shows the BER curves of 2.5Gbps and 10Gbps data streams for b2b measurement. It was found that there is about 6dB penalty between 2.5Gbps and 10Gbps signals, which is consistent with theoretical value. This verifies that the use of orthogonally polarizations for two data streams with different subcarrier frequencies reduces the interference between the two data streams.

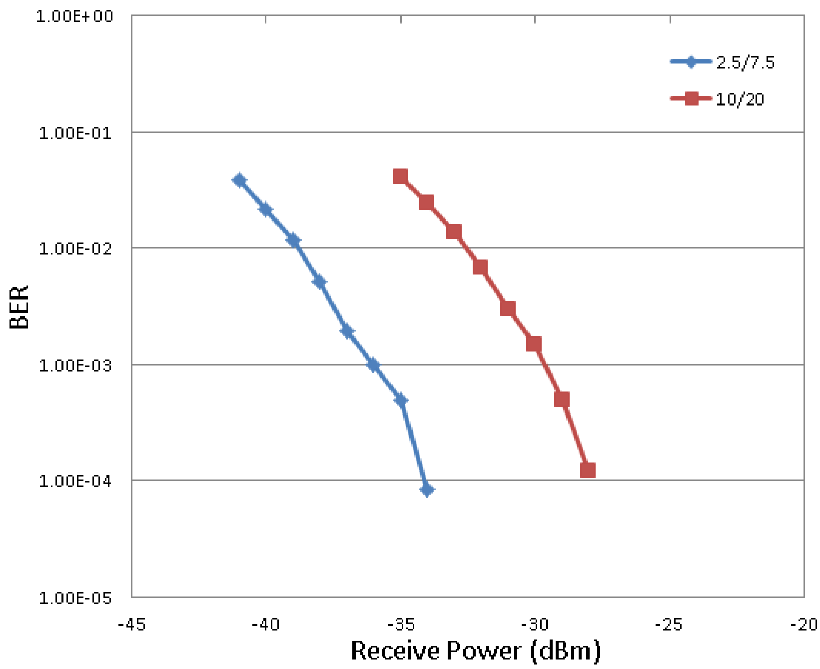

Fig.5.14 BER curves of 2.5Gbps and 10Gbps streams with b2b measurement

5.4.2 Effect of CD and PMD

In the simulation work, it has been found that CD and PMD are the main factors affecting the performance of the system after transmission. For each individual steam, although it is a SSB signal which can overcome power fading due to CD, PMD will still induce power fading similar to DSB signal [61, 62]. For two streams together, it is a DSB signal with two orthogonal polarization subcarriers, because the principal state of polarization (PSP) of a fiber changes randomly, if the state of polarization (SOP) of two SSB signals are not aligned to the PSPs, cross-talks and power fading duo to CD will happen cause by the beating signals, this may explain the reason why the data stream with higher subcarrier frequency has a worse performance after transmission.

5.4.3 Scalable receiver design

In the proposed architecture, there are two kinds of ONUs. One ONU is the so called scalable receiver front-end. Such an ONU does not use mixer and LO for down conversion, the down conversion is achieved in the electric domain, so we only need a PIN receiver. If the receiver has a large bandwidth, the user can receive both the broadcast and P2P data, if the users only need the broadcast data, then a lower bandwidth receiver can be employed. Such a configuration can achieve a cost effective ONU according to different demands, the receiving schemes are only different between receiver bandwidth.

5.4.4 Practical considerations

A good eye diagram is shown in Fig.5.10. However, this is only an ideal case. In the realistic situations, a number of factors can deteriorate the system performance. For example, Pol-MUX is used for downlink signal transmission. It requires the polarization to be orthogonal with each other. If the polarization is not orthogonal, there will be a significant degradation to the eye diagram, because the non-orthogonal parts of signals will generate beating noise which will affect the receiver sensitivity. In practical transmission system, the transmitter should be carefully designed.

In the simulation setup, we simply set the phase of the down-conversion LO to be the same as the subcarrier signal. In the practical receiver front-end, the phase of the LOs needs to be locked with the receiver subcarrier signals. The carrier phase can be recovered using a Costa loop, or the signal can be directly detected by a PIN receiver, and then digital signal processing can be employed to carry out carrier phase estimation to recover the signals.

5.5 Summary

In this chapter, some previous WDM-PON systems with simultaneously providing dual services are reviewed first. A novel Pol-MUX WDM-PON architecture for simultaneously providing dual services achieving scalable ONUs without polarization de-multiplexing and any optical filters is then proposed and demonstrated through simulation. This scheme offers a good solution for overcoming RB effect, CD and power fading to provide dual services bidirectional signal transmission in a PON system.

Chapter 6

Conclusions

6.1 Summary of the thesis

In this thesis, an overview of optical access networks was given including the types, architectures and demands. Three research challenges in the WDM-PON systems are addressed: the colorless ONU, the Rayleigh backscattering, and the dual services data transmission. Attempts were made to provide solutions to these challenges through three WDM-PON schemes. They are the subcarrier multiplexed WDM-PON system, the OFDM-WDM-PON system and the Pol-MUX WDM-PON system. These systems can reduce the Rayleigh backscattering and achieve a cost effective colorless ONU. The Pol-MUX WDM-PON system can further provide simultaneously dual services.

In chapter 1, optical access networks is reviewed and discussed. In particular, a variety of PON features and benefits are showed. Three major contributions of the thesis are introduced.

In chapter 2, discussion on using wavelength division multiplexing for PON system is given. Three research challenges are analyzed and discussed in the end.

In chapter 3, previous WDM-PON systems with signal re-modulation schemes are reviewed as well as previous WDM-PON systems with reduced Rayleigh backscattering effect. A subcarrier multiplexed WDM-PON system based on single sideband modulation is then investigated. The scheme shows a bidirectional PON system using subcarrier multiplexed SSB modulation for downlink data transmission and RSOA re-modulation data at baseband for uplink data transmission. It reduces the effect of RB by modulation the uplink and downlink data onto different optical wavelength. It supports self-heterodyne coherent detection structure in the ONU, so high order modulation and DSP algorithm can be employed to further increase the data rate and equalize the chromatic dispersion. It allows direct detection to be employed for uplink data detection without the need for optical and electrical filtering at the OLT through the use of a high frequency subcarrier and by adjusting the RSOA saturation level.

In chapter 4, a bidirectional hybrid OFDM-WDM-PON system for 40Gb/s downlink and 10Gb/s uplink transmission using RSOA re-modulation is studied. The scheme enables a bidirectional WDM PON system using direct detected OFDM for both downlink and uplink signal transmission. It reduces the power fading effect for high speed downlink transmission by using SSB signal. It reduces the effect of RB noise by modulating the uplink and downlink signals onto different frequencies. It uses the OFDM signals to modulate the bandwidth limited RSOA with high order modulation format and increase the system spectral efficiency and transmission bit rate. It does not require additional light source, modulator or optical filter at the ONUs. Wavelength management can be easily achieved and system complexity can be significantly reduced.

In chapter 5, a Pol-MUX WDM-PON system is evaluated through simulation. The scheme employs a WDM PON system using polarization multiplexing to separate two independent data in the orthogonally polarizations. It reduces the CD and power fading effect for downlink transmission by using SSB signal. It uses two independent data streams to provide dual services, which will not interfere with each other due to the use of orthogonal polarizations. It provides a depolarized light source for a polarization-sensitive RSOA re-modulation for uplink signal transmission. It enables cost effective scalable ONUs to meet demand of different users by using receiver frontends with different bandwidth. It does not require additional optical filters at the ONU, the wavelength management can be easily achieved and system complexity can be significantly reduced.

6.2 Future work

As discussed in chapter 3, the subcarrier multiplexed WDM-PON system only achieves 2.5Gbps downlink and 2.5Gbps uplink transmission. Both the data rate and receiver sensitivity can be increased in the future. The downlink transmission data rate can be increased by using mixer and modulator with higher frequency and broader bandwidth. The uplink transmission data rate can be increased by using higher order modulation format to modulate the RSOA, such as using 4-PAM, QPSK, or OFDM signals. The downlink receiver sensitivity can be increased by using self-heterodyne coherent signal detection and advanced DSP algorithm at the ONU. The uplink receiver sensitivity can be increased by using self-homodyne coherent signal detection and advanced DSP algorithm at the OLT.

As discussed in chapter 4, in the experiments, a number of factors have limited the system performance, such as the non-ideal performance of the IQ mixer, the carrier intermodulation produced by the nonlinear characteristics of the modulator and the linear modulator driver for OFDM signal amplification. We hope to reduce the effect these limiting factors in the future by using different component with better characteristics and also carry out more detailed study on the effect of various factors. For example, one of the limiting factors for downlink transmission is the use of a low sensitivity PIN receiver in the study. We can replace it with a high sensitivity PIN receiver, so that we can achieve a better BER performance for both B2B and 20km transmission.

As discussed in chapter 5, we have shown the simulation results, because of the limited availability of some key experiment devices. We hope the scheme can be verified by experiment. In experimental study, the effect of polarization multiplexing, various noises and the long distance transmission may deteriorate the system performance. In the scheme, the data rate and up-conversion LO frequency of two independent downlink data can be careful designed. We have shown the setup with 5Gbps for both broadcast and P2P data with up-conversion frequencies set at 10GHz and 20GHz. In the future, we can study the effect of data rate and selection of LO frequencies on the performance of the system. The effect of the amount of spectral overlap among the broadcast downlink data, P2P downlink data and uplink data can also be investigated.

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