A Remodulation Scheme for Wavelength-Division Multiplexing Passive Optical Network Using Time-Interleaved Differential Phase Shift Keying Modulation Format

LI, Pulan

A Thesis Submitted in Partial Fulfillment
of the Requirements for the Degree of
Master of Philosophy

in

Information Engineering

The Chinese University of Hong Kong
September 2011

Acknowledgement

First I would like to show my hearty gratitude to my supervisor, Professor Lian-Kan Chen, who generously provides me with strong support and effective feedback on my work, as well as cultures me with cutting-edge information and enlightening knowledge in the field of optical communication. He is a wise man and has a sincere characteristic in himself, so I feel fortunate for having gained tremendous benefits from his sharing of his wisdom and experience during my graduate study, in the growth of my inspiration and enthusiasm on research and an optimistic attitude toward life.

I would also like to express my gratitude Professor Chun-Kit Chan, for his support during the whole process of my research work, his prophetic and creative comments on various research topics, and his prompt advices on my experimental and presentation skills.

It is always a great honor for me to work with the intelligent colleagues in Lightwave Communication Lab, Department of Information Engineering, The Chinese University of Hong Kong. Their kind and crucial help operates to completeness of this thesis. Special thanks must be given to Dr. Jing Xu, Dr. Ming Li, Dr. Yang Qiu and Dr. Zhixin Liu, for their knowledge, experience and kindhearted assistance both on theoretical and experimental parts of my research. My appreciation are also committed to Mr. Kam-Hom Tse, Mr. Wei Jia, Mr. Dong Shen, Mr. Piu-Hung Yuen, Mr. Hum-Tong Lok and Mr. Qike Wang, whose inspiriting discussions enable me to quickly adjust my research work to an effective track.

Last but not the least, there will never be enough words for me to devote my thanks to the continuous support and encouragement of my family and my best friends.

Abstract

Optical networks encounters various challenges nowadays as demands on network capacities continuously increase in the rise of broadband internet and multimedia communication. The wavelength division multiplexed passive optical network (WDM-PON) is one of the most promising candidates for the next generation optical network to support high data rate for signal transmissions between central office (CO) and end users. In access networks, remodulation in WDM-PON has attracted vast interest as a cost effective optical network unit (ONU) solution since it reduces dedicated light sources for upstream signal, meanwhile also provides high speed operation the same as the ONU designs utilizing separated light sources do. Many schemes have been proposed to achieve robust performance for both downstream and upstream transmission especially in bi-directional scenarios. They include novel devices such as reflective semiconductor optical amplifier (RSOA) with high operation data rate up to 10 Gb/s as well as new remodulation formats, e.g., subcarrier modulation (SCM), differential phase-shift keying (DPSK), inverse return-to-zero (IRZ).

In single-fiber bidirectional transmission, Rayleigh backscattering (RB) can significantly affect transmission performance. RB is an intrinsic in-band noise caused by counter-propagating light which cannot be avoided as long as light is travelling in long-span fiber. Many efforts have been devoted to RB noise suppression in single-fiber bidirectional transmission scenario of WDM-PON both optically and electrically, e.g., optical notch filtering and electronic equalization.

In this thesis we firstly reviewed the background of WDM-PON, colorless ONU, bidirectional transmission and RB and discussed previous works dedicated to the investigation of remodulation schemes. Then we proposed and experimentally demonstrated a novel remodulation scheme for WDM-PON using time-interleaved differential phase-shift keying modulation format. With proper time detuning on electrical upstream data with respect to downstream signal, symmetric transmission of downstream and upstream data was achieved, with robust performance on both downstream and upstream transmission, and enhanced tolerance to RB, compared to that of upstream transmission using conventional non-return-to zero on-off-keying (NRZ-OOK) remodulation which was severely limited by RB-induced crosstalk. Simulation works and discussion were also presented in this thesis as an explanation of the enhanced tolerance toward RB noise.

In summary we propose a novel remodulation scheme in WDM-PON using time-interleaved phase remodulation and investigate the transmission performance and enhanced tolerance to RB.

摘要

當今快速發展的寬帶因特網和多媒體通信對網絡帶寬的需求迅速增長，光通訊網絡因而面臨諸多挑戰。多波長無源光網絡（WDM-PON）作為最有前途的網絡結構之一，為光終端（OLT）和用戶之間的高速數據通信提供了有效的解決方案。 在光接入網中，基於 WDM-PON 的重調製（remodulation）吸引了眾多研究興趣，因為它的上行數據可以直接調製在收到的搭載下行數據的載波上，從而不需要在用戶端安裝專門用於上行調製的光源。這一原理能夠極大的減少光網絡單元（ONU）的成本，並且同時保證高效的傳輸質量。如今，經過大量的研究，許多不同種類的結構被開發以實現上行信號的重調製，尤其是在單光纖雙向傳輸的網絡中。研究的主要方向包括對低成本高調製速率的新儀器的開發，如高调制速率（10 Gb/s 以上）的反射性半導體光放大器（RSOA）， 集成反射性電子吸收調製器的半導體光放大器（REAM-SOA）等等；也包括不同的調製格式，例如副載波調製（SCM）， 差分相移鍵控碼（DPSK），反向歸零碼（IRZ）等。

在單光纖的雙向傳輸中，瑞利散射（RB）的現象對傳輸質量造成重要的影響。瑞利散射是一種由反向傳播光造成的固有現象，它與傳輸的信號在同樣的頻帶內， 是一種不可避免的噪聲。為此，許多研究在光域和電域上針對抑制瑞利散射的課題設計了不同的解決方法，比如光陷波濾波器和電均衡的方法。

在本篇論文中，我們首先回顧了WDM-PON，ONU的無色化，單光纖的雙向傳輸和瑞利散射的基本背景知識，然後討論了現有的針對WDM-PON中重調製的研究結果。我們提出并實驗證實了一種新的重調製方式，它使用時間交叉的DPSK調製格式。通過對下行電信號進行適當的時間調整，這個重調製方法實現了上行信號與下行信號的對稱速率傳輸，并表現出優秀的傳輸特性。與此同時，與普通的非歸零碼（NRZ-OOK）作為上行調製格式的重調製結構相比，這個重調製方法顯示了對瑞利散射良好的抑制作用。通過理論分析、仿真結果和實驗測試，我們為這個特性做出了相應的解釋。

綜上所述，在這篇論文中我們提出了一種新的基於時間交互的DPSK調製格式的重調製方法，並且研究了它的傳輸特性與瑞利散射的特性。

Table of Contents

Table of Figures

Chapter 1 Introduction

1.1 Overview of wavelength division multiplexed passive optical network (WDM-PON) and colorless optical network unit (ONU)

Optical network faces with various challenges on the way of practical implementation while demands on the capacity of optical networks dramatically and continuously increase growing nowadays. Optical network hierarchy is illustrated in Fig.1.1. As can be seen, fiber optical transmission system can be categorized into three hierarchical layers, i.e. 1) long-haul network, 2) metropolitan network and 3) access network, respectively. Long-haul networks connect metropolitan networks lying in different large regions with long transmission distance. Residential access network lies on the bottom layer of the whole network hierarchy and provides business and home network services.

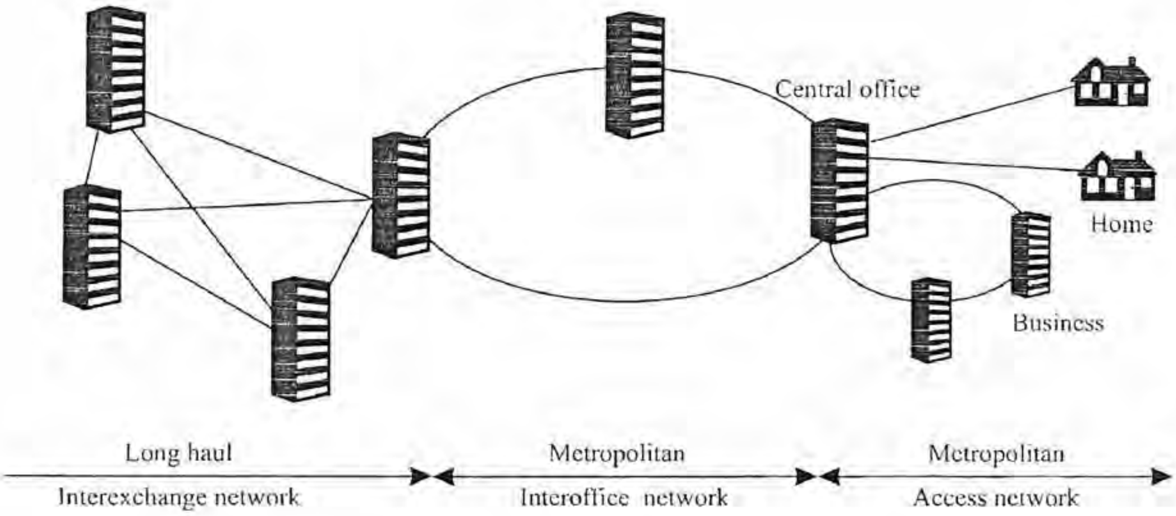


Fig.1.1. Illustration of optical network hierarchy [1].

Fig.1.2 shows a typical schematic architecture of PON for optical access network in a tree topology. Optical line terminal (OLT) in central office (CO) controls all downstream light sources and modulates them with corresponding downstream data. For downstream traffic, after multiplexing, light propagates through a feeder fiber whose length is around tens of kilometer and is delivered to a remote node (RN). Distribution fibers connect the optical network units (ONUs) located at end users to the RN. RN demultiplexes downstream signals and sends them to the connected ONU. For upstream traffic, signals from different ONUs are aggregated at RN and sent back to CO of network operators through feeder fiber. PON employs only passive optical components, thus cost-effectiveness can be achieved as well as centralization of maintenance.

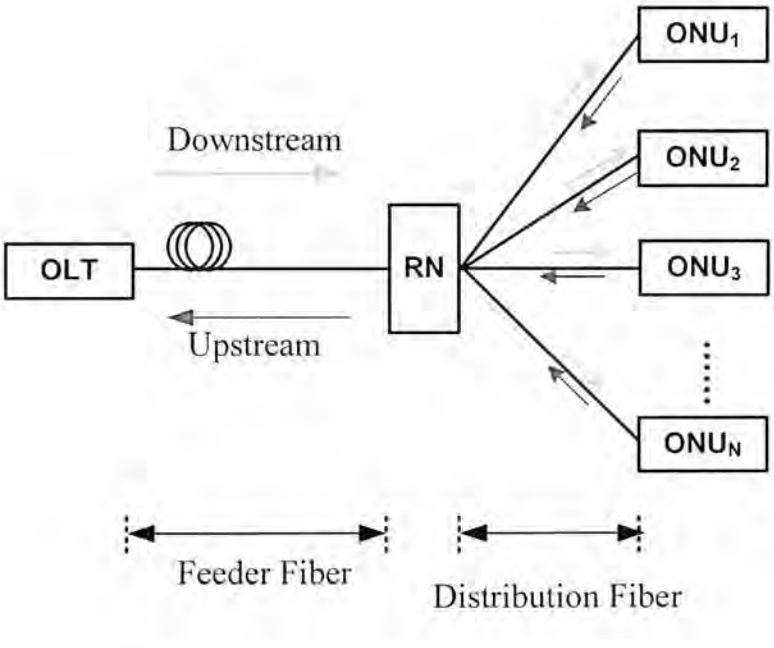


Fig.1.2. Typical architecture of optical access network.

One of the goals of next generation access is to provide gigabit access to users either by increasing the capacity of current optical time-division multiplexing (TDM) PONs up to 10-Gb/s or by implementing optical wavelength-division multiplexing (WDM) PONs, which multiplexes many optical carriers with independent information onto a single fiber [2]. Fig.1.3 depicts the architecture of a WDM-PON. Compared to TDM being challenged by limitation of operation speed and security of the system, the method of WDM provides PONs with larger bandwidth by designating each subscriber with dedicated wavelength able to support high-speed transmission, which is highly desired in future access networks. Another advantage of introducing WDM-PONs is that the implementation is doable on the existing infrastructure by upgrading existing TDM-PONs with WDM overlay.

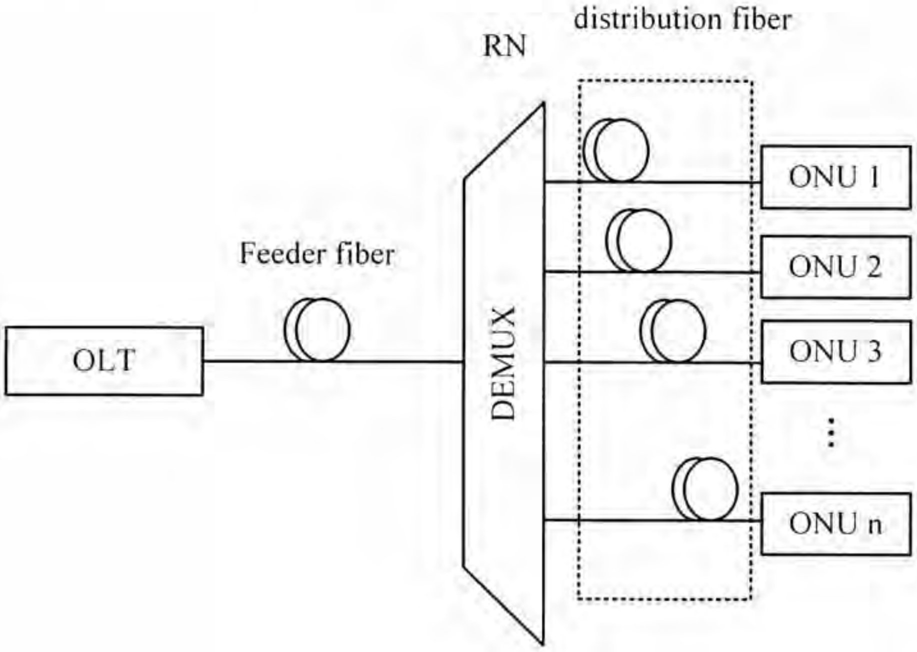


Fig.1.3. Typical architecture of WDM-PON.

One of the most notable problems in WDM-PON compared to current power-splitting-based TDM-PON is the equipment cost of the whole network, such as dedicated transceivers on different wavelength channels for distributed end users. Efforts have been put on colorlessness of ONU, meaning that the transceiver in ONU is wavelength-independent. The most significant benefit of using colorless ONU is that manufacturing expense can be greatly cut down, and maintenance can be much easier if the same equipments are installed in distributed end users. Colorless ONU is also able to improve wavelength flexibility of network.

1.2 Implementation of colorless ONU

As described above in 1.1, WDM-PON will benefit from utilizing colorless ONUs with the same structure and devices. Colorlessness of ONU help decrease the costs of operation, administration, and maintenance functions as well as the production cost since integration in one specific device with exactly the same design makes mass production possible [3]. Colorless ONU has attracted various research interest and different approaches have been proposed to construct colorless ONUs. Three main categories of approaches can be concluded as follows:

Wavelength-tunable ONU

A straightforward method for the realization of colorless ONU is to utilize wavelength-tunable optical components in ONUs [4]. This method has the best wavelength flexibility since arbitrary wavelength can be obtained, if it is provided with a large tunable wavelength range.

Wavelength-tunability of ONU increases the usability of network, but the cost of wavelength-tunable optical components, such as tunable laser, is still too high to make this method into practice. In [4], colorless ONU was reported with a 3-nm tuning range using a dense-wavelength-division multiplexing small form factor pluggable (DWDM-SFP) transceiver. The emission wavelength was tuned by changing external temperature of distributed feedback laser diode (DFB-LD), which constructed the proposed colorless-ONU structure together with an avalanche photodiode (ADP). This device dramatically reduced the cost of a conventional continuous-wave tunable laser based on multi-section pumping and external cavity filtering; however, relatively slow response time (around 10 s) due to temperature control limited the usage of the proposed laser.

Carrier-distributed scheme

A carrier-distributed scheme is briefly demonstrated in Fig.1.4. Light sources for upstream remodulation can be supplied and controlled by OLT, so that no carrier is needed in ONU, significantly cutting down the cost of network. By either using laser diodes with different wavelengths or employing spectrum-slicing to a broadband light source, carriers with arbitrary wavelength can be provided to each ONU together with downlink data transmission [5]. Broadband light source in this type of colorless ONU can be light-emitting diodes (LEDs), superluminescent diodes (SLDs) [5, 6], or be generated via fiber nonlinear effect, i.e., supercontinuum (SC) [7]. Spectrum slicing of LED and SLD can be an effective way of obtaining low-cost broadband light sources, yet suffering from large slicing loss. For spectrum-slicing of SC, it can only be applied to transmission of data in RZ format because the generation of SC spectrum is based on self-phase modulation of optical pulses with very narrow pulse width, so that the light source after slicing is also pulse-shaped.

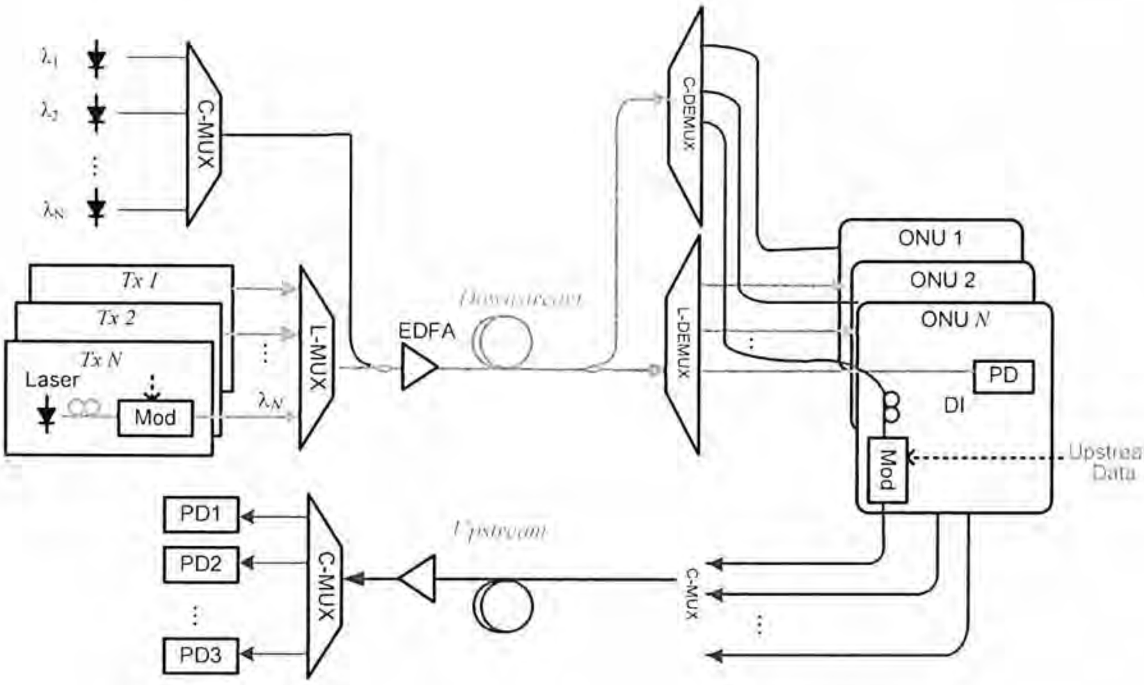


Fig.1.4. Demonstration of carrier-distributed colorless ONU in a bidirectional WDM-PON. Light sources were supplied and controlled by CO.

Remodulation scheme in ONU

Among the colorless ONU solutions, the method of remodulation has attracted remarkably vast interest for its intrinsic colorlessness, since the concept of remodulation is to reuse the downstream modulated lights both for downstream data detection and upstream data remodulation, so that the dedicated light sources in ONU are not needed and only transmitter laser sources, located at central office (CO), are enough to provide optical carriers for both downstream and upstream data transmission. Various devices have been taken into account to construct remodulation schemes, e.g., Fabry–Perot laser diode (FP-LD) [8] and semiconductor optical amplifier (SOA) [9]. Currently, remodulation via reflective devices such as reflective semiconductor optical amplifier (RSOA) is a noteworthy colorless-ONU solution for its ability of reflecting and remodulating light source carrying downstream data with a relatively low cost [10], and the modulation rate of commercial products lies around 2.5 Gb/s. Reflective electro-absorption modulator and semiconductor optical amplifier (REAM-SOA) is another promising candidate with higher operation speed compared to RSOA [11]. Experimental precedents also shows the value of investigating novel remodulation formats its upgrading potential on currently established network, meanwhile improving performance of both downlink and uplink transmission. Previous studies on remodulation in WDM-PON will be discussed in Chapter 2.

1.3 Rayleigh backscattering in WDM-PON

Single fiber operation of WDM-PON, which supports downstream and upstream signals propagation in the same transmission line is highly desirable in optical access network not only because of its cost-effectiveness on fiber link installation and further maintenance, but also for its ability of transmitting two independent signals on the same wavelength simultaneously. Compared to dual-fiber operation, bidirectional transmission has its own sources of system degradation, such as additional insertion loss of optical circulators and reflections at the fiber splices and the connection ends.

Another obvious and maybe most troublesome one among those sources of degradation is Rayleigh backscattering (RB). RB is a fundamental loss of fiber. Different from reflections due to fiber ends and connectors which can be suppressed to -55dB, RB noise cannot be avoided when light is transmitting in fiber.

***Physical background of Rayleigh Backscattering* [12]-[14]**

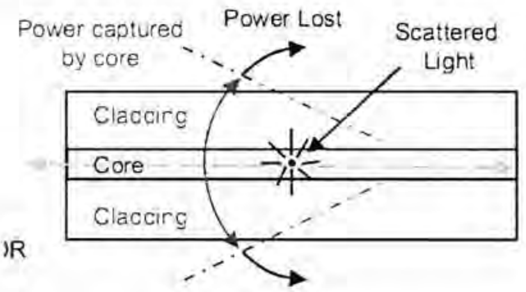


Fig.1.5. Illustration of Rayleigh backscattering in optical fiber [12].

Since optical fiber has small-scale inhomogeneities in the local permittivity at molecular level, light scattering occurs once transmitting in optical fiber [13]. Part of the energy of forwarding light is scattered and propagates in backward direction. Some of the scattered light escapes from cladding, while the other captured by fiber core, leading to a backward transmission. The amount of Rayleigh scattering can be measured by a coefficient

$$\alpha_{scat} = \frac{8\pi^3}{3\lambda^4}(n^8 p^2)(kT_f)\beta \quad [14]$$

where λ is the wavelength of the incident light, n is the refractive index, p is the photoelastic coefficient of the glass, k is Boltzmann constant, T_f is a fictive temperature, and β is the isothermal compressibility. This equation indicates the relationship between RB and wavelength of the incident light into fiber, that the amount of RB is inversely proportional to λ_4.

Categorization of RB in single-fiber bidirectional WDM-PON

RB can be categorized into carrier scattering and signal scattering as shown in Fig. 1.4, depending on whether the reflected light is mainly due to downstream carrier or upstream signals transmission in fiber. Because RB is an in-band noise and the reflected light lies in the same wavelength of desired signal in single fiber transmission, unwanted crosstalk is added on the spectrum of transmitted signal, leading to performance degradation. RB-induced crosstalk is difficult to be removed via conventional band-pass filtering method.

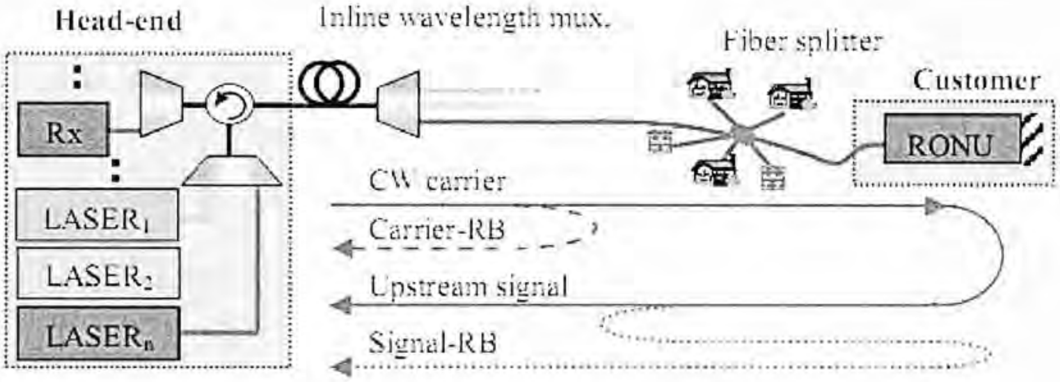


Fig.1.6. Schematic of RB contributions in a carrier-distributed DWDM-PON [15].

As can be seen in Fig.1.5, obviously, RB noise has great influence on the performance of upstream signal in single-fiber bidirectional transmission. Numerous studies have been carried out on the reduction of RB interference both for carrier-distributed schemes and remodulation schemes. In carrier-distributed schemes which mainly focused on suppression of RB crosstalk originated from distributed-carrier during transmission, the technique of wavelength shifting can efficiently separate the reflected narrow spectrum of downstream light source and upstream signal. Optical notch-filtering is also an efficient method to move RB noise which lies in the filtering band of notch filter, whiling preserving the spectrum of signal in its pass-band. Relatively fewer works has been done on RB suppression in remodulation schemes, since the spectral width of RB crosstalk caused by downstream light with data modulated is broader than that in carrier-distributed schemes, making it more difficult to remove the in-band crosstalk. Efforts have been conducted on modulation methods to suppress RB noise, such as optical carrier suppression to separate the spectrum of signal and RB noise plus on optical notch filter. Electrical DC blocking, electrical notch filter plus line coding (intensity modulation/direct detection) and electronic equalization have also been successfully demonstrated with enhanced RB tolerance of transmission system [16-18].

Signals in different modulation formats suffer from dissimilar levels of RB degradation in bidirectional transmission. According to the analysis above, since RB crosstalk is an in-band noise, the larger the spectral overlap between transmitted signal and RB crosstalk is, the severer the degradation will be at the receiver side [19]. For example, symmetric transmission system using the same modulation format both on downlink and uplink will result in poor upstream transmission performance at the receiver end in OLT because the signal spectrum of RB noise has nearly the same spectral width as upstream signal. [19] proposed an approach applying phase modulation in each ONU to broaden the spectrum of intensity modulated upstream signal, thus reducing the spectral overlap. From this aspect, novel modulation formats with unique characteristics of RB tolerance are worth studying, especially for cost-effective bidirectional remodulation scheme in need of robust performance. Detailed reviews and studies of RB crosstalk suppression will be carried out in Chapter 4.

1.4 Motivation of this thesis

As discussed in 1.1, though a promising candidate of future metro/access network advantaging in high data rate transmission, real implementation of WDM-PON in industrial approach requires flexibility as well as reduction of network cost. Colorless ONU can fulfill these two requirements by providing network with wavelength-insensitivity and low cost with the potential of massive manufacturing since the structure of ONU is the same. Three approaches mentioned in 1.2 have been demonstrated experimentally to achieve colorless ONU, but it is the method of remodulation that combines the characteristics of cost-effectiveness and colorlessness in one set, so we take remodulation in WDM-PON as the main interest of this thesis.

Various investigations have been done on remodulation schemes. Remodulation based on reflective devices, such as RSOA, shows its implementation potential with low-cost and commercially-available products, but its maximum modulation data rate (2.5GHz) is still far below satisfaction in future WDM-PON. Albeit recent research results showed that RSOA could reach 10-GHz modulation rate under external control [20], additional specifications for the controlling operation at ONU raised the final cost of network. REAM-SOA is another option for high data-rate operation in ONU, but the high price of device hinders its further implementation.

Single-fiber bidirectional transmission in WDM-PON can also bring down the expense not only on implementation of the fiber link itself but also the potential cost of detection, maintaining and repairing, as only one fiber is needed for simultaneous transmission of downstream and upstream signal. Unique problems emerge in single-fiber bidirectional transmission, including crosstalk induced by Rayleigh backscattering (RB), which is an in-band noise and severely limits the performance of system.

This thesis thus proposed a novel remodulation scheme in bidirectional transmission scenario with enhanced tolerance to RB crosstalk. The concept of time-interleaving is introduced between downstream and upstream data with conventional DPSK modulation. Experimental results and analysis of its transmission performance, timing-misalignment tolerance and RB tolerance will be studied in detail.

1.5 Outline of this thesis

The remaining part of this thesis is organized as follow:

Chapter 2 reviews previous work on remodulation, including the devices in ONU, e.g. injection locked Fabry-Perot laser diode (FP-LD), reflective semiconductor optical amplifier (RSOA) and reflective electro-absorption modulator and semiconductor optical amplifier (REAM-SOA). Different modulation formats in WDM-PON will also be discussed in detail.

Chapter 3 demonstrates the experimental setup of proposed time-interleaved phase remodulation scheme. Transmission performance and effect of timing misalignment will also be demonstrated and discussed in this chapter.

Chapter 4 reviews previous research efforts on RB reduction in bidirectional transmission. Experimental data showed enhanced RB tolerance of our proposed remodulation scheme, following theoretical analysis of observed RB tolerance enhancement.

Chapter 5 summarizes the proposed scheme and lists future potential works.

Chapter 2 Previous works of remodulation for WDM-PON

2.1 Introduction

Figure 2.1 is a schematic demonstration on remodulation scheme in a dual-fiber transmission system. Light sources modulated with downstream data at OLT are transmitted to ONUs and are reused to carry upstream data. The remodulated signals are then sent back to OLT for upstream data demodulation. This re-utilization of lights cuts down the cost of WDM-PON since no dedicated light source is needed at ONU for upstream signal modulation, meanwhile provides ONU with wavelength-insensitive property. Remodulation can also operate in single-fiber bidirectional transmission. Studies have been carried out to construct remodulation-based ONU with different emphasis. In this chapter, modulation devices and modulation methods in remodulation scheme will be discussed in detail.

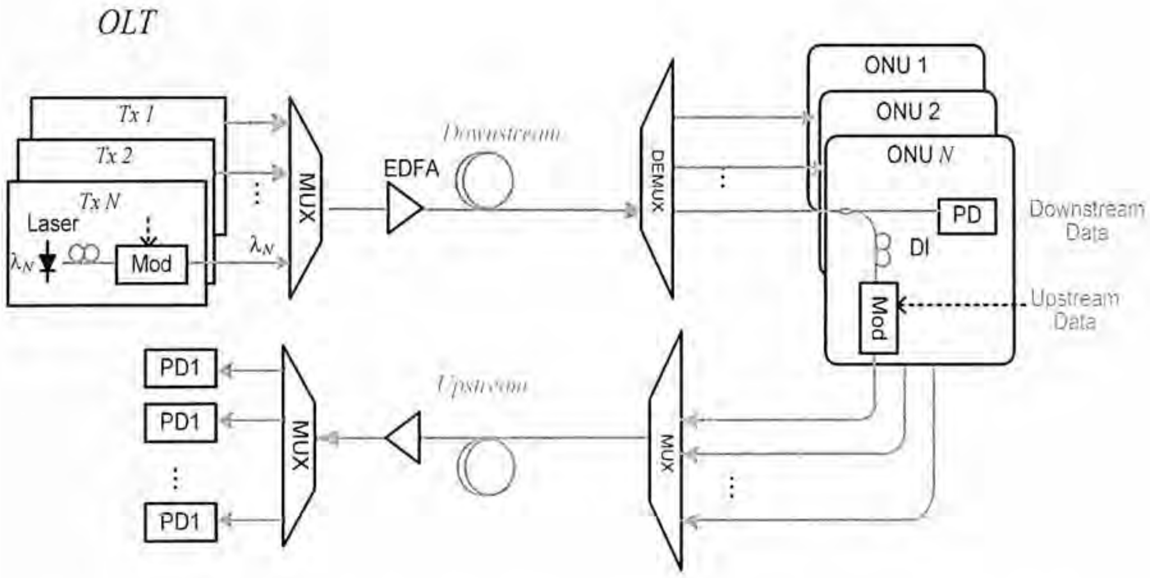


Fig.2.1. Demonstration of a dual-fiber remodulation scheme in WDM-PON.

2.2 Devices utilized by colorless ONU in remodulation schemes

Remodulation can be done on light source carrying downstream data either by an optical modulator or a semiconductor optical amplifier at ONU [9]. Various novel devices which can be used for colorless ONU construction have been proposed and experimentally demonstrated, including injection-locked Fabry–Perot laser diodes (FP-LDs), reflective semiconductor optical amplifiers (RSOAs), and electro-absorption modulators integrated with optical amplifiers (REAM-SOAs), etc.

2.2.1 Injection-locked Fabry-Perot laser diode at ONU

Fig.2.2 shows the architecture of a FP-LD-based ONU. Part of the downstream signal is used to injection lock FP-LD so as to suppress the downstream signal and allow reuse of optical power at the same time. Large side-mode suppression ratio (SMSR) enhanced by injection locking in FP-LD erases downstream data and single mode operation can be achieved, leading to great improvement in dispersion tolerance. Fig.2.3 shows the output spectrum of free-running and injection locked FP-LD. High SMSR can be seen after injection locking, indicating erasure of original signal for further upstream modulation. [8, 21-24].

Since the reused optical power for upstream modulation is with the same wavelength of downstream signal (or within a certain detuning range) in remodulation scheme based on injection locked FP-LD, wavelength registration is not needed at ONU [22]. Upstream data modulation can be done by applying electrical data directly on FP-LD. When the wavelength of downstream light source changes, this remodulation scheme has its own limitation since only carriers matching specific wavelengths of modes generated by FP-LD can perform injection locking for the following remodulation stage, which hinders the flexibility of network. Besides, the polarization status has to be carefully tuned to maximize the output power of FP-LD [24].

In a word, injection-locked FP-LD reuses the optical power of the downstream signal, and the remodulated wavelength depends on the spectral characteristic of FP-LD. This scheme needed relatively high injection power to achieve injection locking, and the extinction ratio (ER) of the downstream signal has to be sacrificed to some degree for the integrity of the upstream signal.

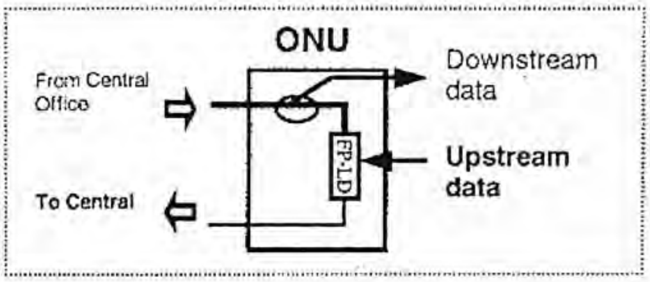


Fig.2.2. Architecture of ONU based on a Fabry-Perot laser diode [8].

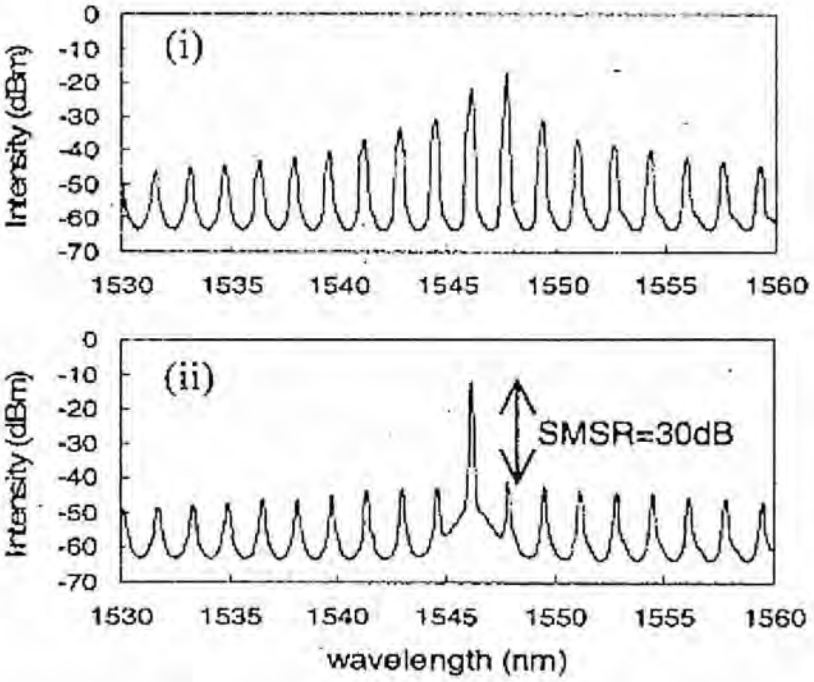


Fig.2.3. Spectrum properties of (i) free-running and (ii) injection-locked FP-LD [8].

2.2.2 Reflective semiconductor optical amplifier

Commercially-available reflective semiconductor optical amplifier (RSOA) can operate at a data rate around 2.5-Gb/s. It can be used to construct laser-free colorless ONU for its low cost, low noise figure and ability of performing remodulation with a relatively simple control method. RSOA has attracted vast interests and various related studies have been carried out in [10, 25-29].

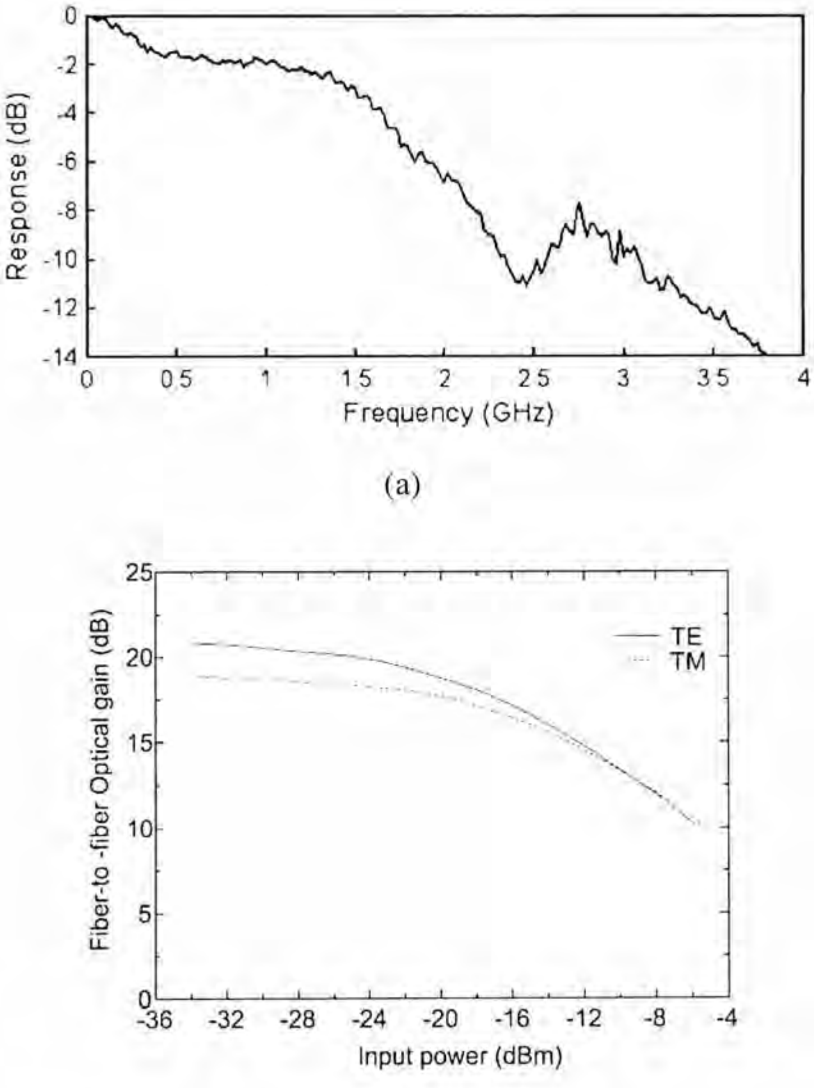
RSOA employs coating of high reflectivity at the ends of SOA waveguides. Carrier can be recovered if gain saturation condition of RSOA is satisfied and upstream electrical data can drive RSOA directly for remodulation. The reflective characteristic of RSOA, similar to injection-locked FP-LD, advantages itself for bidirectional transmission. RSOA has low polarization dependence compared to injection-locked FP-LD, and it can be easily packed into ONU, thanks to its small size. The required injecting power for remodulation operation in RSOA (around -20 dBm) is lower than that for injection-locked FP-LD, offering network sufficient power budge. The frequency response of a conventional RSOA is depicted in Fig.2.4 (a), indicating a modulation bandwidth around 2.5 GHz. The gain saturation property of RSOA, as shown in Fig.2.4 (b), have relatively smaller gain when input power is higher, so that downstream intensity modulated binary data can be erased for the reconstruction of light source at ONU, if downstream signal reaches required extinction ratio [25].

Another newly discovered characteristic of RSOA is the gain-phase coupling property [26]. When RSOA is intensity-modulated, the output signal is accompanied by a phase remodulation which could be expressed by the following equation:

$$\phi(t) = \frac{-\alpha_{eff}}{2}\ln(\Delta G(t)) \qquad (1)$$

This property generates frequency chirps on modulated signal, which can be further used for RB suppression [26] and generation of signal in advanced modulation format [27].

Nowadays, main challenges in RSOA-based ONU include limited modulation bandwidth and available modulation format of RSOA. The modulation bandwidth of commercially available RSOA is around 2.5 GHz. To increase the operation data rate beyond 2.5 GHz, advanced modulation formats generation in RSOA have been investigated and experimentally demonstrated, e.g. quadrature phase-shift keying (QPSK) [27], direct duobinary modulation [28] and phase shift keying (PSK) [29]. Introducing additional components such as DI can also extend modulation bandwidth to 10 GHz [20].



(a)

(b)

Fig.2.4. (a) Frequency response [20] and (b) gain profile [25] of a RSOA.

2.2.3 Reflective electro-absorption modulator and semiconductor optical amplifier (REAM-SOA)

For bit rate up to 10 Gb/s, REAM-SOA with the potential of integration is a suitable candidate as a colorless remodulation module for its robust performance without extra temperature-controlling system for high-speed operation [11, 30-32]. Fig.2.5 illustrates the structure of the REAM-SOA. Electro-absorption effect removed the limitation on operation speed so that EAM can be modulated at a high data rate, while SOA can compensate the high insertion loss of EAM. 10-Gbit/s operation of REAM-SOA in access network has been studied and experimentally demonstrated. For 10-km and 20-km transmission, only 0.4 dB and 1.5 dB power penalties are observed for 10-Gb/s OOK downstream signal and receiver sensitivity of -17.8-dBm was obtained after transmission [30]. In [31], BER curves for 3.5-GHz wireless OFDM signals modulated in QPSK, 16-quatrature amplitude modulation (QAM) and 64QAM format were reported. The wavelength tuning range of REAM-SOA is around 80 nm, guaranteeing colorless operation. Recently, an integrated REAM-SOA at 10 Gb/s with triple-functionality including modulation, detection and noise-mitigated 2R all-optical signal regeneration has been experimentally demonstrated, [32], indicating its further potential of function-integration.

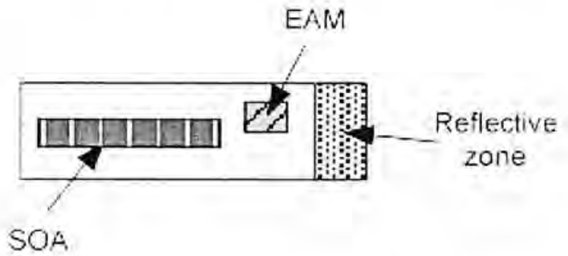


Fig.2.5. Structure of a REAM-SOA [11].

In a word, REAM-SOA is one of the most promising candidates able to support high data rate operation in next generation access network. Based on its potential of high operation speed, another extension as well as challenge of its future utilization is to support 60 GHz millimeter wave signals for radio-over-fiber (RoF) optical system [31]. Till now, the cost of REAM-SOA is still high and far from practical implementation.

2.3 Modulation methods in remodulation schemes

Modulation method is another important issue when designing colorless ONU since the transmission characteristics of different modulation formats has great influence on system performance. Commonly used modulation formats in remodulation scheme include differential phase-shift keying (DPSK), on-off keying (OOK), frequency-shift keying (FSK), inverse-return-to-zero (IRZ), and Manchester coding.

Downstream DPSK, upstream OOK

In this approach, downstream transmission benefits a lot from the constant intensity nature of DPSK signal, leading to small nonlinear distortion during transmission. Compared to the additional gain saturation process for erasing downstream signal for upstream modulation in downstream OOK scheme, upstream data can be directly modulated on downstream light with DPSK modulation because of the constant amplitude characteristic. In [8], DPSK modulation format also helped with suppressing crosstalk between downstream and upstream signals during the injection locking process. This modulation format set has also been successfully demonstrated via experiments in WDM-PON with RSOA-based ONU [33]. One advantage of this remodulation scheme is that it is insensitive to polarization state of input downstream DPSK signals, and rigid synchronization is not required.

One of the key issues in this approach is that the chromatic dispersion tolerance of DPSK signals is poorer compared to OOK signal if data rate increases, which limits the downstream performance since the transmission distance of downstream signal is doubled in remodulation scheme if it is not erased. In [32], a solution was proposed, in which reduced modulation index DPSK was used for downstream transmission.

Chromatic dispersion tolerance was greatly enhanced by utilizing this modulation format, and upstream performance was improved at the same time as the residual dispersion was reduced.

Downstream OOK, upstream DPSK

As discussed above, in remodulation schemes using DPSK format for downstream data modulation, poor chromatic dispersion tolerance of downstream DPSK signal will degrade system performance. In order to eliminate residual chromatic dispersion, an orthogonal modulation format set with downstream OOK and upstream DPSK was proposed. In [34], the extinction ratio (ER) of downstream OOK signal was set to be finite for upstream DPSK signal modulation, which sacrificed performance of downstream transmission to some degree but was rewarded back by better quality of upstream DPSK signal and enhanced chromatic dispersion tolerance of the whole system. DI and balanced detector could be placed at OLT, while only a simple PD was used in each ONU, which could significantly brought down the cost of maintenance. Compared to the scheme above using downstream DPSK modulation format, this scheme is more insensitive to remodulation timing misalignment. Dual-fiber transmission in [34] is upgraded to single-fiber bidirectional transmission in [35], with a phase modulator for upstream remodulation at ONU which can be integrated with the splitter and receiver in silicon.

Downstream FSK

FSK can be applied to remodulation schemes as an option of downstream modulation formats. Similar to the case using downstream DPSK signal, FSK has an intrinsic characteristic of constant intensity, so remodulation can be done directly on downstream FSK signal. The signal can be correctly demultiplexed and transmitted to each ONU via arrayed waveguide (AWG), since the channel pass-band of AWG is large enough for FSK signal with smaller frequency spacing. At the downstream receiver side, a frequency discriminator is used for demodulation of FSK signal.

which brings more flexibility on data rate variance to receiver compared to the rigid requirement of DI in downstream DPSK signal. In [36], negligible penalties for 2.5 G-bit/s downstream FSK signal and 2.5-Gbit/s upstream OOK signal were observed, indicating good signal quality and dispersion tolerance of the proposed scheme.

Downstream IRZ

An IRZ signal is the inversion of conventional return-to-zero (RZ) signal, thus the trailing half-bits of an IRZ signal has power no matter whether the binary data is "0" or "1" [37]. According to this characteristic, upstream data can be modulated on the trailing half-bits of downstream signal in IRZ format without introducing erasure of downstream signal. The pre-coding process of IRZ signal is done in electrical domain by logic AND operation between an RF clock signal and an NRZ RF data signal. Then the pre-coded data is modulated on optical carrier via a Mach-Zehnder intensity modulation (MZ-IM). The bias of MZ-IM is set at the quadrature point of the negative slope of its transmission curve, so that optical signal is a "mark" level when electrical "0" is modulated on optical carrier, and vice versa when electrical signal "1" is modulated. The trailing half of pre-coded electrical signal is always at low voltage level, so the trailing half-bit has power in every time interval. IRZ signal can be directly detected, offering simplicity of optical transceiver for downstream transmission, and the extinction ratio of the remodulated upstream OOK signal can remain in high level at the same time.

Downstream signal using IRZ modulation showed good transmission performance as reported by [37], with only 0.23-dB power penalty observed. A small power penalty of 0.94 dB was found on transmitted upstream signal using NRZ format for remodulation. Remodulation on downstream signal with IRZ modulation format provides the system various advantages as stated above; however, performance of upstream signal degrades if the pulse widths between the two levels are different, which causes power fluctuation, and the synchronization requirement confines the modulation flexibility of upstream signal [38].

Downstream Manchester

Another option using Manchester coding for downstream data modulation was proposed. Similar to the pre-coding procedure of IRZ modulation format, Manchester code can be obtained by XOR operation between downstream NRZ data and RF clock after synchronization in electrical domain. It can also be generated optically by using a delayed Mach-Zehnder interferometer (DMZI). Transition occurs in every bit so that low frequency fluctuation of optical power can be efficiently suppressed. The remodulated 2.5-Gb/s upstream OOK signal showed negligible penalty after 20-km single mode fiber (SMF) transmission when 5-Gb/s downstream Manchester-code-modulated signal in [38]. In [39], 13.5-Gb/s single-sideband (SSB)-Manchester IM downstream signal with reduced ER was utilized for upstream NRZ remodulation at ONU. The dispersion tolerance of SSB Manchester was robust in 100 km transmission. However, generation of Manchester-coded signal requires relatively complicated electrical circuit for logic operation and synchronization control.

Downstream DPSK, upstream DPSK with XOR operation

In order to improve receiver sensitivities at both ONU and OLT sides, DPSK format can be applied to both downstream and upstream modulation. In this case, it is important to correctly detect upstream phase-modulated signal while avoiding the disturbance of downstream phase information. Despite conventional data-erasure method which complicated ONU structure, [40] proposed an effective solution by introducing exclusive-OR (XOR) logic operation on upstream data with the demodulated downstream data. The proposed ONU structure is demonstrated in Fig. 2.9. After pre-coding and XOR operation at ONU, the actual transmitted upstream signal is:

$$D\mathit{trans} = D'\mathit{down} \oplus D'\mathit{up},$$

where D'*down* and D'*up* are pre-coded data. Using the fact that

$$D'\mathit{down} \oplus D'\mathit{down} = 0, \text{ and } 0 \oplus D'\mathit{up} = D'\mathit{up},$$

Only upstream data exists on optical carrier after remodulation. After transmission, upstream signal is demodulated by a DI and received by a PD. Balanced detector can further improve the receiver sensitivity at a value of 3 dB.

It should be noted that the alignment between the downstream and the applied electrical signals to the PM is crucial, and this can be controlled using electrical delay line and electrical buffers. Another issue is that errors in downstream data due to transmission after demodulation will bring errors to upstream data through XOR processing, resulting in degradation of upstream performance.

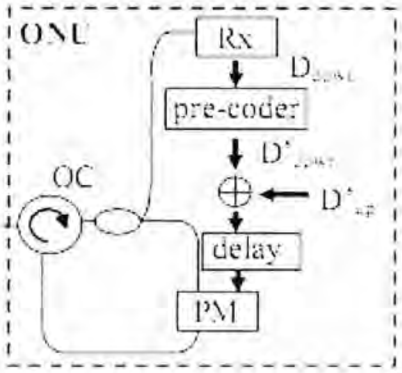


Fig.2.6. Demonstration of XOR-based DPSK remodulation [40].

A comparison on the pros and cons of different modulation formats is concluded in the diagram below.

Modulation method	Need Synchronization?	Complex electrical process?	Receiver complexity	CD tolerance	Others
DS DPSK, US OOK	No	No	Low	Poor	3-dB improvement using balanced detector
DS OOK, US DPSK	Yes	No	Low	Good	3-dB improvement using balanced detector
DS IRZ	Yes	Yes	Low	Good	
DS FSK	No	No	High	Good	
DS Manchester	Yes	Yes	High	Poor	
DS DPSK, US DPSK	Yes	No	Low	Poor	3-dB improvement using balanced detector

Table 1. Comparison between different modulation methods in remodulation scheme.

2.4 Summary

Previous works on remodulation schemes in WDM-PON have been reviewed in this chapter. The discussion can be categorized into two sessions:

1) Devices utilized by colorless ONU in remodulation schemes
2) Modulation methods in remodulation schemes.

When designing a remodulation scheme in WDM-PON, consideration must be taken into characteristics of remodulation devices used in ONU in order to achieve both colorlessness and good performance of the network system. There are several candidates to fulfill different requirement on operation speed of colorless ONUs, including injection-locked FP-LD, RSOA and REAM-SOA. These candidates all support upstream modulation on the same wavelength of downstream signal without adding dedicated light sources.

FP-LD is a suitable device for remodulation speed around 1.25 Gb/s. It has a large SMSR which helps with carrier recovery for upstream remodulation, however, the polarization state of the injected light has to be carefully adjusted to reach maximum output power, and extra effort has to be paid to realize arbitrary detuning of wavelength since the injection-locking process depends on the spectral property of FP-LD. RSOA provides the system with more power budget and lower polarization dependence for bit rate up to 2.5 Gbit/s. The operation speed can be extended to 10 Gbit/s in recent reports, but extra cost for controlling was introduced. For resilient access networks with data rate up to 10 Gbit/s, REAM-SOA is adapted for its large electrical bandwidth. However, the cost of REAM-SOA still too high to be implemented in real network.

For modulation methods in remodulation schemes, SCM is discussed as well as specially-designed modulation formats. Several examples are demonstrated in this chapter, with discussions on respective pros and cons.

In the next chapter, we proposed and experimental demonstrated a novel remodulation scheme using DPSK format on both downstream and upstream data modulation. As will be shown in the experimental results, with proper time-interleaving between downstream and upstream data, the upstream signal can be demodulated at OLT simply with a DI. At the same time, the RB tolerance of the system will be significantly enhanced compared to conventional upstream signal in OOK format. Detailed study on the performance of the proposed scheme has been taken and will be discussed.

Chapter 3 A remodulation scheme based on time-interleaved DPSK modulation format

3.1 Introduction

Among various modulation formats in WDM-PON, DPSK advantages itself for its intrinsic 3-dB improvement of receiver sensitivity using balanced detector and its constant optical intensity which reduces nonlinear distortion caused by intensity variance during transmission. As mentioned in Chapter 2, several approaches using DPSK format for downstream or upstream data modulation have been proposed [33, 36, 40]. The scheme employing orthogonal modulation (downstream: DPSK; upstream: NRZ-OOK) benefited from the constant optical power of DPSK signal, so that IM signal could be remodulated on received downstream signal at ONU directly. This scheme also exhibited excellent tolerance towards timing misalignment. DPSK can also be applied to upstream signal while applying OOK format for downstream modulation to improve downstream dispersion tolerance. The tradeoff of this scheme is that the extinction ratio of downstream OOK signal has to be reduced in order to guarantee existence of power in every bit for DPSK modulation.

To further enhance the receiver sensitivity thus provide network with a larger power budget, DPSK format can be utilized for both upstream and downstream signal in remodulation scheme, in which correct demodulation of upstream data at OLT becomes an important issue. Despite carrier recovery described in chapter 2, modulating upstream signal directly on downstream signal is also an attractive solution for direct reuse of transmitted downstream light sources. In [40], erasure of downstream DPSK signal was achieved by modulating downstream light with electrical data which was obtained by an XOR operation between downstream and upstream data in electrical domain. This remodulation method enabled upstream modulation without disturbance of downstream signal; however, errors in downstream data caused errors in upstream data before transmission. Besides, it sophisticated electrical control circuit at ONU, resulting unwanted cost. One scheme in [41] demonstrated a solution with reduced-modulation-depth DPSK for downstream data modulation (RMD-DPSK) and full-modulation-depth DPSK (FMD-DPSK) for upstream data modulation. Experiments showed its robust performance in single-fiber bidirectional transmission and enhanced tolerance to RB noise since the downstream RMD-DPSK has a relatively narrower spectrum, thus the spectrum of its reflected noise was compressed, leading to a reduction of spectral overlapping between upstream signal and RB noise. DI had to be carefully adjusted to demodulate RMD-DPSK since this modulation format had more rigorous requirement on the pass-band positioning of notch filtering.

A remodulation scheme is proposed in this thesis to further investigate remodulation method using DPSK format for both downstream and upstream data. OLT and ONU use conventional DPSK modulation, and the key to successful operation of the proposed scheme is the proper time-interleaving between downstream and upstream DPSK signals. Time-interleaving technology for phase-modulated signal has been studied both in access network [42] and all-optical signal processing [43] to realize various functions, including data broadcasting and signal time-domain multiplexing of DPSK signals, which will be discussed in this chapter. In our proposed scheme, time-interleaving process can be done in electrical domain by simply using an electrical time delay at ONU. Experimental results will be demonstrated in this chapter, showing its robust performance in single-fiber bidirectional transmission scenario.

3.2 Operation principle: time-interleaving technology for phase-modulated signal

Technology introducing time-interleaving to signal modulation can function as high-data-rate signal generator both electrically and all-optically by combining several low-data-rate signals to one single channel, enhancing the spectrum efficiency as well as the per-channel capacity without introducing expensive high-speed modules [43, 44]. It can also provide access network system with downstream broadcast traffic multiplexing without additional sources [45]. The operation principle of time-interleaved DPSK signal in our proposed remodulation scheme is illustrated in Fig. 3.1. Symmetric transmission is considered, meaning that downstream and upstream data have the same data rate. Conventional DPSK format is used for downstream and upstream modulation. After transmission, downstream light is phase-remodulated with upstream data directly at ONU. Fig.3.1 depicts binary data ("0" and "1") and respective encoded phase information ("0" and " π ") of downstream and upstream signals. The introduction of a *T/2* offset (*T* is the bit period of signal) performs as an XOR operation on the two independent phase modulated patterns [43] and the phase difference between the leading half of a bit in the upstream DPSK signal and the trailing half of the previous bit will not be affected by the original phase modulation of the upstream data [45]. By using a half-bit-delay differential interferometer (DI) at OLT, the received upstream signal can be simply demodulated and the upstream data (blue-colored) can be correctly detected on the trailing half bits of the demodulated signal.

Above all, in our proposed remodulation scheme, time-interleaved DPSK modulation can efficiently superimpose upstream signal into received downstream signal while maintaining a relatively simple detection method. The differential pre-coders for the two tributaries are operated independently compared to [40], and synchronization of two data is needed at ONU.

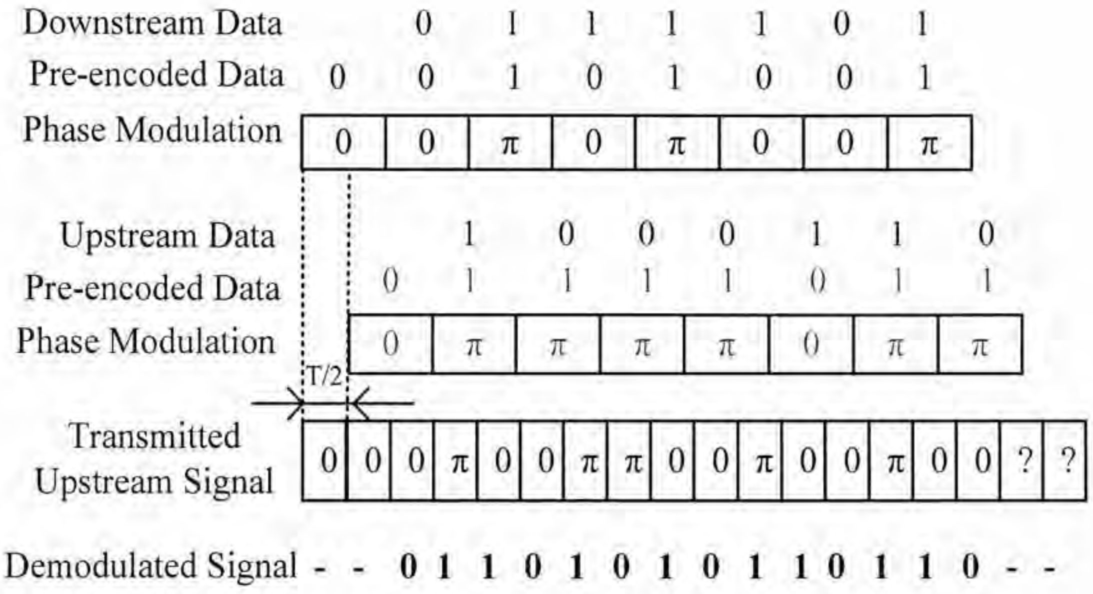
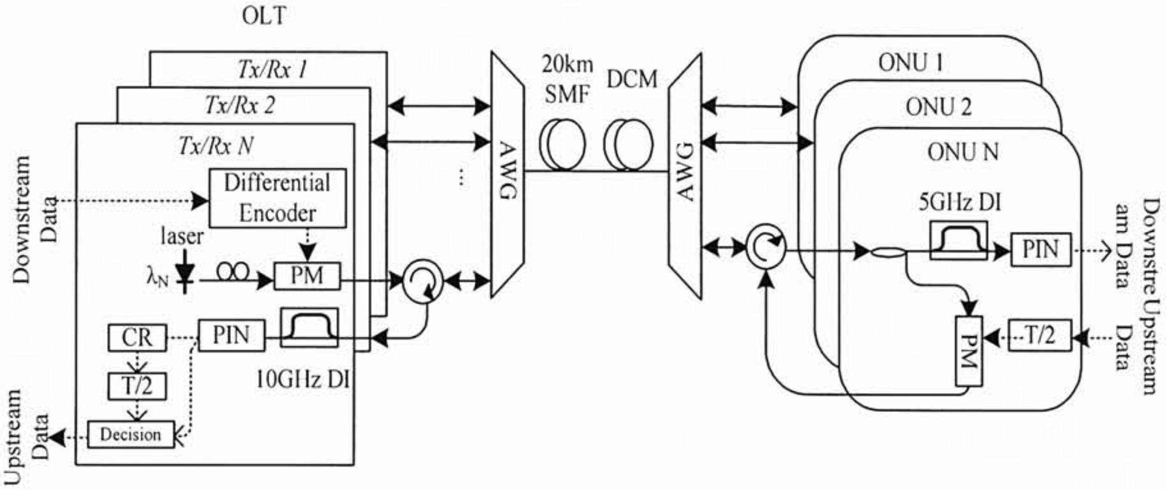


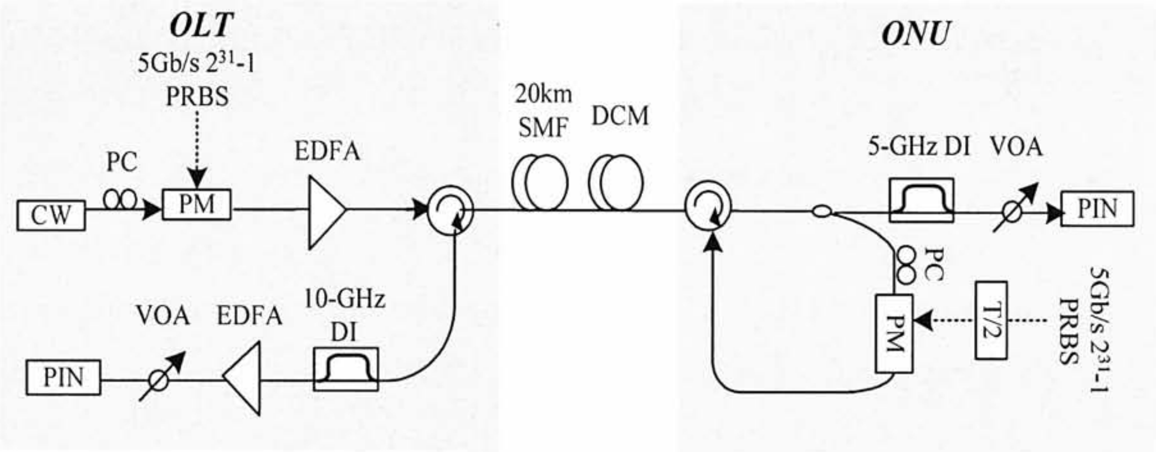
Fig.3.1. Operation principle of time-interleaved DPSK signal.

3.3 System architecture

To investigate and verify the performance of our proposed remodulation scheme, experiments have been carried out. The network architecture of proposed remodulation scheme is depicted in Fig. 3.2 (a). This system architecture operates as follows. Pre-coded signal is phase-modulated on downstream light source at OLT. The modulated signal propagates through an optical circulator before entering feeder fiber, which is essential in single-fiber bidirectional transmission because optical circulator can correctly route counter-propagating downstream and upstream signal to ONU and OLT respectively. After channel multiplexing, downstream signal travels through the transmission line and independent channels are de-multiplexed before being delivered to user ends located in different places. At each ONU, downstream light source is separated into two portions for both downstream data detection and upstream data remodulation. To realize time-interleaved remodulation, a *T/2* time delay is introduced between downstream and upstream data electrically. Then after pre-coding upstream data is phase-modulated and sent back to transmission line. Passing through the same multiplexing/demultiplexing processes, upstream data is demodulated by a *T/2* DI at OLT, following an electrical threshold-decision detection stage.



(a)



(b)

Fig.3.2. (a) Network architecture and (b) experimental setup of proposed remodulation scheme. SMF: single mode fiber; AWG: arrayed waveguide grating; DCM: dispersion compensation module; CR: clock recovery; VOA: variable optical attenuator.

Fig.4.3 (b) depicted experimental setup. One-channel operation and symmetric transmission were considered in our experiments. In this remodulation scheme, 5-Gb/s 2^{31}-1 pseudorandom binary sequence (PRBS) downstream data was modulated on a continuous wave (CW) laser light source at 1552.4 nm via an optical phase modulator (PM) with driving voltage of ~V_{π}., which maximizes the modulation depth of PM used in the experiment, providing DPSK signal with high ER. The polarization state of light source was carefully adjusted by a polarization controller to obtain maximum optical power at the output port of PM. To avoid stimulated Brillouin scattering (SBS) in SMF, the input optical power must be set in a relatively low value, usually below 7.5-dBm. In our experiment, the power of input light was tuned to 3 dBm.

As a remodulation in optical access network, 20 km was generally considered to be a reasonable distance for experiments. The generated signal then was sent into the transmission line of 20-km single-mode fiber (SMF). A dispersion compensation module (DCM) followed the feeder fiber to isolate the effect of chromatic dispersion during transmission. At ONU, a 20:80 optical coupler split the received downstream signal with one portion for demodulation and detection using conventional 5-Gb/s DI and photodiode, while the rest of power was remodulated by another PM with upstream 5-Gb/s 2^{31}-1 PRBS data which was *T/2* time-interleaved via an electrical time delay with respect to downstream data. The polarization state of downstream light before remodulation has also been adjusted by a polarization controller. The remodulated signal was then routed by an optical circulator at ONU to the same transmission line in an opposite direction to downstream signal. After transmission, upstream signal reached OLT and was demodulated by a 10-GHz DI.

The detection in real implementation, as depicted in the structure of OLT modules in Fig.3.2, is to do clock recovery (CR) and then to use the reconstructed clock to sample the received signal on its trailing halves after demodulation. In our experiments, we directly used a 5-GHz clock signal in sampling stage and manually adjusted the synchronization between clock and signal in the following detection stage. The received signal was measured by an electronic oscilloscope for eye diagram detection. Receiver sensitivity and respective BER performance was measured by a 12.5-Gb/s BER tester.

3.4 Experimental results and discussion

Fig.3.3 shows eye diagrams of downstream and upstream signals before and after transmission in the proposed remodulation scheme. The signal-to-crosstalk ratio (SCR) was set to the maximum value without amplification at OLT (around 23 dB in the experiment). As can be seen in the eye diagrams, the received signal at OLT was a 10-Gb/s DPSK signal interleaving upstream and downstream signals in *T/2* with wide-opened eyes at destructive port of a 10-GHz DI. Downstream signal remained in the leading half bits, while upstream signal was in the trailing half bits.

As a comparison, upstream signal using a 5-Gbit/s conventional non-zero on-off-keying (NRZ-OOK) remodulation scheme was also experimentally demonstrated and was shown in Fig.3.3. Time-interleaved DPSK has a clear eye diagram after transmission and little distortion on marks and spaces was observed, while large amount of noise was seen on the marks of NRZ-OOK upstream signal, indicating severe crosstalk effect of RB noise due to downstream signal in bidirectional transmission.

	Time-interleaved DPSK	NRZ-OOK
BTB		
After Transmission		

Fig.3.3. Eye diagrams of time-interleaved DPSK and NRZ-OOK signals before and after bidirectional transmission. BTB: back-to-back.

By properly detuning the sampling point to the trailing half bits with optimized decision threshold, 5-Gb/s upstream signal was successfully detected and the tested BER results are shown in Fig.3.4. The receiver sensitivities of downstream and upstream signal at BER of 10^{-9} are -23.6 dBm and -18.6 dBm, respectively. Downstream signal has negligible penalty (within 0.5 dB) and only around 0.8 dB penalty of upstream signal after bidirectional transmission is observed, implying robust tolerance toward RB crosstalk.

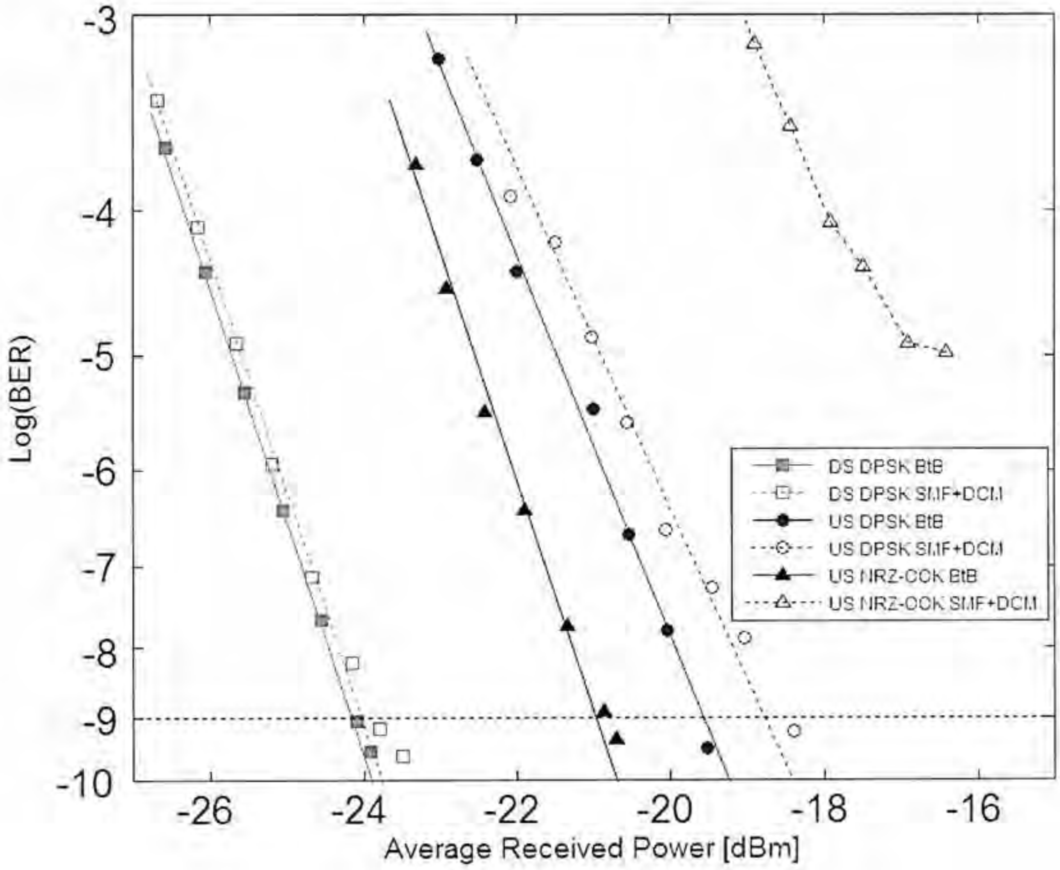


Fig.3.4. BER curves of time-interleaved DPSK and NRZ-OOK signals before and after bidirectional transmission. DS: downstream; US: upstream.

BER curves of NRZ-OOK signal are also plotted as a comparison. It again shows upstream signal in NRZ-OOK format suffered from severe distortion due to RB which led to an error floor in BER curve, even when SCR was the same as that of upstream time-interleaved DPSK signal. Slight distortion in the eye diagram as well as a small value of power penalty after transmission using the proposed remodulation scheme was observed.

3.5 Effect of timing misalignment on proposed remodulation scheme

One of the key parameters in our proposed remodulation scheme is the value of time interleaving between downstream and upstream signals, which is critical for the performance of upstream signal at OLT as demodulation of upstream DPSK signal used a DI with *T/2* time delay on one arm. If upstream data is misaligned from the ideal position in the trailing half bits, its information will be mingled with downstream information, resulting in inaccurate demodulation and unwanted distortion in receiver sensitivity.

Evaluation on timing misalignment tolerance of the proposed remodulation scheme was carried out in our experiments. Different delay time was obtained by tuning the electrical time delay at ONU. The receiver sensitivity at OLT when electrical time delay was set to *T/2* was used as the reference value (0-ps timing misalignment). Fig. 3.5 illustrates eye diagrams of one bit (upstream information on the trailing half bit) with different timing misalignments (misalignment values are mentioned above corresponding eye diagrams. The symbol "- (+)" means upstream data falls behind (ahead of) the one of ideal remodulation with proper time-interleaving.).

As can be seen in the eye diagrams, upstream signal degraded rapidly if inappropriate time interleaving was introduced. Effect of RB on marks also increased when upstream data was not placed properly. To investigate the impact of timing misalignment on system performance more accurately, receiver sensitivities when BER was 10^{-9} under different timing misalignment values were tested and are plotted in Fig.3.6. Penalties were within 3-dB when timing misalignments did not exceed

±25 ps (±*T/8*). If timing misalignment further increased, receiver sensitivity dramatically deteriorated, and error floor was observed in the experiment if timing misalignment exceeded ±50 ps (±*T/4*).

Misalignment	-12.5 ps	-25 ps
		

Misalignment	-37.5 ps	-50ps
		

Misalignment	+12.5 ps	+25 ps
		

Misalignment	+37.5 ps	+50 ps
		

Fig.3.5. Eye diagrams under different timing misalignment.

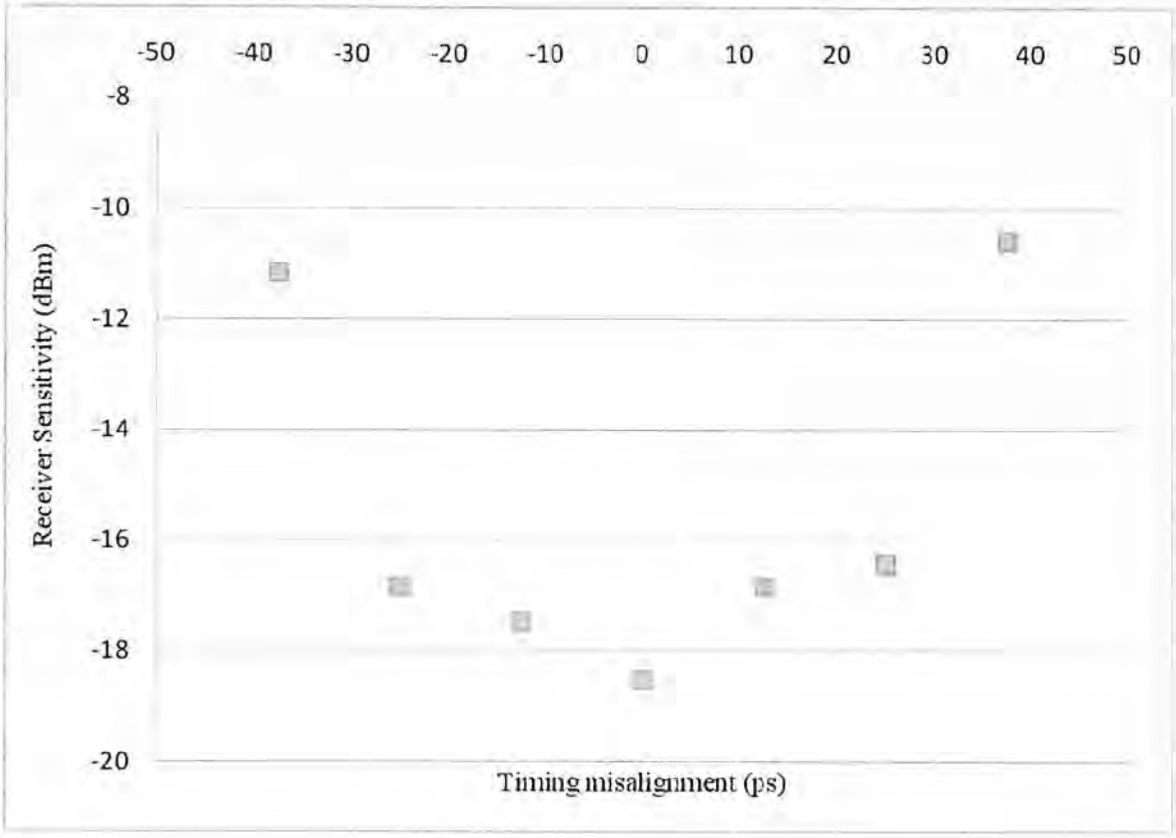


Fig.3.6 Receiver sensitivity under different timing misalignments.

3.6 Summary

In this chapter, we have experimentally demonstrated a novel remodulation scheme in WDM-PON with 20-km transmission distance. Both downstream and upstream data used conventional DPSK modulation with *T/2* time-interleaving. In the experiments, 5-Gb/s electrical PRBS data drove PMs at OLT and ONU for downstream and upstream DPSK modulation and 100-ps time delay was introduced between two data electrically at ONU. After 20-km SMF bidirectional transmission and a DCM for dispersion compensation, upstream signal was successfully demodulated at OLT and output at destructive port of a 10-GHz DI was used for eye diagram analysis and BER testing. The eye diagram of upstream signal was clear on both zeros and marks after transmission, and the penalty of receiver sensitivity was very small, indicating robust tolerance toward RB compared to the transmission results of remodulation scheme using 5-Gb/s upstream NRZ-OOK modulation on downstream DPSK signal.

Effect of timing misalignment on the proposed remodulation scheme was also studied by investigating eye diagrams and receiver sensitivities under different timing misalignment values. A tuning range of ±25 ps (±*T/8*) was observed with 3-dB degradation of receiver sensitivity, while error floor appeared if timing misalignment was too large (±50 ps in our experiments), which severely degraded upstream signal according to the eye diagrams.

Chapter 4 Enhanced Tolerance to Rayleigh Backscattering in Remodulation Scheme Using Time-Interleaved DPSK Format

4.1 Introduction

In chapter 1 the background of RB noise has been introduced. Since RB is an in-band noise, it is challenging to directly filtered RB noise out without impairing the upstream signal itself. The main way of suppressing RB noise is to use narrow-bandwidth filtering at the receiver, removing RB spectrum while preserving spectral information of signals as much as possible. This could be realized both electrically and optically. In electrical domain, the spectrum of downstream signal can be compressed by line coding, and commercially-available narrow electrical filters can be used for RB removing after optical-to-electrical (OE) conversion. Equalization can also perform as a solution via fast digital signal processing technology [16]. In optical domain, the notch-filter-like characteristic of destructive port of DI has attracted many research interests. In order to protect signal spectral components when discarding in-band RB noise by filtering, reduction of spectral overlapping has been considered as one of the most effective methods. This can be done by subcarrier multiplexing, upstream spectrum broadening or downstream spectrum narrowing. In [41], protection of signal spectrum was done by narrowing the spectrum downstream signal using specially designed modulation format, resulting in spectral compression of reflected noise. Light scrambling also alleviated degradation due to RB crosstalk by reducing the coherence of noise and signal [46]. Table 2 lists a comparison between electrical and optical approaches on RB suppression.

	Electrical domain		Optical domain	
	8B10B line coding + electrical filtering [17]	Equalization [18]	SCM + optical band pass filtering [47]	Optical notch filtering using DI [41]
Electrical Processing	Yes	Yes	Yes	No
Stability	Good	Good	Good	Need temperature control
Improvement	12 dB improvement on receiver sensitivity (SCR=18 dB)	2 dB improvement on receiver sensitivity (SCR=20 dB)	1.9-dB penalty after transmission	0.3-dB penalty after transmission

Table 2. Comparison between approaches on Rayleigh backscattering suppression.

As mentioned in Chapter 1, various approaches to alleviate RB-induced crosstalk have been briefly discussed, both in carrier-distributed schemes and remodulation schemes. Till now, most of previous works on RB suppression were done on carrier-distributed schemes. Wavelength shift by using phase modulation combining with single side-band modulation at ONU for remodulation was introduced to spectrally dissociate narrow-bandwidth downstream carrier and upstream signal. Timing walk-off between seeding light and upstream signal is also an efficient approach for WDM-PON solutions providing dedicated light source [48]. To the best of our knowledge, RB suppression in remodulation scheme still needs further investigations theoretically and experimentally.

Our work mainly focused on RB suppression in remodulation scheme. According to the experimental results in Chapter 3, the proposed remodulation scheme presented excellent tolerance toward RB noise. More specific works have been done on evaluation of RB tolerance of our proposed remodulation scheme and experimental results will be demonstrated in this chapter. A detailed analysis will also be proposed to explain the reason of enhanced tolerance

4.2 Studies on Rayleigh backscattering suppression in optical domain

In this session we will review studies on RB suppression in single-fiber bidirectional transmission by optical means. According to the categorization of colorless ONU, this session discusses RB suppression in carrier-distributed schemes and in remodulation schemes respectively.

4.2.1 RB suppression in carrier-distributed schemes

To reduce the spectral overlap between RB caused by downstream transmission and upstream signal, one effective method is to shift the wavelength of upstream signal with an offset to downstream carrier. This can be done by using single sideband modulation at ONU. As shown in Fig.4.1, firstly downstream carrier is shifted by a local oscillator with the frequency of f_s, and then upstream data is phase-modulated on the wavelength-shifted carrier. This frequency offset effectively separates the spectra of RB crosstalk and upstream signal, and the improvement on RB tolerance was 7 dB in the experimental demonstration when signal-to-crosstalk ratio was 20 dB and frequency offset was 2.5 GHz [49].

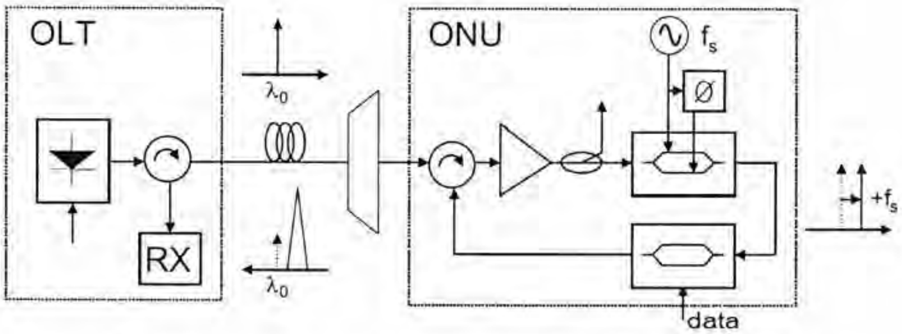
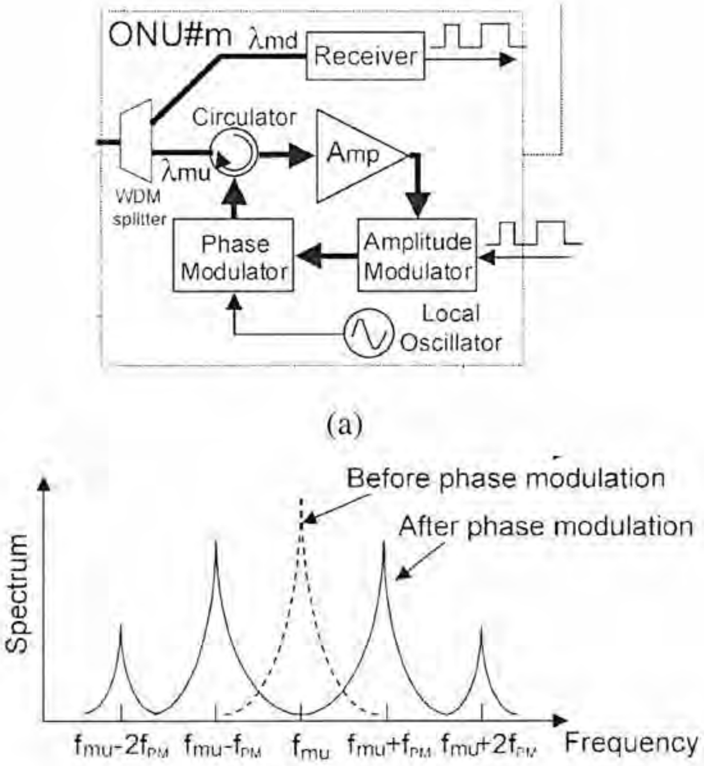


Fig.4.1. RB suppression by using wavelength shifting [49].

Another effective approach in RB suppression is phase scrambling. Fig.4.2 illustrates the working principle of phase scrambling. As can be seen in Fig.4.2 (a), the carrier distributed to ONU is firstly amplitude-modulated with upstream data, and then a local oscillator drives a phase modulator to scramble the spectrum of upstream signal. The spectra before and after phase modulation are depicted in Fig.4.2 (b). Phase scrambling broadens the spectrum of upstream signal, so as the spectral overlap between upstream signal and RB crosstalk. According to the reported experimental results, the improvement on RB tolerance using this remodulation method reached 17 dB when power penalty was with 1 dB [46].



(a)

(b)

Fig.4.2. (a) Schematic and (b) spectra of phase scrambling at ONU [46].

4.2.2 RB suppression in remodulation schemes

Relatively fewer works on remodulation schemes have been done, because it is more difficult to reduce the effect of RB crosstalk in remodulation schemes, which has a broader spectrum of RB noise, compared to RB suppression in carrier distributed schemes,. Using FSK for downstream data modulation can help with RB suppression, since the spectrum of frequency-modulated signal has a broad spectral width, which reduces light coherence [50]. Subcarrier modulation (SCM) also performs as a good solution as illustrated in Fig.4.3 [47]. By using SCM at ONU, A frequency shift between downstream and upstream signal gave rise to a negligible power penalty around 1.9 dB after transmission, implying enhanced tolerance to RB.

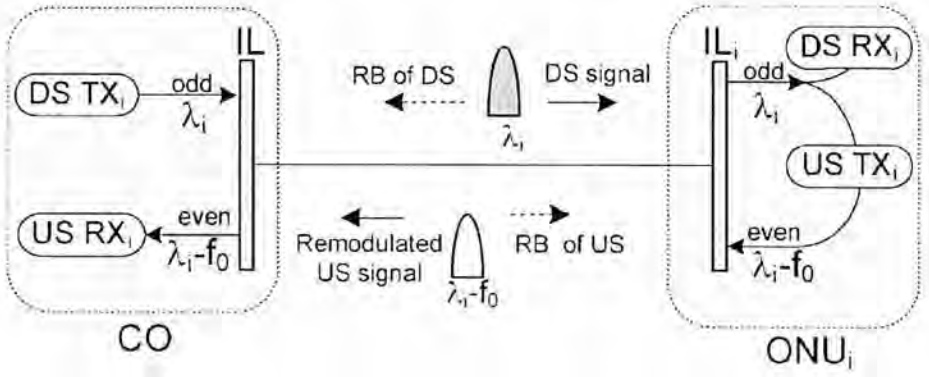


Fig.4.3. Rayleigh backscattering suppression based on subcarrier modulation. DS: downstream; US: upstream; IL: interleaver.

It was also reported in recent research progress that by using DPSK modulation with different modulation depths. The characteristics of this modulation format have been studied in [41] and the system architecture is illustrated in Fig. 4.4. The spectrum relationship in Fig.4.4 shows that, if the modulation depth of downstream DPSK signal is reduced, the spectrum of modulated DPSK signal will be smaller than that with full modulation depth, thus the spectrum of reflected in-band RB noise will be smaller than upstream DPSK signal with full modulation depth, reducing the unwanted spectral overlapping. Thus large portion of RB noise can be filter out via DI when demodulating the upstream signal. Power penalty was observed to be 0.3 dB after transmission, indicating negligible distortion induced by RB crosstalk. Another property of RMD-DPSK is that the extinction ratio of demodulated signal at destructive port remains in a high value, because the demodulation depends on the relative phase different between signals on two arms of DI rather than specific phase information on each bit of signal.

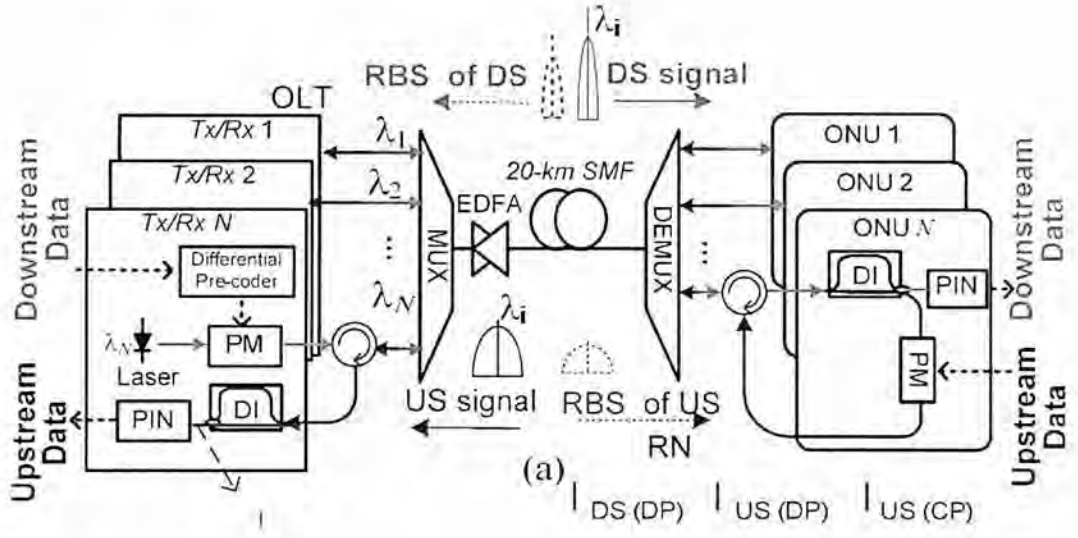


Fig.4.4. Rayleigh backscattering suppression based on DPSK signal with reduced modulation depth [41].

4.2 Experimental setup and results

In order to evaluate effect of RB noise, transmission performance of our proposed remodulation scheme was tested under different SCRs. Fig 4.1 depicts experimental setup. Downstream and upstream data were both 5-Gb/s PRBS signals. Since the RB power is constant as the power of downstream signal remained the same at OLT, SCR before upstream receiver could be changed by tuning output power of PM at ONU. Based on this working principle, an optical attenuator was inserted into the remodulation module after PM and before optical circulator to obtain different SCR values. Upstream signal was then sent back to 20-km SMF and DCM by optical circulator and reached 10-GHz DI for detection after transmission. The operation of remodulation and detection was the same as the one described in Chapter 3.

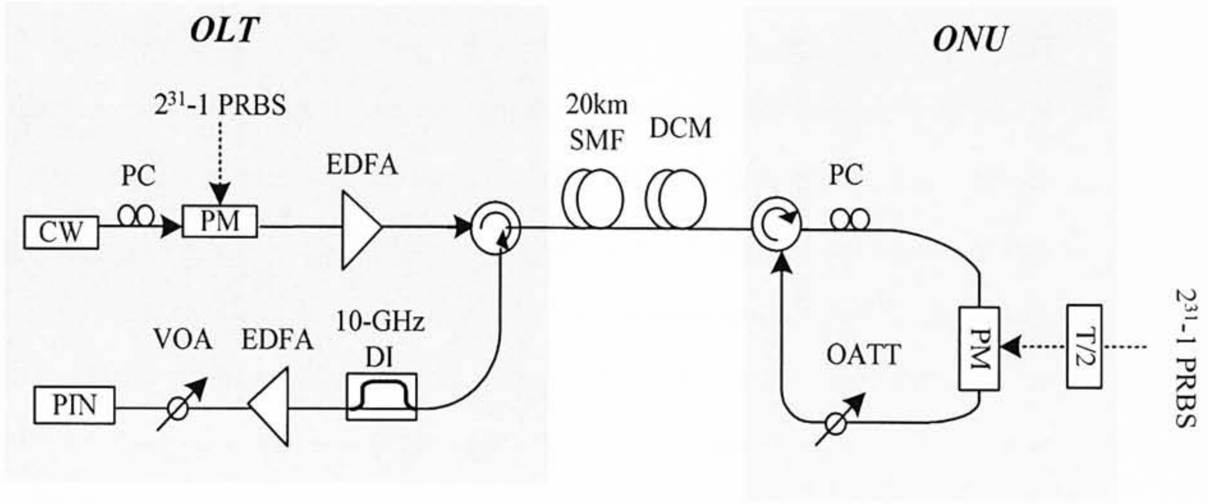


Fig.4.5. Experimental setup. ATT: optical attenuator.

According to previous studies, the value of RB is approximate ~ -33 dB lower than power of downstream light, so in the analysis SCR is calculated by following equation:

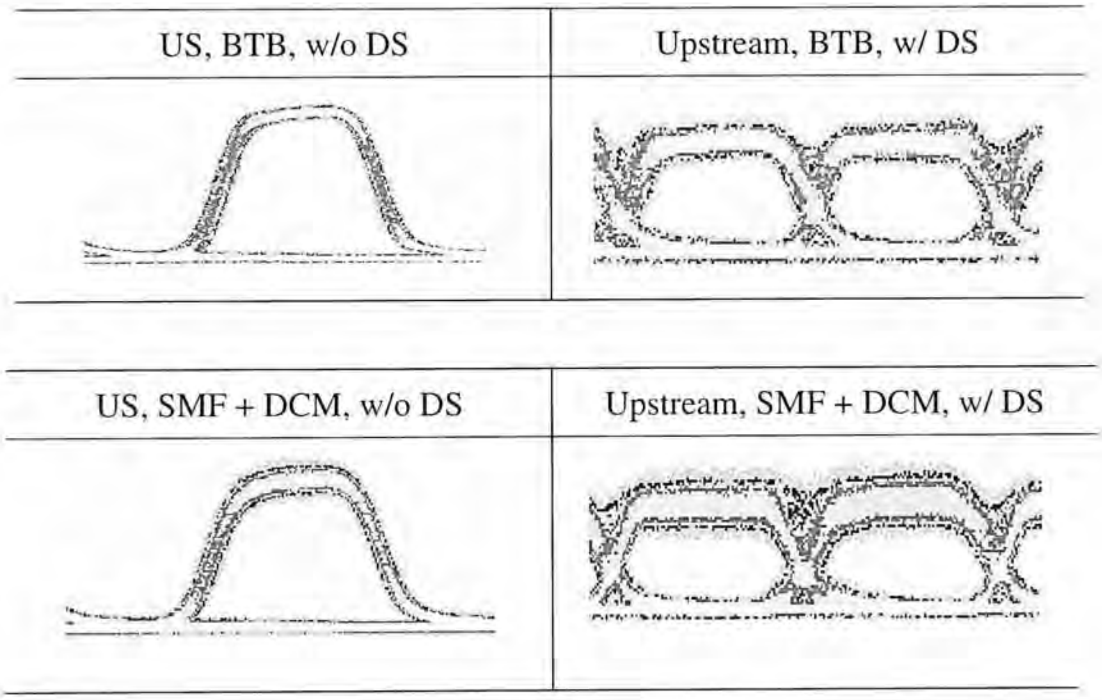
$$\text{SCR (dB)} = P_{upstream} - (P_{downstream} - 33\text{ dB})$$

When the power of downstream light is fixed, corresponding power of upstream light can be calculated. The power variance of upstream signal can be achieved by tuning optical attenuator. The proposed remodulation scheme was examined under different SCR values. Experimental results are depicted in Fig.4.2 (a) and (b) with eye diagrams and Fig.4.2 (c) with receiver sensitivities when SCRs were set at different values.

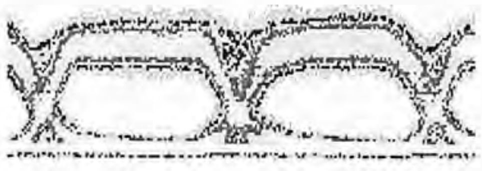
When SCR remained in a high value, as discussed in Chapter 3, negligible distortion was observed on upstream signal after transmission. This can be verified by the clear eye diagrams in Fig.4.2 (a). Compared to the case using 5Gb/s NRZ-OOK signal that error floor was seen when SCR was around 23 dB, eyes of upstream signal on the trailing half bits widely opened in our proposed remodulation scheme, indicating enhanced tolerance to RB crosstalk.

Fig.4.2 (b) shows that although the eyes kept open, upstream signal degraded as

RB crosstalk went larger, with obvious noise on both marks and spaces. To accurately analyze RB tolerance of the proposed remodulation scheme, receiver sensitivities of upstream signal with different SCRs were evaluated experimentally and were plotted in Fig.4.2 (c). Receiver sensitivity, when SCR was tuned to the maximum value without amplification in ONU (23-dB in the experiment), was set to be the reference value when calculating power penalty. According to the results, when SCR was larger than 20 dB, penalties of receiver sensitivity stayed within 1 dB, following a drastically degradation while SCR decreased. When SCR fell below 18-dB, BER of 10^{-9} could not be achieved and error floor was observed in the experiment.



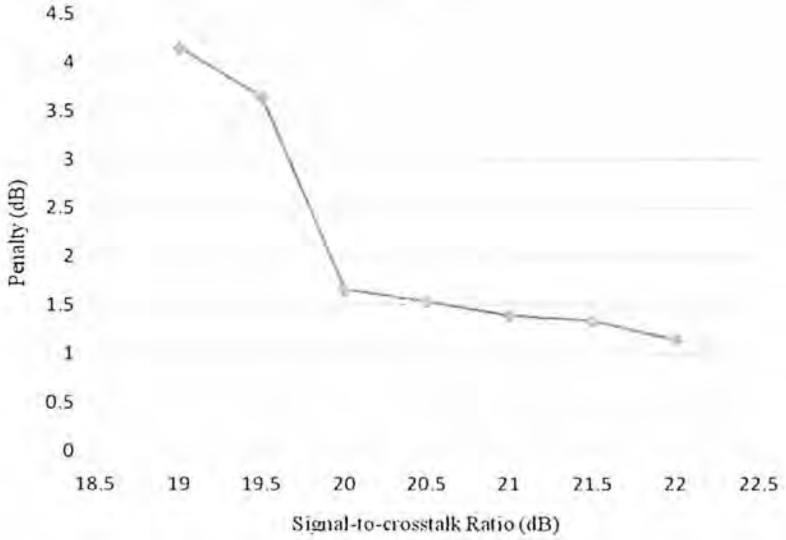
(a)

SCR	22 dB	21 dB
		

SCR	20 dB	19 dB
		

SCR	18 dB
	

(b)



(c)

Fig.4.6. Eye diagrams of (a) upstream signal when SCR was ~23 dB and (b) upstream signals (US) in different SCRs. (c) Receiver sensitivity versus different SCRs. DS: downstream; US: upstream; BTB: back-to-back.

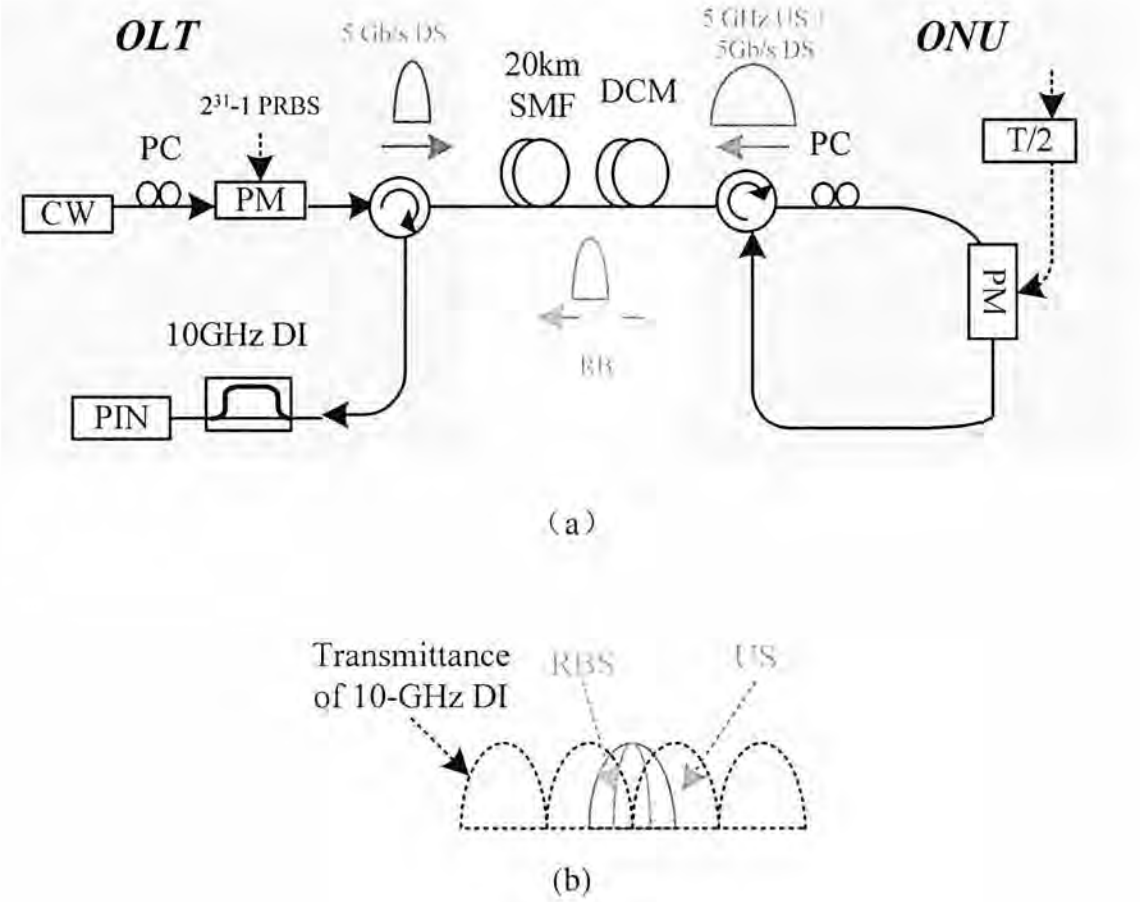
4.3 Discussion on RB suppression effect of the proposed scheme

4.3.1 Theoretical study and simulation results

The reason why our proposed remodulation scheme using time-interleaved DPSK format could be explained by the reduction of spectral overlapping from which notch filtering benefited a lot to achieve RB removing while maintaining most spectral information of upstream signal. Fig.4.3 (a) illustrates the spectra of downstream and upstream signals as well as that of RB. It can be seen that, different from the remodulation scheme which directly remodulate upstream signal with DPSK format without T/2 offset on the coming light source, resulting in phase modulated signal carrying only the XOR of downstream and upstream data, in the proposed remodulation scheme, transmitted upstream signal is actually the combination of downstream and upstream data, forming a 10-Gb/s time-interleaved signal. Thus the spectrum of upstream signal (colored purple) is broadened by a factor of 2 approximately compared to the case that only 5-Gb/s upstream signal is modulated. At the same time, the spectrum of downstream signal (colored green) is still the one of a 5-Gb/s PRBS data modulated with conventional DPSK format, indicating that the spectrum of RB crosstalk (colored blue) caused by downstream data propagating through the transmission line is narrower than that of upstream signal. And then, the overlapping between signal and crosstalk becomes smaller. The notch-filter like transmittance of 10-GHz DI using destructive port also contributed to the improvement on RB tolerance. Compared to 5-GHz DI, more portion of RB could be filtered out through notch filtering with a larger filtering bandwidth by using a 10-GHz DI.

Fig.4.3 (b) sketched the notch filtering effect at destructive port of DI. Reduced overlapping enables filtering of more RB spectrum, and most portions of signal spectral components lies in the pass-band of destructive port of 10-GHz DI at OLT.

allowing elimination of RB noise. Fig.4.4 (a) and (b) demonstrates simulation results of optical spectrums of downstream and upstream signals respectively after passing through 10-GHz DI. It is clear that the spectrum width of upstream time-interleaved-DPSK signal is about two times larger than 5-Gb/s downstream DPSK signal.



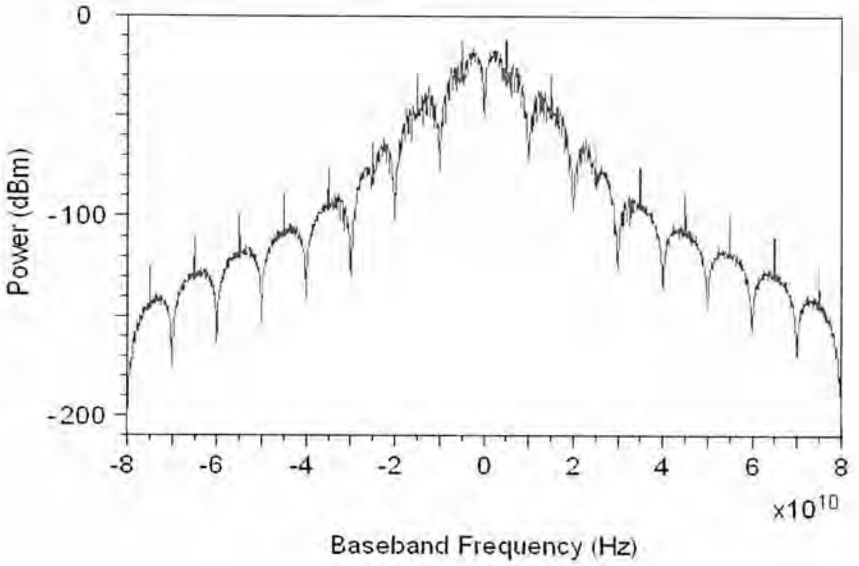
(a)

(b)

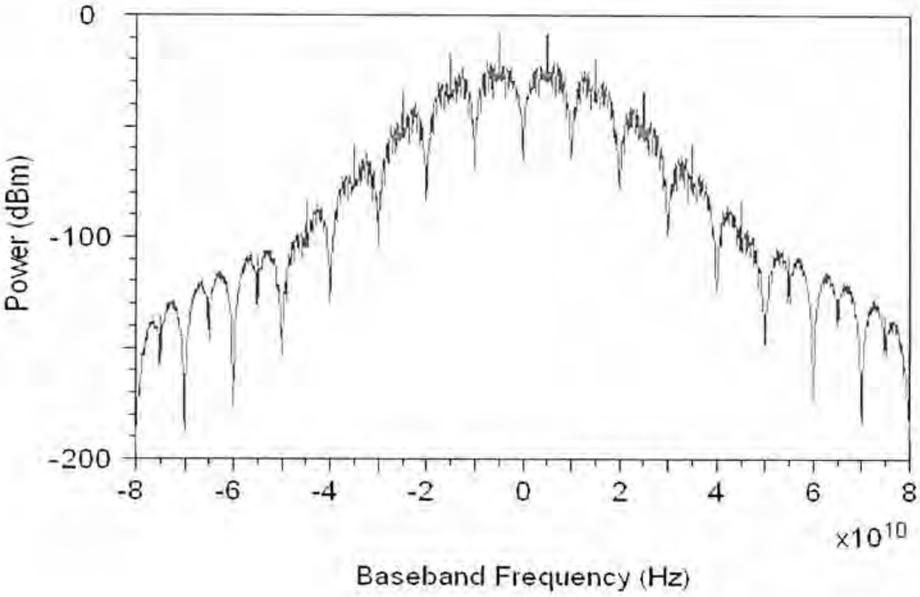
Fig.4.7. Schematic illustration of (a) different signal spectra and (b) notch filtering effect (dashed line: destructive port transmittance of 10-GHz DI) in the proposed remodulation scheme. DS: downstream; US: upstream; RB: Rayleigh backscattering.

This method of RB suppression has some similarities to [41] and [46]. [41] tried to narrow the spectrum of RB noise by compressing the spectrum of downstream signal, and RMD-DPSK was an efficient solution since it achieved spectrum-compression and the demodulated DPSK signal at ONU still remained in high ER. The implementation was simple; however, DI at ONUs must be carefully tuned for demodulation of RMD-DPSK, as its narrow spectrum implied accurate placement of optical filter. [47] used a low-frequency sinusoidal signal to phase-modulate upstream IM data, thus the spectrum of upstream signal sent into transmission line was separated into two sidebands thus was broadened. This phase modulation was carried out in the ONU at a unique frequency and set modulation index. Dummy information (sinusoidal signal in [47]) was added for spectral broadening which introduced unwanted extra cost at ONUs.

Our proposed remodulation scheme advantaged itself for spectrum broadening without introducing additional dummy data, since it was done naturally by downstream signal which was not erased during remodulation process. The implementation was also simple (only one low-cost *T/2* time delay was added in each ONU), while maintaining robust transmission performance and *T/4* timing misalignment tolerance demonstrated in Chapter 3. Furthermore, RB crosstalk in bidirectional transmission could be sufficiently suppressed at the same time by reducing spectral overlapping. However, since the transmitted data contained both downstream and upstream DPSK signal, the CD tolerance was brought down as a sacrifice to obtain RB tolerance enhancement, so a dispersion compensation module was introduced in the proposed scheme to compensate CD distortion. Besides, requirement on the rising and falling time of electrical signal is comparably rigid in our proposed remodulation scheme to guarantee upstream data is accurately placed in halves of bits without distortion introducing by downstream data.



(a)



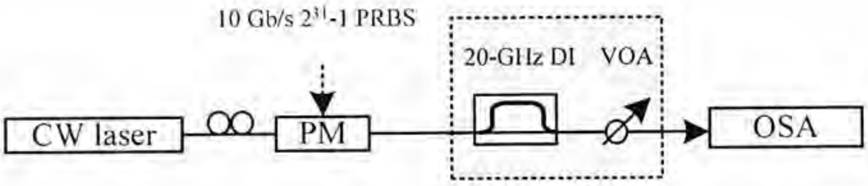
(b)

Fig.4.8. Simulation results of optical spectrums of (a) downstream and (b) upstream signal after DI.

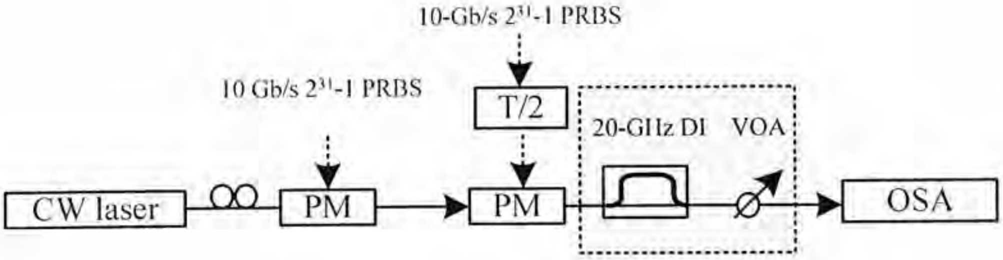
4.3.2 Experimental demonstration of spectral relationship between signals and RB crosstalk

Experimental investigation has been carried out to verify the analysis on RB suppression effect in 4.3.1. The experimental setup is illustrated in Fig.4.5 (a) and (b).

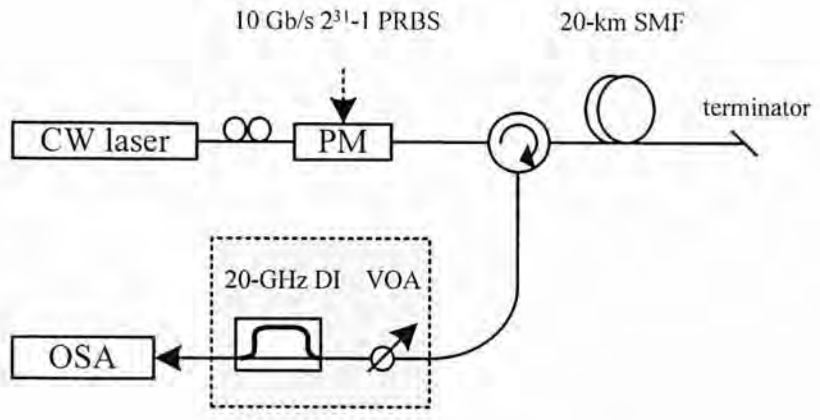
Although 10-Gb/s PRBS data was used for downstream and upstream modulation due to limitations of equipments, it can still derive persuasive and reasonable conclusion for our investigation under the same operation principle. We separately recorded the spectra of downstream signal, upstream signal and RB noise during transmission for comparison. Since distortion due to dispersion was compensated by DCM in our proposed remodulation scheme, upstream time-interleaved signal can be considered equivalent to the one obtained by directly modulate the downstream signal without transmission. In terms of RB crosstalk observation, a 20-km SMF was used as the transmission line, and RB noise caused by downstream 10-Gb/s signal was directed to an optical spectrum analyzer (OSA), whose resolution was 0.06 nm, by an optical circulator. Spectral relationships of downstream signal, upstream signal and RB noise is depicted in Fig. 4.6. In order to compare the signal spectra of different power values (power of RB noise can be ~33-dB lower than that of signals), downstream and upstream signals were manually attenuated. A 20-GHz DI was used for demodulation.



(a) Spectrum analysis of downstream signal.



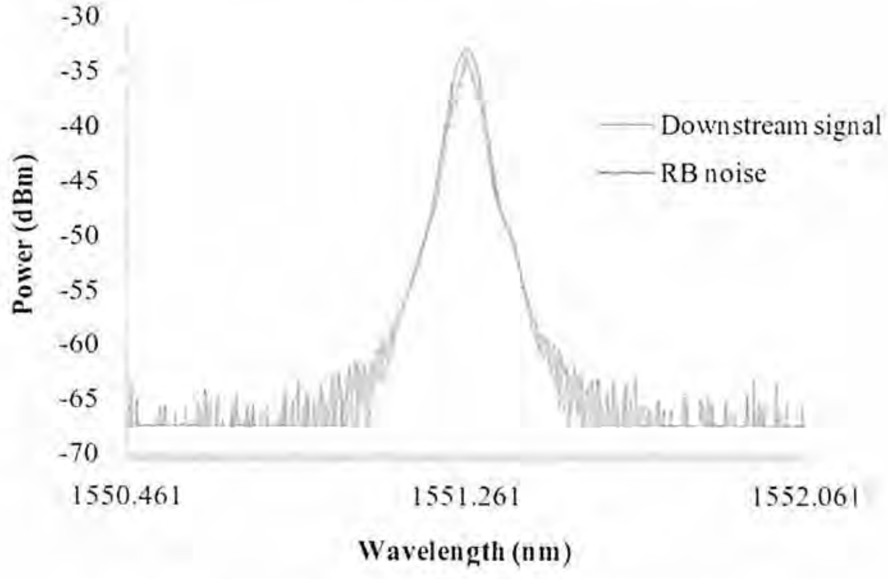
(b) Spectrum analysis of upstream signal.



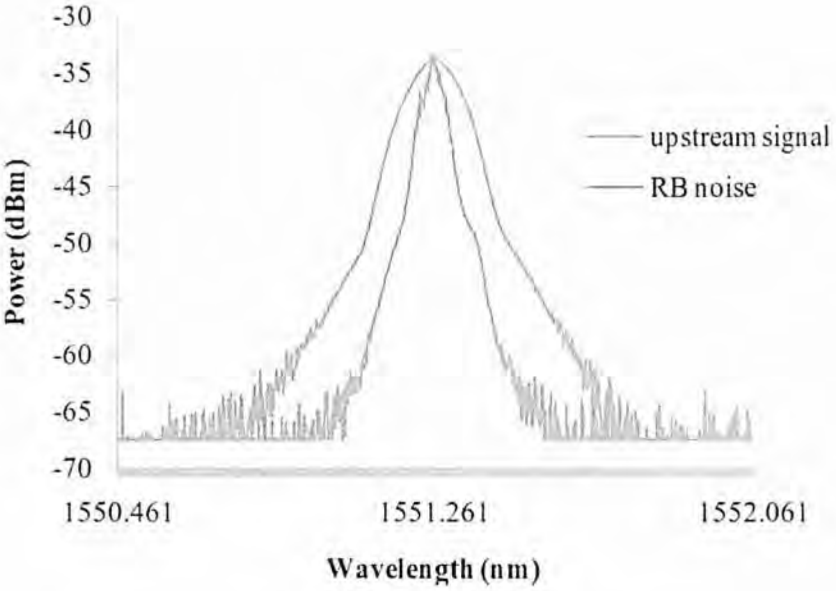
(c) Spectrum analysis of RB noise.

Fig.4.9. Experimental setup for spectrum analysis.

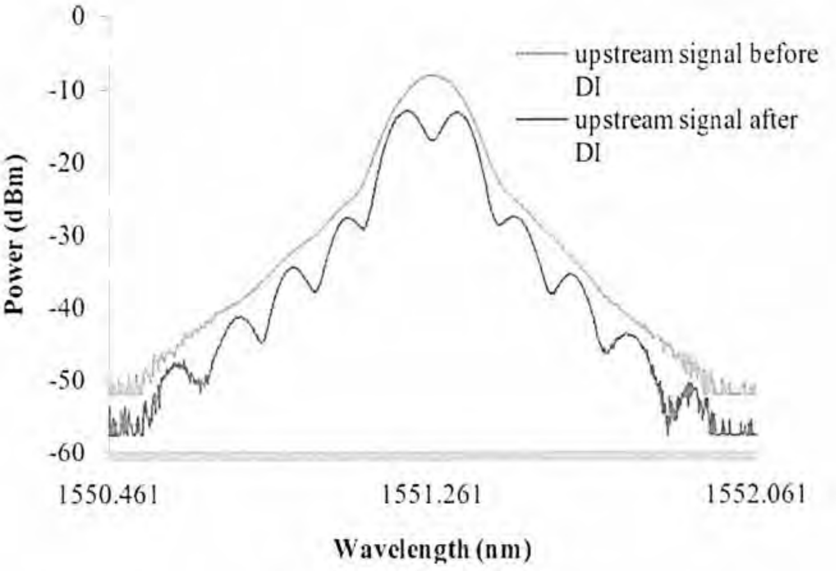
In Fig. 4.6 (a) and (b), it can be clearly seen that spectrum of RB noise is similar to that of downstream signal, and is narrower than that of upstream signal before entering DI, indicating a match to the theoretical analysis in 4.3.1. RB suppression can be observed by comparing spectra in Fig. 4.6 (c) and (d). It shows that DI with half-bit delay has ~15-dB suppression of RB noise, while relatively smaller loss due to notch filtering was observed on upstream signal (around 6 dB), implying strong RB crosstalk suppression with slight distortion on upstream signal.



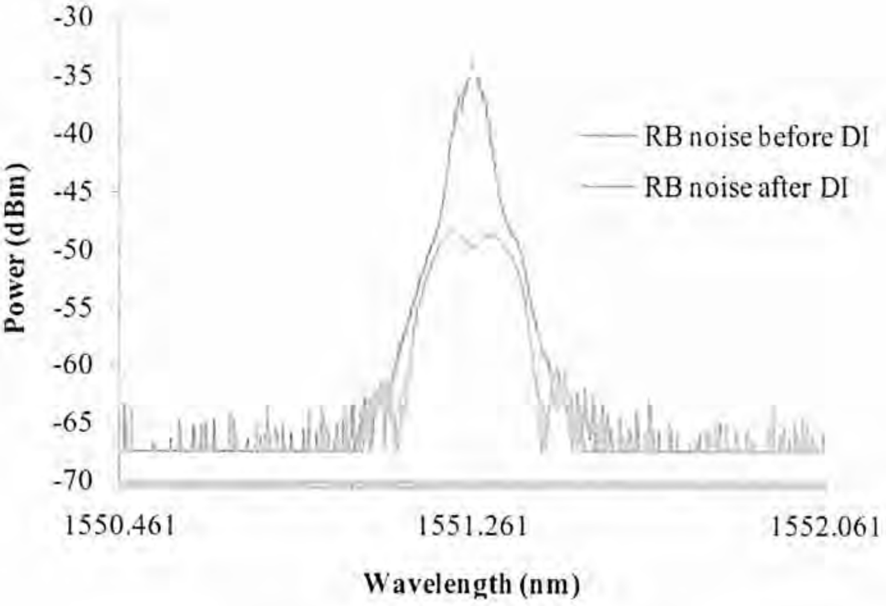
(a) Spetra of downstream signal and RB noise.



(b) Spectra of upstream signal and RB noise.



(c) Spectra of upstream signal before and after DI.



(d) Spectra of RB noise before and after DI.

Fig.4.10. Spectral relationships of downstream signal, upstream signal and RB noise before and after DI.

4.4 Summary

RB tolerance of our proposed remodulation scheme has been studied in this chapter, with demonstration of eye diagrams and receiver sensitivity variance when SCR was set to different values. The proposed remodulation scheme showed enhanced RB tolerance with degradation less than 1 dB for SCR between 19 dB and 23 dB. However, when the RB noise continuously increased, error floor appeared in BER evaluation, indicating severe crosstalk interference.

Discussion has been carried out to explain the reason of this tolerance enhancement by illustrating spectrum relationship between downstream, upstream and RB signals. Upstream signal has a broadened spectrum compared to downstream signal because of our proposed time-interleaved remodulation method. Thus, the spectral overlapping between RB noise and signal is efficiently reduced, from which optical notch filtering by destructive port of DI in the following step will benefit. Comparison has been made between relevant reports in remodulation scheme focusing on RB suppression by reducing spectral overlapping and optical notch filtering. Advantages and drawbacks of our proposed remodulation scheme have been discussed through this comparison.

Chapter 5 Conclusion and Future Works

5.1 Conclusion of this thesis

This thesis comprises two parts, one for background introduction and review of previous work, and another for investigation and discussion of the proposed remodulation scheme using time-interleaved DPSK modulation format. In the review session, firstly an introduction to the architecture of optical communication network has been made. Among the candidates of next generation optical access networks, WDM-PON is a promising choice because the network capacity can be drastically increased by carrying independent data on different wavelengths. Moreover, it can be implemented by upgrading currently-used TDM-PON architecture.

One of the most challenging issues on the implementation of WDM-PON is the cost of optical components for individual ONUs, so network architectures with fewer components while preserving excellent transmission performance and network flexibility are highly desired. Colorless ONU is one of the solutions to fulfill these requirements. Previous works on colorless ONU are categorized into 3 types, i.e. wavelength-tunable scheme, carrier-distributed scheme and remodulation scheme.

Among these three candidates, remodulation scheme can greatly cut down the cost by reusing downstream light source. Devices and modulation formats used in remodulation schemes have been discussed in chapter 2. Three devices were reviewed as candidates for different operation data rates, i.e. injection-locked FP-LD, RSOA and REAM-RSOA, with demonstrations on operation principle and analysis on respective pros and cons. Previous studies on modulation methods in remodulation scheme were also review by explicating operation principles and corresponding characteristics in transmission and at receiving ends.

To construct an efficient colorless ONU based on the reuse of downstream light sources, we proposed a remodulation method utilizing DPSK format for both downstream and upstream signals with proper time interleaving. The operation principle and system architecture were illustrated at first. In our experimental demonstration, successful demodulation of 5-Gb/s upstream signal has been achieved without erasure of 5-Gb/s downstream signal. The transmission performance after 20-km SMF and DCM was evaluated as well as 5-Gb/s conventional NRZ-OOK remodulation scheme as a comparison. Receiver sensitivity degradations of downstream and upstream signals were observed to be within ~0.5 dB and ~0.8 dB respectively in our proposed scheme, indicating resilient transmission performance. Timing misalignment between downstream and upstream data caused distortion on upstream signal after demodulation since correct demodulation at OLT depended on proper time delay placing upstream signal on halves of bits. The effect of timing misalignment was experimentally studied, and we reported timing-misalignment tolerance of ±25 ps ($\pm T/8$) for 3-dB degradation on receiver sensitivity.

RB tolerance of the proposed remodulation scheme was mainly discussed in chapter 4. Compared to eye diagrams and BER curves of remodulation scheme using conventional DPSK format for downstream modulation and NRZ-OOK format for upstream modulation, it could be clearly seen that our proposed scheme enhanced system tolerance toward in-band RB noise. This enhancement was experimentally investigated in detail with theoretical analysis on its reason. Comparison between the proposed scheme and previous work with similar operation principle was made.

5.2 Future works

As stated in chapter 2, network ability of supporting 10-Gb/s bidirectional transmission is desired for future WDM-PON. In our experiment, 5-Gb/s PRBS data was used for downstream and upstream transmission. We chose this operation speed since the bandwidth of BER tester used in our experiment was 12.5-GHz, which could not be used for the demodulation if the data rate was further increased. This experiment has possibility to be demonstrated with 10-Gb/s data rate for both downstream and upstream signals if a robust BER tester with larger bandwidth is used to evaluate the BER performance.

The remodulation process of DPSK signal at each ONU was done by using a conventional PM in our experiment, which increased the total cost of network. In addition, the polarization state of input light had to be carefully adjusted to achieve maximum optical power at the output of PM, introducing instability to the network. Nowadays, DPSK modulation has been successfully demonstrated via RSOA, showing potential of low-cost utilization. It is a polarization-insensitive device, thus not extra stage for polarization controlling is required during remodulation. If RSOA can be used in ONU, our proposed remodulation scheme can probably be a more practical colorless-ONU solution with the characteristics stated above. Further investigation on RB noise suppression in the proposed scheme is worth detailed study in the future both theoretically and experimentally, including investigation on the maximum transmission distance of the proposed scheme with amplifier at ONU, and a more specific mathematical deduction of RB noise caused by downstream transmission.

In chapter 4, we mentioned that the distortion due to chromatic dispersion is a drawback of the proposed remodulation scheme because the spectrum of upstream data is broadened. DCM is a simple solution to recover upstream signal from CD distortion, but it introduces extra loss in the transmission line, which is more severe in bidirectional transmission. Since CD distortion is a linear degradation, efforts can be done on pre-chirping and electronic equalization to further improve power budget of the whole system.

Back to the operation principle of our proposed scheme, time interleaving technology keeps downstream information on the remodulated upstream signal, implying ability of realizing broadcast and multicast functions. In [42] broadcast function has been successfully demonstrated in a 5-Gb/s bidirectional transmission scenario of DPSK downstream and broadcast signal. Research of time interleaving DPSK modulation format can also be extended to higher data rate in long-haul transmission system. Further efforts can be done to add broadcast information to multi-channel signals via all-optical approach.

List of Publications

[1] Pulan Li, Jing Xu and Lian-Kuan Chen, "A novel phase remodulation scheme in WDM-PON with enhanced tolerance to Rayleigh Backscattering," *Opto-Electronics and Communications Conference 2011 (OECC'11)*, 5A4_3, 2011.

Bibliography

[1] Rajiv Ramaswami, Kumar N. Sivarajan, "Optical Networks: A practical Perspective (second edition)", Margan Kaufmann publishers, Academic Press, 2002.

[2] F. Payoux, P. Chanclou, and G. Naveena, "WDM-PON with colorless ONUs,", *IEEE/OSA Optical Fiber Communication Conference / National Fiber Optic Engineers Conference (OFC/NFOEC)*, paper OTuG5, 2007.

[3] Katsumi Iwatsuki, Junichi Kani, Hiro Suzuki, and Masamichi Fujiwara, "Access and metro networks based on WDM technologies", *IEEE J. Lightwave Technol.*, vol.22, no.11, pp.2623-2630, 2004.

[4] Suzuki, H., Fujiwara, M., Suzuki, T., Yoshimoto, N., Kimura, H., Tsubokawa, M, "Demonstration and performance of colorless ONU for coexistence-type WDM-PON using a wavelength-tunable L-Band DWDM-SFP transceiver", *IEEE Photon. Technol. Lett.*, vol. 20, no. 19, pp.1603-1605, 2008.

[5] K. Akimoto, J. Kani, M. Teshima, and K. Iwatsuki, "Gigabit WDM-PON system using spectrum-slicing technologies," *European Conference on Optical Communications (ECOC)*, Paper Th2.4.6, 2003.

[6] M. Zirngibl, et al., "Study of spectral slicing for local access applications", *IEEE Photon. Technol. Lett.*, vol.8, pp.721-723, 1996.

[7] Bo Zhang, Chinlon Lin, Li Huo, Zhaoxin Wang, and Chun-Kit Chan, "A simple high-speed WDM-PON utilizing a centralized supercontinuum broadband light source for colorless ONUs", *IEEE/OSA Optical Fiber Communication Conference / National Fiber Optic Engineers Conference (OFC/NFOEC)*, paper OTuC6, 2006.

[8] Wai Hung, Chun-Kit Chan, Lian-Kuan Chen, and Frank Tong, "An optical network unit for WDM access networks with downstream DPSK and upstream remodulated OOK data using injection-locked FP laser", *IEEE Photon. Technol. Lett.*, vol. 15, no. 10, pp.1476-1478, 2003.

[9] Takesue, H., Sugie, T., "Wavelength channel data rewrite using saturated SOA modulator for WDM networks with centralized light sources", *IEEE J. Lightwave Technol.,* vol.21, no.11, pp.2546-2556, 2003.

[10] J. J. Koponen and M. J. Soderlund, "A duplex WDM passive optical network with 1:16 power split using reflective SOA remodulator at ONU", *IEEE/OSA Optical Fiber Communication Conference / National Fiber Optic Engineers Conference (OFC/NFOEC)*, paper MF99, 2004.

[11] Garreau, A., Decobert, J., Kazmierski, C., et al., "10Gbit/s amplified reflective electroabsorption modulator for colorless access networks", *International Conference on Indium Phosphide and Related Materials*, paper TuA2.3, 2006.

[12] Russell Ellis, "Explanation of reflection features in optical fiber as sometimes observed in OTDR measurement traces", *Corning white paper*, May 2007.

[13] Masataka Nakazawa, "Rayleigh backscattering theory for single-mode optical fibers", *Journal of Optical Society of America,* vol. 73, No.9, 1983.

[14] K.Rajagopal, "Textbook on Engineering Physics", part I, Chapter 3, PHI, New Dehli, 2008.

[15] Banchi, L., Corsini, R., Presi, M., Cavaliere, F.and Ciaramella, E., "Highly improved uplink transmission in bidirectional PONs by using a RZ direct-modulated R-SOA ", *European Conference on Optical Communications (ECOC),* paper Mo.1.B.4, 2010.

[16] C. F. Marki, F. A. Marki and S. C. Esener, "Reduction of interferometric opticalcrosstalk penalty via DC blocking", *IEEE Electr. Lett.*, vol.43, no.11, pp.644, 2007.

[17] A. Chiuchiarelli, et al., "Enhancing resilience to Rayleigh crosstalk by means of line coding and electrical filtering", *IEEE Photon. Technol. Lett.,* vol.22, no.2, pp.85-87, 2010.

[18] Josep Prat, "Rayleigh Back-scattering reduction by means of quantized feedback equalization in WDM-PONs", *European Conference on Optical Communications (ECOC),* paper Th.10.B.3, 2010.

[19] T. Yoshida, S. Kimura, H. Kimura, K. Kumozaki, and T. Imai, "A new

single-fiber 10-Gb/s optical loopback method using phase modulation for WDM optical access networks", *IEEE J. Lightwave Technol.*, vol. 24, no. 2, pp. 786–796, Feb. 2006.

[20] Hoon Kim, "10-Gb/s Operation of RSOA Using a Delay Interferometer", *IEEE Photon. Technol. Lett.*, vol.22, no.18, pp.1379-1381, 2010.

[21] L. Y. Chan, C. K. Chan, T. K. Tong, S.Y. Cheung, F. Tong, and L. K. Chen , "Demonstration of data remodulation for upstream traffic in WDM access networks using injection-locked FP laser as modulator", *IEEE/OSA Optical Fiber Communication Conference / National Fiber Optic Engineers Conference (OFC/NFOEC)*, Paper WU5-1, 2001.

[22] Moon-Ki Hong, Yong-Yuk Won, and Sang-Kook Han, "Simultaneous bidirectional gigabit hybrid transmission system using optical carrier suppression in dual-parallel injection-locked FP-LDs", *European Conference on Optical Communications (ECOC)*, paper We.2.F.6, 2008.

[23] Kwon, H.-C., Won, Y.-Y., and Han, S.-K., "Bidirectional SCM transmission using a noise-suppressed Fabry–Pérot laser diode and a reflective semiconductor optical amplifier in a WDM/SCM-PON link", *IEEE Photon. Technol. Lett.*, vol.19, no.11, pp.858-860, 2010.

[24] C. H. Yeh, C. W. Chow, F. Y. Shih, C. H. Wang, Y. F. Wu, and S. Chi, "Wavelength-tunable laser for signal remodulationin WDM access networks using DPSK downlink and OOK uplink", *IEEE Photon. Technol. Lett.*, vol.21, no.22, pp.1710-1712, (2009).

[25] Wooram Lee, Seung Hyun Cho, MahnYong Park, Jie Hyun Lee, Chulyoung Kim, Geon Jeong, and Byoung Whi Kim, "Frequency detuning effects in a loop-back WDM-PON employing gain-saturated RSOAs", *IEEE Photon. Technol. Lett.*, vol.18, no.13, pp.1436-1438, 2006.

[26] Josep Prat, "Highly improved uplink transmission in bidirectional PONs by using a RZ direct-modulated RSOA", *European Conference on Optical Communications (ECOC)*, paper Mo.1.B.4, 2008.

[27] S. P. Jung, Y. Takushima and Y. C. Chung , "Generation of 5-Gbps QPSK signal

using directly modulated RSOA for 100-km coherent WDM PON", *IEEE/OSA Optical Fiber Communication Conference / National Fiber Optic Engineers Conference (OFC/NFOEC)*, Paper OTuB3, 2011.

[28] M. Omella, V. Polo, J. Lazaro, B. Schrenk and J. Prat, "10 Gb/s RSOA transmission by direct duobinary modulation", *European Conference on Optical Communications (ECOC)*, paper Tu.3.E.4, 2008.

[29] S. P. Jung, Y. Takushima and Y. C. Chung, "Transmission of 1.25-Gb/s PSK signal generated by using RSOA in 110-km coherent WDM PON," *Optics Express*, vol. 18, pp. 14871-14877, 2010.

[30] Christophe Kazmierski, "Remote amplified modulators: key components for 10 Gb/s WDM-PON", *IEEE/OSA Optical Fiber Communication Conference / National Fiber Optic Engineers Conference (OFC/NFOEC)*, Paper OWN6, 2010.

[31] B. Ftaich-Frigui, C. Aupetit-Berthelemot, A.Belhouji, M. Mouhamadou, C. Kazmierski, "Use of a reflective electro-absorption modulator and semiconductor optical amplifier for converged wireless over fiber access networks", *European Conference on Optical Communications (ECOC)*, paper Th.10.B.5, 2010.

[32] Q. T. Nguyen, G. Vaudel, O. Vaudel, L. Bramerie, P. Besnard, A. Garreau, C. Kazmierski, A. Shen, G.H. Duan, P. Chanclou, J.-C. Simon, "Multi-functional R-EAM-SOA for 10-Gb/s WDM Access", *IEEE/OSA Optical Fiber Communication Conference / National Fiber Optic Engineers Conference (OFC/NFOEC)*, Paper OThG7, 2011.

[33] C. H. Wang, F. Y. Shih, C. W. Chow, C. H. Yeh, and S. Chi, "Using downstream DPSK signal for upstream OOK signal remodulation with RSOA in hybrid WDM-TDM passive optical networks", *IEEE/OSA Optical Fiber Communication Conference / National Fiber Optic Engineers Conference (OFC/NFOEC)*, Paper JWA73, 2009.

[34] Jian Zhao, Lian-Kuan Chen, Chun-Kit Chan, "A Novel re-modulation scheme to achieve colorless high-speed WDM-PON with enhanced tolerance to chromatic

dispersion and re-modulation misalignment", *IEEE/OSA Optical Fiber Communication Conference / National Fiber Optic Engineers Conference (OFC/NFOEC)*, Paper OWD2, 2007.

[35] L.Xu and H.K.Tsang, "WDM-PON using differential-phase-shift-keying remodulation of dark return-to-zero downstream channel for upstream", *IEEE Photon. Technol. Lett.*, vol.20, no.10, pp.833-835, 2008.

[36] Ning Deng, Chun-Kit Chan, Lian-Kuan Chen and F.Tong, "Data remodulation on downstream OFSK signal for upstream transmission in WDM passive optical network", *IEEE Electr. Lett.*, vol.39, no.24, 2003.

[37] Guo-Wei Lu, Ning Deng, Chun-Kit Chan, Lian-Kuan Chen, "Use of downstream inverse-RZ signal for upstream data remodulation in a WDM passive optical network", *IEEE/OSA Optical Fiber Communication Conference / National Fiber Optic Engineers Conference (OFC/NFOEC)*, Paper OFI8, 2005.

[38] B.K. Kim, H. Park, S. Park and K. Kim, "Optical access network scheme with downstream Manchester coding and upstream NRZ remodulation", *IEEE Electr. Lett.*, vol.42, no.8, 2006.

[39] Natasa B. Pavlovic, Liliana N. Costa and Antonio L.J. Teixeira, "SSB NRZ and SSB Manchester downstream signals for remodulated extended reach WDM-TDM PONs", *European Conference on Optical Communications (ECOC)*, paper P6.26, 2009.

[40] C. W. Chow, Y. Liu and C. H. Kwok, "Signal remodulation with high extinction ratio 10-Gb/s DPSK signal for DWDM-PONs", *IEEE/OSA Optical Fiber Communication Conference / National Fiber Optic Engineers Conference (OFC/NFOEC)*, Paper OThT2, 2008.

[41] Jing Xu and Lian-Kuan Chen, "Optical phase remodulation for 10-Gb/s WDM-PON with enhanced tolerance to Rayleigh noise", *IEEE/OSA Optical Fiber Communication Conference / National Fiber Optic Engineers Conference (OFC/NFOEC)*, Paper OThG3, 2010.

[42] J. Xu, Z.X. Liu, L.K. Chen, C.K. Chan, "Time-interleaved phase remodulation to enable broadcast transmission in bidirectional WDM-PONs without additional

light sources", *IEEE/OSA Optical Fiber Communication Conference / National Fiber Optic Engineers Conference (OFC/NFOEC)*, Paper OThK4, 2010.

[43] Guo-Wei Lu, Tetsuya Miyazaki, "A spectrum-efficient 80-Gbit/s DPSK transmitter using phase interleaving technology without optical-time or polarization-division multiplexing", *IEEE Lasers and Electro-Optics Society (LEOS) Summer Topical Meetings*, paper TuE3.4, 2007.

[44] Guo-Wei Lu, Kazi Sarwar Abedin, andTetsuy a Miyazaki, "Experimental demonstrations of all-optical phase-multiplexing using FWM-based phase interleaving in silica and bismuth-oxide HNLFs", *IEEE J. Lightwave Technol., vol.27, no.4, pp.409-416, 2009.*

[45] Louis Christen, Yannick K. Lize, Narender Jayachandran, Scott Nuccio, Poorya Saghari , Alan E. Willner, Loukas Paraschis, "Receiver-based temporal pulse carving of DPSK bits for 20 Gbit/s time-multiplexed and time-interleaved systems", *European Conference on Optical Communications (ECOC)*, 2006.

[46] Tomoaki Yoshida, Shunji Kimura, Hideaki Kimura, Kiyomi Kumozaki, and Takamasa Imai , "A new single-fiber 10-Gb/s optical loop back method using phase modulation for WDM optical access networks", *IEEE J. Lightwave Technol.*, vol.24, no.2, pp.786-796, 2006.

[47] Arshad Chowdhury, et al., "Rayleigh Backscattering noise-eliminated 115-km long-reach bidirectional centralized WDM-PON with 10-Gb/s DPSK downstream and remodulated 2.5-Gb/s OCS-SCM upstream signal", *IEEE Photon. Technol. Lett.*, vol.20, no.24, pp.2081-2083, 2008.

[48] Gianluca Berrettini, Gianluca Meloni, Luca Giorgi, Filippo Ponzini, Fabio Cavaliere, Pierpaolo Ghiggino, Luca Potì, and Antonella Bogoni, "Colorless WDM-PON architecture for Rayleigh backscattering and path-loss degradation mitigation", *IEEE Photon. Technol. Lett.*, vol.21, no.7, pp.453-455, 2009.

[49] Josep Prat, Mireia Omella and Victor Polo, "Wavelength shifting for colorless ONUs in single-fiber WDM-PONs", *IEEE/OSA Optical Fiber Communication Conference / National Fiber Optic Engineers Conference (OFC/NFOEC)*, Paper OTuG6, 2007.

[50] Cristina Arellano, et al., "Bidirectional single fiber transmission based on a RSOA ONU for FTTH using FSK-IM modulation formats", *IEEE/OSA Optical Fiber Communication Conference / National Fiber Optic Engineers Conference (OFC/NFOEC)*, Paper JWA46, 2005.