Wavelength division multiplexed passive optical networks with colorless light sources

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Wavelength Division Multiplexed Passive Optical Networks With Colorless Light Sources

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Summary

The emerging internet services need the future passive optical networks (PONs) to provide considerably increased capacity for subscribers. Wavelength division multiplexed (WDM) PON is expected to be the ultimate solution since dedicated wavelengths are assigned to each end user. The main objectives of this thesis are to investigate and propose novel low-cost colorless light sources and novel architectures for WDM-PONs supporting high data rates.

Firstly, the thesis studies the characteristics of injection-locked FP-LDs and their applications in WDM-PON. A 10-Gb/s light source using coherent light injection-locked FP-LDs is proposed. It is expected to be cost-effective, because the coherent seeding lights are shared by many WDM-PONs and low-cost FP-LDs are used as uplink modulator. Performance evaluations in terms of injection power, injected mode selection, wavelength detuning and transmission distance are investigated. It is demonstrated that up to 16 cavity modes of FP-LD can be selected for injection-locking, which shows the feasibility of colorless operation. The coherent light injection-locked FP-LD can also be extended to applications in long-reach WDM-PONs and metropolitan optical networks with proper dispersion compensation.

Secondly, the characteristics of the spectrum-sliced amplified spontaneous emission (ASE) source injection-locked FP-LD in WDM-PON are studied. Results show that the transmission performance of ASE injection-locked FP-LD can be enhanced with optimum ASE bandwidth and proper facet reflectivity and operation conditions of the FP-LD. Using an SOA to suppress the intensity noise of the ASE can also improve the

transmission performance.

Thirdly, downstream subcarrier transmission and carrier remodulation for upstream can effectively avoid the two-wavelength arrangement for each user. But the filter at each ONU to separate the closely spaced optical carrier and subcarriers is costly for practical implementation. In this thesis, a single shared interferometric filter located at the remote node (RN) to separate optical carriers and subcarriers for all users is proposed, which leads to considerable cost reduction in the deployment of WDM-PONs. Based on this idea, two novel carrier-reuse WDM-PON architectures using wavelength-seeded RSOAs have been proposed and experimentally investigated. Architecture I is suitable for the situation where there are two short distribution fibers between the RN and each ONU, while Architecture II is designed for the case where only one distribution fiber is available. Two multi-channel transmission experiments with 1.25-Gb/s data rate for both downlink and uplink are carried out to demonstrate the feasibility of the proposed schemes. Furthermore, the impact of optical carrier to subcarrier ratio (OCSR) of the subcarrier modulated (SCM) light, Rayleigh-backscattering (RB) noise and wavelength mismatch between lasers and filtering profile on system performance is investigated in the proposed carrier-reuse WDM-PON architectures. Analysis is performed on the influence of the RSOA operation temperature, the number of subscribers supported by the proposed WDM-PONs and the colorless operation of ONUs. The data rate enhancement of the architecture is also studied and a 10-Gb/s transmission using injection-locked FP-LDs for both downlink and uplink shows its feasibility.

Lastly, the characteristics of the SCM light are mathematically analyzed and experimentally demonstrated. To the best of author's knowledge, it is the first time to

demonstrate that the modulated data also exhibits on the optical carrier, which introduces crosstalk to the upstream signal once the optical carrier is separated from optical subcarriers and modulated to carry uplink data. The influence of the residual data carried on the optical carrier and its suppression are studied in three kinds of upstream transmission with 1.25-Gb/s data rate based on wavelength-seeded RSOAs. Results show that proper selection of seeding power into RSOAs and operation conditions of the downlink Mach-Zehnder modulator (MZM), such as driving voltage and bias voltage, can significantly suppress the crosstalk.

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List of Abbreviations

ADSL	Asymmetric Digital Subscriber Line
ASE	Amplified Spontaneous Emission
APD	Avalanche Photodiode
APON/ATM-PON	Asynchronous Transfer Mode PON
AWG	Arrayed Wavelength Grating
BBPF	Broadband Band-Pass Filter
BER	Bit Error Rate
BERT	Bit Error Rate Tester
BPF	Band-Pass Filter
BPON	Broadband PON
BTB	Back-To-Back
CDR	Clock and Data Recovery
CO	Central Office
CW	Continuous Wave
DBA	Dynamic Bandwidth Allocation
DCA	Digital Communication Analyzer
DCF	Dispersion Compensation Fiber
DFB	Distributed Feedback
DI	Delay Interferometer
DPCC	Dispersion Pre-Compensation Circuit
EAM	Electro Absorption Modulator
EDFA	Erbium Doped Fiber Amplifier
EPON	Ethernet PON
FBG	Fiber Bragg Grating
FEC	Forward-Error Correction
FP-LD	Fabry-Perot Laser Diode
FSAN	Full Service Access Network
FSK	Frequency Shift Keying
FSR	Free Spectral Range
FTTH/C/N/B	Fiber To The Home/Curb/Node/Building
GPON	Gigabit PON
HDTV	High-Definition Television
IEEE	Institute of Electrical and Electronics Engineers

IF	Interferometric Filter
IN	Intensity Noise
IRZ	Inverse Return-to-Zero
ISDN	Integrated Services Digital Network
ISP	Internet Services Providers
ITU	International Telecommunications Union
LAN	Local Area Network
LAN	Limiting Amplifier
LED	Light Emitting Diode
LO	Local Oscillator
MAN	Metropolitan Area Network
MPN	Mode Partition Noise
MZM	Mach-Zehnder Modulator
NRZ	Not-Return-to-Zero
OAN	Optical Access Network
OCSR	Optical Carrier to Subcarrier Ratio
ODN	Optical Distribution Network
OLT	Optical Line Terminal
ONU	Optical Network Unit
OSA	Optical Spectrum Analyzer
OSNR	Optical Signal to Noise Ratio
PC	Polarization Controller
PM	Power Meter
PON	Passive Optical Network
POTS	Plain Old Telephone Service
PPG	Pulse Pattern Generator
PRBS	Pseudorandom Binary Sequence
PSK	Phase Shift Keying
QoS	Quality of Service
RF	Radio Frequency
RIN	Relative Intensity Noise
RN	Remote Node
RSOA	Reflective Semiconductor Optical Amplifier
SBS	Stimulated Brillouin Scattering
SCM	Subcarrier Modulation
SLD	Super Luminescent Diode
SMF	Single Mode Fiber
SMSR	Side-Mode Suppression Ratio

TDM-PON	Time Division Multiplexing PON
TEC	Thermo-Electric Cooler
TLS	Tunable Laser Source
VCSEL	Vertical Cavity Surface Emitting Laser
VDSL	Very high speed Digital Subscriber Line
VoD	Video-On-Demand
VoIP	Voice-Over-IP
WAN	Wide Area Network
WDM-PON	Wavelength Division Multiplexed PON
WLAN	Wireless Local Area Network

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Chapter 1

Introduction

1.1 Background and motivation

1.1.1 Bandwidth demand in access networks

Today's high-bandwidth applications are exhausting the bandwidth offered by traditional copper access. Tomorrow's bandwidth demand will be even greater. Firstly, email has been embraced as a fundamental communication tool. Lots of emails are sent with files of large size including images, sound or video clips attached, which makes the access network congested. Secondly, network users also use the Internet to search for a dizzyingly wide variety of information to help them at school, work, and in their personal lives. Although information gathering is probably the oldest Internet application, more and more new services, such as digital library, office online, E-learning [1], E-medicine [2] and remote storage services, are rapidly devouring the bandwidth offered currently. Lastly, in recent years, the Internet has moved from its initial setting in academic institutions to the home, and has become a home-based entertainment tool. More and more internet users are coming to enjoy the online videos, music and games. For example, customers are demanding bandwidth support for home applications that include digital radio, home security and telemetry, interactive gaming [3-4], 2-D or 3-D digital high-definition television (HDTV) [5-6], voice-over-IP (VoIP) [7-8], and video-on-demand (VoD) [9-10]. These and other emerging applications will rapidly increase the bandwidth demand of access networks.

Therefore, telecommunication carriers are facing increasing challenges in delivering new and emerging broadband services over the existing networks. The bandwidth demand per user has been estimated to be 100 Mb/s in 2010 and 1 Gb/s in 2020 [11]. To meet this ever increasing demand for bandwidth in the near future, new broadband access networks that can provide sufficient bandwidth to end users need to be deployed soon.

1.1.2 Opportunities for WDM-PONs

The high data rates in the traditional access networks are mainly offered by digital subscriber line (DSL) technologies and cable modems. The access speeds offered by current cable modem systems are 42 Mb/s and 30 Mb/s shared by all users of the node for downstream and upstream, respectively [12-13]. The downstream data rate of DSL systems is up to 1.5 Mb/s (512 Kb/s for upstream) for asymmetric DSL (ADSL) and is increased to 2 Mb/s for high data rate DSL (HDSL). It is expected to reach up to 51.8 Mb/s (6.5 Mb/s for uplink) for asymmetric very high speed DSL (VDSL) or 25.9 Mb/s for symmetrical VDSL [14-15]. It is well known that there is a distance-bandwidth trade-off in all DSL technologies, where the bandwidth decreases with the increase of the transmission distance. For 51.8-Mb/s VDSL system, the typical distance is only around 1000 ft [14], [16]. As a result, the traditional copper-based access networks can not meet the rapidly increasing bandwidth demand.

Passive optical network (PON) based access network is an efficient and vibrant technology which can meet the ever increasing bandwidth demand. PON has been extensively investigated due to its high bandwidth, cost sharing of infrastructure and absence of active components. So far, there are some different PONs that have been

deployed or are being deployed, including asynchronous transfer mode PON/broadband PON (APON/BPON), Gigabit PON (GPON) and Ethernet PON (EPON), as shown in Fig. 1.1 [12], [17]. A typical APON/BPON provides 622 Mb/s of downstream bandwidth and 155 Mb/s of upstream traffic [18]. The GPON standard represents a boost in both the total bandwidth and bandwidth efficiency through the use of larger, variable-length packets. A GPON network delivers up to 2.5 Gb/s for the downstream and 1.25 Gb/s for the upstream [19]. The EPON uses standard 802.3 Ethernet frames with a symmetrical 1.25 Gb/s upstream and downstream data rates [20]. All these PONs use the time division multiplexing (TDM) access technology, where the bandwidth of a single wavelength is shared among all users (typically 32 users in a PON), and hence are referred to as TDM-PON. As a result, although GPON and EPON can offer an aggregated bandwidth over 1 Gb/s, the bandwidth for each user may be not higher than 100 Mb/s, as shown in Fig. 1.1.

Fig. 1.1. Evolution of optical access networks [12], [17].

Today the telecommunications industry is looking into ways to deliver even more bandwidth over longer distances than ever before to meet the bandwidth demand of near future, e.g. more than 1 Gb/s per user in 2020 as predicted in [11]. The exploration of wavelength division multiplexing (WDM) technology can tremendously increase the bandwidth offered by a PON. In a typical WDM-PON, an optical network unit (ONU) located at each user's premises occupies two dedicated wavelengths for downstream and upstream transmission, respectively. (Note that in a carrier-reuse WDM-PON, one dedicated wavelength is sufficient for each ONU for both downlink and uplink). With this method, the bandwidth for each user can easily reach 1 Gb/s and beyond. Another advantage offered by the WDM-PON technology is network security. Unlike TDM-PON, in which a point to multipoint (P2MP) network topology is implemented with passive optical splitters located at the remote node (RN) [20], a WDM-PON offers the point to point connection for each user through dedicated wavelengths, which considerably enhances network security. Besides, the WDM-PON makes it more convenient for capacity upgradation. Its bit rate can be easily upgraded by replacing an old transceiver with a higher speed one. In addition, the WDM-PON is a protocol and line-rate transparent system. All these advantages make WDM-PON be the ultimate solution for future broadband access networks. The nascent WDM-PON offers lots of opportunities for carriers and vendors. So far, Korea Telecom is leading the charge in the development and deployment of WDM-PONs [21].

1.1.3 Challenges in WDM-PONs

As discussed, WDM-PON has been considered as an ultimate solution for the access networks due to its large capacity, easy management, network security and

upgradeability. However, there are still many challenging issues to be addressed before it can be deployed widely round the world.

Compared with the TDM-PON, the WDM-PON may be not cost-effective due to the relative higher costs for the wavelength-specific and stable light sources that are required to meet the multiplexer/demultiplexer grid. The cost is the key issue for the implementation and deployment of WDM-PONs. Although internet users would like to have considerably higher bandwidth in their access networks, they do not want to pay subscription fee much higher than what they are paying for current xDSL or TDM-PON technologies. Another issue is that the craftsman has to make sure that he/she is dealing with the correct wavelength during the installing and maintaining of the WDM-PON. To solve this problem, it is desirable to use wavelength independent operation (also known as colorless operation or color-free operation) of light source at each ONU.

In terms of low-cost and colorless light source for WDM-PONs, the initial efforts involved the spectrum-slicing of broadband incoherent light sources, such as light-emitting diodes (LEDs), amplified spontaneous emission source (ASE) from an erbium doped fiber amplifier (EDFA), and free-running Fabry-Perot laser diodes (FP-LDs). For LEDs and FP-LDs, the data can be directly modulated, while for ASE source an additional external modulator is required, which increases the deployment cost. Furthermore, simple spectrum-slicing these incoherent sources induces strong intensity noise, and thus the data rate of PONs based on these light sources basically is very low and is difficult to be increased to Gigabit per second [22]. Recently, it has been proposed to implement WDM-PONs by using the spectrum-sliced ASE injection-locked Fabry-Perot lasers as the wavelength independent light sources [23].

With this technology, Novera Optics Inc. has released a 1.25-Gb/s WDM-PON system [24]. However, due to the limitation of the intensity noise of spectrum-sliced ASE, no WDM-PON with data rate higher than 1.25 Gb/s has been reported based on this scheme. Even with 1.25-Gb/s transmission, the relatively high required injection power may also be an issue [25]. So far, new architectures for high speed WDM-PON with wavelength independent light sources have attracted a lot of research interests and are the hottest research topic in this area.

In conclusion, the WDM-PON is a promising technology for future broadband access networks. However, some critical issues must be resolved before it can be widely implemented and deployed.

1.2 Objectives

As discussed in the previous section, the cost is vital for practical implementation and deployment of WDM-PONs. The main objectives of this research project are to explore some novel low-cost colorless light sources for WDM-PONs and to improve their transmission performance. Specifically, this research study aims to address the following issues:

1. Investigation on high speed light source using coherent light injection-locked FP-LDs for WDM-PONs.
 - To propose low-cost colorless light sources for 10-Gb/s WDM-PON.
 - To study the performance of the proposed light sources in WDM-PONs and other possible applications.

2. Performance improvement of WDM-PON based on spectrum-sliced ASE injection-locked FP-LDs.
3. Study of the carrier-reuse schemes in WDM-PONs.
 - To propose novel low-cost WDM-PON architectures based on downlink subcarrier transmission and carrier reuse.
 - To evaluate and improve the system performance of the proposed architectures.
4. Analysis and demonstration of the residual data carried on the optical carrier of the subcarrier modulated light and investigation of its impact on the upstream transmission.

1.3 Major contributions

The major contributions of the thesis are listed in the following.

1. This thesis provides a detailed analysis of the performance enhancement of injection-locked FP-LDs and proposes a high speed light source in WDM-PONs using coherent light injection-locked FP-LDs. The coherent seeding light source is shared by a number of WDM-PONs, leading to significant cost reduction. A 10-Gb/s bidirectional WDM-PON experiment is carried out to demonstrate the feasibility of the proposed light source. In addition, performance evaluations in terms of injection power, wavelength detuning and injected mode selection are investigated. (Chapter 3)

2. The thesis studies the applications of the coherent light injection-locked FP-LDs in long-reach WDM-PONs and metropolitan optical networks. The polarization-insensitive injection-locking scheme is also explored by combining a conventional depolarizer with a dual-fiber ring structure. (Chapter 3)
3. The performance improvement of the spectrum-sliced ASE injection-locked FP-LDs in WDM-PON is investigated. Results show that there is an optimum bandwidth, 0.4nm~0.6nm, of the sliced ASE source in terms of receiver sensitivity. The suppression of intensity noise of spectrum-sliced ASE using an SOA can further improve the receiver sensitivity. Proper selection of front-facet reflectivity, operation temperature and bias current of FP-LDs can also significantly improve its transmission performance. (Chapter 4)
4. Two low-cost WDM-PON architectures based on subcarrier modulation (SCM) and carrier reuse are proposed and demonstrated. The key idea is that only one interferometric filter located at the remote node is used to separate the closely spaced optical carriers and subcarriers for all channels. Architecture I is suitable for the situation where there are two distribution fibers between RN and each ONU, while Architecture II is proposed for the case where only one distribution fiber is available. Both architectures are expected to be cost-effective since they eliminate the filter and wavelength selective light source in each ONU. (Chapter 5)
5. The thesis investigates the performance evaluations of the proposed carrier-reuse WDM-PONs in terms of optical carrier to subcarrier ratio (OCSR) of SCM light, Rayleigh-backscattering noise, and wavelength mismatch between signal

wavelength and filter transmission spectrum. The data rate enhancement of the architecture is also studied and a 10-Gb/s transmission based on injection-locked FP-LDs for both downlink and uplink shows its feasibility. (Chapter 5)

6. This thesis mathematically analyzes and experimentally investigates the characteristics of subcarrier modulated light. It is shown that the modulation data exhibits at both optical subcarriers and optical carrier. The residual data will introduce considerable crosstalk once the optical carrier is separated from subcarriers and remodulated for upstream transmission. The crosstalk due to the residual data carried on optical carrier and its suppression are studied in three 1.25-Gb/s carrier-reuse WDM-PONs. Experiments show that proper selection of seeding power into RSOAs and operation conditions of the downlink Mach-Zehnder modulator (MZM), such as driving voltage and bias voltage, can significantly suppress the crosstalk. (Chapter 6)

1.4 Thesis organization

This thesis is organized into seven chapters.

Chapter 1 gives a brief introduction on the background, motivations, objectives, and major contributions of the work presented in the thesis.

Chapter 2 provides an overview of optical access network, and fundamental concepts of TDM-PON, WDM-PON and hybrid WDM/TDM-PON. The current research work about WDM-PONs is classified and reviewed in terms of different light source schemes.

In chapter 3, the performance of coherent light injection-locked FP-LDs is investigated first. Then a high speed light source based on coherent light injection-locked FP-LDs is proposed and demonstrated in a 10-Gb/s bidirectional WDM-PON. Its performance evaluations in term of injection power, injected cavity mode selection, wavelength detuning and transmission distance are investigated. The possible application of the proposed light source is also explored in long-reach WDM-PONs and metropolitan networks. In addition, the feasibility of its polarization-independent operation is discussed.

Chapter 4 investigates the performance improvement of WDM-PONs based on incoherent light injection-locking technology. Firstly, the bandwidth of the injected ASE light is optimized. Secondly, the intensity noise suppression of the spectrum-sliced ASE with an SOA is studied and demonstrated in a WDM-PON. Lastly, the influence of the facet reflectivity and operation conditions of the FP-LDs is discussed.

Chapter 5 first proposes to use a shared interferometric filter at the remote node to separate the optical carriers and subcarriers for all channels in optical carrier-reuse WDM-PONs based on subcarrier transmission. Two low-cost architectures based on this idea are proposed and described in detail. Then two 1.25-Gb/s experiments based on RSOAs for both downlink and uplink using the proposed architectures are carried out and their performance evaluations are studied in term of OCSR of the SCM light, Rayleigh-backscattering noise, and wavelength mismatch between signal wavelength and filter transmission spectrum. In addition, discussions on operation temperature of

RSOAs, number of supported subscribers and colorless operation of ONUs are provided, and the feasibility of the data rate enhancement to 10 Gb/s of the proposed architecture using injection-locked FP-LDs is demonstrated.

In Chapter 6, the characteristic of subcarrier modulated light is mathematically analyzed. The residual data that exhibits on the optical carrier of the SCM light is studied mathematically and experimentally. Three different ONU configurations based on FBG-circulator, coupler-filter and delay interferometer for 1.25-Gb/s upstream transmission in carrier-reuse WDM-PONs are carried out. The crosstalk due to the residual data carried on the optical carrier is studied in all configurations. Suggestions to reduce the crosstalk are discussed.

Finally, Chapter 7 summarizes the work in this thesis and gives some suggestions for the future research in the area.

Chapter 2

Literature Review

2.1 Overview

This chapter briefly introduces the history of optical access networks and reviews the important architectures for access technologies including time division multiplexed passive optical network (TDM-PON), wavelength division multiplexed passive optical network (WDM-PON) and Hybrid WDM/TDM-PON. The light sources for WDM-PONs are classified and discussed in detail.

2.2 Introduction of optical access networks

An optical access network (OAN) is a set of access links sharing the same network-side interfaces and supported by optical access transmission systems. It may include a number of optical distribution networks connected to the same optical line termination. In other words, it is the link between customers and the first point of connection to the network infrastructure — central office (CO). It is also known as either “the last mile” or “the first mile” network. The access network has become the bottleneck in today’s communication network, since it has a very limited communication speed.

A variety of competing access technologies have been developed in the past decade, including the dialup modems, narrowband integrated services digital network (ISDN), digital subscriber line (DSL), coaxial cable modem, the broadband satellites, broadband fixed wireless and wireless local area networks (WLAN) or mobile

systems. Currently, DSL and cable modem are the leading technologies that make use of the existing infrastructure. DSL uses the copper wires to provide data over voice, independent voice and data transmission and plain old telephone service (POTS). The cable modem technology is offered by cable companies to provide broadband services to subscribers. Both systems are limited to the data rates per subscriber in the order of several to tens of Mb/s due to propagation, congestion and crosstalk issues [12].

With the development of the broadband technologies, which include all evolving high speed digital technologies that provide consumers integrated access to voice, high speed data, video, video-on-demand and interactive delivery services, the bandwidth demand from the network users is increasing rapidly [26]. Accordingly, some new technologies are needed to break the existing bandwidth bottleneck and deliver broadband services to both business and individual users.

Optical access network, including fiber to the home/curb/node/building (FTTH/C/N/B), is the most promising broadband access technology due to its superior bandwidth potential [27], compared with the typical bandwidth offered by the cable modem and DSL technologies. Because of their huge bandwidth capacity, optical fibers have already been widely deployed in Wide Area Networks (WANs), Metropolitan Area Networks (MANs) and even Local Area Networks (LANs). The introduction of optical fibers to access networks would eliminate the bottleneck suffered by other access technologies and meet the ever increasing bandwidth demand. Thus, optical access network will be a preferred alternative to other broadband access network technologies for full services (bidirectional voice, video and high-speed data), especially in areas where new access networks are deployed. So far, FTTH has

reached about four million homes in the United States and more than ten million globally [28]. It is projected to reach over 25 million homes in the United States alone by 2010 [28]. With the cost parity and superior performance, the deployment of FTTH has been justified for many service providers.

Passive optical network (PON) is the most promising approach to the implementation and deployment of cost-effective FTTx [29-32], because many end users can share the optical feeder fiber and the central office equipments. Its specifications were originally discussed and determined by the full service access network (FSAN), which is an international group formed by network operators in 1995. Since then, a series of International Telecommunications Union (ITU) standards (G.983/G.982) and Institute of Electrical and Electronics Engineers (IEEE) standards (802.3ah) have been developed. A typical PON consists of an optical line terminal (OLT) at the service provider's office (also known as the central office), a number of optical network units (ONUs) each at an end user's premises and fiber links between the OLT and ONUs (called the optical distribution network (ODN)), as shown in Fig. 2.1. A remote node is located near the ONUs to distribute the data to each ONUs. The OLT provides the interface between the PON and the backbone network, while the ONUs provide the service interface to the end users. A PON is a converged infrastructure that can deliver multiple services such as voice (POTS or VoIP), data, video and/or telemetry, where all of these services are converted and encapsulated in a single packet type for transmission over the PON fiber.

There are various kinds of PON technologies including APON/BPON [33-35], EPON [36-38], GPON [39-42] and WDM-PON. APON/BPON, EPON and GPON belong to

TDM-PON, which is currently the most popular FTTP approach and has been deployed in various regions of the world. WDM-PON is an emerging technology supporting high speed data rate for each end user. TDM-PON and WDM-PON will be discussed in Section 2.3 and Section 2.4, respectively.

Fig. 2.1 Typical PON architecture.

2.3 Time division multiplexed PON

In a TDM-PON, all end users share a single upstream wavelength and a downstream wavelength. The transmission data rate over the PON is the sum of the dedicated data rate to each subscriber. This approach can provide a cost-effective solution due to the low-cost transmitter in each ONU and the sharing of one transmitter and receiver at the CO.

In a TDM-PON, the operations of the downstream and upstream are fundamentally different. The operation principles for the downstream and upstream transmission are

illustrated in Fig. 2.2 and Fig. 2.3, respectively. As shown in Fig. 2.2, the downstream data in the form of packets is broadcast from the OLT (located at the CO) to multiple ONUs. Here, without loss of generality, only three ONUs in the PON are shown. Each packet carries a header that uniquely identifies a particular ONU. In addition, some packets may be intended for all ONUs in the PON and hence be broadcast to all ONUs, while some other packets may be addressed to a particular group of ONUs and hence be multicast to that group of ONUs. At the remote node (RN), the downstream signal is divided into as many separate parts as the number of ONUs by a power splitter. Each individual signal carries all of the ONU-specific packets and is sent to an ONU. At each ONU, only the packets intended for it are accepted and the packets for other ONUs are discarded. For example, although ONU 1 receives packets 1, 2, 3 and 123, it delivers only packet 1 and 123 to its end user.

Fig. 2.2. Downstream traffic flow in a TDM-PON.

The upstream traffic is managed with TDM technology, as shown in Fig. 2.3. Here,

each ONU transmits its upstream data within its dedicated time slots. All time slots are synchronized so that upstream packets from different ONUs do not interfere with each other when the data is coupled into the feeder fiber through the splitter at the RN. For example, ONU 1 transmits its packet 1 in the first time slot, ONU 2 transmits packet 2 in the second non-overlapping time slot, and ONU 3 transmits packet 3 in the third non-overlapping time slot. In order to prevent data collision from different ONUs, scheduling of packets from different ONUs is required in a TDM-PON. A primitive solution is to assign a fixed time slot to each ONU. Although assigning a fixed time slot regardless of its demand is simple, this scheme cannot adapt to heterogeneous bursty traffic and may waste bandwidth considerably. A dynamic bandwidth allocation (DBA) scheme, where the traffic bandwidth in a shared telecommunications medium is allocated on demand and fairly between different users of that bandwidth, can support better quality of service (QoS) in TDM-PONs [43].

Fig. 2.3. Upstream traffic flow in a TDM-PON.

To make TDM-PON cost effective and practical for widespread deployment, the

standardization of the algorithms and protocols must be established. Because of the complexity of the time-sharing algorithms combined with ever increasing bandwidth demands, this standardization process has taken a long time. So far, three kinds of TDM-PON standards, i.e. APON/BPON, EPON and GPON, have been approved. They are briefly described below.

2.3.1 APON/BPON

ATM-PON is the first standardized passive optical network based on asynchronous transfer mode (ATM) protocol. It was proposed by FSAN and accepted as an ITU standard (ITU-T G.983) in 1998. The speed of operation depends on whether the APON is symmetrical or asymmetrical. Symmetrical APONs operate at 155.52 Mb/s for both downstream and upstream transmission. For asymmetrical APONs, the downstream transmission ranges from 155.52 Mb/s to 622.08 Mb/s, but the upstream transmission occurs at 155.52 Mb/s. The whole operation speed is shared by 16 or 32 end users with a passive optical splitter and the data rate for each ONU is about several Mb/s. The use of the term APON led users to believe that only ATM services could be

FSAN decided to broaden it to broadband PON
 nerous broadband services including Ethernet access
 nsions were standardized in BPON, including the
 ent bands in G.983.3 and DBA in G.983.4, both

ecause many vendors feel that the APON standard is
 due to its lack of video capabilities, insufficient

bandwidth, complexity and expense. Also, with the move to Ethernet, they believe that EPONs will eliminate the need for conversion between ATM and IP protocols in the connection of a wide-area network (WAN) and a local-area network (LAN). The Ethernet PON standard of IEEE 802.3ah was completed in 2004 [20], as part of the Ethernet First Mile project. EPON uses standard 802.3 Ethernet frames with a symmetrical 1.25-Gb/s upstream and downstream rate, which is shared by all ONUs. Since early 2006, work has begun on a very high-speed 10 Gb/s EPON (10-GEAPON) standard [44].

2.3.3 GPON

The increasing need for larger bandwidths and the unquestionable complexity of ATM forced the FSAN group to revise their approach. As a result, a new standard called Gigabit passive optical network (GPON) was released and adopted by ITU in 2003. In comparison with the BPON standard, higher transmission rates are specified making GPON capable of supporting data rates of up to 2.48 Gb/s in the downstream as well as the upstream direction. As known, physical reach is the maximum physical distance between the ONU and the OLT, which is corresponding to the maximum service range of the PON. In GPON, two options are defined for the physical reach: 10 km and 20 km. It is assumed that 10 km is the maximum distance over which FP-LD can be used in the ONU for high bit rates such as 1.25 Gb/s or 2.5 Gb/s. Split ratio is an important factor limiting the maximum user number that a PON can serve. Basically, the larger the split ratio is, the more attractive it is for operators. However, a larger split ratio implies greater optical splitting loss, which creates the need for an increased power budget to support the physical reach. Split ratios of up to 1:64 are realistic for current technology.

In this section, the standards for TDM-PON have been reviewed. Table 2.1 summarizes their key features [17]. Here, please note that the available bit rate for each end user is much smaller than the maximum bandwidth offered by the PON due to TDM access technology. The TDM-PON solution can be very attractive as long as the bandwidth demand of the users sharing the PON does not become too large. To overcome the bandwidth limitation in TDM-PONs, a separate video overlay wavelength has been added to provide TV signals that are compatible with existing TV sets and home wiring [17]. Once the bandwidth demand increases significantly, the TDM-PON solution will be no longer suitable. To meet the increasing bandwidth demand of end users, the ultimate solution is the WDM-PON.

Table 2.1. Summary of TDM-PON technology [17]

Item		BPON	EPON	GPON
MAC Layer	Standard	ITU G.983	IEEE 802.3ah	ITU G.984
	Services	Full service (TDM, Ethernet, POTs)	Ethernet data	Full service (TDM, Ethernet, POTs)
	Frame	ATM cell	Ethernet frame	GEM frame
PHY Layer	Distance	10/20 km	10/20 km	10/20 km
	Split ratio	32	16	64
	Downlink bit rate	622 Mb/s	1.25 Gb/s	2.48 Gb/s
	Uplink bit rate	155 Mb/s	1.25 Gb/s	1.25 Gb/s
	Bandwidth	Bit rate	1 Gb/s	Bit rate
	Average bandwidth per user	20 Mb/s (down) 5 Mb/s (up)	60 Mb/s (up & down)	40 Mb/s (down) 20 Mb/s (up)

2.4 Wavelength division multiplexed PON

2.4.1 Background of WDM-PON

Today, bandwidth demand and ever-improving technology are significantly disrupting the telecommunications marketplace. Service providers are facing tremendous opportunities as well as precipitating huge changes in optical access networks.

Fig. 2.4. Bandwidth demand in access networks [28].

The existing infrastructure has not kept pace with the exponential growth in bandwidth demand. New business applications, such as ecommerce, high quality videoconferencing, telemedicine, large-file transfer, data mirroring and data-storage warehousing, are driving the need for ultrahigh bandwidth services. As illustrated in Fig. 2.4, the bandwidth demand increases four times every four years [28]. New species of service providers, such as Internet service exchanges, application service providers and storage service providers are emerging, experiencing rapid growth in their businesses and scrambling for market-share.

To meet the rapid increase in bandwidth demand and capture the market, TDM-PON, especially EPON and GPON, is begun to be deployed all over the world [17]. As discussed in the previous section, the EPON and GPON can offer tens of Mb/s bit rate for each end user. However, the bandwidth demand is still increasing. Applications, such as super definition video, 3-D video technology and interactive 3-D gaming consume larger and larger bandwidth. As shown in Fig. 2.4, the bandwidth demand per user is predicted to reach 100 Mb/s in 2010, and 1 Gb/s in 2020 [11]. In a WDM-PON, each ONU can be served by dedicated wavelengths to communicate with the CO. As a result, the data rate for each ONU is significantly increased in WDM-PONs, compared with that in the TDM-PONs. Some vendors and carriers have started to look to WDM-PONs for higher bandwidth demand in the near future. Among the players in the nascent WDM-PON segment, Korea Telecom is leading the charge on the carrier side, with field trials in 2004 and volume deployment in 2005. The carrier has deployed 100,000 lines till the first quarter of 2007 [21], [45].

2.4.2 WDM-PON architecture

WDM-PON enables highly efficient use of the fiber plant by sharing the single feeder fiber among all end users. Fig. 2.5 illustrates a typical WDM-PON architecture. The OLT, which resides at the CO, consists of an array of transmitters and receivers. Each transmitter or receiver is set at an ITU-T wavelength band. A dedicated downstream wavelength channel is assigned to each end user. All downstream channels are then combined with an arrayed wavelength grating (AWG) or WDM multiplexer and passed to the remote node (RN) through a single feeder fiber. At the RN, another AWG is used to demultiplex all the dedicated wavelength channels, each

corresponding to an ONU. Each dedicated channel then passes through a distribution fiber and is received by an ONU for downstream data detection. The upstream signal from each ONU's transmitter is delivered over the same distribution fiber and passes through the AWG and the feeder fiber back to the OLT.

Fig. 2.5. A typical WDM-PON architecture.

So far, there are two kinds of upstream wavelength assignments, including downstream wavelength reuse [100-111], and two dedicated wavelengths arrangement for both downstream and upstream transmission [52-99]. In the first case, the downstream signal is separated into two parts, one for downstream data detection and the other for upstream remodulation. In the other case, each ONU is assigned with two dedicated wavelengths, one for the downstream transmission and the other for the upstream transmission. To make the upstream wavelength transmit back to the OLT through the same light path as that of the downstream, a cyclic AWG is necessary and

the wavelength separation between downstream and upstream is exactly the free spectra range (FSR) of the AWG. There are various structures for the two dedicated wavelength arrangements, which will be discussed in detail in Section 2.6.

Unlike a TDM-PON where an optical splitter is used to split/combine the optical light, a WDM-PON uses an AWG to separate and combine optical signals of different wavelengths corresponding to different ONUs. In a WDM-PON, the path between OLT and each ONU is virtually point-to-point connected through the dedicated wavelength. As a result, a WDM-PON has inherent advantages over a TDM-PON in terms of bandwidth, protocol transparency, security, simplicity in electronics and so on.

2.5 Hybrid TDM/WDM-PON

As discussed, a TDM-PON can offer a relatively low subscription cost to each subscriber by sharing a single wavelength channel among multiple subscribers. However, it inevitably sacrifices per-subscriber bandwidth, and the number of subscribers in a practical TDM-PON is typically limited to 32. On the other hand, a WDM-PON can incorporate more subscribers without sacrificing bandwidth by adding more wavelength channels and offers great security and protocol transparency. Nevertheless, as shown in Fig. 2.4, the bandwidth demand in the coming years is still much lower than that offered by a WDM-PON, i.e. 1 Gb/s. Therefore, a compromise approach is to combine TDM and WDM techniques for near-future deployment [46-50]. The Hybrid TDM/WDM-PON (Hybrid PON) is expected to achieve relatively low per-subscriber cost as compared with a WDM-PON, while meeting the bandwidth demand for the near future.

Fig. 2.6. Typical architecture of a Hybrid TDM/WDM-PON.

Fig. 2.6 shows a typical architecture of hybrid TDM and WDM PON [51]. The difference between a hybrid TDM/WDM-PON and a WDM-PON or a TDM-PON is the structure of the RN. The hybrid TDM/WDM-PON has a double-star topology. At the RN, the downstream wavelength channels are demultiplexed with an AWG firstly. Then, each wavelength channel is further split for a number of ONUs. Every wavelength channel is encoded with TDM protocol. Similar to the TDM-PON, each ONU receives the packets on its dedicated time slot and drops all other packets. Assuming that the RN consists of a 1×16 AWG and 16 1×8 power splitters, the hybrid PON can support 128 subscribers. Since each wavelength channel is shared by 8 users, the per-subscriber cost is expected to be reduced. However, because one channel is shared by only 8 users, instead of typical 32 users in a pure TDM-PON, the bit rate

per subscriber is expected to be increased.

The hybrid TDM/WDM-PON may be an interim choice between the TDM-PON and the WDM-PON. However, with the rapid increase of the bandwidth demand, the WDM-PON is the ultimate solution for access networks. Before WDM-PONs practical and wide deployment in the world, the cost of each ONU, especially the cost of light source, must be reduced. Recently, most of research work is focused on this critical issue. In next section, the current work on this topic is to be reviewed.

2.6 Light source for WDM-PON

2.6.1 Background

In a WDM-PON, a point-to-point connection is set up between the OLT and each ONU using a dedicated wavelength. Clearly it is necessary to specify each user with a pair of wavelengths to communicate with the CO, one for downstream and another for upstream. This can be achieved by using a wavelength-specific optical source such as a DFB laser, which is commonly used in WDM transmission systems. However, this brings about many issues. Firstly, the cost of a DFB laser is still very high. Secondly, the wavelength of each user should meet the multiplexer and demultiplexer grid and should be stabilized during the entire lifetime of the PON. A thermo-electric cooler (TEC) has been commonly used to this end. Another key issue is the installation of the WDM-PON. The craftsman must make sure that he/she is dealing with the correct wavelength. To address these concerns, wavelength independent operation of light source (also know as colorless operation or color-free operation) at each ONU is desired. With a colorless light source, the problem of dedicated wavelength assignment for each ONU can be easily dealt with in the central office.

So far, many light source schemes have been proposed to meet the requirement of colorless operation [29], [45]. These include the use of tunable laser diodes, spectrum-slicing of broadband light source, self-seeding of reflective semiconductor optical amplifier (RSOA), carrier distribution from central office, external seeding of Fabry Perot laser diode (FP-LD)/RSOA and downstream wavelength remodulation. In the following sections, the reported WDM-PON architectures will be reviewed based on different light sources.

2.6.2 Tunable lasers

Fig. 2.7. WDM-PON with tunable lasers as the light sources.

Laser diodes with wavelength stability and tunability can easily meet the requirement for WDM-PON. With the tunable lasers as the downstream and upstream light sources, the WDM-PON structure is very simple. As shown in Fig. 2.7, each connection between the central office and a subscriber consists of two sets of transmitter and

receiver, for uplink and downlink, respectively. Two cyclic AWGs, located at the CO and RN, are used to multiplex/demultiplex WDM channels. The wavelength of tunable laser source (TLS) is tuned to match the wavelength grid of its connecting AWG port.

With TLS, the bit rate of the WDM-PON can be easily upgrade to 10 Gb/s or even higher. The problem with such a tunable laser approach is that a much more sophisticated laser is required within the customer's ONU, compared with conventional EPON and GPON systems. Tunable lasers should be ensured to operate at the correct wavelength channel through internal wavelength lockers, an external network wavelength reference or some other schemes. Furthermore, most of the TLSs are not designed for high speed direct modulation, particularly for tunable mechanism based on external cavity structure. In addition, the current cost of a TLS itself is also too high to be used as an ONU light source. As a result, the current TLS is not a cost-effective light source for WDM-PON.

2.6.3 Spectrum-slicing of broadband light source

Spectrum-slicing of broadband light source was proposed for WDM transmission early before the emergence of WDM-PON [52-57]. Due to its significantly low cost, it has been proposed to implement WDM-PON using spectrum-sliced incoherent light sources such as light-emitting diodes (LEDs) [58-59], free-running FP-LD/RSOA [60] and amplified spontaneous emission (ASE) sources at the end of the last century [61-62].

Fig. 2.8 shows a typical bidirectional WDM-PON architecture using spectrum-sliced

LED as light sources [63]. In the CO, the outputs of directly modulated LEDs are spectrum-sliced and multiplexed by a $1 \times N$ cyclic AWG, and are then sent to the remote node through the feeder fiber. Optical circulators are used to separate the downstream and upstream channels in the network. At the RN, the downstream channels are demultiplexed by another cyclic AWG. After being demultiplexed, each channel passes through a circulator and is detected by a detector. Similarly, each upstream data is modulated on an LED located in each ONU, spectrum-sliced at the RN, and transmitted back to the CO.

Fig. 2.8. Bidirectional WDM-PON using light-emitting diodes spectrum-sliced with cyclic arrayed-waveguide grating [63].

Using the spectrum-slicing technique, it is often difficult to secure an adequate amount of system margin due to the large slicing loss and low output power of LEDs. This problem could be relaxed to some extent by using high-power LEDs and high sensitive receivers, such as avalanche photodiodes (APDs). Reference [63] presented a WDM-PON with high-power superluminescent diodes (SLDs), in which the bit rate was upgraded from 155 Mb/s to 622 Mb/s. However, a dispersion precompensation circuit (DPCC) and a forward-error correction (FEC) technique were used in this

experiment to suppress the dispersion penalty and thus improve the receiver sensitivity.

Fig. 2.9. Downstream transmission of WDM-PON with spectrum-sliced ASE as light source [66-67].

Another way to enhance the power budget of this kind of WDM-PON is to spectrum-slice the high-power broadband light source from free-running FP-LDs [52], [64], RSOAs [65] and erbium doped fiber amplifiers (EDFAs) [66-67]. The WDM-PON architectures with spectrum-sliced RSOAs and FP-LDs are similar to that in Fig. 2.8, only replacing the LEDs with RSOAs or FP-LDs. The spectrum-sliced light source is much more suitable for downstream transmission since the broadband light source can be shared by all users. A downstream transmission of WDM-PON based on spectrum-sliced ASE source is shown in Fig. 2.9 [66-67]. Two cascaded EDFAs with a band-pass filter (BPF) constitute a high-power broadband light source. The broadband light source is spectrum-sliced with an AWG. Each of the spectrum-sliced light sources is modulated by data via a modulator, such as an electro absorption modulator (EAM) and is combined together with an AWG for downlink

transmission.

The significant advantage of spectrum-slicing scheme would be considerable cost reduction compared with the WDM coherent light source such as DFB laser. In addition, these networks could be robust to the temperature-induced drift of the arrayed waveguide grating (AWG) placed at the remote node (RN) [68-69]. However, due to the intrinsic large intensity noise of spectrum-sliced light sources, the bit rate of such a network is limited to hundreds of Mb/s currently.

2.6.4 Self-seeding of FP-LD/RSOAs

Fig. 2.10. Network architecture of WDM-PON with directly modulated self-seeded FP-LD [70].

The scheme using self-seeded FP-LD/RSOA has been proposed for reducing the intensity noise and increase the bit rate [70-71]. Fig. 2.10 shows a WDM-PON with self-seeded FP-LDs as the upstream light sources [70]. For self-injection (self-seeding) scheme, an upstream signal from each FP-LD is fed back to the FP-LD itself. This feedback signal is provided by a fiber Bragg grating (FBG) at the RN. However, this scheme requires precise wavelength matching among the AWG, FBG and FP-LDs.

Code mark inversion data format is also required in this scheme to balance the spectral power [70]. Furthermore, the polarization fluctuation of the light path may deteriorate its performance. A self-seeded polarization insensitive RSOA based WDM-PON can somewhat remove these limitations [71]. However, the cost of temperature-independent FBG may be still an issue.

Fig. 2.11. Network architecture of WDM-PON with directly modulated self-seeded RSOA [72].

In 2006, a new self-seeded RSOA scheme with a broadband feed-back was proposed [72]. This scheme exploits the broadband ASE emitted from each RSOA in conjunction with a broadband bandpass filter (BBPF) at the remote node (RN), as shown in Fig. 2.11. A part of the signal power from each ONU passing through the AWG is amplified by the EDFA at the RN and then fed back to seed the RSOA to achieve a low relative intensity noise (RIN). The band pass filter (BPF) at each ONU is used to emulate the WDM filter (which separates uplink and downlink signal). A 1.25-Gb/s upstream transmission is demonstrated to exhibit good transmission and crosstalk performances [73]. However, in order to compensate for the high roundtrip insertion loss (greater than 24 dB) experienced by the seeding light of the RSOA, an

active EDFA is used at the RN, which is not desirable.

Fig. 2.12. Configuration of upstream transmission for carrier-distributed WDM-PON. a)-d) Different ONU configurations for upstream transmission.

2.6.5 Carrier distribution

In a carrier-distributed WDM-PON (also called loop-back WDM-PON) as shown in the architecture in Fig. 2.12, the uplink optical carriers are provided by the carrier generation module in the CO. These carriers are sent to the feeder fiber via an optical circulator, separated at the remote node by an AWG and distributed to each

corresponding ONU [74-75]. At each ONU, the carrier is modulated with uplink data and sent back to the CO via the same distribution fiber and the feeder fiber. The optical carriers can be generated at the CO using an array of tunable laser diodes and can also be generated via other ways like supercontinuum generation. In carrier-distributed WDM-PONs, bidirectional transmission of the continuous wave (CW) light and the modulated signal may cause a technical issue. The optical signal-to-noise ratio (OSNR) is degraded by the back-reflection, including stimulated Brillouin scattering (SBS) noise, Rayleigh backscattering (RB) noise [76] and any reflection from connectors or splice points. To reduce the effect of SBS, some techniques such as broadening the linewidth of the CW light [77] and using a broadband ASE light source instead of a coherent CW light [78] have been proposed. By using two feeder fibers, the backward reflection can be further reduced [79]. In such a configuration, the circulator is located at the RN rather than the CO, with one fiber for downlink transmission and carrier distribution, and the other one for uplink transmission. However, the two-feeder-fiber configuration may increase the implementation cost.

The ONUs in carrier-distributed WDM-PON may also have different configurations. The most straightforward way is to use an external modulator (MOD) to encode uplink data onto the distributed carrier, as shown in Fig. 2.12(a). The reach in this configuration is significantly limited by the backward reflection and high insertion loss of MOD. Basically optical gain provided at ONUs can alleviate this reflection induced degradation and compensate for the power loss. Correspondingly, three other configurations with optical gain at ONUs have been proposed [22], as shown in Fig. 2.12 (b)-(d). Fig. 2.12(b) is the ONU configuration based on a modulator and an

optical amplifier, such as a SOA, where the former is used for data modulation and the latter is used to provide optical gain. In some cases, two amplifiers are used to achieve sufficient gain, which are located before and after the modulator, respectively. Generally, the MOD can be an MZM or an EAM. However, a polarization matching is required if an MZM is used due to its characteristic of polarization dependence, which makes the system more complex and unstable. As a result, EAM is widely used in this configuration. Fig. 2.12(c) shows the ONU configuration based on a traveling wave SOA. The SOA is used as both modulator and amplifier, which simplifies the ONU configuration.

All these configurations described above (Fig. 2.12 (a)-(c)) need an optical circulator to combine the upstream signal back to the same transmission fiber, which may increase the cost of each ONU. To eliminate the optical circulator, a configuration using a reflective SOA for both data modulation and power amplification was proposed, as shown in Fig. 2.12(d) [80-82]. In such a scheme, with high reflective coating at the rear facet of the SOA, the CW signal seeded in the RSOA will be amplified, modulated and reflected back. With anti-reflective coating at the front facet of the SOA, the seeding efficiency of the distributed carrier is high. Since the operation wavelength range of current RSOAs is more than 100 nm, this ONU is wavelength independent. So far, lots of work about RSOA-based WDM-PONs has been reported [83-84]. The modulation bandwidth of an ROSA is limited by the reflection structure and is not larger than 2.5 GHz for most commercially available RSOAs. In most reported WDM-PONs, the bit rate is up to 1.25 Gb/s [85-87]. In 2007, researchers in Centre for Integrated Photonics (CIP) reported a 2.5 Gb/s WDM-PON based on RSOAs seeded by spectrum-sliced ASE [88]. Using RSOAs as colorless light sources

at ONUs is promising, since the cost of RSOAs is expected to be significantly reduced.

2.6.6 Remote external seeding of semiconductor lasers

Recently, low-cost semiconductor lasers such as FP-LDs have been used as light sources at ONUs. Compared with an RSOA, the cost of an FP-LD may be much lower, since the coating on both ends is not necessary. In this scheme, the seeding light from the CO is sent to the ONUs, and then injected into FP-LDs to achieve single wavelength operation [89-90], as shown in Fig. 2.13. The configuration of WDM-PONs using remote external light seeded FP-LDs is similar to that of the carrier-distributed WDM-PON. The main difference between these two schemes is that the uplink wavelength for carrier-distributed scheme comes from the CO, while it comes from the laser in each ONU for external seeding scheme discussed in this section, where the seeding light from the CO is used for injection-locking of the uplink laser instead of uplink carrier.

Fig. 2.13. Configuration of upstream transmission for remote external seeding WDM-PON based on FP-LDs [89-90].

In most experiments reported so far, the low-cost semiconductor lasers are FP-LDs [91-93], while some work using vertical cavity surface emitting lasers (VCSELs) has also been reported [101-102]. Here, the scheme with FP-LDs is reviewed first. A free-running FP-LD exhibits many cavity modes, and strong mode partition noise appears with the spectrum-slicing technique. With the injection of seeding light, the cavity mode of the FP-LD located near the injection wavelength can be locked and enhanced in intensity while other cavity modes are suppressed, leading to quasi-single mode operation. In most cases, a broadband incoherent source like ASE is used as seeding light [94-95], which is spectrum-sliced by an AWG located at the remote node. ASE noise has the advantages such as low-cost and polarization insensitivity, while the scheme using spectrum-sliced ASE source suffers from strong intensity noise (IN) caused by spontaneous-spontaneous beat noise. This IN can also be transferred to the injection-locked mode of the FP-LD, leading to degraded receiver sensitivity of the directly modulated FP-LD. Different spectrum widths of ASE noise exhibit different levels of IN and require different injection powers to achieve the same side-mode suppression ratio (SMSR) for a given FP-LD. Therefore, the AWG bandwidth also plays an important role in improving the FP-LD output performance [96]. Due to the relatively broad bandwidth of the spectrum spliced ASE source, the required power for injection locking an FP-LD is relatively high, particularly when the data rate is up to Gigabit per second, leading to stronger backward reflection of the seeding light inside the feeder fiber. This reflection as well as the excess intensity noise converted from the seeding light to the FP-LD limit the PON reach and data rate. The current maximum bit rate based on this scheme is still not higher than 1.25 Gb/s. In order to further increase the data rate, the use of high-quality seeding light sources with low IN is essential.

Upstream transmission using FP-LDs injection-locked by a polarization-insensitive supercontinuum pulse source has been demonstrated to increase the bit rate to 2.5 Gb/s [97].

VCSEL also has the potential for low-cost mass production since the entire cavity can be grown with one-step epitaxy on a GaAs substrate, which makes manufacturing and testing easy [98]. VCSELs with wavelengths of 850 nm and 1310 nm are commercially available and have been widely used for LAN applications. In these years, some high-speed VCSELs with long wavelength have been reported [99-100]. As a result, the WDM-PONs with injection-locked VCSELs were demonstrated in [101-102]. However, a free-running VCSEL oscillates at a single wavelength, unlike multimode operation of an FP-LD, which makes it wavelength dependent. As discussed, the wavelength dependent ONU makes the network implementation and maintenance more complex.

2.6.7 Downlink wavelength remodulation

For all the schemes discussed above, each ONU requires two wavelengths arrangement for downstream and upstream, respectively. The two wavelengths arrangement not only increases the implementation cost of each connection (between the CO and each ONU), but also halves the maximum user number supported by one PON for a given operation wavelength band. To circumvent this problem, downstream carrier remodulation approaches have been proposed recently [103-117]. The downlink signals can be modulated at either baseband or onto subcarriers.

2.6.7.1 Baseband modulation

Fig. 2.14. WDM-PON architecture with downlink carrier remodulation. ONU1, ONU2 and ONU3 represent three different types of ONU structures. [103-105]

For the baseband modulation scheme, the downlink signal is separated into two parts by an optical directional coupler at each ONU, with one part used for downlink detection and the other part used as the uplink carrier. External intensity modulators (Mod) [103], FP-LDs [104] and RSOAs [105] have been used to remodulate the downlink wavelength, corresponding to the configuration of ONU1, ONU2 and ONU3 as shown in Fig. 2.14. If an external modulator is used, the optical amplifier, such as an SOA, may be required to compensate the power loss of the light path. And the downlink data should have extremely low extinction ratio [103]. In the case of using an FP-LD for uplink data modulation, the downlink wavelength is injected into the FP-LD to lock one of the cavity modes. In this case, basically the downlink data rate is much higher than that of the uplink, and the FP-LD also functions as a low pass filter to remove most of the downlink data components. The extinction ratio of the downlink data should be also low enough to make the power of injected light at both the bit “1” and bit “0” well

above the threshold of injection locking [104]. If an RSOA is used for uplink data modulation, it should be operated under the saturation condition to suppress the downlink data. When the RSOA is operated in the unsaturated region, the performance of the upstream signal could be seriously degraded due to the uncompressed thick '1-level' [106]. Even if the RSOA is operated in the saturated region, the extinction ratio of the downstream signal should be still sufficiently small [106]. Some experiments have demonstrated that the use of the negatively detuned demultiplexer at the CO in a downlink wavelength-reuse WDM-PON based on an RSOA can further suppress the residual downstream component included in optical upstream data [107].

To reduce the cost, conventional not-return-to-zero (NRZ) format is preferred for both downstream and upstream data modulation. However, the NRZ downstream scheme requires low extinction ratio of the downstream signal for wavelength-reuse, as discussed above, which deteriorates the downstream performance. Manchester coding [108-109] and inverse return-to-zero (IRZ) format have been considered [110-111] to overcome this limitation. As shown in Fig. 2.15, the electrical signal '10' and '01' are modulated as optical 'mark' and 'space' level when the Manchester coding is used; while electrical signal '0' and '1' are modulated as optical 'mark' (bit 1) and 'space' (bit 0) level when the IRZ coding is used. As a result, both codes always include optical power within one bit period regardless of 'mark' or 'space' level. When the upstream data rate is much lower than the downstream data rate, the downstream wavelength can be remodulated directly with the upstream data, no extinction ratio sacrifice needed for the downstream data. Further more, with Manchester coding, the power of the downstream signal is higher in the high frequency band, and the power

at low frequency component is very low, as shown in Fig. 2.16 [112]. For low speed upstream modulation such as 155 Mb/s, the crosstalk from downlink data can be ignored. However, both Manchester coding and IRZ format need more bandwidth and are more complex compared with NRZ format.

Fig. 2.15. Operation principle of data remodulation on IRZ and Manchester coding.

Fig. 2.16. The RF spectra of downstream signals modulated at 1.25 Gb/s using various coding formats [112].

To reduce the effect of downlink data crosstalk, some other advanced modulation formats including phase shift keying (PSK) [113] and frequency shift keying (FSK) [114] have also been proposed to achieve constant amplitude in the downlink signal. However, fiber dispersion and optical filtering induced dispersion (from WDM multiplexing and demultiplexing) will induce phase modulation (PM) to amplitude modulation (AM) conversion and introduce crosstalk. In addition, the cost and stability of the optical demodulator used for PSK and FSK demodulation at each ONU are still an issue.

2.6.7.2 Subcarrier modulation

Recently, subcarrier modulation scheme was introduced in WDM-PONs based on downstream light remodulation [115-117]. In this scheme, downstream data is modulated at optical subcarriers and the optical carrier is reused for upstream data modulation. The filtering technology is a key issue since the optical carrier and subcarriers are closely spaced. So far, an optical filter such as narrow band fiber Bragg grating (FBG) [117] or delay interferometer (DI) [115] has been used to separate the optical carrier and subcarriers at each ONU. The separated optical subcarrier is then received with a baseband optical receiver for downstream data detection, and the optical carrier is reused for upstream data modulation with an external modulator. Because the downstream and upstream data are modulated and transmitted at subcarriers frequency and baseband, respectively, the crosstalk in this scheme is expected to be lower than the scheme (as described in Section 2.6.7.1) where both downlink data and uplink data are modulated on the baseband. However, the scheme with FBGs is challenging in terms of filter sharpness and wavelength stability, while the scheme using a DI in each ONU suffers from high cost and phase stability.

2.7 Conclusions

This chapter briefly introduced the optical access network and passive optical network. Three types of PONs including TDM-PON, WDM-PON and Hybrid WDM/TDM PON, were reviewed and discussed. Their respective advantages and disadvantages were also presented. Furthermore, the different colorless light sources for WDM-PONs were classified and discussed in detail. Various recently reported WDM-PONs using different light sources were reviewed in terms of the configuration, performance and cost.

Chapter 3

Coherent Light Injection-Locked FP-LDs for High-Speed WDM-PONs

3.1 Overview

As discussed in Chapter 2, cost effective and colorless light source is the most important issue in the practical implementation of WDM-PONs. Using FP-LDs as light sources has attracted a lot of attentions and interests because of their significantly low price and quasi-colorless operation. However, the performance of spectrum-spliced FP-LDs is not suitable for high speed optical transmission due to its large mode partition noise (MPN). Recently, the injection-locked FP-LD was proposed as a low-cost light source for WDM-PONs. Many experiments and system demonstrations have been reported [89-97]. In this chapter, the characteristics of the coherent light injection-locked FP-LD are studied and its applications are investigated in WDM-PONs. A new high speed light source using FP-LDs injection-locked by shared coherent seeding lights is proposed and demonstrated in a 10-Gb/s bidirectional WDM-PON. Its performance evaluations in term of injection power, injected cavity mode selection, wavelength detuning and transmission distance, and other possible applications are investigated.

3.2 Theoretical analysis of injection-locked FP-LDs

3.2.1 Theoretical model

Like all other semiconductor lasers, an externally injection-locked FP-LD can also be described with the multimode rate equations for the electric field E of the active

region and carrier density N inside the active region [118-121]. Assuming that the electric field E is normalized and $|E(t)|^2$ is corresponding to the photon density, the rate equations can be written as [118]

$$\frac{dE_0}{dt} = \frac{1}{2}(1 + j\alpha)(G_0 - l_c)E_0(t) + F_0(t) + \kappa E_{inj}(t)\exp(j\Delta\omega), \quad (3-1)$$

$$\frac{dE_i}{dt} = \frac{1}{2}(1 + j\alpha)(G_i - l_c)E_i(t) + F_i(t), \quad (3-2)$$

$$\frac{dN}{dt} = \frac{1}{qV} - \gamma_c N - \sum_i G_i |E_i|^2, \quad (3-3)$$

where E_i is the complex amplitude of the i -th mode ($i = 0, 1, 2, \dots$), E_{inj} is the complex amplitude of the injected light, F_i is the spontaneous emission noise coupled into the i -th mode, and k is the coupling constant. The last term in (3-1) represents the external injection. The gain of the i -th mode G_i , loss of the cavity l_c , carrier recombination rate γ_c and the angular frequency detuning between injection light and zeroth laser mode at the free-running state $\Delta\omega$ are given as [118]

$$G_i = \frac{\Gamma \nu_g a(N - N_0)}{1 + (2i\Delta\omega_{mode}/\Delta\omega_g)^2} \cdot \frac{1}{1 + \varepsilon \sum |E_i|^2}, \quad (3-4)$$

$$l_c = \nu_g \left[l_{int} + \frac{1}{2L} \cdot \ln \left(\frac{1}{R_f R_b} \right) \right], \quad (3-5)$$

$$\gamma_c = (A + BN + CN^2), \quad (3-6)$$

$$\Delta\omega = \omega_{inj} - \omega_0, \quad (3-7)$$

where ω_0 is the angular frequency of the zeroth mode and v_g is the group velocity.

The other parameters are summarized in Table 3.1. The rate equations can be solved numerically by using 4-order Runge-Kutta method [118].

Table 3.1. Physical parameters for simulating the external light injected FP-LD

λ	Peak wavelength	1554.2 nm
L	Cavity length	350 μm
w	Width of the active region	2.5 μm
d	Depth of the active region	0.2 μm
Γ	Confinement factor	0.3
n_g	Group index	3.5
k	Coupling efficiency	1.0e11 s^{-1}
α	Line-width enhancement factor	3.5
β_{sp}	Spontaneous emission factor	4e-3
l_{int}	Internal loss	30 cm^{-1}
R_f	Reflectivity of the front facet	32 %
R_b	Reflectivity of the rear facet	32 %
a	Gain constant	2e-16 cm^{-2}
N_0	Transparent carrier density	1e18 cm^{-3}
A	Non-radiative recombination coefficient	1e8 cm^{-2}
B	Radiative recombination coefficient	2e-10 cm^{-3}
C	Auger recombination coefficient	4e-29 cm^{-3}
ε	Gain compression factor	3.6e-17 cm^{-3}
η	Coupling coefficient between pigtail fiber and laser diode	0.4
$\Delta\omega_g$	3-dB gain bandwidth	10 π THz
$\Delta\omega_{\text{mod}}$	Mode spacing of FP-LD	200 π GHz

3.2.2 Quasi-single wavelength operation

Assuming that the injection power is -8 dBm and the external light is injected without frequency detuning, the optical spectra of the coherent light injection-locked FP-LD is shown in Fig. 3.1.

Fig. 3.1. Simulated optical spectra of the injection-locked FP-LD. Injection power = -8dBm.

Without external injection, the free-running FP-LD exhibits multi-longitudinal modes oscillation. The spectrum-slicing technique can effectively eliminate the crosstalk among different channels due to the spectrum overlapping of multi-mode FP-LDs and reduce the dispersion penalty. However, the large mode partition noise (MPN) of the simple spectrum-sliced FP-LD limits its data rate. With external injection, the FP-LD operates as a quasi-single wavelength light source, as shown in Fig. 3.1. Simulation results show that the operation wavelength can be locked at any evaluated cavity mode. Fig. 3.1 shows two representative injection-locked modes, one is locked at the main mode (Mode 0), and the other is locked at the left side mode (Mode 2). For both cases, the side mode suppression ratios (SMSR) of the injection-locked FP-LD are more than 30 dB. The high SMSR makes it suitable for high speed data transmission. Many cavity modes offer a wavelength selection for injection locking, which makes it possible for colorless operation.

3.2.3 Frequency shift of the injection-locked FP-LD

It should be noted that the laser frequency is shifted to lower frequency side after injection locking compared with the free-running state. Although the injected external light frequency is exactly matched with the free-running mode, the mode frequency of the FP-LD is shifted to the longer wavelength side after injection locking. The frequency shift is due to the change of carrier induced refractive index of the FP cavity. The resonance condition in an FP-LD is discussed to explain the frequency detuning. Generally, the m -th longitudinal mode corresponding to the FP cavity resonance is given by

$$f = \frac{c}{2n(N)L} \times m, \quad (3-8)$$

where c is the light velocity in vacuum, f is the longitudinal mode frequency, and $n(N)$ is the refractive index of the active region in the FP-LD cavity, which increases with the decrease of carrier density N . The oscillation frequency detuning of the injection-locked FP-LD is proportional to the carrier density and can be expressed as the following relation [122-123],

$$\Delta\omega(N) = \frac{\alpha}{2} g (N - N_{th}) = \frac{\alpha}{2} g \Delta N, \quad (3-9)$$

where N_{th} is the carrier density when the FP-LD works in the threshold condition, and g is the linear gain coefficient. Equation (3-9) shows the cavity resonance frequency must shift to lower frequency because the carrier is reduced from its threshold value due to optical injection [122]. The carrier density difference ΔN is proportional to the amplitude of injected light [123] as shown in equation (3-10).

$$\Delta N = N - N_{th} = -K \frac{A_{inj}}{A} \cos \phi, \quad (3-10)$$

where, K is a constant, ϕ is the phase difference between the internal and injected fields.

3.3 Experimental characterization of coherent light injection-locked FP-LDs

From the investigations above, the following findings about an externally injection-locked FP-LD are observed. On one hand, it can achieve single wavelength operation. On the other hand, its operation wavelength can be selected among some free-running cavity modes by changing the injection wavelength. With this characteristic, the injection-locked FP-LD can work as a quasi-coreless light source and its operation wavelength can be arranged in the central office, which makes it possible for centralized control. All these make externally injection-locked FP-LDs promising low-cost light sources for optical access networks. As known, the characteristics of directly modulated transmitters may determine the transmission performance of WDM-PONs. In this section, the modulation characteristics of the injection-locked FP-LD are experimentally investigated. Please note that the injected seeding light can be either coherent light or incoherent light. In this chapter, only coherent seeding light injection scheme is studied to achieve high-speed transmission. The incoherent seeding light injection technique will be discussed in the next chapter.

The experimental setup is shown in Fig. 3.2. The seeding light (injection light) came from a distributed feedback (DFB) laser. Two variable optical attenuators were used to adjust the seeding light power and detection power, respectively. The polarization state

of the seeding light was matched with the FP-LD by a polarization controller (PC). 10-Gb/s data was directly modulated onto the FP-LD through a bias Tee. The optical spectra and eye diagrams of the externally injection-locked FP-LD were measured with an optical spectrum analyzer (OSA) and a high speed oscilloscope (OSC).

VOA: variable optical attenuator, OSA: optical spectrum analyzer, OSC: oscilloscope,
 DFB: distributed feedback laser, TEC: temperature controller, PC: polarization controller,
 PPG: pulse pattern generator, FP-LD: Fabry Perot laser diode

Fig. 3.2. Experimental setup of the coherent light injection-locked FP-LD.

The FP-LD used in the experimental demonstration has a threshold current of 18 mA and was biased at 40 mA (with around 1-dBm output power) to achieve sufficient modulation bandwidth. The operation temperature of the laser was maintained at room temperature with a temperature controller (TEC). Firstly, the modulation bandwidth of the FP-LD under a coherent light injection is evaluated. Here, the injected wavelength was fixed at the cavity mode of 1556.88 nm.

The small signal modulation responses (not normalized) of the FP-LD with different optical injection powers were studied, and measured results are shown in Fig. 3.3. The horizontal axis denotes the modulation frequency, and the vertical axis denotes the

ratio frequency (RF) power, which is the peak power of the RF component measured with an RF spectrum analyzer. As shown in the figure, for the case of free-running operation without external optical injection, the modulation response reaches the maximum at a frequency corresponding to the relaxation oscillation frequency, which was 6.5 GHz in the experiment. The 3-dB bandwidth was about 8.3 GHz in this case, which is defined as the frequency whose RF power decreases 3 dB from the peak value. With the external optical injection, the resonance frequency is increased. When the injection light power was -10 dBm, the resonance frequency was increased to 7.8 GHz and 3-dB bandwidth was enhanced to about 9.0 GHz. With further increase of the injection power to -7 dBm and -2.2 dBm, the resonance frequency was increased to 8.9 GHz and 10.2 GHz, respectively. In these cases, the 3-dB bandwidth was enhanced to 9.8 GHz and 11.1 GHz, respectively.

Fig. 3.3. Small signal modulation responses of an FP-LD with different injection powers.

Fig. 3.4. Measured spectra of FP-LD before and after injection. Injection power: -8 dBm. (a) full span spectra, (b) close look of the cavity mode at 1556.8 nm.

Fig. 3.4 shows the measured optical spectra of a 10-Gb/s directly modulated FP-LD with and without the external injection of coherent CW seeding light. The FP-LD was biased at 40 mA again and driven by a pseudo random bit sequence (PRBS) with a

word length of $2^{15}-1$ which was provided by a pulse pattern generator (PPG). The driving voltage of 2 V_{p-p} from the PPG was applied without any drive amplifier. Without optical injection, multiple cavity modes were oscillated with wavelength ranging from 1545 nm to 1563 nm and with mode spacing of around 140 GHz, as shown in Fig. 3.4. After the injection of CW light around the cavity mode of 1556.88 nm with injection power of -8 dBm, the cavity mode located at that wavelength was injection-locked and enhanced in optical intensity, while other modes were suppressed significantly. The intensity difference between the locked mode at 1556.88 nm and the other side modes was more than 40 dB, as shown in the solid curve of Fig. 3.4 (a), which is similar with the simulated results in trend as shown in Fig. 3.1. This high SMSR and a narrow spectral width were observed even after a 10-Gb/s data signal was modulated to the laser, as shown in Fig. 3.4 (b). Note that the injection-locked wavelength was slightly shifted towards the long wavelength side as discussed in Section 3.2. The significantly reduced linewidth after injection-locking helps to achieve a larger dispersion tolerance and considerably reduce crosstalk from adjacent channels when multiple WDM channels are transmitted.

In a practical WDM-PON, the light source in each ONU should be able to work with any WDM channel. To achieve this, FP-LD has to be able to be injection-locked at any of the selected cavity modes. The colorless operation of the externally injected FP-LD was studied by measuring the SMSR of its output spectrum with different injection wavelength. The injection wavelengths were adjusted around the cavity modes to get the optimum SMSR. Figure 3.8 shows the measured SMSR of the directly modulated FP-LD with different injection-locked cavity modes. Here, all the 16 cavity modes (refer to Fig. 3.4(a)) can be individually selected with high SMSR.

As shown in Fig. 3.5, flat SMSRs with less than 3-dB ripple is achieved for 12 central wavelengths. Even for the wavelengths located at the far edge sides, the SMSRs are still greater than 30 dB. It should also be noted that the injection-locked FP-LD is not as completely colorless as an RSOA which will be discussed in Chapter 5 and 6. The mode separation of FP-LDs should be made in accordance with the channel spacing. However, the wavelength of a FP-LD can be shifted via temperature variation to match the wavelength arrangement if necessary.

Fig. 3.5. Measured side mode suppression ratio of the injection-locked FP-LD (at room temperature). Bias current: 40 mA.

In addition to the single mode operation and colorless performance, injection-locking can also drastically suppress the relaxation oscillation. Fig. 3.6 (a)-(d) show the simulated back-to-back (BTB) waveforms of the directly modulated free-running FP-LD and injection-locked FP-LD. Without injection-locking, the overshoot was very strong because of the relaxation oscillation. This relaxation oscillation was

considerably suppressed when the FP-LD was injection-locked by an external seeding light. Compared with the waveform before injection-locking, the DC component (or logical “0” level) was slightly increased after injection-locking. This slightly reduces extinction ratio, but is not expected to introduce any significant penalty as the transmission distance is short, particularly in the access and metro applications.

Fig. 3.6. Waveforms and eye diagrams of FP-LD with/without injection locking. Simulated waveforms for 2.5-Gb/s data modulated free-running FP-LD (a), and injection-locked FP-LD (b). Simulated waveforms for 10-Gb/s data modulated free-running FP-LD (c) and injection-locked FP-LD (d). Measured eye diagrams for 10-Gb/s data modulated free-running FP-LD and injection-locked FP-LD.

The observations of the suppression for relaxation oscillation were also verified in the experiments. Fig. 3.6(e) and Fig. 3.6(f) show the measured eye diagrams of FP-LD with and without coherent light injection-locking. As shown in Fig. 3.6 (f), the relaxation oscillation is significantly suppressed with external light injection.

3.4 High speed WDM-PON with coherent light injection-locked FP-LDs

The above study has shown that FP-LDs with external injection can be used as potential light sources of optical access networks due to its low-cost and coreless operation. Compared with the spectrum-sliced light source, externally injection-locked FP-LDs have many advantages, such as high output power, direct modulation and low relative intensity noise. So far, the typical seeding light used for injection locking FP-LDs is the narrow-band ASE noise spectrum-sliced from an EDFA as discussed in Chapter 2. Using such a scheme, upstream transmission has been demonstrated with the bit rate up to 1.25 Gb/s.

However, Using FP-LDs that are injection-locked by spectrum-sliced broadband incoherent light source, the data rate is still limited because of the conversion of excess intensity noise (IN) from the seeding light to the FP-LDs. In order to further increase the data rate, the use of high-quality coherent seeding light sources is a choice. But coherent seeding light source is essentially more costly than incoherent one. In the remaining of this section, a novel architecture for high speed WDM-PONs is proposed, in which the costly coherent seeding light source is shared among different PONs so that the overall cost can be considerably reduced.

3.4.1 Proposed WDM-PON architecture

Fig. 3.7. Proposed architecture for high speed WDM-PON with shared coherent seeding lights.

Fig. 3.7 shows the schematic of the proposed WDM-PON architecture using coherent light injection-locked FP-LDs. In the CO, there are two sets of continuous-wavelength laser sources, one of which is used as the uplink seeding light source and the other as the downlink seeding light source. In the following discussions, it is assumed that the downlink and uplink are operated at different wavebands, including C band and/or L band. As shown in Fig. 3.7, the CW laser outputs for the uplink or downlink seeding are multiplexed by an optical multiplexer (MUX1 or MUX2) and pass through a depolarizer (Dep), which converts a linearly polarized light into a depolarized light, thus eliminating the polarization-dependence of the conventional injection-locking. These multiplexed and depolarized lights are used as the WDM seeding lights. As shown in Fig. 3.7, the multiplexed seeding lights are split into many parts by a power

splitter. Each split branch is then amplified through an EDFA to compensate the splitting loss. If necessary, the split branch can be further split again by another power splitter. Each output of the second splitter can be used as the seeding lights for the downlink or the uplink of one WDM-PON. Therefore, a single set of WDM laser sources can be shared by many WDM-PONs whose OLTs are located in the same central office. This is expected to significantly reduce the cost for the deployment of WDM-PONs. Considering the sharing of seed light and low-cost of directly modulated FP-LDs, the scheme is expected to be cost-effective.

Within each WDM-PON, a split branch of the downlink seeding light is fed into the FP-LDs via an optical circulator and a demultiplexer (DMUX1) such that each FP-LD is injection-locked to a single longitudinal mode. The injection-locked FP-LDs are then directly modulated with downlink data, producing the downlink optical signals. The downlink signals are then combined with the uplink seeding light by a coarse WDM coupler and launched into a feeder fiber (standard single mode fiber) via an optical circulator. The combined downlink signals and the uplink CW seeding light are then demultiplexed at the remote node (RN) by a cyclic arrayed waveguide grating (AWG). Note that the wavelengths for the uplink and downlink are allocated in such a way that the uplink wavelengths occupy one free spectrum range (FSR) of the cyclic AWG, and the downlink wavelengths occupy another FSR of the AWG. Due to the periodicity of the cyclic AWG [124], the uplink CW seeding light at λ_{ui} and the downlink signal at λ_{di} go to the same i -th optical network unit (ONU _{i} , $i=1, 2, \dots, n$), where they are separated by another coarse WDM coupler. The downlink signal is directly detected by a photo-detector. The uplink seeding light at λ_{ui} is then fed into a temperature-controlled FP-LD to injection-lock its cavity mode at λ_{ui} . The FP-LD is

directly modulated with uplink data and its output is combined with other uplink channels at the RN by the AWG and sent back to the central office via the same feeder fiber. Note that only one representative ONU (i.e., ONU1) is shown in Fig. 3.7 to make the architecture clearer. Compared with a conventional downlink transmitter using a DFB laser and an external modulator, a CW light injection-locked FP-LD provides better link budget since it does not suffer from power loss arising from the external modulator and also needs a much lower driving voltage.

3.4.2 Experimental results and discussions

Fig. 3.8. Experimental setup for high speed WDM-PON upstream transmission.

To demonstrate the proposed high speed WDM-PON, an experiment was carried out to investigate its transmission performance. The experimental setup for the uplink transmission is shown in Fig. 3.8. Sixteen distributed feedback lasers (DFB) were combined together as a multi-channel coherent seeding light source through an AWG (AWG1). The power of each channel was 3 dBm. The combined seeding light was fed to an optical attenuator (ATT1) with 12-dB insertion loss, which was

intended to emulate an optical splitter with 16 branches. The power of each channel of the combined light source was then amplified to 6 dBm, which was limited by the gain of the EDFA used. Another tunable optical attenuator (ATT2) was inserted following the EDFA to emulate another power splitter and to adjust the injected light power. The length of the feeder fiber was 10 km. The depolarizer was temporarily replaced with a polarization controller (PC) before injection. The combined seeding light was demultiplexed by AWG2 at the RN. The 16 demultiplexed seeding lights were then fed into 16 corresponding ONUs to injection-lock their corresponding FP-LDs. In this experiment, the same FP-LD was used as the upstream transmitter for each ONU by injection-locking different individual modes. The FP-LD was injection-locked to a CW seeding light channel and directly modulated with a 10-Gb/s upstream data. The received upstream optical power was monitored by a power meter (PM) through a 10:90 coupler at the CO. The detected upstream signal was measured by a bit error rate tester (BERT) after a receiver (Rx), which consists of a PIN photo detector, a limiting amplifier (LA) and a clock and data recovery module (CDR).

Fig. 3.9 shows the measured receiver sensitivities at 10^{-9} BER after 10-km uplink transmission as a function of injected CW light power for four different uplink channels (wavelengths). The back-to-back receiver sensitivity was -18.3 dBm without injection, which was limited by the performance of the non-optimized optical receiver. As shown in Fig. 3.9, the sensitivity is significantly improved with the increase of the injection power when the injection power is less than a certain critical value (e.g. approximately -8 dBm and -8.6 dBm for the cases with injection wavelength of 1562.5 nm and 1556.88 nm, respectively). This is partly because the modulation bandwidth increases with the increase of the injection power, as shown in Fig. 3.3. Another reason is the

Fig. 3.9. Measured receiver sensitivity as a function of the injected light power for different injection wavelengths.

improved SMSR of the injection-locked FP-LD when injection power is higher. Once injection power is too low, it is not sufficient to lock the FP-LD well. For example, at the injection wavelength of 1555.786 nm, BER less than 10^{-9} was not achieved without BER floor when the injection power was lower than -9.1 dBm. However, the receiver sensitivity remains almost unchanged when the injection power is greater than the critical value. As the injection power was increased to greater than -8.6 dBm, the sensitivity remained at about -17.2 dBm for the injection wavelength of 1555.786 nm. Further increase in the injection power from -8.6 dBm to -2 dBm resulted in no noticeable change in receiver sensitivity. This is desirable for practical systems since the injection power may fluctuate because of various reasons including component degradation. Considering the power loss between light source and the FP-LD in the experiments was about 7.5 dB (including the insertion loss of circulator, feeder fiber, AWG and PC) and the required injection optical power was -8 dBm, the required

output power of seeding light source (measured after ATT2 in Fig. 3.8) for each channel was -0.5 dBm, which can be easily met with typical DFB lasers and EDFAs.

In order to demonstrate that the FP-LD can indeed be used as an wavelength independent light source with many wavelength channels selectable using the injected CW light, the FP-LD was injection-locked at any of the 16 cavity modes individually to measure their BER performance. When the injection wavelength was located at the relatively strong cavity modes (close to the gain spectrum peak) such as 1555.786 nm and 1556.88 nm, the receiver sensitivity was better. On the other hand, when relatively weak cavity modes (1545.54 nm and 1562.502 nm) were used for injection-locking, the receiver sensitivity became worse because the SMSR ratio was relatively low at these wavelengths for a given injection power.

Fig. 3.10. Minimum required injection power for all channels with a certain FP-LD.

Fig. 3.10 shows the measured minimum required injection power for achieving BER

of 10^{-9} after 10-km uplink transmission for different injection wavelengths. Here, the received optical power at the receiver was fixed at -15 dBm. The minimal required injection power for the best case was -9 dBm at both wavelengths of 1555.786 nm and 1556.88 nm. While it was -8.2 dBm for the worst case at the edge wavelength of 1562.502 nm. Even when the injection wavelength was located at the far edge of the FP-LD gain spectrum, $\text{BER} < 10^{-9}$ was still achieved without BER floor when the injected optical power was greater than -8 dBm. This is an important advantage of using FP-LD as the uplink wavelength source of ONUs. That is, many wavelengths can be selected flexibly, thus reducing the inventory requirement of the service providers for WDM-PON operation. The relatively high required injection power maybe due to the high reflection of the front facet of the FP cavity since the laser diode used in this experiments is without any coating. A laser with high-reflection (HR) coating at rear facet and anti-reflection (AR) coating at front facet should reduce the required injection power.

In practical systems, the wavelengths of both the seeding light source and the FP-LD vary with the temperature and bias current. Even with a temperature controller, its central wavelength may still fluctuate slightly and randomly. So it is important to examine the detuning range between the injected wavelength and injection-locked wavelength. Large detuning range is desirable to offer more operational margin. The stable locking range of the externally injection-locked semiconductor lasers has been studied widely in past decades [125-127]. However, once the injection-locked FP-LD is directly modulated with a data, the BER performance of FP-LD still varies depending on the SMSR even in the stable locking range. In this section, the effective locking range was experimentally studied by measuring BERs after 10-km uplink

transmission while detuning the external injection wavelength. In this experiment, one DFB laser was temporarily replaced with a tunable laser to adjust the wavelength detuning and the cavity mode with a wavelength of 1556.87 nm was used for testing the injection-locking range. The measured results are shown in Fig. 3.11. Here, the injected optical power and bias current were maintained at -7 dBm and 40 mA, respectively, and the received optical power at the receiver was set at -15.5 dBm for all the cases. As shown in Fig. 3.11, the BER is dependent on the injected wavelength, and the detuning range is about 0.029 nm (3.6 GHz) for which the BER less than 10^{-9} was achieved. This large tolerance to injection wavelength mismatch is of practical importance.

Fig. 3.11. BER vs. injection wavelength detuning.

Fig. 3.12 shows the measured bit error rate versus received optical power for various uplink transmission distances. Here, the injected optical power was fixed at -7

Fig. 3.12. Measured bit error rate versus received optical power for various uplink transmission distances.

Fig. 3.13. Eye diagrams of FP-LD after 21-km uplink transmission.

dBm. As shown in Fig. 3.12, the power penalty increases with the transmission distance. For the back-to-back (BTB) case, the receiver sensitivity at BER of 10^{-9} was -18.3 dBm. This was degraded to -17.1 dBm, -16.2 dBm and -14.8 dBm for the transmission fiber of 10 km, 15 km and 18.8 km, respectively. For longer transmission fiber, the BER floor occurs at $\text{BER} > 10^{-9}$ may be due to chromatic dispersion and backward reflection.

The experiments demonstrated the chromatic dispersion is main reason for the BER degradation. Fig. 3.13 shows the eye diagrams of the 21-km uplink transmission without and with dispersion compensation. Apparently, significant distortion of the eye diagram occurred after 21-km transmission without dispersion compensation. In order to study the influence of the dispersion, one piece of dispersion compensation fiber (DCF) with -340 ps/nm was inserted before the demultiplexer. With the dispersion compensation, the eye opening was considerably improved. The receiver sensitivity at BER of 10^{-9} for 21-km transmission with dispersion compensation was -16.8 dBm, as shown in Fig. 3.12 . This is much better than the case of 15-km SMF and 18.8-km SMF without dispersion compensation. Note that even with the dispersion compensation, the power penalty for 21-km uplink transmission was still slightly greater than that for 10-km transmission. This might be due to backward reflections of the seeding light, including the laser front-facet reflection, Rayleigh backscattering and stimulated Brillouin scattering (SBS). (The impact of Rayleigh backscattering will be discussed in Chapter 5). These reflections were mixed with the uplink data which could not be separated by the WDM demultiplexer, and contributed to in-band crosstalk.

3.4.3 Applications to long-reach networks

In the previous subsection, the FP-LD with external optical injection shows a good performance in 10-Gb/s transmission. Since the FP-LD has some significant advantages, e.g. low cost and high speed direct modulation, it will be very promising if it can be applied to longer distance transmission systems. In this subsection, experiments are carried out to investigate the transmission performance for the long-reach link using the proposed CW light injection-locked FP-LDs as the transmitters. The experimental setup is shown in Fig. 3.14. The main difference

between this setup with that in Fig. 3.8 is that, in this experiment, the CW light injected into the FP-LDs does not go through the feeder fiber, which avoid the impact of the backward reflection. All other experimental conditions are same as that in Fig. 3.8. In the demonstration of the long link transmission, the emphasis is on future applications to long-reach WDM-PONs and metropolitan-scale optical networks.

Fig. 3.14. Experimental setup for long-reach link using the proposed high speed light source.

Fig. 3.15 shows the BER versus the received optical power for different downlink transmission distances. Here, the injected optical power was fixed at -7 dBm, while the transmission distance was varied in a large range from 10 km to 240 km. When the transmission distance was 10 km and 15 km, the downlink signal received at the ONU was in good eye opening without dispersion compensation. Once the transmission fiber is longer than 20 km, fiber dispersion induces considerable distortion to the received signal. However, with dispersion compensation, the proposed light source can be used to extend the application further to long-reach networks, such as the metropolitan-scale

optical networks. Fig. 3.15 shows that the transmissions over 40-km, 80-km, 160-km and 240-km SMF could be achievable with 0.5-dB, 0.9-dB, 1.7-dB and 3.6-dB power penalty, respectively. The eye diagrams with 160-km and 240-km transmission are shown in the insets. Here, the transmission link was divided into several spans and each span was with 80-km SMF fiber. The dispersion in each span was fully compensated by a dispersion compensation fiber (DCF). Two EDFAs in each span were used to compensate the power loss induced by transmission fiber and DCF, which were located before and after the DCF.

Fig. 3.15. BER versus the received optical power for different downlink transmission distances. Inset: the eye diagrams with 160-km and 240-km transmission.

The long extended transmission distance not only makes the CW light injected FP-LD as a potential light source in metropolitan-scale optical networks, but also benefits to

long-reach WDM-PONs. Generally, a typical transmission distance between a CO and each subscriber (ONU) in a PON is about 10 km or 20 km. Ideally, the service coverage with a CO is proportional to the square of the transmission length of the PON. Then, if a long-reach transmission is possible from CO to ONU, the coverage to be serviced by one CO can be increased greatly [128-129]. For example, when extending the maximum transmission distance of a PON from 20 km to 60 km, it is possible to provide services for a certain area (where the ender users are sparsely distributed) by using only one CO, while the same area may require 9 COs to cover the services when using a PON with 20-km reach. Then, the traffic generated on the subscriber's premises can be directly transmitted to an edge switch in the long-haul network [128]. As a result, the hierarchy of the overall network is simplified, and the equipment and management costs can be reduced considerably by reducing the number of COs.

3.5 Elimination of polarization effects

The performance of injection-locked FP-LDs intrinsically depends on the polarization state of the injected light. In a practical system, the polarization state of the injected light varies due to the temperature change and strain of fiber and environment which are difficult to predict and control. Therefore, polarization-insensitive injection-locking scheme is crucial. Unfortunately, the experiment has shown that the commercial depolarizer based on delayed polarization orthogonal multiplexing technique could not effectively eliminate the polarization dependence. Different from non-coherent injection, coherent injection-locking requires more diversified polarization states of the injected light to make it polarization insensitive since the optical phase is also involved in the interaction between the optical fields of the

FP-LD and the injected light [130-131]. To achieve better and random polarization diversity, the use of a dual fiber ring structure combined with a commercially available conventional depolarizer is proposed.

The fiber depolarizer used in the experiments is shown in Fig. 3.16. The objective is to achieve more polarization diversity for injected CW light. The fiber ring is made of a single-mode fiber directional coupler [132]. Two pigtails of the coupler are spliced together to form a fiber ring. A polarization controller is placed inside the ring. Once the light transmits in this loop, its polarization will be changed by a small value depending on the PC. The more loops the light transmits in the ring, the more polarization diversity states the light will have. A commercial optical fiber depolarizer is used together with the dual fiber ring to make the seeding light have more polarization diversity states. With this scheme, the degree of polarization was smaller than 1% and more diversified polarization states are achieved for injected CW light. As a result, the polarization dependence of the proposed seeding light source can be greatly reduced.

Dep: depolarizer, DC: directional coupler, PC: polarization controller

Fig. 3.16. Fiber depolarizer with more polarization diversity

Fig. 3.17 shows the back-to-back BER performance with different polarization states. Here, the injection wavelength was 1555.786 nm, the injection power was -2 dBm and the received optical power was -15.5 dBm. In this experiment, the fiber ring depolarizer was not temperature-controlled and the induced phase fluctuation in the ring introduced some instability in the output of the depolarizer. Author believes that the required injection power can be reduced considerably if a stabilized dual ring depolarizer is used. In experiments, the angle of the half-wave plate in PC was rotated over 0 to 180 degrees, which corresponds to the rotation range of 0 - 360 degree in the polarization state of the seeding light. Fig. 3.17 shows that over the whole 0 - 180 degree rotation angle of the half-wave plate, only slight BER variation is observed due to random polarization states of the injected light. This result shows that the proposed depolarization configuration is indeed polarization insensitive for injection-locking.

Fig. 3.17. BER performance as a function of rotation angle of half-wave plate in the polarization controller.

3.6 Conclusions

In this chapter, the performance of the injection-locked FP-LDs was first studied and showed that injection-locking offers quasi-single wavelength operation, increased modulation bandwidth, reduced relaxation oscillation and narrower linewidth. Then, a high-speed light source using coherent light injection-locked FP-LDs was proposed. A 10-Gb/s WDM-PON over 10-km as well as 15-km single mode feeder fiber was experimentally investigated using the proposed light source and very good BER performance was achieved with injection locking any of the 16 cavity modes of the FP-LD used. Performance evaluations in terms of injection power, transmission distance and wavelength detuning were also investigated. With proper dispersion compensation, the proposed light source was demonstrated to be useful for longer transmission needed in long-reach WDM-PONs and metropolitan optical networks. The allowable wavelength detuning range at BER of 10^{-9} was observed to be up to 3.6 GHz. In addition, the polarization-insensitive injection-locking scheme was also demonstrated by combining a conventional depolarizer and a dual-fiber ring structure. In general, a 10-Gb/s light source for WDM-PON based on coherent light injection-locked FP-LDs was proposed. Its transmission performance and possible applications in long-reach networks were investigated. The proposed architecture is cost-effective since the multiple CW seeding light sources are shared by many WDM-PONs, and low-cost FP-LDs are used as light sources for data rates as high as 10 Gb/s.

Chapter 4

Optimization of Incoherent Light Injection-Locked FP-LDs in WDM-PONs

4.1 Overview

In Chapter 3, the low-cost FP-LDs injection-locked by external coherent light and their applications in high speed WDM-PONs have been studied. Compared with the coherent light injection-locked FP-LD, the data rate of spectrum-sliced incoherent light injection-locked FP-LD may be limited at about 1.25 Gb/s due to the intensity noise (IN) of the spectrum-sliced light, as discussed in Chapter 2. However, incoherent light injection has an essential advantage, polarization insensitivity. As a result, FP-LDs injection-locked by the incoherent seeding light, e.g. spectrum-sliced ASE, have been widely studied in WDM-PONs in the past years. Most studies were focused on novel architectures and their applications in WDM-PONs. In this chapter, the optimization of the light source based on spectrum-sliced ASE injection-locked FP-LDs in WDM-PONs is studied. The filter bandwidth optimization, intensity noise suppression of the spectrum-sliced ASE and the optimization of front-facet reflectivity and operation conditions, such as bias current, operation temperature and injected mode location, of the FP-LDs are investigated in detail.

4.2 Introduction to incoherent light injection-locked FP-LDs

Incoherent light source gains a lot of attentions in WDM-PONs due to its low cost. In some early work, light-emitting diodes (LEDs), amplified spontaneous emission (ASE)

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source and reflective semiconductor optical amplifiers (RSOAs) have been simply spectrum-sliced with a narrow-bandwidth filter, e.g. arrayed waveguide grating, as WDM-PON light sources. Using these methods, it effectively eliminates the need of wavelength-specific optical transmitters at the customer premises. However, the methods with the simple spectrum-slicing technique have a major disadvantage, intrinsic high intensity noise. The high intensity noise inherently limits the bit rate of transmission data.

In the past years, the spectrum-sliced incoherent light has been proposed to be used as the seeding light for external injection of FP-LDs to suppress its high intensity noise. It is well known that the free-running FP-LD shows a multi-mode output and the distribution of the output spectrum is a function of time [94]. It is easy to observe the power of a particular cavity mode fluctuates randomly with time. The origin of the fluctuation is randomness of the spontaneous emission coupled to any cavity mode [32], [133]. Thus, the mode partition noise (MPN) of spectrum-sliced FP-LD is high. Since the mode power is proportional to the spontaneous emission coupled to the lasing mode, it is possible to achieve a single-mode oscillation from an FP-LD by injecting a narrow-band ASE. In this case, a mode that is the nearest to the peak wavelength of the injected ASE can be locked and the other modes may be suppressed. Its operation principle is the same as coherent light injection-locked FP-LD model as described in Chapter 3. As a result, the MPN of an FP-LD may be decreased significantly [134-135] with external ASE injection.

The use of the spectrum-sliced ASE for the injection locking of FP-LDs and its application in WDM-PONs were first published by researchers of Korea Advanced Institute of Science and Technology (KAIST) in 2000 [94]. Their proposed light source

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is shown in Fig. 4.1. The broad-band ASE source was a two-stage EDFA pumped with laser diodes at 1480 nm. A bandpass filter with a bandwidth of 9 nm was used between two stages of the EDFA to limit the spectral width of the ASE within one free spectral range of the arrayed waveguide grating (AWG). The broad-band ASE was sliced spectrally by the AWG, and each spectrum-sliced ASE was then injected into an FP-LD.

Fig. 4.1 WDM-PON with ASE injection-locked FP-LDs [94].

With this architecture, the authors demonstrated a 155-Mb/s uplink transmission over the WDM-PON. In reference [94], a 28-dB side mode suppression ratio (SMSR) was achieved when the injected ASE power and bias current were -14 dBm and 8 mA (threshold current is 5 mA), respectively. It is noted that the bias current was set at very low level in that work and as a result, the injection power was quite low. Generally, the electrical modulation bandwidth of the FP-LD increases with the increase of the bias current. In order to get a large modulation bandwidth, the bias current should be much larger than its threshold value. Unfortunately, with the increase of the bias current, the required injection power increases significantly. Early works reported in literature demonstrated the uplink transmission at data rate of 155

Mb/s [94], [136]. In 2005, the researchers of Samsung Electronics demonstrated a 622 Mb/s uplink transmission and a 1.25-Gb/s downlink transmission in 10-km standard single mode fiber with this method [51]. However, to the best of the author's knowledge, there is no comprehensive study on the bandwidth effect and IN suppression of spectrum-sliced ASE source on the injection-locking of FP-LDs until now.

4.3 Optimization of bandwidth of the injected ASE seeding light

4.3.1 Broadband ASE source

The most popular broadband light source used for spectrum-sliced WDM-PONs is the ASE from an EDFA. Fig. 4.2 shows two configurations for broadband ASE light sources. The single stage structure shown in Fig. 4.2(a) is a simple conventional ASE source. The pump laser, which locates at the wavelength of 980 nm or 1480 nm, is launched into erbium doped fiber through a coarse WDM. Two isolators are used to block the backward ASE noise, reflection and any perturbation of external light. Without any filter in the single stage structure, the ASE source covers whole fluorescence spectrum. In some WDM-PONs, their upstream channels can not cover the whole fluorescence spectrum of the amplifier transitions. Fig. 4.2(b) shows a double-stage structure, which can offer more power that is concentrated in the WDM-PON operational wavelength range. Here, an optical filter is inserted between two EDFA stages. The bandwidth of the filter is around the free spectral range of AWGs used in the WDM-PONs and may be much smaller than the EDFA's fluorescence spectrum. Adjusting the coupling ratio of the 1×2 splitter, it is easy to make the second stage EDFA work in the saturated state and maximize the output power. The broadband filter can also be replaced with a comb filter to pre-compose all

WDM channels [137].

(a). Single stage broadband ASE Source

(b). Double-stage broadband ASE Source

Fig. 4.2. Broadband ASE source

In this chapter, the spectrum-sliced ASE with the double-stage ASE source is used to injection-lock FP-LDs. The following sections provides the detailed investigations on the spectrum-sliced ASE bandwidth optimization, intensity noise suppression of the injected ASE light and optimization of the FP-LDs including front-facet reflectivity and operation conditions such as bias current, temperature and mode location.

4.3.2 Bandwidth optimization of injected ASE light

The spectrum-sliced ASE injection-locked FP-LDs have some significant advantages.

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Similar to coherent light injection, the spectrum-sliced ASE can force the FP-LDs under single mode operation, and many cavity modes can be available for injection-locking. Besides, the ASE injection-locked FP-LDs are polarization insensitive due to the unpolarized aspect of the ASE source. Furthermore, the relatively wider ASE bandwidth makes it easier for injection wavelength matching compared with the coherent light injection. All these make ASE injection-locked FP-LDs promising in WDM-PONs.

However, spectrum-sliced ASE source inherently suffers from intensity noise (IN). Because the spontaneous emission is a random process and the excited ions relax from any broadened upper energy level to the ground level randomly, the emission power at a certain frequency is also random. Although the total power of the ASE is relatively stable, the relative intensity noise (RIN) of the any spectrum-sliced narrow-band spectrum is quite large. This intensity noise will be transferred to the injection-locked mode of the FP-LD when the spectrum-sliced ASE is used to injection-lock FP-LDs, which degrades the output performance of the injection-locked FP-LD. As reported, the intensity noise of the spectrum-sliced is dependent on the filter bandwidth [138-139]. Therefore, the output performance of an injection-locked FP-LD is affected by the filter bandwidth of the spectrum-sliced ASE source. However, so far, there is no comprehensive study on the impact of the slicing filter bandwidth on the injection locking of FP-LDs.

Fig. 4.3 shows the experimental setup for investigating the bandwidth effect on the uplink transmission performance. Two EDFAs were cascaded to form the broadband ASE source, with a band pass filter of 3-nm bandwidth in between to limit the ASE

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spectral width. The output power of the broadband ASE source was 16 dBm. The ASE source was then spectrum-sliced by a fiber Bragg grating (FBG) via an optical circulator. The sliced ASE source was injected into an FP-LD via another circulator with an insertion loss of 0.6 dB. To investigate the impact of spectrum width of the sliced ASE source, a number of uniform FBGs with a bandwidth of 0.2 nm, 0.30 nm, 0.4 nm, 0.58 nm and 0.68 nm, respectively, were used to slice the broadband ASE source. All the uniform FBGs were fabricated with the same phase mask and their central wavelengths were fixed to around 1555 nm by adjusting their respective strain to facilitate the comparison.

Fig. 4.3. Experimental setup for bandwidth optimization of the seeding light.

The optical spectra of the sliced narrow band ASE sources are shown in Fig. 4.4. The FP-LD was temperature controlled to align the cavity mode with the injected narrow band ASE signal. Being used as a light source, the FP-LD was directly modulated by pseudo-random bit series (PRBS) data with a word length of $2^{23}-1$ at 1.25 Gb/s, which

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was provided by a pulse and pattern generator (PPG). The output of FP-LD was then transmitted over a 10-km SMF and detected by a receiver (Rx) with a built-in avalanche photodetector (APD) and clock data recover (CDR), followed by a bit error rate tester (BERT) and digital communication analyzer (DCA). Note that the receiver used in Section 4.3 and 4.4 has a better sensitivity (about 2 dB) than that used in other sections. The FP-LD used in the experiment had a conventional facet reflectivity of 32% with no anti-reflection (AR) and high-reflection (HR) coating applied. It had a threshold current of 18 mA and was biased at 20 mA in this investigation to get sufficient modulation bandwidth.

Fig. 4.4. Optical spectra of narrow-band ASE seeding light spectrum-sliced with different FBGs.

Fig. 4.5 shows the output of the FP-LD without and with ASE injection (0.3-nm filter bandwidth). Without the ASE injection, the FP-LD exhibits multiple mode oscillation,

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while with the injection of 1.8-dBm ASE power (before taking into account the coupling losses between fiber pigtail and the FP-LD), single mode operation can be achieved with a SMSR about 30 dB.

Fig. 4.5. Optical spectra of the FP-LD with and without spectrum-sliced ASE injection.

Fig. 4.6 shows the measured SMSR as a function of injected ASE power for different filter bandwidths. The required injection power to achieve a given SMSR depends on the bias current and the bandwidth of the sliced ASE source. Basically a higher bias current offers a larger laser modulation bandwidth, while it also supports more cavity modes to oscillate, leading to a higher required injection power to achieve a given SMSR. For all the bandwidths evaluated, SMSR increases with the increase of injection power in a nearly linear relationship. Narrower band ASE source can achieve higher SMSR under the same injected ASE power, since its energy is more centralized and confined in the bandwidth range. This leads to higher efficiency in power utilization for injection-locking. It is expected that the required injection power can be reduced if AR

coating is applied to the FP-LD front facet, which will be discussed in Section 4.5.

Fig. 4.6. Side mode suppression ratio (SMSR) vs. injected ASE power.

Fig. 4.7 shows the receiver sensitivity (BER at 10^{-9}) as a function of SMSR with different filter bandwidths for the back-to-back (BTB) case. The FP-LD without ASE injection has the best receiver sensitivity (-36.1 dBm). While with injection, the receiver sensitivity degrades with the increase of SMSR for all the filter bandwidths evaluated. The performance degradation after ASE injection may be attributed to the reflected ASE noise from the front facet and intensity noise conversion from the sliced ASE source to the injection-locked FP-LD output. Furthermore, a higher SMSR requires a higher injection power, leading to increased reflection and intensity noise conversion. Fig. 4.7 also shows that injection-locking with a broader ASE bandwidth exhibits worse BTB receiver sensitivity since more injected ASE power is required to achieve the same SMSR, leading to stronger reflection and intensity noise conversion.

Fig. 4.7. Back-to-back receiver sensitivity vs. SMSR.

Fig. 4.8 shows the receiver sensitivity as a function of SMSR after 10-km SMF transmission. Compared with the BTB case, the receiver sensitivity after 10-km transmission degrades for all the filter bandwidths evaluated in this investigation due to the effects of fiber chromatic dispersion. Especially for the case with lower SMSR, the deterioration of the chromatic dispersion is much more serious. Although the free-running FP-LD shows best performance in the BTB case, it exhibits the worst receiver sensitivity (-27.7 dBm) after 10-km transmission. As shown in Fig. 4.8, with a narrow band ASE injection, the receiver sensitivity improves by at least 3.3 dB to 6.6 dB after 10-km SMF transmission for all the filter bandwidths evaluated compared with the free-running case. Please note that for each individual filter bandwidth, there exists an optimal SMSR that achieves the best receiver sensitivity. This may due to the combined effects of dispersion, intensity noise conversion and reflected ASE noise from the FP-LD front facet. For a low SMSR, dispersion impairment caused by the

other cavity modes is dominant while reflection and intensity noise conversion are less significant since less injection power was used. For a high SMSR, dispersion impairment becomes smaller while reflection and intensity noise conversion are more significant due to the largely increased injection ASE power. Fig. 4.8(b) also shows the optimal SMSR is lower for a larger filter bandwidth. This is because, for wider seeding light, the injection-locked mode of the FP-LD is wider so that more power is confined in it and other modes occupy less percentage of the total power for a given SMSR, leading to reduced dispersion impairment caused by other side modes.

Fig. 4.8. Receiver sensitivity vs. SMSR after 10-km transmission.

For the 10-km SMF transmission at 1.25 Gb/s evaluated in this experiment, the optimal receiver sensitivity using a larger filter bandwidth exhibits slightly better sensitivity. Fig. 4.9 shows the receiver sensitivity after 10-km SMF transmission versus filter bandwidth under different SMSRs. For each SMSR, there is a corresponding optimal

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filter bandwidth. When the SMSR is 28 dB, the optimal bandwidth is around 0.3 nm. Whereas, when the SMSR is 26 dB, the optimal bandwidth increases obviously. In the experiments, due to the shortage of corresponding filter, the exact optimal bandwidth was not achieved. However, from the trend of the existing experimental results, the optimal bandwidth should be around 0.5 nm. Further more, when the SMSR is between 24 dB and 22 dB, the optimal filter bandwidth is increased to around 0.6 nm. Therefore, the optimal filter bandwidth is relatively larger for a lower SMSR. This is also attributed to the combined contribution of dispersion, IN conversion and reflection. In the experiments, for a 10-km link length and 1.25-Gb/s bit rate, the best receiver sensitivity is about -34.3 dBm and the corresponding optimal bandwidth is around 0.58 nm.

Fig. 4.9. Receiver sensitivity vs. filter bandwidth for different SMSRs.

In a practical system, for a given broadband ASE source, the power spectrum density is

constant no matter what kind of filters is used. Therefore, it is useful to examine the optimized filter bandwidth with a constant seeding power density. Fig. 4.10 shows the measured receiver sensitivity as a function of filter bandwidth with a constant seeding power density. Here, the power density of the broadband ASE (before spectra slicing) was about 3.5 mw/nm. In all investigated values, the optimized filter bandwidth was still around 0.58 nm. However, the acceptable filter bandwidth is much tolerant to deviation from the optimal value. When the bandwidth of the filter is located between 0.4 nm and 0.6 nm, the receiver sensitivity is quite good.

Fig. 4.10. Receiver sensitivity vs. filter bandwidth with a constant seeding power density.

4.4 Intensity noise suppression of injected ASE seeding light

As discussed above, a spectrum-sliced ASE source inherently suffers from intensity noise (IN). This IN of the sliced ASE source is converted to the injection-locked mode and affects the output performance of the wavelength-locked FP-LD. An SOA operated

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under saturation condition can be used to suppress the IN of the sliced ASE source for injection-locking an FP-LD. The noise suppression effect of an SOA can be understood as follows. The propagation of optical power P and carrier density $N(z, t)$ in an SOA is described by the following equations [140-142].

$$\frac{\partial P}{\partial z} - \frac{1}{v_g} \frac{\partial P}{\partial t} = [\Gamma g(N) - a_{\text{int}}] P, \quad (4-1)$$

$$\frac{\partial N}{\partial t} = \frac{J}{qd} - \frac{N}{\tau} - \frac{\Gamma}{\hbar v A} g(N) P, \quad (4-2)$$

where v_g is the group velocity, Γ the mode confinement, $g(N)$ the gain coefficient, a_{int} the internal loss, J the injected current density, q the electronic charge, A the active region area, d the active layer thickness of the SOA, τ the spontaneous carrier lifetime, and ν the input central frequency.

Considering the case where there is a large saturating power of the optical beam and a small perturbing signal representing the noise superimposed on it, the optical power and carrier density can be linearized and described as

$$P = P_0 + \frac{1}{2\pi} \int_{-\infty}^{+\infty} \Delta P(\Omega) \exp(j\Omega t) d\Omega, \quad (4-3)$$

$$N = N_0 + \frac{1}{2\pi} \int_{-\infty}^{+\infty} \Delta N(\Omega) \exp(j\Omega t) d\Omega, \quad (4-4)$$

where P_0 and N_0 are time average value. ΔP and ΔN stand for the noise. Ω is the angular frequency at which the perturbing signal varies. By submitting (4-3) and (4-4) to (4-1) and (4-2), the relative intensity noise suppression ratio (electrical) can be achieved in decibel as [142]

$$\eta = 20(\log e) \int_0^L dz \frac{\Gamma g(N_0) \frac{\Gamma g' P_0}{Ahv} \left(\frac{1}{\tau_d} + \frac{\Gamma g' P_0(z)}{Ahv} \right)}{\Omega^2 + \left(\frac{1}{\tau_d} + \frac{\Gamma g' P_0(z)}{Ahv} \right)^2}, \quad (4-5)$$

Where g' is the differential gain coefficient. Equation (4-5) shows that P_0 , and $\Gamma g(N_0)$ have to be as large as possible for getting a high noise reduction. For a given SOA, P_0 , and $\Gamma g(N_0)$ depend on the input power and bias current. Higher input power and larger bias current is desirable to get a greater reduction in IN [142].

Fig. 4.11. Experimental configuration for intensity noise suppression.

IN suppression of the injected ASE source reduces the IN conversion to the injection-locked mode of the FP-LD and improves its output performance. To demonstrate this, an experimental configuration with a saturated SOA, shown in Fig. 4.11, was carried out. The broadband ASE source was first spectrum-sliced via an FBG with a central wavelength of 1555 nm and passed through an SOA to suppress its IN and then injected into a directly modulated FP-LD as a seeding light. The SOA in the experiment is a commercial product that is polarization insensitive. It has a noise figure

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of 6 dB and a saturation output power of 10 dBm. The input power of SOA was 0 dBm which was limited by the power of ASE source. Other experimental conditions were the same as the bandwidth effect investigation shown in Fig. 4.3.

Fig. 4.12. Measured BER vs. received power after 10-km transmission with a 3-dB filter bandwidth of 0.4 nm. (SMSR = 28dB).

Fig. 4.12 shows the measured BER as a function of received optical power after 10-km SMF transmission with a 3-dB filter bandwidth of 0.4 nm. Without using the SOA, the strong intensity noise from the sliced ASE noise is transferred to the FP-LD output. With the use of the SOA, the IN of the sliced ASE noise is suppressed considerably and hence the intensity noise at the output of the injection-locked FP-LD is also reduced, leading to improved receiver sensitivity. The improvement was about 0.3 dB in the experiment, as shown in Fig. 4.12. Since its saturation power was quite high, the SOA can not work in deep saturation condition. The author believes a SOA with lower saturation power can improve the receiver sensitivity more significantly.

Fig. 4.13. Measured BER vs. received power after 10-km transmission with a 3-dB filter bandwidth of 0.68 nm. (SMSR = 28dB).

The improvement in receiver sensitivity is also observed in the BER evaluation with 0.68-nm bandwidth, as shown in Fig. 4.13. But the amount of the improvement was not as significant as that of 0.4-nm bandwidth, as the spectrum-slicing induced IN is smaller in the former case. Since reflected ASE noise from the front facet also contributes to the performance degradation, it is believed that the receiver sensitivity improvement will be more significant if the FP-LD front facet is anti-reflection coated, which will be discussed in the next section.

The performance of the injection-locked FP-LD after 10-km transmission with a different value of SMSR has also been evaluated. Here the filter bandwidth was maintained at 0.4 nm, and SMSR was reduced from 28 dB to 25 dB. Fig. 4.14(a) and (b) show the measured BER as a function of received optical power with 25-dB SMSR for the cases of BTB and after 10-km transmission, respectively. The

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improvement in receiver sensitivity due to the noise suppression of the SOA is around 0.26 dB, as shown in Fig. 4.14(b). At the lower SMSR, the receiver sensitivity was also improved when the intensity noise of injected ASE source was suppressed. But the amount of improvement was not as significant as when SMSR is higher. This may be attributed to the lower required injection power, leading to less IN conversion to the FP-LD output.

Fig. 4.14. BER vs. received power with SMSR = 25dB. (a) BTB, and (b) after 10-km transmission.

Fig. 4.15. Experimental setup for investigating the influence of the reflectivity of the FP-LD cavity.

4.5 Study of cavity reflectivity and operation conditions of FP-LD

Beside the bandwidth and IN of the spectrum-sliced ASE, the FP-LD itself, including its facet reflectivity, operation temperature and bias current can also influence the output performance of injection-locked FP-LD. In this section, author will study this aspect.

Fig. 4.15 is the experimental setup. Two EDFAs were cascaded to generate broadband incoherent ASE light. The ASE source was spectrum-sliced by an AWG via an optical circulator. The AWG has a 3-B bandwidth of around 0.45 nm. The central wavelength of the spectrum-sliced ASE source injected into FP-LDs was changed by selecting different output channels of the AWG. Three FP-LDs were used in this investigation. Two of them were customized with the same rear-facet reflectivity of 90%, but different front-facet reflectivity of 3% and 10%, respectively. The other FP-LD was

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un-coated with reflectivity of 32% for both facets. The threshold currents of the three FP-LDs are 18.5 mA, 16 mA and 18 mA, respectively. They were biased above 22 mA to get sufficient modulation bandwidth. Each FP-LD was temperature controlled to align its selected cavity mode with the wavelength of injected spectrum-sliced ASE noise. The FP-LDs were modulated directly by a PRBS with a word length of $2^{23}-1$ at 1.25 Gb/s provided by a PPG. The modulation voltage was 2 V_{pp}. The output of the three FP-LDs was transmitted over 10-km SMF, respectively, and detected by an optical receiver (Rx).

4.5.1 Impact of laser front-facet reflectivity

Firstly, the impact of the laser front-facet reflectivity was investigated. Here the author measured the receiver sensitivities of the three FP-LDs with front-facet reflectivities of 3%, 10% and 32% for the back-to-back case and the 10-km transmission case. The operation temperature of the FP-LDs was maintained at around 20 °C. Their optical spectra are shown in Fig. 4.16. Here, the bias current for all three FP-LD was 25 mA and their free spectrum ranges are 0.8 nm, 1.1 nm and 1.1 nm, respectively. The central wavelengths of spectrum-sliced ASE noise injected into the FP-LDs were located around the strong mode at 1538.75 nm, 1553.81 nm and 1554.28 nm, respectively. At each measurement of receiver sensitivity, the bias current of the FP-LDs was adjusted and the temperature of the FP-LDs was also slightly adjusted to get the minimal receiver sensitivity.

The measured BER performances of the directly modulated FP-LDs with narrow band ASE injection are shown in Fig. 4.17. The performance of the FP-LD with 3% front-facet reflectivity had the best receiver sensitivity at a given input ASE power as

Fig. 4.16. Optical spectra of the FP-LD with different front-facet reflectivity. (a) 3%, (b) 10%, (c) 32%.

well as the largest injection power operation margin for all the three lasers evaluated.

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This is because the reflected ASE noise power of the FP-LD with 3% front-facet reflectivity is the smallest among the three FP-LDs. While the laser with 10% front-facet reflectivity exhibits just slightly worse receiver sensitivity compared with that of 3% reflection, and further reducing the reflectivity is not necessary to give better performance. Basically, too high front-facet reflectivity induces more reflected ASE while too low front-facet reflectivity may not be able to provide sufficient modulation bandwidth. Considering the results obtained for 1% reflectivity [94], it is expected that 1%-10% would be a good range for front-facet reflectivity of FP-LDs. Fig. 4.17 shows that receiver sensitivity improves with the increase of injected ASE power. This is due to a higher SMSR achieved with a higher injection ASE power. It also shows that performance of FP-LDs after 10-km transmission is slightly degraded (around 0.2-dB degradation for all ASE injection powers measured) compared with the BTB case due to fiber dispersion. The difference are very small because of its high SMSR (>30 dB).

Fig. 4.17. Measured receiver sensitivity as a function of injected ASE power for FP-LDs with front-facet reflectivity of 3%, 10% and 32%. Hollow: back to back, Solid: after 10-km transmission.

4.5.2 Impact of operation temperature

The impact of operation temperature of FP-LDs is investigated in this section. Large temperature operation range is desirable for practical implementation. Here the receiver sensitivity of the FP-LD with front-facet reflectivity of 3% after 10-km transmission at operation temperature of around 20 °C, 27 °C and 50 °C, respectively, was measured. The central wavelengths of the spectrum-sliced ASE noise were 1538.75nm, 1543.6nm, 1551.44nm, respectively. At each measurement of receiver sensitivity, the bias current of the FP-LD was adjusted and temperature of the FP-LD was slightly adjusted to get the optimal receiver sensitivity.

Fig. 4.18. Measured receiver sensitivity as a function of injected ASE power with different operation temperature.

Fig. 4.18 gives receiver sensitivities as a function of injected ASE power under the operation temperature of 20 °C, 27 °C and 50 °C respectively. Operating the FP-LD at

low temperature has better receiver sensitivity, while operating at high temperature has slightly broader operation range for injected ASE power. In this experiment, operating at 20 °C, it has the minimal receiver sensitivity, -32 dBm, while operating at 50 °C, it has a slightly better receiver sensitivity when the ASE injection power is lower than 0 dBm. However as the injection power is in the region of interest, the receiver sensitivity is still better than -25 dBm even for operation temperature up to 50 °C.

4.5.3 Impact of bias current

The impact of bias current of FP-LDs was also investigated. Fig. 4.19 shows the measured receiver sensitivity as a function of the bias current with different ASE injection powers. The receiver sensitivity of the FP-LD with front-facet reflectivity of 3% after 10-km transmission was measured with ASE injection power of 3, 2, 1 and 0 dBm, respectively. The central wavelength of the spectrum-sliced ASE noise was 1538.75 nm. Fig. 4.19 also shows that there is an optimal bias current for the FP-LD for a given injection power. This is due to the combined effect of the electronic modulation bandwidth and the backward reflection. On one side, the higher the bias current, the larger the modulation bandwidth of the FP-LD is. On the other hand, a higher bias current induces more modes oscillating and requires more injection power to suppress other cavity modes, which introduces more backward reflection and deteriorates the BER performance. The optimal bias current is increased with the increase of ASE injection power. Meanwhile the dynamic operation range for the bias current is also increased when the injection ASE power is increased.

Fig. 4.19. Measured receiver sensitivity as a function of bias current after 10-km transmission with injection ASE power of 3, 2, 1 and 0 dBm.

4.5.4 Selection of injection-locked cavity mode

It is more desirable that more side-modes can be selected for injection locking to make the FP-LD colorless. However, when the injection wavelength located at weak mode, the performance may be degraded due to its lower SMSR for a given injection power, as discussed in Section 3.4.2. In this section, the selection of the mode selection of the spectrum-sliced ASE injection-locked FP-LD was investigated.

In this investigation, the FP-LD with front-facet reflectivity of 10% was used. The operation temperature of the FP-LD was maintained at around 20 °C. The main mode and 4 side-modes of the FP-LD were selected for injection locking by the spectrum-sliced ASE noise, as shown in Fig. 4.20. The central wavelengths of the 5 modes of the free-running FP-LD were 1557.2 nm (Main mode), 1559.3nm (Mode A),

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1554.0nm (Mode B), 1551.7nm (Mode C) and 1549.8 nm (Mode D), respectively. The receiver sensitivity was measured as a function of injected ASE power after 10-km transmission under the injection of these five cavity modes. The bias current and operation temperature of FP-LD was slightly adjusted to get the best receiver sensitivity at each measurement.

Fig. 4.20. Optical spectra of free-running FP-LD and seeding light. The reflectivity of front-facet of FP-LD is 10%. The 3-dB bandwidth of seeding light is 0.45 nm.

Fig. 4.21 shows the receiver sensitivity as a function of injected ASE power for various modes. Injection-locking the main mode of the FP-LD gives the best receiver sensitivity performance. In general, the receiver sensitivity degrades as the selected mode is away from the main mode. For the modes close to the main mode like modes A and B, the receiver sensitivity becomes slightly worse than that of the main mode. While for some edge modes like modes C and D, the degradation in receiver sensitivity

is more considerable, particularly when the injected ASE power is relatively low. The power penalties relative to the main mode for mode A-D were 0.05 dB, 0.1 dB, 0.2 dB and 0.3 dB, respectively, when the injected ASE power was 3 dBm. However, the power penalties for modes C and D were increased to 0.65 dB and 2.45 dB, respectively, when the injected ASE power was reduced to 0 dBm. There were still up to ten modes whose receiver sensitivity degradation was very small in the typical region of injection power.

Fig. 4.21. Measured receiver sensitivity vs. injected ASE power for injection-locking different modes after 10-km transmission.

Above discussions show that the required injection power for incoherent light injection-locked FP-LD is quite high as compared with the coherent injection scheme.

With properly designed FP-LDs, the required injection power can be made smaller. So far, due to its significant advantages such as polarization insensitivity and low-cost, the incoherent light injection-locked FP-LD has been widely deployed in Korea, much in advance of the scheme with coherent injection.

4.6 Conclusions

In this chapter, the impact of filter bandwidth of the spectrum-sliced ASE source on the injection-locking of FP-LDs for WDM-PON applications was first experimentally studied. Results showed that the injection power required to achieve a given SMSR depends on the bias current and the sliced ASE source bandwidth, and there is an optimum bandwidth, 0.4nm~0.6nm, of the sliced ASE source in terms of receiver sensitivity after transmission. Furthermore, the impact of intensity noise of the spectrum-sliced ASE source and its suppression for a wavelength-locked FP-LD using an SOA were investigated. Experimental results showed that the output performance of a directly modulated wavelength-locked FP-LD was improved by the intensity noise suppression. In addition, the impact of the front-facet reflectivity, operation temperature, bias current and injection-locked mode location of FP-LDs was examined in this work. The transmission performance of FP-LDs can be improved significantly by selecting proper front-facet reflectivity, operation temperature and optimal bias current of FP-LDs. It is also somewhat dependent on which cavity mode is selected, while many cavity modes can be selected to make it work colorless. In general, optimal selection of bandwidth of spectrum-sliced ASE, front-facet reflectivity, operation temperature and bias current of FP-LD can improve the transmission performance of ASE injection-locked FP-LDs.

Chapter 5

Downstream Subcarrier Transmission and Carrier Reuse in WDM-PONs

5.1 Overview

The light source schemes discussed in Chapter 3 and Chapter 4 require two distinct wavelengths for each end user, one for downlink and the other for uplink. To utilize wavelengths more effectively and avoid the two wavelengths arrangement for each user, downstream wavelength remodulation approach has been proposed. In such a scheme, the downlink signals can be modulated at either baseband or subcarriers [113-115], [117], [143]. In the former case, the downlink signal is split into two parts at each ONU, with one part for downlink detection and the other part used as the uplink carrier. However, the uplink data suffers from strong crosstalk from the downlink data [143] when not-return-zero (NRZ) format is used. To reduce the effect of downlink data crosstalk, some advanced formats including phase shift keying (PSK) [113] and frequency shift keying (FSK) [114] have been proposed. Nevertheless, the cost and stability for PSK and FSK demodulation at each ONU is still an issue. In the later case, the downstream data is modulated at subcarriers and the optical carrier is separated from subcarriers at the receiving side and remodulated for upstream transmission [115], [117]. In this case, the optical carrier filtering is a key issue since it is so closely spaced with the optical subcarriers. Till now, the optical filtering is employed in each ONU [115], [117], which introduces high cost.

This chapter first proposes to use one single interferometric filter at the RN to separate

the optical carriers and subcarriers for all channels. Based on this idea, two novel WDM-PON architectures are proposed and demonstrated. The system performance of the proposed architectures is investigated in terms of optical carrier to subcarrier ratio, back-reflection and wavelength mismatch. In addition, analysis is performed on operation temperature of RSOA, number of supported subscribers, colorless operation of each ONU and data-rate enhancement of the architecture.

5.2 Interferometric filter for carrier-reuse WDM-PONs

In a downstream optical subcarrier transmission and carrier-reuse scheme, the wavelength distance between optical carrier and subcarriers is usually several GHz. The conventionally designed optical filter is difficult to separate these signals. A narrow band fiber Bragg grating (FBG) combined with an optical circulator is a choice for this purpose, as shown in Fig. 5.1(a). Here, the downstream subcarrier modulated wavelength, including both optical carrier and subcarriers, is represented as SCM light. When the SCM light is launched into the circulator-FBG based filter, the optical subcarriers pass through and appear at port 2, but the optical carrier is reflected by the FBG and appears at port 3. The transmission spectrum of the FBG should be sharp sufficiently and its reflectivity should be high enough to separate the optical carrier and subcarriers. As discussed before, the colorless operation of ONU is desirable for practical deployment. In this case, the central wavelength of FBG should be tunable. However, the tunable FBG and optical circulator are much costly for each subscriber, and the stability of a tunable FBG is also an issue.

In this thesis, it is proposed to use an interferometric filter (IF), such as a delay interferometer (DI) or an optical interleaver, to separate the optical carrier and

Fig. 5.1. Optical filters for downstream subcarrier transmission and carrier-reuse WDM-PON. (a) Circulator-FBG based filter, (b) Interferometric filter, (c) Transmission spectra of interferometric filter.

subcarriers, as shown in Fig. 5.1 (b). A simple IF consists of two 3-dB couplers with a small optical path difference between two arms. The transmission spectra of the two output ports are complementary to each other so that the optical carrier and subcarriers appear at two different output ports. Due to its periodical characteristic, the filter can be

used for separating multiple optical signals in a broad range of wavelength. Assuming that the WDM channel spacing, denoted by $\Delta\lambda$, is $n \times \text{FSR}$, where FSR is the free spectral range of IF and n is an integer starting from 2, e.g. 10, and the subcarrier frequency is half of the FSR. Once the WDM light is launched into this filter, all optical carriers and subcarriers should be separated and appear at different output ports, as shown in Fig. 5.1 (c). Based on this characteristic, two novel carrier-reuse WDM-PON architectures are proposed in the following section.

5.3 Proposed architectures

5.3.1 Architecture I

The proposed first architecture is shown in Fig. 5.2. At the CO, each individual downlink data stream is mixed with the subcarrier signal at a frequency of f_{sc} and modulated onto a Mach-Zehnder modulator to generate subcarrier modulated (SCM) light. The data rate (R_d) should be smaller than f_{sc} to make it easy for wavelength separation. The experimental study shows that $R_d = f_{sc}/4$ is a good choice to achieve good bit-error-rate (BER) performance. After being multiplexed by an optical multiplexer (MUX), all WDM channels are transmitted over the feeder fiber via an optical circulator. At the RN, a single interferometric filter, e.g. optical interleaver or DI, is used to separate all the optical carriers and subcarriers. Note that this filter has a free spectral range of FSR , which is twice of f_{sc} , and the WDM channel spacing is multiple integer times of FSR. Therefore the filter can transmit all optical carriers to one output port and all subcarriers to the other output port. For example, downlink light located at λ_1 is separated into an optical carrier (represented by $\lambda_{c, 1}$) and a pair of optical subcarriers (represented as $\lambda_{sc, 1}$) after the DI, as shown in the bottom part of Fig. 5.2. The separated subcarriers from carriers are subsequently demultiplexed into

individual subcarrier pairs by a WDM multiplexer (MUX3) and then fed to each corresponding ONU via a distribution fiber for downlink detection with baseband receivers. Similarly, the optical carriers are also demultiplexed with another multiplexer (MUX2). Through another dedicated distribution fiber, each optical carrier is then directly injected into an RSOA located at ONU, where the upstream data is modulated to the optical carrier. All the uplink channels are combined again and pass through the same MUX2, IF and feeder fiber back to the CO for uplink data detection. The proposed scheme is expected to significantly reduce the implementation cost of WDM-PONs for the following reasons: (i) each ONU only consists of a baseband receiver with direct detection and an RSOA, (ii) the IF is shared by all the downlink and uplink channels, (iii) the wavelengths are centrally arranged in the CO and hence it is easy to manage.

Fig. 5.2. Architecture I of the proposed carrier-reuse WDM-PON with two distribution fibers between each ONU and the RN.

As shown in Fig. 5.2, Architecture I necessitates two distribution fibers for two unidirectional transmissions between each ONU and the RN. For new deployment of fiber infrastructures, since the fiber is short and cheap, it is believed that the additional fiber will only marginally increase the cost. While for some existing fiber infrastructures, two distribution fibers between the RN and each ONU may not be available. To deal with such a problem, another carrier-reuse WDM-PON architecture is proposed in the next sub-section.

5.3.2 Architecture II

The proposed second carrier-reuse WDM-PON architecture is shown in Fig. 5.3, where only one distribution fiber supports both downstream and upstream transmission between the RN and each ONU. As shown in Fig. 5.3, the novelty of Architecture II is that an $N \times N$ (or $2 \times N$ as only two ports are needed to be connected on the left side) cyclic AWG combined with low cost coarse WDM couplers are introduced to make the transmission between the RN and each ONU bidirectional over a single distribution fiber. As in the Architecture I, the downstream light from the CO is first separated into optical carriers and subcarriers with a single shared IF at the RN. All the optical subcarriers (carrying downlink data) are then launched into input port 1 of the $N \times N$ AWG router (e.g. 32×32 AWG), while all the optical carriers (as seeding lights) are launched into input port $N/2 + 1$ (e.g. 17 if $N = 32$). Here, N channels are supposed to occupy one free spectral range (FSR) of the AWG with equal spacing, which means $\text{FSR} = N \times (\text{channel spacing})$ (e.g. $32 \times 0.8 = 25.6$ nm). The $\lambda_{\text{sc}, i}$ and $\lambda_{\text{c}, i}$ in Fig. 5.3 denote the optical subcarrier pair and the optical carrier of the i -th wavelength channel, respectively. Due to the cyclic property of the AWG router [144], a pair of subcarriers

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at $\lambda_{sc, i}$ and an optical carrier at $\lambda_{c, (i + N/2)}$ entering at the two inputs of the AWG, respectively, will emerge on the same output port, as shown in Fig. 5.3.

Fig. 5.3. Architecture II of the proposed carrier-reuse WDM-PON with one distribution fiber between each ONU and the RN.

It should be noted that, unlike Architecture I where both downlink and uplink data of an ONU are carried on $\lambda_{sc, i}$ and $\lambda_{c, i}$ located in the same wavelength channel, the downlink and uplink data of an ONU in Architecture II are carried on $\lambda_{sc, i}$ and $\lambda_{c, i + N/2}$, which are located at two different wavelength channels, as shown in the bottom of Fig. 5.3. Here, without loss of generality, the wavelengths arrangement for a WDM-PON using an 8×8 AWG router is shown in Table 5.1. Assume that all the subcarriers enter at port 1 and all the carriers enter at port 5. ONU1 receives its downstream data at wavelength $\lambda_{sc, 1}$ entering at input port 1 of the 8×8 AWG, and also an optical carrier at wavelength $\lambda_{c, 5}$

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entering at input port 5 of the 8×8 AWG. Similarly, wavelengths $\lambda_{sc, 5}$ and $\lambda_{c, 1}$ are assigned to ONU5 for downlink and uplink transmission, respectively. In general, two ONUs (ONU i and ONU $(N/2 + i)$, where $i = 1, 2, \dots N/2$) will use a pair of wavelengths with a wavelength separation equal to a half of the FSR of the $N \times N$ AWG.

Table 5.1 Wavelengths arrangement for Architecture II of the proposed WDM-PON based on 8×8 cyclic arrayed waveguide grating router.

<div style="display: inline-block; transform: rotate(-45deg);">In \ Out</div>	ONU1	ONU2	ONU3	ONU4	ONU5	ONU6	ONU7	ONU8
Port 1 (Subcarriers)	$\lambda_{sc, 1}$	$\lambda_{sc, 2}$	$\lambda_{sc, 3}$	$\lambda_{sc, 4}$	$\lambda_{sc, 5}$	$\lambda_{sc, 6}$	$\lambda_{sc, 7}$	$\lambda_{sc, 8}$
Port 5 (Carriers)	$\lambda_{c, 5}$	$\lambda_{c, 6}$	$\lambda_{c, 7}$	$\lambda_{c, 8}$	$\lambda_{c, 1}$	$\lambda_{c, 2}$	$\lambda_{c, 3}$	$\lambda_{c, 4}$

At each ONU, the optical carrier and subcarrier pair are then separated by a conventional low cost coarse WDM coupler for downlink signal detection and uplink signal remodulation. Being used as uplink modulators, commercial RSOAs have a very broad operation range and can work in the whole C and L band. Assuming the WDM-PON covers all these wavelengths, a low cost coarse WDM coupler can be used in each ONU for optical carrier and subcarriers separation since the wavelength separation between them equals half of wavelength band of PON. If the channel number is 32 or 64, a coarse wavelength demultiplexer that separates wavelengths with a distance of 12.8 nm or 25.6 nm respectively can be used. However, for a WDM-PON with only a few ONUs (e.g. 8 ONUs), where small AWG (e.g. 8×8 AWG) is used, the wavelength separation between the optical carrier and the subcarriers for each ONU may be too small to be separated by conventional low cost coarse WDM couplers. To deal with this issue, it is proposed to use two different wavelength bands that are

separated by more than one FSR of the AWG. More specifically, the first half of the operating channels are assigned with wavelengths at $\lambda_1, \lambda_2, \lambda_3, \lambda_4$ and the second half of the operating channels are assigned with wavelengths at $n \times \text{FSR} + \lambda_5, n \times \text{FSR} + \lambda_6, n \times \text{FSR} + \lambda_7, n \times \text{FSR} + \lambda_8$, where n is an integer starting from 1. Then the wavelength separation can be increased to $(1/2 + n) \times \text{FSR}$, hence a low cost coarse WDM coupler still can be used to separate the optical carrier and the subcarriers at each ONU.

5.4 Experiment setup and results

This section describes two multi-channel transmission experiments, which are carried out to verify the proposed architectures.

5.4.1 Experiment for the proposed Architecture I

Fig. 5.4 shows the experimental setup for the proposed architecture I. Here, eight wavelengths from DFB laser diodes were multiplexed and modulated via an MZM. The channel spacing was 100 GHz, which is 10 times of the FSR of the DI used. 1.25-Gb/s PRBS data with a word length of $2^{31}-1$ was mixed with a 5-GHz radio frequency (RF) subcarrier signal and then amplified to drive the MZM. The MZM was biased at the quadrature point. The feeder fiber was a 20-km standard SMF. A DI with 10-GHz FSR was used as the interferometric filter at the RN to separate all optical carriers and subcarriers. Its transmission spectra were aligned to match WDM wavelengths by temperature control. Then all subcarriers and optical carriers were simultaneously separated into port 3 and port 2, respectively, and subsequently demultiplexed by two separate demultiplexers. The channel spacing of both demultiplexers is 0.8 nm and the 3-dB pass bandwidth is 0.5 nm, which is sufficient to support the subcarrier

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transmission. The demultiplexed optical carriers and subcarriers were then sent to ONUs via two separate 1-km distribution fibers. At each ONU, the optical carrier was injected into a polarization insensitive RSOA, which was biased at 60-mA current. The total link loss was about 14.3 dB, including 4.0 dB from SMF, 3.5 dB from each of the two MUXs, 2.7 dB from the DI and 0.6 dB from the optical circulator. The seeding light power was around -12 dBm and the output power of the seeded RSOA was 1 dBm when operating temperature was fixed at 20°C by a temperature controller (TEC). The 1.25-Gb/s upstream data was directly modulated onto the RSOA, which was driven by a pulse pattern generator with pulse amplitude of 2 Vpp, but no extra driver being used.

Fig. 5.4. Experimental setup for the proposed Architecture I with two distribution fibers between each ONU and the RN.

Fig. 5.5(a)-(c) shows the optical spectra of the downstream signals measured before and after the DI. Fig. 5.5 (d)-(f) are the close looks of SCM light, optical carrier and subcarriers at 1549.3 nm, respectively. All optical spectra in this work were measured by an optical spectrum analyzer with a resolution of 0.01 nm. Before passing through the DI, the optical carrier to subcarrier ratio (OCSR) was about 9.2 dB. In this thesis,

Fig. 5.5. Transmission spectra of the downstream light (SCM) (a), optical carriers (b), optical subcarriers (c) and the respective close look @ 1549.3 nm (d-f).

OCSR is defined as the power difference between optical carrier and fundamental subcarriers. It can be adjusted by changing the driving voltage of the MZM. After the DI, the OCSR of signals at port 3 was reduced to about -8 dB due to the suppression of optical carriers, which is suitable for baseband detection. The OCSR of the signals at

port 2 of the DI was increased to about 22 dB due to the suppression of the fundamental subcarriers. The high suppression of the subcarriers is beneficial to upstream remodulation and transmission.

Fig. 5.6. Optical spectra of the free running RSOA (a) and upstream signal at 1549.3 nm (b).

Fig. 5.6 shows the optical spectra of the free-running RSOA and upstream signal. Without external seeding, the output of RSOA was a wide band ASE noise. Its 3-dB bandwidth was about 58 nm. With external seeding, the wavelength at seeding light was amplified and the noise was suppressed, as shown in Fig. 5.6(b). Since the output wavelength of RSOA can be excited in a much wide range, one regular RSOA can be used for any ONU, which makes it very convenient to employ, update and maintain the ONUs.

The signals for both downstream and upstream transmissions were directly detected with a 1.25-GHz conventional baseband APD receiver, which is integrated with a limiting amplifier (LA) and clock and data recovery device (CDR). The measured bit

Fig. 5.7 Measured bit error rates vs. received optical power. (a) Downstream transmission of wavelength 1549.3 nm, and (b) upstream transmissions for all 8 channels.

error rates (BERs) are shown in Fig. 5.7. The receiver sensitivity of downstream wavelength 1549.3 nm at $\text{BER} @ 10^{-9}$ was -31.2 dBm for 21-km (feeder fiber + distribution fiber) transmission link. The inset is the eye diagram of downstream signal measured with a 2.85-GHz PIN photo-detector in conjunction with an oscilloscope. There was almost no power penalty observed compared with the back-to-back (BTB) case, in which the feeder fiber and distribution fiber were removed, as shown in Fig. 5.7(a). Other downlink channels exhibit almost the same performance. Similar to the downlink, no penalty was observed between BTB case and after transmission for the uplink. Fig. 5.7(b) shows the uplink BER after transmission for all the 8 channels measured with the same RSOA. The slight difference in receiver sensitivity among different channels is due to their respective wavelength mismatch between signal wavelength and DI's transmission spectra, which will be discussed in next section.

Fig. 5.8. Experimental setup for the proposed Architecture II with a single distribution fiber between each ONU and the RN.

5.4.2 Experiment for the proposed Architecture II

Fig. 5.8 shows the experimental setup for the proposed Architecture II. Sixteen wavelengths, ranging from 1541.3 nm to 1553.3 nm, from DFB laser diodes were combined and modulated via an MZM and transmitted in this WDM-PON. All optical subcarriers and optical carriers were first separated by the DI at the RN. The subcarriers emerging at port 3 of the DI were launched into the first input port of a 16×16 cyclic AWG router. Likewise, the carriers emerging at port 2 of the DI were launched into the 9th input port of the 16×16 AWG router. The AWG router works in room temperature without temperature control. Optical carrier and corresponding subcarrier pair from each output port were then sent to the corresponding ONU via 1-km distribution fiber. At each ONU, the optical subcarriers and carrier were demultiplexed with a coarse WDM filter for downlink signal detection and uplink data remodulation, respectively. All other operation conditions were the same as the case for Architecture I experiment.

Fig. 5.9 shows the optical spectra of the downstream signals measured before and after

Fig. 5.9. Optical spectra measured before and after the RN. (a) 16-channel downstream light before the RN, (b) light to ONU 1 after the RN, and (c) light to ONU 9 after the RN.

the RN (including DI and AWG router). The OCSR of the downlink signal was still maintained at about 9.2 dB for all the 16 channels. Please note that the optical spectra at the two outputs of the DI were similar to that in the previous experiment so that they are not shown here. The optical spectra at output ports 1 and 9 of the AWG router, corresponding to ONU1 and ONU9, are shown in Fig. 5.9(b) and Fig. 5.9(c), respectively. The OCSR for the channel at 1541.3 nm was reduced to -8.9 dB for subcarriers and increased to 25 dB for optical carrier after passing through the RN,

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which is shown in the insets of Fig. 5.9 (b) and Fig. 5.9(c). All other channels exhibit similar performance. For ONU1, the downlink data was carried on channel 1 (1541.3 nm) and seeding light was located on channel 9 (1547.7 nm). The crosstalk of other channels was suppressed to more than 40 dB and can be ignored.

Fig. 5.10. Measured BER vs. received optical power. (a) downlink and (b) uplink for ONU1 and ONU 9. Inset: eye diagram of downlink signal for ONU1.

The measured BER performances for both downstream and upstream transmissions are shown in Fig. 5.10. The receiver sensitivities of ONU1 (CH1, 1541.3 nm) and ONU9 (CH9, 1547.7 nm) at BER of 10^{-9} for downstream data were -31.1 dBm and -31.2 dBm, respectively, for the 21-km transmission link. The inset is the eye diagram of downstream signal for ONU1. Fig. 5.10(b) shows the uplink BER after 21-km transmission for ONU 1 and ONU 9 using the same RSOA. Similar to Architecture I, there was no significant power penalty observed between the BTB case and the case of 21-km transmission for both uplink and downlink. Comparing Fig. 5.10(a) and Fig. 5.10(b), it can be found that the downlink signal for ONU1 and

uplink signal for ONU9 have a slight power penalty in receiver sensitivity. Since both downlink data for ONU1 and seeding light for ONU9 came from the same downlink channel (CH1), this slight difference in receiver sensitivity among different ONUs may be due to their respective wavelength alignment between laser wavelength and DI's transmission spectra. Beside wavelength alignment, RB noise of the downlink carrier and uplink signal and OCSR of the SCM light are also important factors affecting the performance of the proposed system. The influence of these factors will be elaborated in the Section 5.5.

Comparing the results in Fig.5.7 and Fig.5.10, it can be seen that there is no significant difference in the receiver sensitivity for both the downlink and uplink transmissions. That is these two architectures have similar transmission performance. The main difference between these two architectures may be the implementation cost. Architecture I requires two $1 \times N$ MUX and $2 \times N$ distribution fibers, but architecture II requires one $2 \times N$ AWG, N distribution fibers and N CWDM couplers. It is complicated to estimate which architecture is more cost-effective. For a new fiber infrastructure to be implemented, a cable with two fiber strands can be easily installed for each user in the distribution optical connection. The additional cost coming from a short extra distribution fiber should be very low since standard fiber is not costly. In this case, both architectures can be used. But the first architecture may be a little more economical since the second architecture needs a CWDM coupler in each ONU. On the other hand, the second architecture is much suitable for the case where the fiber infrastructure is already deployed and only one fiber between the RN and each of the ONUs is available. In this case, the first architecture does not work.

5.5 Performance evaluation

In this section, all experimental results discussed here were obtained from the setup shown in Fig. 5.4, i.e. Architecture I. However the conclusions drawn from the results are also applicable to Architecture II.

5.5.1 Optical carrier to subcarrier ratio

Fig. 5.11. Measured downstream BER vs. received optical power under different OCSRs.

The influence of OCSR of the downstream signal was first studied. Here, the OCSR was changed by adjusting the driving voltage of the MZM through varying the gain of the driver between the mixer and the MZM. The OCSR increased with the decrease in the driver gain. The lowest OCSR, 7.2 dB, was obtained with the maximum driver gain. The measured BERs of downstream data as a function of received optical power for different OCSRs are shown in Fig. 5.11. The representative results are given at wavelength of 1554.1 nm. All other channels had similar performance. The downlink

performance degraded with the increase of the OCSR because a higher OCSR induces a larger residual carrier intensity and relatively lower subcarrier intensity. This in turn transfers more baseband power to the fundamental subcarrier in RF spectrum after photodetection. Compared with the case of 7.2-dB OCSR, an OCSR of 14.1 dB gives about 6-dB power penalty. Therefore, lower OCSR is desirable for downstream transmission.

Fig. 5.12. Measured upstream BERs and eye diagrams with different OCSRs.

On the other hand, low OCSR may deteriorate the upstream system performance. Fig. 5.12 shows the measured BER of the upstream transmission with different OCSRs. The BER performance of uplink improves with the increase of the downstream signal's OCSR. When the OCSR is increased from 7.2 dB to 11.3 dB, the receiver sensitivity at BER of 10^{-9} was improved by more than 1 dB. The improvement in

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receiver sensitivity by increasing OCSR might be attributed to the reduced residual downlink data, which will be discussed in Chapter 6. Further increase in OCSR from 11.3 dB to 14.1 dB only improves the receiver sensitivity by 0.15 dB. OCSR higher than 14 dB cannot further improve the upstream performance. This could be because at sufficiently high OCSR, the effect of residual downlink data is negligible. The eye diagrams for OCSR = 7.2 dB and 14.1 dB are also shown in this figure. For the case of OCSR = 7.2 dB, some residual downlink data exhibits on the top of the eye of the upstream signal. While for OCSR = 14.1 dB, there is no residual data. In summary, ~ 11-dB OCSR is a good choice to balance both the uplink and downlink performance. Nevertheless, a wide range of OCSRs can be used in practical implementation.

5.5.2 Rayleigh-backscattering noise

The required seeding power of RSOA is also an important parameter for power budget of the PON system. Fig. 5.13 shows the receiver sensitivity of the upstream transmission versus the seeding light power. In this experiment, a tunable attenuator was inserted between MZM and circulator in Fig. 5.4 to adjust the seeding light power. Experiments show when the seeding power was as low as -24 dBm, the receiver sensitivity was still at -26.4 dBm. The low required seeding power and received optical power enhance the margin of power budget for the whole WDM-PON.

Considering that a typical downlink transmitter power is 0 dBm per channel. According to the experimental setup, the insertion loss of both the uplink and downlink was about 14.3 dB, the seeding power was typically about -15 dBm. With -15 dBm input power, the output power of the RSOA was -5dBm and the received optical power at the uplink receiver was about -19.3 dBm. Fig. 5.13 shows that the uplink receiver sensitivity

was about -30 dBm with -15 dBm seeding power. Therefore, the power margin for uplink was as high as 10.7 dB. For the downlink, the received optical power was about -22.3 dBm if the OCSR was 11 dB. Considering that the receiver sensitivity was -31.6 dBm, as shown in Fig. 5.12, the power margin for the downlink was about 9.3 dB. The high power margin for both the uplink and downlink makes the system quite tolerant for link loss.

Fig. 5.13. Receiver sensitivity versus seeding light power into the RSOA.

On the other hand, the receiver sensitivity was improved as the seeding power was increased. The improvement was significant when the seeding power was less than -14 dBm since the higher seeding light power increases the optical signal to noise ratio (OSNR) of the upstream light. However, the improvement became minor when the seeding power was greater than -14 dBm, due to the increased Rayleigh-backscattering impairment [22] and partial saturation of RSOA. The output power of the RSOA as a function of seeding power is shown in Fig. 5.14. Here, the output power of RSOA

increases with the increase of the seeding power and the gain becomes saturated with further increase of the seeding power. Higher seeding power benefits the signal performance due to the larger OSNR of uplink signal and increased modulation bandwidth of RSOA. However, a higher seeding power means a higher downlink transmission power. This introduces higher RB noise, which deteriorates the performance of the uplink signal. Fig. 5.14 also shows the uplink signal to the downlink RB noise ratio. When the seeding power is lower than -14 dBm, the signal to RB noise ratio is higher than 22 dB. In this case, the receiver sensitivity increases with seeding power. While when the seeding power further increases, the signal to RB noise ratio decreases rapidly. As a result, signal performance may not be further improved with increase of seeding power.

Fig. 5.14. Output power of the RSOA and signal to Rayleigh-backscattering noise ratio versus seeding power.

Beside the downlink RB noise, the uplink RB noise launched back to the RSOA is amplified and also deteriorates the upstream BER [145]. To demonstrate the influence

of the uplink RB noise, the seeding light power was fixed and the uplink signal power was varied by adjusting the bias current of the RSOA. The receiver sensitivity of upstream transmission is shown in Fig. 5.15 as a function of the bias current of RSOA. It was observed that the maximum bias current can not get the best receiver sensitivity. Although higher bias current increases the signal power and modulation bandwidth, it also increases the uplink RB noise. The other factor is the degradation of OSNR with further bias increase. In the experiments, the optimum bias current was about 60 mA.

Both the downlink RB noise and the uplink RB noise deteriorate the performance of carrier-reuse WDM-PON, especially for long reach WDM-PON. In this thesis, a general WDM-PON with 20-km feeder fiber was demonstrated. To increase the reach of the proposed architecture, bidirectional transmission in one fiber is better to be avoided. One possible solution is to use two feeder fibers, one for downlink and another for downlink.

Fig. 5.15. Receiver sensitivity versus bias current of RSOA.

5.5.3 Wavelength mismatch

To reduce the maintenance cost of optical access networks, the completely passive (without power supply) RN is desirable. In a practical system, the tunable DI in this experiment should be replaced with an athermal DI to make the RN be completely passive. Currently, the athermal DI may still suffer from some minor wavelength drift due to the environment temperature fluctuation. This wavelength drift of the DI may introduce the wavelength mismatch between the WDM laser wavelength and the transmission curve of the DI. As a result, the system must be tolerant to some wavelength mismatch.

Fig. 5.16. Measured receiver sensitivity versus wavelength mismatch between DI and laser. The bottom is eye diagrams for downlink under different levels of wavelength mismatch.

Fig. 5.16 shows the measured receiver sensitivity versus the wavelength mismatch for both uplink and downlink transmission. Here, the seeding light power was -12 dBm and OCSR = 11 dB when there was no wavelength detuning. The receiver sensitivity deteriorates with the wavelength mismatch. For downlink transmission, the wavelength mismatch introduces residual carrier power. The eye diagrams in Fig. 5.16 show an increase in the DC component in the detected downlink signal with the increased wavelength mismatch. This DC level is due to the increased residual carrier in the detected downlink signal due to wavelength mismatch. When the frequency mismatch is 1.25 GHz, the DC component is half of the peak power, which introduces 5.5-dB power penalty. For uplink transmission, the residual data due to the wavelength mismatch is suppressed significantly when the wavelength detuning is small because of the partial saturation and low frequency response of the RSOA. On the other hand, for the case of wavelength detuning larger than 1.1 GHz, the receiver sensitivity deteriorates rapidly. This is mainly due to the increased residual data on seeding light and the decreased seeding power with the increase of wavelength mismatch. However, the experiments showed that a receiver sensitivity of better than -28 dBm could be maintained with a wavelength mismatch of ± 1.15 GHz for the downstream and ± 0.94 GHz for the upstream, which is larger than the temperature dependent frequency shift of current commercial athermal DI (± 0.75 GHz) when its operating temperature varies in the range of 0-70°C, showing the practical feasibility of the proposed scheme.

To increase the tolerable wavelength mismatch of the proposed system, a flat-top interleaver can be used instead of the DI. The flat-top filter can effectively enhance the tolerance of wavelength mismatch. Besides the interleaver, a DI with a larger FSR can also increase the tolerance against wavelength mismatch. Since $f_{sc} = \text{FSR}/2$, a larger

FSR corresponds to a higher f_{sc} , which in turn requires a higher bandwidth downlink modulator and hence increases the modulator's cost. Therefore, FSR can not be very high and it is believable that FSR = 20 GHz is a reasonable choice. Fig. 5.17 shows the receiver sensitivity of the downstream transmission as a function of frequency mismatch with 10-GHz and 20-GHz free spectral ranges. Here, the data rate for both cases was 1.25 Gb/s. The solid lines are the simulation results with commercial simulation tool (*VPITransmissionMaker*). The experimental results (indicated as the diamond symbols) show the similar performance and verify the results of the simulation. For 20-GHz FSR, the tolerant wavelength-mismatch increases to 2.4 GHz when the received signal power is -28 dBm.

Fig. 5.17. Receiver sensitivity versus frequency mismatch with different DI FSRs for downstream transmission. Solid line: simulation, Diamond: experiment.

5.6 Discussions

5.6.1 Temperature control of RSOA

So far, RSOA has been widely used in WDM-PON research and is considered as a very promising device for WDM-PON applications. However, the gain of RSOA fluctuates with temperature. As a result, a temperature controller (TEC) is required to maintain a certain operating temperature. While the TEC in each ONU may increase the implementation cost.

The experiments showed that when the operating temperature was varied from 20 °C to 35 °C, the OSNR of the uplink light was always greater than 45 dB and the variation of

Fig. 5.18. Output power and OSNR of RSOA vs. operation temperature

the OSNR was smaller than 1 dB, but the output power of the seeded RSOA decreased from 1 dBm to -3 dBm, corresponding to 0.267 dB/°C, as shown in Fig. 5.18. In this experiment, the RSOA was biased at 60 mA and the power of the seeding light was -12 dBm. It should be noted that the operation temperature variation is unlikely to be very

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large, since ONUs are usually located indoors. When the operation temperature of RSOA increases from 20 °C to 70 °C, the output power may decrease to around -12.3 dBm ($1-0.267 \times 50$). Here, a linear relationship is assumed between temperature and output power, as shown in Fig. 5.18. Assuming that the uplink receiver sensitivity is about -32 dBm as shown in Section 5.4 and 5.5, the power margin of the system ($=\text{output power} (-12.3\text{dBm}) - \text{receiver sensitivity} (-32\text{dBm}) - \text{link loss} (14.3\text{dB})$) is still as large as 5.4 dB, which shows the feasibility without using a temperature controller (TEC). The operating temperature of the RSOA used in the experiments must be smaller than 40 °C (as specified by the manufacturer), which is the reason that a TEC was used here. Recently, the photonics supplier, Centre for Integrated Photonics (CIP), has released a 1.25-Gb/s RSOA with uncooled operation [146]. For practical implementation, this kind of RSOAs can be used to remove the temperature controller.

5.6.2 Number of subscribers

Fig. 5.19. Optical spectrum of the free running RSOA (solid line) and optical signal to noise ratio (OSNR) of the seeded RSOA (diamond), where seeding power was -12 dBm.

The number of subscribers that can be supported by the proposed architectures depends on the wavelength operation range of the RSOAs used. Fig. 5.19 shows the measured output spectrum of the free-running RSOA used in the experiments. The measured OSNR of the uplink light for the wavelength ranging from 1510nm to 1590nm is also included in Fig. 5.19. Here, the input seeding light power was -12 dBm. The OSNR for wavelength greater than 1590nm was not measured due to the lack of lasers with corresponding wavelength. As shown in the figure, the RSOA's spectrum bandwidth is very broad and its 3-dB bandwidth is as large as 58 nm. The OSNR of the uplink light was greater than or equal to 40 dB in a range of 80 nm (1510nm-1590nm) when it was biased at 60 mA and seeding power was -12 dBm. Therefore, it is more than sufficient for the proposed architecture to support typical PONs with 16, 32 or 40 WDM channels. Assuming that the channel spacing is 0.8 nm and the AWG has enough ports, it can support up to 100 $((1590\text{nm}-1510\text{nm})/0.8\text{nm}=100)$ WDM channels.

5.6.3 Colorless operation

Colorless operation is important for each ONU in WDM-PON. The proposed Architecture I can definitely be colorless. In this section, the colorless operation of Architecture II is discussed.

Fig. 5.20 shows an example of the wavelength assignment for the ONUs. As shown in Fig. 5.20(a), a low cost coarse WDM coupler (e.g. C/L band WDM) can be used in each ONU, where the light is separated into two parts, one with wavelength longer than a certain wavelength λ_c , the other with wavelength shorter than λ_c . For each ONU, the downlink light consists of two wavelengths, one is located in the first half of the FSR of

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Fig. 5.20. Wavelength de-multiplexing at ONUs using coarse WDM couplers in the Architecture II.

the AWG, and the other is located in the second half of the FSR of the AWG. Suppose λ_c is located at the center of operation wavelength band of the PON, and then all ONUs can use identical coarse WDM couplers to separate wavelengths and hence becomes colorless.

However, the use of coarse WDM couplers indeed induces some limitation when its filter profile is not sufficiently sharp. In this case, some channels located at the raised or fall edge of the transfer function of the WDM coupler could be avoided to make all ONUs colorless (see Fig. 5.20(b)). Another solution for this is to divide the users into 2 groups, one including the 1st and 3rd quarter of the users and the other including the 2nd and 4th quarter of the users, as shown in Fig. 5.20(c). For example, all 16 ONUs can be divided into two groups if using a 16×16 AWG, group one includes (ONU1, ONU2, ONU 3, ONU4) and (ONU9, ONU10, ONU11, ONU12), group two includes (ONU5, ONU6, ONU7, ONU8) and (ONU13, ONU14, ONU15, ONU16). Then all downstream lights for group one located in two bands, λ_1 - λ_4 and λ_9 - λ_{12} . One coarse WDM coupler whose raised and fall edge of transfer function is located between λ_5 and λ_8 can be used for each user in group one. Similarly, another coarse WDM coupler whose raised and fall edge of transfer function is located between λ_9 and λ_{12} can be used for each user in group two. Then each group can use one kind of WDM coupler. Although two types of WDM couplers are required, the ONUs in each group are still colorless.

5.6.4 Data-rate enhancement

With the increasing bandwidth demand, the WDM-PON may be required to upgrade

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to 10 Gb/s and above in the near future. In Chapter 3, a 10-Gb/s WDM-PON based on coherent light injection-locked FP-LD has been discussed. In the following of this section, the feasibility of the 10-Gb/s transmission in the carrier-reuse WDM-PON with the proposed architectures in Section 5.3 is to be discussed. The data rate of the proposed architectures was mainly limited by the modulation bandwidth of RSOAs and backward-reflection in the bi-directional transmission. To eliminate the limitation, the high speed FP-LD used in Chapter 3 and unidirectional transmission are employed in new architecture.

Fig. 5.21. Architecture for 10-Gb/s carrier-reuse WDM-PON.

The newly proposed architecture for 10-Gb/s carrier-reuse WDM-PON is shown in Fig. 5.21. At the CO, each individual downlink data stream (e.g. 10 Gb/s) is mixed with a subcarrier signal (e.g. 25 GHz), which is then used to drive an MZM to generate SCM light. After being multiplexed, all WDM channels (e.g. with 100-GHz channel spacing) are transmitted over a 10-km SMF to the RN. At the RN, a single optical interferometric

filter (e.g. a DI with FSR of 50 GHz) is used to separate all the optical carriers and subcarriers. Note that the free spectral range (FSR) of the DI should be twice of subcarrier frequency, and the WDM channel spacing is multiple integer times of the FSR, as discussed in Section 5.3. As a result, the filter can transmit all optical carriers to one output port and all subcarriers to the other output port. The subcarriers are then subsequently demultiplexed into individual subcarrier pairs by a WDM demultiplexer (MUX3) and fed into each corresponding ONU via a distribution fiber for downlink detection. Similarly, the optical carriers are also demultiplexed with another multiplexer (MUX2). Through another dedicated distribution fiber, each optical carrier is then injected into an FP-LD located at the ONU to make it operate under a single wavelength, where the upstream data is directly modulated onto the FP-LD. Since both downlink and uplink wavelengths are located in the same WDM channel, the crosstalk from the backscattering of downlink signal may significantly deteriorate the uplink performance, especially for 10-Gb/s transmission. To reduce the influence of the crosstalk, a circulator is employed between the DI and MUX2. The uplink WDM signals are then sent back to the CO through the circulator and another feeder fiber for uplink detection.

The experimental setup is shown in Fig. 5.22. As discussed, the channel spacing should be integer times of the DI's FSR. For 100-GHz WDM channel spacing and 10-Gb/s data rate, a DI with a FSR of 50 GHz is a proper choice. However, due to the limitation of the experimental condition, a DI with a FSR of 40 GHz was used in this experiment. Here, the data for both downlink and uplink were two individual 10-Gb/s PRBS series with a word length of $2^{15}-1$. The downlink data was mixed with a 20-GHz clock signal (subcarrier) by a broadband mixer and modulated onto the light from a DFB laser

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through an MZM. An EDFA and attenuator (ATT) were used to adjust the injection power. A bandpass filter (BPF) was used to suppress the ASE noise of the EDFA. A polarization controller (PC) was inserted between the circulator and the FP-LD to adjust the polarization state of the injection light to match the FP-LD. Note that for practical implementation, the PC should be replaced by a shared polarization diversifier located at the CO. The feeder fibers for both uplink and downlink are 10-km single mode fiber. The FP-LD used has a threshold current of 18 mA, and a facet reflectivity of 32% for both ends. It was biased at 40 mA to get enough modulation bandwidth. The receiver consists of a PIN photo detector, a LA and a CDR module. The output voltage of the CDR was optimized in this experiment.

Fig. 5.22. Experimental setup for 10-Gb/s carrier-reuse WDM-PON.

Before the DI, the OCSR of the SCM light was about 11 dB, but it was suppressed to -21 dB at output port 3 of the DI for downlink data detection, as shown in Fig. 5.23(b). Fig. 5.23(c) shows the bit error rate (BER) performance of the downstream transmission. For the back-to-back (BTB) case, where the 10-km downlink feeder fiber was removed, the receiver sensitivity at 10^{-9} BER was -21.6 dBm. After 10-km transmission, there was about 1.5-dB power penalty due to fiber dispersion.

Fig. 5.23. Measured downlink performance. (a) eye diagram, (b) optical spectra, and (c) BER.

The OCSR of the light emerging at output port 2 of the DI was enhanced to more than 34 dB. The light was then injected into an FP-LD to lock one of the cavity modes. With the optical carrier injection power of -9 dBm, the optical mode located near the injection wavelength was enhanced in intensity while other modes were suppressed to nearly 40 dB lower than the injection-locked wavelength. The optical spectrum of uplink signal is shown in Fig. 5.24(b). Fig. 5.24(c) shows the measured BER performance as a function of received optical power for both the BTB case and that after 10-km uplink transmission. The receiver sensitivity at BER of 10⁻⁹ was -19.5 dBm for the BTB case, while 1.2-dB power penalty was observed after 10-km uplink

transmission. The eye diagrams after downlink and uplink transmission are also shown in Fig. 5.23(a) and Fig. 5.24(a), respectively.

Fig. 5.24. Measured uplink performance. (a) eye diagram, (b) optical spectra, and (c) BER.

In the discussions above, the OCSR of SCM light was fixed at 11 dB. Since the OCSR is an important parameter as shown in Section 5.5.1, it is necessary to examine how the OCSR of SCM light affects the receiver sensitivities for both downlink and uplink in this experiment. Here, the optical power of the SCM light launched into the downlink feeder fiber was fixed at 0 dBm and its OCSR was changed by adjusting the modulation index of the MZM.

Fig. 5.25. Receiver sensitivity vs. OCSR of the SCM light.

Fig. 5.25 shows the receiver sensitivities for both downlink and uplink as a function of the OCSR. As shown in Fig. 5.25, a larger OCSR results in a worse sensitivity for the downlink. As the OCSR increases, more residual optical carrier component appears in the detected downlink signal, which degrades the receiver sensitivity of the downlink signal. Moreover, the power of the optical subcarriers decreases with the increase of OCSR. As a result, the power margin was not enough for downlink when the OCSR was larger than 17 dB. On the other hand, a larger OCSR benefits the uplink transmission. When the OCSR was smaller than 8 dB, the receiver sensitivity degraded significantly. The main reason is that the power of the optical carrier decreases with the reduction in OCSR. When the OCSR was smaller than 8 dB, the injection light power was not sufficient to well lock the FP-LD. While when the OCSR was larger than 8 dB, the receiver sensitivity could be maintained to around -18.4 dBm. The experiments have shown that the proposed scheme works very well when the OCSR is changed between 8 dB and 17 dB, thus indicating a large operating

range.

5.7 Conclusions

Downlink subcarrier modulation and carrier reuse was studied in this chapter. Firstly, two novel carrier-reuse WDM-PON architectures based on wavelength-seeded RSOAs were proposed and experimentally investigated in detail. Architecture I is suitable for the situation where two short distribution fibers between the RN and each ONU are available, while Architecture II is designed for the case where there is only one distribution fiber between the RN and each ONU. Both architectures use only one interferometric filter located at the RN to separate all downlink optical carriers (seeding light) and subcarriers (downlink data) simultaneously, leading to considerable cost reduction in the deployment of WDM-PONs. Two multi-channel transmission experiments with 1.25-Gb/s data rate for both downlink and uplink were carried out to demonstrate the feasibility of the proposed schemes. The experimental results showed very good BER performance. Furthermore, the impact of the OCSR of the SCM light, Rayleigh-backscattering noise and wavelength mismatch on transmission performance was investigated. In addition, discussions on further improving the system performance were provided. The feasibility of the data-rate enhancement to 10 Gb/s of the proposed architectures was also demonstrated with injection-locked FP-LDs. In general, using a shared DI at the RN to separate the optical carriers and subcarriers for all channels was proposed in carrier-reuse WDM-PONs. Some novel architectures based on this idea were investigated and demonstrated their feasibilities.

Chapter 6

Crosstalk in SCM and Carrier-Reuse WDM-PONs

6.1 Overview

In Chapter 5, two WDM-PON architectures based on downstream subcarrier modulation (SCM) and carrier reuse were proposed and examined experimentally. These architectures can effectively avoid the two wavelengths arrangement and hence increase the number of users that can be supported by a WDM-PON. These architectures are also expected to reduce the crosstalk from the downstream data to the upstream data. So far, the reused optical carrier was considered as a pure CW light [117], [147], and the crosstalk between uplink and downlink data was not analyzed and investigated in the literature and Chapter 5.

In this chapter, the characteristic of subcarrier modulated light is mathematically analyzed and experimentally demonstrated. It is shown that the residual baseband data is also present at the optical carrier once it is separated from subcarriers using optical filtering. The residual data will introduce some crosstalk when the optical carrier is reused for uplink data modulation. The crosstalk is investigated in three 1.25-Gb/s carrier-reuse WDM-PON upstream transmission schemes based on wavelength-seeded RSOAs. Suggestions for crosstalk suppression in these schemes are also discussed.

6.2 Characterization of subcarrier modulated light

6.2.1 Mathematical analysis model of subcarrier modulation

Fig. 6.1 Schematic of a WDM-PON with subcarrier transmission and carrier reuse.

In this work, a generic carrier-reuse WDM-PON architecture is considered, as shown in Fig. 6.1, where the downstream data is encoded with subcarrier modulation. For each channel, the downstream data is mixed with a local oscillator (LO) to upconvert the data to a subcarrier. The mixed signal is then used to modulate a CW light by an MZM to generate SCM light. All channels are then combined together by a WDM multiplexer (MUX1), sent through a feeder fiber via an optical circulator, demultiplexed by a WDM multiplexer (MUX2) at the remote node (RN) and go to ONUs via distribution fibers. At each ONU, an optical filter is used to separate the optical carrier with the subcarriers, where the downstream data is detected by a baseband receiver and the optical carrier is reused for modulating upstream data. For upstream remodulation, it is desirable that the optical carrier to be reused does not carry downstream data. In the existing works [117], [147], the optical carrier of the SCM light was considered as a pure unmodulated light. However, the study showed that this is an approximation

which is only true for small signal modulation. Indeed, after being filtered, the downstream optical carrier does carry downstream data information, which cannot be ignored for large signal modulation since the modulation index on the optical carrier is significant and the upstream performance will be considerably affected. This was examined both analytically and experimentally in this chapter.

At each downstream transmitter end, the output optical field of the modulator can be expressed as equation (6-1) [148].

$$E(t) = E_{in} \exp(j\omega_c t) \left\{ \cos \left[\frac{\pi}{V_\pi} \left(V_m(t) \cos(\omega_{rf} t) + V_b \right) \right] \right\}, \quad (6-1)$$

where E_{in} and ω_c are the amplitude and carrier frequency of the input light, respectively, V_b is the bias voltage of the MZM, ω_{rf} is the angular frequency of the local oscillator, and V_π is the driving voltage of the modulator for π phase shift. Equation (6-1) ignores the insertion loss of the modulator. $V_m(t)$ is the driving voltage, which can be expressed as

$$V_m(t) = \sum_{k=1}^{\infty} b_k A_m f_k(t), \quad kT_b \leq t \leq (k+1)T_b, \quad (6-2)$$

where T_b is the bit duration of the downstream data, $b_k = 0$ or 1 is the bit value, A_m is the amplitude, and $f_k(t)$ is the data waveform. Expanding equation (6-1) in terms of Bessel functions leads to

$$E(t) = E_{in} \exp(j\omega_c t) \left\{ \cos(\alpha) \left[J_0(\beta(t)) + 2 \sum_{n=1}^{\infty} (-1)^n J_{2n}(\beta(t)) \cos(2n\omega_{rf} t) \right] - 2 \sin(\alpha) \sum_{n=0}^{\infty} (-1)^n J_{2n+1}(\beta(t)) \cos((2n+1)\omega_{rf} t) \right\}, \quad (6-3)$$

where $\alpha = \pi V_b / V_\pi$, $\beta(t) = \pi V_m(t) / V_\pi$. Equation (6-3) can be expressed as

$$\begin{aligned} E(t) = & E_{in} \cos(\alpha) J_0(\beta) \exp(j\omega_c t) \\ & + E_{in} \cos(\alpha) \sum_{n=1}^{\infty} (-1)^n J_{2n}(\beta) \exp[j(\omega_c \pm 2n\omega_{rf} t)] \\ & - E_{in} \sin(\alpha) \sum_{n=0}^{\infty} (-1)^n J_{2n+1}(\beta) \exp[j(\omega_c \pm (2n+1)\omega_{rf} t)] \end{aligned} \quad (6-4)$$

Equation (6-4) shows that the subcarrier modulated optical field contains many frequency components at ω_c , $\omega \pm \omega_{rf}$, $\omega \pm 2\omega_{rf}$, and so on. The first term is the optical carrier. The other terms are the subcarriers located at $\omega \pm \omega_{rf}$, $\omega \pm 2\omega_{rf}$, ..., respectively.

Depending on the bias condition, the resulting output of the MZM can be different. For example, if the bias voltage $V_b = V_\pi / 2$ ($V_b = V_\pi$ for power transfer function), then $\cos(\alpha) = 0$, and the optical carrier and all the even numbers of subcarriers will be suppressed. Generally, the MZM is biased at the quadrature point $V_b = V_\pi / 4$ for the purpose of optical carrier reuse. In this case, the optical field can be expressed as

$$\begin{aligned} E(t) = & \frac{E_{in}}{\sqrt{2}} \left\{ J_0(\beta(t)) \exp(j\omega_c t) - J_1(\beta(t)) \exp[j(\omega_c \pm \omega_{rf} t)] \right. \\ & \left. - J_2(\beta(t)) \exp[j(\omega_c \pm 2\omega_{rf} t)] + \dots \right\} \end{aligned} \quad (6-5)$$

The amplitude of each mode is a function of $\beta(t)$, which is a function of $V_m(t)$. Therefore all the optical modes including the optical carrier are modulated by the baseband data. Fig. 6.2 shows the simulated optical spectrum of a subcarrier modulated

signal with a resolution of 1.25 GHz, where, $V_b = V_\pi/4$, $A_m = 0.17V_\pi$, $f_{rf} = \omega_{rf}/2 = 12.5$ GHz and data rate was 1.25 Gb/s. The optical carrier and some subcarriers are observed in the spectrum, where the intensity of higher order subcarrier components is much lower. The optical carrier to subcarrier ratio (OCSR) of the SCM light is 15.3 dB. In this work, the OCSR is defined as the power difference between optical carrier and fundamental subcarriers, as shown in Fig. 6.2. The linewidth of each mode is broadened due to data modulation.

Fig. 6.2 Optical spectrum of the subcarrier modulated signal under $V_b = V_\pi/4$ and $V_m = 0.17 V_\pi$.

6.2.2 Residual data on optical carrier

The envelope detection of (6-5) gives the detected signal power

$$P(t) = |E(t)|^2 = \frac{|E_{in}|^2}{2} \left\{ J_0^2(\beta(t)) + 2 \sum_{k=1}^{\infty} J_k^2(\beta(t)) + \sum_{k=0}^{\infty} J_k J_{k+1}(\beta(t)) \cos(\omega_{rf} t) + \dots \right\}, \quad (6-6)$$

The first two terms are baseband data, which results from the self-beating of each mode,

the third term is the fundamental subcarrier which is from the beating between the adjacent modes. Considering the bandwidth of a receiver is much smaller than the subcarrier frequency, the baseband data is then given by

$$P(t) = \frac{|E_{in}|^2}{2} \left(J_0^2(\beta(t)) + 2 \sum_{k=1}^{\infty} J_k^2(\beta(t)) \right), \quad (6-7)$$

From the Neumann's addition theorem of Bessel function [149], the following equation (6-8) can be achieved.

$$P(t) = \frac{|E_{in}|^2}{2} \left(J_0^2(\beta(t)) + 2 \sum_{k=1}^{\infty} J_k^2(\beta(t)) \right) = \frac{|E_{in}|^2}{2} \quad (6-8)$$

Equation (6-8) shows that the baseband power of the SCM light is a constant after photo detection, which means there is no data spectrum component (except a DC) at baseband, and all the data components are carried on subcarriers in RF spectrum. If the optical carrier and subcarriers is separated with an ideal optical filter, their corresponding power, P_c and P_{sc} , can be gotten as

$$P_{sc}(t) = |E_{in}|^2 \sum_{k=1}^{\infty} J_k^2(\beta(t)), \quad (6-9)$$

$$P_c(t) = |E_{in}|^2 J_0^2(\beta(t)) / 2 = |E_{in}|^2 / 2 - P_{sc}(t), \quad (6-10)$$

Equation (6-9) shows that downstream data appears on baseband after optical filtering, which is suitable for downlink baseband detection. On the other hand, the power of the optical carrier is not a constant after it is separated from optical subcarriers, as shown in (6-10). This can be verified by the power spectra shown in Fig. 6.3 (a)-(c). Fig. 6.3(a) shows most power appears around the subcarrier frequency in the SCM light and

Fig. 6.3 Power spectra of subcarrier modulated signal. (a) SCM light including optical carrier and subcarriers, (b) separated optical subcarriers, and (c) separated optical carrier.

there is only a DC around low frequency. Here, SCM light is defined as the subcarrier modulated light, which includes optical carrier and subcarriers. However, if the optical carrier is filtered out for upstream reuse, the downstream data can be recovered by baseband detection, as shown in Fig. 6.3(b). After removing the optical carrier, the data spectrum appears at baseband and the second order subcarrier is also strongly enhanced. Some residual fundamental subcarrier is also observed due to the beating of adjacent (optical) subcarrier modes. Fig. 6.3(c) shows the power spectrum of the optical carrier. Strong DC component appears at the optical carrier, which benefits the light remodulation. However, some baseband data components are also observed. The residual downlink data appearing at the optical carrier may introduce considerable crosstalk when it is reused for uplink.

6.3 Crosstalk of the residual data

Fig. 6.4 Waveforms of the optical carrier and subcarriers. $V_b = V_\pi/4$, $V_m = 0.17V_\pi$. Inset: measured eye diagram of the optical carrier.

The data waveforms carried by the optical carrier and subcarriers are shown in Fig. 6.4,

which were separated using optical filtering. As predicted in (6-10), the data carried on the optical carrier was the inverted version of that on the subcarriers. Experimental results also demonstrated that the downstream optical carrier contained baseband data component as shown in the inset, where $V_b = V_\pi/4$ and $A_m = 0.17V_\pi$.

Extinction ratio is an important parameter to evaluate the quality of the filtered optical carrier. For carrier-reuse purpose, low extinction ratio is desirable. Defining extinction ratio as the intensity ratio of mark to space, it can be expressed as

$$ER = \frac{J_0^2(0)}{J_0^2\left(\frac{A_m}{V_\pi} \pi\right)} . \quad (6-11)$$

Fig. 6.5. Extinction ratio of the optical carrier and the power of the optical subcarriers as a function of modulation amplitude (relative to V_π).

Fig. 6.5 shows the extinction ratio of the optical carrier as well as the power of the

optical subcarriers as a function of the RF signal modulation amplitude applied to the downlink modulator, A_m . The power of the optical subcarriers increased with A_m . To meet the power budget of the downlink, the amplitude of the RF signal should be high enough. On the other hand, higher RF signal amplitude induced a higher extinction ratio of the optical carrier, which means a larger power variation at the optical carrier. This would introduce considerable crosstalk to the uplink signal. Therefore, there should be a trade-off.

Fig. 6.6 The bit error rate (BER) of the upstream transmissions with downstream modulator turned on: +, and turned off: ◇.

In order to demonstrate the influence of the residual downstream data at the optical carrier on the upstream signal, the upstream transmission of the WDM-PON was simulated and its results are shown in Fig. 6.1. Here the transmission fiber was 21-km SMF whose dispersion is 16 ps/nm·km. The downlink modulator was biased at the quadrature point. An ideal optical filter with 0.1-nm bandwidth was used to separate

optical carrier and subcarriers. An external modulator was used for uplink data modulation. Subcarrier frequency and data rate were 12.5 GHz and 1.25 Gb/s, respectively. The modulation voltage V_m was $0.17V_\pi$ and the OCSR of the SCM light was 15.3 dB. The optical receiver was an APD detector, whose avalanche multiplication factor was 3.0. Fig. 6.6 shows the bit error rate (BER) performance of the upstream transmission. For comparison, the situation where CW light was used for uplink carrier was also considered, which was emulated by turning off the downstream modulator. The receiver sensitivities @ BER of 10^{-9} for carrier remodulation and CW light modulation were -31.5 dBm and -32.3 dBm, respectively. There was a 0.8-dB power penalty for carrier-reuse scheme compared with that of CW light modulation. Inserted eye diagram also showed the residual data on the top of eye. In the next section, the characteristics of the downlink subcarrier transmission and carrier-reuse scheme in an RSOA based WDM-PON are experimentally investigated, where three different configurations are considered.

6.4 Crosstalk suppression in RSOA-based carrier-reuse WDM-PONs

In the previous section, an external modulator was used for uplink data modulation to demonstrate the effect of residual downlink data resided at the optical carrier. It has been found that the uplink performance does suffer from crosstalk. The external modulator also imposes additional insertion loss and reduces link power margin. An RSOA employed in a WDM-PON for direct data modulation not only gives additional gain for incident optical power to compensate power losses from device and transmission fiber, but also suppresses the amplitude fluctuation and reduces the intensity noise of seeding light [147] when the RSOA is operated in the gain saturation region. Therefore RSOAs have been widely proposed as potential ONU light sources in

carrier distribution WDM-PONs.

The amplitude fluctuation suppression characteristic of a saturated RSOA is expected to suppress the effect of the residual downlink data carried on the optical carrier (seeding light). To demonstrate this, experiments were carried out for carrier-reuse WDM-PONs incorporating an RSOA at each ONU, as shown in Fig. 6.1. The downstream signal was modulated in ASK format by mixing a 1.25-Gb/s data stream with a 12.5-GHz clock signal. The modulated signal then passed through a circulator, a MUX, a 21-km SMF, and a DeMUX before it was fed into an ONU. The 3-dB bandwidth for both MUX and DeMUX is 0.5 nm, which is more than sufficient to support the subcarrier transmission. The optical subcarriers and carrier were separated using optical method in each ONU or at the RN for downlink detection and carrier reuse, respectively. The upstream data was then directly modulated to the reused optical carrier using an RSOA, and then sent back to the CO through the same transmission fiber, and detected by the uplink receiver at the CO. Here three different configurations for separating optical carrier and subcarriers are considered, which are based on optical circulator and fiber Bragg grating (FBG), fiber coupler and optical band reject filter, and delay interferometer. The influences of the residual data carried on the reused optical carrier on the uplink transmission are examined in detail for each of the configurations.

6.4.1 FBG-circulator based carrier-reuse scheme

First the ONU configuration using a fiber Bragg grating (FBG) and an optical circulator as shown in Fig. 6.7 is discussed. After passing through the circulator, the downstream SCM light was fed into the FBG whose central wavelength is at the optical carrier

frequency. The transmitted subcarriers were then detected by a 1.25-Gb/s baseband optical receiver, while the reflected optical carrier was used to seed an RSOA via the optical circulator. The 1.25-Gb/s upstream data was directly modulated onto the RSOA. The output of RSOA was then transmitted back to CO through the optical circulator and feeder fiber for uplink detection. The FBG used here is a self-fabricated simple apodized FBG with reflectivity of 99.8 % and a 3-dB pass-bandwidth of 0.15 nm. It was operated at room temperature, with no special wavelength and temperature control applied. The transmission and reflective spectra of FBG are both shown in the inset of Fig. 6.8.

Fig. 6.7. FBG-circulator based ONU architecture.

Fig. 6.8 shows the measured spectra of the lights measured before circulator, receiver and RSOA, respectively. The OCSR of the SCM light was 15.3 dB as shown by the solid line. After passing through the FBG filter, the OCSR of the light detected by the downlink receiver was reduced to -20 dB due to the suppression of the optical carrier, as shown in the dashed line. The seeding light reflected by the FBG has an OCSR of 20.4 dB due to the suppression of optical subcarriers, as shown by the dotted line of Fig.

6.8. The detected downstream BER as a function of received optical power is shown in Fig. 6.9. Here the receiver sensitivity at BER of 10^{-9} was -32.1 dBm. All eye diagrams in this chapter were measured with a 2.85-GHz PIN photodetector in conjunction with an oscilloscope and shown in the inset.

Fig. 6.8. Optical spectra of the downstream signal before (solid line) and after (dashed line) the FBG and reflected optical carrier (dotted line).

Fig. 6.9. BER of 1.25-Gb/s downstream signal as a function of received optical power. (OCSR of the SCM light was 15.3 dB.)

Fig. 6.10 shows the receiver sensitivity @ BER of 10^{-9} of the upstream signal (measured at the CO) as a function of seeding power. Here, the bias current of the RSOA was 60 mA and its free-running optical output power was around -8.5 dBm. It can be seen, the receiver sensitivity improves with the increase of the seeding power because a higher seeding power leads to a higher optical signal to noise ratio (OSNR).

Fig. 6.10. Receiver sensitivity of upstream signal with different values of OCSR of the SCM light. RSOA bias current $I_b=60$ mA. Inset: eye diagram of uplink signal when OCSR=15.3dB and seeding power was -25 dBm.

As discussed in Fig. 6.5, higher RF signal amplitude for downstream subcarrier modulation not only induces a higher optical subcarriers power, which corresponds to a lower OCSR, but also induces a larger power fluctuation at the optical carrier. In order to demonstrate the impact of the residual data at the optical carrier on the performance

of the upstream transmission, the receiver sensitivities of the upstream signal with different values of the OCSR of the SCM light were also shown in Fig. 6.10. Here, the OCSR was changed by adjusting the driving voltage of the MZM, V_m . The receiver sensitivity was improved with the increase of OCSR because a higher OCSR was corresponding to a lower power fluctuation of the seeding light — optical carrier. To demonstrate the power penalty of the optical carrier reuse in the WDM-PON upstream transmission, the receiver sensitivity of upstream transmission with CW seeding light was also shown in Fig. 6.10. In this case the downstream modulator was turned off. Here the power penalty is defined as the difference between the receiver sensitivities with and without the subcarrier modulation. Similar to that in the previous chapter, lower OCSR leads to higher power penalty for a given seeding light power. For a given OCSR, higher seeding power leads to lower power penalty. For the case of OCSR = 15.3 dB, the power penalty was about 0.8 dB when the seeding power was as small as -25 dBm, which is as same as the simulation result in Fig. 6.6 since the RSOA worked in linear amplification region in this case. The corresponding eye diagram was shown in the inset of Fig. 6.10. As observed, there was some power fluctuation on top of the eye pattern due to the residual downstream data. When the seeding power further increases, the gain of the RSOA decreases and the gain saturation of the RSOA suppresses the power fluctuation of the seeding light. In the experiments, the power penalty was reduced to 0.4 dB when the seeding power was -15 dBm and OCSR was 15.3 dB. While once the seeding power was greater than -10 dBm, the power penalty was negligible for any OCSR evaluated.

6.4.2 Coupler-filter based carrier-reuse scheme

As analyzed and discussed in Section 6.3, when the downlink MZM is biased around

the quadrature point, the downstream SCM light contains no baseband data in the power spectrum, as shown in Fig. 6.3. It is expected that there will be no crosstalk from the downlink data if the downstream SCM light is directly intensity remodulated at baseband by uplink data.

Fig. 6.11 Coupler and band reject filter based ONU architecture.

Here an ONU is considered, in which an RSOA is used to directly modulate the upstream data onto the downstream SCM light without removing the optical subcarriers. The proposed ONU structure is shown in Fig. 6.11. Different from the FBG-circulator based scheme, in this scheme the downstream SCM light is split into two parts with a 3-dB coupler. Part of the SCM light is used for downstream data detection using an optical band reject filter, e.g. FBG integrated with an isolator, to remove the optical carrier. The other part of the downstream SCM signal is fed into an RSOA as a seeding light. Then, the upstream light includes the baseband upstream data and some high frequency subcarrier (downstream data) in its power spectrum, as shown in Fig. 6.11. The high frequency component can be easily suppressed by the

uplink receiver as its response frequency may be quite lower than subcarrier frequency.

Fig. 6.12 Optical spectrum of the upstream signal with coupler-filter based ONU.

Fig. 6.12 shows the optical spectrum of the upstream signal. Here, the OCSR of SCM light was 15.3 dB and seeding power was -10 dBm. After input the RSOA, both optical carrier and subcarriers were amplified and modulated with a 1.25-Gb/s baseband upstream data.

In this scheme, the performance of the upstream system should be sensitive to V_b . Once the bias of the downstream modulator deviates from the quadrature point, the power of the seeding light is no longer constant. Fig. 6.13 shows the receiver sensitivity of the upstream signal based on the downstream light reuse scheme as a function of seeding power with different bias voltages of the downlink modulator. Here, V_m is fixed at $0.17 V_\pi$. The best performance was obtained when the bias voltage of the downstream data modulation was $V_\pi/4$ as predicted in (6-8). To make it easier for comparison, the

receiver sensitivity curve for the CW case is also included into Fig. 6.13, shown as the solid diamond. In the case of $V_b = V_\pi/4$, there was no baseband frequency component in the power spectrum of downstream SCM light and its receiver sensitivity curve was similar to the case based on the CW laser seeded RSOA. Different from the FBG-circulator based scheme (corresponding to the case of OCSR = 15.3 dB), the power penalty in this scheme was quite small even if the RSOA works in linear amplification region, which verifies no significant crosstalk from the downstream SCM light. The small power penalty observed may be due to its larger dispersion since the optical spectrum of uplink light is broader in this scheme.

Fig. 6.13 Receiver sensitivity of upstream signal based on the downstream carrier reuse as a function of injected optical power with different bias voltages of the downstream modulator. Bias current of RSOA: $I_b = 60$ mA.

The transfer function of the MZM used is shown in Fig. 6.14(a). The MZM was biased

Fig. 6.14. Transfer function of MZM (a) and waveforms of the SCM light with different bias voltage. (b) $0.35 V_\pi$ (c) $0.3 V_\pi$ (d) $0.25 V_\pi$ (e) $0.2 V_\pi$ (f) $0.15 V_\pi$

at raised region in this experiment. Fig. 6.13 shows higher or lower bias voltage introduced excess crosstalk due to the symbiotic data of the downstream signal located at the baseband spectrum since the baseband intensity was not constant in this case. Especially when bias voltage was smaller than $V_\pi/4$, significant power penalty was induced because the optical carrier was suppressed and more power fluctuation existed in the SCM downstream light for a given power, as shown in Fig. 6.14. For example,

when this bias voltage was $0.12 V_\pi$ and seeding power was -16 dBm, the power penalty was 2 dB compared with the CW light seeding scheme shown in Fig. 6.13.

Although the coupler-filter based ONU requires more power budget due to the splitting loss of the fiber coupler, this scheme is better in that it has a smaller power penalty caused by the residual data carried at the optical carrier when the MZM is biased around quadrature point.

6.4.3 DI based carrier-reuse scheme

As known, colorless operation is important for the implementation of WDM-PON. Both carrier-reuse schemes in Section 6.4.1 and Section 6.4.2 employ a FBG to separate the optical carrier and subcarriers. To make the ONUs colorless, the central wavelength of the FBG may be required to be tunable to match the downlink wavelength. Beside FBGs, an interferometric filter, e.g. delay interferometer (DI), can also work as a narrow bandpass filter to separate the optical carrier and subcarriers. Due to the periodical characteristic of DI, it is easy to make the ONUs colorless. Furthermore, the DI can be used in each ONU and can also be shared in the RN. The later can effectively reduce the implementation cost since only a single filter is required for all users and has been discussed in Chapter 5. Here this structure is also investigated to evaluate the impact of the residual downstream data carried on optical carrier.

In the remote node, a DI and two demultiplexers are used to separate the optical carrier and subcarriers for all channels, as shown in Fig. 6.15. In this case, each ONU only consists of a downstream baseband receiver and an RSOA.

Fig. 6.15. DI based carrier-reuse WDM-PON scheme.

Fig. 6.16. Optical spectra of downstream light measured before the downlink receiver (a), and the RSOA (b).

In this investigation, the local oscillator frequency was 5 GHz, which is half of the free spectral range of the DI. Both upstream and downstream data rates were 1.25 Gb/s. The optical spectra of the optical subcarriers (downlink data) and carrier (seeding light) for ONU1 are shown in Fig. 6.16. The subcarriers were launched into the baseband receiver for downstream data detection, while the optical carrier (and residual even

order subcarriers whose intensity was much lower than optical carrier) was seeded into the RSOA for upstream data remodulation. The seeding power was -12 dBm.

Fig. 6.17. Measured upstream BERs of DI based scheme.

The measured BER of the upstream transmission with different OCSRs was studied to demonstrate the influence of the residual downstream data on system performance in this scheme, as shown in Fig. 6.17. It is known that lower OCSR corresponds to higher subcarrier power. And higher subcarrier power introduces larger power fluctuation of the optical carrier, as shown in (6-10). The larger power fluctuation introduces more crosstalk when the optical carrier is remodulated and deteriorates the BER performance of the uplink. As a result, higher OCSR induces a larger power penalty as shown in Fig. 6.17. It is also observed that the improvement of BER sensitivity at a larger OCSR (higher than 14 dB) was not significant. This could be caused by the fact that at a sufficiently high OCSR, the effect of the residual downlink data is negligible and the RSOA is operated under saturation conditions. Therefore, the residual downstream data carried at the optical carrier introduces the crosstalk to the upstream signal in carrier-reuse WDM-PONs, mainly in the situation of large signal modulation.

Fig. 6.18, Uplink power penalty vs. OCSR for the three schemes.

In the following, the performance of the three kinds of carrier-reuse schemes is summarized. Here, the seeding light power was -12 dBm for all schemes. For the coupler-filter based scheme, the OCSR was 15.3 dB when the modulator was biased at the quadrature point. When the bias current deviated from the quadrature point, the OCSR was changed accordingly. All other experimental conditions for these three schemes were the same. Fig. 6.18 shows the best performance for the coupler-filter based scheme was achieved when $\text{OCSR} = 15.3 \text{ dB}$. Higher or lower OCSR can both deteriorate the receiver sensitivity. For both the FBG-circulator based scheme and the DI based scheme, the power penalty decreases with the increase of the OCSR of SCM light. However, if the maximum tolerable power penalty of the system is 1 dB, the three schemes can all work well when OCSR is larger than 9 dB.

6.5 Conclusions

In this Chapter, the characteristics of the subcarrier modulation were mathematically analyzed. The study showed that the modulated data exhibits on both optical carrier and subcarriers. Residual data appears on the optical carrier once it is separated from optical subcarriers using an optical method. Simulation results showed that a 0.8-dB power penalty was introduced due to the crosstalk from the residual data when the optical carrier was modulated with an MZM and transmitted in a 21-km link. The influence of residual data and its suppression were also studied in three kinds of 1.25-Gb/s WDM-PON uplink schemes based on wavelength seeded RSOAs. For FBG-circulator based scheme, proper selection of OCSR of the SCM light (corresponding to proper driving amplitude of MZM) and seeding power into RSOAs can effectively suppress crosstalk. When the seeding power was greater than -10 dBm, the crosstalk was negligible for OCSR from 11.4 dB to 26.8 dB. For coupler-filter based scheme, the crosstalk was sensitive to bias voltage of the downlink modulator, MZM, and there was almost no crosstalk when MZM was biased at quadrature point. Compared with above schemes, DI based scheme can effectively reduce the deployment cost since it is shared by all ONUs. The crosstalk in this scheme was suppressed effectively when OCSR was larger than 11.3 dB. In general, the residual data carried on the optical carrier indeed introduces crosstalk when it is separated using optical filtering and is reused for data transmission. Proper selection of seeding power into RSOAs and operation conditions of the downlink MZM, such as driving voltage and bias voltage, can significantly suppress the crosstalk.

Chapter 7

Conclusions and Future Work

7.1 Conclusions

This thesis has investigated the characteristics and optimization of light sources and proposed some new schemes for wavelength division multiplexed passive optical networks (WDM-PONs). To improve the transmission performance and make the optical network unit colorless, various light sources have been proposed and demonstrated in WDM-PONs. In particular, light sources using external light injection-locked FP-LDs and downlink subcarrier transmission and carrier-reuse scheme have been studied in detail.

In Chapter 3, the injection-locking techniques for FP-LDs have been studied. It has been demonstrated that injection-locking increases modulation bandwidth, reduces relaxation oscillation and narrows laser linewidth of FP-LDs. a high-speed light source using coherent light injection-locked FP-LDs has been proposed and experimentally demonstrated in a 10-Gb/s WDM-PON. Performance evaluations have been investigated in terms of injection power, injected mode selection, wavelength detuning and transmission distance. It has been demonstrated that up to 16 cavity modes of the FP-LD can be used for injection-locking and the allowable wavelength detuning range at BER of 10^{-9} is up to 3.6 GHz. With proper dispersion compensation, the proposed light source has been shown to be useful for long-reach WDM-PONs and metropolitan optical networks. The polarization-insensitive injection-locking has also been demonstrated by combining a conventional depolarizer and a dual-fiber ring structure.

The proposed WDM PON architecture is cost-effective, since the multiple coherent laser sources with different wavelengths located at the central office can be shared by many WDM-PONs and low-cost FP-LDs are used as light sources in ONUs for data rates as high as 10 Gb/s.

In Chapter 4, the characteristics and performance enhancement of the spectrum-sliced amplified spontaneous emission (ASE) source injection-locked FP-LDs in WDM-PON applications have been discussed. The experimental investigations have shown that the required injection power depends on the bias current and sliced ASE bandwidth. The optimum ASE injection bandwidth is about 0.4nm~0.6nm. The impact of intensity noise (IN) of the spectrum-sliced ASE source and the IN suppression using an SOA have also been investigated. Lastly this chapter has also experimentally examined the impact of front-facet reflectivity, operation temperature, bias current and injection-locked mode location of FP-LDs on the transmission performance. The experimental results have demonstrated that the output performance of FP-LDs can be improved significantly by selecting proper front-facet reflectivity, operation temperature and optimal bias current of FP-LDs.

In Chapter 5, the technique of downlink subcarrier transmission and carrier reuse for the uplink has been studied. Firstly, a single shared interferometric filter located at the remote node (RN) to separate optical carriers and subcarriers for all users has been proposed, which leads to considerable cost reduction in the deployment of WDM-PONs. Based on this idea, two novel carrier-reuse WDM-PON architectures have been proposed and experimentally investigated in detail. Architecture I is suitable for the situation where two short distribution fibers between the RN and each optical network user (ONU) are available, while Architecture II is designed for the

case where there is only one distribution fiber between the RN and each ONU. In both architectures, the downlink data carried on the subcarriers is directly detected with conventional baseband receivers, while the separated optical carriers are reused and injected into RSOAs as the uplink light sources, which eliminates the necessity of specific wavelength sources at ONUs. Secondly, two multi-channel transmission experiments with 1.25-Gb/s data rate for both downlink and uplink have been carried out and good performance has been achieved, which has demonstrated the feasibility of the proposed scheme. Thirdly, the impact of optical carrier to subcarrier ratio (OCSR) of the subcarrier modulated (SCM) light, Rayleigh-backscattering noise and wavelength mismatch on system transmission performance has also been investigated in detail. Lastly, issues on the influence of temperature on the RSOA's performance, the number of subscribers supported by the WDM-PON, and the colorless operation of ONUs have been discussed and suggestions have been provided. The data rate enhancement of the architecture has also been studied and a 10-Gb/s transmission with injection-locked FP-LDs for both downlink and uplink has shown its feasibility.

In Chapter.6, the characteristics of the subcarrier modulated light have been mathematically analyzed. It has been demonstrated that the modulated data exhibits on both optical carrier and subcarriers. Residual data appears on the optical carrier once it is separated with an optical method. Simulation results have showed that a 0.8-dB power penalty is introduced due to the crosstalk from the residual data when the optical carrier is modulated with an MZM and transmitted in a 21-km link. Three different ONU configurations for 1.25-Gb/s upstream transmission in carrier-reuse WDM-PONs based on wavelength-seeded RSOAs have been experimentally demonstrated. For FBG-circulator based scheme, proper selection of OCSR of the SCM light and the seeding power can effectively suppress crosstalk. The crosstalk has been demonstrated

to be negligible for OCSR from 11.4 dB to 26.8 dB with seeding power greater than -10 dBm. For coupler-filter based scheme, the crosstalk is sensitive to bias voltage of the downlink modulator, MZM, and it has been shown that there was almost no crosstalk when MZM was biased at quadrature point. Compared with above schemes, DI based scheme effectively reduces the deployment cost, since the DI can be shared by all ONUs. The crosstalk in this scheme has been suppressed well when OCSR was greater than 11.3 dB. In general, the residual data carried on the optical carrier indeed introduce crosstalk when it is separated from optical subcarriers using optical filtering and reused for data transmission. Proper selection of seeding power into RSOAs and operation conditions of downlink MZM, such as driving voltage (corresponding to proper OCSRs) and bias voltage can significantly suppress the crosstalk.

7.2 Future work

As discussed in this thesis, WDM-PON is an ultimate solution of the optical access network. It offers a secure broadband access and enables various services for each user. However, there are still some interesting problems and challenges in WDM-PONs that are worth studying in future.

Broadcast is an important service for access network, however WDM-PON is not well suited for the delivery of broadcast services since it utilizes arrayed-waveguide grating (AWG) in the RN for the virtual point-to-point connectivity. In this thesis, the broadcast service was not included in the proposed architectures. Therefore, the issue of providing broadcast service needs to be addressed in the future. One possible solution is to use a broadband light source located at a wavelength band different from the downlink and uplink wavelengths as the broadcast light source. However, this will

reduce the subscriber number supported by a WDM-PON as half of the PON wavelength bandwidth is dedicated for the broadcast. As a result, using a single wavelength to carry both bidirectional private data and broadcast data is an interesting subject to be studied. One suggestion is to modulate the downstream private data and broadcast data on optical carriers and subcarriers, respectively, and then reuse the optical carrier for upstream transmission. More work can be done to reduce the crosstalk from the baseband data carried on optical carrier.

Inter-networking of ONUs to enable interaction between subscribers located at a particular area is also an interesting topic. Some work has reported to setup a virtual optical networking using an $N \times N$ AWG in the RN [144], [150-151]. In Architecture II of Chapter 5, only 2 input ports of $N \times N$ AWG are used, while other input ports are free. One possible continuous work is to connect the inter-networking of ONUs with the architecture.

For WDM-PONs with bit rate higher than 1 Gb/s, most of the colorless light sources, especially injection-locked FP-LD, require a temperature controller (TEC) to maintain their operation wavelengths and output power. This would increase the implementation cost of each ONU. In addition, the bias current of the FP-LD and RSOA is quite high (20-60mA), which is more power consuming. Future work can be focused on how to make the colorless light source work without TEC and the methods to reduce power consumption.

Author's Publications

- [1] **Z. Xu**, Y. J. Wen, W-D. Zhong, C. J. Chae, X-F. Cheng, Y. Wang, C. Lu, and J. Shankar "High-speed WDM-PON using CW injection-locked Fabry-Pérot laser diodes," *Optics Express*, vol. 15, Issue 6, pp.2953-2962, 2007. (Chapter 3)
- [2] **Z. Xu**, Y. J. Wen, W-D. Zhong, M. Attygalle, X-F. Cheng, Y. Wang, and C. Lu "Carrier-reuse WDM-PON using a shared delay interferometer for separating carriers and subcarriers" *IEEE Photonics Technology Letters*, vol. 19, pp.837-839, 2007. (Chapter 5)
- [3] **Z. Xu**, Y. J. Wen, W-D. Zhong, M. Attygalle, X-F. Cheng, Y. Wang, T. H. Cheng, and C. Lu, "WDM-PON architectures with a single shared interferometric filter for carrier-reuse upstream transmission," *Journal of Lightwave Technology*, vol. 25, pp.3669-3677, 2007. (Chapter 5)
- [4] **Z. Xu**, Y. J. Wen, W-D. Zhong, M. Attygalle, T. H. Cheng, X. Cheng Y.K Yeo, and C. Lu, "Characteristics of subcarrier modulation and its application in WDM-PON," submitted to *Journal of Lightwave Technology*. (Chapter 6)
- [5] X. Cheng, Y. J. Wen, Y. Dong, **Z. Xu**, Yixin Wang, and Chao Lu, "Optimization of spectrum sliced ASE source for injection-locking a Fabry-Pérot laser diode", *IEEE Photonics Technology Letters*, vol. 18, pp. 1961 – 1963, 2006. (Chapter 4)
- [6] **Z. Xu**, Y. J. Wen, C. J. Chae, Y. Wang, and C. Lu "10 Gb/s WDM-PON upstream transmission using injection-locked Fabry-Perot laser diodes," Optical Fiber Communication Conference, *OFC'06*, paper JThB72, 2006. (Chapter 3)
- [7] **Z. Xu**, Y. J. Wen, M. Attygalle, X. Cheng, W.-D. Zhong, Y. Wang, and C. Lu, "Multiple channel carrier-reused WDM passive optical networks," *the 32nd European Conference on Optical Communications, ECOC'06*, Post deadline paper: Th4.3.2, 2006. (Chapter 5)

- [8] **Z. Xu**, Y. J. Wen, W.-D. Zhong, T. H. Cheng, X. Cheng, Y. Wang, and Y.K Yeo, "10-Gb/s carrier-reuse WDM-PON based on injection locked FP-LDs," submitted to *Optoelectronics and Communications Conference (OECC08)*, OECC'08. (Chapter 5)
- [9] **Z. Xu**, Y. J. Wen, W.-D. Zhong, X. Cheng, Y. Wang, M. Attygalle, J. Shankar, and C. Lu, "Crosstalk in downlink carrier reused WDM-PONs based on subcarrier modulation," *12th Optoelectronics and Communications Conference (OECC07)*, paper. 11A2-1, 2007. (Chapter 6)
- [10] **Z. Xu**, G. Zhou, C. Lu "Optical 4-ASK signal generation through four-wave mixing," *19th Annual Meeting of the IEEE Lasers and Electro-Optics Society, LEOS'06*, pp. 505- 506, 2006.
- [11] X-F. Cheng, Y. J. Wen, **Z. Xu**, Y. Wang, J. Shankar, P. Shum "In-service fault localization in WDM passive optical networks, " *Optical Fiber Communication Conference, OFC'07*, paper. JThA79, 2007.
- [12] X. Cheng, Y. J. Wen, **Z. Xu**, W. Kuang, and Y. Wang, "A novel protection scheme for WDM passive optical networks", *the 32nd European Conference on Optical Communications, ECOC'06*, paper We3.P.151, 2006.
- [13] Y. J. Wen, X. Cheng, **Z. Xu**, Y. Wang, and J. Shankar, "Light sources for WDM passive optical networks," *International Conference on the Optical Internet, COIN'07*, Invited paper WeA2-5, 2007.
- [14] X. Cheng, Y. J. Wen, **Z. Xu**, Y. Wang, and J. Shankar, "Impact of facet reflectivity and operation condition on injection-locking Fabry-Perot laser diodes with spectrum sliced ASE noise in WDM-PON," *Conference on Lasers and Electro-Optics, CLEO'07*, paper JTuA137, 2007.

References

- [1] D.R. Garrison, and T. Anderson, *E-Learning in the 21st Century -A Framework for Research and Practice*, New York, 1st Edition, 2003.
- [2] S. K. Mun and J. W. Turner, "Telemedicine: Emerging e-medicine," *Annual Review of Biomedical Engineering*, vol. 1, pp. 589-610, 1999.
- [3] W. Cai, P. Xavier, S.J. Turner, and B-S. Lee, "A scalable architecture for supporting interactive games on the internet," *16th Workshop on Parallel and Distributed Simulation*, pp. 54-61, 2002.
- [4] S. Wright and S. Tischer, "Architectural considerations in online game services over DSL networks," *IEEE International Conference on Communications, ICC'04*, pp. 1380-1385, 2004.
- [5] R. Kishimoto and I. Yamashita, "HDTV communication systems in broadband communication networks," *Communications Magazine, IEEE*, vol. 29, pp. 28-35, 1991.
- [6] R. Schafer, "Review and future directions for 3D-video," Keynote speech of *Picture Coding Symposium, PCS'06*, 2006.
- [7] T.J. Walsh and D.R. Kuhn, "Challenges in securing voice over IP," *IEEE Security & Privacy Magazine*, vol. 3, pp. 44-49, 2005
- [8] M. Adda, A. Peart, and L. Rochfort, "Voice over IP on wireless networks," *Information and Communication Technologies, ICTTA'06*, vol. 2, pp. 2742-2747, 2006.
- [9] N-F. Huang and H-I. Liu, "Wavelength division multiplexing-based video-on-demand systems," *IEEE Journal of Lightwave Technology*, vol. 17, pp.155-164, 1999.
- [10] F. Thouin and M. Coates, "Video-on-demand networks: design approaches and future challenges," *IEEE Network*, vol. 21, pp. 42-48, 2007.

-
-
- [11] J. George, "FTTH design with the future in mind: optical infrastructure scalable to 25 year bandwidth demands," *Digest FTTH conference*, Session 7D, 2005.
- [12] R. E. Wagner, J. R. Igel, R. Whitman, M. D. Vaughn, A. B. Ruffin, and S. Bickham, "Fiber-based broadband-access deployment in the United States," *IEEE Journal of Lightwave Technology*, vol.24, pp. 4526-4540, 2006.
- [13] M. N. O. Sadiku and C. Aduba, "Cable modem technology," *IEEE Potentials*, vol. 19, pp. 26-27, 2000.
- [14] V. K. Bhagavath, "Emerging high-speed xDSL access services: architectures, issues, insights, and implications," *IEEE Communications Magazine*, vol.37, pp. 106-114, 1999.
- [15] D. Jenkinson, "DSL in the access network," *IEE Multimedia in the Local Loop - the DSL Seminar*, pp. 5/1-5/3, 2000.
- [16] W. Chen. *DSL simulation techniques and standards development for digital subscriber lines*, Macmillan. 1998.
- [17] C-H. Lee, W. V. Sorin, and B. Y. Kim, "Fiber to the home using a PON infrastructure," *IEEE Journal of Lightwave Technology*, vol. 24, pp. 4568-4583, 2006.
- [18] *ITU standard G.983.1*.
- [19] *ITU standard G.984.1*.
- [20] *Institute of Electrical and Electronics Engineers (IEEE) 802.3ah*. Available online: <http://www.ieee802.org/3/ah/index.html>
- [21] Press Release of Novera Optics Inc. "Novera optics expands Korea telecom engagement with new 30,000-line DWDM PON deployment in Q1/2007," Available online: <http://www.noveraoptics.com/news/index.php#turbolight>
- [22] Y. J. Wen, X. Cheng, Z. Xu, Y. Wang, and J. Shankar, "Light sources for WDM passive optical networks," *International Conference on the Optical Internet, COIN'07*, WeA2-5, 2007.

- [23] C. -H. Lee, S. -M. Lee, K. -M. Choi, J. -H. Moon, S. -G. Mun, K. -T. Jeong, J. H. Kim, and B. Kim, "WDM-PON experiences in Korea [Invited]," *Journal of Optical Networking*, vol. 6, no. 5, pp. 451–464, 2007.
- [24] <http://www.noveraoptics.com/technology/turbolight.php>
- [25] K. Y. Park, J. S. Baik, T. W. Oh, and C. H. Lee, "Intensity noise suppression and 1.25 Gb/s transmission using a wavelength-locked Fabry–Pérot laser diode with filtered ASE injection," *OptoElectronics Communication Conference, OECC'04*, pp. 200–201, 2004.
- [26] K. G. Coffman and A. M. Odlyzko, "Internet growth: is there a "Moore's law" for data traffic?" *Handbook of Massive Data Sets*, Kluwer, 2001.
- [27] D. Gutierrez, K. S. Kim, S. Rotolo, F-T. An, and L. G. Kazovsky, "FTTH standards, deployments and research issues," (Invited paper) *8th Joint Conference on Information Sciences, JCIS'05*, pp. 1358-1361, 2005.
- [28] John George, "Applications compelling fiber to the home," *The FTTH Prism*, vol. 3, pp. 47-55, 2006.
- [29] K. S. Kim, "On the evolution of PON-based FTTH solutions," (Invited Paper) *Information Sciences*, vol. 149/1-2, pp. 21-30, 2003.
- [30] B. Lung, "PON architecture 'futureproofs' FTTH," *Lightwave*, vol. 16, pp. 104-107, 1999.
- [31] J. R. Stern, J. W. Ballance, D. W. Faulkner, S. Hornung, D. B. Payne, and K. Oakley, "Passive optical local networks for telephony applications and beyond", *IEE Electronics Letters*, vol. 23, pp. 1255-1257, 1987.
- [32] S. J. Park, C. H. Lee, K. T. Jeong, H. J. Park, J. G. Ahn, and K. H. Song, "Fiber-to-the-home services based on WDM passive optical network," *IEEE Journal of Lightwave Technology*, vol. 22, pp. 2582–2590, 2004.

-
-
- [33] I. Van de Voorde and C. Van der Plas, "Full service optical access networks: ATM transport on passive optical networks," *IEEE Communications Magazine*, vol. 34, pp. 70-75, 1997.
- [34] B. Miah and L. Cuthbert, "An economic ATM passive optical network," *IEEE Communications Magazine*, vol. 35, pp. 62-68, 1997.
- [35] N. Terada, H. Ishii, T. Tachi, Y. Okumura, and H. Kotera, "An MPEG2-based digital CATV and VOD system using ATM-PON architecture," *the Third IEEE International Conference on Multimedia Computing and Systems, ICMCS'96*, pp:522 – 531, 1996.
- [36] G. Kramer, B. Mukherjee, and A. Maislos, "Ethernet passive optical networks," Wiley-Interscience, New York, NY, USA, 2003.
- [37] G. Kramer and G. Pesavento, "Ethernet passive optical network (EPON): building a next-generation optical access network," *IEEE Communications Magazine*, vol. 40, pp. 66-73, 2002.
- [38] G. Kramer, B. Mukherjee, and G. Pesavento, "Ethernet PON (ePON): design and analysis of an optical access network," *Photonic Network Communications*, vol. 3, pp. 307-319, 2001.
- [39] O. Marmur. "GPON-the next big thing in optical access networks," *Lightw. Mag.* Online: http://lw.pennnet.com/Articles/Article_Display.cfm?Section=ONART&Subsection=Display&ARTICLE_ID=172564&KEYWORD=FlexLight&p=13.
- [40] S. Smith, "Business class services over a GPON network," *Optical Fiber Communication Conference, OFC'06*, paper: Jthb96, 2006.
- [41] T. Van Caenegem, E. Gilon, X.-Z. Qiu, P. Solina, and K. Cobb, "Prototyping ITU-T GPON, the new efficient and flexible FTTP PON solution," *International Symposium on Subscriber Loops Services, ISSLS'04*, 2004.
-
-

-
-
- [42] J. Jiang, M.R. Handley, and J.M. Senior, "Dynamic bandwidth assignment MAC protocol for differentiated services over GPON," *IEE Electronics Letters*, vol. 42, pp. 653-655, 2006.
- [43] M.P. McGarry, M. Maier, and M. Reisslein, "Ethernet PONs: a survey of dynamic bandwidth allocation (DBA) algorithms," *Communications Magazine, IEEE*, vol. 42, pp. S8-15, 2004.
- [44] *Institute of Electrical and Electronics Engineers (IEEE) P802.3av. Available online: <http://www.ieee802.org/3/av/index.html>*
- [45] C-H. Lee, S-M. Lee, K-M. Choi, J-H. Moon, S-G. Mun, K-T. Jeong, J. H. Kim, and B. Kim, "WDM-PON experiences in Korea [Invited]," *Journal of Optical Networking*, vol. 6, pp.451-464, 2007.
- [46] J. Chen and L. Wosinska, "Analysis of protection schemes in PON compatible with smooth migration from TDM-PON to hybrid WDM/TDM-PON," *Journal of Optical Networking*, vol. 6, pp. 514-526, 2007.
- [47] F-T An, K. S. Kim, D. Gutierrez, S. Yam, E. Hu, K. Shrikhande, and L. G. Kazovsky, "SUCCESS: A next generation hybrid WDM/TDM optical access network architecture," *IEEE Journal of Lightwave Technology*, vol. 22, pp. 2557-2569, 2004.
- [48] K. S. Kim, D. Gutierrez, F-T. An, and L. G.Kazovsky, "Design and performance analysis of scheduling algorithms for WDM-PON under SUCCESS-HPON architecture," *IEEE Journal of Lightwave Technology*, vol. 23, pp. 3716-3731, 2005.
- [49] Y.-L. Hsueh, M. S. Rogge, W.-T. Shaw, L. G. Kazovsky and S. Yamamoto, "SUCCESS-DWA: a highly scalable and cost-effective optical access network," *IEEE Communications Magazine*, vol. 42, pp. S24-S30, 2004.
- [50] C. Bock, J. Prat, and S. D. Walker, "Hybrid WDM/TDM PON using the AWG FSR and featuring centralized light generation and dynamic bandwidth allocation," *IEEE Journal of Lightwave Technology*, vol. 23, pp. 3981-3988, 2005.
-
-

-
-
- [51] D. J. Shin, D. K. Jung, H. S. Shin, J. W. Kwon, S. Hwang, Y. Oh, and C. Shim, "Hybrid WDM/TDM-PON with wavelength-selection-free transmitters," *IEEE Journal of Lightwave Technology*, vol. 23, pp. 187–195, 2005.
- [52] R. D. Feldman, E. E. Harstead, S. Jiang, T. H. Wood, and M. Zirngibl, "An evaluation of architectures incorporating wavelength division multiplexing for broad-band fiber access," *IEEE Journal of Lightwave Technology*, vol. 16, pp. 1546–1556, 1998.
- [53] E. S. Son, K. H. Han, J. K. Kim, and Y. C. Chung, "Bidirectional WDM passive optical network for simultaneous transmission of data and digital broadcast video service," *IEEE Journal of Lightwave Technology*, vol. 21, pp. 1723–1727, 2003.
- [54] U. Hilbk, T. Hermes, J. Saniter, and F.-J. Westphal, "High capacity WDM overlay on a passive optical network," *IEEE Electronics Letters*, vol. 32, no. 23, pp. 2162–2163, 1996.
- [55] M. H. Reeve, A. R. Hunwicks, W. Zhao, S. G. Methley, L. Bickers, and S. Hornung, "LED spectral slicing for single-mode local loop application," *IEEE Electronics Letters*, vol. 24, pp. 389–390, 1988.
- [56] J. S. Lee, Y. C. Chung, T. H. Wood, J. P. Meester, C. H. Joyner, C. A. Bums, J. Stone, H. M. Presby, and D. J. DiGiovanni, "Spectrum-sliced fiber amplifier light source with a polarization-insensitive electro absorption modulator," *IEEE Photonics Technology Letters*, vol. 6, pp. 1035–1037, 1994.
- [57] L. Boivin and B. C. Collings, "Spectrum slicing of coherent sources in optical communications," *Optical Fiber Technology*, vol. 7, pp. 1–20, 2001.
- [58] M. Oksanen, O. P. Hiironen, A. Tervonen, A. Pietilainen, E. Gotsonoga, H. Jarvinen, H. Kaaja, J. Aarnio, A. Grohn, M. Karhiniemi, V. Moltchanov, M. Oikkonen, M. Tahkokorpi, and T. Wallenius, "Spectral slicing passive optical access network trial," *Optical Fiber Communication Conference, OFC'02*, pp. 439–440, 2002.
- [59] M. H. Reeve, A. R. Hunwicks, W. Zhao, S. G. Methley, L. Bickers, and S.
-
-

-
-
- Hornung, "LED spectral slicing for single-mode local loop application," *IEE Electronics Letters*, vol. 24, pp. 389–390, 1988.
- [60] S. L. Woodward, P. P Iannone, K. C. Reichmann, and N. J. Frigo, "A spectrally sliced PON employing Fabry-Perot lasers," *IEEE Photonics Technology Letters*, vol.10, pp.1337-1339, 1998.
- [61] D. K. Jung, S. K. Shin, C.-H. Lee, and Y. C. Chung, "Wavelength division multiplexed passive optical network based on spectrum slicing techniques," *IEEE Photonics Technology Letters*, vol. 10, pp. 1334–1336, 1998.
- [62] M. Zirngibl, C. R. Doerr, and L. W. Stulz, "Study of spectral slicing for local access applications," *IEEE Photonics Technology Letters*, vol. 8, pp. 721–723, 1996.
- [63] K. H. Han, E. S. Son, H. Y. Choi, K. W. Lim, and Y. C. Chung, "Bidirectional WDM PON using light-emitting diodes spectrum-sliced with cyclic arrayed-waveguide grating," *IEEE Photonics Technology Letters*, vol. 16, pp. 2380-2382, 2004.
- [64] S. L. Woodward, P. P Iannone, K. C. Reichmann, and N. J. Frigo, "A spectrally sliced PON employing Fabry-Perot lasers", *IEEE Photonics Technology Letters*, vol.10, pp.1337-1339, 1998.
- [65] S-B. Park, D. K. Jung, D. J. Shin, H. S. Shin, I. K. Yun, J. S. Lee, Y. K. Oh, and Y. J. Oh, "Colorless operation of WDM-PON employing uncooled spectrum-sliced reflective semiconductor optical amplifiers," *IEEE Photonics Technology Letters*, vol. 19, pp. 248-250, 2007.
- [66] J.H. Lee, C.H. Kim, Y.-G. Han and S.B. Lee, "Broadband, high power, erbium fibre ASE based CW supercontinuum source for spectrum-sliced WDM PON applications," *IEE Electronics Letters*, vol. 42, pp. 549-550, 2006.
- [67] D. K. Jung, S. K. Shin, C.-H. Lee, and Y. C. Chung, "Wavelength division multiplexed passive optical network based on spectrum-slicing techniques," *IEEE Photonics Technology Letters*, vol.10, pp. 1334-1336, 1998
- [68] Y. S. Jang, C.-H. Lee, and Y. C. Chung, "Effects of crosstalk in WDM systems
-
-

using spectrum-sliced light source,” *IEEE Photonics Technology Letters*, vol. 11, pp. 715–717, 1999.

[69] D. K. Jung, S. K. Shin, H. G. Woo, and Y. C. Chung, “Wavelength tracking technique for spectrum-sliced WDM passive optical network,” *IEEE Photonics Technology Letters*, vol. 12, pp. 338–340, 2000.

[70] S. Hann, T-Y. Kim, and C-S Park, “Direct -modulated upstream signal transmission using a self-injection locked F-P LD for WDM-PON”, *European Conference of Communications, ECOC’05*, paper We3.3.3, 2005.

[71] H-C. Kwon, Y-Y. Won, and S-K. Han, “A self-seeded reflective SOA-based optical network unit for optical beat interference robust WDM/SCM-PON link,” *IEEE Photonics Technology Letters*, vol. 18, pp 1852-1854, 2005.

[72] E. Wong, K. L. Lee, and T. Anderson, “Directly-modulated self-seeding reflective SOAs as colorless transmitters for WDM passive optical networks,” *Optical Fiber Communication Conference, OFC’06*, paper PDP49, 2006.

[73] E. Wong, K. L. Lee, and T. B. Anderson, “Directly modulated self-seeding reflective semiconductor optical amplifiers as colorless transmitters in wavelength division multiplexed passive optical networks,” *IEEE Journal of Lightwave Technology*, vol. 25, pp. 67-74, 2007.

[74] H. Suzuki, H. Nakamura, J. Kani, and K. Iwatsuki, “A carrier-distributed wide-area WDM-based passive optical network (WDM-PON) accommodating 10 gigabit Ethernet-based VPN services,” *European Conference of Communications, ECOC’04*, paper Tu4.6.3, 2004.

[75] N. Buldawoo, S. Mottet, H. Dupont, D. Sigogne, and D. Meichenin, “Transmission experiment using a laser amplifier-reflector for DWDM access network,” *European Conference of Communications, ECOC’98*, vol. 1, pp. 273–274, 1998.

[76] M. Fujiwara, J.-I. Kani, H. Suzuki, and K. Iwatsuki, “Impact of Backreflection on Upstream Transmission in WDM Single-Fiber Loopback Access Networks,” *IEEE*

Journal of Lightwave Technology, vol. 24, pp.740-746, 2006.

[77] T. Maekawa, M. Okayasu, and K. Wakita, “Bidirectional transmission experiment employing a single light source and waveguide-type modulator,” *the 8th International Workshop Optical/Hybrid Access Networks, OAN’97*, 1997.

[78] M. D. Feuer, M. A. Thomas, and L. M. Lunardi, “Backreflection and loss in single-fiber loopback networks,” *IEEE Photonics Technology Letters*, vol.12, pp. 1106-1108, 2000.

[79] J.-I. Kan, M. Ima, K. Akimoton, O. Achio, H. Suzuki, and K. Atsukni, “A WDM-Based optical access network for wide-area Gigabit access services,” *IEEE Communication Magazine*, vol. 41, pp. S43- S48, 2003.

[80] B. W. Kim and W. R. Lee, “Loop-back wavelength division multiplexing passive optical network,” *US Patent 20060093360*, available online: <http://www.freepatentsonline.com/20060093360.html>.

[81] J. M. Kang and S. K. Han, “A novel hybrid WDM/SCM-PON sharing wavelength for up- and down-link using reflective semiconductor optical amplifier,” *IEEE Photonics Technology Letters*, vol. 18, pp. 502–504, 2006.

[82] W. Lee, S. H. Cho, M. Y. Park, J. H. Lee, C. Y. Kim, G. Jeong, and B. Y. Kim, “Frequency detuning effects in a loop-back WDM-PON employing gain-saturated RSOAs,” *IEEE Photonics Technology Letters*, vol.18, pp.1436–1438, 2006.

[83] P. Healey, P. Townsend, C. Ford, L. Johnston, P. Townley, I. Lealman, L. Rivers, S. Perrin, and R. Moore, “Reflective SOAs for spectrally sliced WDM-PONs,” *Optical Fiber Communication Conference, OFC’02*, pp. 352–353, 2002.

[84] H.S. Shin, D.K. Jung, D.J. Shin, J.S. Lee, I.K. Yun, S.W. Kim, H.C. Shin, S.T. Hwang, Y.J. Oh, and C.S. Shim, “Temperature characteristics of a wavelength-seeded reflective SOA in WDM-PONs,” *European Conference of Communications, ECOC’04*, paper: Tu4.6.5, 2004.

[85] S. J. Park, G-Y. Kim, and T-S. Park, “WDM-PON system based on the laser light

injected reflective semiconductor optical amplifier,” *Optical Fiber Technology*, vol. 12, pp. 162-169, 2006.

[86] P. Healey, P. Townsend, C. Ford, L. Johnston, P. Townley, I. Lealman, L. Rivers, S. Perrin, and R. Moore., “Spectral slicing WDM-PON using wavelength-seeded reflective SOAs”, *IEE Electronics Letters*, vol. 37, pp. 1181-1182, 2001.

[87] F. Payoux, P. Chanclou, M. Moissard, and R. Brenot, “Gigabit optical access using WDM PON based on spectrum slicing and reflective SOA,” *European Conference of Communications, ECOC'05*, paper We 3.3.5, 2005.

[88] A. Borghesani, D. Smith, A. Poustie, and R. Wyatt, “High temperature, colourless operation of a reflective semiconductor optical amplifier for 2.5Gbit/s upstream transmission in a WDM-PON,” *European Conference of Communications, ECOC'07*, vol. 3, paper 6.4.1, 2007.

[89] H. S. Kim, D. J. Shin, I. K. Kang, S. B. Park, J. H. Lee, J. H. Cho, K. H. Cho, S. J. Lee, D. K. Jung, H. S. Shin, S. T. Hwang, Y. Oh, and C. S. Shim, “Demonstration of bi-directional WDM-PON based on ASE-injected FP-LD’s for supporting HDTV channels and internet services,” *OptoElectronics Communication Conference, OECC'04*, paper 13B2-2, 2004.

[90] W. Lee, S-H. Cho, J. Park, B. k. Kim, and B. Kim, “Noise suppression of spectrum-sliced WDM-PON light sources using FP-LD,” *ETRI Journal*, vol. 27, pp. 334-336, 2005.

[91] K-M. Choi, J-S. Baik, and C-H. Lee, “Color-free operation of dense WDM-PON based on the wavelength-locked Fabry–Pérot laser diodes injecting a low-noise BLS,” *IEEE Photonics Technology Letters*, vol. 18, pp. 1167-1169, 2006.

[92] L. Y. Chan, C. K. Chan, D. T. K. Tong, F. Tong, and L. K. Chen, “Upstream traffic transmitter using injection-locked Fabry-Perot laser diode as modulator for WDM access networks,” *IEE Electronics Letters*, vol. 38, pp.43-45, 2002.

-
-
- [93] H-C. Kwon, W-S. Jang, and S-K Han, "WDM-PON downstream optical link using wavelength-locked FP-LD by spectrally-sliced FP-LD," *IEICE-Transactions on Communications*, vol. E88-B, pp. 384-387, 2005.
- [94] H. D. Kim, S.-G. Kang, and C. H. Lee, "A low-cost WDM source with an ASE injected Fabry-Perot semiconductor laser," *IEEE Photonics Technology Letters*, vol. 12, pp. 1067-1069, 2000.
- [95] J. Shin, D. K Jung, J. K. Lee, J. H. Lee, Y. H. Choi, Y. C. Bang, H. S. Shin, J. Lee, S. T. Hwang, and Y. J. Oh, "155 Mbit/s transmission using ASE-injected Fabry-Perot laser diode in WDM-PON over 70°C temperature range," *IEE Electronics Letters*, vol. 39, pp. 1331-1332, 2003.
- [96] X. Cheng, Y. J. Wen, Y. Dong, Z. Xu, X. Shao, Y. Wang, and C. Lu, "Optimization of spectrum-sliced ASE source for injection-locking a Fabry-Pérot laser diode," *IEEE Photonics Technology Letters*, vol. 18, pp. 1961-1963, 2006.
- [97] Y. J. Wen and C. J. Chae, "WDM-PON upstream transmission using Fabry-Perot laser diodes externally injected by polarization-insensitive spectrum-sliced supercontinuum pulses," *Optics Communications*, vol.260, pp.691-695, 2006.
- [98] C. Chang-Hasnain, "Progress and prospects of long-wavelength VCSELs," *IEEE Communications Magazine*. vol. 41, pp. S30-S34, 2003.
- [99] X. Zhao, M. Moewe, L. Chrostowski, C.-H. Chang, R. Shau, M. Ortsiefer, M.-C. Amann, and C. J. Chang-Hasnain, "28 GHz optical injection locked 1.55 μm VCSELs," *IEE Electronics Letters*, vol. 40, pp. 476-478, 2004
- [100] L. Chrostowski, C. H. Chang, and C. J. Chang-Hasnain, "Injection-locked 1.55 μm tunable VCSEL for uncooled WDM transmitter applications," *IEEE Photonics Technology Letters*, vol. 16, pp. 888-890, 2004.
- [101] E. Wong , X. Zhao, Connie J. Chang-Hasnain ,W. Hofmann, and M. C. Amann, "Uncooled, optical injection-locked 1.55 μm VCSELs for upstream transmitters in WDM-PONs," *Optical Fiber Communication Conference, OFC'06*, paper PDP50, 2006.
-
-

- [102] W-S. Tsai, H-H. Lu, S-J. Tzeng, T-S. Chien, S-H. Chen, and Y-C Chi, "Bidirectional dense wavelength-division multiplexing passive optical network based on injection-locked vertical-cavity surface-emitting lasers and a data comparator," *Optical Engineering*, vol. 45, paper 095003, 2006.
- [103] N. Deng, W. Hung, C-K. Chan, L-K. Chen and F. Tong, "A novel wavelength modulated transmitter and its application in WDM passive optical networks," *Optical Fiber Communication Conference, OFC'04*, paper MF79, 2004.
- [104] L.Y. Chan, C.K. Chan, D.T.K Tong, E Tong and L.K. Chen, "Upstream traffic transmitter using injection-locked Fabry-Perot laser diode as modulator for WDM access networks," *IEE Electronics Letters*, vol. 38, pp. 43-44, 2002.
- [105] H. Takesue and T. Sugie, "Wavelength channel data rewrite using saturated SOA modulator for WDM networks with centralized light sources," *IEEE Photonics Technology Letters*, vol. 21, pp. 2546-2548, 2003.
- [106] W. Lee, M. Y. Park, S. H. Cho, J. H. Lee, C. Y. Kim, G. Jeong, and B. Y. Kim, "Bidirectional WDM-PON based on gain-saturated reflective semiconductor optical amplifiers," *IEEE Photonics Technology Letters*, vol.17, pp.2460–2462, 2005.
- [107] W. Lee, S.H. Cho, M.Y. Park, J.H. Lee, C. Kim, G. Jeong and B.W. Kim, "Wavelength filter detuning for improved carrier reuse in loop-back WDM-PON," *IEE Electronics Letters*, vol.42, pp. 596- 597, 2006.
- [108] S. Y. Kim, S. B. Jun, Y. Takushima, E. S. Son, and Y. C. Chung, "Enhanced performance of RSOA-based WDM PON by using Manchester coding," *Journal of Optical Networking* vol.6, pp.624-630, 2007.
- [109] B. K. Kim, B. Y. Yoon, B. T. Kim, H. Park, and S. Park, "WDM passive optical networks with symmetric up/down data rates using Manchester coding based remodulation," *European Conference of Communications, ECOC'06*, paper Tu4.5.5, 2006.
- [110] G-W. Lu, N. Deng, C-K. Chan, and L-K Chen, "Use of downstream inverse-RZ

signal for upstream data remodulation in a WDM passive optical network,” *Optical Fiber Communication Conference, OFC’05*, paper OFI8, 2005.

[111] H. S. Chung, B. K. Kim, H. Park, S. H. Chang, M. J. Chu, and K. J. Kim, “Effects of inverse-RZ and Manchester code a wavelength re-used WDM-PON,” *the 19th Annual Meeting of the IEEE Lasers and Electro-Optics Society, LEOS’06*, paper TuP3, pp. 298-299, 2006.

[112] S. Y. Kim, E. S. Son, S. B. Jun, J. H. Lee, D. H. Lee, E. D. Sim, and Y. C. Chung, “Effects of downstream modulation formats on the performance of a RSOA-based WDM PON,” *Proceedings of SPIE*, paper 63531Q, 2006.

[113] W. Hung, C-K. Chan, L-K. Chen, and F. Tong, “An optical network unit for WDM access networks with downstream DPSK and upstream remodulated OOK data using injection-locked FP Laser,” *IEEE Photonics Technology Letters*, vol. 15, pp. 1476-1478, 2003.

[114] N. Deng, C-K. Chan, L-K. Chen, and F. Tong, “Data remodulation on downstream OFSK signal for upstream transmission in WDM passive optical network,” *IEE Electronics Letters*, vol. 39, pp. 1741-1743, 2003.

[115] M. Attygalle, T. Anderson, D. Hewitt, and A. Nirmalathas, “WDM passive optical network with subcarrier transmission and baseband detection scheme for laser-free optical network units,” *IEEE Photonics Technology Letters*, vol. 18, pp. 1279-1281, 2006.

[116] T.-Y. Kim and S.-K. Han, “Reflective SOA-based bidirectional WDM-PON sharing optical source for up/downlink data and broadcasting transmission,” *IEEE Photonics Technology Letters* vol. 18, pp. 2350–2352, 2006.

[117] M. Attygalle, N. Nadarajah, and A. Nirmalathas, “Wavelength reused upstream transmission scheme for WDM passive optical networks,” *IEE Electronics Letters*, vol. 41, pp. 1025-1027, 2005.

[118] K-Y. Park, S-G. Mun, K-M. Choi, and C-H. Lee, “A theoretical model of a

wavelength-locked Fabry-Perot laser diode to the externally injected narrow-band ASE,” *IEEE Photonics Technology Letters*, vol.17, pp.1797-1799, 2005.

[119] G. P. Agrawal and N. K. Dutta, *Semiconductor Lasers*, 2nd Ed. New York: Van Nostrand, 1993.

[120] J. Horer and E. Patzak, “Large-signal analysis of all-optical wavelength conversion using two-mode injection-locking in semiconductor lasers,” *IEEE Journal of Quantum Electronics*, vol. 33, pp. 596–608, 1997.

[121] T. Yee and D. Welford, “A multimode rate-equation analysis for semiconductor lasers applied to the direct intensity modulation of individual longitudinal modes,” *IEEE Journal of Quantum Electronics*, vol.22, pp. 2116-2122, 1986.

[122] A. Murakami, K. Kawashima, and K. Atsuki, “Cavity resonance shift and bandwidth enhancement in semiconductor lasers with strong light injection,” *IEEE Journal of Quantum Electronics*, vol.39, pp. 1196-1204, 2003.

[123] F. Mogensen, H. Olesen, and G. Jacobsen, “Locking conditions and stability properties for a semiconductor lasers with external light injection,” *IEEE Journal of Quantum Electronics*, vol. QE-21, pp. 784–793, 1985.

[124] K. Okamoto, T. Hasegawa, O. Ishida, A. Himeno, and Y. Ohmori, “32×32 arrayed-waveguide grating multiplexer with uniform loss and cyclic frequency characteristics,” *IEE Electronics Letters* vol. 33, pp.1865–1866, 1997.

[125] I. Petitbon, P. Gallion, G. Debarge, and C. Chabran, “Locking bandwidth and relaxation oscillations for an injection-locked semiconductor laser,” *IEEE Journal of Quantum Electronics*, vol. 24, pp. 148-154, 1988.

[126] C.E. Moeller, P.S. Durkin, and G.C. Dente, “Mapping the injection-lock band of semiconductor lasers,” *IEEE Journal of Quantum Electronics*, vol. 25, pp. 1603-1608, 1989.

[127] A. Gavrielides, V. Kovanis, and T. Erneux, “Analytical stability boundaries for a semiconductor laser subject to optical injection,” *Optics Communications*, vol. 136, pp.

253-256, 1997.

[128] S.-M. Lee, S.-G. Mun, M.-H. Kim, and C.-H. Lee, "Demonstration of a long-reach DWDM-PON for consolidation of metro and access networks," *IEEE Journal of Lightwave Technology*, vol. 25, pp.271-276, 2007.

[129] S. Hornung, D. Payne, and R. Davey, "New architecture for an all optical network," *Optical Fiber Communication Conference, OFC'05*, paper OTuH7, 2005.

[130] N. Kashima, "Dynamic properties of FP-LD transmitters using side-mode injection locking for LANs and WDM-PONs," *IEEE Journal of Lightwave Technology*, vol.24, pp. 3045-3058, 2006.

[131] J. M. Liu, H. F. Chen, X. J. Meng, and T. B. Simpson, "Modulation bandwidth, noise, and stability of a semiconductor laser subject to strong injection locking," *IEEE Photonics Technology Letters*, vol.9, pp.1325-1327, 1997.

[132] M. Martinelli and J. C. Palais, "Dual fiber-ring depolarizer," *IEEE Journal of Lightwave Technology*, vol.19, pp. 899-905, 2001.

[133] K. Petermann, *Laser Diode Modulation and Noise*. London, U.K.: Kluwer, 1988.

[134] K. Iwashita and K. Nakagawa, "Suppression of mode partition noise by laser diode light injection," *IEEE Journal of Quantum Electronics*, vol. QE-18, pp. 1669-1674, 1982.

[135] S. Kobayashi, J. Yamada, S. Machida, and T. Kimura, "Single-mode operation of 500 Mbit/s modulated AlGaAs semiconductor laser by injection locking," *IEEE Electronics Letters*, vol. 14, pp. 746-748, 1980.

[136] D. J. Shin, D. K. Jung, J. K. Kee, Y. K. Oh, J. H. Lee, H. S. Kim, C. H. Lee, S. T. Hwang, J. H. Ko, Y. J. Oh, T. I. Kim, and C. S. Shim, "Transmission of HDTV and Ethernet data over a WDM-PON employing ASE-injected Fabry-Perot laser diodes," *Optical Fiber Communication Conference, OFC'04*, paper WO3, 2004.

- [137] H. S. Shin, D. K. J., H. S. Kim, D. J. Shin, S. B. Park, S. T. Hwang, Y. J. Oh, and C. S. Shim, "Spectrally pre-composed ASE injection for a wavelength-seeded reflective SOA in a WDM-PON," *European Conference of Communications, ECOC'05*, paper We3.3.7, 2005.
- [138] A. McCoy, P. Horak, B. C. Thomsen, M. Isben, and D. J. Richardson, "Noise suppression of incoherent light using a gain-saturated SOA: implications for spectrum-sliced WDM systems," *IEEE Journal of Lightwave Technology*, vol. 23: pp. 2399-2409, 2005.
- [139] S. Kim, J. H. Han, and J. Lee, "Intensity noise suppression in spectrum-sliced incoherent light communication systems using a gain-saturated semiconductor optical amplifier," *IEEE Photonics Technology Letters*, vol. 11, pp.1042-1044, 1999.
- [140] A. D. McCoy, P. Horak, B. C. Thomsen, M. Ibsen, M. R. Mokhtar, and D. J. Richardson, "Improving signal quality in a spectrum-sliced WDM system using SOA based noise reduction," *IEEE Photonics Technology Letters*, vol. 17, pp.241-243, 2005.
- [141] G. P. Agrawal and N. A. Olsson, "Self-phase modulation and spectral broadening of optical pulses in semiconductor laser amplifiers," *IEEE Journal of Quantum Electronics*, vol. 25, pp.2297-2306, 1989.
- [142] M. Zhao, G. Morthier, and R. Baets, "Analysis and optimization of intensity noise reduction in spectrum sliced WDM systems using a saturated semiconductor optical amplifier," *IEEE Photonics Technology Letters*, vol .14, pp.390-392, 2002.
- [143] L. Y. Chan, C. K. Chan, D.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-locking FP laser as modulator," *Optical Fiber Communication Conference, OFC'01*, paper WU5, 2001.
- [144] C-J. Chae and R. S. Tucker, "Passive virtual optical networking technique using a cyclic N×N arrayed waveguide grating for multiple multihop ring networks," *IEEE Photonics Technology Letters*, vol. 16, pp.948-950, 2004.
-

- [145] M. Fujiwara, J.-I. Kani, H. Suzuki, and K. Iwatsuki, "Impact of backreflection on upstream transmission in WDM single-fiber loopback access networks," *IEEE Journal of Lightwave Technology*, vol. 24, pp. 740-746, 2006.
- [146] Press release of CIP, "Innovative reflective semiconductor optical amplifier optimized for next-generation passive optical networks," Available online: http://www.ciphotonics.com/cip_press.htm
- [147] J. Yu, O. Akanbi, Y. Luo, L. Zong, T. Wang, Z. Jia, and G-K. Chang, "Demonstration of a novel WDM passive optical network architecture with source-free optical network units," *IEEE Photonics Technology Letters*, vol. 19, pp. 571-573, 2007.
- [148] G. H. Smith, D. Novak, and Z. Ahmed, "Overcoming chromatic-dispersion effects in fiber-wireless systems incorporating external modulators," *IEEE Transactions on Microwave Theory and Techniques*, vol. 45, pp. 1410-1415, 1997.
- [149] M. Abramowitz and I. A. Stegun, *Handbook of mathematical functions with formulas, graphs, and mathematical tables*, 9th printing. New York: Dover, pp. 358-364, 1972.
- [150] C.-J. Chae and R. S. Tucker, "Implementation of multiple optical virtual private networks over WDM passive optical network," *IEE Electronics Letters*, vol. 40, pp. 331-333, 2004.
- [151] C.-J. Chae, V. T. An, and R. S. Tucker, "Bandwidth-efficient modular wavelength router for large-scale multihop virtual optical ring networks," *IEEE Journal of Lightwave Technology*, vol. 23, pp. 1015-1022, 2005.