Study of Architectures and Protection Schemes for High-speed WDM-based Passive Optical Access Networks Utilizing Centralized Light Sources for Colorless Optical Network Units

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Abstract

In recent years, a wavelength-division-multiplexed passive optical network (WDM-PON) architecture using centralized broadband light sources (BLS) at the central office (CO) has emerged as an attractive solution for next-generation broadband access architecture. Since no wavelength-specific transmitter is incorporated at the customer site optical network units (ONU), all ONUs are wavelength independent ("colorless"), thus wavelength management is relaxed that greatly eases the network maintenance.

In this thesis, a simple high-speed WDM-PON access architecture is proposed and demonstrated using centralized high-nonlinearity photonic-crystal-fiber (PCF) based supercontinuum broadband light source for upstream optical carrier supply. A broadcast scheme over such WDM-PON is also proposed and investigated. With this configuration, each ONU can receive its own dedicated optical channel carrying the baseband digital channel with the broadcasted signal.

Another critical issue in network design and real-time operation is network survivability. In this thesis, a protection architecture based on centralized BLS WDM-PON is proposed to protect against link failure between the remote node (RN) and the optical line terminal (OLT). By adopting appropriate wavelength assignments and incorporating optical switches at the OLT, the protection function can be readily achieved.

摘要

近幾年來，基于交換中心集中寬光源波分複用無源光網絡結構已經演變成爲一種很吸引的適合下一代寬帶接入網的解決方案。因爲在客戶端的光網絡單元沒有引入特定波長的發射器，全部的光網絡單元都是波長無關的（無色的），從而放松了波長管理的要求，大大降低了網絡維護費用。

本論文中，我們提出了一種簡單高速波分複用無源光網絡接入結構，其使用中央集中的基于高非線性光子晶體光纖的超連續譜光源作爲上行訊號供應。同時，我們也提出跟研究了一種基于此波分複用無源光網絡的廣播方案。在此結構中，每個光網絡單元都將接收到運載基帶信號跟廣播信號的特定光信道。

另一個網絡設計跟實時操作中的關鍵要點是網絡的自我恢複能力。本論文中，我們提出一種基于集中寬光源波分複用無源光網絡的保護結構來保護遠端節點與光網路終端設備之間的光纖鏈路。在光網路終端設備端采用光開關以及適當的波長分配，保護功能可以很輕易的實現。

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Chapter 1

Introduction to Passive Optical Networks

1.1 Passive Optical Network (PON)

In telecommunications, an access network, also referred to as the "local loop", or "last mile network", is a network that connects subscribers to service providers' central offices (COs) over public ground. With the popularity of Internet and explosive growth of data traffic, broadband access users are growing rapidly. All kinds of new emerging services and applications such as IPTV, video conferencing, online gaming, VOIP, etc. are increasingly popular, which require higher performance access networks and high access bandwidths. However, existing digital subscriber line (DSL) or cable television (CATV) based networks with limited bandwidth may not be able to meet the future access bandwidth requirements. With the maturity of optical access technology and the pressing market demands, optical access network has been becoming an inevitable trend.

The optical path is "transparent" to bit rate, modulation format, and protocol. Such transparency results from that fact that nothing that specific to the bit rate, modulation format, etc. is being installed between the service provider and the customer, allowing services to be mixed or economically upgraded in the future as needed. New services and/or new customers can be added by changing service-specific equipment only at the ends of the network, and only for those customers affected. Such flexibility is not the case in most of today's other access network architectures.

Among all optical access network proposals, passive optical network has received increasing amount of attention in recent years. This approach differs from most of the telecommunications networks in place today by featuring "passive" operation and the term "passive" simply describes the fact that optical transmission has no power requirements or active electronic parts once the signal is going through the network. Active networks like DSL and cable have active components in the network backbone equipment, in the central office, in the neighborhood network infrastructure, and in the customer premise equipment. PONs have only passive light transmission components in the neighborhood infrastructure with active components only in the central office and the customer premise equipment.

1.1.1 PON architecture

PON is an optical fiber-based system that brings signals all or most of the way to the end user. It is a shared bandwidth, point-to-multipoint architecture shown in Fig. 1.1 .

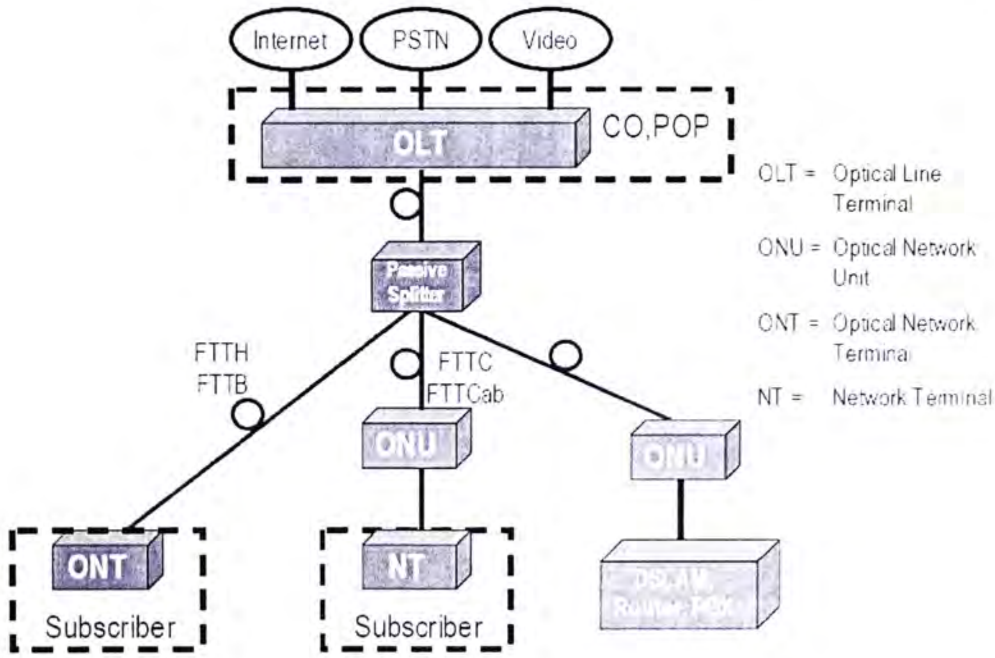

Fig. 1.1 Architecture of a passive optical network [1]

On the side of the central office (CO), there is an optical line termination (OLT), on the user's side there is an optical network unit (ONU). Using a passive point-to-multipoint fiber network, consisting of optical fibers and one or more splitters (in cascade), a number of ONUs are connected to an OLT in a tree topology. Bus and ring topologies are considered less suitable for user connections, as they run a higher risk of individual users causing disruptions for other users. The key component of a PON is the passive splitter, dividing a downstream signal and distributing data to the subscribers on the PON. This allows for an expensive piece of fiber cable from the exchange to the customer to be shared amongst many customers thereby dramatically lowering the overall costs of deployment. An ONU can be combined with a network termination (NT) producing an optical network termination (ONT). Architectures can be designed for various fiber-to-the-x (FTTX), such as office, home, cabinet, and curb applications, depending on where the PON terminates.

1.1.2 PON benefits

PON solutions have many benefits so that it has received much support. For one thing, PON lowers upfront network costs. It is a sound point-to-multipoint architecture that multiple customers can be supported on a feeder fiber. Thus fewer fibers (and therefore, fewer network elements) are required to support the carrier's services. PON shares the costs of fiber and much of the equipment located with the service provider among several customers, while also eliminating expensive, powered equipment between the service provider and these customers.

Secondly, eliminating the need for active network elements also eliminates the need for powering, heating and cooling electronics in the PON network. Thus PON is easy for operation and maintenance due to the passive aspect.

Last but not the least is the high reliability. Because PON is a fiber based solution, it is not vulnerable to the issues associated with copper networks such as electrical interference. Also, fewer network elements in the PON mean fewer possible points of failure and possibly higher availability of services to customers.

1.2 The History of PON

The first formal PON activity was initiated in the spring of 1995 when a group of seven major network operators established the Full Service Access Networks (FSAN) consortium [2]. This group's goal was to define a common standard for PON equipment so that equipment vendors and operators could come together in a competitive market for PON equipment. The result of this first effort was the 155 Mb/s PON system specified in the ITU-T G.983 series of standards. This system has known as the B-PON system, and it uses Asynchronous Transfer Mode (ATM) as its bearer protocol (also known as the APON protocol). The APON Standards were later enhanced to support 622 Mb/s bit rates as well as additional features in the form of protection, Dynamic Bandwidth Assignment and more.

On a parallel track, in early 2001, the IEEE established the Ethernet in the First Mile (EFM) group, which works under the auspices of the IEEE 802.3 group. The EFM work is concentrated on standardizing a 1.25 Gb/s symmetrical system for Ethernet transport only.

In 2001 the FSAN group initiated a new effort for standardizing PON networks operating at bit rates of above 1 Gb/s. Apart from the need to support higher bit rates, the overall protocol has been opened for re-consideration and the sought solution should be the most optimal and efficient in terms of support for multiple services, Operation, Administration, Maintenance and Provisioning (OAM&P) functionality and scalability. As a result of this latest FSAN effort, a new solution has emerged into the optical access market place - GPON (Gigabit PON), offering high bit rate support while enabling transport of multiple services, specifically data and TDM in their native formats, at a high efficiency.

1.3 WDM-PON

All the PONs described above are Time Division Multiplexed Passive Optical Network (TDM-PON), where each subscriber can only access the central office within a limited time interval. The limited bandwidth as a result of this time sharing is not expected to satisfy future video-based applications. To try to solve this limitation, an additional high-performance broadcast-based optical video overlay is combined with the TDM-PON. This adds considerable cost and complexity since two separate communication systems must be developed and maintained. Both quality-of-service and network management may be difficult to ensure due to the complexities associated with the time multiplexing of data and the high-performance video overlay. Also, the security of the communication link is not guaranteed since each subscriber on the TDM-PON receives all the data sent to the others on the network. This will be a major concern for potential business subscribers.

For a long time Wavelength Division Multiplexing (WDM) in the forms of Dense WDM and Coarse WDM has been applied in long-distance networks and MANs, respectively. WDM technology with wavelength splitters could eventually provide an attractive solution on the last mile. Carriers want to connect each customer site with a wavelength of light, but they want to avoid having to dedicate a fiber to every wavelength. WDM-PON addresses this issue by bundling together multiple wavelengths so they can be carried over a single access line from the carrier's central office to a Remote Node (RN) to a cluster of customer sites. At that point, the wavelengths are broken out and each one is steered into a different short length of fiber to an individual site. A Wavelength Division Multiplexed Passive Optical Network (WDM-PON), whose architecture is shown in the Fig. 1.2 below [3], allocates a different wavelength to each subscriber. This provides a separate and secure point-to-point, high-data-rate channel between each subscriber and the central office. The network management is much simpler than a TDM-PON and all future services can be delivered over a single network platform. This common network architecture will satisfy all future needs for both residential and business subscribers.

There are many advantages of WDM-PON. First of all, because of dedicated bandwidth for each ONU (no sharing as in the TDM case), we can get higher bandwidth in WDM-PON. Secondly, receivers at ONUs only operate at channel rate, while the receiver at each ONU in TDM network has to operate at the aggregated rate. Flexibility is another benefit in that data rate on each wavelength channel can be different. Finally, it eliminates ranging or collision avoidance scheme for upstream path in the WDM networks.

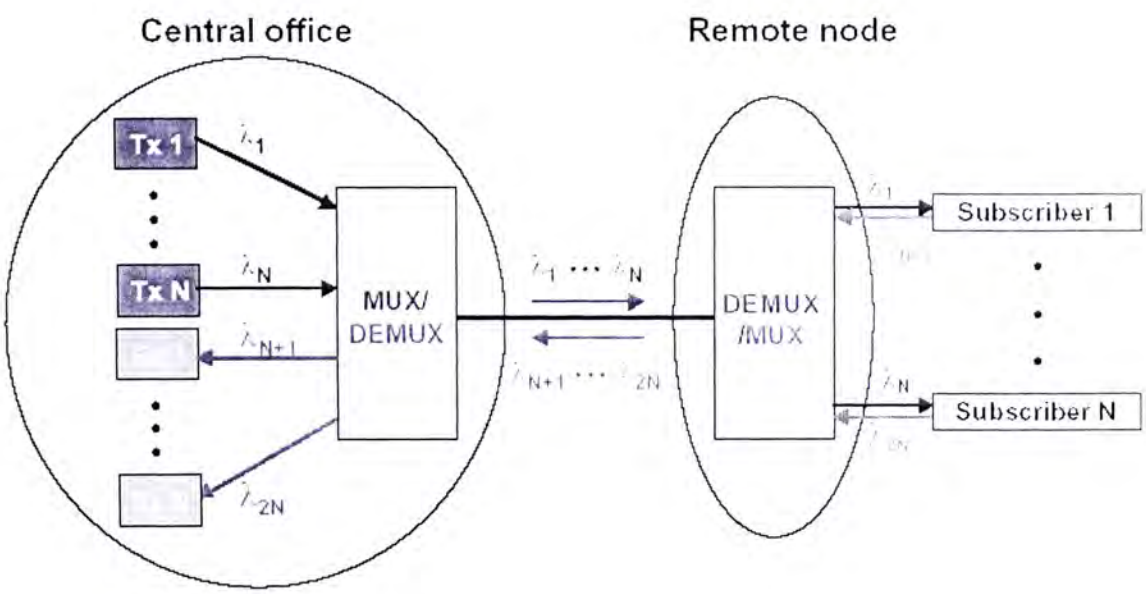

Fig. 1.2 A WDM-PON architecture [3]

Historically WDM networks have been expensive since they had to use expensive wavelength specific sources, e.g. DFB-lasers, in order to maintain pre-assigned wavelengths. In addition, they had high installation and maintenance costs. Coarse WDM consists of relatively inexpensive lasers functioning at large wavelength distances (20 nm). Nowadays the Extended Wavelength Band optical fibers are commercial available. In these optical fibers the water absorption peak between the 1300 nm window and 1550 nm window is eliminated; as a result more "coarse" wavelengths can be used for a WDM-PON.

It will probably be some years before WDM-PON has an acceptable price-performance ratio, but the technology can be deployed to bring existing PON to a higher performance level. WDM-PON is a realistic prospect. Solutions for technological and operational issues have been devised and have already partly been tested.

1.4 Outline of This Thesis

The organization of the remaining chapters of this thesis will be as followings:

- In Chapter 2, several previous WDM-PON architectures for colorless ONUs are outlined, including the following approaches: (1) Spectrum slicing BLS employed at the ONU; (2) Centralized broadband light source (BLS) for upstream optical carrier supply; (3) Reuse or remodulation of the downstream carrier at the ONU.

- In Chapter 3, a simple high-speed WDM-PON access architecture for colorless ONUs is proposed and demonstrated using a centralized supercontinuum broadband light source, generated in a high-nonlinearity photonic-crystal-fiber (PCF), for upstream optical carrier supply. Also, a broadcast scheme over WDM-PON by spectrum-slicing a broadband light source based on supercontinuum generation is proposed and investigated in this chapter.

- In Chapter 4, a protection architecture based on the centralized broadband light source WDM-PON is proposed, so as to integrate and extend the capability to protect against link failure between the remote node and the optical line terminal. Finally, experimental investigation will be discussed.

- In Chapter 5, the thesis is summarized and future work is described.

Chapter 2

Previous Schemes for Colorless ONU Operation in WDM-PON

2.1 Introduction

The main problem with WDM-PON is that a wavelength-specific or tunable distributed-feedback (DFB) laser was required at each ONU, adding to network cost and complexity. Moreover, usually the wavelength is assigned to an ONU in a fixed manner. This makes upgrades in the network topology difficult as they require manual reconfiguration of the equipment in the customers' premises, which significantly increases the cost of maintenance. The solution to this is the development of so called "colorless" ONUs. Here "colorless" means all the ONUs are wavelength independent. Because all ONUs are identical, it lowers the costs of operation, administration, and maintenance (OA&M) of the network. Besides, since all the ONUs are with the same specification, mass production becomes possible which can also lower the production cost.

2.2 Previous WDM-PON Architectures for Colorless ONU Operation

There are several approaches to realize colorless ONUs in WDM-PON.

- Employ identical light source, e.g. the LED or super-luminescent diode (SLD) as broadband source at each ONU. The signals generated by the ONUs are spectrally sliced and multiplexed by the Array Waveguide Grating (AWG) at the remote node.

- Employ a centralized broadband light source (BLS) at the OLT for upstream optical carrier supply. The BLS are spectrally sliced at the RN and distributed to each ONU for upstream data modulation. The modulator at each ONU can be based on several options, e.g. $LiNbO_3$ intensity modulator, Electro-Absorption Modulator (EAM), Fabry-Perot (FP) laser diodes, or reflective semiconductor optical amplifiers (R-SOA).

- Re-use or re-modulate the downstream carrier at the ONU.

We will review those schemes in this section.

2.2.1 Spectrum slicing BLS employed at the ONU

One can employ identical broadband light source at each ONU, which can be either LED [4-5] or SLD [6-7]. By employing spectrum-slicing technologies, it can realize wavelength-independent ONUs.

Fig. 2.1 shows the typical configuration of the spectrum-slicing WDM-PON system [7]. Each ONU creates its upstream optical signal by modulating a SLD with an electrical signal, as well as receiving its downstream signal. The broad-spectral optical signal from the ONU is spectrally sliced, multiplexed by λ MUX2, and then passed to the OLT. The wavelength-independent ONU is achieved by spectrum-slicing technologies.

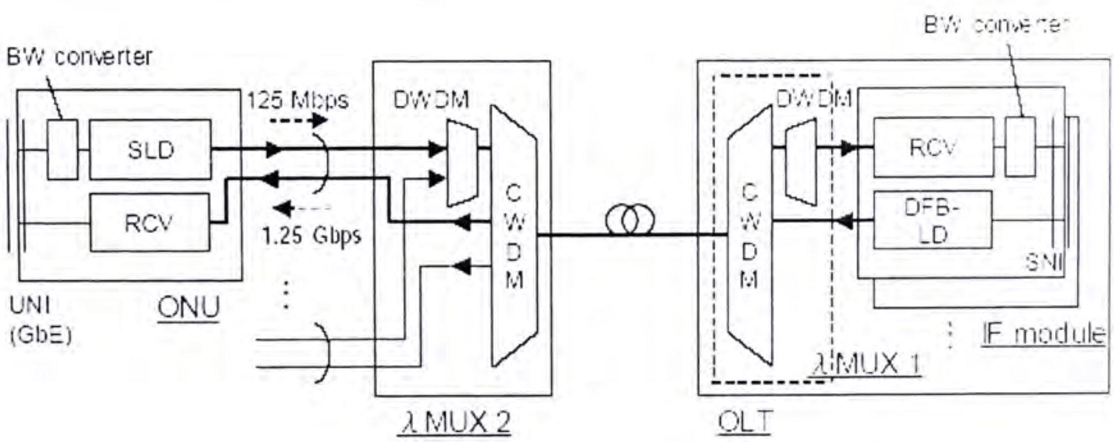

Fig. 2.1 WDN-PON configuration with spectrum-slicing scheme [7]

Several works on spectral slicing have focused on the use of LED's as broadband sources. Though LED's are commercially low-cost, their output power is insufficient to accommodate many channels by spectrum-slicing which limits the area a

WDM-PON can serve. This problem could be relaxed to some extent by using high-power LEDs, while the modulation speed is always limited to hundreds of Mb/s (e.g. 125 Mb/s) due to the incoherent nature of LEDs.

2.2.2 Centralized broadband light source (BLS) for upstream optical carrier supply

By centralizing the broadband light source at the central office which will be used as the upstream optical carrier, there is no wavelength specific transmitter located at any ONU. The elimination of the light source at the ONU avoids its stabilization and provisioning. Moreover, this approach can support potentially high-speed and long-distance WDM-PONs.

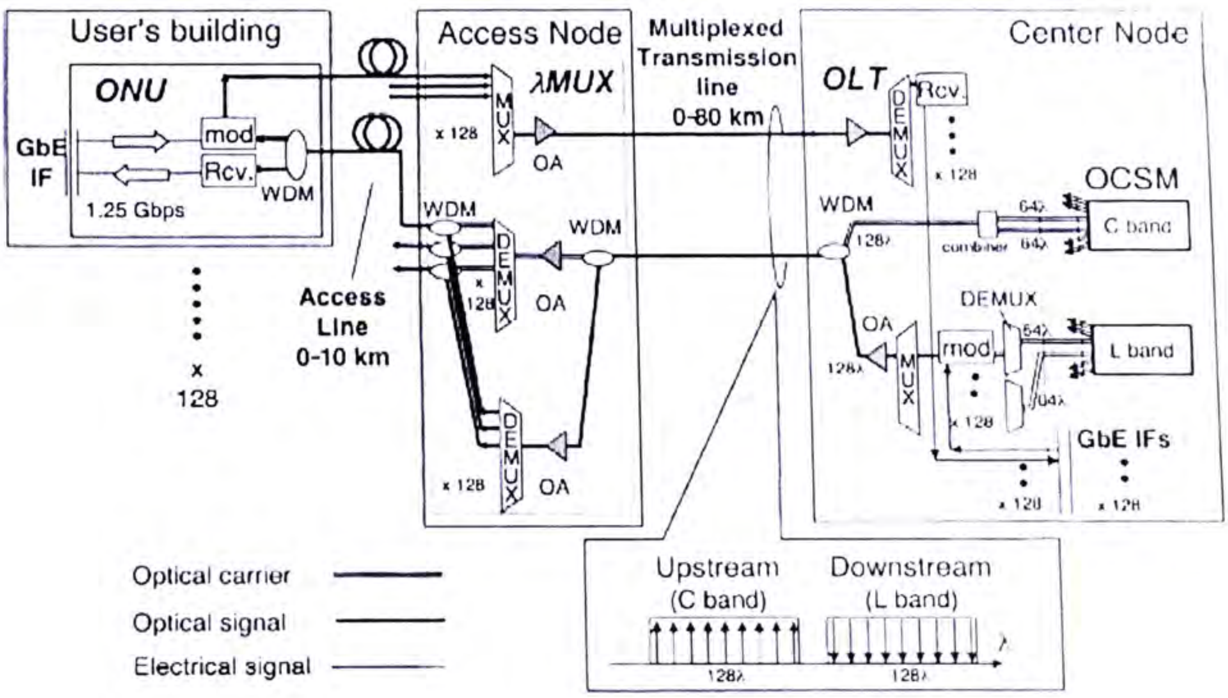

Fig. 2.2 Wide-area access network with optical carrier supply scheme [8]

Fig. 2.2 shows configuration of the wide-area access network with colorless ONU operation [8]. The optical carrier supply module (OCSM) [9] in the center node (CN) supplies the optical carriers for downstream signals to the OLT within the CN, as well as those for upstream signals to the ONUs via the network. 128 wavelengths with 25-GHz spacing in the C band (1530–1565 nm) and the same number of wavelengths in the L band (1565–1625 nm) are utilized as the wavelengths of the up and downstream optical signals, respectively. Two optical fibers are used between the CN and the AN as well as between the AN and each ONU. In the upstream direction, an ONU comprising an optical modulator (mod) modulates the carrier wavelength provided by the OLT with its data. The advantage of such an approach is that ONUs do not have to be equipped with expensive light sources. This not only lowers the overall cost of the equipment but also makes ONUs transparent to the signal and different wavelengths can be used at any time.

In [10], a DWDM SuperPON was proposed to distribute CW wavelength-reference, or "seed" channels from a central location within the network, which are shared among, and modulated by, the customers on the PON to generate the upstream channels. Fig. 2.3 illustrates schematic diagram of SuperPONs system. The inset to the figure shows an example DWDM channel allocation plan (100GHz spacing) in which the C-band is divided into two, with the 'blue' half (1525nm-1543nm) carrying downstream channels (to customer) and the 'red' half (1547nm-1565nm) carrying upstream channels (from customer). The layout is divided into four notional locations: customer ONU, cabinet, local exchange and central/core exchange. The local exchange contains the seed source, which is a tunable external cavity laser (ECL) followed by an SOA booster amplifier. They use a monolithically-integrated, electro-absorption modulator semiconductor amplifier (EAM-SOA) as a colorless ONU in this DWDM SuperPON system.

The above two schemes can operate at high speed (e.g. Gb/s) over long distance (e.g. 80km) by employing optical amplifiers at the RN, which make the access networks not really "passive", so called "SuperPONs".

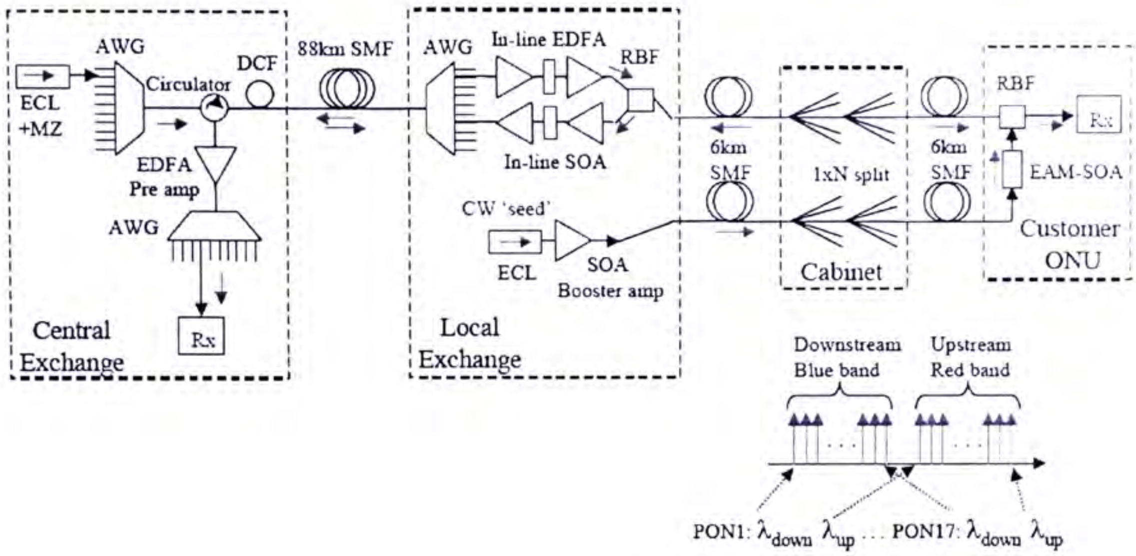

Fig. 2.3 Schematic diagram of SuperPONs system [10]

Besides intensity modulator and EA modulator, FP-LD [11-12], or R-SOA [13-14] can also be used for upstream modulation. In [12], a low-cost bidirectional WDM passive optical network employing colorless uncooled transceivers and super-luminescent diode based broadband light sources was proposed. They showed that such a transceiver can be locked to the signal from a spectrum-sliced broadband light source.

Fig. 2.4 shows the proposed WDM-PON architecture with bidirectional BLS injected to FP-LD. The unique features of the network were the BLSs feeding the bidirectional transceivers with unpolarized incoherent seed lights. The up and down seed lights were spectrum-sliced at the RN and CO AWGs and subsequently injected into the up and down transceivers, which integrates an uncooled Fabry–Pérot laser diode (FP-LD), respectively. As a result of the injection, the operating wavelengths of the transceivers were predominantly determined by the spectrum-sliced unpolarized seed lights. This injection architecture allows all transmitters to replace each other, making them "colorless". The colorless transmitters provide a great advantage to service providers by not having to stock spare wavelength-defined transmitters for each WDM channel.

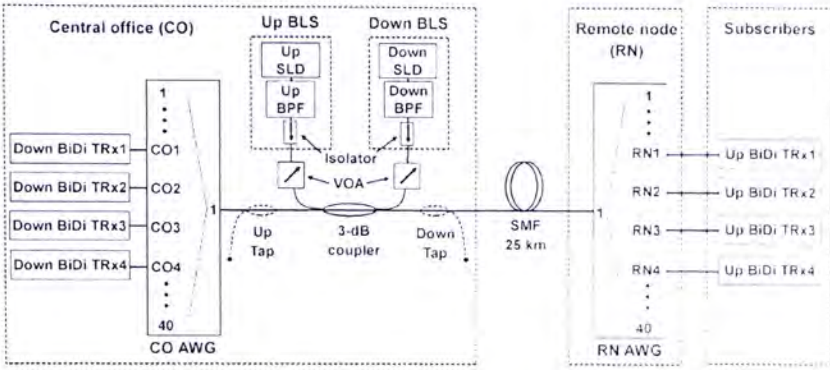

Fig. 2.4 WDM-PON architecture with BLS injected to FP-LD [12]

Although colorless operation can be achieved with cost-effective transmitters, the upstream bit rate was still confined at 155 Mb/s, which may not fulfill the expected growth of bandwidth demands.

A reflective semiconductor optical amplifier has also been used as such a WDM-modulator in a unidirectional Link by amplifying and modulating spectrally sliced amplified spontaneous emission of WDM channels [13-14]. In [14], a WDM-PON architecture which employs R-SOA as a modulator was proposed. In the architecture, continuous wave single-mode laser diode light is injected into an R-SOA. They fabricated the external cavity laser (ECL) for the injection light source and multi-channel transceiver module for the OLT.

Fig 2.5 shows the architecture of the proposed WDM-PON which employs an R-SOA as a transmitter. Optical carriers of laser lights of C-band (~1550nm) and O-band (~ 1300nm) are injected into and modulated by the R-SOA in the ONU and OLT, respectively. The multi-channel transceivers in OLT and ECL in optical carrier supply unit (OCSU) are fabricated by the hybrid integration of R-SOA, monitor PD and PD arrays on the silica based planar lightwave circuit (PLC) platform. The platform for the multi-channel transceiver contains two arrayed waveguide gratings (AWG's), each of which is coupled with the O band R-SOA and C band PD array, respectively. The PLC platform for ECL consists of an AWG and the grated waveguides for wavelength selective partial mirror.

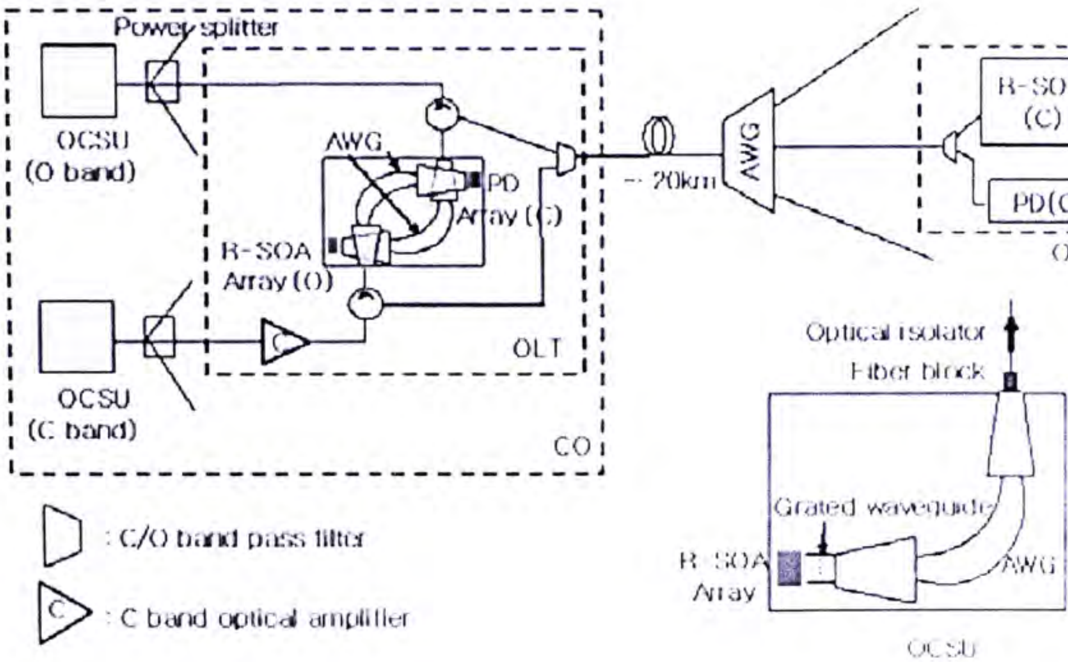

Fig. 2.5 Architecture of the proposed WDM-PON with R-SOA as a modulator [14]

The optical fiber and AWG in the remote node is simultaneously used for the O band downstream optical signals, C band injection lasers and C band upstream optical signals. The periodic property of the transmission wavelength spectrum of AWG is exploited for the simultaneous transmission of two bands using the single AWG in RN. That is, the grating orders of AWG for wavelengths in O and C bands are different, and each band is used for downstream and upstream transmission, respectively.

2.2.3 Reuse of the downstream carrier at the ONU

The last approach to realize colorless ONU is to reuse the downstream wavelength received at the ONU as upstream data carrier. The OLT generates the high-speed downstream data on each wavelength channel to the respective ONU. At the ONU, the downstream signal is tapped out partially for data detection. The rest of the signal is fed into an upstream transmitter where the downstream signal power is re-modulated with the upstream data. The re-modulated upstream carrier is then routed back to the central office via the RN. This architecture offers two distinct advantages. Firstly, no dedicated light sources are required at ONU's, thus completely eliminating the need for wavelength management and network maintenance issues at ONU side, which can lead to lower network construction and operation cost. Secondly, the looped-back signal received at OLT can additionally be used as a monitoring signal to facilitate downstream wavelength control.

There are several modulation schemes proposed to re-modulate the downstream wavelength for upstream transmission [15-17]. In [15], a remodulation-based WDM-PON architecture using constant-intensity optical DPSK as the downstream modulation format was proposed. In this scheme, a Fabry-Perot (FP) laser diode located at an ONU was injection-locked by a portion of the received optical power from the DPSK downstream wavelength and was simultaneously directly modulated to produce the upstream signal.

Fig. 2.6 illustrates the proposed WDM-PON architecture with N ONUs. The majority of the received power at the ONU is fed into a DPSK demodulator to recover the downstream signal whereas the remaining power is injected into an FP laser for injection locking. The injection-locked FP-LD is simultaneously direct-modulated with the upstream data and its output can be routed back to the CO. Using this kind of re-modulation scheme, complexity of both ONU and OLT can be greatly reduced, directly reducing the cost and enhancing the robustness of the network.

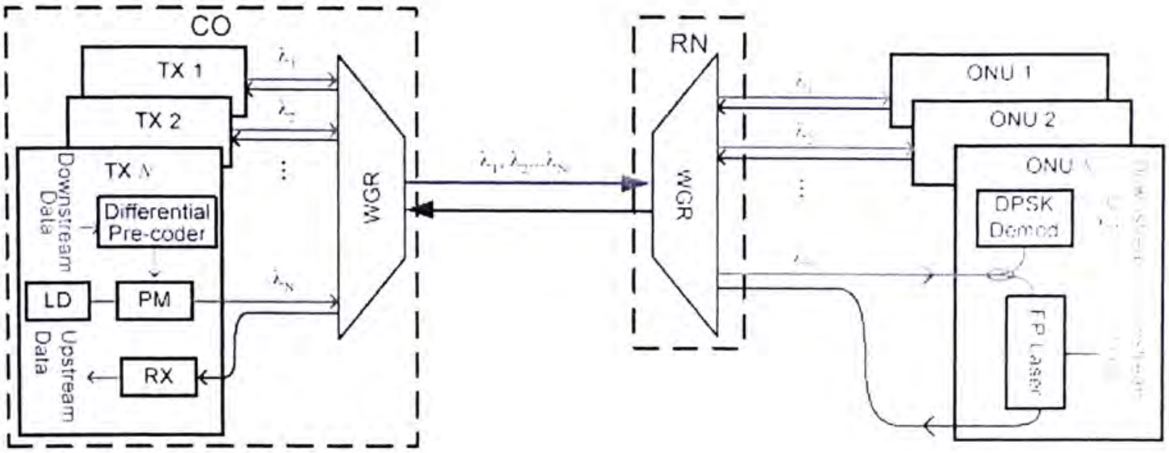

Fig. 2.6 WDM-PON using DPSK as the downstream modulation format and injection locked FP-LD for upstream OOK modulation [15]

However, in the case of employing FP-LD, the upstream traffic suffered from severe crosstalk with the downstream data, particularly when the extinction ratio of downstream traffic was high and the polarization states of downstream signals need to be adjusted for maximizing gain of FP-LD.

An alternative scheme is to erase the downstream data before the carrier is used for upstream data modulation. In [16], the author used a deeply saturated SOA modulator located in the ONU to erase the data on a low extinction-ratio downstream signal and modulate it with new data to generate an upstream signal.

Fig. 2.7 shows the configuration of a WDM-PON that using a deeply saturated SOA modulator as data rewriter. The optical bit sequence of a downstream signal, designed with a relatively low extinction ratio (ER), is amplified with an optical amplifier and input into an SOA. The SOA functions as both a power saturation device and a modulator. The SOA gain saturation leads to a considerable reduction in the difference between the mark and the space level. As a result, the downstream signal modulation pattern is almost erased. At the same time, they modulate the lightwave by modulating the SOA injection current with a different signal. Thus, it can generate an upstream signal with the same wavelength as the downstream signal.

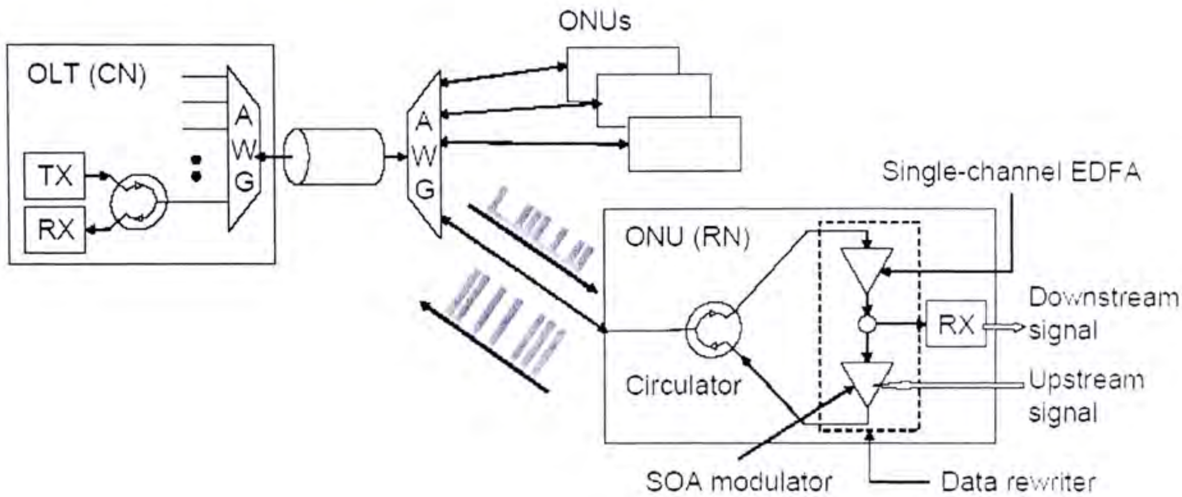

Fig. 2.7 WDM-PON using a deeply saturated SOA modulator as data rewriter [16]

The above structure, however, would be costly due to the use of extra optical amplifier such as an erbium-doped fiber amplifier. To reduce such expensive ONU cost, an unsaturated RSOA operating in the linear regime has been proposed as a low-cost ONU [17].

Fig. 2.8 shows the layout and the basic principle of the experimental setup used in this work. The downstream signal in the central office is modulated with high bit rates and a small extinction ratio. Each wavelength channel is passively split to ONUs where it is received and remodulated with the RSOA with a slower modulation and a high extinction ratio. In this setup the reflections become significant with high split ratios and attenuation. The increased attenuation can be compensated by launching more power to the fiber, simultaneously increasing backreflections. Unidirectional fibers were used between central office and curb in order to prevent the coupling of the Rayleigh backscattering of the downstream signal and the reflection of the curb AWG to upstream receiver.

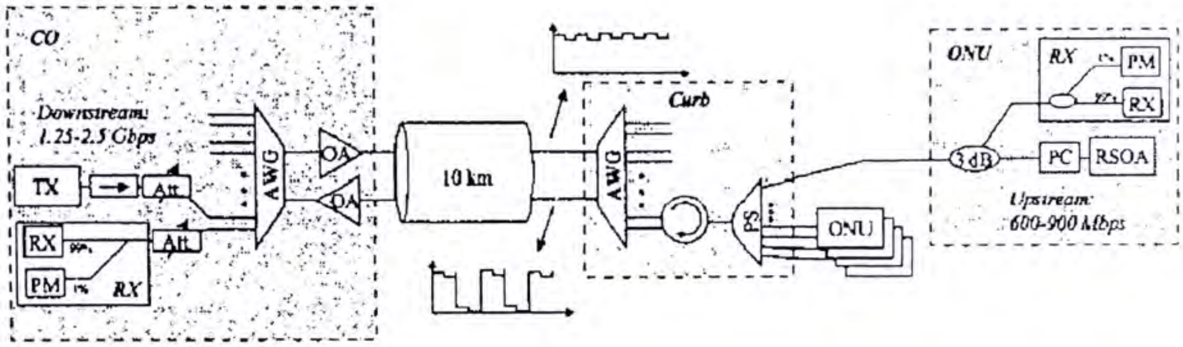

Fig. 2.8 WDM-PON architecture using unsaturated R-SOA remodulator at ONU [17]

Although an RSOA in the linear regime has the optical gain higher than that in the saturation regime, this scheme sacrificed the extinction ratio of the downstream data to reduce the crosstalk to the upstream signal.

Other than using FP-LD and RSOA for remodulation, a novel WDM-PON scheme that exploits the use of injection-locked vertical-cavity surface-emitting lasers (VCSELs) for operation as directly-modulated ONU transmitters was proposed in [18], which also does not require external light sources for injection locking, external modulators for modulation of upstream signals. They used DFB lasers that carry downstream signals to also serve a second function as master lasers to injection-lock ONU slave VCSELs onto the WDM grid.

Fig. 2.9 shows the schematic of a WDM-PON implementing injection locking of VCSELs. At each ONU, an optical splitter divides the optical power of the demultiplexed downstream signal to feed a downstream receiver and a slave VCSEL via an optical circulator. The slave VCSEL responds only strongly to the wavelength but not the data from the master DFB laser, thus, its data does not influence the upstream information.

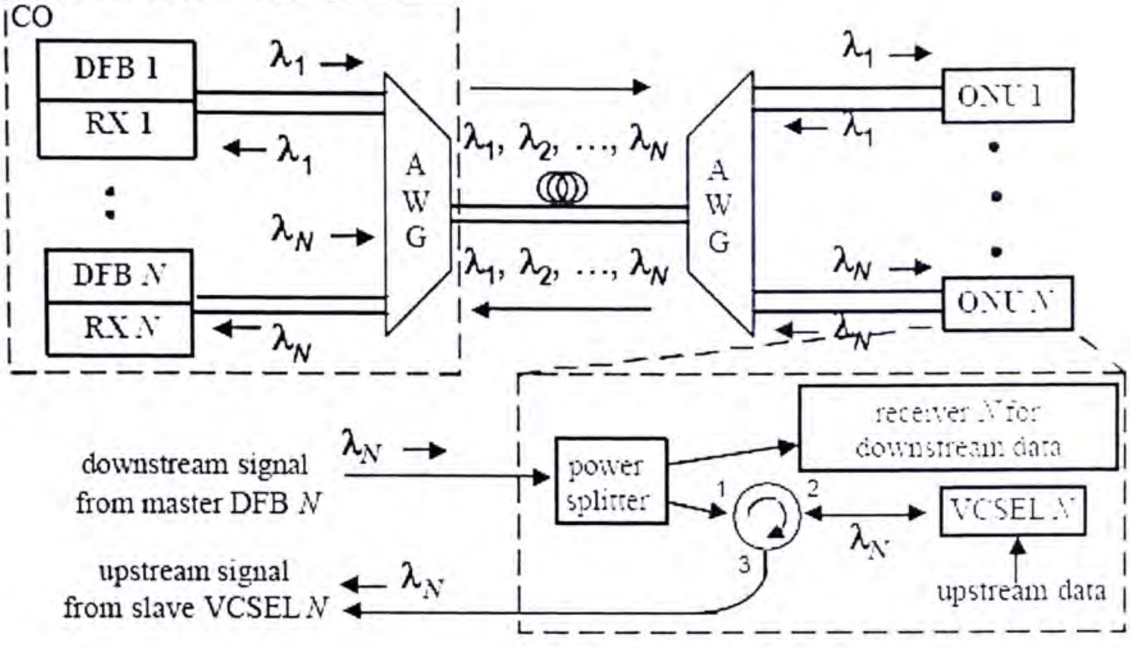

Fig. 2.9 WDM-PON with injection locking VCSELs [18]

2.3 Summary

In this chapter, we have outlined several approaches to realize colorless ONUs in WDM-PON, which are (1) Spectrum Slicing BLS employed at the ONU; (2) Centralized broadband light source (BLS) for upstream optical carrier supply; (3) Reuse or remodulation of the downstream carrier at the ONU.

Among these approaches, when reusing or re-modulating the downstream carrier, either polarization states of downstream signals at the ONU need to be adjusted, or upstream traffic suffered from severe crosstalk with the downstream data. What is more, the upstream transmission rate can be very high (e.g. 2.5 Gb/s) and distance covered can be very large (e.g. 40 km). Thus, the centralized BLS WDM-PON is the most attractive, which can completely fulfill the expected growth of bandwidth demands. In this network, optical carriers for upstream signals are supplied from the CO to ONUs, modulated in the ONUs, and looped back to the CO. Thus, the CO administers all wavelengths and the ONU supports any wavelength channel.

In the next chapter, we will discuss a simple WDM-PON access architecture using centralized PCF-based supercontinuum broadband light source for upstream optical carrier supply, which can support high speed transmission. By spectrum-slicing centralized broadband light sources based on supercontinuum generation, all ONUs can be designed to be wavelength independent ("colorless").

Chapter 3

WDM-PON with a Centralized Supercontinuum Broadband Light Source for Colorless ONUs

3.1 Introduction

As discussed in the last chapter, WDM-PON architecture with a centralized broadband light source for upstream carrier supply is most attractive for broadband access. There are several approaches to obtain the broadband spectrum among which, one attractive mechanism is supercontinuum generation (SCG) [19]. In such a method, the pulses are generated from a laser source, and then launched into a nonlinear fiber, where the spectrum of the pulses is significantly broadened through the nonlinear optical interactions. Supercontinuum generation is a promising technique to generate broadband light owing to its easy implementation, flexible design and large number of supported optical channels. It has been investigated for use in dense wavelength division multiplexed (DWDM) transmission systems [20-21]. In this chapter, we propose and demonstrate a simple high-speed WDM-PON access network architecture using a centralized supercontinuum broadband light source for upstream optical carrier supply. The elimination of the light source at the ONU avoids the need for wavelength stabilization and provisioning at ONU, and all ONUs are wavelength independent ("colorless"). Also, a broadcast scheme over WDM-PON by spectrum-slicing of a broadband light source based on supercontinuum generation is proposed and investigated.

3.1.1 Introduction to Supercontinuum Generation

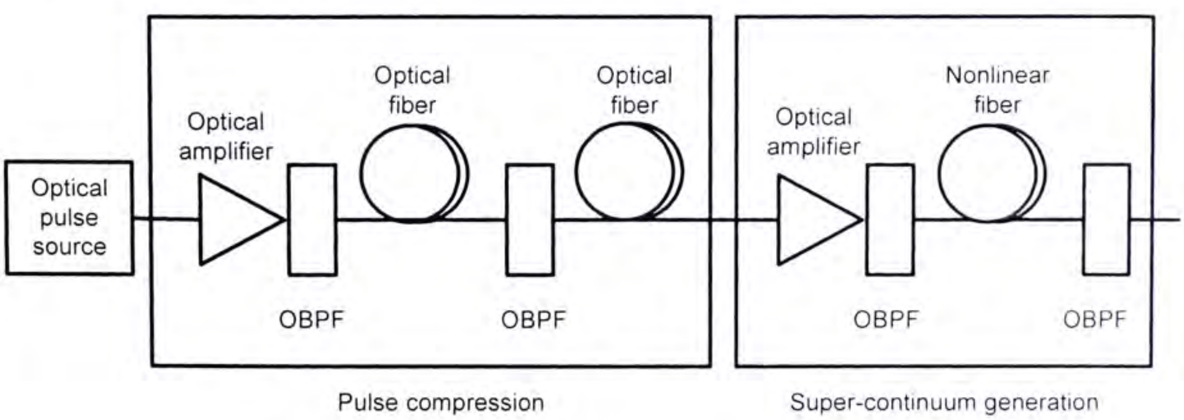

Fig. 3.1 Implementation of supercontinuum generation

Fig. 3.1 shows a typical implementation of SCG. Pulses are obtained from an actively mode-locked laser, a gain-switched laser diode, or an electro-absorption modulated DFB laser. Before SCG, a pulse compression stage can be employed, as the pulse with narrower pulse width would help to attain a broader spectrum. The compressed pulses are then amplified and launched into a *nonlinear* fiber, where the spectrum of the pulses is broadened along the propagation. Optical filter may be used at the output of the nonlinear fiber to slice WDM channels for transmission. The amplifier before the nonlinear fiber is used to enhance the nonlinearity for a wider spectrum broadening.

Supercontinuum generation is the formation of broad continuous spectra by propagation of high power laser pulses through a nonlinear medium. The term supercontinuum does not cover a specific phenomenon but rather a plethora of nonlinear effects, which, in combination, lead to extreme pulse broadening. It is the combined results of dispersion and many nonlinear processes, such as self-phase modulation (SPM), cross-phase modulation (XPM), four-wave mixing (FWM), and Raman scattering. These nonlinear effects are capable of generating new frequency components. SCG is usually obtained by propagating optical pulses through a strongly nonlinear media, e.g. optical fibers. Of special current interest is the photonic crystal fiber (PCF), mainly due to their unique dispersion characteristics, which can allow a strong nonlinear interaction over a significant length of fiber. Even with quite moderate input powers, very broad spectra are achieved. The characteristics of PCF will be introduced next.

3.1.2 Introduction to Photonic Crystal Fibers

Photonic crystal fibers (also called holey fibers or microstructure fibers) are a new type of glass optical fibers in which the cladding contains a regular array of microscopic air-holes running along the entire length of the fibers. Standard fibers guide light by total internal reflection between a core with a high refractive index, embedded in a cladding with a lower index, while PCF obtains its waveguide properties not from a spatially varying material composition but from an arrangement of very tiny and closely spaced air holes. The size and position of these holes determine the optical behaviour of the fiber and it is possible to create fibers with highly unusual optical properties not attainable with conventional fiber technology. There is a great variety of hole arrangements, leading to PCFs with very different properties.

There are two fundamental classes of PCFs: index-guiding PCFs and fibers that confine light through a photonic bandgap (PBG). An index guiding PCF comprises a solid glass high-index core embedded in an air-filled cladding structure where a number of air holes are arranged in a pattern that runs along the length of the fiber, creating a hybrid air-silica material with a refractive index lower than the core. We refer to this type of PCF in the following part of this thesis.

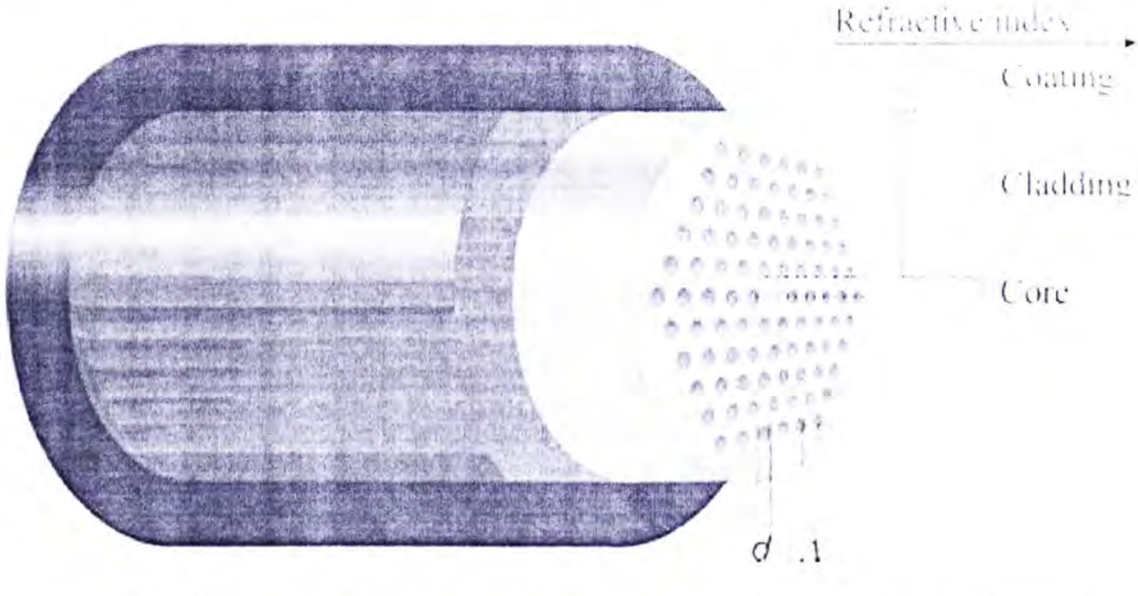

Fig. 3.2 Schematic of the classical triangular cladding single-core PCF [22]

Fig. 3.2 shows the schematic of the classical triangular cladding single-core photonic crystal fiber, in which light is guided in a solid core embedded in a triangular lattice of air holes [22]. The fiber structure is determined by the hole-size d, and the hole-pitch Λ. Like standard fibers, the PCF is coated with a high index polymer for protection and to strip off cladding-modes.

3.1.3 Supercontinuum Generation in a Photonic Crystal Fiber

As mentioned previously, a supercontinuum source typically consists of a pulsed laser and a nonlinear element, in which a combination of non-linear effects broadens the narrow-band laser radiation into a continuous spectrum without destroying the spatial coherence of the laser light. PCF are well suited as the nonlinear medium due to their design degrees of freedom which make it possible to enhance the nonlinear effects by reduction of their effective area and tailor their dispersion in order to favour soliton generation [23] or phase-matched processes [24] in the wavelength range of interest.

Next, we propose and demonstrate a simple high-speed WDM-PON access network architecture using a centralized supercontinuum broadband light source for upstream optical carrier supply. Since a high nonlinearity PCF is very efficient for supercontinuum generation [25], our SC broadband source is based on the use of a PCF.

3.2 WDM-PON with Centralized Supercontinuum Broadband Light Source

3.2.1 Motivation

Colorless (wavelength-independent) optical network units are desirable for access network, since it decreases the costs of operation, administration, and maintenance (OA&M) functions, as well as the production cost as mass production becomes possible with just one specification. Previous works on achieving colorless ONU we discussed in the previous chapter, the bit rates were very limited, which may not fulfill the expected growth of bandwidth demands.

Here we propose a simple high-speed WDM-PON access architecture utilizing centralized high nonlinearity PCF based supercontinuum broadband light source for colorless ONU. In our scheme, only a modulator is employed in one ONU, while each upstream optical carrier is supplied via the source located at the central office. Since no wavelength-specific transmitter is incorporated at the customer site optical network units, wavelength management at the ONU is relaxed and thus this greatly reduces the network cost.

3.2.2 Proposed Access Network

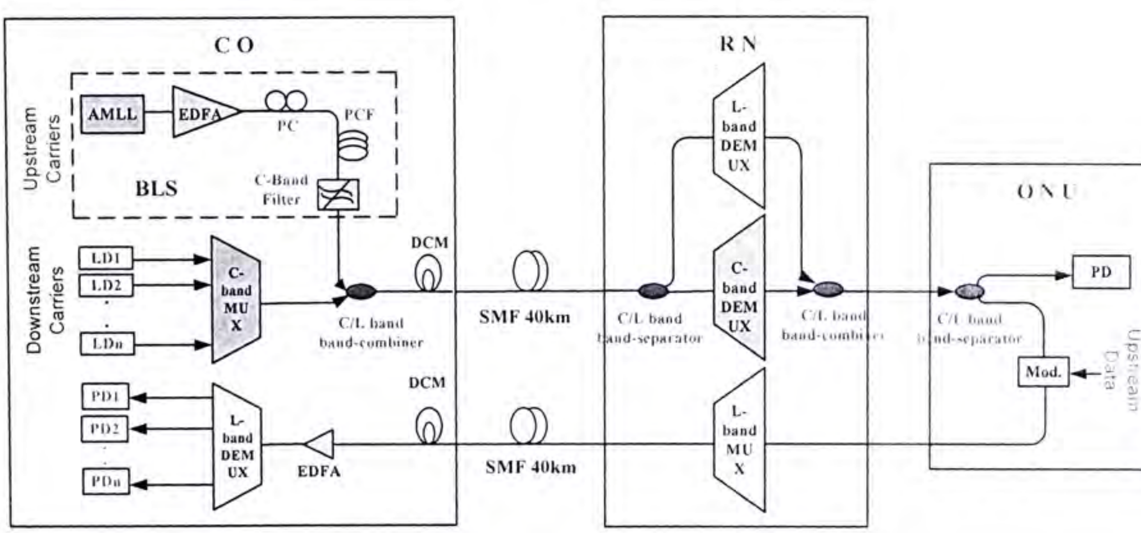

Fig. 3.3 Proposed architecture of bidirectional WDM-PON [26]

The architecture of our proposed WDM-PON is shown in Fig. 3.3 [26]. The network comprised of a CO, a remote node, and 8 ONUs. We used conventional C band for upstream data transmission and L band for downstream data transmission. The CO consisted of a broadband light source (BLS), L band DFB laser transmitters, optical receivers, a L band multiplexer (MUX), a C band demultiplexer (DEMUX), a C/L band wavelength division multiplexer (WDM), an erbium doped fiber amplifier (EDFA), and two dispersion compensation modules (DCM). The supercontinuum BLS, consolidated in the CO to supply upstream optical carriers to ONUs, consisted of an actively mode-locked laser (AMLL), an EDFA, a polarization controller (PC), a piece of nonlinear photonic crystal fiber and a C band bandpass filter.

The RN consisted of only C/L band MUX/DEMUX and WDM filter to combine and divide downstream signals and supplied optical carriers, thus it was all passive. In the network, each ONU consisted of an optical modulator, an optical receiver, and a C/L band WDM filter. Since there is no light source, the colorless ONU can support any wavelength channel, which minimized the costs of system operation and maintenance, but at the expense of an external modulator at the ONU.

A 1-ps pulse train centered at 1550 nm was generated by a semiconductor-laser-based actively mode-locked laser with a repetition rate of 10GHz, and then amplified by an EDFA delivering up to 23 dBm average power before input to 64m of a dispersion-flattened highly nonlinear PCF from Crystal Fiber A/S. The overall dispersion of this PCF is flat over a wide wavelength range (less than -3ps/km/nm over 1500-1600nm) with the nonlinear coefficient of the PCF was 11.2 $(W \cdot km)^{-1}$ [27]. The dispersion variation is less than 1 ps/km/nm in the 1550nm range. Due to the fiber birefringence, a PC is used before the PCF. The C band bandpass filter centered at 1550 nm (bandwidth: 13 nm) was used behind the PCF to limit the spectral width of the supercontinuum to be at the C band for upstream carrier use, which is separated from the L band downstream channels. The L band DFB lasers directly modulated at 10 Gb/s were combined with the C band upstream carrier, and then sent to the RN through a 40 km long single mode fiber. To suppress the effect of fiber dispersion, we used a dispersion compensation module at the CO. These combined signals were separated by a C/L band WDM filter, and demultiplexed at the RN respectively. Two pre-assigned wavelengths were selected to send to each ONU. One carried downstream signal in the L band, and the other was an optical upstream carrier in the C band.

At each ONU, the downstream signal and upstream carrier were divided by the C/L band WDM filter, the downstream signal was received by a photodetector (PD), while the upstream carrier was first modulated at 10 Gb/s with a 2^{31}-1 pseudorandom bit sequence (PRBS) pattern, and then sent to the CO through 40 km SMF transmission line after being multiplexed at the RN. After passing through an optical amplifier, the upstream signals were demultiplexed, and finally received in individual optical receivers at the CO.

3.2.3 Experimental demonstration and results

Since the downstream data was transmitted by single DFB laser diode separately, we only demonstrated 8 upstream channels supplied by the SC source with 200GHz channel spacing.

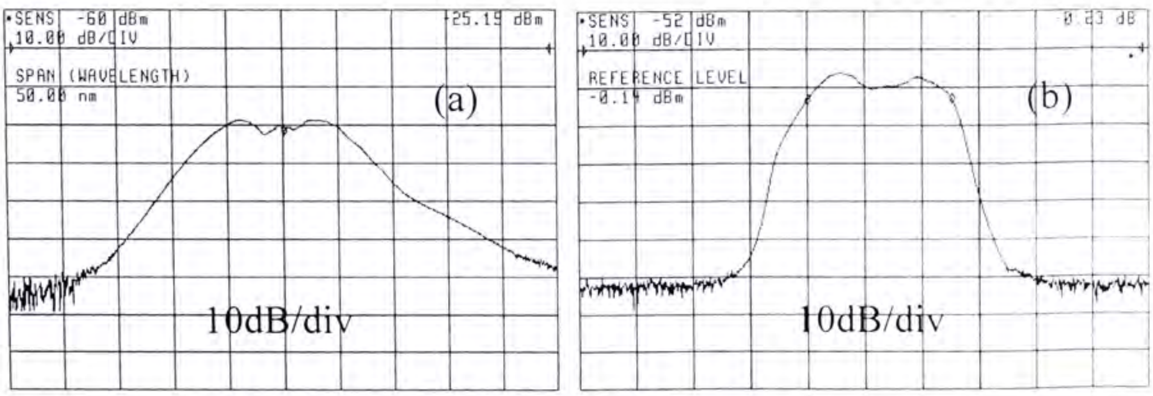

Fig. 3.4 Optical spectra of SC generation (a) before and (b) after C band bandpass filter

Fig. 3.4 shows the generated supercontinuum spectrum before and after the C band bandpass filter at CO. The spectrum was broadened to 25nm (-20 dB bandwidth) after SC generation and we filtered out 13nm in C band for use as upstream carriers.

Because the spectrum was inherently not smooth, it resulted in optical power variation among different channels. After being demultiplexed, the maximum difference in received power between two channels was 3.6 dB. The spectrum of channel 2 (with maximum optical power) and channel 8 (with minimum optical power) is shown in Fig. 3.5.

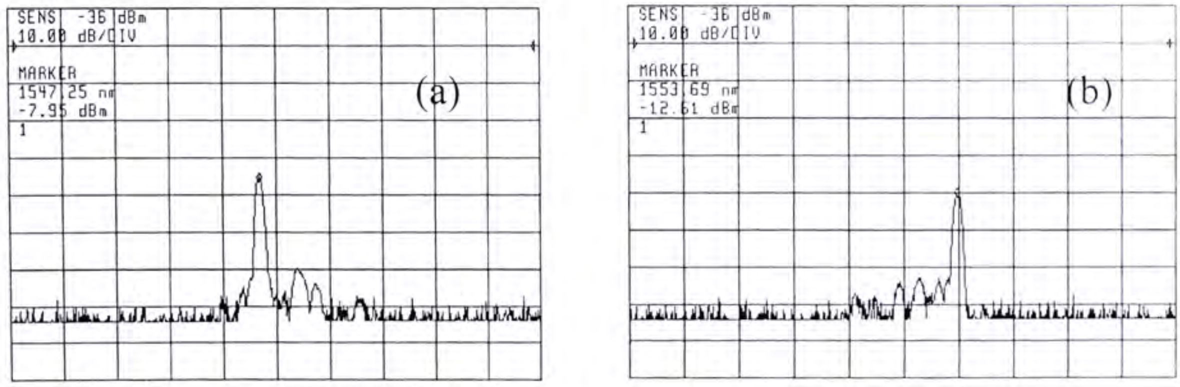

Fig. 3.5 Optical spectra of different upstream channels

(a) Channel 2 centered at 1547.7 nm (with the highest power);

(b) Channel 8 centered at 1557.6 nm (with the lowest power)

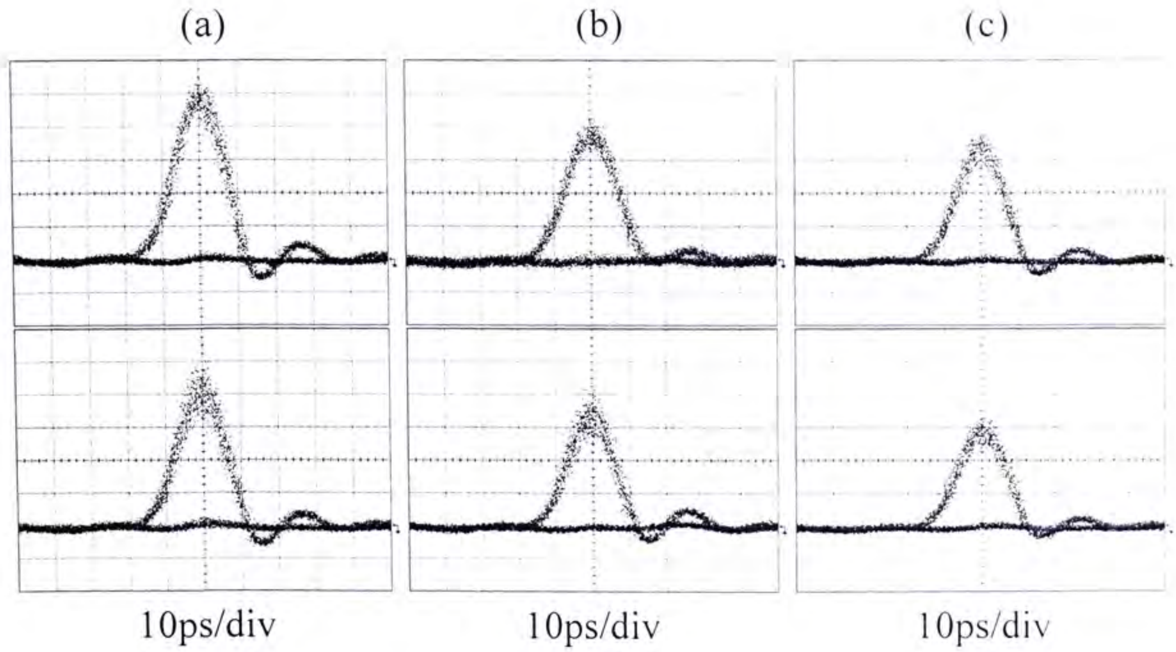

Fig. 3.6 Eye diagrams of different upstream channels before (upper row) and after (lower row) upstream transmission: (a) Channel 2 centered at 1547.7 nm; (b) Channel 5 centered at 1552.5 nm; (c) Channel 8 centered at 1557.36 nm.

Fig. 3.6 shows the eye diagram at the BER of 10^{-9} of the upstream channel 2, 5 and 8 after modulation at the ONU and after upstream transmission at the receivers in the CO, respectively. We observed clear eye diagrams as shown in Fig. 3.6 in spite of the power variation. Fig. 3.7 shows the BER performances of all 8 upstream optical channels after upstream transmission. It can be seen that all channels were transmitted error-free (bit-error rate < 10^{-9}) albeit with variation in channel performance.

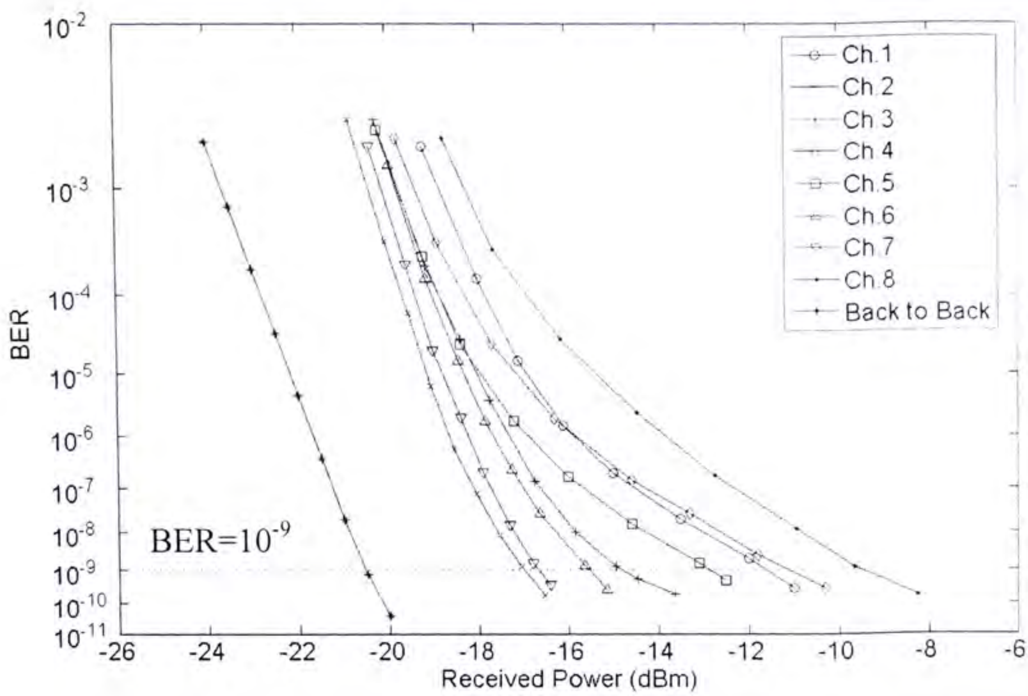

Fig. 3.7 BER performances of 10 Gb/s upstream channels after transmission

3.2.4 Discussions

From Fig. 3.7, we can see the power penalty of upstream channel 2 was the smallest, while upstream channel 8 was the largest among all the channels after transmission. Fig. 3.8 shows the receiver sensitivity versus different upstream channels. According to [28], the large power penalties of channel 1 and channel 8 were due to the comparable low optical power after spectrum splicing. The power penalties of channel 4 and channel 5 were mainly due to the degraded OSNR near the pump wavelength, while the power penalties of channel 3 and channel 6 were mainly due to the timing jitter or intensity fluctuations caused by the fiber nonlinear effect. Since channel 2 and channel 7 got little effects on both OSNR degradation and fiber nonlinear effect, they were with the minimum power penalty.

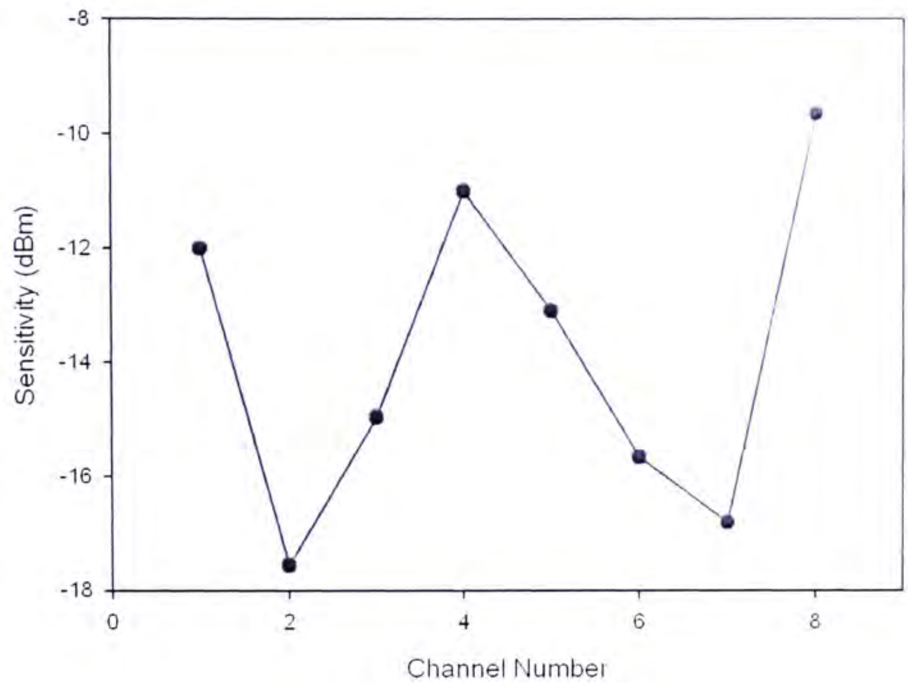

Fig. 3.8 Receiver sensitivity versus different upstream channels

In our experiment, 23 dBm optical power was generated from the supercontinuum broadband light source. The splicing loss was 15 dB (for the worst channel) at the DEMUX in RN, thus the total downlink loss (caused by DCM, 40 km long SMF, WDM coupler, DEMUX) was 30 dB. At each ONU, the upstream carrier experienced 9 dB loss for modulation, and the uplink loss (caused by MUX, 40 km long SMF, DCM) was 18 dB. Since the receiver sensitivity with pre-amplifier was -38 dBm at 10Gb/s, there was still a 4 dB power margin for the worst channel.

Due to the limit of EDFA, the maximum power input to the PCF was only 23 dBm, which limited the bandwidth of the SC spectrum. The SC spectrum can extend over 60 nm with an average pump power of 30 dBm [25], which cover the C and L bands used for optical communication. In that case, the supported channel number can be readily extended to 16 or 32. To achieve the colorless ONU operation, external modulators are needed in each ONU for the upstream signal, and here we assume that such modulators would be low cost in high volumes.

3.2.5 Conclusion

We have proposed and demonstrated a simple high-speed WDM passive optical network architecture using a centralized nonlinear PCF-based supercontinuum broadband light source for upstream optical carriers in colorless ONUs. 8 channel bidirectional transmissions at 10Gb/s over 40 km distance were demonstrated. All 8 channels achieved error-free transmission albeit with variation in channel performance. In future work, we can upgrade the proposed WDN-PON using higher power EDFA, providing more upstream optical carriers for a larger number of ONUs.

3.3 Broadcast Signal Delivery over a WDM-PON based on Supercontinuum Generation

3.3.1 Motivation

In a traditional WDM-PON, broadcasting signal was combined with the downstream data, and can reach each ONU by passing through the optical power splitter. Other than power-splitting passive optical networks [29], in the wavelength-routed PON, AWG (array-waveguide grating) is used. The output ports of demultiplexer (DEMUX) can pass a specific wavelength only so that we can not exploit the broadcasting nature of PON in downstream. Thus we can not deliver broadcast signals to all ONUs using traditional single wavelength for power-splitting PON. Previous works for broadcasting in such networks have focused on the use of broadband LED source [30] or sub-carrier multiplexing (SCM) technique [31]. However, the transmission capacity is limited by using LED, and the link quality to support SCM transmission need to be very high to ensure good carrier-to-noise ratio (CNR).

In this section, we propose and demonstrate a simple high-speed WDM-PON access architecture using supercontinuum broadband light source for *broadcast* carrier supply. Our SC broadband source is based on the use of a high-nonlinearity photonic crystal fiber, due to its high efficiency for supercontinuum generation. Each ONU is assigned a separate wavelength for broadcast service. It may not be cost-effective initially, but since broadcast services are likely to be provided by different providers, it may be necessary to assign a separate wavelength from the management aspects. What is more, it is convenient to achieve unicast and multicast, not only broadcast in this scheme. We simultaneously transmit broadcast and point-to-point (PTP) downstream data at 10 Gb/s over 40 km of single mode fibers.

3.3.2 Proposed network architecture

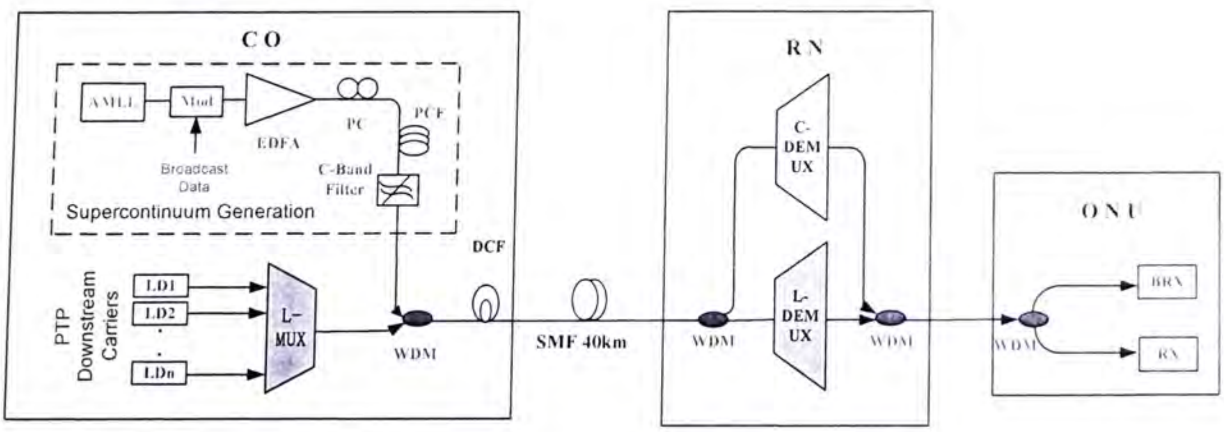

Fig. 3.9 WDM-PON Architecture with both PTP and broadcast service delivery

The proposed WDM-PON architecture is shown in Fig. 3.9. We used conventional C band for broadcast data transmission and L band for PTP data transmission. The network comprised of a CO, a RN, and 8 ONUs. The PCF-based broadband supercontinuum source was similar as that described in the Fig. 3.3 at the last chapter. The C band bandpass filter centered at 1550 nm (bandwidth: 13 nm) was used behind the PCF to limit the spectral width of the supercontinuum to be at the C band for broadcast use, which is separated from the L band PTP downstream channels. The L band DFB lasers directly modulated at 10 Gb/s were combined with the C band broadcast signals, and then sent to the remote node (RN) through 40 km long single-mode fiber. To compensate the effect of fiber dispersion, we used a dispersion-compensation fiber module at the CO. These combined signals were separated by a C/L band WDM filter, and demultiplexed at the RN respectively. Two pre-assigned wavelengths were selected to send to each ONU. One carried PTP downstream signal in the L band, and the other carried broadcast signal in the C band, both of which were received by separate optical receivers (RX).

3.3.3 Experiment results and discussions

Since the PTP downstream data was transmitted by single DFB laser diode separately, we only demonstrated 8 broadcast channels supplied by the SC source with 100GHz channel spacing.

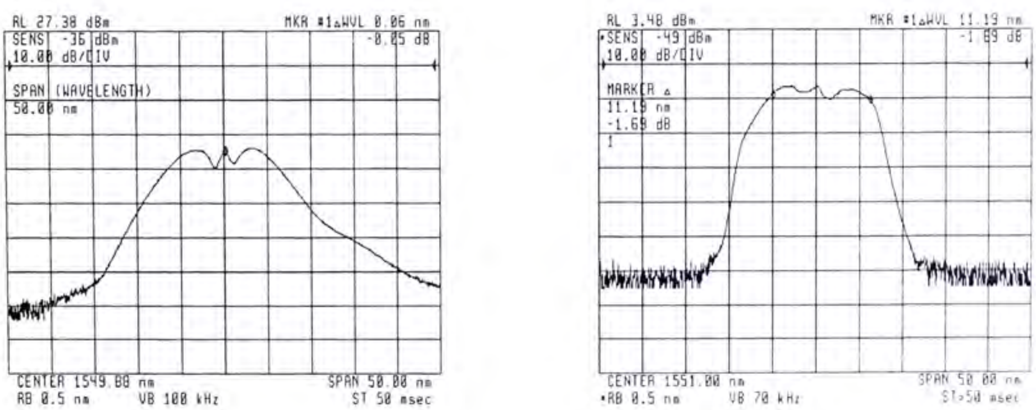

Fig. 3.10 Optical spectra of SC generation (a) before and (b) after C band bandpass filter

Fig. 3.10 shows the generated supercontinuum spectrum before and after the C band bandpass filter. The spectrum was broadened to 25nm (-20 dB bandwidth) after SC generation and we filtered out 13nm in C band for broadcast use. Because the spectrum was inherently not smooth, it resulted in optical power variation among different channels. After being demultiplexed, the maximum power difference between two channels was 3.6 dB.

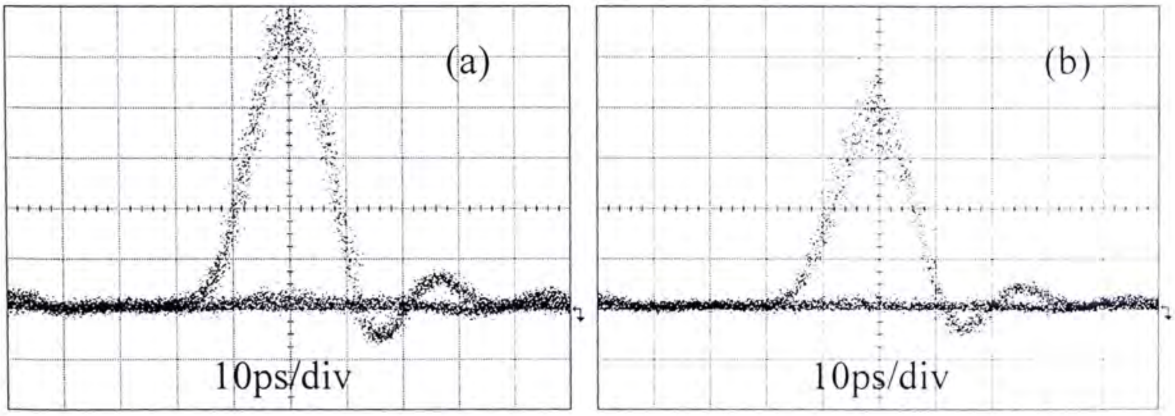

Fig. 3.11 Eye diagrams of different downstream broadcast channels

(a) Channel 4 centered at 1550.12 nm (with the highest power);

(b) Channel 8 centered at 1556.55 nm (with the lowest power)

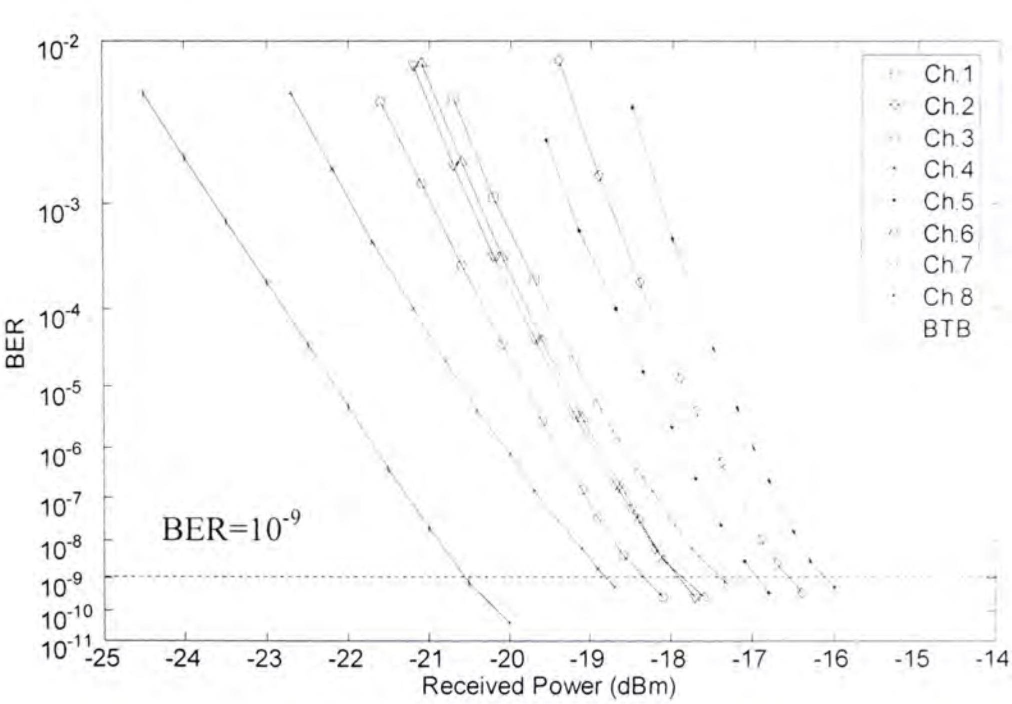

Fig. 3.12 BER performances of 10 Gb/s broadcast channels

Fig. 3.11 shows the eye diagram of the broadcast channel 4 (with maximum optical power) and channel 8 (with minimum optical power) after transmission. We observed clear eye diagrams as shown in Fig. 3.11 in spite of the power variation. Fig. 3.12 shows the BER performances of all 8 broadcast optical channels. It can be seen that all channels were transmitted error-free (bit-error rate $< 10^{-9}$) albeit with variation in channel performance.

3.3.4 Conclusion

We have proposed and demonstrated a simple high-speed WDM passive optical network architecture using a nonlinear PCF-based supercontinuum broadband light source for downstream broadcast. 8-channel transmission at 10Gb/s over 40 km distance was demonstrated. All 8 channels achieved error-free transmission albeit with variation in channel performance.

3.4 Summary

In this chapter, we proposed two schemes of simple high-speed WDM-PONs, both using a supercontinuum broadband light source based on a nonlinear PCF. The first one used a centralized supercontinuum broadband light source for upstream optical carrier supply. "Colorless" ONU operation has been demonstrated in a 10Gb/s transmission over 40 km distance. The second one used a PCF-based supercontinuum broadband source for broadcast signals over dedicated wavelengths. Broadcast delivery has been demonstrated in a 10Gb/s transmission over 40km distance. These two examples illustrated the potentially useful applications of SCG in WDM optical access networks.

Chapter 4

A Survivable WDM-PON with Colorless Optical Network Units

4.1 Introduction

As the access networks evolve from today's technology towards the future all-optical technology, and with the implementation of wavelength-division multiplexing technology in metro and access networks, any kind of network failure due to link breakage or component failure will interrupt the broadband services to the subscribers and definitely translates into enormous loss in data and business. Thus, fault management to monitor and detect any network failure occurred, and then to perform the appropriate remedy so as to re-route or restore the data traffic to minimize the data loss becomes one of the crucial aspects in network management. Since survivability at the optical layer provides protection to higher layer protocols that may not have built-in protection, to assure network reliability, survivable optical access network architectures with protection and restoration functionalities are highly desirable [32].

4.2 Previous Protection Schemes

Most optical access networks employ a point-to-multipoint network topology, thus any link breakage between the RN and an ONU will suspend all services on that link and isolate the affected ONU from the OLT. The network architecture has to provide network path redundancy and be incorporated with automatic protection switching mechanism to re-route the affected data traffic onto the alternate protection paths. The ITU-T Recommendation on PON (G.983.1) [33] suggested four possible fiber duplication and protection switching scenarios, as shown in Fig. 4.1, though they were regarded as optional protection mechanisms. Note that the RN only comprises 1×N optical power splitter(s) in ITU-T G.983.1, but those protection architectures can also be applied to WDM-PON by replacing the optical power splitters by wavelength demultiplexers. Fig. 4.1 shows the four suggested protection architectures with different levels of protection. Fig. 4.1(a) duplicates the fiber feeder between the OLT and the RN only. Fig. 4.1(b) doubles the optical transceivers at the OLT and also duplicates the fiber feeder between the OLT and the RN. Protection switching is done by switching the data to the backup optical transceiver at the OLT. Fig. 4.1(c) doubles not only the OLT side facilities but also the RN and the ONU sides. Failure at any point can be recovered by switching to the backup facilities. Fig. 4.1(d) incorporates an additional power splitter circuit to cope with the case that not all ONUs have duplicate optical transceivers, due to some environmental constraints.

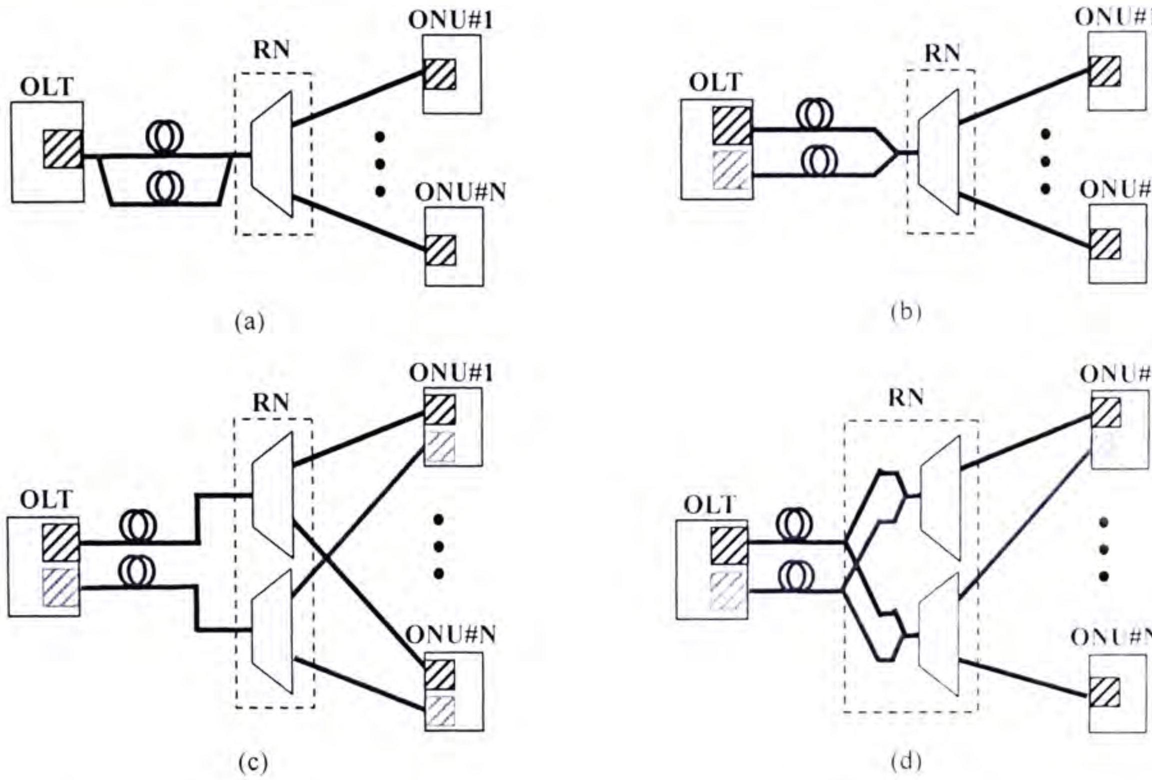

Fig. 4.1 Protection switching architectures suggested by ITU-T G.983.1 [33]

To facilitate network protection and restoration, it is desirable to have fault-tolerant network architectures, which can detect the link failure and automatically restore the network traffic via other alternative or backup paths. Recently, several protection architectures for WDM optical access networks have been proposed. In [34], a self-healing DWDM/SCM modified star-ring architecture (MSRA) was proposed, in which two adjacent RNs were connected by a ring, and each ring was connected with multiple ONUs. The self-healing function can be performed at remote nodes by using optical switches (OS) to reconfigure the ring subnets. In case of fiber cut between RN and the OLT, the traffic on both of its attached rings would be bypassed and forwarded to its adjacent RN so that the affected ONUs can still be in contact with the OLT. The network architecture is shown in Fig. 4.2. Complexity in scalability, inflexible topology without sufficient variations, and high equipment cost become some critical problems in this scheme.

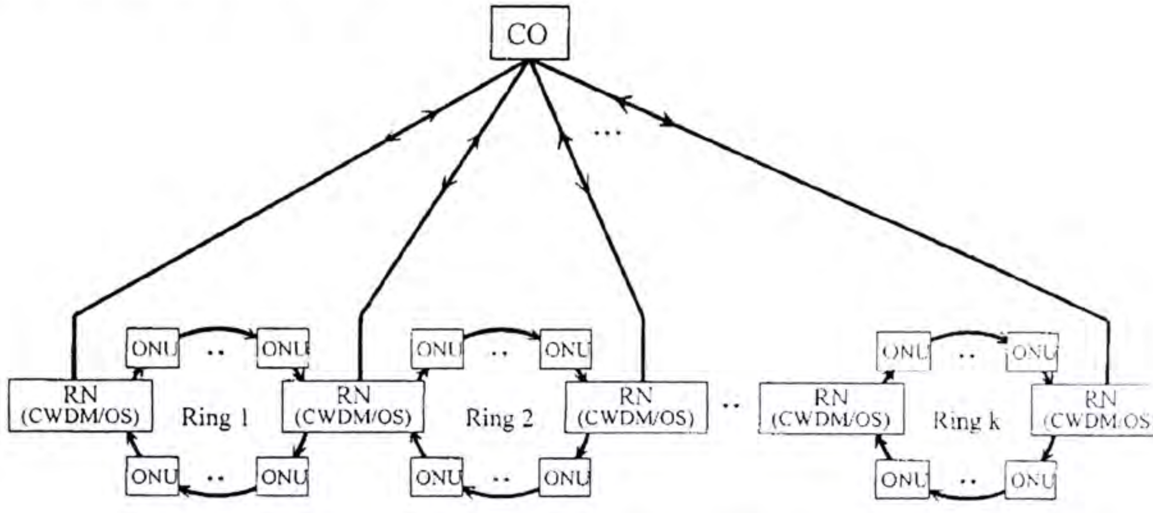

Fig. 4.2 Block diagram of the modified WDM star–ring architecture [34]

A self-protected WDM-PON architecture was proposed in [35-36]. As shown in Fig. 4.3 [35], two adjacent ONUs were grouped and the corresponding downstream and upstream wavelengths were connected to the OLT via the same output port of the AWG at the RN. This was achieved by utilizing the periodic spectral property of the AWG and with proper wavelength assignment. The two ONUs in the same group were connected by a piece of protection fiber and a pair of protection switches were incorporated into each ONU for signal re-routing. In case of fiber cut between a particular ONU and the RN, the protection switches in the ONUs in the same group will be activated. Both the affected downstream and upstream wavelengths will be re-routed to its adjacent ONU before being routed back to the OLT via the same AWG output port. In this way, the normal traffic on the adjacent ONU was not affected while the OLT could still keep in connection with the affected ONU. Thus, the OLT would be transparent to such fiber failure.

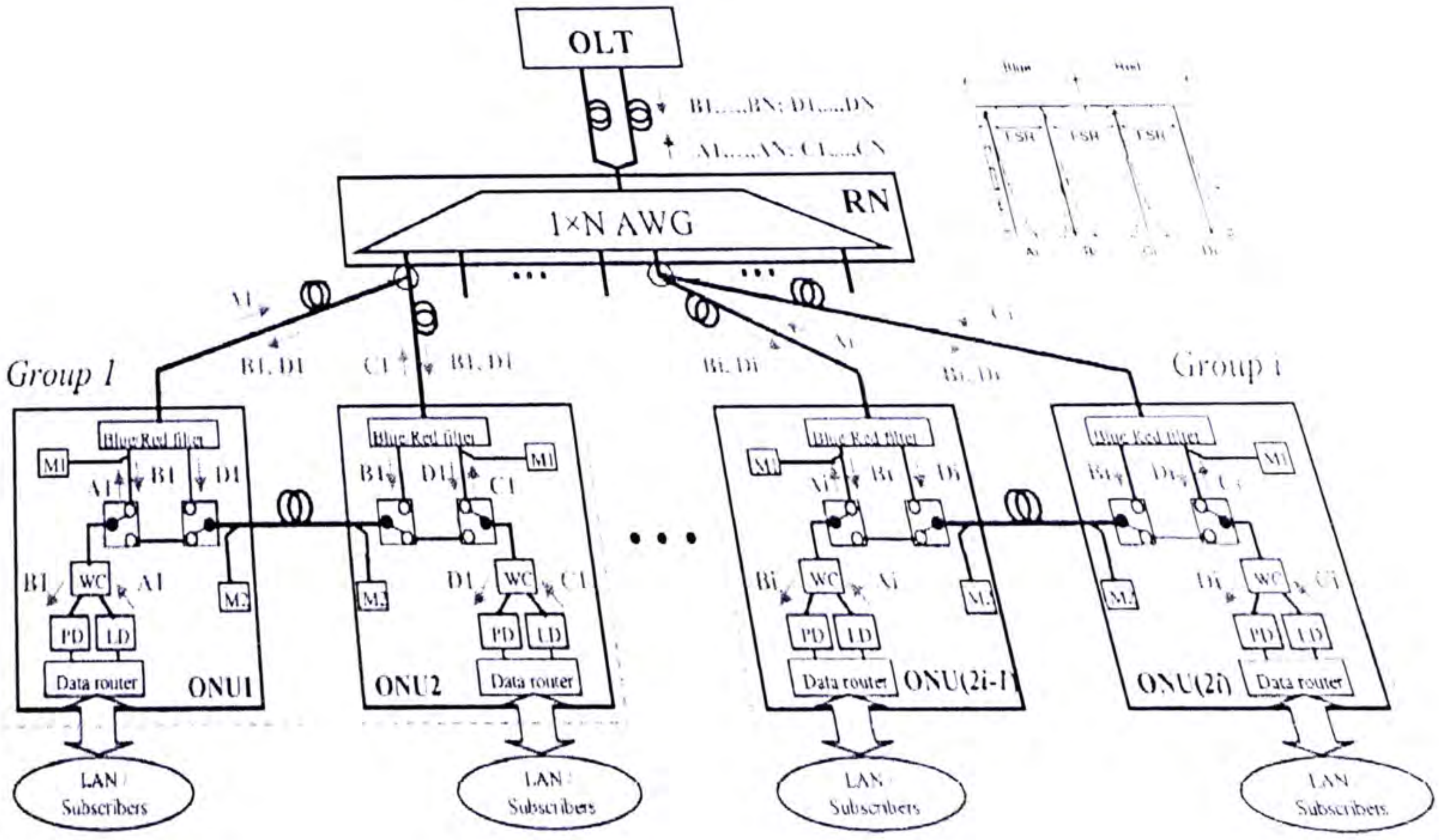

Fig. 4.3 Proposed self-protected WDM-PON network architecture [35]

Although these above architectures are designed to enhance the network reliability, the protection schemes are only applicable to one-fiber based WDM-PON system, which connects the RN and each ONU with one distribution fiber link. However, in the WDM-PON scheme with centralized light sources at the central office for upstream carrier supply, two-fiber based architecture using two separate fiber links between RN and each ONU is always used to avoid back reflections. To assu network reliability, survivable network architectures with protection and restora functionalities are highly desirable for such two-fiber based systems.

In [37] a wavelength-shifted protection scheme for two-fiber based centr achieved. Although this protection scheme is based on two-fiber WDM-PON system, it duplicated a set of transmitters, receivers in the CO to provide network resource redundancy, which largely increased both the network complexity and the cost.

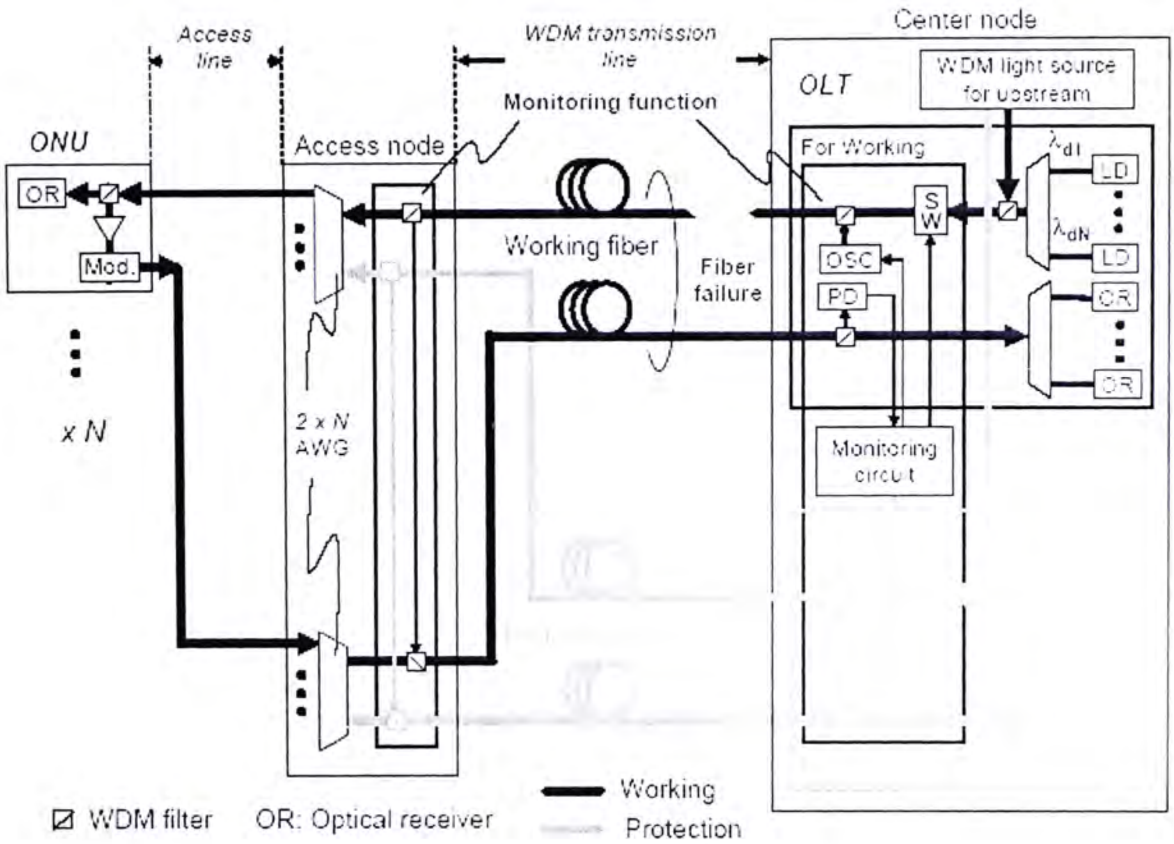

Fig. 4.4 Proposed centralized BLS WDM-PON using wavelength-shifted protection scheme [37]

4.3 A Survivable WDM-PON with Centralized BLS

In this section, we propose a survivable architecture to protect the feeder fiber link in a centralized BLS WDM-PON that only one set of transceivers are needed at the CO, and all monitoring and protection equipment is consolidated at the CO. Besides, the ONU design is simpler and no protection equipment is needed at the ONU. Thus, the amount of required network resources is significantly reduced.

4.3.1 Network topology and wavelength assignment

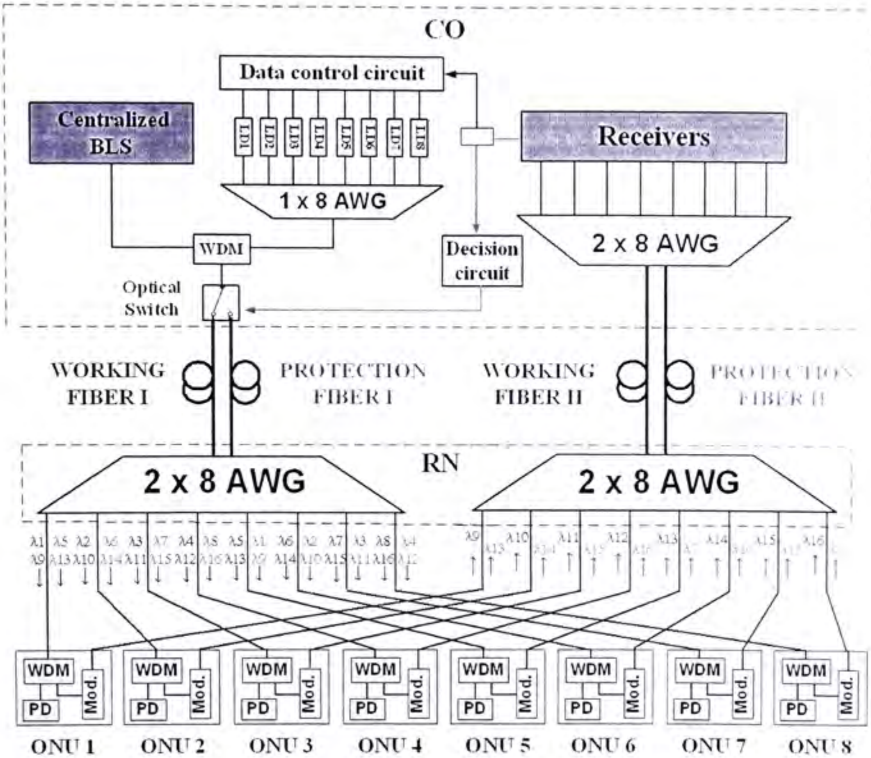

Fig. 4.5 Proposed WDM-PON access network architecture with 8 ONUs [38]

Fig. 4.5 illustrates our proposed WDM-PON architecture with N ONUs [38]. Without loss of generality, 8 ONUs are considered as an example. WDM broadband light sources (BLS), supplying un-modulated optical carriers in the C-band are centralized at the CO, and they are to be modulated at the ONUs for the upstream traffic, thus no wavelength-specific transmitter is incorporated at the subscriber side. The downstream channels are assigned with L-band wavelengths. Both the L-band downstream wavelengths and the C-band BLS wavelengths are combined by the L/C combiner, followed by a 1×2 optical switch, which connects to the RN via a pair of working and protection fiber feeders. Under normal operation, the switch is connected to the working feeder fiber. The RN consists of two identical 2×N AWGs, one for the downstream wavelengths and the other for the upstream wavelengths. The AWG dedicated for the upstream traffic at the RN connects to the receivers at the CO via another pair of working and protection feeder fibers. The spectral transmission peaks of the two AWG input ports are spaced by half of the free-spectral range (FSR) of the AWG. Wavelength assignment plan for upstream and downstream wavelengths is shown in Fig. 4.6. There are two fibers connecting RN and each ONU. One distribution fiber delivers a downstream signal and an optical carrier to each ONU, while the modulated upstream signal is delivered back to RN through the other fiber. Since there is no light source in the ONU, such a colorless ONU can support any wavelength channel.

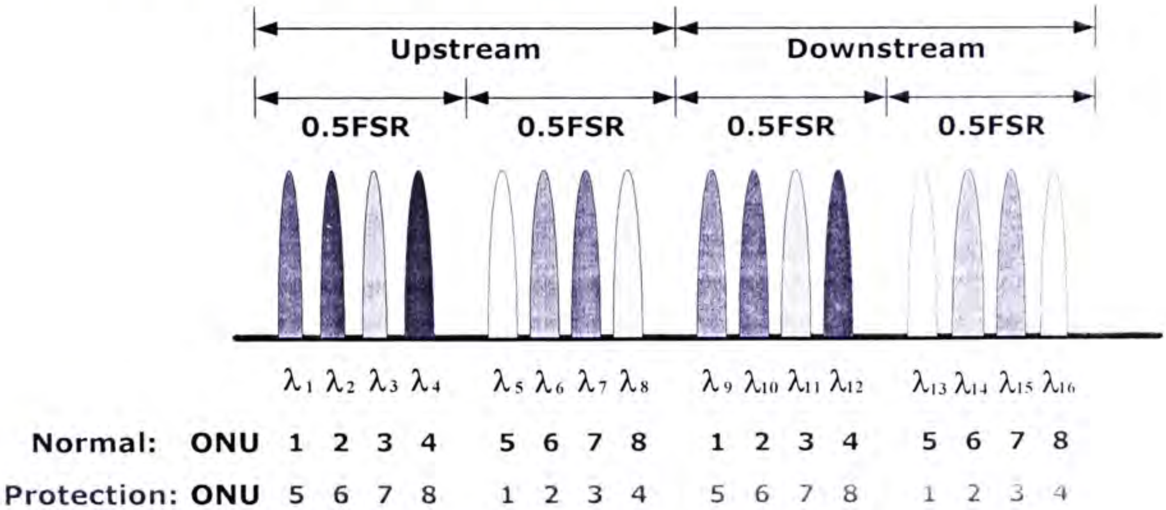

Fig. 4.6 Proposed wavelength assignment plan

4.3.2 Protection operation principles

Under normal operation, the switch is connected to the working fiber I. Both the downstream wavelength λ_i ($i = 1, 2, \ldots, N$) and upstream carrier λ_{i+N} are transmitted via working fiber I to ONU_i ($i = 1, 2, \ldots, N$). At each ONU, downstream wavelength λ_i was received by a photodetector (PD), while the optical carrier λ_{i+N} is modulated by upstream signal and sent back to the CO via working fiber II. In this case, only the working fibers are used, and there is no traffic running on the protection fibers.

In case of any cut in the working feeder fiber, the CO will detect the power loss of upstream signals. So, the data control circuit will change the status of the downstream signals. The downstream signal destined for ONU_i (i = 1, ..., N/2) is changed to another wavelength $\lambda_{i+N/2}$, while the downstream signal destined for ONU_j (j = N/2+1, ..., N) is changed to wavelength $\lambda_{j-N/2}$. At the same time, the decision circuit will trigger the optical switch to connect to the protection fiber I. Thus, both the downstream wavelength λ_i (i = 1, 2, ..., N) and upstream carriers λ_{i+N} are transmitted via the protection fiber I to the RN. With the wrap-around spectral periodicity property of the AWG, the downstream wavelength λ_i (i = 1, ..., N/2) and the upstream carrier λ_{i+N} are routed and sent to $ONU_{i+N/2}$, while the downstream wavelength λ_j (j = N/2+1, ..., N) and the upstream carrier λ_{j+N} are routed and sent to $ONU_{j-N/2}$. At the ONU, the dedicated downstream signals are received, while the upstream carriers are modulated and sent back to CO via the protection fiber II. As the colorless ONU in such carrier distributed WDM-PONs can handle any wavelength, there is no protection equipment needed in any ONU.

4.3.3 Experimental results

We have experimentally investigated the transmission performance and the protection switching of our proposed WDM-PON access network architecture. ONU 1 with working downstream and upstream wavelengths of 1546.52 nm and1581.36 nm, respectively; and protection downstream and upstream wavelengths of 1549.72 nm and 1584.73 nm, respectively, was demonstrated. The data rate for both the upstream and the downstream channels was 2.5 Gb/s. The standard single mode fiber (SMF) link between the CO and the RN was 20-km long, while that between the RN and each ONU was 8-km long. Two 16×16 AWG with 100 GHz channel spacing and an FSR of 12.8 nm were used in the RN. At the CO side, EDFAs were inserted in front of the AWG in order to compensate for the insertion loss. We have measured the bit-error-rate (BER) performance using 2.5 Gb/s 2^{23}-1 PRBS data for both the upstream and the downstream traffic under normal and protection modes, respectively. An avalanche photo diode (APD) receiver was used in our experiment. From the results depicted in Fig. 4.7, nearly no power penalty was observed for both normal and protection operations. We have also measured the switching time in case of the simulated fiber cut. The fiber link between the CO and the RN was intentionally disconnected to simulate the fiber cut scenario, with the result shown in the inset of Fig. 4.7. The switching time was measured to be about 5 ms.

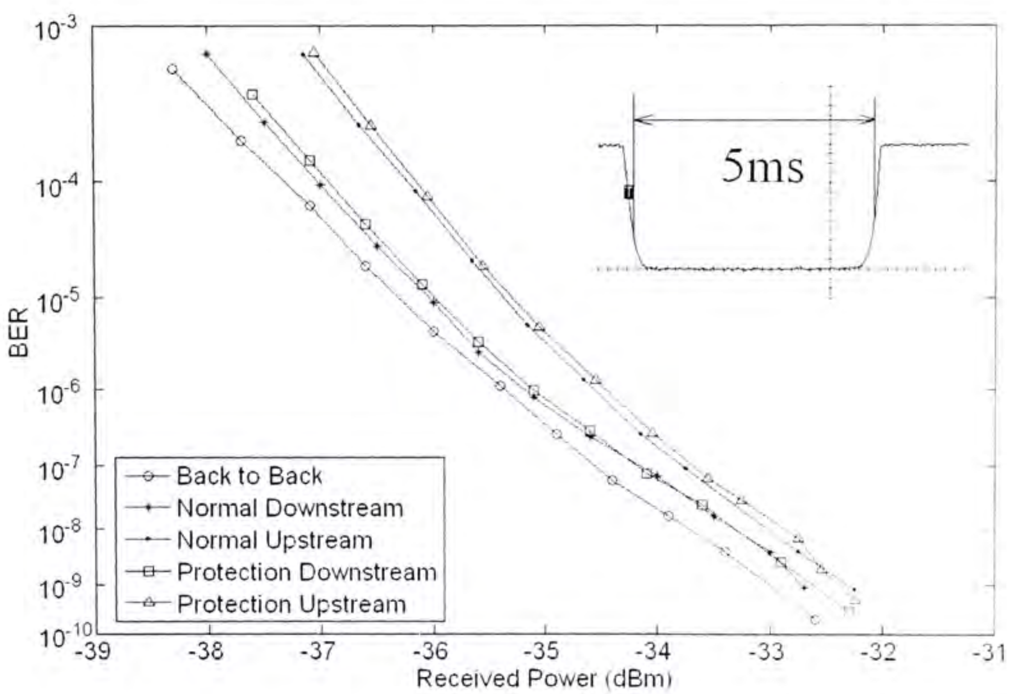

Fig. 4.7 BER characteristics under normal and protection states

Inset shows the switching time during traffic restoration

4.4 Summary

In this chapter, we have proposed a simple protection architecture for optical carrier distributed WDN-PONs, so as to integrate and extend the capability to protect against link failure between the remote node and the optical line terminal. By adopting appropriate wavelength assignments and incorporating optical switches at the OLT, fast protection and traffic restoration against feeder fiber failure can be achieved successfully. The protection switching is performed at the CO, and the ONU is kept simple and colorless. The bi-directional transmission of the 2.5 Gb/s signal over the WDM-PON have been experimentally demonstrated and characterized. In the proposed protection scheme, only one set of transceivers are needed at the CO, and all monitoring and protection equipment is consolidated at the CO. However, data switching between downstream signals is necessary when any feeder fiber failure occurs.

Chapter 5

Summary and Future Work

5.1 Summary of the Thesis

The objective of this thesis is to investigate the design of simple high-speed wavelength division multiplexing passive optical network access architectures for colorless ONU operation with protection schemes to enhance access network reliability and simplify fault management.

In chapter 1, the evolution of passive optical network was reviewed. In particular, the introduction and challenge of WDM-PON were presented.

In chapter 2, several previous WDM-PON architectures for colorless ONUs were outlined. We reviewed three different approaches to achieve colorless ONU operation: (1) Spectrum Slicing BLS employed at the ONU; (2) Centralized broadband light source for upstream optical carrier supply; (3) Reuse or remodulation of the downstream carrier at the ONU.

In Chapter 3, a simple high-speed WDM-PON access architecture for colorless ONUs was proposed and demonstrated using a centralized supercontinuum broadband light source, generated in a high-nonlinearity PCF, for upstream optical carrier supply. By spectrum-slicing centralized broadband light Sources based on supercontinuum generation, all ONUs were wavelength independent ("colorless"), and the elimination of the light source at the ONU simplifies provisioning at the ONU site. In the later part of this chapter, a broadcast scheme over WDM-PON by spectrum-slicing a broadband light source based on supercontinuum generation was proposed and investigated. With this configuration, each ONU can receive its own dedicated optical channel carrying the baseband digital channel with the broadcasted signal. Both upstream carrier supply and broadcast delivery had been demonstrated in a 10Gb/s transmission over 40km distance. These two examples illustrated the potentially useful applications of SCG in WDM optical access networks.

In Chapter 4, another issue of access network protection in case of fiber cut was discussed. A protection architecture based on the centralized broadband light source WDM-PON was proposed, so as to integrate and extend the capability to protect against link failure between the RN and the OLT. Because the ONU is colorless, it can handle any wavelength, not only a dedicated one. By adopting appropriate wavelength assignments and incorporating optical switches at the OLT, the protection function can be readily achieved. Experimental investigation was discussed at the end this chapter.

5.2 Future Work

In the chapter 3, we presented two network architectures for WDM-PON using PCF-based supercontinuum generation as the broadband light source at the central office, which was used to enable the downstream broadcast and upstream transmission in two proposed schemes, respectively. In the future, we may integrate these two into one complete solution using higher power EDFA to generate wider band SC light source.

We may also explore the survivable optical access network architecture with more functions. In particular, the reconfigurable architecture with monitoring / protection capability can be investigated. Multiple-access WDM-PON that all network users can exchange data in spite of broadcast and unicast services from OLT can be further investigated. Novel multicast schemes with reconfigurable architecture can also be studied.

Current TDM-PON architectures are economically feasible, but bandwidth-limited. WDM will be needed in next-generation access networks in order to offer higher bandwidths and have more flexible, dynamically reconfigurable networks. Thus, it is also important to provide a smooth migration and upgrade path from the current

TDM-PON to future WDM-PON architectures. We expect an ideal solution to extend the capacity of optical access networks without drastically changing the fiber infrastructure. This issue would be a subject of future interest.

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