# 國立交通大學

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## 碩 士 論 文

星形環狀被動式光纖網路之錯誤偵測與自動復原機制

Fault Identification and Self-Healing Function in the
Star-Ring Passive Optical Networks

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中 華 民 國 九 十 六 年 七 月

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## 摘　　要

在這篇論文中，我們展示並分析一些關於光纖光柵感測網路及擁有全保護機制之星形環狀被動式光纖網路的能力。

在第一個部份，我們討論不同架構下的點對多點技術之光纖光柵感測網路系統。當被動式光纖網路有任何的光纖損傷發生時，這些感測系統會運用光纖光柵和光纖雷射結構去偵測出此連線錯誤的狀況。我們也提出一個簡單的方式可以偵測出網路中的連線錯誤。

在第二個部分，我們提出具有光纖光柵感測系統之星形環狀被動式光纖網路。這個網路架構提供了錯誤偵測與自動復原機制，可以迅速的恢復訊號流量。結合了這些功能，可提昇光纖網路中訊號傳輸的品質還有可靠度，我們對於這個架構的可行性更做了進一步的評估與確認。上述的這些研究，將有助於被動式光纖網路的發展。

Fault Identification and Self-Healing Function in the Star-Ring Passive Optical Networks

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ABSTRACT

In the thesis, we demonstrate and analyze the capability of the fiber Bragg grating sensor networks and star-ring passive optical networks with full protection mechanism.

The first part presents and discusses the different architecture of fiber Bragg grating sensor systems for point to multipoint topology. This sensor system applies the FBGs and fiber laser scheme to detect the link fault conditions when any fiber cut occurs in the passive optical networks. We also propose one kind of easy way to detect the link faults in the networks.

In the second part, we proposed the star-ring passive optical networks with FBG sensor system. This network architecture implements the fault identification and self-healing function to restore the traffic promptly. By incorporating these functions, the optical network will improve the quality and reliability of data communication. We do the further evaluation and verify the practicability of this architecture. These investigations will be useful in the development of the passive optical networks.

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# List of Acronyms

| | |
|---|---|
| **A/D** | Analog to digital converter |
| **ADSL** | Asymmetric digital subscribe line |
| **APC** | Angled physical contact |
| **ASE** | Amplified spontaneous emission |
| **ATT** | Attenuator |
| **BR** | Back-reflection |
| **CM** | Continuous-mode |
| **CO** | Central office |
| **CS** | Calibration constant |
| **EMI** | Electro-magnetic interference |
| **FBG** | Fiber Bragg grating |
| **FTTH** | Fiber to the home |
| **GEPON** | Gigabit Ethernet Passive Optical Network |
| **GPIO** | General purpose I/O |
| **GPON** | Gigabit Capable Passive Optical Network |
| **MCU** | Microcontroller unit |
| **OA** | Optical amplifier |
| **OLT** | Optical line terminal |
| **ONU** | Optical network unit |
| **OSA** | Optical spectrum analyzer |
| **OTDR** | Optical time domain reflectometer |
| **P2MP** | Point-to-multipoint |
| **P2P** | Point-to-point |
| **PD** | Photo detector |

| | |
|---|---|
| **PON** | Passive optical network |
| **SC** | Star coupler |
| **SMSR** | Side mode suppression ratio |
| **SNR** | Signal-to-noise ratio |
| **SMF** | Single mode fiber |
| **TDM** | Time division multiplexing |
| **TF** | Tunable filter |
| **WDM** | Wavelength division multiplexing |

# Chapter 1

# Introduction

## 1.1 Description of Passive Optical Network Technology

In the recent years, the growth of the ADSL (asymmetric digital subscribe line) services have continued to increase the access line speeds. However, the physical property of the metallic cables limits the transmission speed and distance. Optical access is expected to become the next-generation broadband service next to ADSL and passive optical network (PON) will play an essential role in this kind of system. Passive optical networks are base on point-to-multipoint (P2MP) technology. They are consisted of an optical line terminal (OLT) in the central office (CO) and the optical network unit (ONU) in the end of the fiber. There are only passive elements such as optical splitters and optical couplers used in the path between OLT and ONU. A PON minimizes fiber construction for cost saving and allows long-distances transmission than ADSL. Fiber to the home (FTTH) bases on passive optical network (PON) technology represents an attractive solution for providing high bandwidth and cost effective solution from the central office (CO) to residences or small office. Additionally, it is easy to upgrade to higher bit rate and video broadcasting. Those advantages let PON technology get more and more attention by the system providers as the last mile solution.

## 1.2 Why the Monitor System and Self-Healing Function

Passive Optical networks consist of a signal, shared optical fiber connecting to central office by the optical splitter. Each PON port can be divided by many subscribers base on how to construct the system. It enhances the penetration of fiber further form central office to the subscriber side. This kind of PON structure with higher data-rate services to the subscriber and enormous communication capability, any fiber link loss or fiber cut will lead to tremendous loss in business for system provider. Furthermore, the reliability is the same important issue as the cost effective for the system provider in the PON. An effective and flexible monitoring and self-healing configurations are highly necessarily when the fiber link faults occur. Moreover, the self-haling function will increase the reliability and perform the protection to avoid the disconnection form the central office.

A typical PON with the tree and branch architecture does not equip the monitoring capability. Against network failure such as the fiber cut in the network will loss the business. Network operators desire the monitor system to protect their infrastructure. The optical time domain reflectometer (OTDR) is a well-known instrument for monitoring the fiber line. OTDR analyze the backscattered power form point-to-point type of the fiber line to identify the status of the fiber link. However, the OTDR is not adequate for the PON architecture base on point-to-multipoint. The backscattered power from other branches will impact the OTDR. Though several methods base on multi-wavelength OTDR were proposed, the architectures need wavelength tunable pulse light source it will impose high-maintenance cost. Therefore, a number of monitoring concepts base on cost effective fiber Bragg grating (FBG) were proposed and demonstrated, such as the technology of the remote sensing of FBG using the optical amplifier (OA). FBGs play an important role in the monitor systems that have been widely applied to measure the strain, temperature, vibration, pressure sensor and optical sensor configurations. A large scale sensor system with 60 FBG elements has been demonstrated by using a combination of wavelength division multiplexing (WDM) and time division multiplexing (TDM) techniques [3]. The advantages of the FBG sensor system, such as a multiplexing capability, passive operation and electro-magnetic interference (EMI) immunity have been more and more attractive and proper for the passive optical networks. By combining with the monitor system, the networks can identify the link status and provide protection and self-healing functions by construct a ring architecture or redundant route to increase the reliability of the system. Therefore, the optical networks with monitor system and self-healing function become indispensably.

## 1.3 Organization of the Dissertation

This dissertation is consisted of five chapters as the following. In chapter 1, we make a brief introduction of the passive optical networks. The necessary and benefits of monitor system and self-healing in the PON architecture are also presented in this chapter. In chapter 2, we describe the principles of the various monitor systems in the current development. We base on the FBG sensor system and focus on the technology of how to identify and analyze the monitor signal reflected from FBGs in this chapter. Moreover, a new ideal that will be more cost effective and flexible way to implement is presented. We propose the real time monitor circuit combining with the microcontroller. Reflected signals from FBGs in the optical access system will be acquire and transfer form the circuit. The results of the link status will be showed on the monitor of computer. It is an easy and direct way to identify the link status in the monitor system.

In chapter 3, we apply the fiber Bragg grating sensor system in the PON architecture. We analyze the performances of the various FBG sensor systems. Moreover, by combining with the proposed monitor system showed in chapter 2, we propose the new star-ring passive optical network with self-healing and monitor function. In this chapter, we make deep analysis and discussions of the proposed architecture. Finally, we make conclusions and summary in the chapter 4.

# Chapter 2

## Fiber Bragg Grating Sensor System

Passive optical networks (PONs) are base on point-to-multipoint topology and without any active components between optical line terminal (OLT) and optical network units (ONUs). An OLT serves 16 or more ONUs that any kind of network failures due to component failures or link breakages will interrupt the broadband services to subscribers. However, if the fiber link failure occurs between central office (CO) and ONU, the affected ONU becomes unreachable from the OLT and will cause tremendous data and business loss for the system providers. Therefore, it is critical issue to build the fault management in the PON to enhance the network reliability. In order to build the fault management, the monitor infrastructure is needed to be constructed first to monitor and sensing link status in the PON. A FBG sensor system can sense any link faults and feedback the backward signals to the CO for the fault management system that can process actions on those conditions. The sensor system should be performed without affecting the services to the subscribers. In this chapter, we will introduce the various approaches to accomplish the FBG sensor system and analyze the performances of them. We will do some experiment to find out the best approach to integrate FBG sensor system into PON architecture. Moreover, we will propose the new approach to detect the monitoring signal from sensor system for PON technology and demonstrate the concepts and circuit for this monitor structure.

## 2.1 Simple Fiber Bragg Grating Sensor System

Fiber Bragg Grating (FBG) plays an important role in the sensor system due to it low losses, simplicity, flexibility and the same dimension as the optical fiber. Moreover, FBG sensors base on the wavelength division multiplexing technology are suitable for self-healing monitoring structure. Furthermore, in comparison with the traditional electrical sensors, the FBG sensors have no EM emission and are insusceptible to Electromagnetic Interference (EMI). A large number of FBGs can be integrated in many kinds of optical networks as the sensors and are suitable in particular for the branch structure such as passive optical networks (PON) to monitor the link status.

FBG works as a sensor by reflecting a very narrow bandwidth of light centered at the Bragg wavelength within the transmission spectrum. The Bragg grating and the guiding properties will determine the reflected wavelength. Moreover, the FBG sensor system with multiplexing capability is easy to apply in the various PON systems. However, it needs a broadband light source, tunable filter (TF) and detector to complete the sensor system. We use the optical amplifier as the broadband light source in this thesis. Besides, the detectors are wavelength-insensitive, we need to integrate the TF that can select the wavelength and scan the wavelength range of the FBGs. The result of reflecting signal from FBGs will determine if the transmitted route linked in the FBG sensor system. In the present division, we will demonstrate the principle and discuss the various structures of the FBG sensor systems.

Fig.2.1 shows the traditional PON architecture which any fiber fault can not be detected and alarmed. We implement the FBGs in the branches of PON and demonstrate the brief configurations of FBG sensor system in the Fig.2.2. By including this FBG sensor system in central office (CO), the system provider will be easier to maintain the quality and increase the reliability of this system. Fig.2.3~Fig.2.5 demonstrate the three concepts of the proposed FBG sensor system based on point to multi-point topology. Those FBG sensor systems consist of the optical amplifier as the broadband light source, the fiber Fabry-Perot tunable filter (TF), 2x2 optical coupler (C1), a piece of single mode fiber (SMF), various wavelengths of FBG and optical spectrum analyzer (OSA). The widely tunable range of the TF is approximate from 1534nm to 1574nm, low insertion loss (0.5dB), low polarization-dependent loss (0.1dB) and the average 3 dB bandwidth is 0.4nm. A lasing wavelength can be external controlled the voltage from 0V to 12V on TF. Therefore, we can construct the tunable laser source by combining the TF with optical amplifier. By using this kind of tunable laser source, the sensor system can dynamically sweep the whole wavelength of FBGs to interrogate FBG sensor in each branch. TF can select the central wavelength of FBG from EDWA into the system through C1. The FBG reflects the optical amplifier's residual amplified spontaneous emission (ASE) power that will be detected by the OSA from C1. The OSA constantly checks the reflected signal form the FBG and can monitor the conditions of the fiber-link. Those architectures are the basis concepts of the FBG sensor system and the multiplexing capability can be used in any kind of passive optical networks, such as GEPON (Gigabit Ethernet Passive Optical Network) and GPON (Gigabit Capable Passive Optical Network).

The scheme of the Fig.2.3 show the first concept of FBG sensor system that allows the in-service monitoring [1] [2]. In the scheme, we utilize the optical amplifier as the broadband light source and TF selects the same wavelength as the FBG. The selected light feed into the system through C1 and was reflected by the FBG with the same center wavelength of light in one of the branches. A reflected signal extracted by using C1 and showed in the OSA that can identify the status of fiber between CO to FBG in the system. If the fiber is cut between this segment, there will not any backward signal is detected by the OSA.

Fig.2.4 shows a different structure with Fig2.3. An optical amplifier is used as the broadband light-source. The difference between the pervious architecture is the fiber-laser-based concept is implemented into the system to enlarge the sensor power [3]. In this scheme, optical amplifier generates the monitoring light source feed into each branch by splitter. The light will be reflected from FBG with the same selected wavelength of TF. This backward light is gained by optical amplifier and feeds into the system through C1 cycle by cycle until the power amplified to the maximum value. The sensor system can be constructed and detected the monitor signal on the OSA.

We propose a new architecture in the Fig.2.5 [4]. The capability and structure of this kind of fiber-ring-laser based sensor system is similar to the Fig.2.4. Optical amplifier is also used as the broadband light-source in this system. By tuning with a tunable filter, we can interrogate a proper wavelength of light to fit the FBG in the branch. The selected light feeds into optical amplifier through C1 directly. The light was gained cycle by cycle through the same route until to the maximum power instantly at the beginning and then feed into the system. The FBG reflected the light and arrived to the OSA from C1. By identifying the reflected light, we can judge the status of the fiber link.

## 2.2 FBG Sensor Systems in PON Architecture

PON is base on the point to multipoint topology and the tree architecture is particular a basic structure usually used. We introduce the basic concepts of FBG sensor system in the previous division. This sensor system can integrate into the PON by using star coupler (SC) as the Fig.2.6 shown. For this kind of networks, the OLT and ONU inter-communicate through SC as the tradition PON using optical splitter. We place the optical amplifier in the FBG sensor system as the transmitted monitor signal and improve the quality of network. This sensor system can accommodate more subscribers for PON application. We also localize the individual FBG in each branch separated from NxN SC. Each ONU with unique central-wavelength of FBG connected to the OLT and FBG sensor system through a star coupler. In the following division, we will base on the previous FBG sensor system to setup the experiment and simulate the performance on the PON architecture. Furthermore, we will do some further test on those structures to analyze the capability and discuss the results.

### 2.2.1 Basic Experimental Setup

According to the concepts of FBG sensor systems in the previous division, we do further discussions on FBG sensor systems first and simplify the structures of FBG sensor systems as the Fig.2.7, Fig.2.9, Fig.2.11 shown to evaluate the performance of them. Fig.2.7 is the experimental setup based on Fig.2.3. Fig.2.9 shows the experimental setup using the concept of the Fig.2.4

and the Fig.2.11 is the continuation of the Fig.2.5. Those architectures consist of an optical amplifier as a broadband light, TF with approximate 40nm tunable range , 2x2 fiber coupler with coupling ratio 50:50, 1554.56nm FBG, ONU optical transceiver to simulate the real application in PON, optical spectrum analyzer (OSA) and 5dB or 9.8dB fix attenuator (ATT) to simulate the optical loss of star coupler. We need to place the optical termination on the unused port of the 2x2 coupler to reduce the back-reflection influence on the discontinuous point. In those experiments, we will analyze the phenomenon and difference on the spectrum on the OSA and find the proper one for the further architecture in the following division.

### 2.2.2 Result and Discussion

In the Fig.2.7, we alternate the voltage of TF to coincide with the same wavelength of FBG. When control voltage is equal to 4.09 volt, we will get the maximum reflected monitor power form 1554.56nm FBG. The reflected power is purely determined by the monitor power level from optical amplifier and the reflectivity of FBG. We don’t construct feedback loop in this architecture and the reflected light is measured form optical spectrum analyzer (OSA) as the Fig.2.8 shown. When the ATT is 9.8dB that is similar to the loss of the 8x8 star coupler, we can find the signal-to-noise ratio (SNR) of backward monitor signal form FBG is less then 3dB (△power). As we know, for the PON system, one optical line terminal (OLT) needs to serve a lot of subscribers. This monitor light power of optical amplifier is not sufficient to support many subscribers due to the loss from optical SC in PON. If we want to improve the

SNR in this system, we need to find out the optical amplifier with very high output power. This kind of amplifier is very expensive and not makes sense.

In order to increase the monitor power to improve the SNR, we construct the feedback loop in Fig.2.9. The lasing wavelength of this kind of fiber laser is determined by the FBG in conjunction with the TF with the same center wavelength. The reflected signal from FBG passes the 2x2 optical coupler(C1) and is amplified by the optical amplifier till maximum power. The spectrum in Fig.2.10 (a) showed the SNR of monitor power is about 39.22dB when we used 5dB attenuator. This power is much higher than Fig.2.8 (a). However, when we used the 9.8dB attenuator to simulate the 8x8 star coupler, the backward signal from FBG is exhaust on the path before it reach optical amplifier. The monitoring signal can be enlarged anymore as the Fig.2.10 (b) shown due to the gain is less than loss. Moreover, the experiment shown that the noise level is high in this structure due to the original power from optical amplifier is extracted from C1 even the wavelength of monitor source and FBG is not concordant. This will degrade the SNR for this sensor system. Due to those previous reasons, this FBG sensor system can work anymore when the splitting ratio of star coupler is large than 8x8. The OLT can serve less then eight customers. As we know, the splitting ratio of GEPON is 1x16 and GPON is even more. This is not suitable for the currently PON application.

Fig.2.11 architecture overcomes the shortage of Fig.2.7 and Fig.2.9. A feedback loop is constructed directly by the optical amplifier, TF and 2x2 coupler for this fiber-ring-laser structure. The monitor light source will be amplified cycle by cycle until the feedback reaching the saturated amplified spontaneous emission (ASE) power at beginning. Fig.2.12 (a) (b) shows the spectrum at the different voltage of the TF. The SNR is about 36.11dB and

27.04dB with 5dB and 9.8dB fix attenuator.

The experimental results showed the architecture in Fig.2.12 possessed the best SNR and can tolerate more splitting ratio of SC for PON application. Fig.2.13 showed the wavelength distribution on the "point A" in Fig.2.12 when we alternate the operating voltage of the TF. The tuning range of this FBG sensor system is approximate 40nm. In other words, this system supports at least 20 branches by using 2nm interval of FBG per branch. Furthermore, we will do further discussion and extension base on this architecture in the following division.

## 2.3 Fault Identification in the FBG Sensor System

Conventionally, single-wavelength light source from optical time-domain reflectometer (OTDR) was used to detect the fault condition in branched networks. However, this kind of scheme suffers from Rayleigh back-scattered light from different branches which could not be differentiated at the OTDR [5]. OTDR based on a multi-wavelength source [6] was also proposed but the wavelength tunable monitoring source is very high cost. This solution is only use for practical application. Recently we proposed a passive surveillance scheme [7] by using fiber Bragg gratings to slice and reflect the unused portion of the amplified spontaneous emission (ASE) of EDFA to detect fiber fault in branch. However, the relative weak ASE power limits the transmitted fiber distance and splitting ratio of splitter to limit the capacity of branch. The other approach to improve this weakness is feed the ASE back into the EDFA through a wavelength tunable filter as the wavelength-sweeping monitoring laser source [8]. But those fault detections are difficult to integrated into real PON system due to the system can not be interrupted. Any interrupt will reduce the quality of the network and cause the tremendous business loss. We will propose new architecture in the next divisions that can support the real time fault monitor in the PON system at working condition.

### 2.3.1 Back-Reflection Influence

In the FBG sensor systems showed in the previous division, the signal-to-noise ratio (SNR) will determinate the capability of the whole sensor systems, such as the maximum transmitted distance and maximum splitting rate of the star coupler in passive optical network. Most of the various PONs are required to transmit the distance up to 10km or more form central office to ONUs and the splitting rate of optical splitter can reach 1:16 in GEPON (Gigabit Ethernet Passive Optical Network) or more in GPON (Gigabit capable Passive Optical Network) application. Therefore, how to enlarge the SNR of the sensor system will determinate if this sensor system can work well in the real various PONs. In order to increase the SNR for our proposed sensor system, we need control the back-reflection from disconnected point carefully. Any back-reflected power will inject into the optical amplifier and be gained from the pumping laser into the optical amplifier through 2x2 fiber coupler. Therefore, we need terminate with an angled physical contact (APC) connector to suppress the unwanted reflection at the fiber end and improve the SNR. Unfortunately, we can’t avoid all back-reflection (BR) effect from construction of the network. The cause of the BR can come form any disconnected point, such as the dust between junction plane of fiber, angle shift of fiber core and the wear of the fiber. In order to realize the immunity of proposed sensor system, we setup the experiment by using different architectures that showed in Fig.2.14 and Fig.2.15. We add the 15dB back-reflection on the point A, B, C and D individual to simulate disconnected situation in the system and observe the influence of the BR on the OSA.

The experimental results are showed in the Fig.2.16 and Fig.2.17. Those show the influence of the back reflection form the cleaved or polished end of a fiber cause by difference of refractive indices of air and glass. Any discontinuous point will reflect the light that degraded the ability of the sensing system. For the Fig.2.14 structure, the undesired light form discontinuous point in the central office will be detected even without the monitor signal from branch. It is very difficult to identify the real monitor signal and undesired light. The signal-to-noise-ratio (SNR) will be degraded if we can not control the back-reflection well. Therefore, we need avoid this phenomenon and improve this architecture as Fig.2.15 shown. We separate the path of the sensing system and OSA that back reflection light of monitor light source form discontinuous point will be isolated and improve SNR. By using this architecture, the FBG sensor will be more stable and reliable.

### 2.3.2 Wavelength-Sweeping Architecture

Fig.2.18 showed the proposed fiber laser configuration for the fault identification by using FBG sensor system in the tree-structured of PON. This experimental setup composes of an optical amplifier as the broadband light source, a 2x2 coupler with splitting ratio of 50/50, a fiber Fabry-Perot tunable filter (TF) with a free spectral range of 40nm and a pass band of 0.7nm, an 8x8 star coupler (SC), a low cost photo detector (PD) to detect the reflected monitor signal, the GEPON optical transceiver and three different central wavelengths of FBGs. The central wavelengths of FBG1 to FBG3 are 1552.23nm, 1554.56nm, and 1556.36nm. Their power reflectivities are about 99％ and average 3-dB bandwidth were 0.2 nm.

This scheme utilizes the optical amplifier as the broadband light source which feed into the TF will select out the particular wavelength. This feedback loop will generate a saturated laser emission. In order to construct the fault identification, the fiber Fabry-Perot tunable filter (TF) need to provide wavelength selection in the ring laser cavity by changing the sweeping voltage controlled by the computer through user programmable general purpose I/O (GPIO). This sweeping voltage interrogates FBG in each branch and the selected FBG will reflect the light generating from optical amplifier. This backward light will be detected by the commercial and low cost PD and convert to current. This current can be acquired by current mirror circuit and we can get the voltage by connector the resistor to ground. After calibration and calculated process with real power read form power meter at first, we can get the calibration constant [9]. We can transfer the voltage to the real power value by using this calibration constant (CS) that memorized in the memory of microcontroller. Moreover, by using computer, we can control the power supply to set the operating voltage on TF. The monitor light from optical amplifier will be generated the different wavelength with different voltage on TF. We need to set the proper sweeping range of operating voltage of TF, interval and delay time for each adjusted step. The backward monitor signals from branches are detected by the circuit and processed and calibrated to the real power by the firmware as Fig.2.19 (a) shown. By changing the voltage step-by-step on TF, we can real-time interrogate the FBGs in branches cycle by cycle.

For this fault identification, we need place individual and sequential FBGs with same interval of central wavelength on each branch (central wavelength of FBG1, FBG2 and FBG3 are 1552.23nm, 1554.56nm, and 1556.36nm; the interval is approximate 2nm). It means this FBG sensor system needs to detect the same number of channels for normal operation. For example, there are three FBGs in our experimental setup. We need have the same number of peak (FBG1~FBG2) showed in the Fig.2.19 (a) for normal operation. The link status of each branch can be monitored by checking the reflected power of the corresponding channel. All reflected monitor power is detected by this proposed monitor system. If the power level is below the detection limit at a certain channel as the FBG2 channel in the Fig.2.19 (b) shown. This indicates there maybe have the fiber cut or too much loss at this corresponding channel

In the experimental results, the FBG sensor system will find out the link fault immediately if any fiber fault occurred on the path between CO and individual branches. The system maintainer can surveil the link status of the network directly from the monitor and can get signal from firmware.

### 2.3.3 Principle and Circuit Design

In the proposed architecture, we use the photo detector (PD) to detect the monitor signal that is backward from FBGs and the intensity of light is transformed into electrical signals. Fig.2.20 shows the detector circuit and the principle of the fault identification system. The XP2401 is made by Panasonic and is used as the current monitor IC to duplicate the monitor current (Imon) detected form photo detector. The output level produces a signal proportion to this current monitored (Imon) by external resistor (R1). For example, if we place the R1 equal to 1k ohm, the circuit will provide 1V/mA of voltage proportional to the Imon. The voltage converted into digital signal through an analog to digital converter (A/D) in the DS1859 IC and then placed on the 2-wire bus (I2C) for easy access by the host. DS1856 is one kind of microcontroller unit (MCU) made by Maxim. Moreover, in order to connect and process the signal by computer, we can use interface board to transfer the signal from I2C to RS-232 (Recommended Standard 232). Furthermore, we can do calibration to ensure that there is a one-to-one correspondence from input to output. We can read the real light power by using power meter and then calibrate the real monitor light power by using the calibrate constants. The use of calibration constants is detailed in the SFF-8472 standard. The received power will result in the same digital value after calculating in DS1856, regardless of the type or characteristic of PD.

### 2.3.4 Experimental Results and Discussion

It needs the expensive OSA to surveil the link status in the FBG sensor system. In this division, we demonstrate the cost-saving solution to detect the fault conditions in the PON by using FBG sensor technology. This fault identification system will be easy to implement and integrate in central office. By using MCU base circuit, we can process the signal as our demand and set various conditions to monitor system. This is a very flexible way for system provider to manage the entire system by firmware. However, there are many individual PONs is managed in CO. Each PON needs one FBG sensor system. In order to save the total cost of network construction, we proposed the architecture as Fig.2.21 shown for the feature work. In this architecture, system provider can share the same fault identification system for individual PONs by switching optical switch in the central office instead of placing FBG sensor system one by one. This is the cost saving and workable solution in the fault identification system.

In this chapter, we presented the various FBG sensor systems and found out the suitable architecture for the point to multipoint topology. We provided the architecture to integrate FBG sensor system with PON by using optical star coupler and this one is insensitive of back-reflection form discontinuous points. By possessing high SNR of this FBG sensor system can serve more than 16 subscribers for PON application. This sensor system will provide the real-time fault identification for the PON. System providers will be easier to maintain and realize the situation of network by monitoring the link status through this sensor system. Moreover, we proposed the low cost solution and easy way to process the backward monitor signal in the CO. In brief, the PON facilitate fault identification will strengthen system maintainers to hold the link status of PONs.

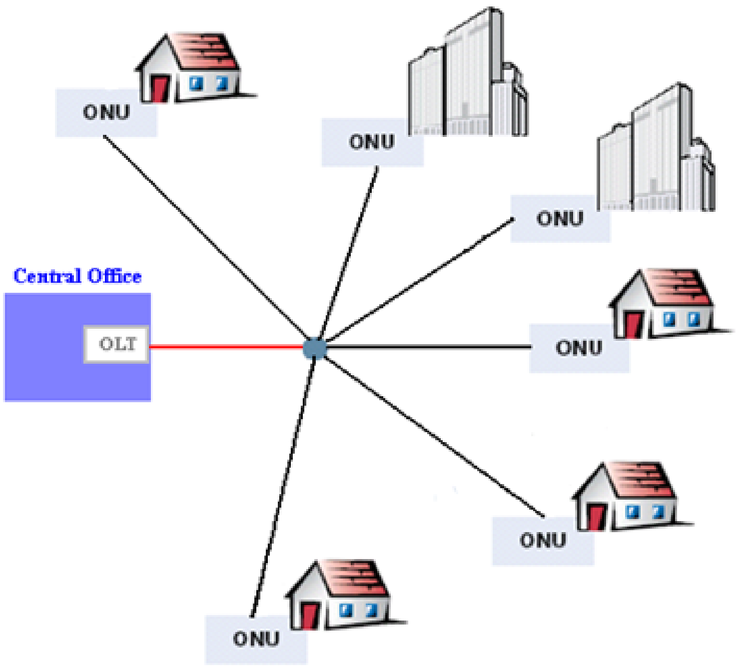



**Fig. 2.1** Traditional architecture of the passive optical networks.

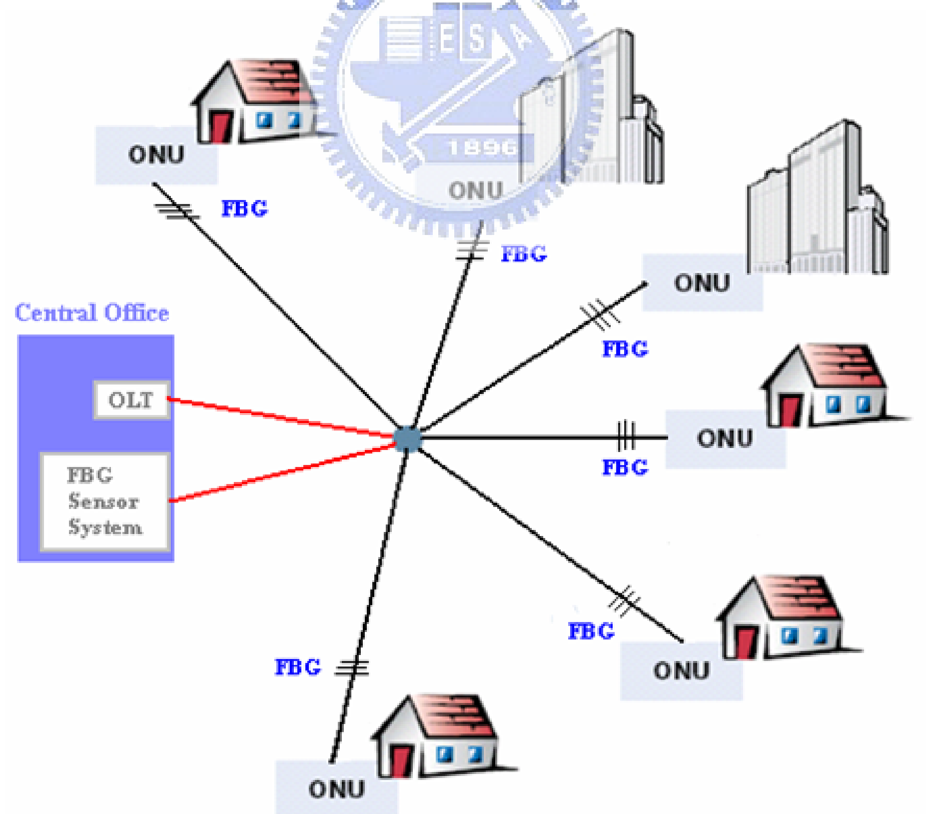



**Fig. 2.2** Brief concept of the fiber Bragg grating sensor system in the passive optical networks.

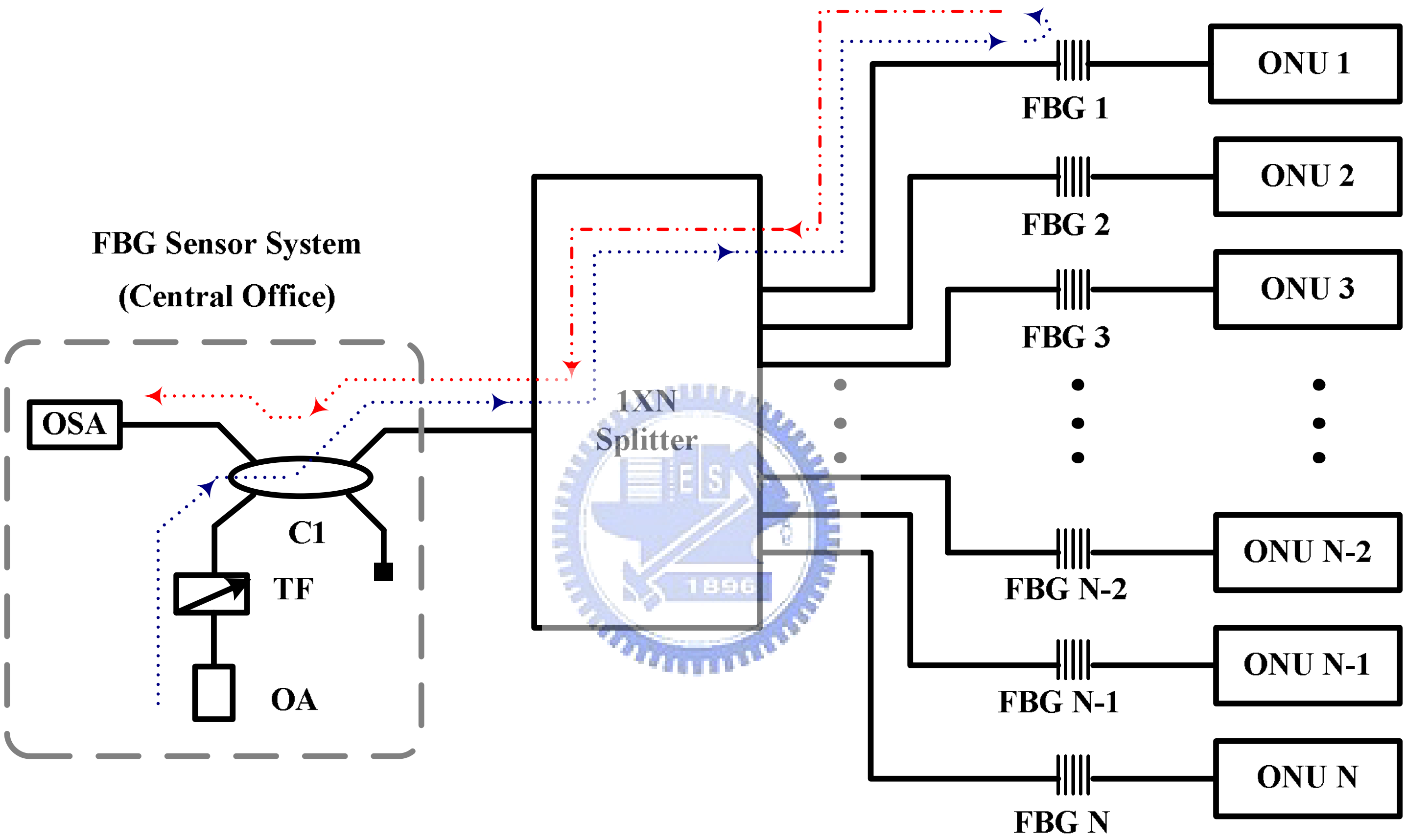



**Fig. 2.3** Concept-1 : The demonstrated FBG sensor system. ( OA: Optical Amplifier, TF: tunable band-pass filter, FBG: fiber Bragg grating, C1: 2x2 optical coupler, OSA: Optical Spectrum Analyzer ).

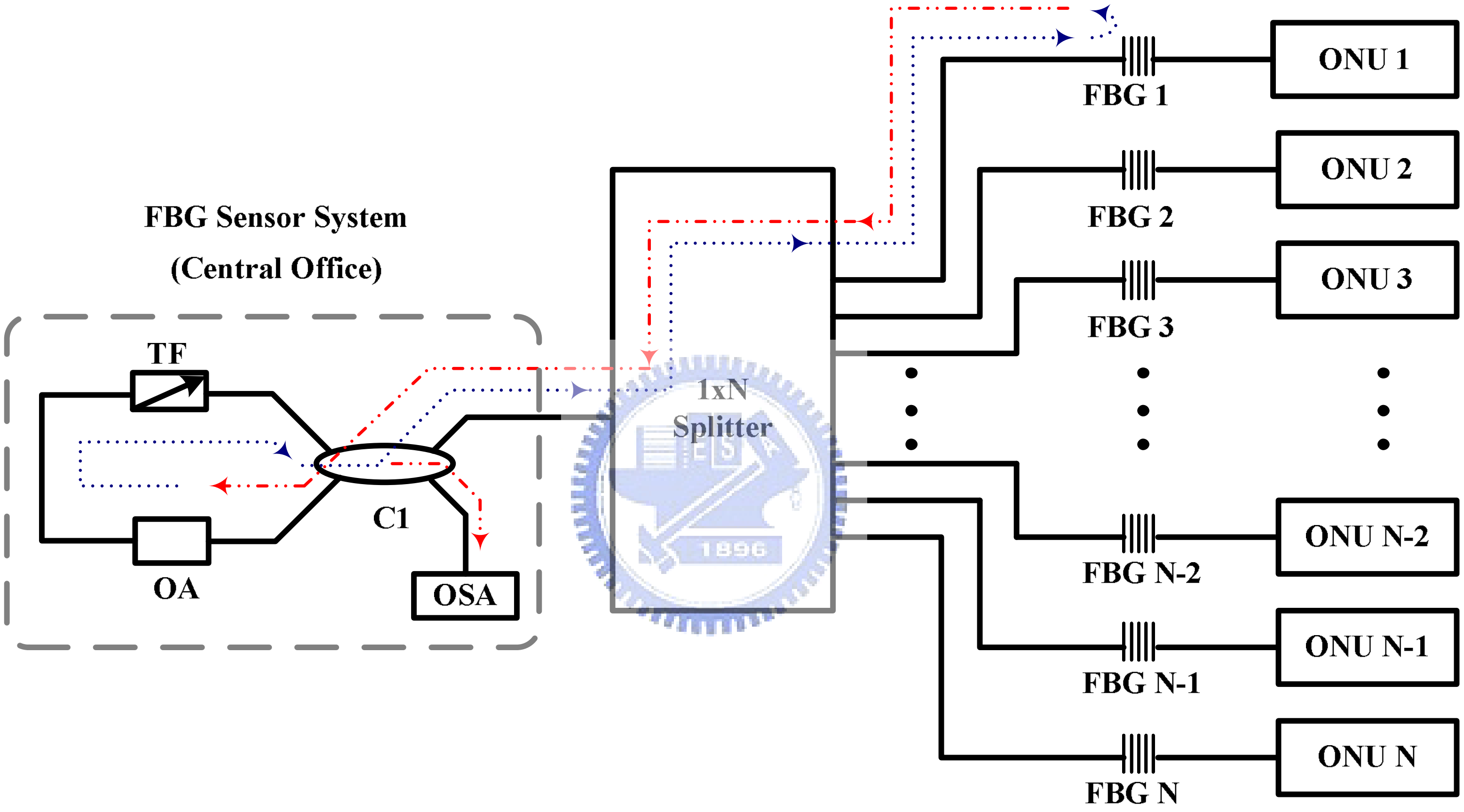



**Fig. 2.4** Concept-2 : The demonstrated FBG sensor system. ( OA: Optical Amplifier, TF: tunable band-pass filter, FBG: fiber Bragg grating, C1: 2x2 optical coupler, OSA: Optical Spectrum Analyzer ).

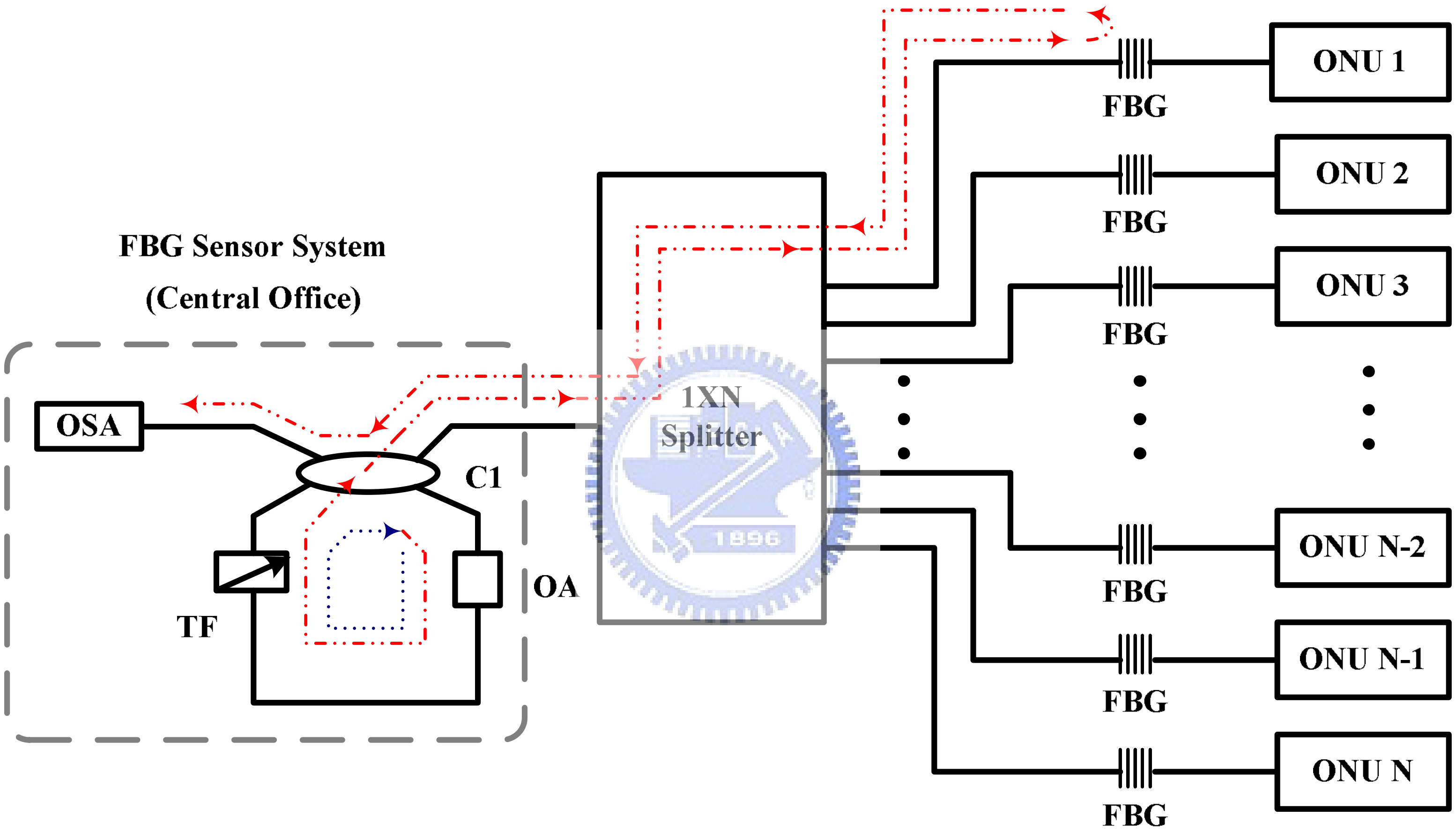



**Fig. 2.5** Concept-3 : The demonstrated FBG sensor system. ( OA: Optical Amplifier, TF: tunable band-pass filter, FBG: fiber Bragg grating, C1: 2x2 optical coupler, OSA: Optical Spectrum Analyzer ).

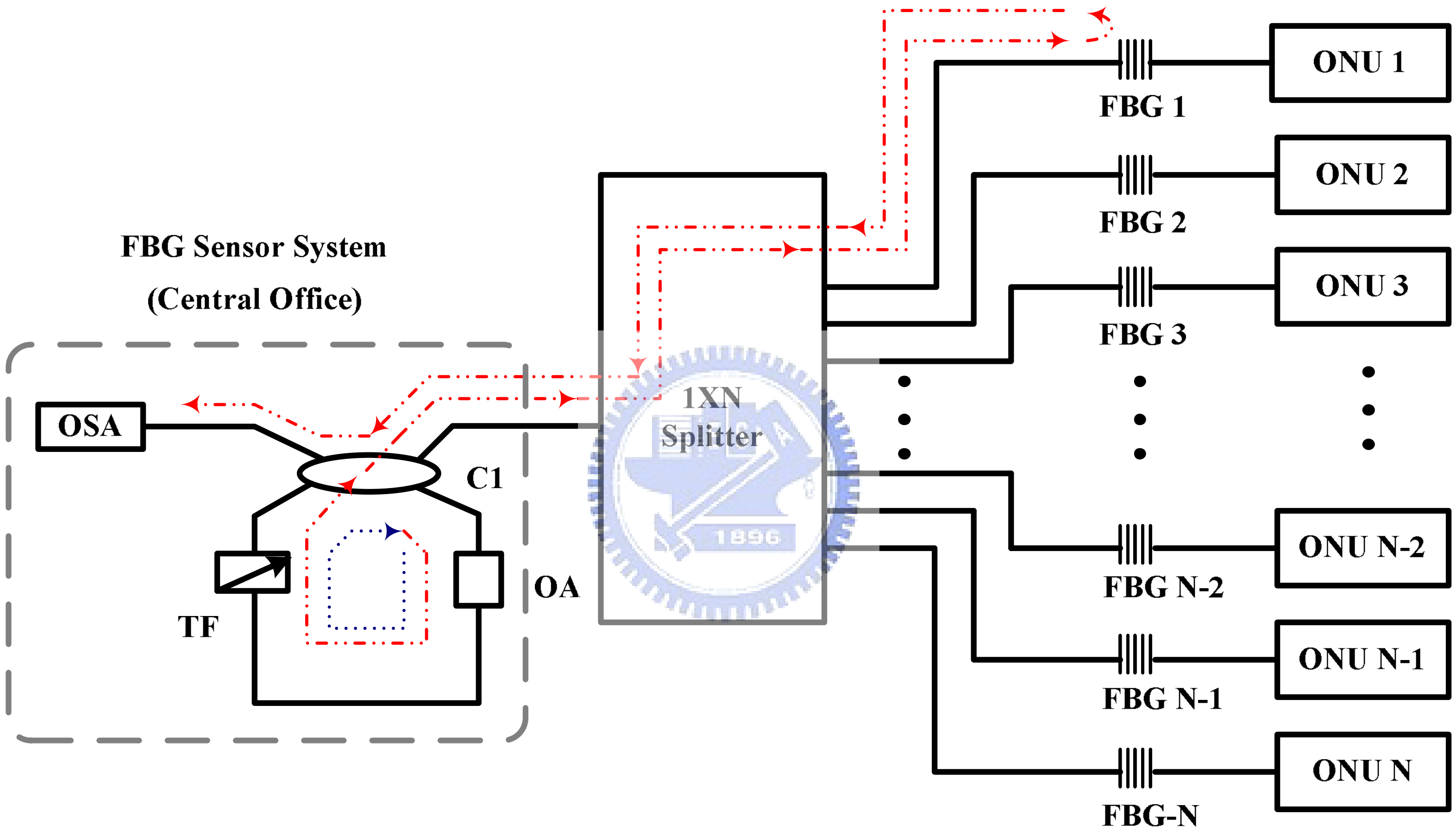



**Fig. 2.6** The PON architecture with FBG sensor system by using star coupler. ( OLT: Optical line terminal, SC: Optical star-coupler, FBG: fiber Bragg grating ).

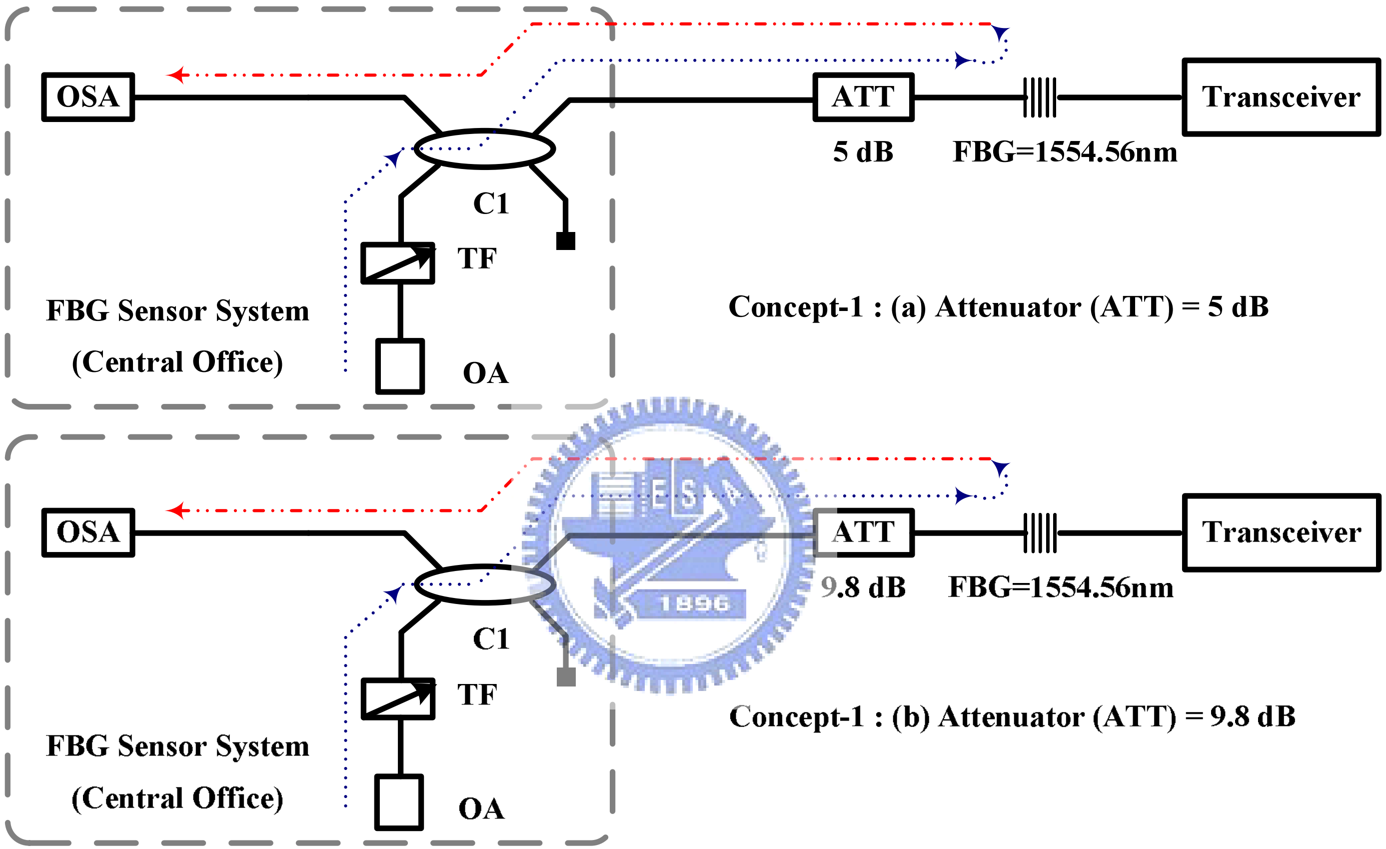
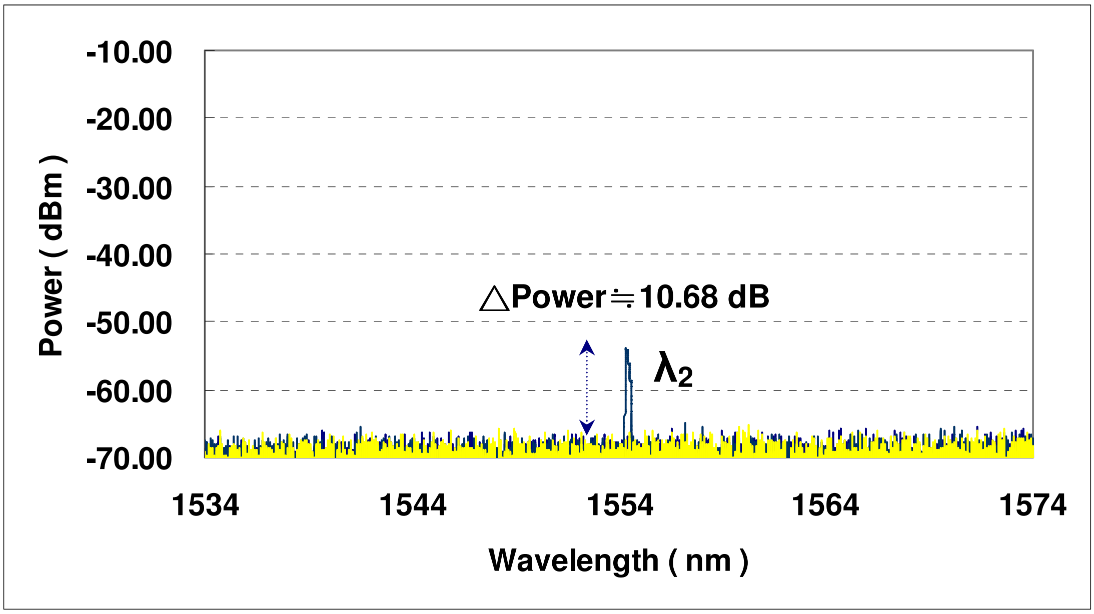
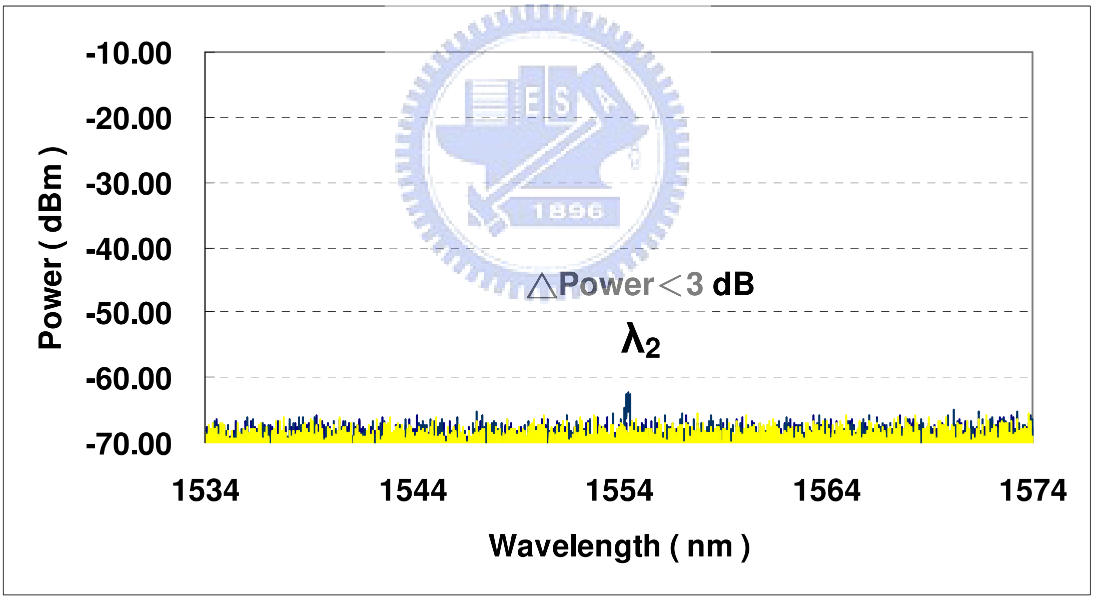



**Fig. 2.7** Experimental setup of concept-1 for FBG sensor system in PON . (a) Using 5dB attenuator between C1 and FBG. (b) Using 9.8dB attenuator between C1 and FBG. (OA: Optical Amplifier, TF: tunable band-pass filter, FBG: fiber Bragg grating=1554.56nm, C1: 2x2 optical coupler, ATT: 10dB Fix attenuator, OSA: Optical Spectrum Analyzer).




(a) Attenuator = 5 dB




(b) Attenuator = 9.8 dB

**Fig. 2.8** Experimental results of concept-1 in Fig.2.7 for FBG sensor system in PON. (a) Output spectrum in Fig.2.7(a). Peak-Power = -54.21dBm. (b) Output spectrum result in Fig.2.7(b). Peak-Power = -62.70 dBm. ( Operating voltage of TF :λ2 (≒1554.56nm) =4.09 V )

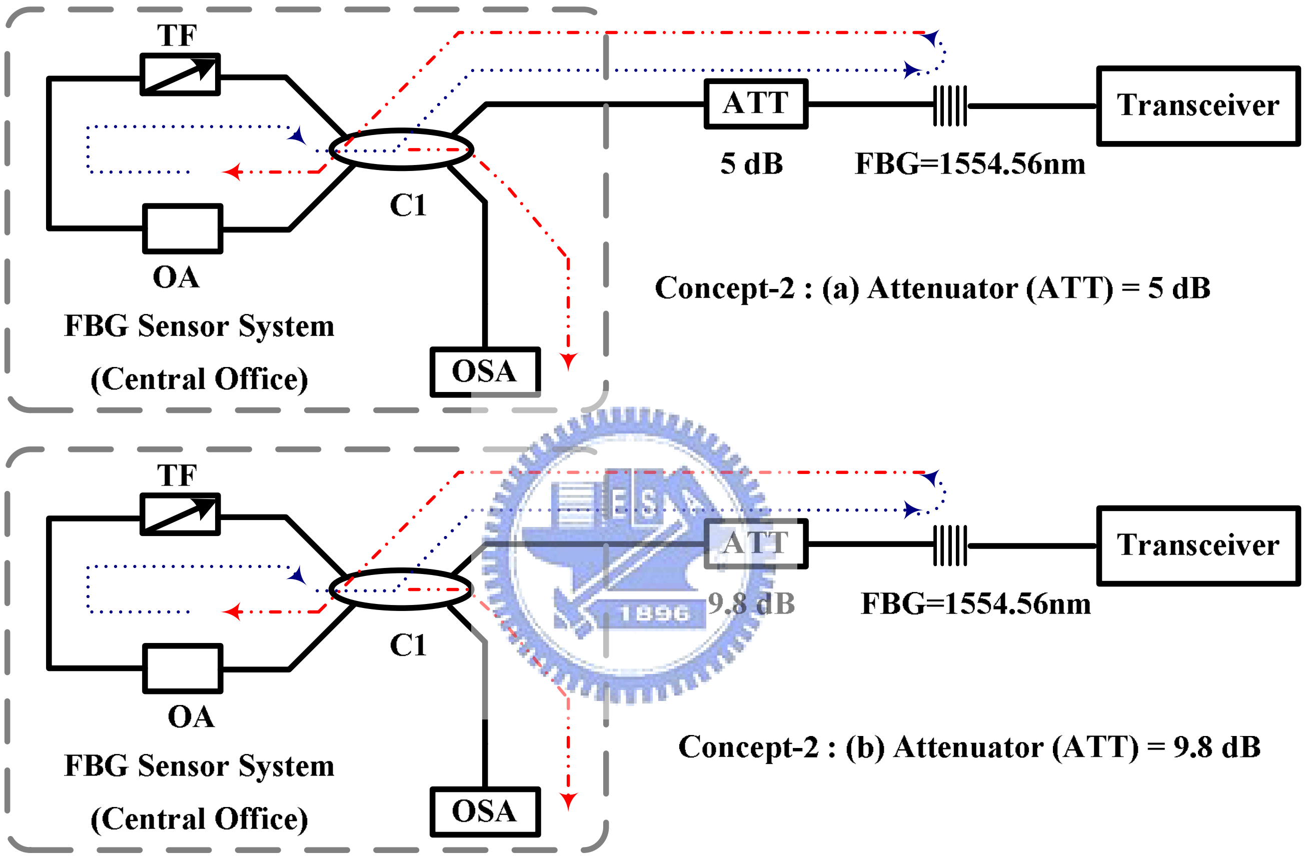
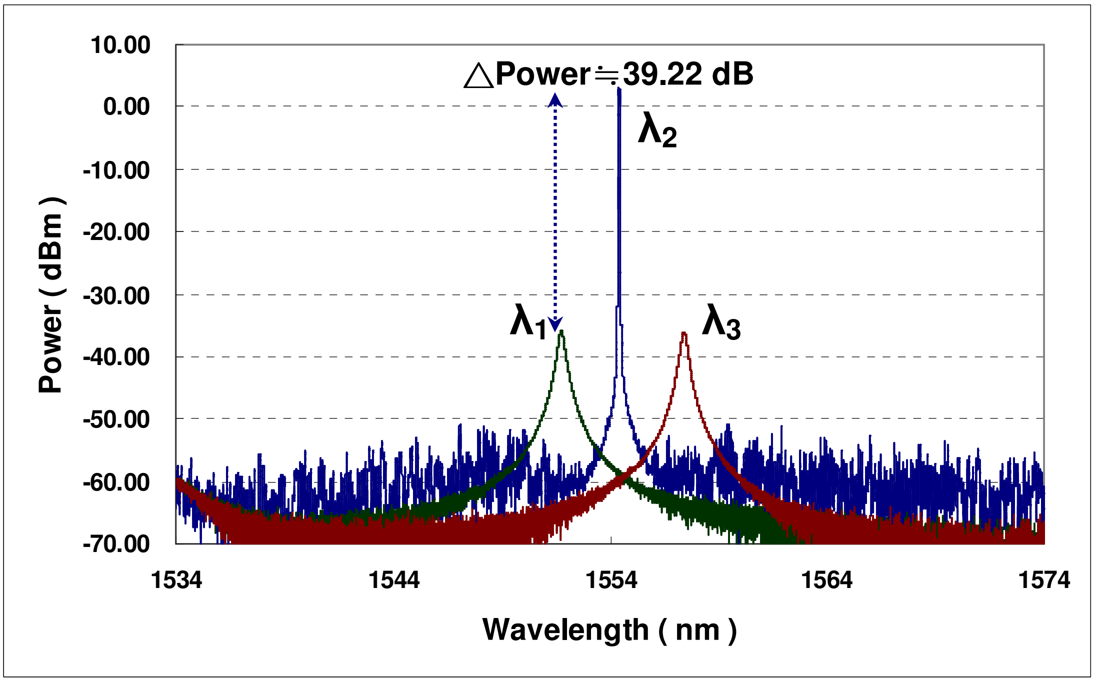
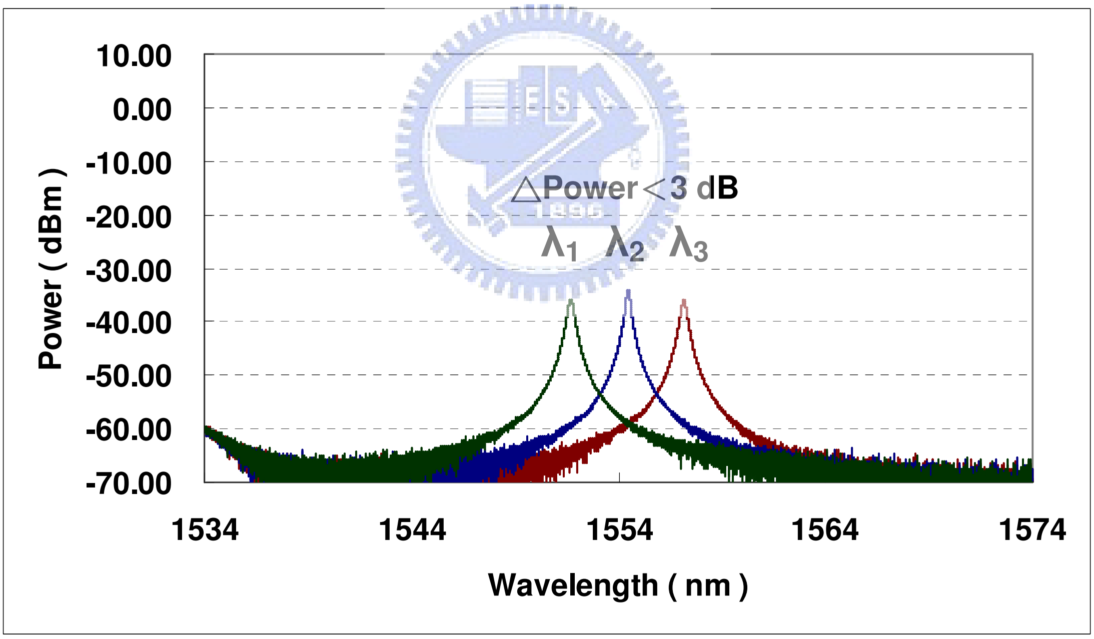



**Fig. 2.9** Experimental setup of concept-2 for FBG sensor system in PON . (a) Using 5dB attenuator between C1 and FBG. (b) Using 9.8dB attenuator between C1 and FBG. (OA: Optical Amplifier, TF: tunable band-pass filter, FBG: fiber Bragg grating=1554.56nm, C1: 2x2 optical coupler, ATT: 10dB Fix attenuator, OSA: Optical Spectrum Analyzer).




**(a) Attenuator = 5 dB**




**(b) Attenuator = 9.8 dB**

**Fig. 2.10** Experimental results of concept-1 in Fig.2.9 for FBG sensor system in PON. (a) Output spectrum in Fig.2.9(a). Peak-Power = +3.24 dBm. (b) Output spectrum result in Fig.2.9(b). Peak-Power = -35.38 dBm. ( Operating voltage of TF : λ1=3.36 V ; λ2 (≒1554.56nm) =4.36 V ; λ3=5.36 V )

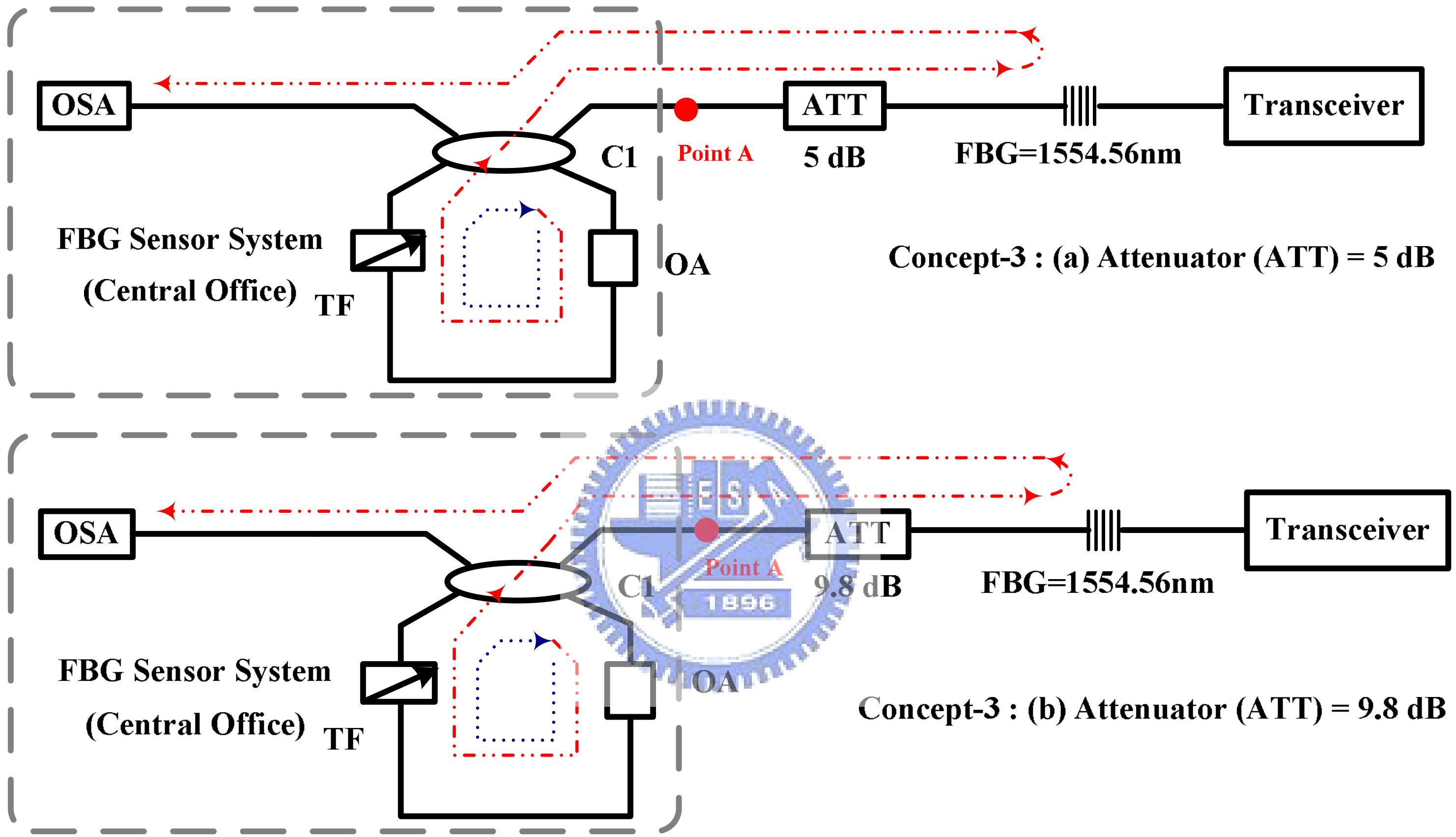
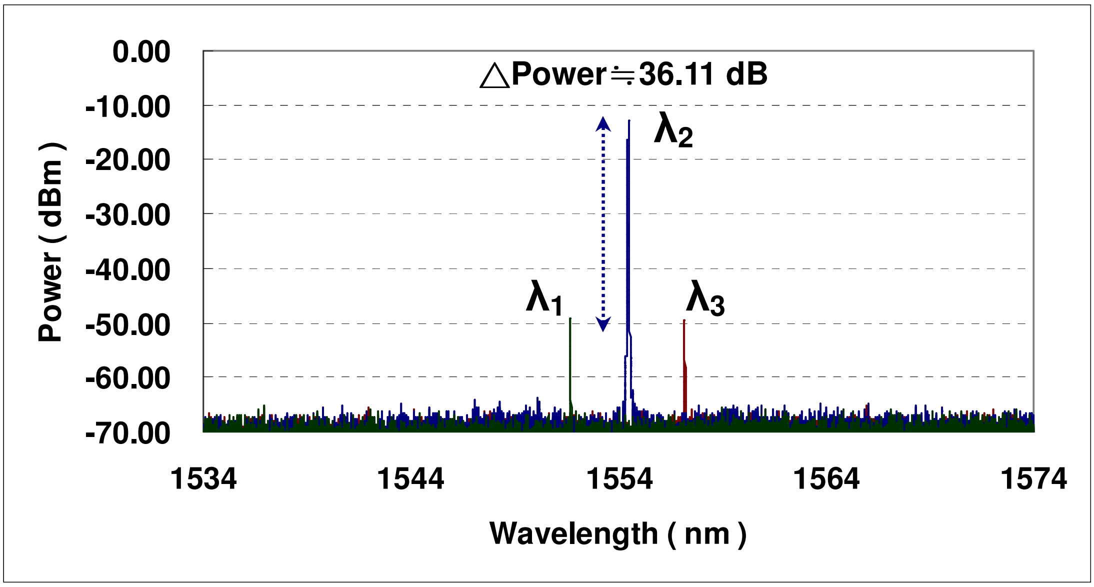
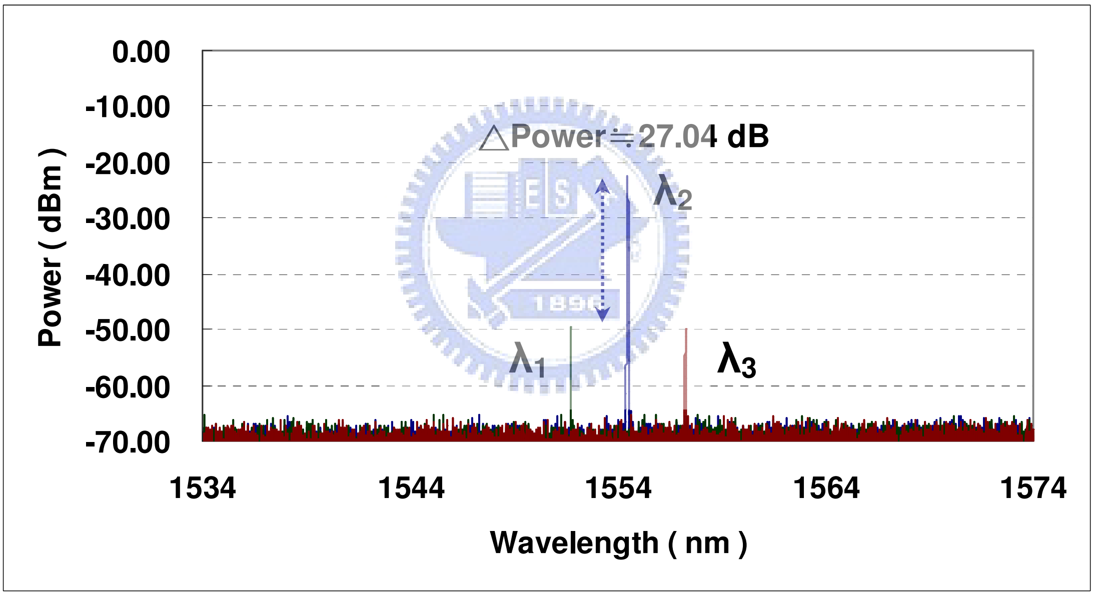



**Fig. 2.11** Experimental setup of concept-3 for FBG sensor system in PON . (a) Using 5dB attenuator between C1 and FBG. (b) Using 9.8dB attenuator between C1 and FBG. (OA: Optical Amplifier, TF: tunable band-pass filter, FBG: fiber Bragg grating=1554.56nm, C1: 2x2 optical coupler, ATT: 10dB Fix attenuator, OSA: Optical Spectrum Analyzer).




**(a) Attenuator = 5 dB**




**(b) Attenuator = 9.8 dB**

**Fig. 2.12** Experimental results of concept-1 in Fig.2.11 for FBG sensor system in PON. (a) Output spectrum in Fig.2.11(a). Peak-Power = -13.21dBm. (b) Output spectrum result in Fig.2.11(b). Peak-Power = -22.53 dBm. ( Operating voltage of TF : λ1=3.20 V ; λ2 (≒1554.56nm) =4.20 V ; λ3=5.20 V ).

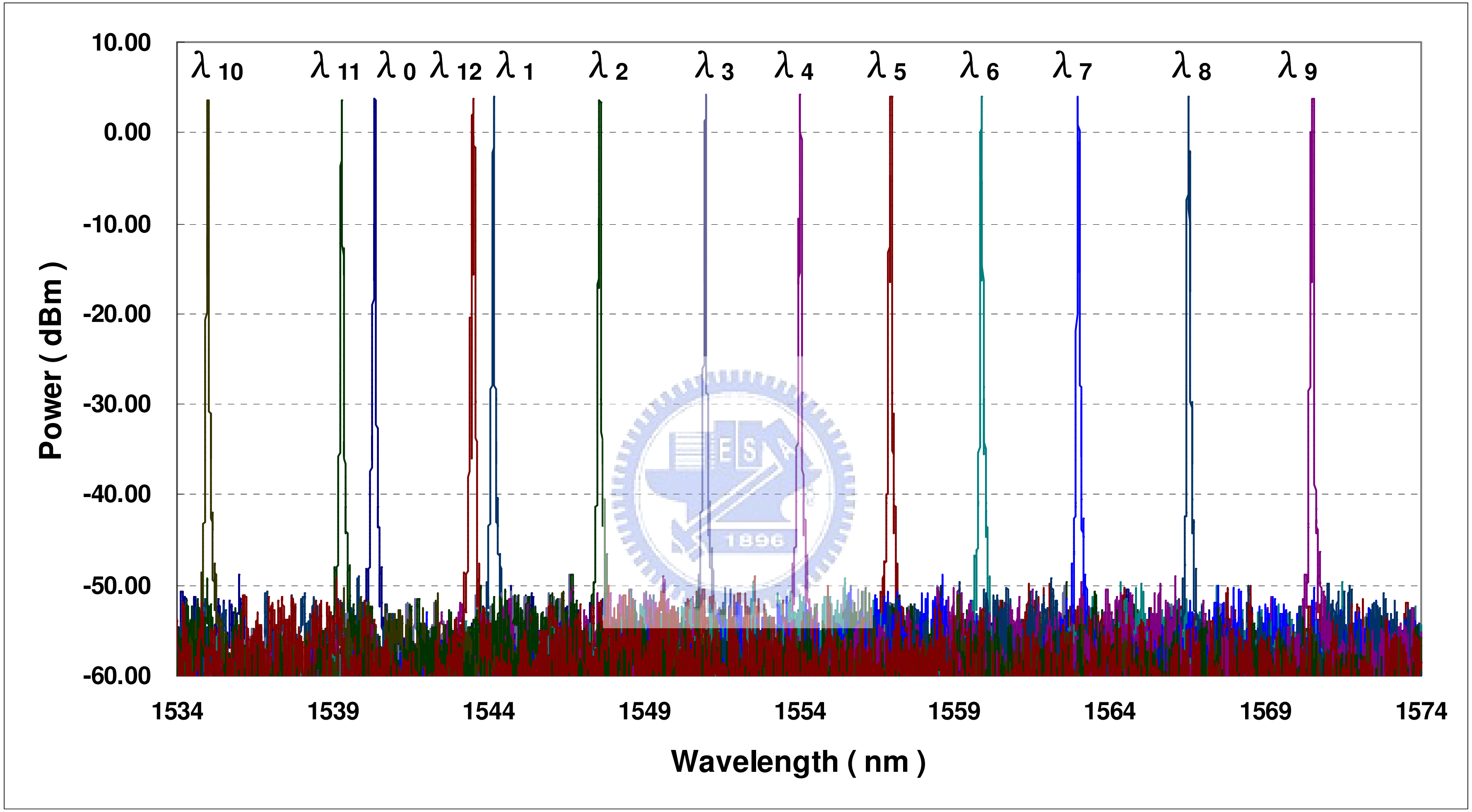



**Fig. 2.13** The output spectra of monitoring light source at point A in Fig.2.11. We alternate the operating voltage of TF form 0Volt to 12Volt. (λ0=0V ; λ1=1V ; λ2=2V ; λ3=3V ; λ4=4V ; λ5=5V ; λ6=6V ; λ7=7V ; λ8=8V ; λ9=9V ; λ10=10V ; λ11=11V ; λ12=12V).

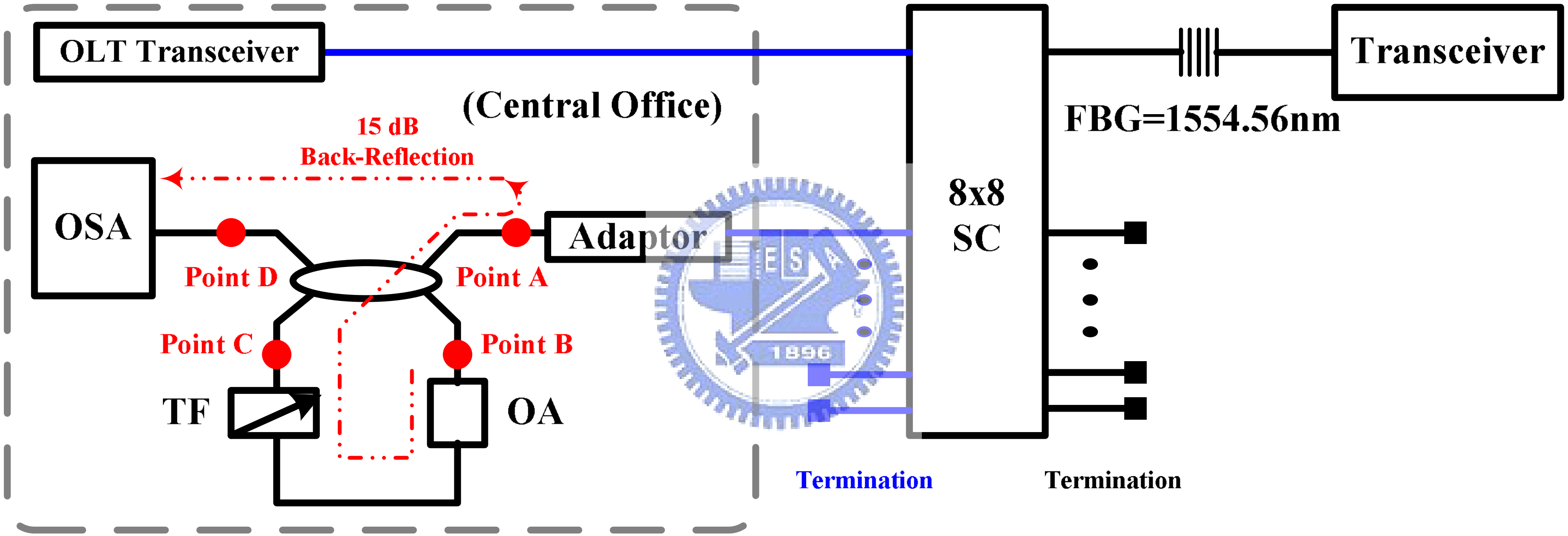



**Fig. 2.14** Experimental structure-1 to emulate the influence of back-reflection in the FBG sensor System. We add the 15dB back-reflection at point A/B/C/D alternately.

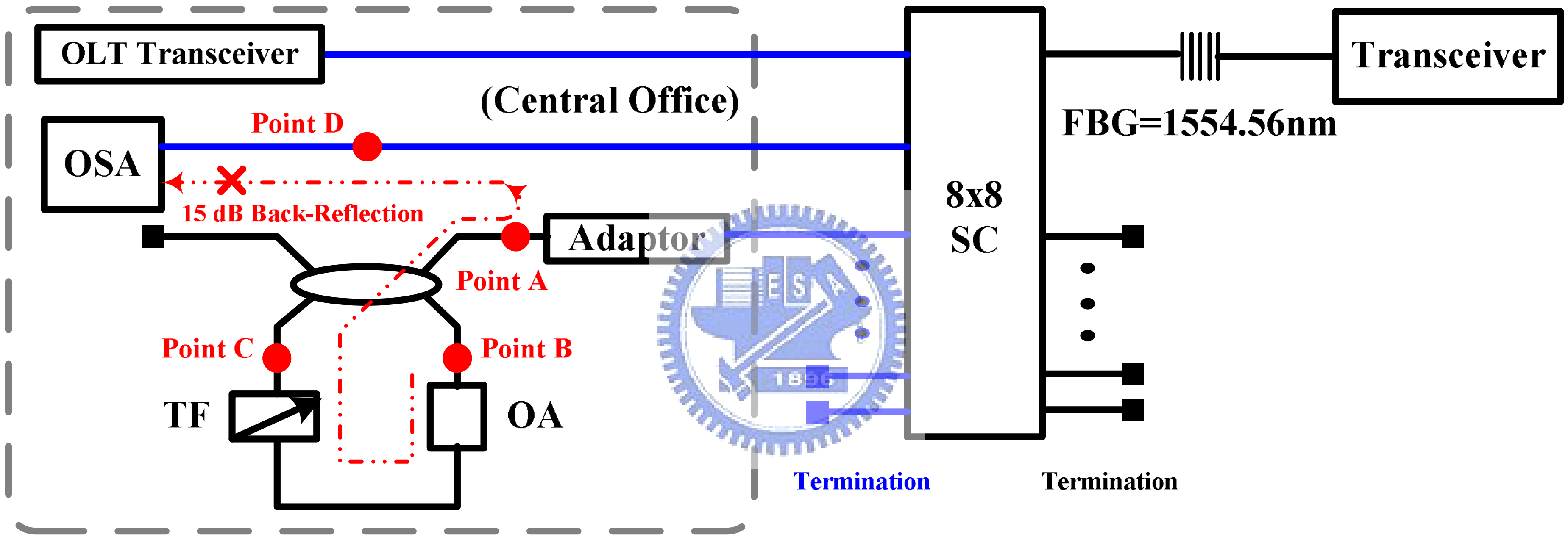
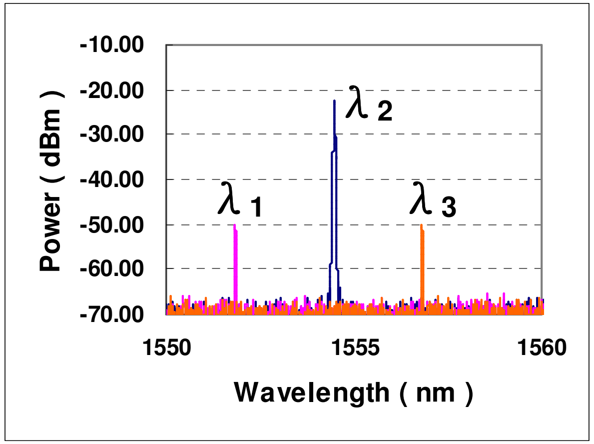
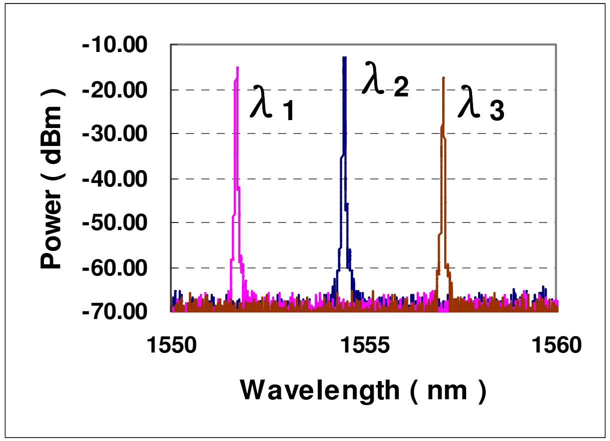


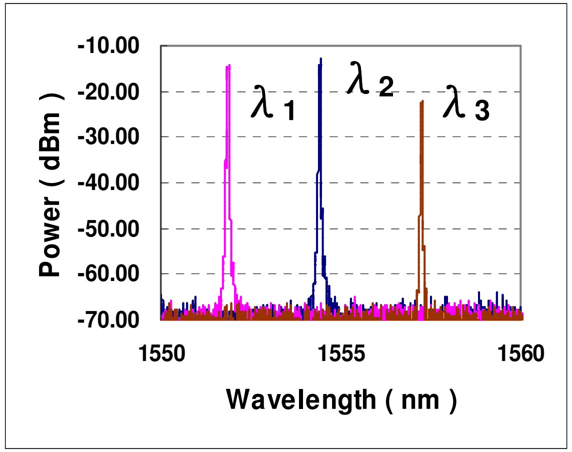

**Fig. 2.15** Experimental structure-2 to emulate the influence of back-reflection in the FBG sensor System. We add the 15dB back-reflection at point A/B/C/D alternately.



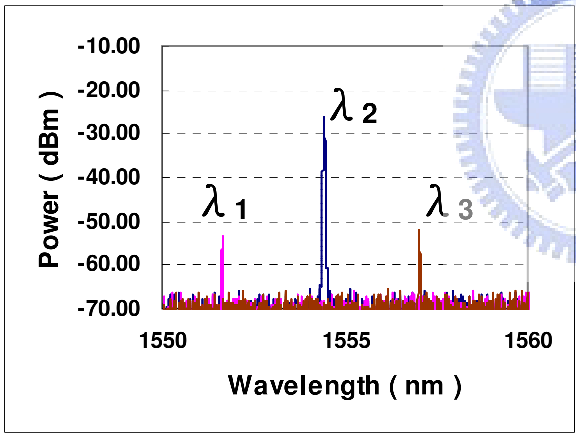

(a) Original condition (Without back-reflection)



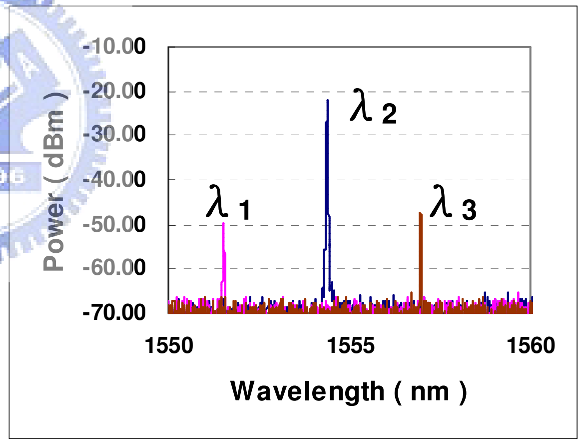

(b) Spectrum at point A




(c) Spectrum at point B

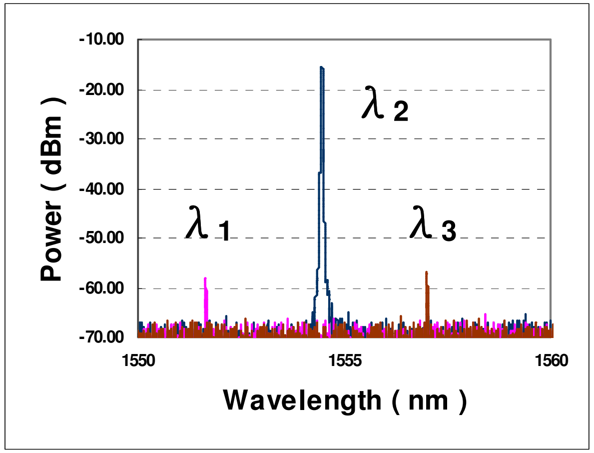



(d) Spectrum at point C

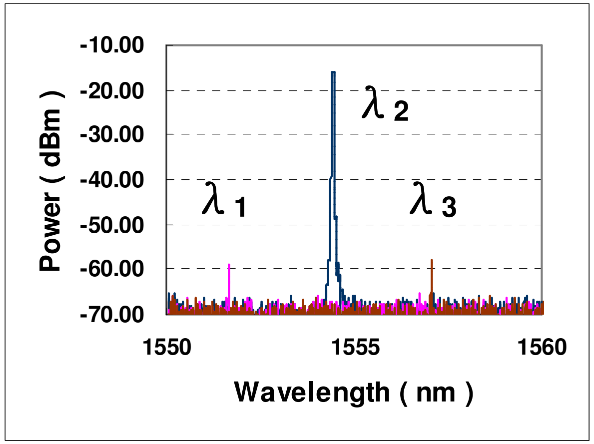



(e) Spectrum at point D

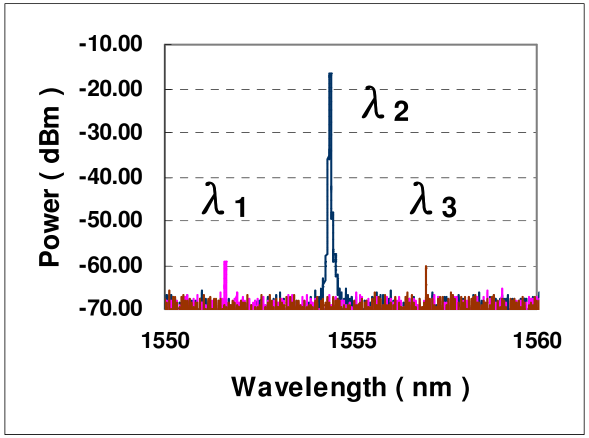
**Fig. 2.16** Output Spectra on OSA when we added the 15dB back-reflection on each point (A~D) alternately in the FBG sensor System for structure-1. (Operating Voltage of TF : λ0≒1.08V；λ1≒2.08V；λ2≒3.08V；λ1≒1554.51nm ).



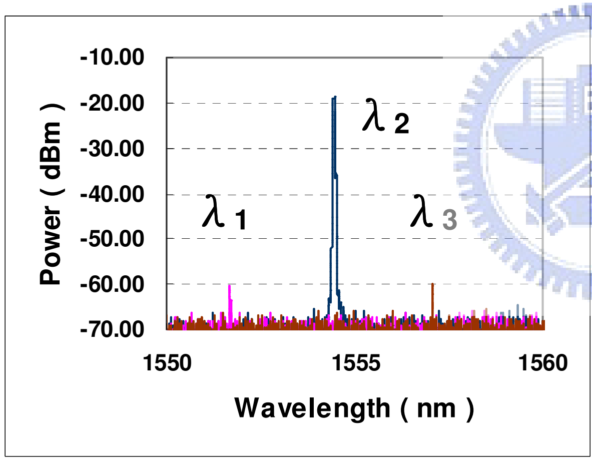

(a) Original condition (Without back-reflection)



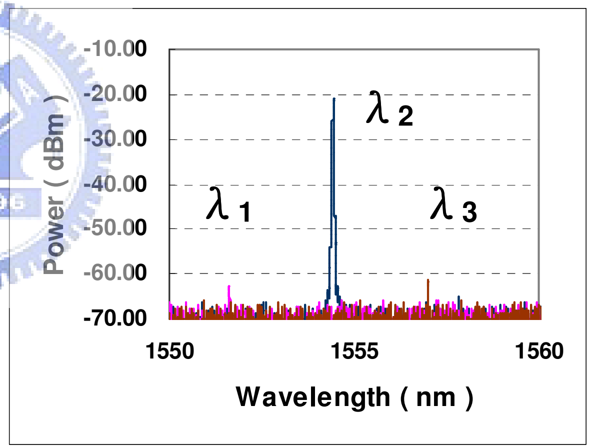

(b) Spectrum at point A




(c) Spectrum at point B




(d) Spectrum at point C




(e) Spectrum at point D

**Fig. 2.17** Output Spectra on OSA when we added the 15dB back-reflection on each point (A~D) alternately in the FBG sensor System for structure-2. (Operating Voltage of TF : $\lambda 0 \doteqdot 0.86V$ ; $\lambda 1 \doteqdot 1.86V$ ; $\lambda 2 \doteqdot 2.86V$ ; $\lambda 1 \doteqdot 1554.46nm$ ).

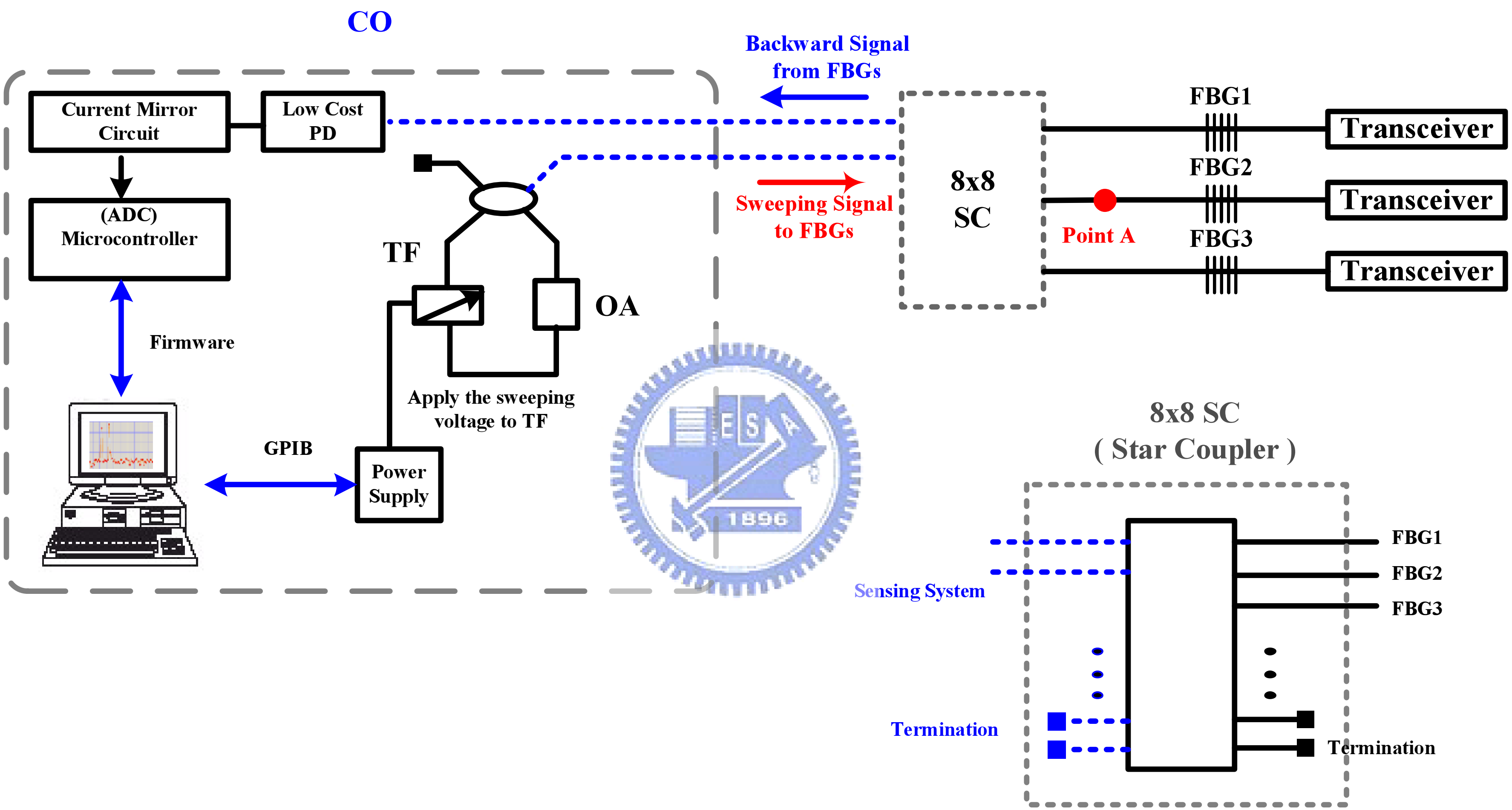
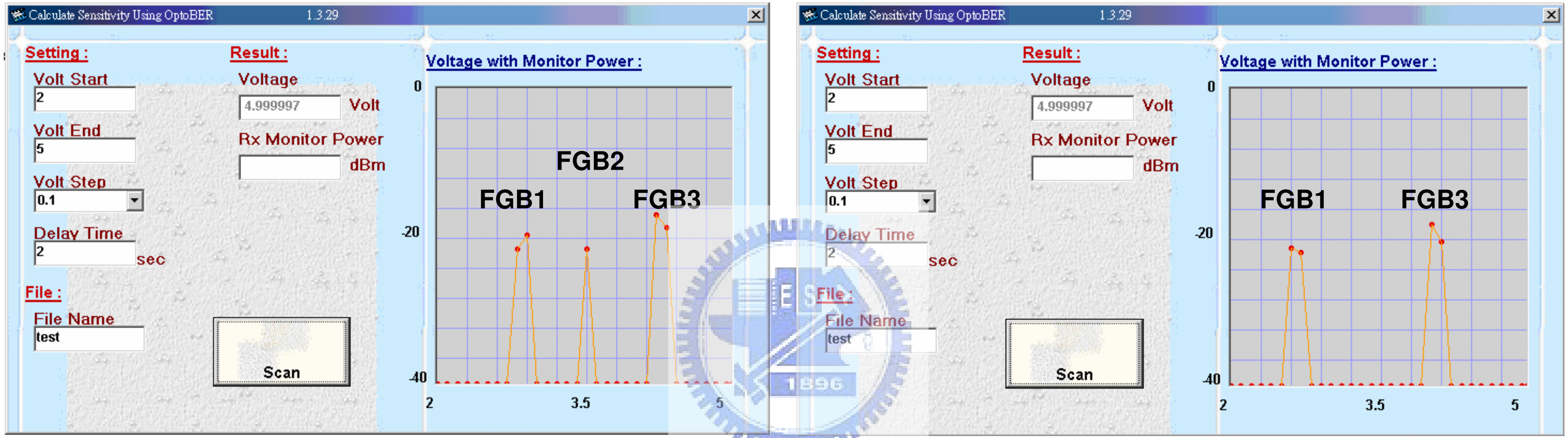



**Fig. 2.18** A proposed fault identification system. The backward signal is detected by a photo detector and processed by the circuit. We can directly observe the link status on the monitor of the computer. (FBG1=1552.23nm, FBG2=1554.56nm, FBG3=1556.36nm).




(a) Normal condition (B) Fiber broken at point A in Fig.2.18

**Fig. 2.19** A screen of FBG sensor system base on Fig.2.18 architecture. (Volt Start / Volt Stop : Setup the sweeping voltage of TF ; Volt Step : Setup the step of sweeping voltage ; Delay Time : The delay time between each step ).

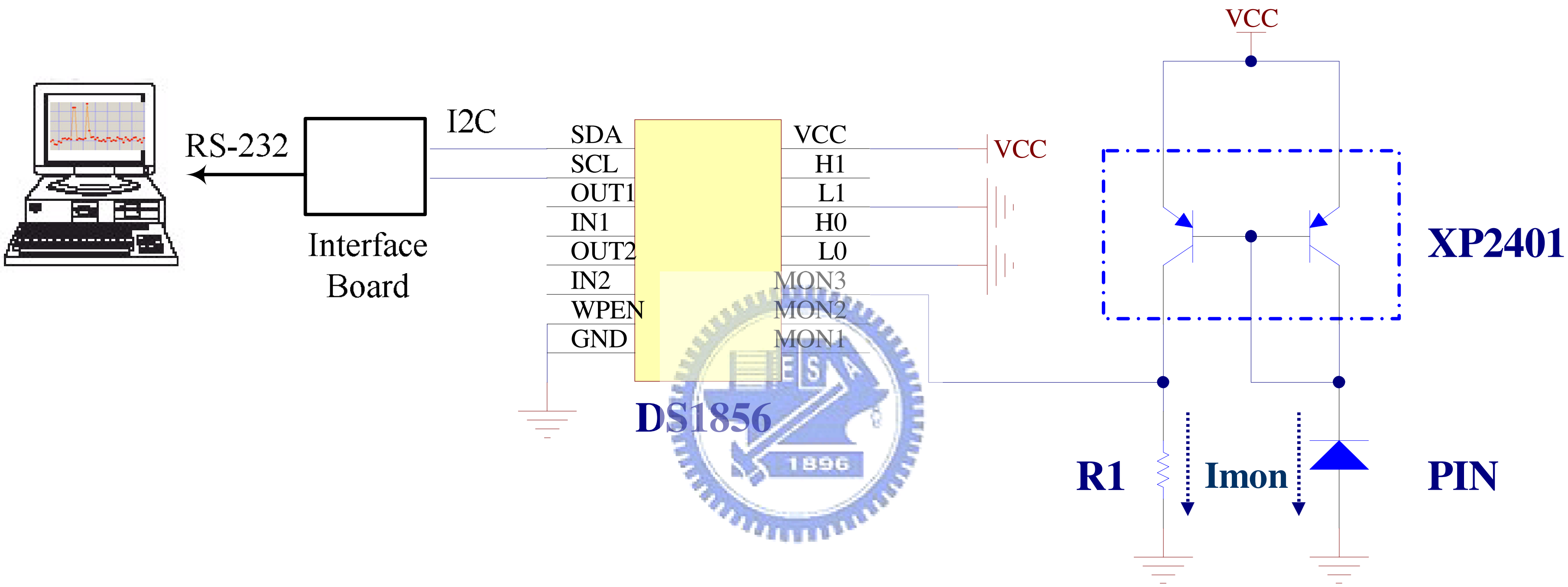



**Fig. 2.20** A circuit and the function block about the proportion of fault identification system.

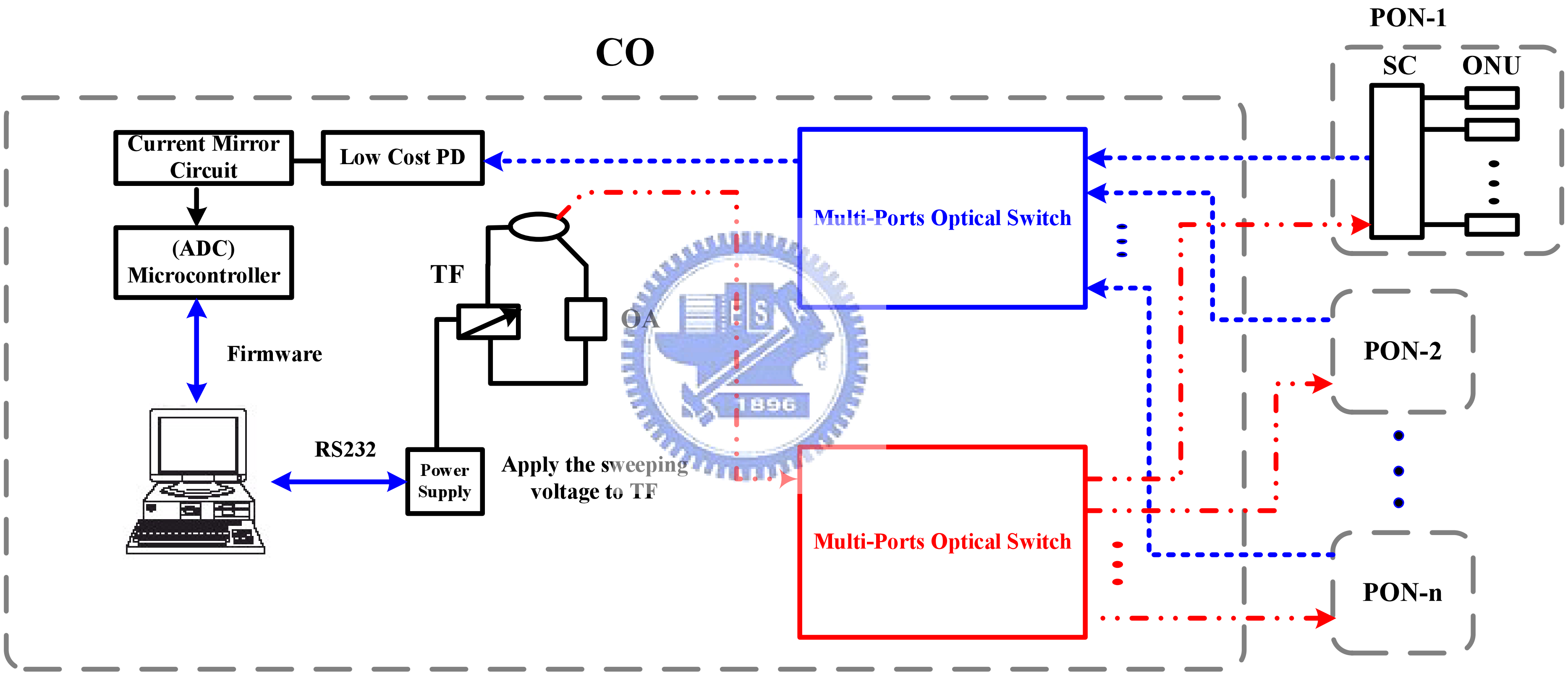



**Fig. 2.21** FBG sensor system serves several PONs.

# Chapter 3

## Star-Ring Passive Optical Network with FBG Sensor System and Self-Healing Function

Network protection is a critical issue to achieve a reliable access network particularly for the passive optical network (PON) employed a point-to-multipoint or a star network topology. Any kinds of network failure will interrupt the broadband service to the subscribers. In order to facilitate the network protection and restoration, the ITU Recommendation on PON (G.983.1) [10] have suggested four possible fiber duplication and protection switching scenarios, as illustrated in Fig.3.1. In order to enhance the reliability and quality of data traffic, those protection architectures reserve the redundant paths and incorporated with automatic protection switching mechanism to re-route the affected data traffic into the alternate protection paths. Those architectures lack for fault identification to monitor any link failures and alarm to perform the appropriate treatment to minimize the data loss. Thus, fault management by using FBG sensor system introduced in the previous chapter is necessary for the PON to detect and monitor link failures occurred. However, the fault management provides the capability to detect and alarm the network failures, it doesn't include the ability to re-route or restore the data traffic. We need combine with the protective and self-healing architecture to minimizing the data loss. In order to facilitate such protection and self-healing function, the network architecture has to be specially designed to provide a redundant path and incorporated with automatic protection switch mechanism to re-route the data traffic into the particular protection path. The adjacent ONUs in the proposed network architecture in this chapter can be grouped together to protect each other from distribution fiber cut by interconnecting fiber and optical switch. When the link failure occurs, system manager can switch the optical switch to another state and try to re-route again by using another interconnecting route. The group protection method by connecting fiber to adjacent ONU is potentially low cost when compared with the conventional method of providing redundancy by duplicating fiber links. In this chapter, we will demonstrate and analyze the performance of the proposed star-ring PON architecture within the fault identification and self-healing function.

## 3.1 Star-Ring Passive Optical Network

Passive access networks employ the star network topology that shares one fiber from optical splitter to central office. Any link breakage will suspend all service and cause date loss from ONU to OLT. In order to alleviate and improve this situation, we include the star-ring architecture to connect each ONU and provide protection path from ONU to OLT. In this chapter, we will propose and demonstrate the star-ring network architecture integrating FBG sensor system for passive optical network with path protection and self-healing capability. Bi-directional traffic can be restored promptly in the ONU when the link failure occurs. Fig.3.2 shows the brief architecture of PON with fault identification and self-healing function that can provide the real-time surveillance and restore for the link status.

### 3.1.1 Proposed Star-Ring PON Architecture

Fig.3.3 shows the proposed star-ring architecture for PON such as gigabit Ethernet PON (GEPON), gigabit capable PON (GPON) [11]. The central office (CO) is comprised of the FBG sensor system for fault identification, feeder fiber, optical switch, OLT optical transceiver that compose of CWDM filter with 1310 band pass filter to isolate the feedback monitor signal. For the FBG sensor system, it consists of optical amplifier and TF as monitor broadband light source, low cost photo detector, such as receiver optical sub-assembly (ROSA) to detect the monitoring signal. The downstream signals and sensor light source from CO are broadcasted by the star coupler (SC) and transmitted to the ONUs on each branch. In a traditional PON access network, ONUs shared single optical fiber connecting a service provider's central office. Any fiber cut on this path will suspend the all data link and cause the tremendous date and business loss. In order to prevent the fiber breakage on this segment, we replace the traditional 1xN splitter by NxN SC and reserve a redundant path between OLT and SC. This network will be re-routed by switching the status of optical switch in the CO when link failure occurs. In the ONU side, it comprises the FBGs with unique center wavelength in each branch for FBG sensor system and ONU transceiver that compose of CWDM filter with 1550 cut function to isolate the monitor signal pass through FBG. Besides, the 1x2 optical coupler with splitting ratio of 50/50 and the 2x2 optical switch in ONU will construct the protective ring architecture. The optical switch will change the state when link failure occurs to accomplish the self-healing function and restore the data link through another path.

### 3.1.2 Fault Monitor System and Self-Healing Function

Fig.3.4 and Fig.3.6 show the normal transmitting route in the proposed network. This star-ring PON architecture possessing the self-healing function and it will reroute automatically by switch the optical switch. The fault state will also can be detected by the FBG sensor system. There are two kinds of fiber failures shown in the Fig.3.5 and Fig.3.7. One is between ONUs and SC due to fiber broken and the other is feeder fiber failure between CO and SC. When the fault occurs as the Fig.3.5 shown, the system in the ONU side will detect the loss of signal and generate the control signal to reconfigure the route automatically by switching the optical switch. At the same time, the FBG sensor system will detect the lack channel of broken path.

However, when the link fault occurs between the CO and SC, a drastic drop of data link will be detected and distinguish the condition by the OLT system. After judging and confirm by OLT system, the optical switch in CO will switch the state to reroute and restore the affected traffic to recover the data link. The self-healing function between CO and SC is constructed by using optical switch and redundant protection fiber in this network. In this situation, the FBG sensor system doesn't have the capability to detect due to lack of monitoring path.

Moreover, if the fiber fault occurs on the path between FBG sensor system in CO and SC, the sensor system can't detect any monitor signal in FBG sensor system. System maintainers need to find out the broke point and recondition it. The phenomenon in the sensor system for various failure conditions is different. System providers are easy to identify and judge which fault conditions occur and take right action by using this FBG sensor system.

## 3.2 Analyze the Complete Performance of the Architecture

In order to realize and simulate the performance of the proposed star-ring PON with fault identification and self-healing system, we need to setup some experiment and estimate the ability of this architecture as the Fig.3.8 shown. In the CO, it consists of optical amplifier and TF as monitor broadband light source, low cost photo detector, such as receiver optical sub-assembly (ROSA), OLT GEPON optical transceiver that composes of 1310nm band pass CWDM filter to isolate the feedback monitor signal and 1490nm transmitted light. We can control the state of the 2x2 optical switch to the protection path when the feeder fiber broken. CO and ONUs are connected by an 8x8 optical star coupler (SC). Between the OLT to SC, there is one 10km backup fiber link, in additional to the 10km working fiber feeder. The fault-monitoring broadband light source transmitted the signal into the SC through the 10km fiber and broadcast to each ONUs. The monitor signal will be reflected from FBG and received through 10km fiber by the photo detector. We connected three ONUs to SC that with individual wavelength of FBG to reflect the fault-monitor signal (FBG-1=1552.23nm, FBG-2=1554.56nm, and FBG-3=1556.36nm) to SC. In each ONU, it consist of 1x2 optical coupler that connecting the local and adjacent ONU, the automatic protection 2x2 optical switch and PX-20 GEPON ONU optical transceiver that can transmitted burst signal and received traditional continuous-mode (CM) signal.

In the following division, we will measure the power budget of the FBG sensor system and estimate the maximum splitting ratio for this proposed PON architecture. Furthermore, we use the PX-20 transceiver in this system and it is necessary to guarantee the signal of the sensor system will not degrade the performance of the transmitted date signal. Finally, we will measure influence of the BER of this system when we add or drop the FBG sensor system.

### 3.2.1 Power Budget of the Monitor Signal

PON is based on point-to-multipoint (P2MP) architecture that allows several customers to share the same single fiber between CO and ONUs. The splitting of fiber increased the power loss than point-to-point (P2P) solution. We need wider range of power budget for this kind of application. For example, one OLT need serve 16 ONUs in GEPON and may be 16 or more for GPON application. However, the power level of reflected monitor signals is dependent on the power of the optical amplifier and the link loss of monitoring route. As the link loss or the splitting ratio of star couple increases, the power level of the monitor signal decreases at the same time and maybe exceed the monitoring capability. The sensor system will can’t work proper and reasonable.

We simplify the architecture as the Fig.3.9 shows to simulate the power budget and link loss for the fault monitor system in the proposed network. We use the attenuator to attenuate the power of monitor light source. The reflected monitor signal and wavelength can be identified by the optical spectrum analyzer (OSA). The experimental setup consists of SC, FBG, optical amplifier, TF, 8x8 SC, attenuator and OSA. The component and path loss in this FBG sensor system is shown in Table 3.1. We can calculate the power budget of this proposed architecture and simulate if we can implement 16x16 SC for real

GEPON applications. In the experimental result, the SNR is large than 10dB when the ATT (attenuator) is 3.1dB. It means we can support splitting ratio reach 16 at least.

### 3.2.2 Influence of the Sensing Source

In our demonstrated star-ring GEPON architecture, we use 1000BASE-PX-20-U (Upstream) and 1000BASE-PX-20-D (Downstream) optical transceivers. For those PX-20 transceivers, we use 1310nm and 1490nm DFB laser as the light source to transmit the upstream and downstream signal in the PON. In order to guarantee the well link of the system, IEEE 802.3ah standard specify the transmitter spectral limit as the Table 3.2 shown.

For the receiver side, the PIN detector in the ONU transceiver is the broadband responsive device. It will detect the monitor light source form FBG sensor system. In order to prevent this monitor light source to degrade the performance of ONU transceiver, we need to choose right CWDM filter with 1550nm cut function as the Fig.3.10 shown in transceiver to isolate the undesired signal. In the OLT transceiver, we used the 1310nm band pass filter to isolate the 1490 transmitted light and backward monitor light from FBG sensor system. Besides, the DFB laser is very sensitive for any coherent light and the back reflected signal from any disconnected point. However, the fault monitoring light source is the broadband and sweeping light. It closed to the 1490nm which is the operating wavelength of PON. We need to make sure if this fault monitor signal will cause any influence on the performance of DFB laser in transceivers. Fig.3.11 shows the comparison results of spectrum when fault monitor light source is added and dropped out of network. We can find the side mode suppression ratio (SMSR) is almost the same and the monitor signal will not degrade the performance of transmitter.

### 3.2.3 Dispersion Penalty and Bit-Error-Rate

We use a commercial 1490nm DFB laser in the OLT transceiver and 1310nm DFB laser in the ONU. The wavelength of FBGs are distributed around 1550nm and we need to used CWDM filter with 1550nm cut function in the receiver side of the ONU to isolate the monitoring light source. In order to guarantee the performance of the proposed architecture, we need to make sure if the monitor light source in the fault identification system will influence the data link. Fig.3.12 shows the setup and equipment list of BER measurement system. For the downstream, the transmitter of OLT transceiver is directly modulated by 1.25 Gb/s non-return-tozero with $2^7$-1 pseudorandom bit sequence that generated by a pattern generator. The full architecture setup of the experiment is shown in Fig.3.8. We implement the long distance of fiber (L1~L4) to simulate the real condition and measure the dispersion penalty in the proposed system. Fig.3.13 shows the BER of the downstream and upstream with and without monitoring light source. Fig.3.14 shows dispersion penalty of the downstream.

### 3.2.4 Results and Discussion

The results show the monitoring light source has slightly influence of the data link. This data link of the star-ring architecture can work well when the fault identification and self-healing system is implemented. This proposed architecture can fully support the GEPON structure. The splitting rate of the GEPON is 1:16. If we want to increase the splitting rate for GPON, we need to increase the power budget of the monitoring system. This fault identification system is very flexible to extend and implement for the PON.

Moreover, the customers in PON may require reciprocal communication link such as teleconferencing and interactive video games. For the PON system, the OLT need serve many OUNs. It is a heavy loading for local communication. This star-ring architecture with the BM optical receiver in the ONU that facilitates intercommunication links via local area network to provide cost saving solution and efficient bandwidth allocation of the network [12]. Fig.3.15 shows the feature work of the GEPON architecture with local network.

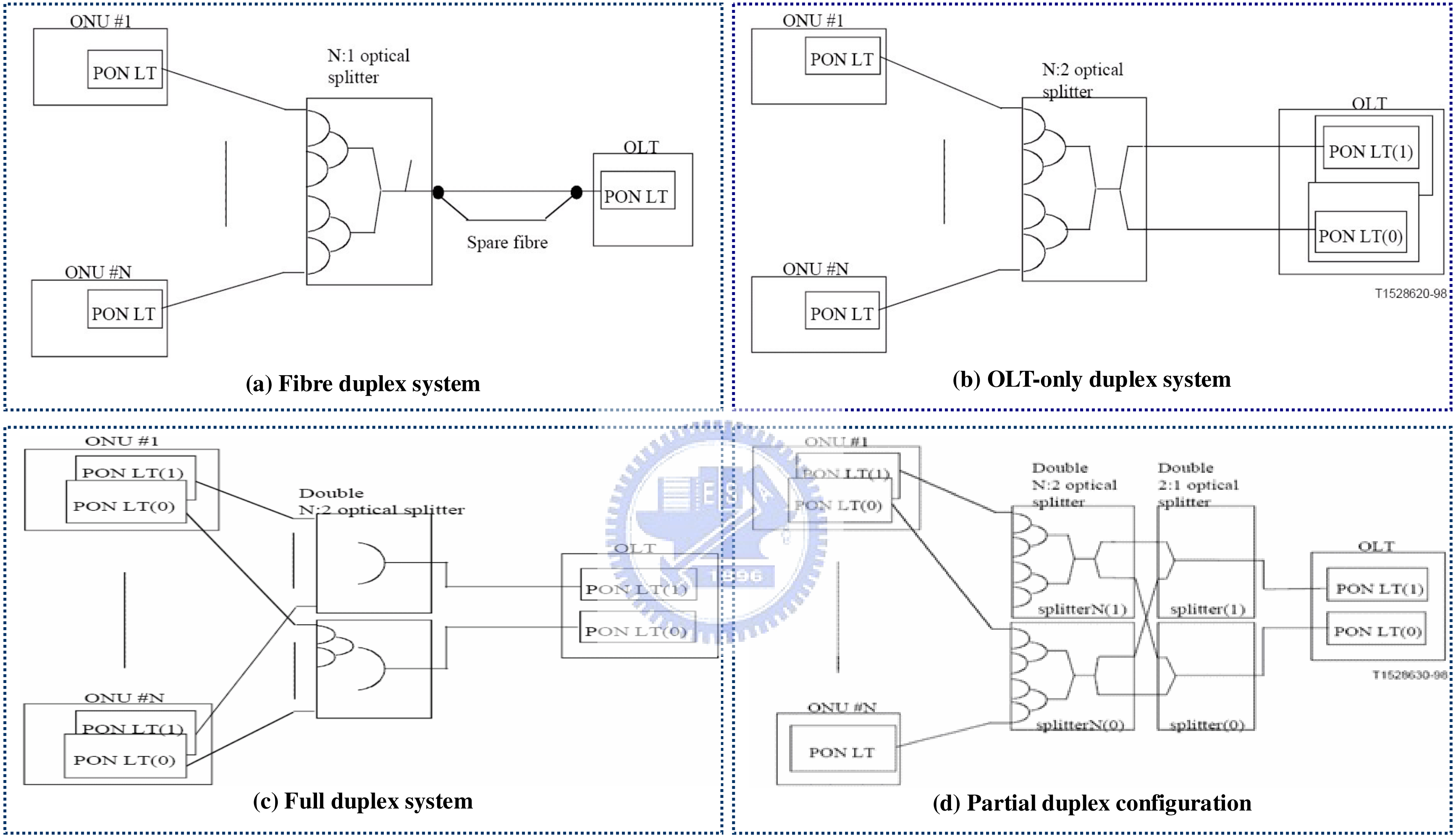



**Fig.3.1** Four fiber duplication and protection switch scenarios suggested from ITU G.983.1. (a) Fibre duplex system , (b) OLT-only duplex system , (c) Full duplex system , (d) Partial duplex configuration. (Reference form ITU G.983.1).

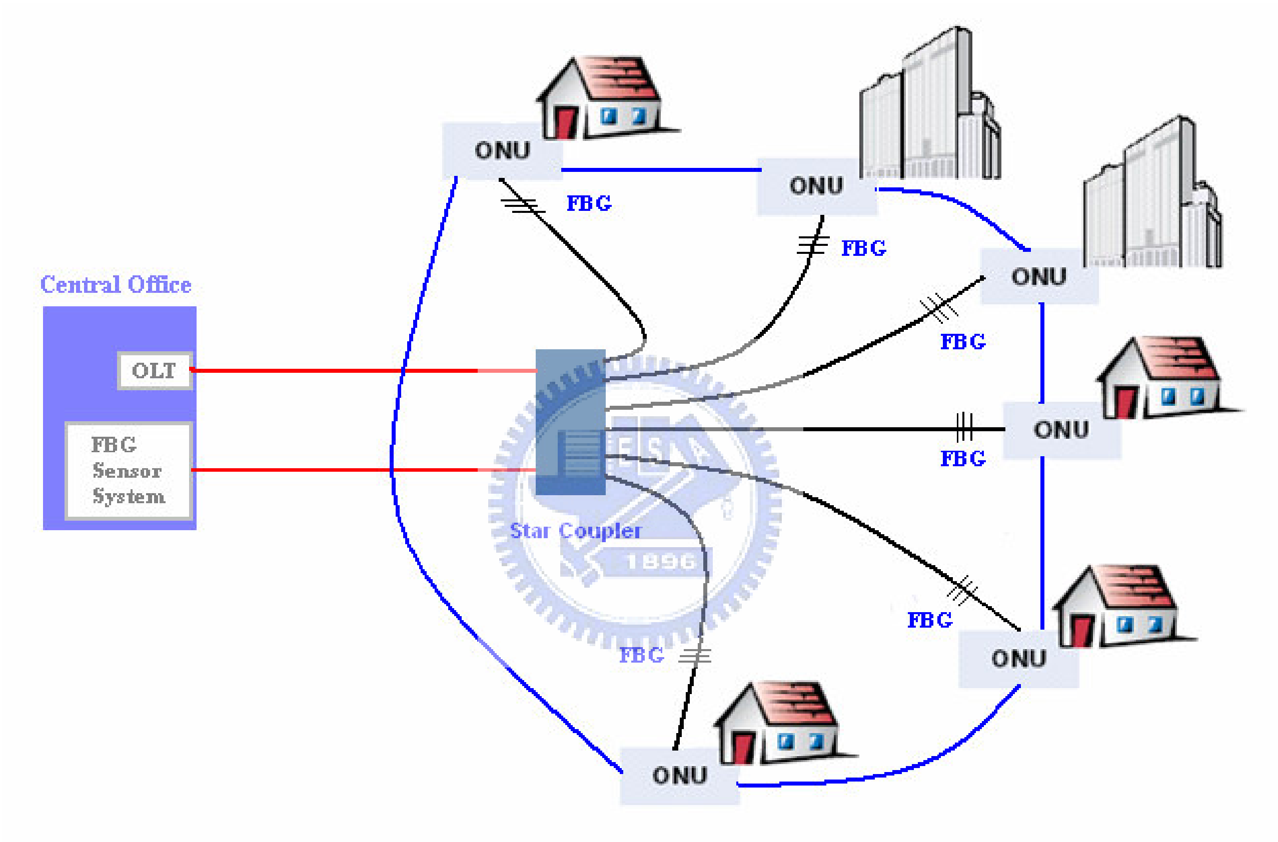



**Fig.3.2** Brief concept of star ring PON architecture with fault identification and self-healing function.

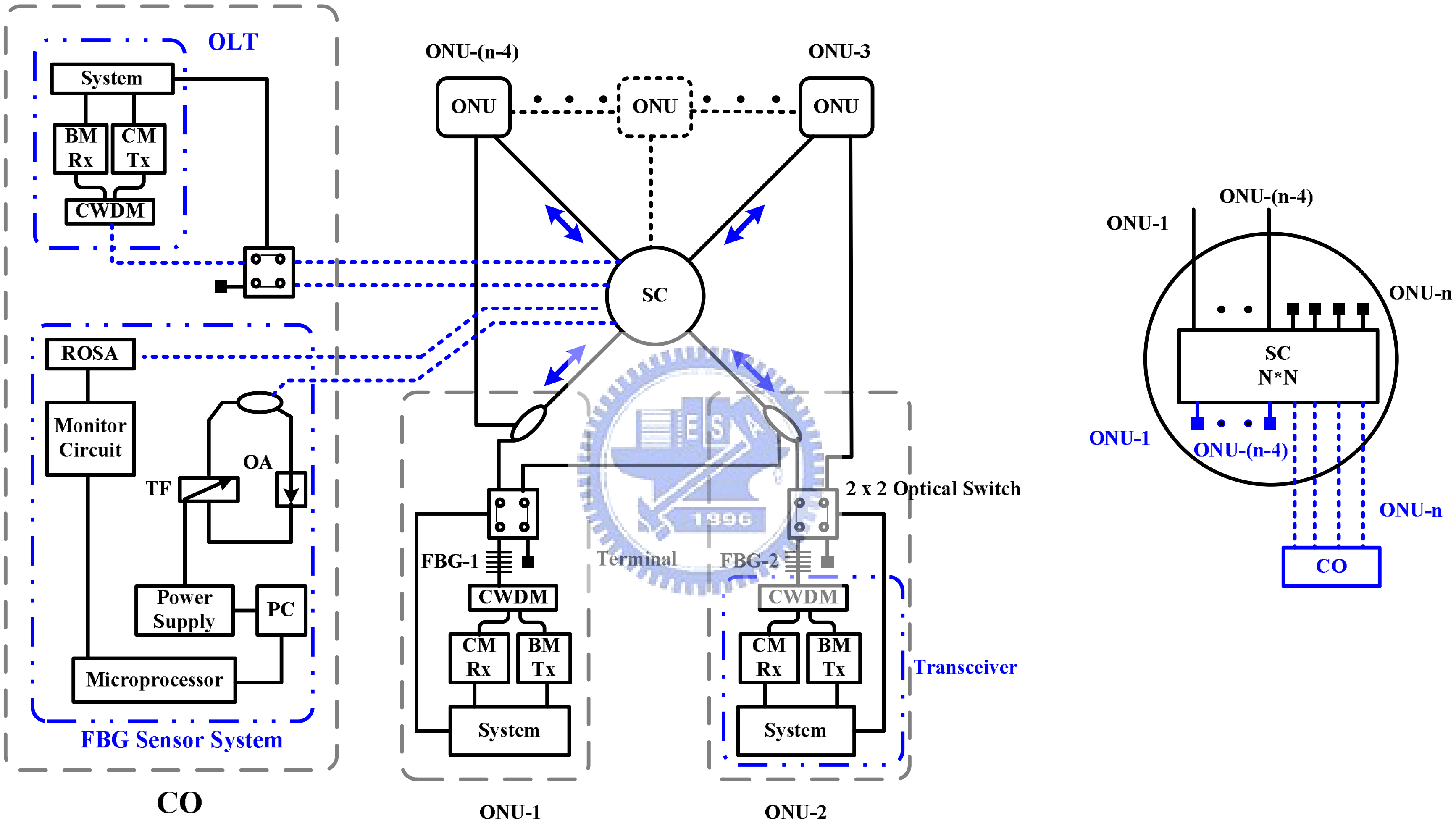



**Fig.3.3** Proposed star-ring PON architecture with FBG sensor system and self-healing function.

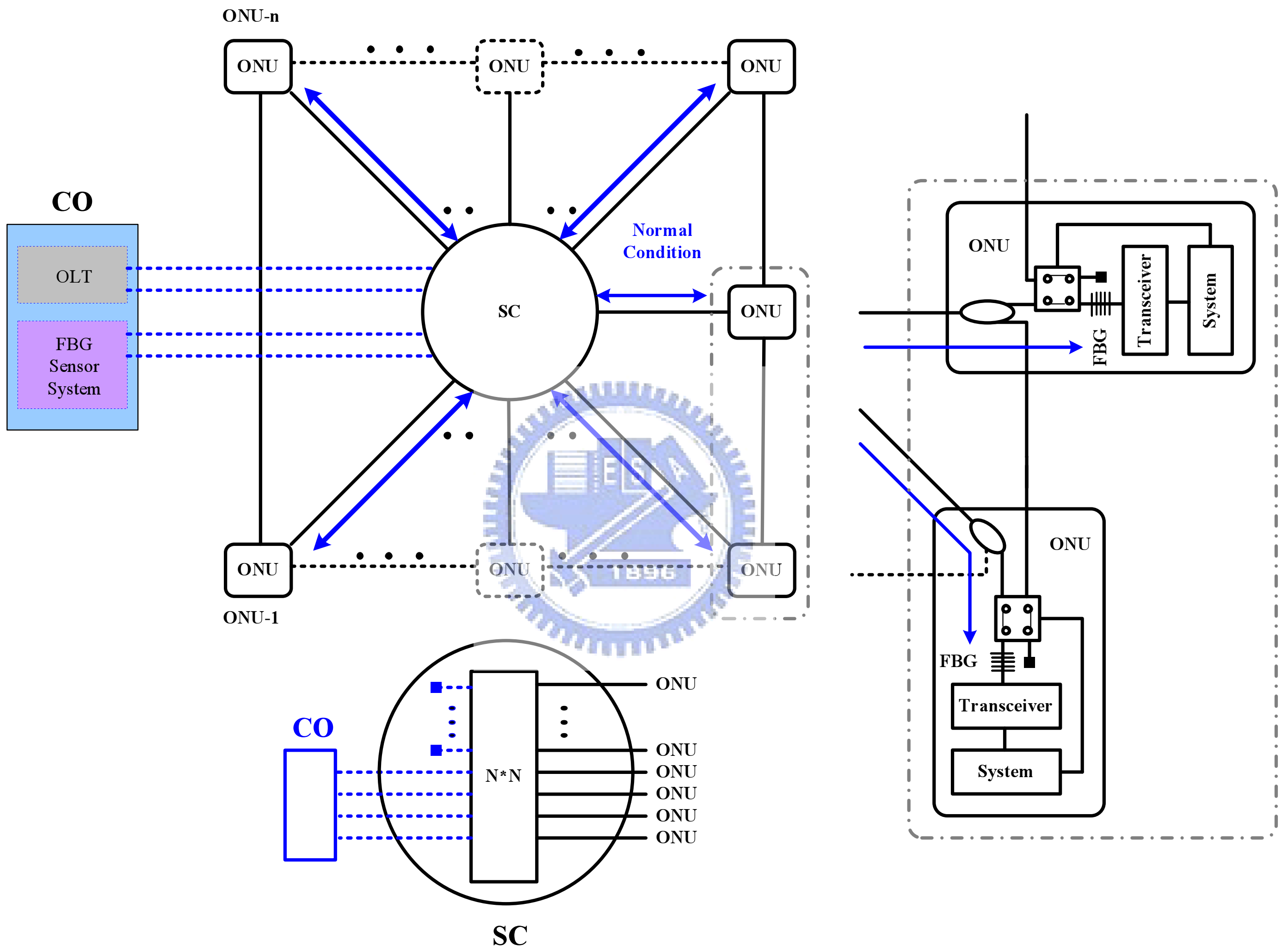



**Fig.3.4** Normal condition in ONU side : Star ring PON architecture with self-healing function.

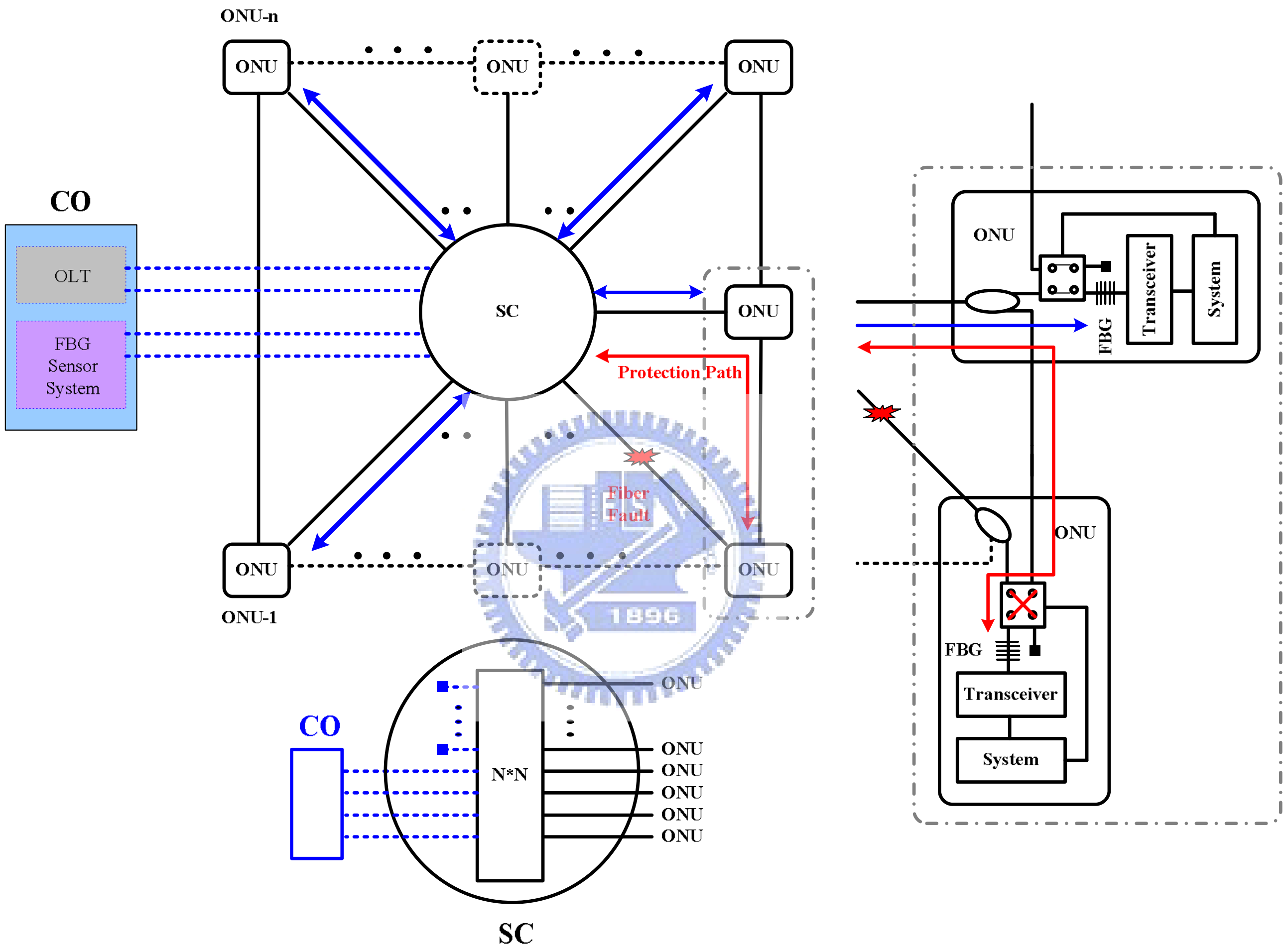



**Fig.3.5** Self-healing function when fiber fault occurs in ONU side : Star ring PON architecture with self-healing function.

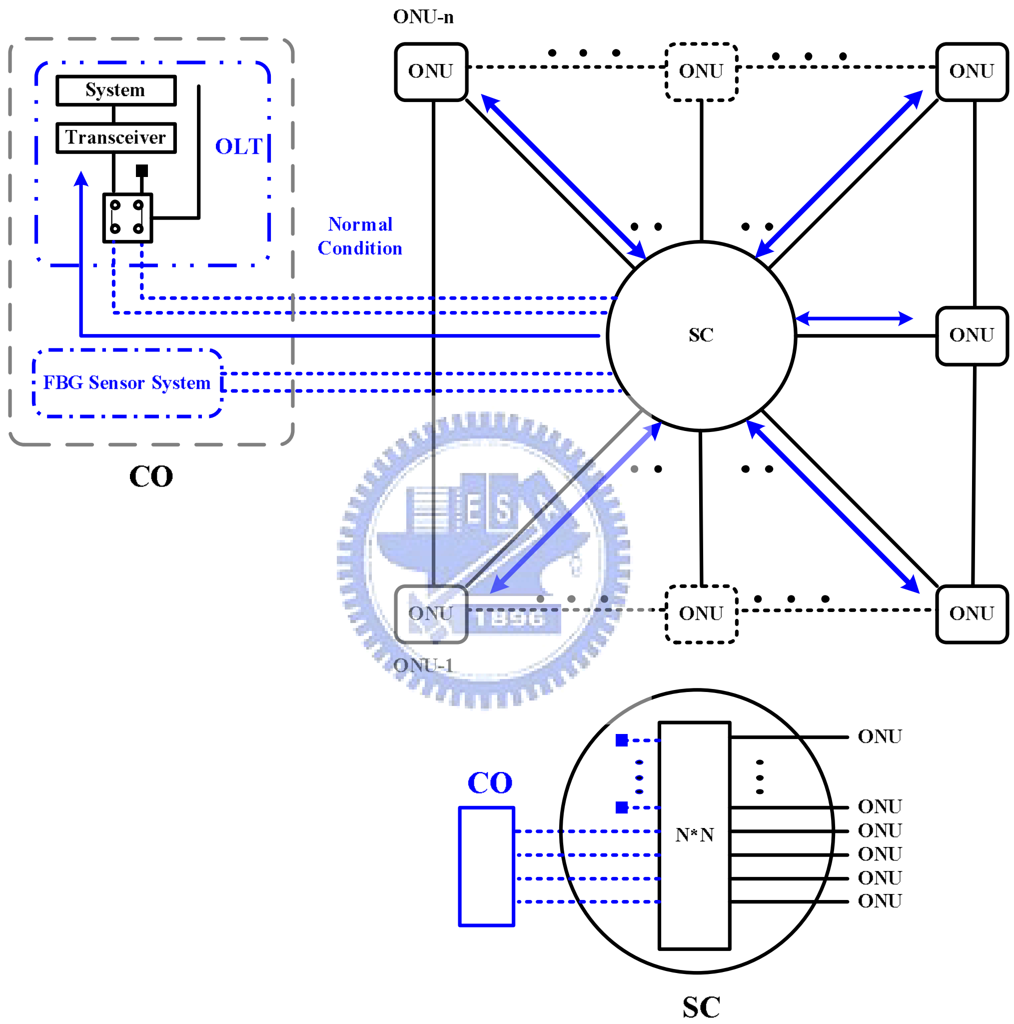



**Fig.3.6** Normal condition in CO side : Star ring PON architecture with self-healing function.

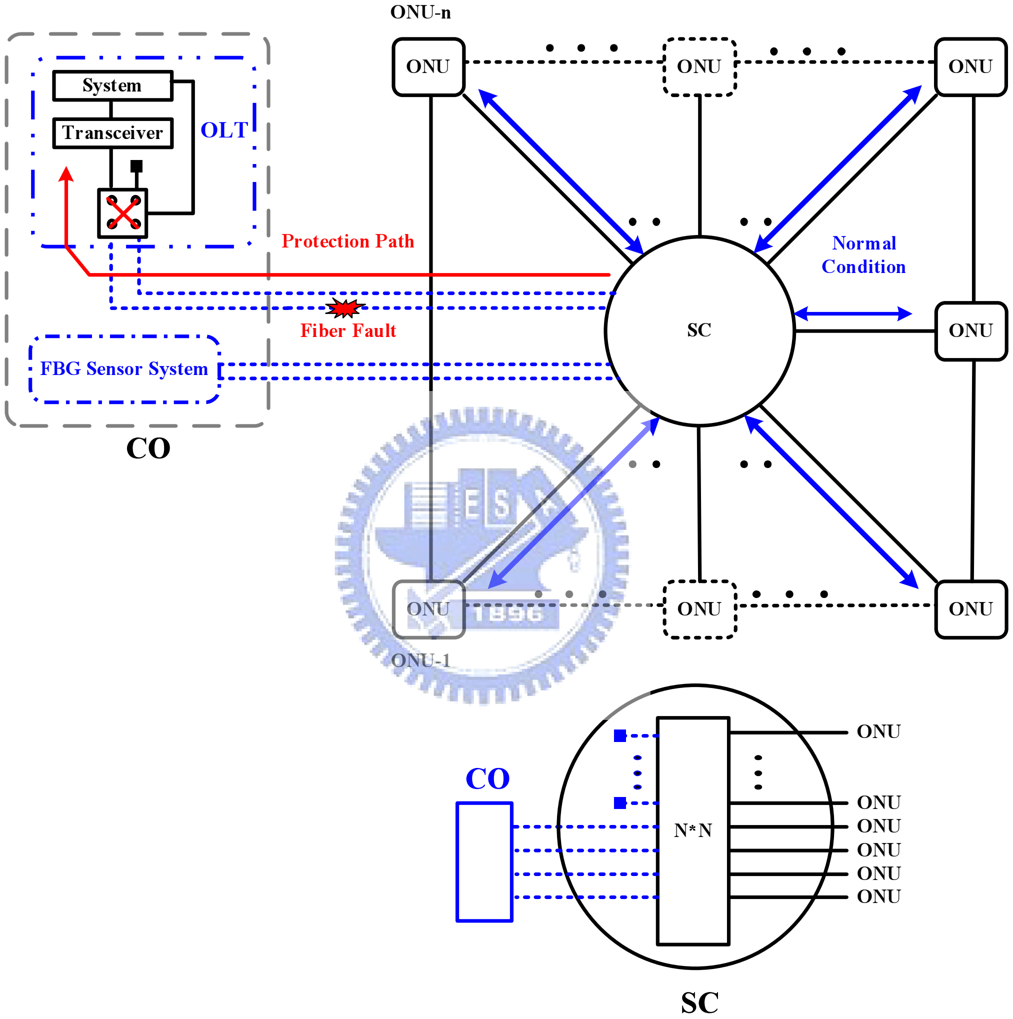



**Fig.3.7** Protection path in CO side : Star ring PON architecture with self-healing function.

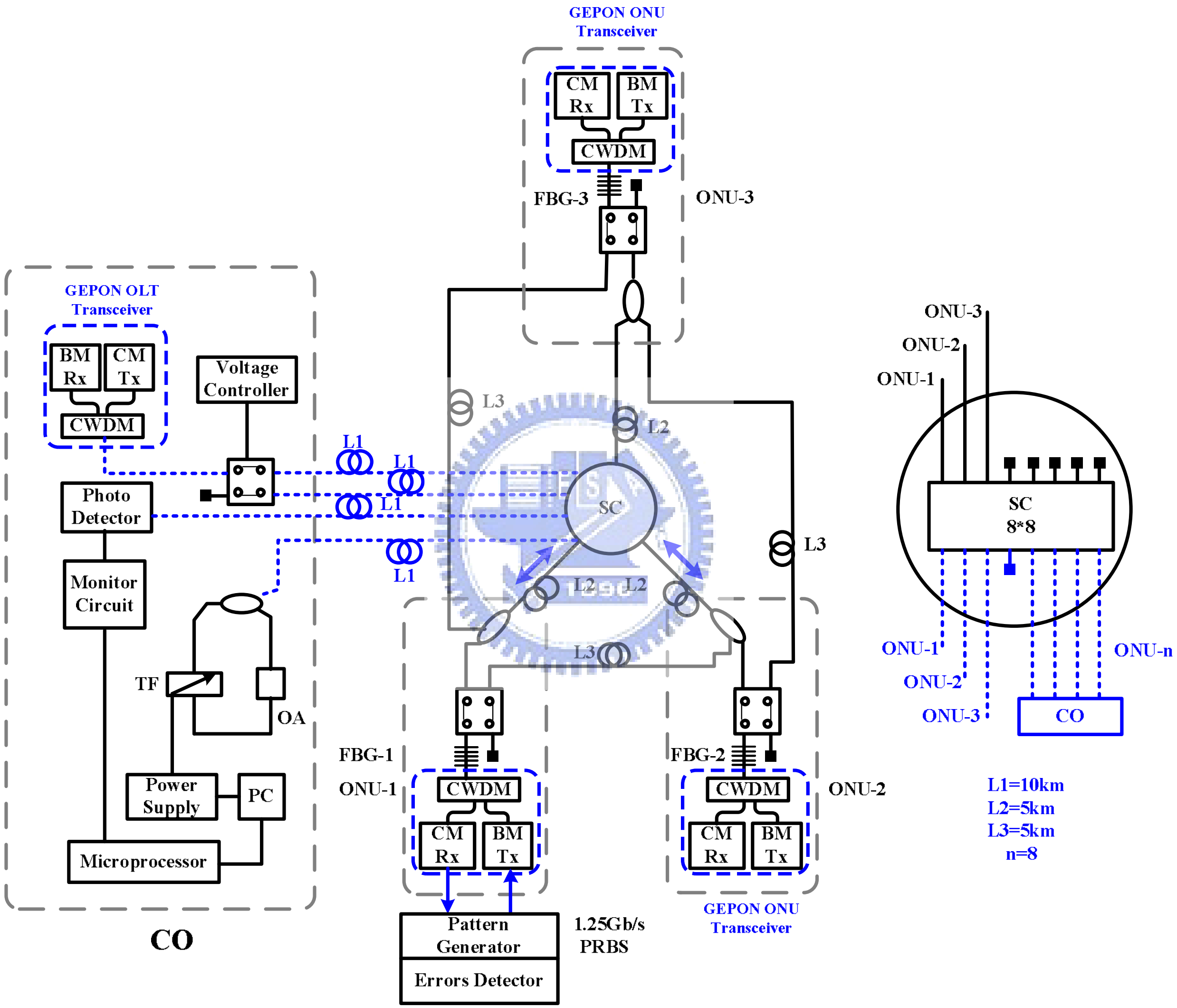



**Fig.3.8** Experimental setup for propose PON architecture with fault identification and self-healing function.

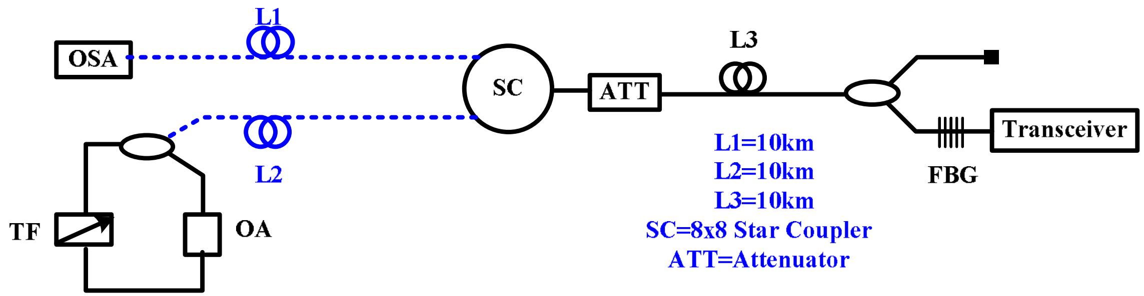



**Fig.3.9** The experiment setup to estimate the power budget of the fault identification system. (ATT: Optical attenuator)

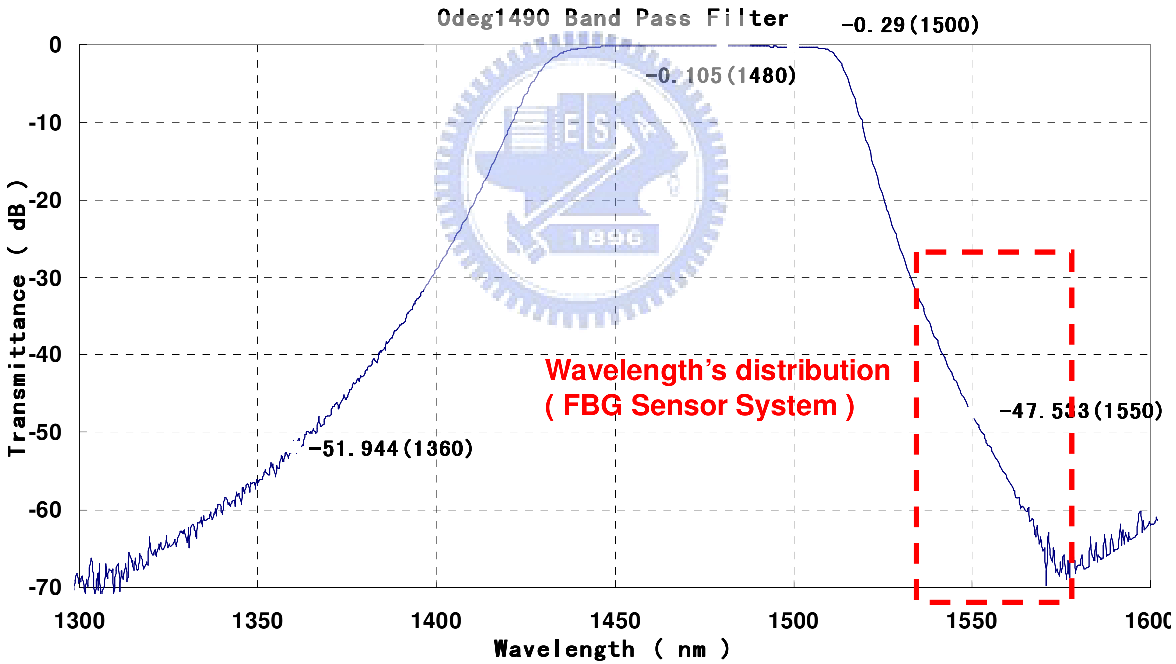



**Fig.3.10** The character of the CWDM band pass filter used in the ONU transceiver.

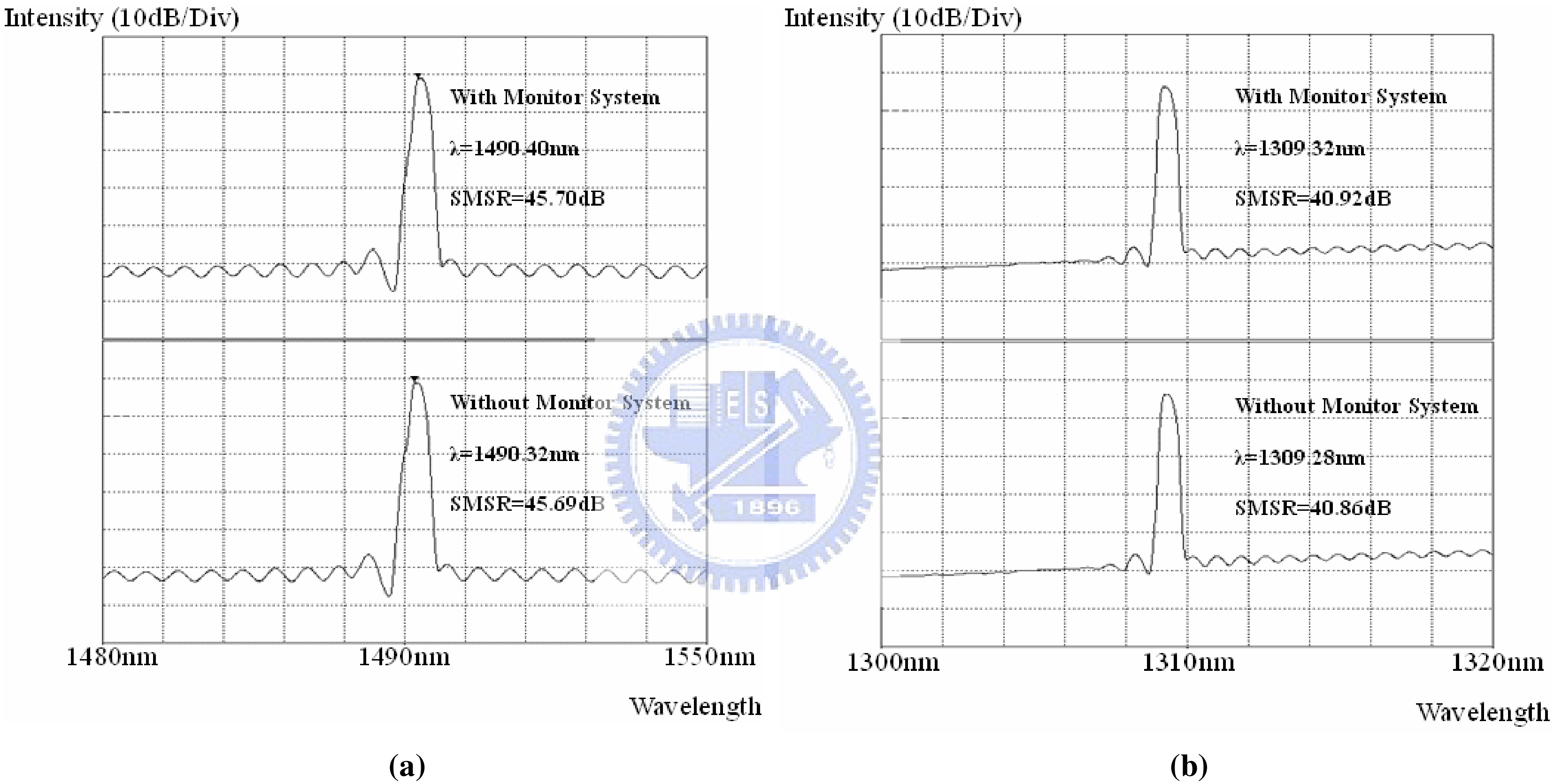
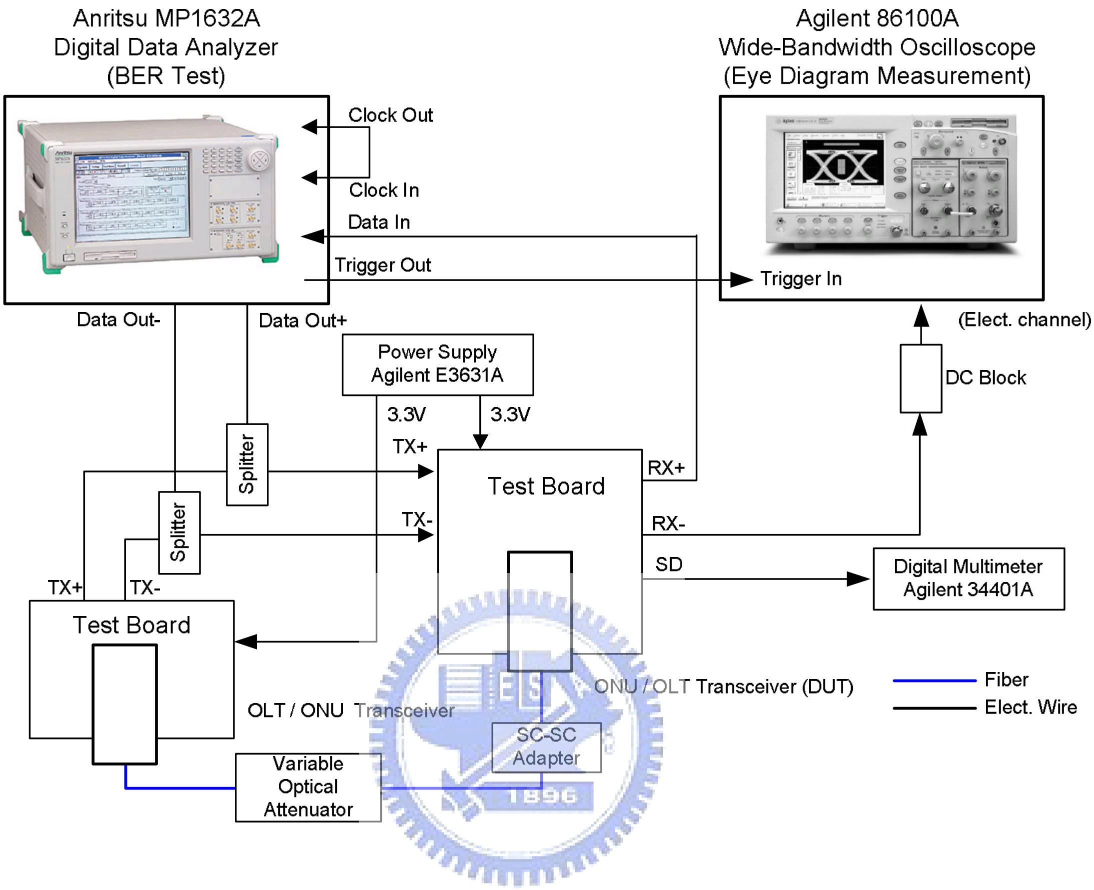



**Fig.3.11** Optical spectrum comparisons when fault monitor light source is added and dropped out of network. (a) The light spectrum of the OLT transceiver. (b) The light spectrum of the ONU transceiver.

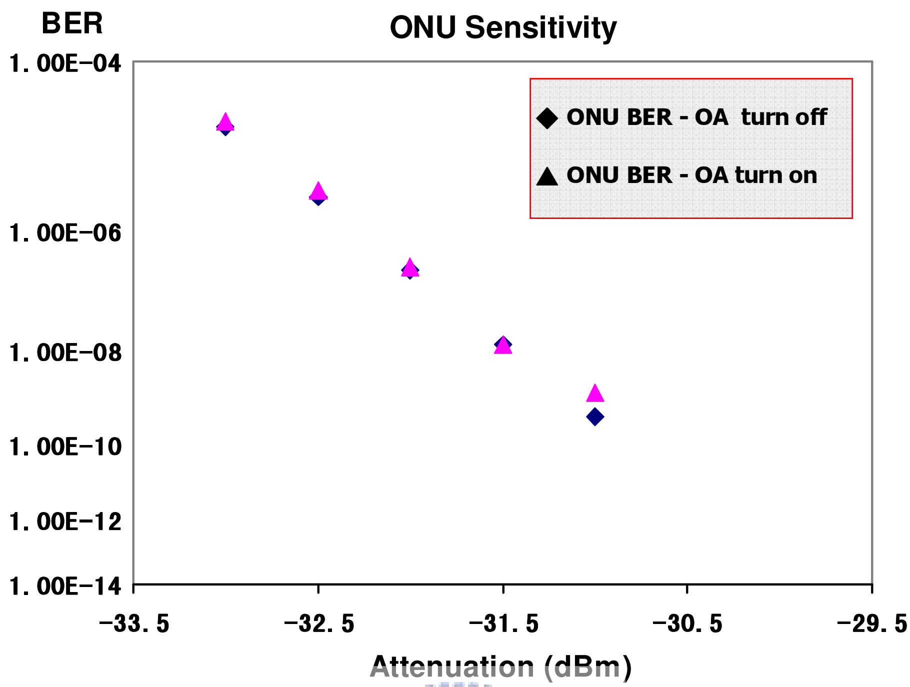
**BER - Measurement System Block Diagram**



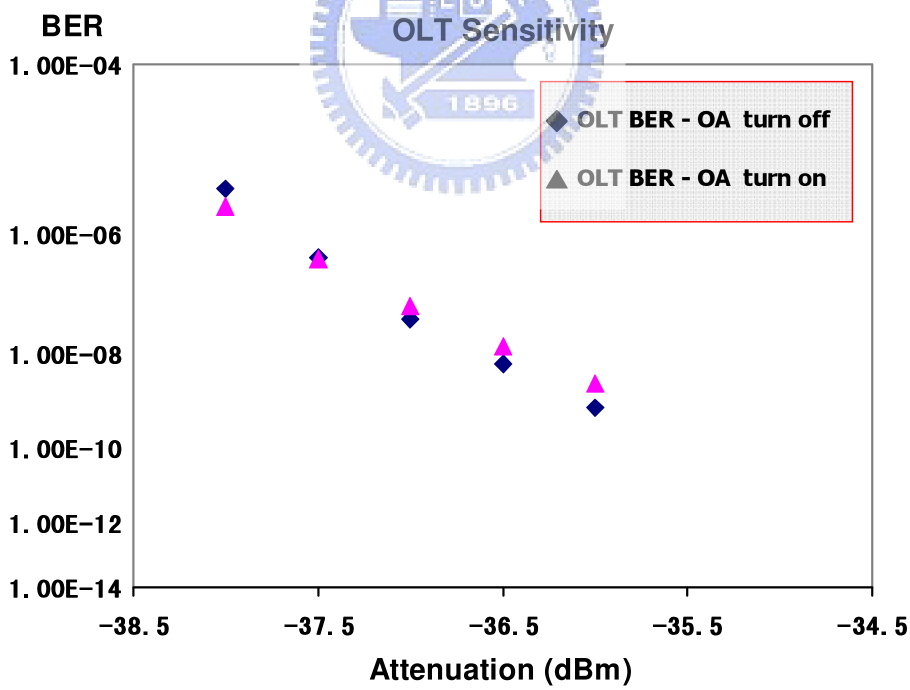

## Testing Equipment List

| Testing Items | Equipment |
|---|---|
| Pattern Generator | Anritsu MP1632A |
| Bit error rate tester | Anritsu MP1632A |
| Wide bandwidth oscilloscope | Agilent 86100A |
| Power supply | HP E3631A |
| Variable Optical Attenuator | HP 8156A |
| Optical Power Meter | HP 8153A |

**Fig.3.12** The Bit-Error-Rate testing setup and the equipment list in this block diagram. (Reference from EZconn Corporation)




(a) BER of downstream – OLT to ONU




(b) BER of upstream – ONU to OLT

**Fig.3.13** BER test result at the ONU and OLT transceiver with and without EDWA light source.

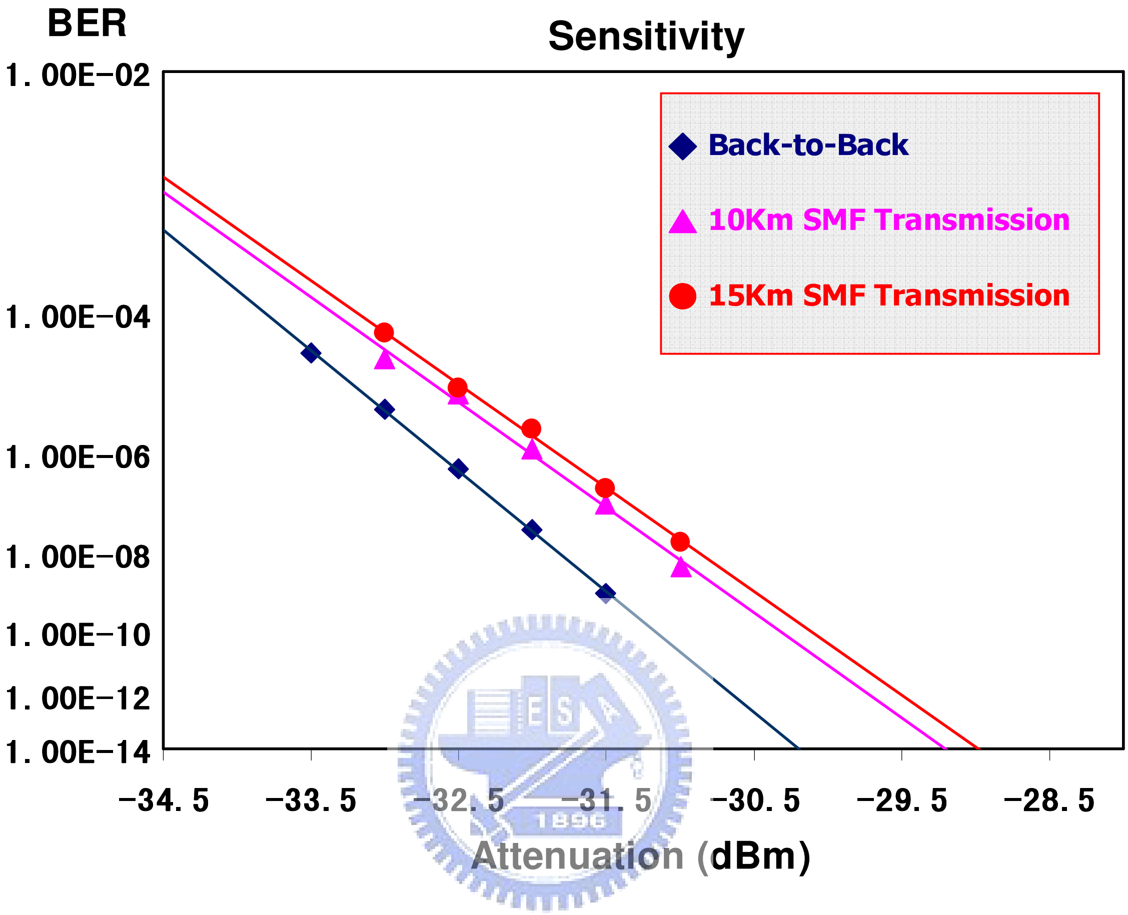



**Fig.3.14** Dispersion penalty – BER measurement

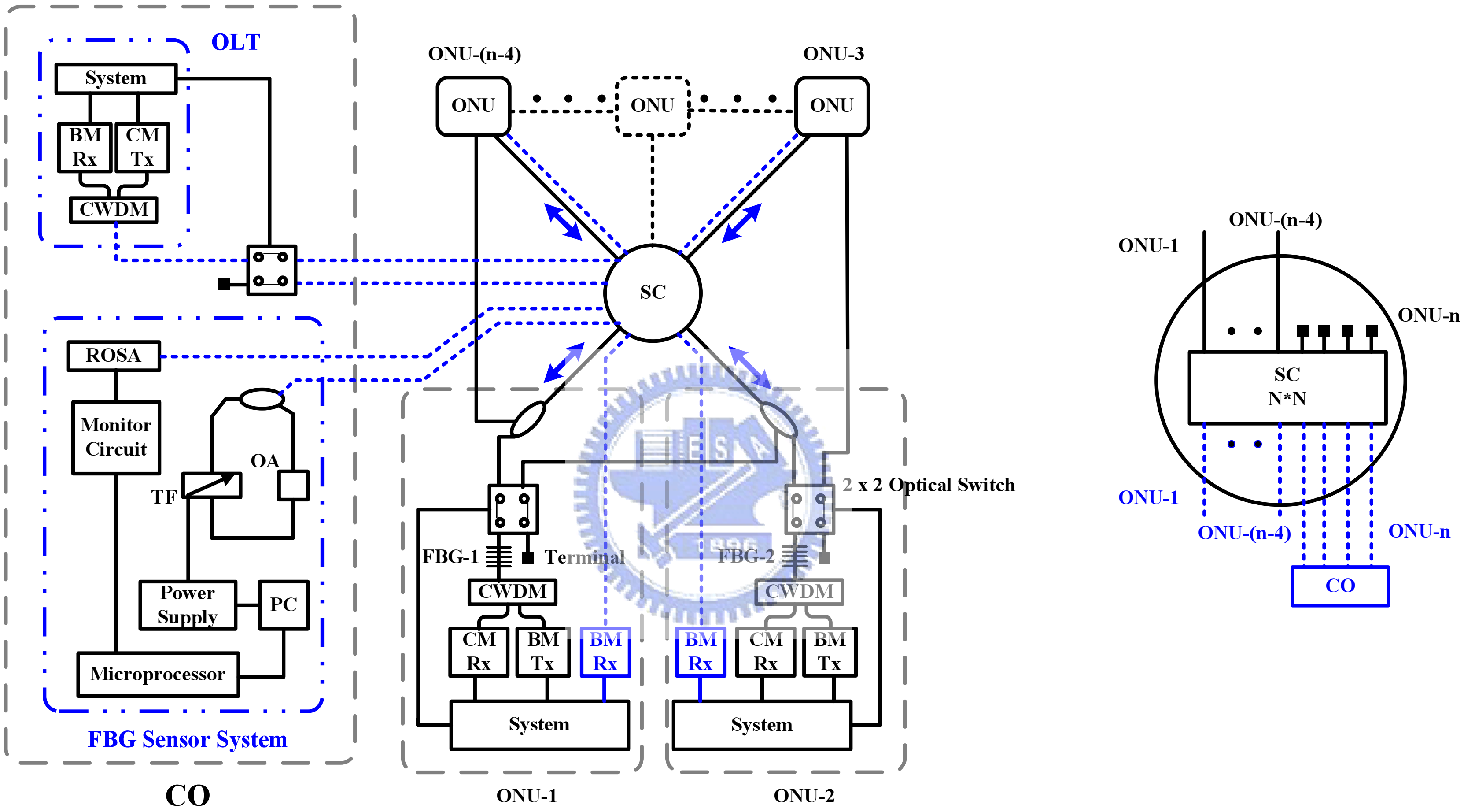



**Fig.3.15** Feature work: Fault identification and self-healing structure for the GEPON. This architecture includes the local customer network.

| | Downstream Path | Upstream Path |
|---|---|---|
| L2 Fiber Loss | 0.2 dB/km (1550nm) | 0.2 dB/km (1550nm) |
| 3dB Coupler Loss | 3.2 dB | 3.2 dB |
| 8x8 SC Loss | 11.5dB | 11.5dB |
| L3 Fiber Loss | 0.2 dB/km (1550nm) | 0.2 dB/km (1550nm) |
| 3dB Coupler Loss | 3.2 dB | 3.2 dB |
| L3 Fiber Loss | 0.2 dB/km (1550nm) | 0.2 dB/km (1550nm) |
| 2x2 Optical Switch Loss | 0.6 dB | 0.6 dB |
| FBG Loss | 0.75 dB | 0.75 dB |
| Connectors Loss | 0.3x3=0.9 dB | 0.3x3=0.9 dB |
| Insertion loss of the TF | 1.9 dB | |

**Table.3.1** Components loss in the fault identification system.

| Center Wavelength | RMS spectral width (max)[2] | RMS spectral width to achieve epsilon ε <=0.10 (informative) |
|---|---|---|
| **nm** | **nm** | **nm** |
| **1260** | **0.72** | **0.62** |
| **1270** | **0.86** | **0.75** |
| **1280** | **1.07** | **0.93** |
| **1290** | **1.40** | **1.22** |
| **1300** | **2.00** | **1.74** |
| **1304** | **2.5** | **2.42** |
| **1305** | **2.55** | **2.5** |
| **1308** | **3.00** | |
| **1307** | | |
| **1320** | **2.53** | **2.2** |
| **1321** | **2.41** | |
| **1330** | **1.71** | **1.48** |
| **1340** | **1.29** | **1.12** |
| **1350** | **1.05** | **0.91** |
| **1360** | **0.88** | **0.77** |
| | | |
| **1480 to 1500** | **0.44** | **0.30** |

**Table.3.2** The specification of the transmitter spectral limit in IEEE 802.3ah for GEPON. (Reference from IEEE 802.3ah)

# Chapter 4

## Conclusions

Due to the multi-broadcasting of the passive optical networks, any fiber cut will cause the tremendous business loss for system provider and quality degrade of data link for the customer. In this thesis, we proposed the FBG sensor system to identify the fiber cut and provide the self-healing function to restore the data link when data loss occurred in the network. We accomplish those functions by using the star-ring PON architecture with FBG sensor system.

In the previous chapters, the demonstrations of FBGs sensor networks and protection mechanism in the passive optical networks have been explored. We introduced the structure and insufficiency of passive optical networks in chapter 1. We innovated the concepts of FBGs sensor system and self-healing function for improving the reliability of PONs.

In the chapter 2, we introduced the working principle of simple fiber Bragg grating sensor systems. Moreover, three basic concepts of FBG sensor system are demonstrated and analyzed experimentally. The optical amplifier incorporated with fiber Fabry-Perot tunable filter as the monitoring light source and construct the different fiber laser schemes with FBGs in those experiments. We find the best FBG sensor system from the experiments and integrated this one into the PONs based on point-to-multipoint architecture. Moreover, in order to identify the fault in the system, we proposed a new fault identification structure for the PON application and demonstrated this wavelength-sweeping technology. We used a low cost architecture to complete the fiber fault detection. This function will enhance the ability of CO to manage the entire network system.

In the chapter 3, we demonstrate the star-ring passive optical networks with self-healing function and integrate the previous fault identification system. The self-healing function is a tremendous improvement on the reliability and data link quality for the PON. If any link faults occurred in this proposed star-ring network architecture, the fault will be detected by the fault monitor system and reroute to the protection path automatically by optical switches to recover the data link.

We investigated and demonstrated the proposed star-ring passive optical network with fault identification and self-healing function in the thesis. This architecture provides the real-time fault monitor system in the central office for system provider. Any fiber cut in the branches of network will be detected in the CO side. The system provider will be easier to maintain and solve the problems. This proposed architecture provides the self-healing function and can reroute to the protection path when link fault occurs in the ONUs to improve the reliability and quality for the PON application.

# References

[1] A. D. Kersey, M. A. Davis, H. J. Partrick, M. Leblance, K. P. Koo, C. G. Askins, M. A. Putnam, and E. J. Friebele, “Fiber grating sensors,” *J. of Lightwave Technology*, vol. 15, pp. 1442-1463, 1997.

[2] Chun-Kit Chan, Frank Tong, Lian-Kuan Chen, Jian Song, and Dennis Lam, “A Practical Passive Surveillance Scheme for Optically Amplified Passive Branched Optical Networks,” *IEEE Photonics Technology Letters*, vol. 9. No.4, 1997.

[3] A. D. Kersey and W.W. Morey, “Multi-Element Bragg-Grating Based Fiber-Laser Strain sensor,” *Electronics Letters*, vol. 29, 1993.

[4] Peng-Chun Peng, Jia-He Lin, Hong-Yih Tseng, and Sien Chi, “Intensity and Wavelength-Division Multiplexing FBG Sensor System Using a Tunable Multiport Fiber Ring Laser,” *IEEE Photonics Technology Letters*, vol. 16, No.1, 2004.

[5] Y. Koyamada, T. K. Horiguchi, and S. Furukawa, “Recent progress in OTDR technologies for maintaining optical fiber networks,” *Tech.Dig., IOOC’95*, Hong Kong, 1995, paper FA1-4.

[6] K. Tanaka, M. Tateda, and Y. Inoue, “Measuring the individual attenuation distribution of passive branched optical networks,” *IEEE Photon. Technol. Lett.*, vol. 8, pp. 915–917, 1996.

[7] C. K. Chan, F. Tong, L. K. Chen, J. Song, and D. Lam, “A practical passive surveillance scheme for optically amplified passive branched optical networks,” *IEEE Photon. Technology. Lett*, vol. 9, pp. 526–528, 1997.

[8] Chun-Kit Chan, Frank Tong, Lian-Kuan Chen, Keang-Po Ho, Dennis Lam, ” Fiber-Fault Identification for Branched Access Networks Using

Wavelength Sweeping Monitoring Source," *IEEE Photonics Technology Letters*, vol. 11, NO. 5, 1999.

[9] SFF Committee, " SFF-8472 Specification for Diagnostic Monitoring Interface for Optical Xcvrs, " Rev 9.5, 2004.

[10] Telecommunication Standardization Sector of ITU " Broadband Optical Access Systems Based on Passive Optical Network (PON)," ITU G.983.1 (10/98).

[11] Elaine Wong, Nishaanthan Nadarajah, Chang-Joon and Ampalavanapillai Nirmalathas, " Passive Optical Network Architectures with Optical Loopbacks," *IEEE*, 2005.

[12] Elaine Wong, and Chang-Joon, " CSMA/CD-Based Ethernet Passive Optical Network with Optical Internetworking Capability Among Users," IEEE Photonics Technology Letters, vol.16, NO.9, 2004.