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Abstract. Nowadays, optical networks are becoming dense while detecting faulty branches in the tree-structured networks has become problematic. Conventional methods are inconvenient as they require an engineer to visit the failure site to check the optical fiber using an optical time-domain reflectometer. An innovative monitoring technique for tree-structured network topology in Ethernet passive optical networks (EPONs) by using the erbium-doped fiber amplifier to amplify the traffic signal is demonstrated, and in the meantime, a residual amplified spontaneous emission spectrum is used as the input signal to monitor the optical cable from the central office. Fiber Bragg gratings with distinct center wavelengths are employed to reflect the monitoring signals. Faulty branches of the tree-structured EPONs can be identified using a simple and low-cost receiver. We will show that this technique is capable of providing monitoring range up to 32 optical network units using a power meter with a sensitivity of -65 dBm while maintaining the bit error rate of 10^{-13} . © The Authors. Published by SPIE under a Creative Commons Attribution 3.0 Unported License. Distribution or reproduction of this work in whole or in part requires full attribution of the original publication, including its DOI. [DOI: [10.1117/1.OE.52.9.096112](https://doi.org/10.1117/1.OE.52.9.096112)]

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1 Introduction

The passive optical network (PON) is renowned as the best architecture for employing fiber-to-the-home (FTTH) system due to the passive components implementation in the transmission line and optimal fiber infrastructure. By considering the types of multiplexing, PON can be divided into two classes: time division multiplexing (TDM) and wavelength division multiplexing. For PON, there are only passive components between the optical line terminal placed at the central office and the optical network unit (ONU) located on the customer premises. In TDM-PON, a single optical fiber carries all traffic channels to a remote node, where all the channels will be split by a passive optical power splitter into different fibers connected to the ONU. This architecture, which has no electronic components with a tendency to breakdown, is estimated to reduce the operation-and-maintenance expenses (OPEX). Operators do not need to provide and monitor electrical power or maintain extra batteries in this area.^{1,2}

A number of studies have been conducted on several types of monitoring systems in PON. For example, Yao et al.³ claimed that with the implementation of an optical power splitter in PON to split the downstream signals, the spatial information concerning location of fiber flaw occurrence might be missing during channel transmission. This difficulty is one of the drawbacks of applying optical time-domain reflectometer (OTDR) for monitoring and fault locating purposes. Classic OTDR is only suitable for fault location in point-to-point networks.^{4,5}

Numerous fiber fault locations have been recommended for point-to-multipoint PONs. For example, Sankawa et al.⁶

suggested a fault location method using an OTDR for point-to-multipoint networks. However, that approach is hard to implement due to the small loss changes as the number of branches increases. Although this technique is able to locate the fault, it is unable to determine the faulty branch. The multiwavelength OTDR method used a costly arrayed waveguide grating to allocate a distinct wavelength to each branched fiber.⁷ This technique required the waveguide design with specific wavelength features. A monitoring technique that inserts OTDR roles in the transceiver was also implemented in Ref. 8. A technique proposed in Ref. 9 employed embedded OTDR and required ONU modification. Ozawa et al.¹⁰ presented optical link monitoring of PONs using a tunable OTDR. The branch was identified using a tunable OTDR and a wavelength selective reflector was set at the end of each branch. Different filter wavelengths were applied at the ONU. The employment of OTDR into branched PONs brought a number of problems, such as deficiency of dynamic range to monitor the fiber link after the splitter, an extensive measurement time due to averaging to achieve an appropriate OTDR trace, and recurrence of the measurement on several ONUs and the dead zone reflection that cause difficulties in determining the similar-length branches of monitoring reflection peaks.¹¹

Other monitoring schemes based on optical frequency-domain reflectometer have recently emerged. However, it involves either a very coherent laser source for satisfactory measurement range¹² or some complicated modulation schemes superimposed with downstream signal.² A current approach based on interferometric devices located at the optical network (ONTs) relaxes the necessity of the light source linewidth.¹³ However, this method distinguishes

only breakdowns in the network. As a marginal approach, a self-injection-locked reflective semiconductor optical amplifier located at each ONU was recommended.¹⁴ However, this method requires a protocol extension and therefore is not applicable to all PON protocols.

An FTTH monitoring based on Zigbee wireless sensor network was also presented in Ref. 15. It uses a low-cost device, real-time monitoring, automatic restoration, and fast detection time. Sensors are inserted in every line to ensure the operation of networks. However, the employment of active devices in the design is less preferred due to power efficiency. Optic to radio frequency converters in the optical sensor will also cause a higher loss.

In Ref. 16, a monitoring technique based on fiber Bragg gratings (FBGs) and semiconductor optical amplifier (SOA) was demonstrated. The monitoring system configuration is as shown in Fig. 1. The amplified spontaneous emission (ASE) spectrum of the SOA is used as the monitoring signal. Each branch in the network will reflect a unique reflection spectrum and is analyzed using optical spectrum analyzer (OSA). However, the use of OSA for the analysis of the reflection spectrum is quite expensive and less preferred. In addition, the additional ASE spectrum also increases the cost.

Another monitoring technique proposed in Ref. 17 uses ASE spectrum of S-band erbium-doped fiber (EDF) as the monitoring signal with distinct FBGs at each ONU to reflect the monitoring signal. The system configuration is as shown in Fig. 2. The S-band erbium-doped fiber amplifier (EDFA) module comprises two stages of EDFA. The first stage fiber with a length of 20 m can provide low noise figures and medium gain by forward pumping. The second stage fiber with 30-m length will produce large output power by backward pumping. In order to reduce backward ASE and improve noise figure performance, an optical isolator is inserted between the two stages. This fiber Fabry-Perot (FFP) filter provides wavelength selection in the ring laser cavity by applying an external voltage (<12 V) on the piezoelectric transducer of the FFP filter. The results are detected by an OSA with a 0.05-nm resolution. This system requires complicated and costly S-band EDF and the use of OSA, which will also increase the monitoring cost. The number of ONUs is also restricted by the limited bandwidth of the S-band EDFA.

Another fault identification scheme was also conducted in Ref. 18, as illustrated in Fig. 3. This technique uses the unused EDFA gain as the monitoring signal and the integrity

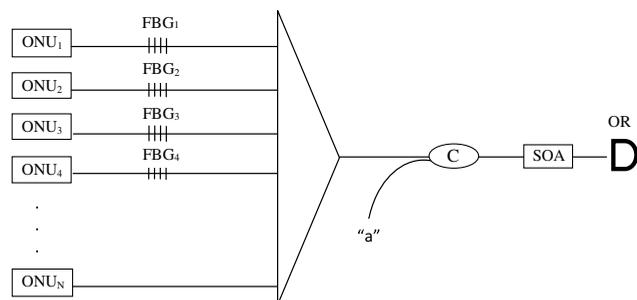


Fig. 1 Fiber laser sensor is utilized to monitor the fiber faulty of tree-structured PON. OR is the optical reflector, C is the bidirectional 3-dB Coupler, OLT is the optical line terminator, and ONU is the optical network unit. The OSA is placed at point "a."¹⁶

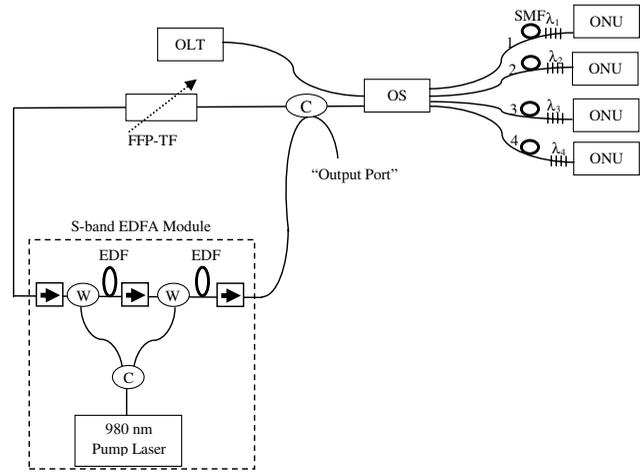


Fig. 2 Experimental setup of the proposed S-band erbium-doped fiber (EDF) laser scheme for monitoring the fiber fault in passive optical networks (PONs).¹⁷

of the distribution fiber or branch is analyzed by observing the power level of the monitoring signal using a power meter. The light source is constructed by looping back some of the EDFA emission to its input through a tunable Fabry-Perot etalon filter (FPF), thus producing a gain-clamped saturated laser emission with wavelength tuning by applying a periodic saw-toothed voltage of a few kilohertz to the FPF. The gain-clamped signal is for sweeping through the unused EDFA gain spectrum periodically and thus works as a wavelength-sweeping monitoring light source. An FBG of distinct center reflection wavelength is located at the end of each fiber branch as the branch identifier. When the FBG center wavelength is equal to the wavelength sweeping monitoring source, an optical pulse is then generated and reflected to a monitoring photodiode. However, a constraint of this system is that the maximum length of each fiber branch is limited to 12.5 km. It also requires FBGs with stable thermal response and can be obtained by using abtemperature-compensated package, but will increase the cost of the monitoring system. The number of users that can be served is also limited to the EDFA spectrum and tunable Fabry-Perot (FP) bandpass filter specification.

From the monitoring schemes mentioned above, it can be concluded that the previous monitoring techniques are high in cost and a limited number of users can be served. This motivates this research into designing a simple, low-cost, and efficient monitoring system that can monitor a greater number of ONUs for tree-structured TDM-PONs.

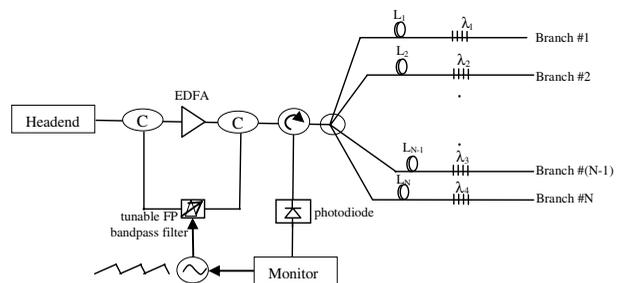


Fig. 3 Fiber fault monitoring scheme for an optical amplified branched network.¹⁸

In this article, we demonstrate a new monitoring technique of tree-structured network topology in TDM-PONs to detect optical fiber failure using residual ASE signal which is generated from the EDFA in the system while dedicated FBG is employed at each branch in the network to create the reflected signal. The signals were recorded by using a simple and low-cost receiver design which comprises an automatic tunable FBG (tunable filter) and a power meter. By observing the power level of the reflected signal from the dedicated FBGs and by using the low-cost receiver, we are able to determine any breakdown that may occur in any branch of the ONUs. OTDR was incorporated in the system so that fault localization can be measured. The following section describes several current trends of fiber fault monitoring techniques, whereas the proposed fault monitoring design system is described in detail in Sec. 2. Section 3 examines the results and analysis of the system performance, followed by a conclusion.

2 Fiber Fault Monitoring System Design

The proposed monitoring system utilizes the unused ASE spectrum of the EDFA as a monitoring signal. The signals were reflected by the dedicated FBGs. Only a tunable filter (tunable FBG) and a power meter are applied to monitor the monitoring signal. Figure 4 shows the proposed fiber fault TDM-PONs monitoring system simulated using Optisystem. The system consists of the downstream signal centered at 1550 nm that is transmitted and amplified in the C-band EDFA's region. The unused ASE spectrum is used as the monitoring signal. The monitoring signal is

transmitted through the FBGs. Each FBG has a distinct center wavelength and is located at the end of the branch as the branch identifier. The length of the feeder fiber is fixed at 23 km, whereas the length of the distribution fiber varies from 0.4 to 2 km, as illustrated in Fig. 4. The FBGs will reflect the monitoring signals via a circulator to the monitoring unit. In the monitoring unit, the signal is automatically filtered using a tunable FBG filter at specific Bragg wavelength. The signal will be then analyzed using a power meter. When a fault is detected, an optical switch will automatically exchange the path to OTDR so that the fault can be located. In this way, the faulty branch can be detected and the location of the fault can be identified.

In this monitoring system, a distributed feedback (DFB) laser downstream signal with center wavelength of 1550 nm and optical power of -40 dBm is used. The downstream signal is amplified using a C-band EDFA and the amplified spectrum of the signal is as shown in Fig. 5 below. The unused spectrum of the EDFA is used as the monitoring signal.

In this simulation, a C-band EDFA, operating at wavelength of 1528 to 1563 nm, is used to amplify the downstream signal, and in the meantime, the unused ASE spectrum is used as the monitoring signal. For eight branches of ONUs, eight FBGs are used with distinct center wavelength ranges from 1556 to 1559.5 with 0.5 nm spacing. The bandwidth of each FBG is 0.4 nm. A PC controlled tunable FBG is used as the automatic tunable filter to filter the signal in accordance with the FBG wavelengths. An optical power meter with sensitivity of -65 dBm is capable of being applied in this monitoring system.

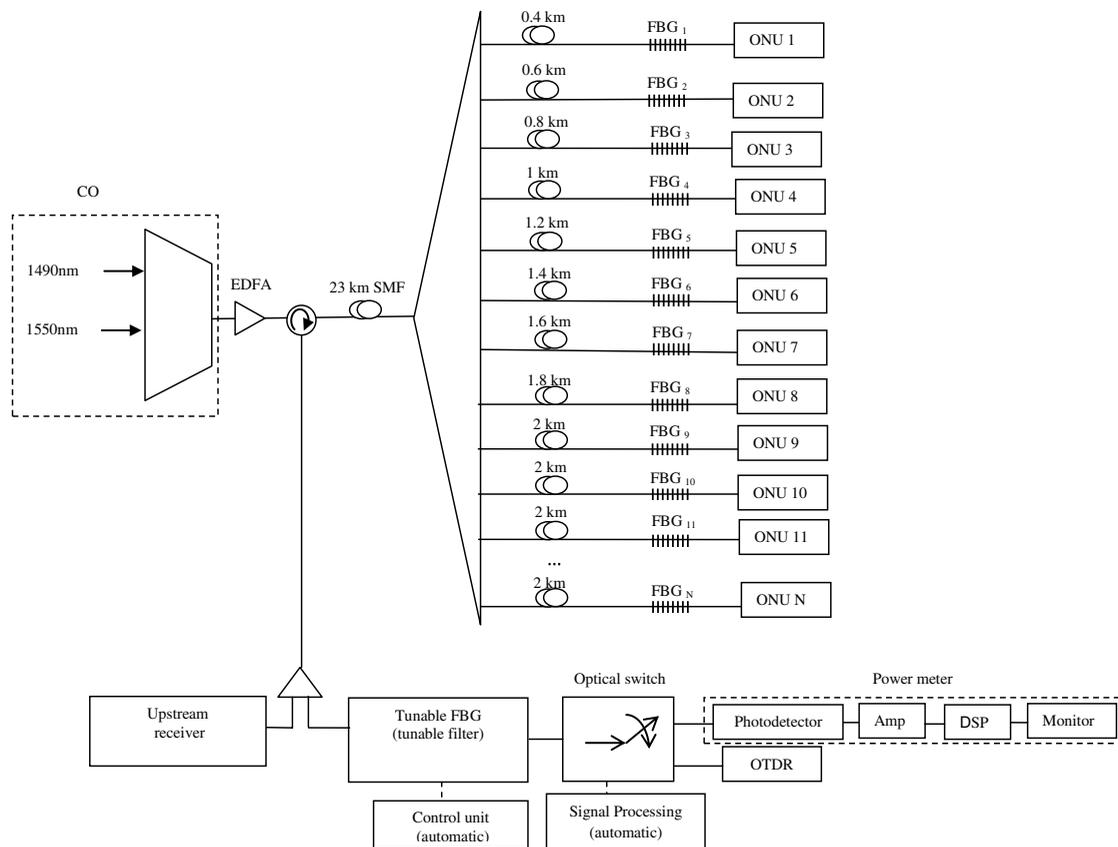


Fig. 4 Block diagram of time division multiplexing (TDM)-PON monitoring system. SMF is the single-mode fiber and ONU is the optical network unit.

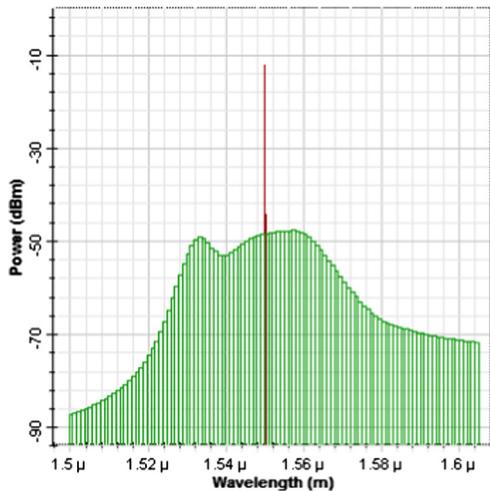


Fig. 5 The amplified spectrum of 1550-nm downstream signal.

3 Results and Discussion

In this section, the performance of this monitoring system is analyzed. The power budget for this system was investigated for the first branch of eight ONUs. The power was measured using an optical power meter. All loss values mentioned were based on typical values. Basically, the mean input power of the 1550-nm DFB laser was -43 dBm and it was amplified to 9.4 dBm using an EDFA. The attenuation loss for the 23.4 km optical fiber (forward and backward path) was measured as 0.2 dB/km \times 23.4 km \times $2 = 9.4$ dB. The circulator insertion loss (forward and backward path) was 1 dB \times $2 = 2$ dB. The insertion loss for the power splitter (forward and backward path) was 9.6 dB. The optical switch insertion loss was 0.7 dB. At the monitoring receiver, another 1×2 splitter with a 3 dB loss was applied. The pass-through loss of the FBG was 0.1 dB, and the FBG reflected loss was 17.1 dB. The tunable filter insertion loss was 9.2 dB. Thus, the monitoring signal received at the power meter was -41.6 dBm. A simulation for 32 ONUs was conducted and it was found that the lowest monitoring power received was -55 dBm. The power degradation of ~ 10 dB indicates that there is a fiber breakdown in the network. Thus, a power meter with sensitivity of -65 dBm was suitable for monitoring the monitoring signal.

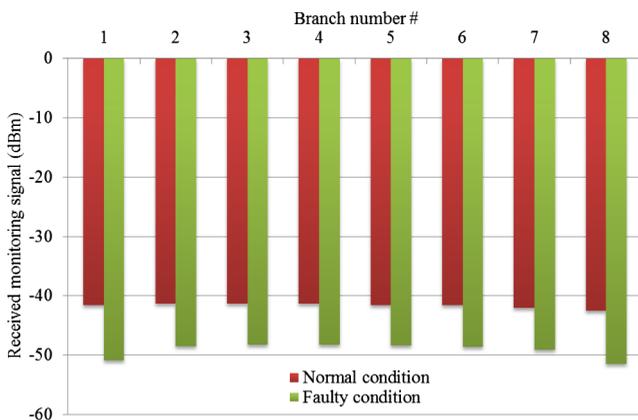


Fig. 6 The received monitoring signal at the specific branch during normal condition and when there is a fault in the network.

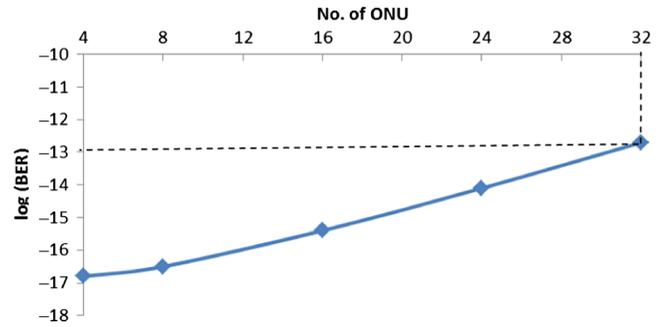


Fig. 7 Bit error rate (BER) versus number of ONUs with the monitoring system.

Figure 6 shows the monitoring signal power received at each branch by using a power meter during normal conditions and when there is a fault at each branch in the network. A different power meter value is achieved due to the unflattened gain profile of the ASE spectrum. It can be seen that during normal conditions at branch #1, the monitoring power received was -41.6 dBm and when there is a fault at that branch, the received monitoring power decreases to -50.9 dBm. When the power meter value has a decrement of at least 7 dB or maximum degradation of ~ 10 dB, this means that there is a fault at a specific branch in the network.

A bit error rate (BER) analyzer is inserted at the end before each ONU in order to observe the performance of the system. Figure 7 shows the BER versus number of ONUs with the monitoring system. As the number of ONUs increases, the BER will also increase and the performance

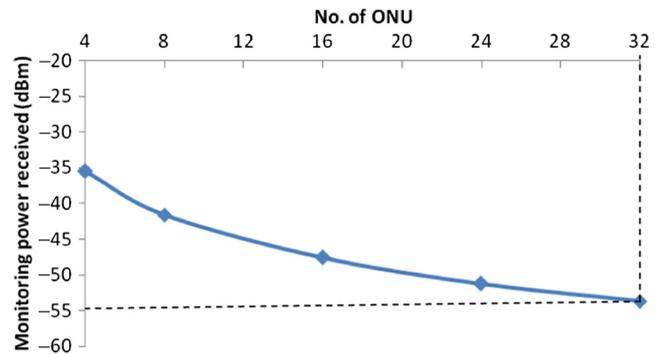


Fig. 8 The received monitoring power that is measured using a power meter versus number of ONUs.

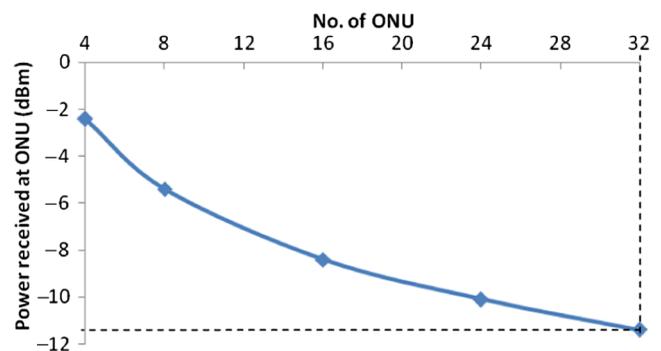


Fig. 9 The received downstream signal power versus number of ONUs.

Table 1 Comparison of different monitoring techniques in terms of complexity and their power budget.

	Radio frequency self referencing + fiber Bragg gratings (FBGs) ²²	U-band monitoring ²³	Brillouin optical time-domain reflectometer (OTDR) + Brillouin-shifted fibers ²⁴	Tunable OTDR + FBG ²⁵	ONT with embedded OTDR ²⁶	Our proposed FBGs + OTDR
Equipment cost and complexity	Very low	High	Very high	Very high	High	Very low
Number of elements	High	Low	High	High/low	Very low	Low
Outside plant modification	Yes (simple)	No	Yes (very complex)	Yes (very simple)	Yes (complex)	Yes (simple)
Impact on power budget	Medium	Medium	Very low	Low	Very low	Low

of the system will degrade. The BER curves show that the BER for 32 ONUs is -13 dB or 10^{-13} . Thus, this system can be performed for up to 32 ONUs as it is lower than the standard maximum BER for Ethernet passive optical network (EPON) which is 10^{-9} .

Figure 8 illustrates the received monitoring power versus number of ONUs. There is a decrement in the monitoring power received as the number of ONUs increases. Figure 8 depicts that the minimum detectable monitoring power for 32 ONUs is -55 dBm. Based on Ref. 19, we choose an optical power meter with a sensitivity of -65 dBm as the degradation of power level of ~ 10 dBm indicates a fiber breakdown. It can be concluded that up to 32 ONUs can be monitored by using the power meter¹⁹ as compared to the monitoring system, which applied a costly tunable OTDR that can monitor up to 16 ONUs.²⁰

Figure 9 shows the downstream signal power received versus the number of ONUs. Again, the downstream received power diminishes as the number of ONUs increases. The allowable receiver sensitivity in EPON for 20-km downstream signal is -27 dBm.²¹ From Fig. 7, the received downstream signal power for 32 ONUs is -11.4 dBm. Thus, this monitoring system is suitable to be applied for a maximum of 32 ONUs as the received signal is lower than the standard value.

Table 1 shows a comparative analysis of different monitoring techniques used in terms of their complexity and power budget. From the table, we can conclude that this monitoring technique is the simplest technique with a low number of monitoring components and a cost-effective approach with a low impact in terms of power budget. Although outside plant modification is necessary, the modification is quite simple and low in cost. In conclusion, it can be summarized that this monitoring system is capable of monitoring up to 32 ONUs by using a power meter with -65 dBm sensitivity. The received downstream signal power for 32 ONUs is -11.4 dBm with BER of 10^{-13} . However, system performance can be increased by using a more sensitive power meter.

4 Conclusion

This monitoring system comprises EDFA, which is used to amplify the downstream signal power, whereas the residual ASE signal generated from the EDFA is used as the monitoring signal. The monitoring part comprises a low-cost

receiver, an automatic tunable FBG acting as a tunable filter and a power meter to detect faults that may occur in the network. An optical switch will automatically switch to OTDR when a fault is detected. Thus, the fault can be located using the OTDR after signal processing in the control unit. This monitoring system is suitable to be implemented in TDM-PON with a bit rate of 1.25 Gbps. By using a power meter with a sensitivity of -65 dBm, the maximum number of ONUs that can be monitored is 32 ONUs with minimum monitoring received power of -55 dBm, and a received downstream signal power of -11.4 dBm while maintaining the BER of 10^{-13} . This centralized monitoring system has a simple design configuration and low equipment cost. System performance may be increased by using a higher sensitivity power meter.

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