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Real-time Monitoring of Ethernet Passive Optical Network Using Burst-mode FBGs

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This paper describes a real-time monitoring system in Ethernet passive optical networks (EPON) that uses burst-mode fiber Bragg grating (FBG) optical sensors. The FBG interrogation unit in the optical line terminal (OLT) transmits the monitoring wavelength to optical network units (ONUs). The FBG sensor unit in each ONU returns a burst-mode monitoring signal to the OLT. As the system applies time division multiple access (TDMA), a uniform Bragg wavelength can be used to monitor the EPON system. The FBG interrogation unit analyzes the received burst-mode monitoring signals and outputs fault information on the ONU branches in EPON. The simulation results show the effectiveness of the proposed monitoring system based on TDMA. In addition, we compared the proposed TDMA-based monitoring system with a WDMA-based monitoring system.

Keywords : Real-time monitoring, Ethernet passive optical network, Burst-mode fiber Bragg grating
OCIS codes : (060.3735) Fiber Bragg gratings; (060.4250) Networks; (060.4510) Optical Communications

I. INTRODUCTION

The access network is a segment of the network that connects commercial and residential subscribers to the central office (CO). A passive optical network (PON) is the most flexible, scalable, and future-proof optical access technology that involves point-to-multipoint topology. Time division multiplexing (TDM)-based PON is the most mature and cost-effective solution when compared to wavelength division multiplexing (WDM) PON, hybrid PON, and orthogonal frequency division multiplexing (OFDM) PON [1].

Ethernet PON (EPON) is a PON-based network that carries data traffic encapsulated in Ethernet frames. An EPON system consists of an optical line terminal (OLT) located at the central office (CO), a number of optical network units (ONUs) near end users, and one or multiple optical splitters [2, 3]. In the downstream direction, the OLT broadcasts Ethernet frames and the ONUs selectively receive their frames. Meanwhile, in the upstream direction, each ONU transmits traffic to the OLT during timeslots exclusively assigned to it. Hence, time division multiple access (TDMA) is used in the upstream direction to avoid frame collisions.

Several fault monitoring methods use fiber Bragg grating (FBG) sensors in PON. For example, one study reported on a network surveillance system [4]. This method requires the use of a high cost amplified spontaneous emission source as the monitoring signal, which is reflected by a FBG and monitored by a WDM analyzer. Another study reported on a fiber-fault monitoring technique for PON based on FBG sensors [5]. By monitoring the number of instances of wavelength lasing, the optical fiber-fault of the branches can be detected without affecting the in-service channels. A different study presented a monitoring system for tree-structured passive optical networks using a low-cost superluminescent LED [6]. It uses uniform FBG and phase-shifted FBG spectra that act as branch identifiers. Another real-time monitoring system for EPON has been presented [7]. This monitoring system uses a distributed feedback (DFB) laser with high side lobes as the monitoring signals. The wavelengths of the reflection spectrum of FBGs with different spectrum shape and amplitude are used to differentiate distribution fibers in the network. However, this method requires expensive DFB laser arrays to implement in the OLT. Another efficient monitoring method using optical frequency domain reflectometer (OFDR) and FBG

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sensors has been described [8]. This monitoring method uses OFDR at the OLT and interferometer units at the ONU. Each interferometer unit includes a uniform FBG and creates a periodic beat signal with a unique beat frequency on the OFDR trace that is used to evaluate the integrity of the corresponding branch. Another centralized real-time monitoring system with low bandwidth requirement of monitoring source for TDM-PON has been presented [9]. This technique also employs an OFDR interferometer based on FBG for P2MP monitoring. A fault monitoring system for PON based on a burst-mode FBG sensor has been presented [10]. This monitoring method uses a superluminescent LED as the monitoring source at the OLT and burst-mode FBG sensor units at the ONU.

In this paper, we proposed a real-time monitoring system in EPON using a burst-mode uniform FBG sensor unit. The system uses Fabry-Perot LD as the monitoring source. By transmitting the reflection signal of the burst-mode uniform FBG sensor to the OLT during the timeslot period allocated to each ONU, TDMA data transmission and TDMA monitoring signal transmission can proceed simultaneously. The rest of this paper is organized as follows: In Section II, we introduce the operation of FBG and the application of the FBG sensor, then propose the fault monitoring method using a burst-mode FBG sensor unit. Section III presents the simulation results of the proposed monitoring system and the conventional monitoring system in EPON. The final conclusions are then discussed in Section IV.

II. MONITORING SYSTEM OF EPON

A fiber Bragg grating, as shown in Fig. 1, is a type of distributed Bragg reflector constructed in a short segment of optical fiber. When broadband light is transmitted to an FBG sensor, it reflects particular wavelengths of the light and then transmits all others. The reflected wavelength, referred to as the Bragg wavelength, is defined as follows [11]:

$$\lambda_B = 2n_e \Lambda \quad (1)$$

where λ_B is the Bragg wavelength, n_e is the effective refractive index of the grating in the fiber core, and Λ is the grating period.

The FBGs can be used as sensing elements in an optical fiber sensor because the Bragg wavelength is sensitive to strain and temperature. The relative shift in the Bragg wavelength, $\triangle\lambda_B/\lambda_B$, due to an applied strain (ϵ) and a change in temperature (ΔT), is expressed as follows [12]:

$$\Delta\lambda_B/\lambda_B = (1-p_e)\cdot\epsilon + (\alpha_\Lambda + \alpha_n)\cdot\triangle T \quad (2)$$

where $\Delta\lambda_B$ is the wavelength shift, λ_B is the initial wavelength, p_e is the strain-optic coefficient ($p_e \approx 0.22$), ϵ is the strain experienced by the grating, α_Λ is the thermal expansion coefficient ($\alpha_\Lambda \approx 0.55 \times 10^{-6}$/°C), and α_η is the thermo-optic coefficient ($\alpha_\eta \approx 8.6 \times 10^{-6}$/°C).

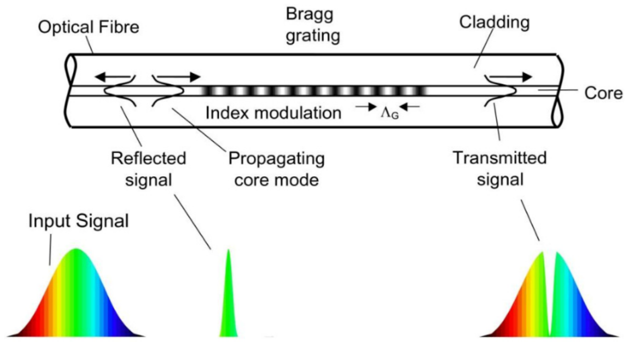

FIG. 1. Schematic diagram of fiber Bragg grating.

The primary application of FBGs is in optical communications systems. FBGs can be used as notch filters, multiplexers, and demultiplexers with an optical circulator, or they can be used in an optical add-drop multiplexer (OADM). They are also used in fault monitoring of optical communications systems, especially in TDM-PON systems. A conventional fault monitoring system of TDM-PON with FBG sensors uses WDM or OFDM technology [4-9]. In this case, each ONU branch is identified by the distinct Bragg wavelength of each FBG sensor.

The proposed TDM-based monitoring system of EPON is shown in Fig. 2. Because TDMA is applied for upstream data transmission of EPON, the burst-mode uniform transmitters are used for every ONU. Hence, the use of a burst-mode transmission technique is necessary for the uniform FBG sensor units of ONUs. The OLT, which is located at the central office, transmits downstream data using the 1490 nm wavelength and transmits video data using the 1550 nm wavelength to the ONUs, and receives upstream data using the 1310 nm wavelength transmitted from ONUs. The FBG interrogation unit in the OLT uses a Fabry-Perot LD as a monitoring source and transmits on the 1650 nm wavelength to the ONUs.

The optical signals reflected from the FBG sensor units of ONUs are amplified by an optical amplifier, such as the bismuth-doped fiber amplifier (BDFA), to support more fiber branches and to compensate the transmission and splitting losses. The amplified signals are transmitted to the optical spectrum analyzer (OSA) or signal processing unit through the FBG burst-mode optical receiver. Upon detection of fiber branch failure, an optical time-domain reflectometer (OTDR) can be used for fault localization of EPON [13]. WDM multiplexer/demultiplexer devices in OLT and ONUs are used to both join and split the several signals of the 1310 nm, 1490 nm, 1550 nm, and 1650 nm wavelengths.

The ONUs receive the downstream data using the 1490 nm wavelength and transmit the upstream data using the 1310 nm wavelength. For upstream data transmission, the

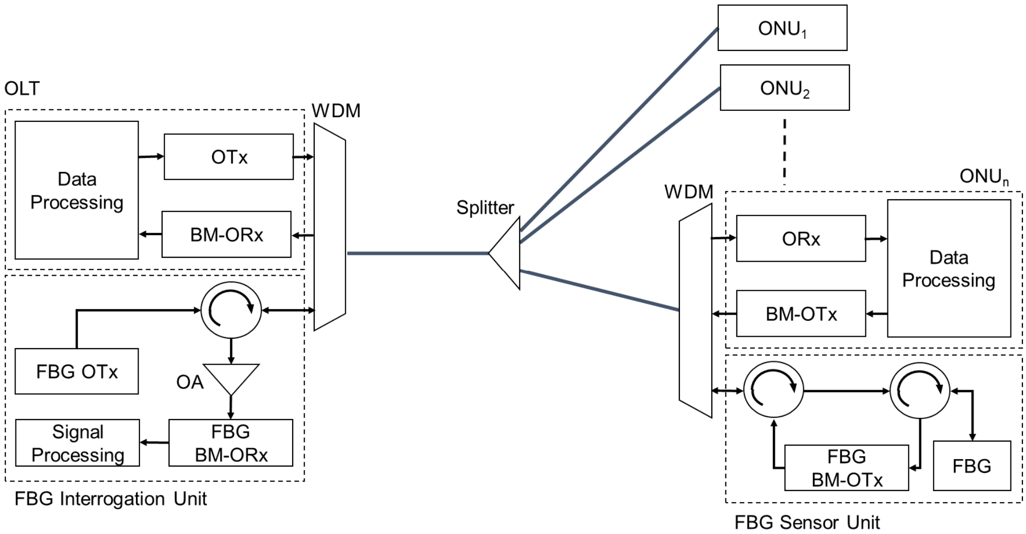

FIG. 2. PON monitoring system using burst-mode uniform FBG sensors.

data are transmitted during the dedicated timeslot allocated to each ONU by the OLT. The FBG sensor units in ONUs uses two circulators, an external modulator and a uniform FBG sensor. Two circulators are used to receive the optical signal and transmit the Bragg wavelength of 1650 nm. An external modulator, such as the Mach-Zehnder modulator, is used to transmit the modulated signal to the OLT. For fault monitoring of an EPON system, burst-mode uniform FBG sensor units are used in every ONU. The FBG sensor signal is also transmitted during the dedicated timeslot allocated the each ONU by the OLT. The burst-mode enable signal from the burst mode transmit block of ONU is applied to make the burst-mode FBG sensor module.

The OLT uses a multi-point control protocol (MPCP) to assign a timeslot to each ONU [2]. Several bandwidth allocation algorithms have been proposed in attempts to improve upstream data transmission performance [14-16]. Because dedicated timeslots are used to transmit upstream data, the burst mode transmission of the monitoring signal can be applied from ONUs to the OLT. The FBG interrogation unit in the OLT transmits the monitoring signal of 1650 nm to the ONUs, and the FBG sensor unit in each ONU returns the Bragg wavelength of 1650 nm during the dedicated timeslot to the OLT.

III. SIMULATION

The proposed monitoring system of EPON using burst-mode uniform FBG sensors is simulated with OptiSystem simulation software. Let us consider a situation in which four ONUs are connected to an OLT and the EPON line rate is 10 Gbps. The distances between the OLT and the four ONUs are 14 km, 16 km, 18 km, and 20 km, respectively. The FBG interrogation unit is located at the central office and the FBG sensor units are equipped in the ONUs. The output power of the FBG interrogation unit is set to 13.5 dBm and the wavelength of 1650 nm with the bandwidth of 10 nm is assigned. The bandwidth of the FBG sensor is set to 0.01 nm. The attenuation coefficient of the fiber is set to 0.2 dB/km and the insertion loss of the circulators and the WDM multiplexers/demultiplexers is set to 1 dB. The loss of the 1×4 splitter is set to 6.2 dB. The default simulation parameters are listed in Table 1.

TABLE 1. Simulation parameters

Parameter	Value
Number of ONUs	4
EPON line rate	10 Gbps
Distance between the OLT and an ONU	14~20 km
Monitoring wavelength	1650 nm
Bandwidth of monitoring signal	10 nm
Transmitter power of FBG interrogation unit	13.5 dBm
Bandwidth of Bragg wavelength	0.01 nm

Figure 3 shows a simulation design of an OLT and FBG interrogation unit. In the FBG interrogation unit, an optical circulator is used to transmit and receive the 1650 nm monitoring signal from the ONUs. Figure 4 shows a simulation design of an ONU and FBG sensor unit which uses a burst-mode uniform FBG sensor with the Bragg wavelength of 1650 nm. For burst mode operation of the FBG sensor unit, the burst mode enable signal is applied from the ONU transmitter to the FBG sensor unit. This means that the timeslot for upstream data transmission is also used for monitoring signal transmission from ONUs to the OLT. We assume that a static bandwidth allocation or fixed timeslot allocation is applied, and that the allocated timeslot for each ONU is 10 nsec.

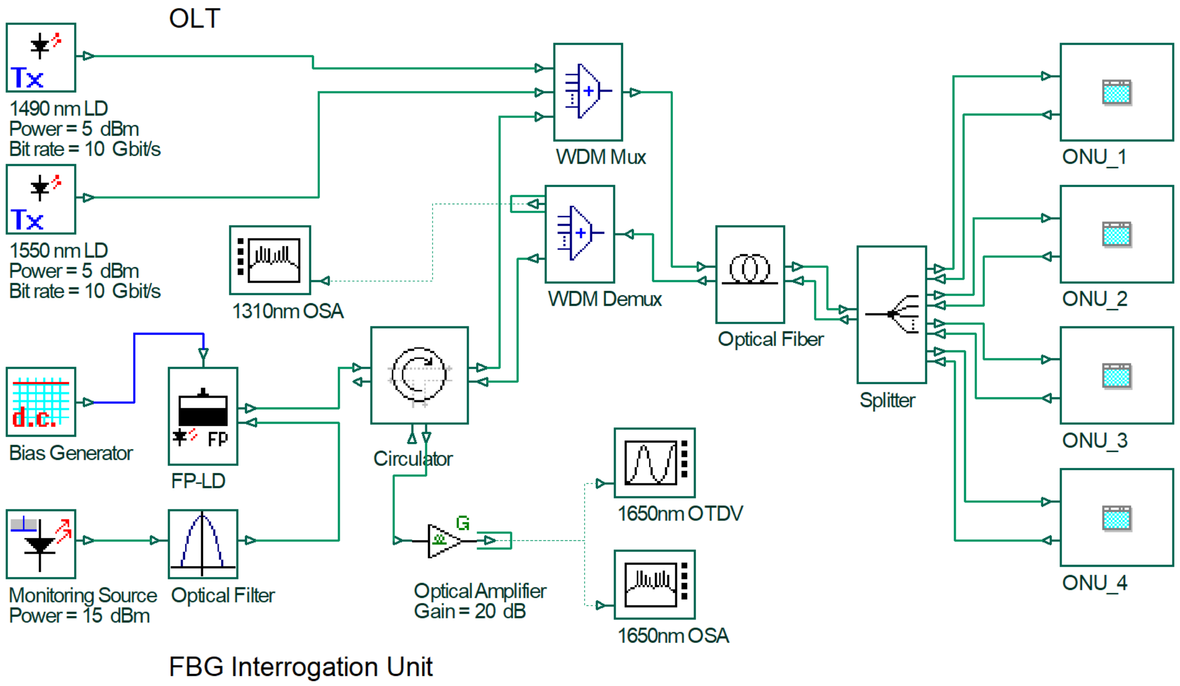

FIG. 3. Simulation design of OLT and FBG interrogation unit.

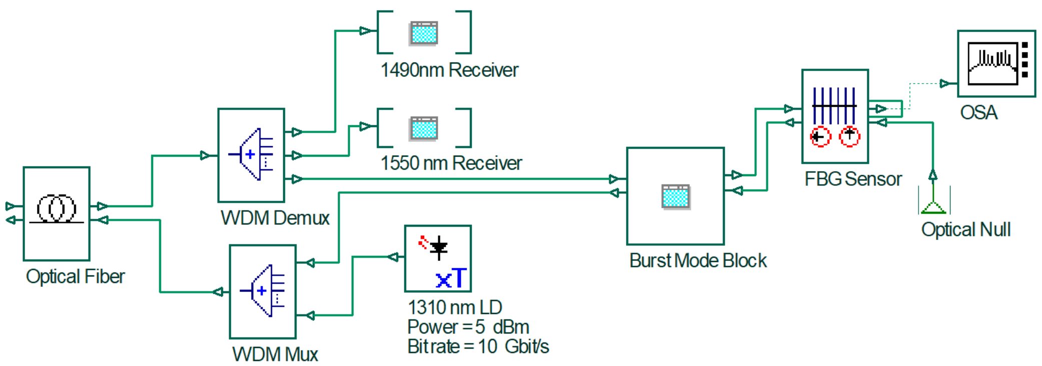

FIG. 4. Simulation design of ONU and FBG sensor unit.

The first simulation is performed for the conventional WDM-based monitoring system of EPON [4-7]. Because four different FBGs are used, the Bragg wavelength of each FBG sensor is assigned as 1648.91 nm, 1649.58 nm, 1650.03 nm, and 1650.63 nm. In the case of normal operation, the output spectrum of the WDM-based monitoring system of EPON is shown in Fig. 5. The received optical powers of the center wavelengths of the four FBGs are -14.96 dBm, -15.77 dBm, -17.19 dBm, and -17.97 dBm, respectively. This is attributed to the different distances between the OLT and the ONUs. The intensity of the reflected signal power decreases as the distance from OLT to ONU increases. The attenuation loss for the 2 km optical fiber is measured as 2 km × 0.2 dB/km × 2 = 0.8 dB.

In the case of fault operation of ONU_2, the output spectrum of the WDM-based monitoring system of EPON is shown in Fig. 6. Because ONU_2 has an optical fault, no optical signal is observed from ONU_2 to the OLT. The received optical signals from ONU_1, ONU_3, and ONU_4 are the same as those in the case of normal operation. By analyzing the optical spectrum, the optical fault monitoring of each ONU can proceed easily. However, the WDM-based sensor signal transmission in TDM-based PON is not a low-cost monitoring solution because a uniform FBG module is required in each ONU.

The second simulation is performed for the proposed TDM-based monitoring system of EPON. A burst-mode uniform FBG sensor is used in each ONU, and the Bragg wavelength of 1650 nm is assigned. In the case of normal operation, the output spectrum of the TDM-based monitoring system of EPON is shown in Fig. 7. The optical spectrum analyzer shows only one reflected FBG signal of 1650 nm, because a burst-mode uniform FBG sensor is used in each ONU. The peak reflected power of

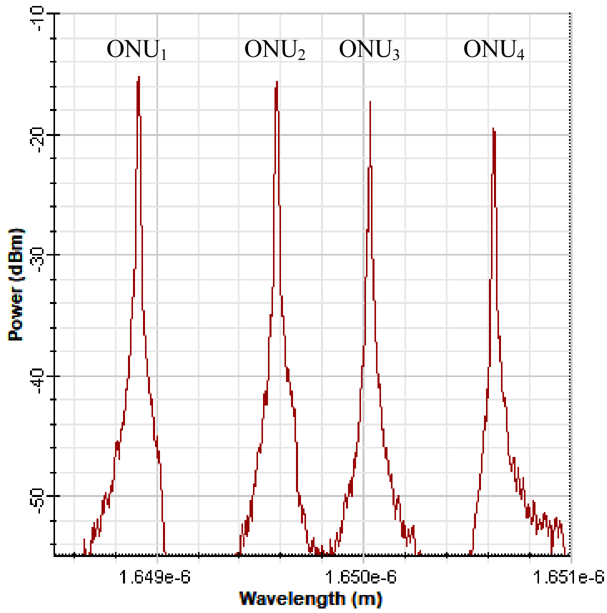

FIG. 5. Output spectrum of WDM-based monitoring system in normal operation.

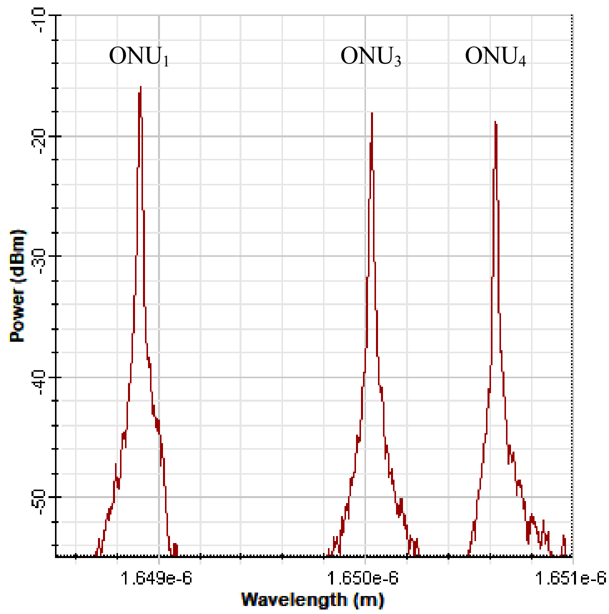

FIG. 6. Output spectrum of WDM-based monitoring system in fault operation of ONU_2.

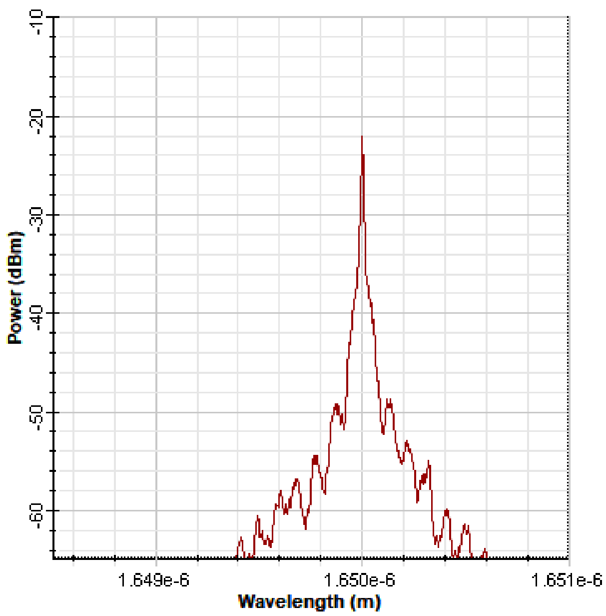

FIG. 7. Output spectrum of proposed TDM-based monitoring system in normal operation.

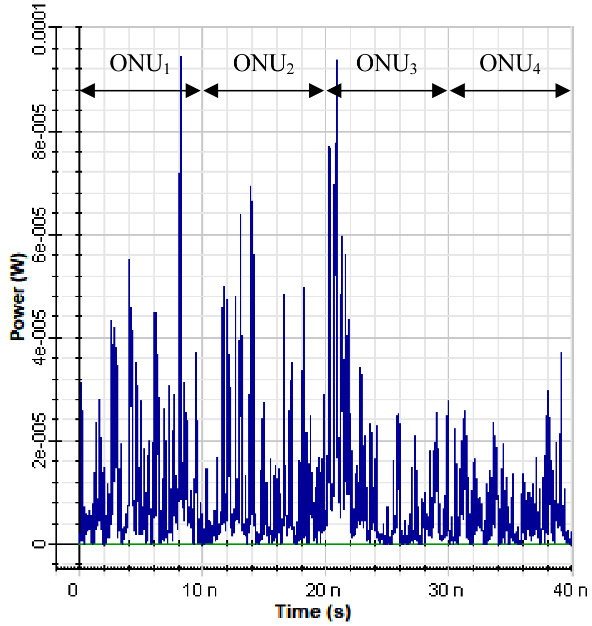

FIG. 8. Output signal of proposed TDM-based monitoring system in normal operation.

-22.03 dBm is lower than that of WDM-based monitoring system. This is because two circulators and an external modulator are used in a TDM-based monitoring system. The circulator insertion loss in each ONU is 1 dB × 3 = 3 dB. Additional loss is attributed to the MZI modulator. The monitoring signal of the TDM-based monitoring system of EPON is shown in Fig. 8. Because the fixed timeslot of 10 nsec is allocated for each ONU, the burst mode monitoring signal is returned continuously to the FBG interrogation unit with the period of 40 nsec.

In the case of fault operation of ONU_2, the output signal of the TDM-based monitoring system of EPON is shown in Fig. 9. Because ONU_2 has an optical fault, no optical signal is observed during 10~20 nsec. The optical signal can be seen during each timeslot except for the second timeslot. This indicates that ONU_1, ONU_3, and ONU_4 are in the normal operation and that ONU_2 is in the fault operation. The combination of the TDM-based data transmission and the TDM-based sensor signal transmission allows the deployment of the uniform ONUs with the

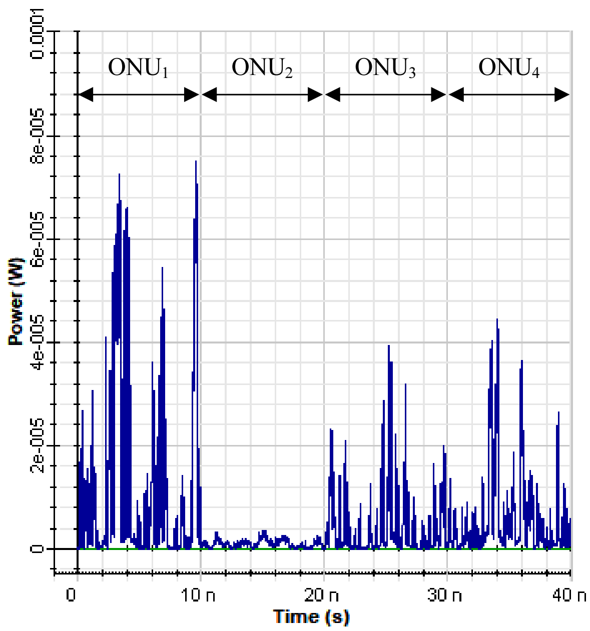

FIG. 9. Output signal of proposed TDM-based monitoring system in fault operation of ONU_2.

TABLE 2. FBG characteristics

Type of FBG	Bragg wavelength	Distance between OLT and ONU	Received optical power
FBG1	1648.91 nm	14 km	-14.96 dBm
FBG2	1649.58 nm	16 km	-15.77 dBm
FBG3	1650.03 nm	18 km	-17.19 dBm
FBG4	1650.63 nm	20 km	-17.97 dBm
Burst-mode FBG	1650.00 nm	14~20 km	-22.03 dBm

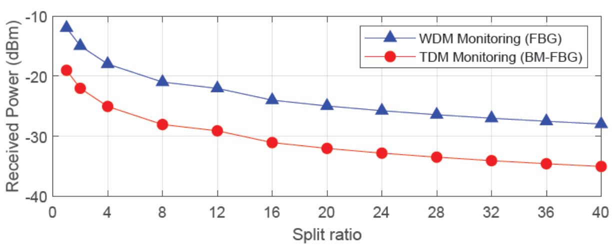

FIG. 10. Received power of FBG based monitoring system of EPON.

uniform FBG sensors. The proposed TDM-based monitoring system can support more fiber branches, such as 1 × 32 splitter, 1 × 64 splitter.

In the conventional WDM-based monitoring system [7], expensive DFB laser arrays and differentiated FBGs are used to monitor the fiber faults of ONUs. On the other hand, the proposed TDM-based monitoring system uses a Fabry-Perot LD as a monitoring source in the OLT and burst-mode uniform FBGs in the ONUs. Table 2 shows the FBG characteristics of the first and second simulations. In these two simulations, Fabry-Perot laser diode is used as the common monitoring source in the OLT. The received optical power of burst-mode FBG is 7.07 dB lower than that of the FBG1. Even though the loss of burst-mode FBG is about 7 dB greater than that of conventional FBG, burst-mode FBG sensor enables the proposed monitoring system to be integrated into EPON system and controlled by the OLT using MPCP protocol. Figure 10 shows the received powers of WDM and TDM based monitoring systems. It is found that TDM based monitoring system with burst-mode FBG sensor can be applied for EPON with 32 ONUs.

IV. CONCLUSION

In this paper, we propose a new method for monitoring the physical layer faults between the OLT and ONUs in EPON. The FBG interrogation unit, which is located at the CO, serves as the light source for FBG optical sensors in ONUs and also analyzes the reflected monitoring signal from the ONUs. We proposed a new design of burst-mode FBG sensor unit. The burst-mode FBG sensor module enables ONUs to transmit burst-mode monitoring signal to the OLT. By using burst-mode FBG, the TDM-based upstream data transmission and the TDM-based monitoring signal transmission are applied for a simple and cost-effective monitoring system of EPONs. The simulation results reflected the performances of the conventional WDM-based monitoring system and the proposed TDM-based monitoring system of EPONs. The proposed TDM-based monitoring system can be integrated into EPON system and controlled by the OLT using MPCP protocol because of the usage of the burst-mode FBG sensor.

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