Analysis of Optical Frequency Domain Reflectometry (OFDR) Interferometer for Passive Optical Network (PON) Monitoring

Faris Aiman Asha'ari, Nani Fadzlina Naim, and A.Ashrif A. Bakar

***Abstract*—This paper presents the design of Optical Frequency Domain Reflectometry (OFDR) interferometer for Passive Optical Network (PON). This monitoring system is anticipated for Point-to-Multipoint (P2MP) network monitoring. The interferometer is designed based on Fiber Bragg Grating (FBG) which are placed in every distribution fibers and one FBG is placed at the receiver. The FBGs reflections spectra will produce beat frequencies which will distinguish the branches. By comparing the Distributed Feedback (DFB) Laser and Light Emitting Diode (LED) at 1530nm centre wavelength as the monitoring source, the spectra produced by both monitoring sources were observed in the RF spectrum analyzer. It is found that the system is capable to monitor up to 64 customers with the downstream power received of -24.5 dBm and 0.08 dB of excess power margin.**

***Index Terms*—Optical Frequency Domain Reflectometry (OFDR); Fiber Bragg Grating (FBG); Point-to-Multipoint (P2MP); Passive Optical Network (PON); RF Spectrum Analyzer;**

I. INTRODUCTION

PON has been widely used in the communication system. It must also be very reliable to ensure there is no disturbance in consumer daily usage [1]. Standard P2MP PON consist of Optical Line Terminal (OLT) and Optical Network Unit (ONU). The data services are transferred from OLT to ONU along the feeder fiber. Before reaching the ONU, the optical power is split to multiple output along the distribution fibers via optical splitter. To ensure the quality and reliability of the communication services, especially the fiber optics based infrastructure for high-speed data and information distribution, there were many research to develop monitoring systems to detect the fiber fault in PON [2].

OFDR is one of the techniques to measure back reflections spectra from optical fiber components. The early prototype of OFDR consist of optical source, local oscillator, device under test, and spectrum analyzer. In this monitoring system which is based on OFDR, local oscillator and device under test are made of FBG. RF spectrum analyzer is used to visualize the signals in frequency domain.

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The conventional technique is by using Optical Time Domain Reflectometry (OTDR) which is known to be very good at detecting fiber failure for Point-to-Point (P2P) network. OTDR is not the best solution for P2MP network monitoring because of the problem to identify multiple branches [3]. There were many improvements in OTDR method to be embedded in P2MP network but the monitoring system becomes more complex and less cost-effective [4]. But, for the P2MP network, there are some difficulties in fiber break detection. As the number of the splitting ratio increase, the light source which is used specifically for monitoring purpose will degrade as it reaches the receiver. The monitoring system in P2MP network also needs high bandwidth of monitoring source

Multiple monitoring techniques had been introduced. The major technique that had been given multiple stages of improvement is the OTDR. One of the technique is by using tunable laser and single wavelength OTDR. In [5], the tunable laser is the monitoring source of the system and OTDR is the visualizer to display the back-reflected signal. This method detects the failure and calculates the distance of fiber cut. But it has trouble in determining the fault location because of the superimposition of the signals from all branches in P2MP.

In [6], it introduces an improvement over the standard OTDR which is called the Embedded OTDR. This system uses optical transceiver modules for OTDR measurement. The result generated from complex computer arithmetic shows the signal including the distance and length of the fiber. But the demonstration provided for P2P network only.

Another technique which the major improvement of OTDR in P2MP network monitoring is Brillouin OTDR. In [7], the system uses an algorithm called Brillouin Frequency Shift (BFS) in the signal computing. They demonstrated the result with 8 signals indicates 8 branches PON. But, this technique required complex design and algorithm with multiple components for signal processing. PON with a larger number of branches is not promised to be embedded with this technique.

PON monitoring system based on Optical Coding was introduced [8]. They use different encoder made of FBGs at each branch as the branch identifiers to be decoded by the network recognition algorithm at the receiver. The method was the new improvement over the previous optical decoders and was claimed to reduce the power loss. The authors attached the diagram of the spectra that showed the overall received signals.

But the signals that distinguish the branches were not in the array. The signals were also overlapped each other to generate higher peak than other signals. This technique requires intricate analyzation.

Another technique in PON monitoring system is by using Self-Injection Reflective-Semiconductor Optical Amplifier (SL-RSOA). In [9], without using another dedicated monitoring source, they utilize the upstream data signals for identification. The results signify the situation that indicated both normal and failure fiber condition. Although it was declared that the effect on upstream transmission was minor, this is not the best option for the fiber fault detection system since it still has a negative impact on the performance parameters.

Another technique by using FBG's reflection spectrum as the branch identifier is presented in [10]. The authors used same Bragg wavelength but different FBG's bandwidth and reflectivity for every 2 branches to minimize the bandwidth source requirement. However, this system still needs 10.8 nm bandwidth of the Amplified Spontaneous Emission (ASE) source to monitor up to 32 customers. Besides, the employment of Optical Spectrum Analyzer (OSA) as the receiver is less preferred due to high cost and high bandwidth requirement [11].

In [12], the OFDR technique monitoring system for PON was demonstrated. By using Tunable Laser (TLS) as the monitoring source and the interferometer based on FBG and an optical reflector placed in each branch, the beat frequency generated was used as the branch identifier. They demonstrated 3 signals that indicate 3 branches and show the difference between normal and faulty condition. They also included the temperature information based on FBGs wavelength measurement in their analysis. They also validate a complex signal processing by using Inverse Fast Fourier Transform (FFT) to convert the signals into frequency domain.

The monitoring system for PON that employ OFDR method is presented in this paper. Higher spatial resolution and sensitivity are the main advantages of OFDR [13]. The objective of this project is to design a cost-effective OFDR interferometer based on FBG. Then, analyze the beat frequency produced by the reflection spectra on the RF spectrum analyzer. In addition, this PON monitoring system is able to monitor large number of customers by using narrow bandwidth of the monitoring source. In this paper, the comparison between two different monitoring sources which are Distributed Feedback (DFB) Laser and Light Emitting Diode (LED) as the monitoring source are also demonstrated.

II. OPERATIONAL PRINCIPAL

OFDR interferometer based on FBG monitoring system is embedded in TDM-EPON based on network architecture that was designed in the Optisystem photonic simulation software. The implementation of the FBG in each branch is presented in the system design. The FBGs will act as the sensor to reflect various center wavelength back to the receiver. To apply the interferometer concept, FBGx with fixed Bragg wavelength is installed before the coupler as shown in Fig. 1. This single reflection spectrum will interfere with the combined reflection spectra from all branches. The interferometer concept is by interfering 2 signals with different frequencies to create a beat signal [14]. Thus, generating distinct beat frequencies that will be distinguished the branches.

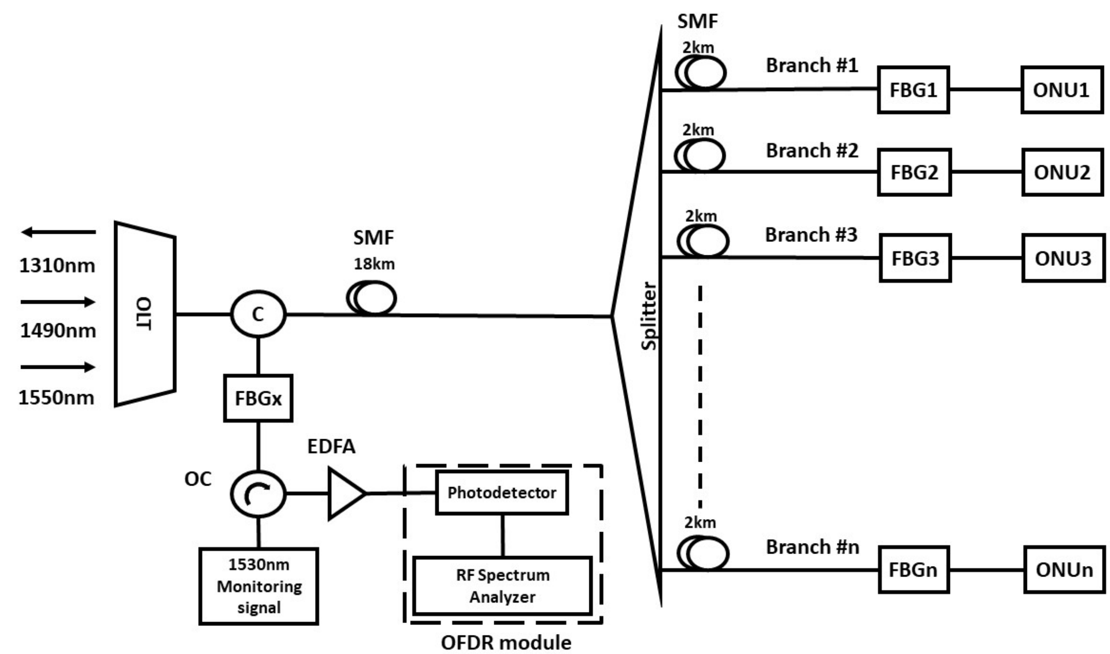

Fig. 1.Block Diagram of PON monitoring system consist of Optical Line Terminal (OLT), Coupler (c), Fiber Bragg Grating (FBG), Single Mode Fiber (SMF), Splitter, Optical Oscillator (OC), 1530nm of monitoring signal, Erbium Doped Fiber Amplifier (EDFA), Photodetector, RF Spectrum Analayzer, and Optical Network Unit (ONU)

Fig. 1 shows the block diagram of the designed PON which consists of Optical Line Terminal (OLT), Single Mode Fiber (SMF), splitter and Optical Network Unit (ONU). The components that are included in PON for fiber fault monitoring purposes are a coupler, an optical circulator, 1530nm monitoring signal, Fiber Bragg Grating (FBG), Erbium Doped Fiber Amplifier (EDFA) and OFDR module which contains the Photodetector and RF spectrum analyzer. The coupler is used to inject the monitoring signal into the fiber to be distributed to all branches. The circulator will direct the received spectra to the OFDR module for visualization process. The EDFA will amplify the signal for higher amplitude signal.

The FBGx that is located before the coupler will reflect larger bandwidth of the 1530nm monitoring source for the merging spectra from all branches with higher reflectivity to generate constructive interference which will result in a beat signal. In this experiment, we test with two different light sources which are LED and DFB laser to determine the beat frequencies produced by both sources. Fig. 2 shows the spectrum of LED source with the (blue line) and DFB source with the (green line) at 1530nm center wavelength. LED is a cost-effective broadband source while DFB laser is a narrowband laser source.

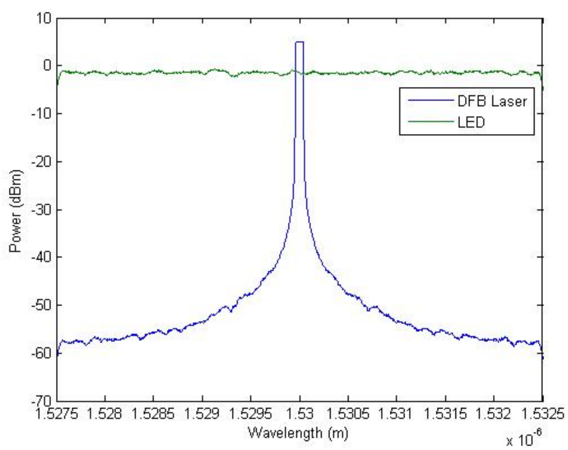

Fig. 2. Spectrum of DFB laser and LED at center wavelength of 1530nm

FBGx has fixed 1530nm Bragg wavelength and was set with higher bandwidth and lower reflectivity than the FBGn. Thus, the reflected signal of FBGx will have enough bandwidth to interfere with other FBGs reflected spectra from all branches in the distribution fibers. The Bragg wavelength of FBGs in the distribution fibers was set with lower bandwidth and high reflectivity to reduce the noise when the constructive interference occurs.

Equation (1) is used to calculate the beat frequency, Δf which will determine the beat frequencies between all branches in the RF spectrum analyzer. Lambda, λ is the centre wavelength of the FBGx which is 1530nm. Delta lambda, $\Delta\lambda$ is the difference between FBGn and FBGx. C is the speed of light which is 299792458 m/s.

$$\Delta f = \frac{c(\Delta\lambda)}{\lambda^2} \quad (1)$$

III. RESULT AND DISCUSSION

Optisystem simulation software is used and FBGs with different center wavelength is placed in each distribution fibers. This experiment was conducted using PON with 4 ONU, 8 ONU, 16 ONU, 32 ONU, and 64 ONU. By using two different types of monitoring source, the beat signals produced by both sources are observed. The result is exported from RF spectrum analyzer in the Optisystem as text files. Then, the data from the text file were copied to Matlab to plot the graph.

Fig. 3 to Fig. 7 shows the comparison between LED and DFB laser as the monitoring source in the 4, 8, 16, 32, and 64 branches network, respectively. The spectrum (green line) presents peaks generated from LED source while the signals (blue lines) presents peaks generated from DFB Laser. The amplitude of the signals produced by the LED is higher than DFB laser. This is because the LED is a broadband source.

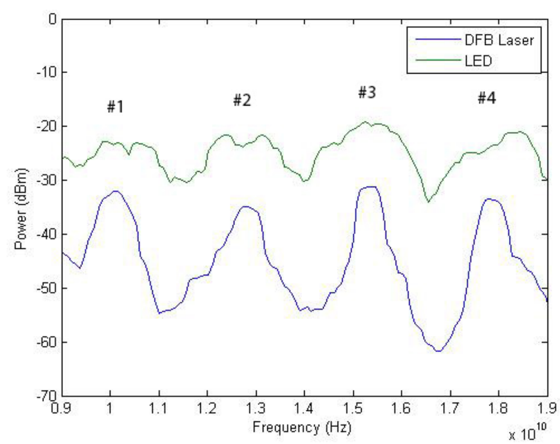

Fig. 3. FBGs reflection spectra for 4 branches network. Green lines show the spectrum produced by LED source while blue lines show spectrum produced by the DFB laser

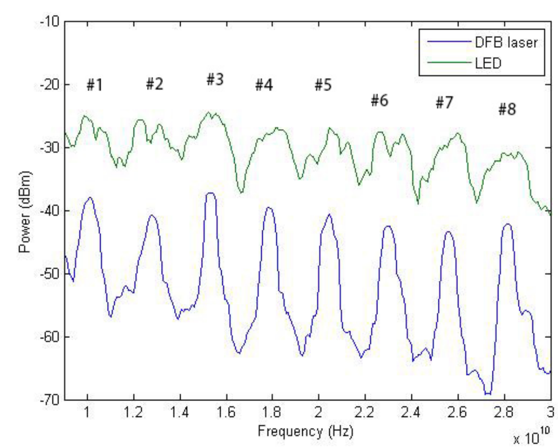

Fig. 4. FBGs reflection spectra for 8 branches network. Green lines show the spectrum produced by LED source while blue lines show spectrum produced by the DFB laser

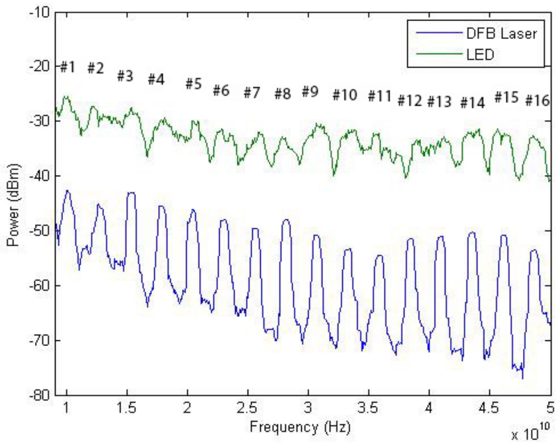

Fig. 5. FBGs reflection spectra for 16 branches network. Green lines show the spectrum produced by LED source while blue lines show spectrum produced by the DFB laser.

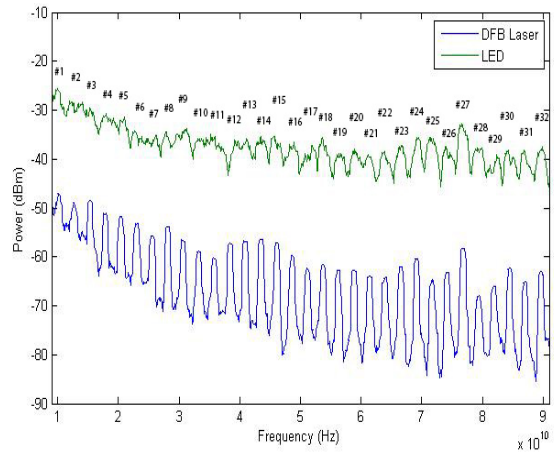

Fig. 6. FBGs reflection spectra for 32 branches network. Green lines show the spectrum produced by LED source while blue lines show spectrum produced by the DFB laser.

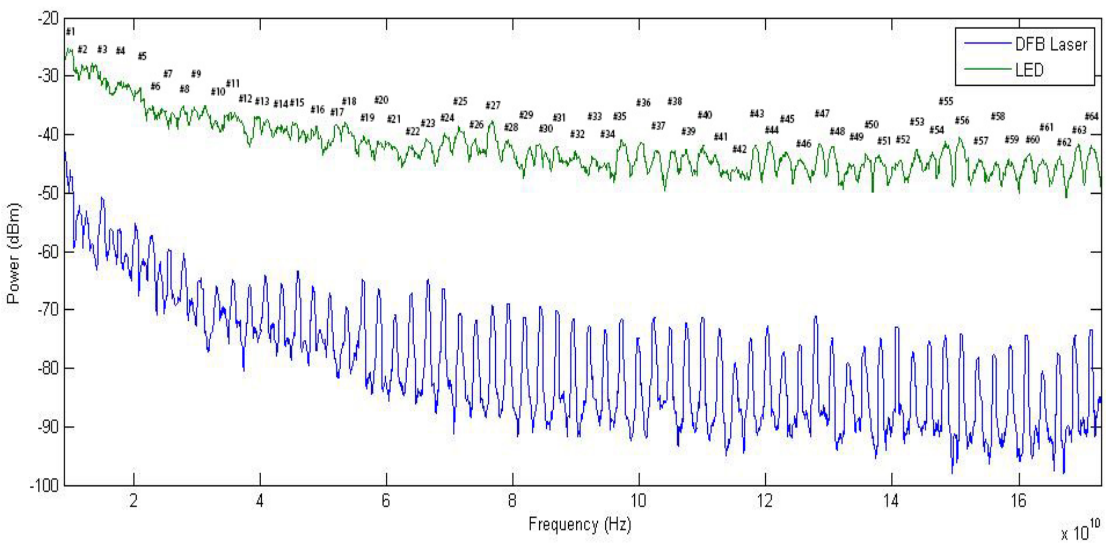

Fig. 7. FBGs reflection spectra for 64 branches network. Green lines show the spectrum produced by LED source while blue lines show spectrum produced by the DFB laser

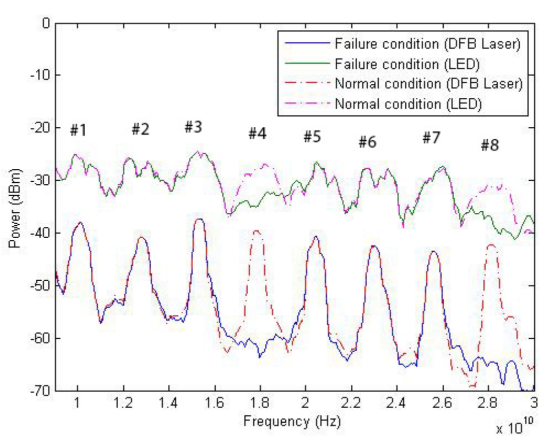

Fig. 8. FBGs reflection spectra for 8 branches network. This diagram shows that there are fiber failures at branch #4 and #8 which is at 17.9 GHz and 28.2 GHz, respectively

Therefore, the amplitude of the signal throughout the band is also almost constant. Every center wavelength assigned to each FBGs in the distribution fibers taken from the LED monitoring source were consistent in power and amplitude. Hence, with consistent signals power, the reflected spectrum produced by the FBG is also high and consistent in amplitude. The case is different as compared with DFB laser, it is a narrowband source. Although the power of center frequency of the laser is higher than LED, the sideband is less power. The center wavelength assigned to the FBGs taken from DFB laser as the monitoring source is not uniform as it gets lower until it reaches to the maximum sideband.

Based on Fig. 8, we demonstrated the difference between normal and failure conditions for both signals produced by LED and DFB Laser. We can see that there are 8 peaks for both signals represent 8 ONUs. The purple dash-dot lines represent normal condition for the signal produced by LED and red dash-dot lines represent normal condition for signal produced by DFB laser. The breakdown is located at 4th and 8th ONU's which is marked by #4 and #8 marker for both signals. We can see that the amplitude of the signals are decreased in the 4th and 8th peaks at 17.9GHz and 28.2 GHz indicates that there is breakdown at both branches. From Fig. 8, it can be observed that the signal-to-noise ratio (SNR) for DFB laser is higher as compared to LED. This is due to characteristics of DFB laser which has high amplitude at 1530 nm and lower amplitude at the side lobes. Thus, it produces a higher SNR spectrum in the RF spectrum analyzer. Thus, DFB laser is a more suitable choice of monitoring source as it has higher SNR and can easily be observed for fiber failure detection.

Fig. 9 shows the graph for 1490nm downstream signal power received versus number of users. To observe the power transmitted, Wavelength Division Multiplexing (WDM) analyzer was placed before the ONU. The diagram indicated that the power received is inversely proportional to the number of the user. The higher the number of users, the lower the power received. The network with 64 customers has the lowest power received at -24.5 dBm. A higher number of splitting ratio contribute to higher optical splitter insertion loss.

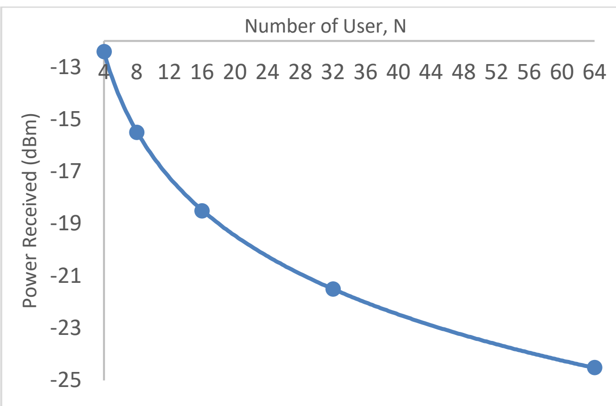

Fig. 9. Power received (dBm) versus Number of user, N

Fig. 10 shows the graph of the monitoring power (1530nm) at the OFDR module versus the number of user. To measure the power, WDM analyzer was placed at the receiver before RF spectrum analyzer. As illustrated in the diagram, the overall monitoring power received for the DFB laser source is -8 dBm for network with 4, 8, 16, 32, and 64 ONUs. Even the number of customers in the network grow higher, the monitoring power received is consistent due to placement of FBGx that reflected high power direct to the receiver.

Fig. 11 illustrates the graph of excess power margin versus number of splitting ratio. The components in between the OLT and ONU produced losses. The losses created by coupler, optical fibers, splitter with 64 splitting ratios and FBG are 0.25dB, 4dB, 20.1dB and 0.15dB. The power transmitted is 0.58dB. As the number of splitting ratio increase, the excess power margin decrease. It can be established that with the excess power margin of 0.08dB, 64 ONUs can be monitored.

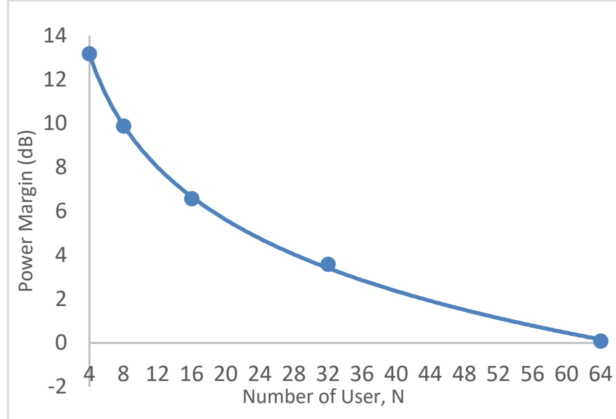

Fig. 10.Number of user,N versus Monitoring power received (dBm)

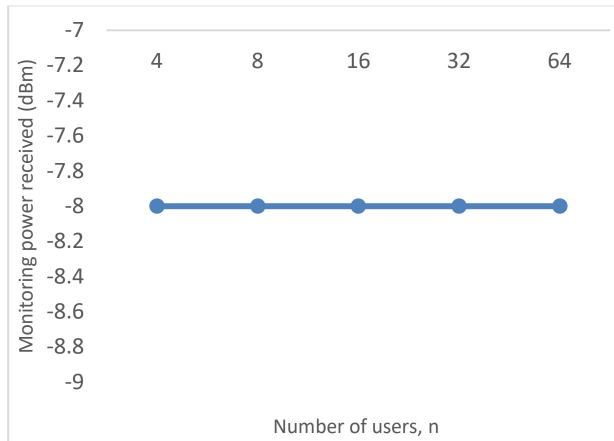

Fig. 11. Power Margin (dB) versus Number of user, N

IV. CONCLUSION

For PON monitoring system, the OFDR interferometer which utilizes the interference concept to produce beat signal is presented. The OptiSystem software is used to simulate the PON design that had been embedded with the OFDR interferometer. Each FBG is assigned with specific center wavelength so that the reflected signal will produce different value of beat frequency for different branch. By using the RF spectrum instead of OSA, the estimated cost for this system has been reduced. From the signals produced by both DFB Laser and LED, we can conclude that DFB laser is a better choice as monitoring source instead of LED in terms of Signal-to-Noise Ratio (SNR). Even the number of customers in the network increased, the DFB laser source has no difficulty to produce the beat frequency for each branch as compared to the LED source. When there is fiber fault, the amplitude of signal decreased. It is found that by using both monitoring source, this system is capable to monitor up to 64 customers with power received of -24.5 dBm and excess power margin of 0.08 dB.

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REFERENCES

[1] R. Kaur and S. Dewra, "A Review on Passive Optical Network," pp. 2773–2779, 2015.

[2] M. M. Rad, K. Fouli, H. A. Fathallah, L. A. Rusch, and M. Maier, "Passive optical network monitoring: Challenges and requirements," *IEEE Commun. Mag.*, vol. 49, no. 2, pp. S45–S52, 2011.

[3] N. F. Naim, J. K. Elektrik, and E. Sistem, "Passive Optical Access Network Monitoring Using L- Band ASE Source with Fiber Bragg Grating," no. December, pp. 16–17, 2013.

[4] M. P. Fernández, L. A. B. Rossini, J. P. Pascual, A. Pablo, and C. Caso, "DSP-Enhanced OTDR for Detection and Estimation of Events in PONs," vol. 8400, pp. 1–10, 2017.

[5] B. Tonello, E. Autizi, F. Chiarello, A. Galtarossa, L. Palmieri, and M. Santagiustina, "MONITORING OF WDM PONs BY MEANS OF A SINGLE WAVELENGTH OTDR AND A TUNEABLE LASER," no. Figure 2, pp. 2–5.

[6] H. Schmuck, J. Hehmann, M. Straub, and T. Pfeiffer, "Embedded OTDR techniques for cost-efficient fibre monitoring in optical access networks," *2006 Eur. Conf. Opt. Commun. Proceedings, ECOC 2006*, pp. 10–11, 2006.

[7] N. Honda, D. Iida, H. Izumita, and Y. Azuma, "In-service line monitoring system in PONs using 1650-nm brillouin OTDR and fibers with individually assigned BFSs," *J. Light. Technol.*, vol. 27, no. 20, pp. 4575–4582, 2009.

[8] X. Zhou, F. Zhang, and X. Sun, "Centralized PON monitoring scheme based on optical coding," *IEEE Photonics Technol. Lett.*, vol. 25, no. 9, pp. 795–797, 2013.

[9] M. Thollabandi, K. W. Shim, S. Hann, and C. S. Park, "A surveillance technique based on spectral analysis of SL-RSOA for PS-PON," *2008 IEEE PhotonicsGlobal Singapore, IPGC 2008*, no. 1, pp. 2–4, 2008.

[10] N. F. Naim *et al.*, "Real-Time Monitoring System for Ethernet Passive Optical Access Network," pp. 6–8, 2015.

[11] N. F. Naim, A. Najad, S. Seroja, and N. Ya, "Optical Network Monitoring System using Residual Power of EDFA and Fiber Bragg Gratings," pp. 102–106, 2017.

[12] K. Yüksel, M. Wuilpart, V. Moeyaert, and P. Mégret, "Novel monitoring technique for passive optical networks based on optical frequency domain reflectometry and fiber Bragg gratings," *J. Opt. Commun. Netw.*, vol. 2, no. 7, p. 463, 2010.

[13] B. Huttner, B. Gisin, O. Guinnard, N. Gisin, R. Passy, and J. P. Von der Weid, "Optical frequency domain reflectometer for characterization of optical networks and devices," *ComTec*, vol. 77, no. 1, pp. 20–23, 1999.

[14] A. Reza, S. Tofighi, M. Bathaee, and F. Farm, "Optical Fiber Interferometers and Their Applications," *Interferom. - Res. Appl. Sci. Technol.*, 2012.