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Execution Simulation Design of Fiber-to-the-home (FTTH) Device Ingress Networks Using GPON with FBG Based on OptiSystem

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***Abstract*—Consumers require high-speed data transmission for different activities, such as smartphone usage, live broadcasting of news, and video conferencing. Therefore, a reliable communication network is needed to provide this kind of service to users. Fiber to the home (FTTH) is an optical fiber architecture that uses fiber cables in the access network for direct and final connection to homes or offices of customers. Networks based on FTTH can offer high performance, speed, and quality. An optical fiber communication system based on FTTH device ingress network using gigabit passive optical networks (GPONs) with fiber Bragg grating (FBG) and optical amplifier is designed and analyzed in this study. The developed design based on the FTTH device and FBG shows a low bit error rate (BER) for downstream and upstream configurations with an optical fiber length of 20 km. Downstream and upstream configurations achieve a Q-factor of 89.5 and 181.3, respectively. Achievable sensitivity of the developed system is −28 dBm, while the received signal based on OptiSystem is −25.59 dBm. FTTH with FBG will play a major role in the future and provide effective solutions for a wide variety of applications in network communication systems and data transmission rates.**

***Keywords*—fiber to the home; fiber Bragg grating; power link budget; Q-factor; gigabit passive optical networks**

I. Introduction

OPTOELECTRONICS and telecommunications have attracted considerable attention from researchers and manufacturers due to their considerable progress in commercial applications for optical fiber components and improved data transmission rate [1]. Optical fiber cable has low loss compared to electrical transmission lines. Optical fibers have many properties such as: immunity to electromagnetic interference, and resistance to corrosive and flammable environments as well as reactive, which are suitable for applications of optical fiber communication systems [2]. The optical fiber communication system, which was first developed in 1970, has been continuously implemented in many new applications and installations [3]. The demand for high transmission rates, long transmission distances, high speeds, and large transmission bandwidths has increased with the development of optical fiber communication technology [4].

Optical fiber to the home (FTTH) is a fiber optic network configuration distributed to customers at home or a station site that provides triple-play and intensive services of broadband internet, television, and latency-sensitive telephone services [5].

FTTH networks are a new technique that can provide gigabit passive optical network (GPON) technology [3] with high speed data rate for home and company users. The FTTH offer is unmatched given that all types of data, such as TV, Internet, and telephony, are provided with a single connection. Furthermore, fiber optic cables from a central office through a fiber distribution hub (FDH) and network access point (NAP) to the home via a terminal, which serves as a junction box, is the fundamental construction of FTTH access networks [5].

The enhancement of signal quality based on fiber Bragg grating (FBG) technology has become an essential touchable research area. FBG is a new technology that applies multi-disciplinary cross technology and offers unique wavelength multiplexing capability for the installation of optical data bus networks [6, 7]. Moreover, FBG is characterized by small size, light weight, implantable structure, multiplexity, and absence of electromagnetic interference [3, 4, 8].

At present, the demand for high-speed data rate of communication has been increasing due to customer requirements for numerous applications, such as live broadcasting, video streaming on the Internet, and video conferencing. W. Awalia and A. B. Pantjawati [8] designed a communication network for FTTH devices to investigate system performance parameters of bit error rate (BER), quality factor (Q-factor), and power link budget resulting from the OptiSystem simulator. The researchers applied a length of 17 km with a wavelength of 1490 and 1310 nm for downstream and upstream configurations, respectively, in their parameter simulation process; obtained a maximum Q-factor for the downstream configuration of 6.8; and analyzed and tested the performance of the FTTH device network design with an optical fiber length of 17 km.

A noble technology design for FTTH devices with FBG and optical amplifier (OA) is developed and implemented in this study to meet international standards and needs of users. Therefore, the main focus of this project is to test the performance of GPON networks of FTTH devices with an implementation of FBG and OA for upstream and downstream configurations using the OptiSystem software simulator. OptiSystem software is applied to model the developed design precisely; investigate eye diagrams, the minimum value of BER, and Q-factor; calculate the power link budget; and enhance the network performance. Finally, the performance of total attenuation, power margin, and receiving power for the entire input power of the system is analyzed.

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II. FTTH Communication Systems

FTTH is a new home optical fiber technology that reaches the user's residence and provides optimal and the latest optical communication network system in terms of transmission rate quality. This novel technology for transmitting unlimited amounts of data and information inside glass wires at very high speeds equivalent to the speed of light can download movies and programs in seconds [9]. FTTH is a passive network with wide bandwidth and advantages, including flexible protocols, high stability of Internet connection, low loss, imaginative speed, and immunity against external interference (rain, storms, winds, and snow), due to its use of optical fiber cables [10].

FTTH devices aim to send and receive all types of data for the user through optical fiber cables from the central office to homes (central call center of the house). Accordingly, FTTH is an optical signal transmission format from the provider center to the user area that uses optical fiber cables as channels. The FTTH technology improves with the innovation of fiber optic systems that use copper wires for triple-play services [11]. The application of optical fiber communications requires the transmission of information from one place to another. However, optical fiber is used by many telecommunication companies to transmit telephone, Internet communication, and cable television signals. Figure 1 shows a basic communication system consisting of a transmitter, optical fiber cable used as communication channel or transmission line, and a receiver.

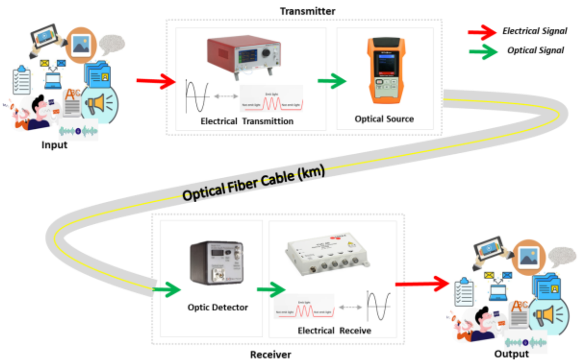

Fig. 1. Block diagram of an optical fiber communication system

The FTTH configuration consists of several main devices. The first device is optical line termination (OLT) that serves as the end-point of the passive optical network service and provides an interface between passive optical network (PON) systems and service providers (video, data, or voice/phone services). The second device is the optical distribution cabinet (ODC), which is a passive composite outdoor or indoor apparatus that operates as a splitter or distribution point of the feeder cable into a distribution cable. The third device is the optical distribution point (ODP) that divides the distribution cable into a drop cable using a 1:8 splitters. The fourth device is optical network unit (ONU)/optical network terminal (ONT), which is a composite apparatus at the customer side [12, 13].

An OLT comprises numerous ODNs that operate for transport and distribution of data from the OLT to the ONU. Passive splitter is a supporting element that assists in the distribution of optical power to all branches [14]. Figure 2 displays the basic network connection of fiber to the home using a passive splitter. As a result, the usage of the single optical fiber starts from the OLT to many customers' houses.

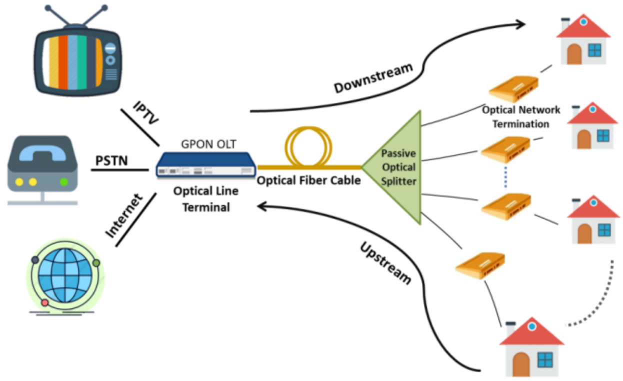

Fig. 2. Connection network of FTTH using a passive splitter

III. FBG Principle Operation

FBGs are used as a specific wavelength reflector of line optical fiber to block certain wavelengths. FBGs are considered excellent sensor elements suitable for measuring various engineering parameters, such as temperature, strain, pressure, tilt, displacement, acceleration, and load, as well as the presence of different industrial, biomedical, and chemical substances. Advantages of using FBGs include perfect signal shaping and filtering element for a growing field of applications, high sensitivity, ideal for harsh environments, small size, easy integration into diverse systems, electrically immune, immunity to electromagnetic and radio frequency interferences, and light in weight [15, 16]. Notably, FBGs are a type of distributed Bragg reflector constructed in a short segment of the optical fiber that reflects particular wavelengths of light and transmits others by creating aperiodic variation in the refractive index (RI) of the fiber core, which generates a wavelength-specific dielectric mirror. Figure 3 shows the principle operation of FBG light with curve spectra of input, transmitted, and reflected signals [15]. Consequently, a small reflected light is concerted into a large reflected light at a certain wavelength. This wavelength is called Bragg's wavelength precisely when the grating period is nearly half the input light's wavelength [17-19]. The remainder of the light is transparent [1, 12, 14].

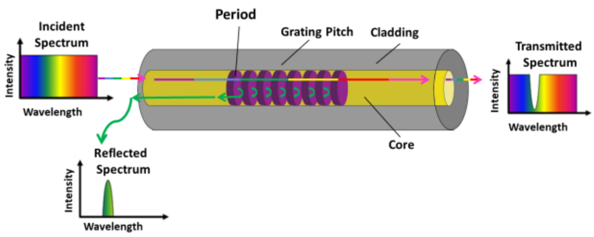

Fig. 3. Principle operation of the FBG light

The grating period or the distance of grating determines the reflected wavelength, which is also known as the Bragg wavelength. The relationship of the Bragg wavelength with the grating period is expressed as follows [20]:

$$\lambda_B = 2n_{eff}\,\Lambda, \tag{1}$$

where λ_B (Bragg grating wavelength) is the free-space wavelength of the input light reflected from the grating, n_{eff} is the effective RI of the fiber core at the free-space center wavelength, and Λ is the FBG grating distance [20].

IV. OPTISYSTEM SIMULATOR

OptiSystem produced by the Optiwave Company in Canada is a comprehensive and constructive software simulator for optical fiber communication that can design, optimize, and test several classifications of optical fiber links in the broad spectrum of physical layers of the optical fiber network. Optical fiber networks are based on the realistic modeling of optical fiber communication systems. OptiSystem is a powerful and novel simulation environment with extensive library tools of active and passive components, including realistic and wavelength-dependent parameter sweeps and optimizations, and composed of great devices and layout descriptions. Long-haul schemes to local and metropolitan area networks are verified through simulations in the OptiSystem [2, 16,18,19, 22].

V. POWER LINK BUDGET

The power link budget, a remarkable and necessary calculation for communication networks, is designed beyond the threshold of the required power. Hence, the power link budget calculation is applied on the basis of ITU-TG.984 standardizations and implemented via industry instruction. The coverage distance is a maximum of 20 km while the receiving power is a maximum of −28 dBm. Consequently, equations (2–4) are used to calculate the power budget link of total damping.

The total attenuation for the FTTH device is calculated as follows [22]:

$$a_t = L \,.\, a_s + N_c \,.\, a_c + Ns \,.\, a_s + S, \tag{2}$$

where a_t is the total attenuation that occurs along optical fiber cables, L is the length of fiber, a_s is the loss of optical fiber, N_c is the number of optical couplers, a_c is the loss of couplers, Ns is the number of optical splice, and S is the amplification.

Incoming power achieved from transmitted or outlet power and reduced via total attenuation with a safety margin of 6 dB is calculated as follows [21] [22]:

$$P_R = P_T - (a_t + S), \tag{3}$$

where P_R is the receiving signal power and P_T is the power transmitted.

Power margin values obtained with receiver devices of emissivity value sensitivity, reduced damping, and a safety margin are expressed as follows [21] [22]:

$$M = (PT - PS) - (at + S), \tag{4}$$

where M is the power margin and P_S is power receiver sensitivity.

Parameter values in equations 2, 3, and 4 are specification bases of network builders for each FTTH device.

VI. SIMULATION SETUP AND DESIGN

Systematic block schemes of downstream and upstream configurations of the FTTH device with FBG and OA for communication networks are designed and constructed. Consequently, the provider requires accomplishing analysis circumstances and field needs of network communication. Thus, the implementation of the FTTH device with a maximum of 13.248 cores is installed for a distance of 20 km [24]. The international standard is implemented in both the simulation and calculation of power budget link. Simulation models of downstream and upstream configurations are designed via the OptiSystem software, as shown in Figs. 4 and 5, respectively. Hence, a real configuration is implemented in the simulator.

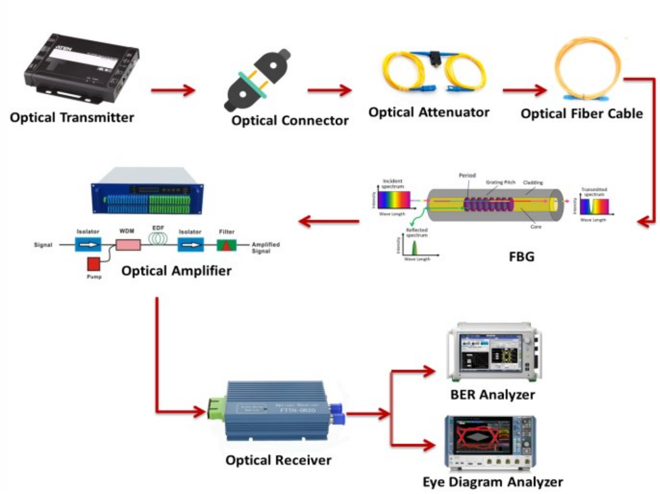

Fig. 4. Downstream model design

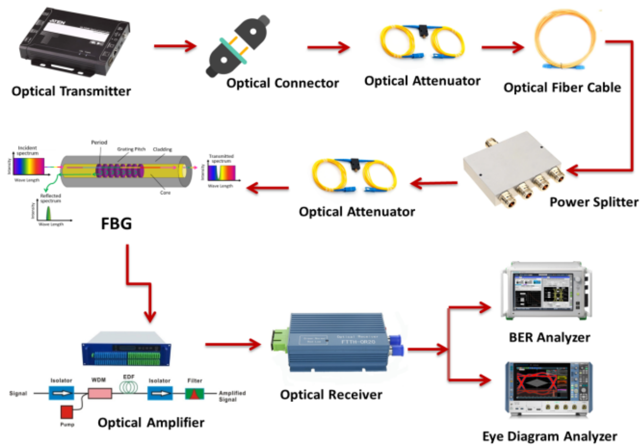

Fig. 5. Upstream model design

The developed downstream and upstream designs consist of a transmitter, connectors, attenuators, power splitter, optical fiber link, FBG, OA, and a receiver, as shown in Figs. 4 and 5, respectively. The electrical signal is converted into optical form via a transmitter. The transmitter then sends the resulting optical signal to the optical fiber cable. Connectors are flexible deviced linking fiber cables that require rapid connection and disconnection. Attenuators are used to investigate power level margins by installed permanently in order to suitably match transmitter and receiver levels. A power splitter is a passive optical device that allows the distribution of a light signal in an optical fiber between two or more fibers [24].

Optical fiber cables provide data connection between two points (point-to-point connection). SMF is characterized by high data rate and low dispersion, used as an optical fiber cable, and suitable for long-haul distances required in FTTH devices. FBG is a type of distributed Bragg reflector constructed in a short segment of the optical fiber that reflects specific wavelengths of light and transmits others. An optical amplifier can intensify multiple optical signals simultaneously and is applied to compensate for the loss of an optical fiber in long-distance optical network communication. The BER analyzer is a quantitative measurement of signal quality for digital communication systems, while an eye diagram analyzer is used to quantify the signal quality and check if the signal received can be decoded. Finally, the improved transmitted signal is detected from FBG and OA through the receiver. Settings of global specification parameters of the FTTH device for the simulation model are listed in Table I.

TABLE I
GLOBAL SPECIFICATION PARAMETERS OF THE FTTH DEVICE

Devices	Customize
Attenuation coefficient	Maximum of 0.2 dB/km
Splice loss	0.1 dB
Connectors (insertion loss)	0.25 dB
Splitter 1:4	Maximum of 7.25 dB
Splitter 1:8	Maximum of 10.38 dB
Distance	Maximum of 20 km
Rx sensitivity	−18 dBm
Optical attenuators (attenuation)	0.1 dB
Optical amplifier (noise figure)	4 dB
Optical amplifier gain	20 dB
FBG length	8 mm

Table II presents the catalogue of materials required in the design of the FTTH network communication system which are divided by segment for the downstream configuration.

VII. RESULTS AND PERFORMANCE ANALYSIS

Developed designs of the FTTH device using GPON with FBG and OA are constructed for downstream and upstream configurations with a maximum optical fiber length of 20 km, downstream wavelength of 1490 nm, and upstream wavelength of 1310 nm. Designs are simulated via the OptiSystem simulator 7.0 software. The schematic of downstream configuration of the FTTH device is shown in Fig. 6. The novelty of the developed simulation design is the implementation of FBG component that results in high performance with an ideal evaluation in the power link budget. The power link budget (dBm), eye diagram, minimum BER (dB), and Q-factor are tested and obtained under different values of optical input power with a maximum SMF length of 20 km and an attenuation coefficient of 0.2 dB/km.

The optical fiber cable, FBG port terminals, optical power meters, and optical spectrum analyzers are connected at input and output ports to measure the transmitted and received power. The optical signal is then converted to an electrical signal via the optical receiver. The performance of the minimum BER and Q-factor is assessed using the optical receiver connected to eye diagram analyzers. Figure 6 shows the model of downstream configuration. Feeder cable of the minimum STO presents a core capacity of 288 for both duct and aerial systems with G.652.D cable type. The type is loose tube (max 2x288 core) or ribbon cable (> 288 cores) [20].

TABLE II
CATALOGUE OF MATERIALS

Segment	Material type	Material
Feeder segment	Termination material	Optical distribution network Optical directional coupler
	Cable	48FO duct G.652.D 48FO aerial G.652.D
	Other	Splitter 1:4 Connector Fiber optic patch cord
Distribution segment	Termination material	Optical distribution point
	Cable	48FO duct G.652.D 48FO aerial G.652.D
	Other	Splitter 1:8 Connector
Drop segment	Termination material	Fiber optic temperature sensor
	Cable	48FO duct G.657.A 48FO aerial G.657.A
	Other	Connector Fiber Bragg grating
Indoor segment	Termination material	Optical network unit (ONU)/ optical network terminal (ONT)
	Cable	Drop indoor G.657.A Connector Fiber optic patch cord
	Other	Unshielded twisted pairs (UTP), coaxial cables Fiber Bragg grating Optical amplifier Connector

The passive splitter in the downstream configuration used an ODC ratio of 1:4 to ensure that one piece of OLT core can distribute maximum light signals of 32 ONTs/ONUs at once. The light signal from one ODP is transmitted to eight ONTs using a passive splitter of 1:8. The configuration of the upstream model design is illustrated in Fig. 7.

Eye diagram or pattern is applied to engineering communication networks to optimize the performance of signal quality and visualize how waveforms send multiple bits of data that can potentially lead to errors in the interpretation of these bits. Figure 8 shows the detailed areas of the eye diagram. The opening of the vertical eye pattern presents the amount of alteration in the signal level that indicates the difference between 1 and 0 bit. In order to distinguish between 1 and 0 bit, a bigger difference is made. The opening of the horizontal eye pattern presents the amount of jitter present in the signal. A minimal signal waveform distortion indicates an open eye diagram. The signal waveform distortion is due to inter-symbol interference, and noise performs as closure of the eye pattern.

The use of an eye diagram analyzer is a simple method for performance analysis with accuracy estimation of a digital transmission system. This measurement performed in the time domain shows the distortion effect of a waveform. Figures 9a–9d show eye diagrams and optical spectrums before and after using FBG and OA in the downstream configuration of the developed FTTH device. Figure 9a displays that the eye diagram is unclear and slightly closed, thereby leading to a low Q-factor value of 6.8. Measuring optical spectrums are applied to monitor output signals after each component with an optical spectrum analyzer (OSA), where the optical power is as a

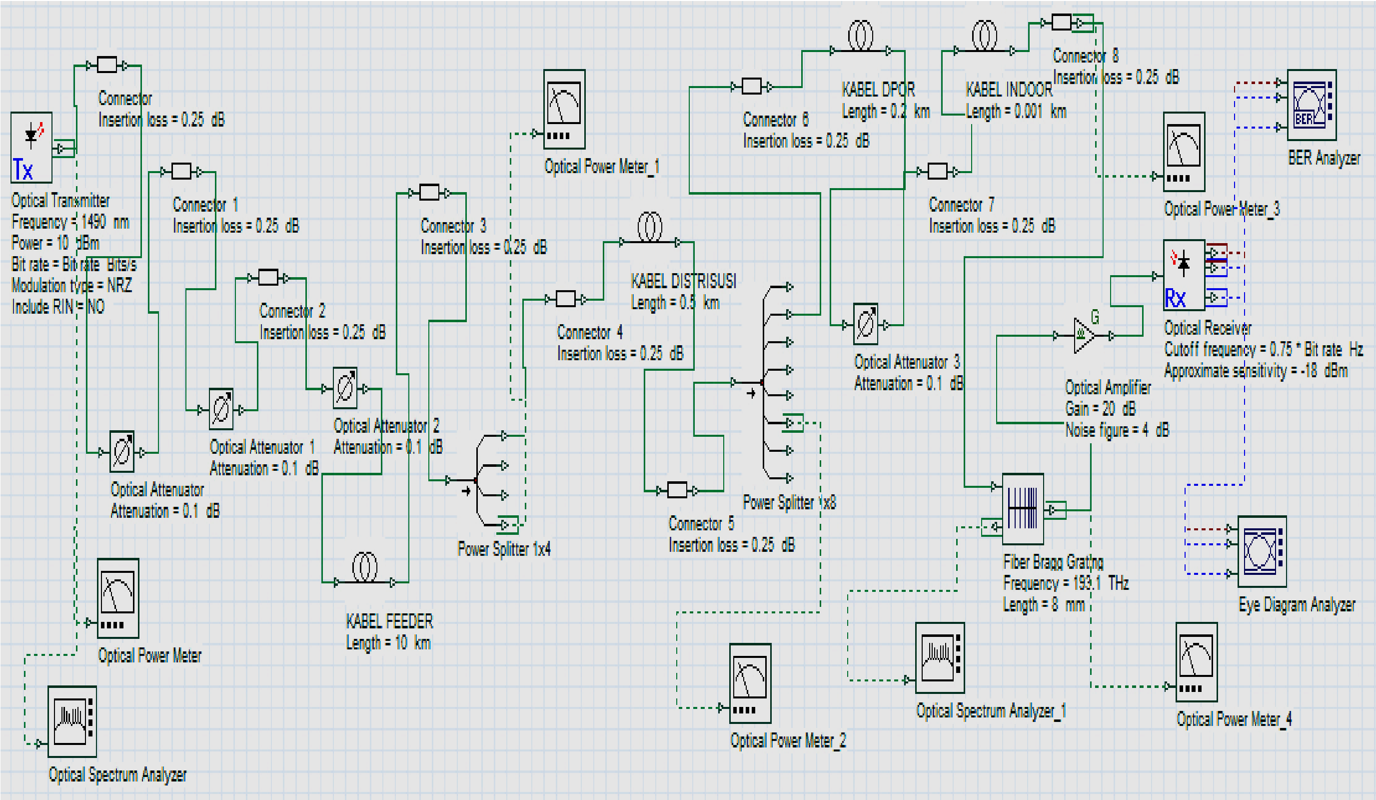

Fig. 6. Downstream configuration model

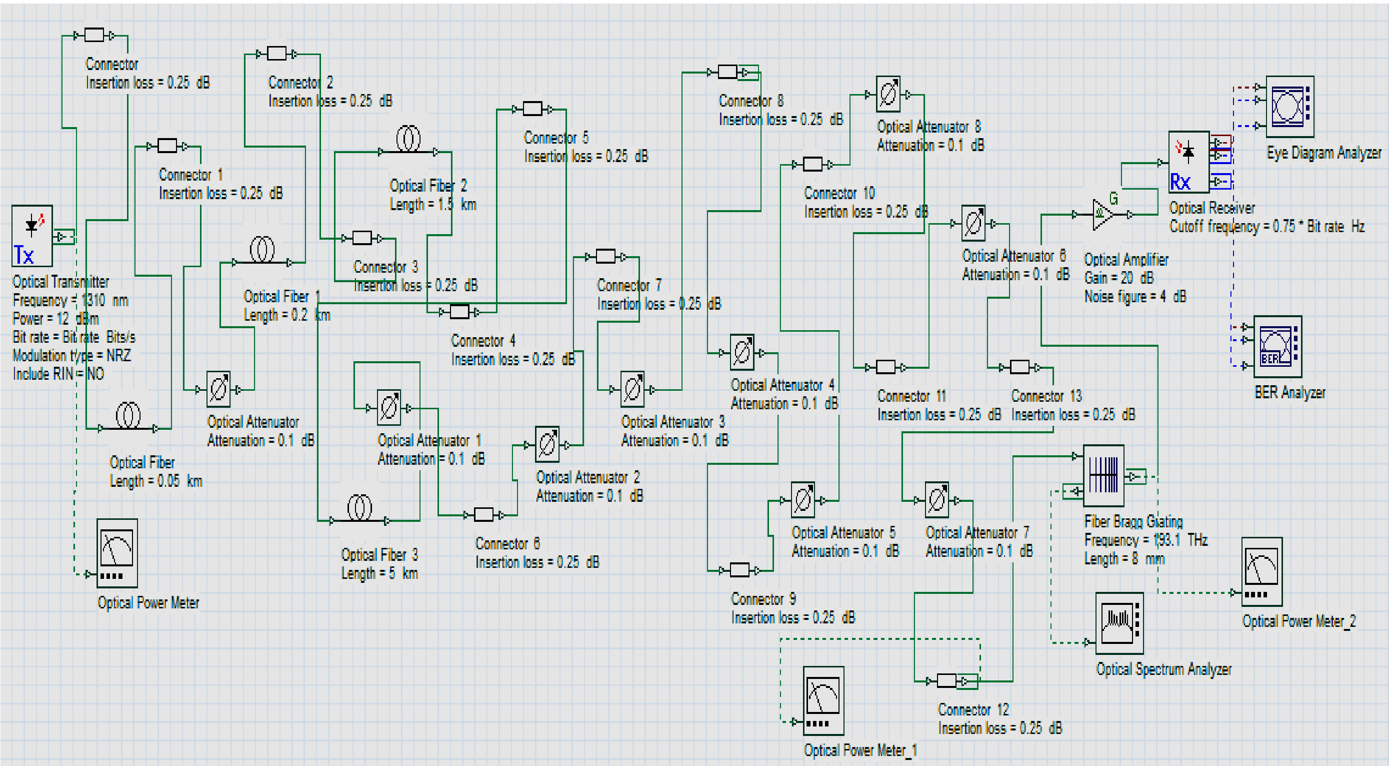

Fig. 7. Upstream configuration model

function of the wavelength. Figures 9b and 9d present the spectrum curve for the developed simulation design with and without FBGs and OA, respectively. Figure 9c demonstrates a clear and completely open eye diagram that leads to a high Q-factor value of 89.5, with a 0 BER value obtained for the downstream configuration. The BER is evaluated using the simulator to monitor the fiber optic network performance along with the power link budget [20]. Red lines in Figs. 9a and 9c indicate the minimum BER for the developed design without and with FBG and OA, respectively.

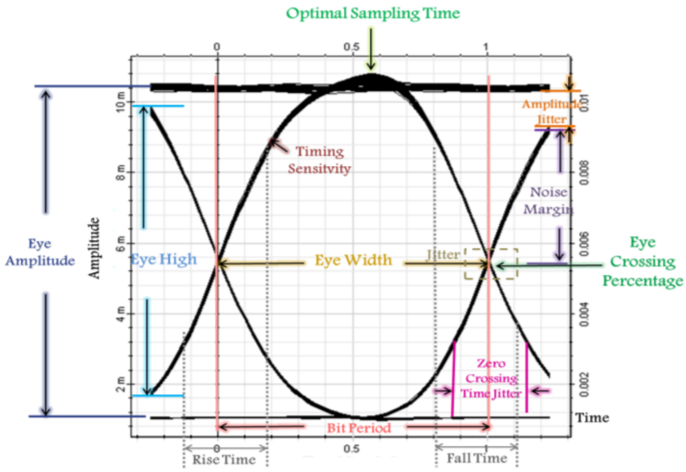

Fig. 8. Horizontal and verticals parts of the eye diagram

Figures 10a and 10c illustrate the respective eye diagrams before and after using FBG and OA for the upstream configuration of the FTTH device. Figure 10a shows the close and noisy eye diagram with high distortion. Figure 10c presents a fully open and clear eye diagram without any distortion. The Q-factor value is 181.3, with 0 BER value for the upstream configuration. Figures 10b and 10d depict the spectrum curve of the upstream configuration for the developed simulation design without and with FBG and OA, respectively. Red lines in Figs. 10a and 10c indicate the minimum BER for the developed design without and with FBG and OA, respectively.

Calculation parameters of the power link budget and BER values are obtained after the simulation process. However, three main parameter values of the power link budget, namely, total attenuation, receptivity, and power margin, are investigated and analyzed. The modernity of the developed simulation design that uses FBGs and OA in the FTTH device indicates high performance in terms of low attenuation and high transmission rate. The results of the power link budget calculation for the downstream configuration of the FTTH device implementation are listed in Table III. The power link budget is calculated to determine the performance level of the new cable network installation before its implementation into the device. Power transmission (T_x), receiving power (R_x), loss of optical fiber (a_s), loss of couplers (a_c), and power receiving sensitivity (P_s) are recorded and measured using the OptiSystem simulator. As shown in Table III, the maximum accepted distance is 20 km, the value of the power margin must be greater than or equal to 0 dB (power margin $\geq$ 0 dB). The received power value is greater than or equal to the receiver's sensitivity of −28 dBm ($P_{Rx} \geq P_{sensitivity}$). Finally, the total attenuation value must be less than or equal to 25 dB.

Tables IV and V present the results of output readings at different input power values with Q-factor for downstream and upstream model designs, respectively. However, increasing the input power increases of the Q-factor for downstream and upstream model designs unless the input power exceeds 25 and 15 dBm, respectively. Transmitted and received power values increase gradually with the increase of the input power.

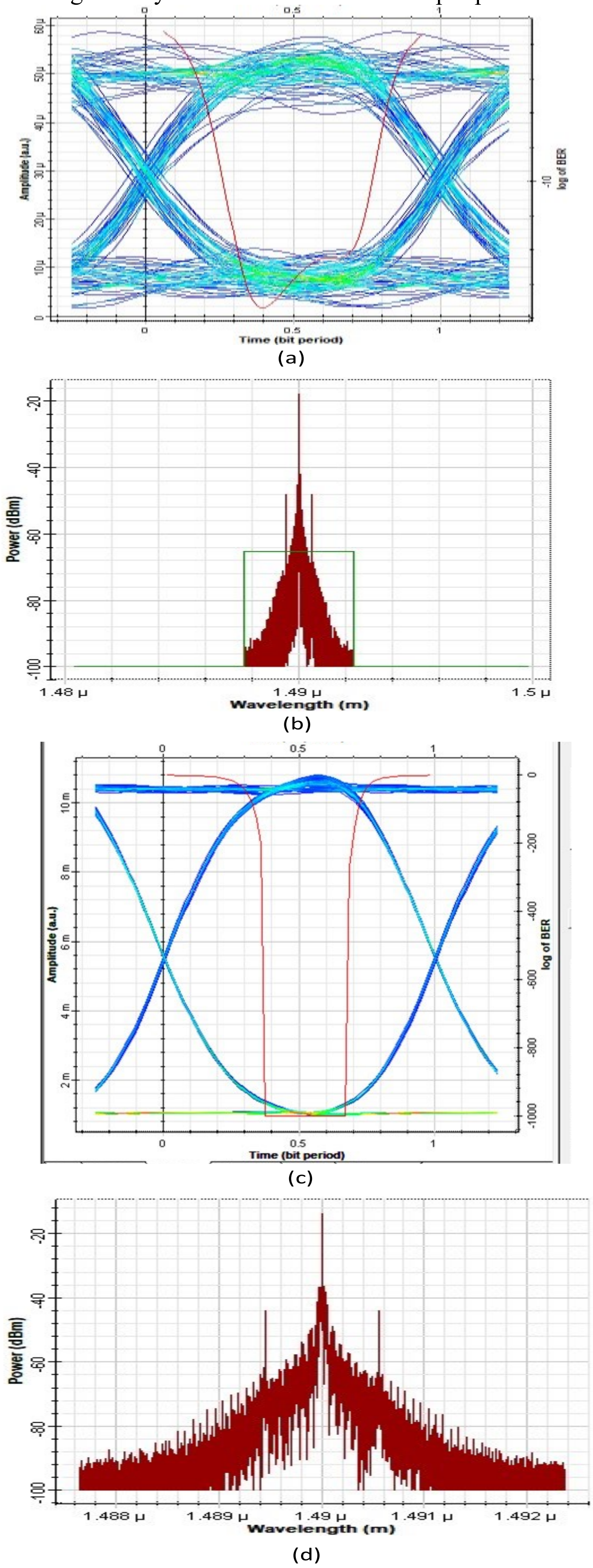

Fig. 9. Eye diagrams and spectrums of the downstream configuration: (a) eye diagram and (b) spectrum before using FBG and optical amplifier and (c) eye diagram and (d) spectrum after using FBG and optical amplifier

By comparison, BER values slightly increase with the increase of the input power. The input power value must be less than 25 dBm to maintain a high Q-factor value. The value of the received power will increase and cause losses, as shown in Table IV. Increasing the input power value to more than 25 dBm affects the Q-factor value, increases the attenuation in the eye diagram, and increases the value of the received power, as shown in Table V.

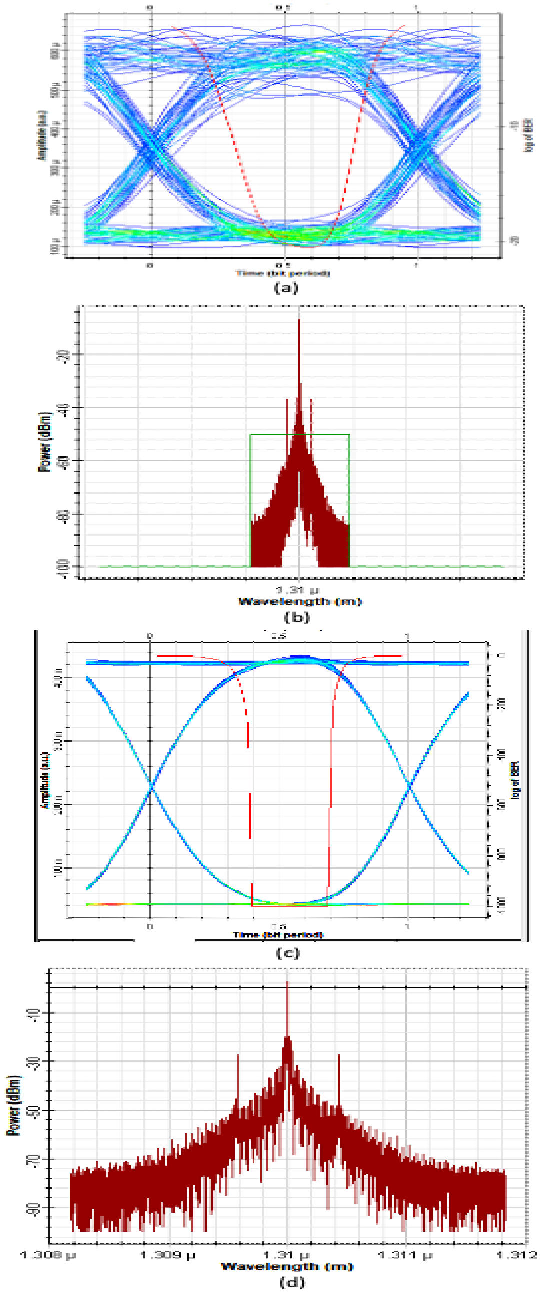

Fig. 10. Eye diagrams and spectrums of the upstream configuration: (a) eye diagram and (b) spectrum before using FBG and optical amplifier and (c) eye diagram and (d) spectrum after using FBG and optical amplifier

TABLE IV
OUTPUT RESULTS WITH DIFFERENT POWER VALUES FOR THE DOWNSTREAM CONFIGURATION

Input power (dBm)	Q-factor	BER (dB)	T_X (dBm)	R_X (dBm)
5	86.5473	0	2.355	−17.486
10	89.5832	0	7.355	−12.486
15	92.8594	0	12.355	−7.486
20	92.7516	0	7.3551	−2.486
25	90.8971	0	22.355	2.415
30	24.848	$9.42248e^{-137}$	27.355	7.514
35	9.3887	$2.69518e^{-021}$	32.354	12.513

TABLE V
OUTPUT RESULTS WITH DIFFERENT POWER VALUES FOR THE UPSTREAM CONFIGURATION

Input power (dBm)	Q-factor	BER (dB)	Tx (dBm)	Rx (dBm)
1	180.068	0	−1.645	−7.394
3	180.532	0	0.355	−5.395
6	181.02	0	3.355	−2.395
12	181.373	0	9.355	3.605
15	180.474	0	12.3555	6.605
20	168.256	0	17.355	11.605
25	138.038	0	22.355	16.605
30	42.0989	0	27.305	21.605
40	3.6211118	0.000119777	37.254	31.605

Table VI shows the comparison of the proposed designed with and without FBGs and OA for both downstream and upstream configurations. New developed models are simulated on the basis of FBGs and OA for the FTTH device. The results are compared with those of W. Awalia et al. [8] and S. Verma et al. [6]. The proposed models demonstrate high and stable performance with low BER in the communication network system, with advantages of high transmitted and received power values, low BER, high Q-factor, and noble signal quality performance with low attenuation. The simulation design is generally characterized by an excellent Q-factor respectively.

The developed design shows high received power and clear eye diagram compared with the results of W. Awalia et al. [8] of 6.8 and 41.9 for downstream and upstream configurations, respectively. The Q-factor in our study is significantly higher than that in S.Verma et al. [6] at a Q-factor equal 9.1, 8.5, and 7.7 for L equal 20, 30 40 km, respectively. The developed design shows a high signal output power of −12.486 and −7.394 dBm for downstream and upstream configurations using FBGs and OA compared with that of W. Awalia et al. [8] and S. Verma et al. [6].

TABLE III
RESULTS OF THE POWER LINK BUDGET CALCULATION FOR THE DOWNSTREAM CONFIGURATION

Distance (km)	Power transmission (dBm)	Receiving power (dBm)	Total attenuation (dB)	Power receiving sensitivity (dBm)	Power margin (dB)
2	7.355	−12.886	15.65	−21.295	4.295
4	7.355	−13.286	16.15	−21.795	3.795
6	7.355	−13.686	16.65	−22.295	3.295
8	7.355	−14.086	17.15	−21.795	2.795
10	7.355	−14.486	17.65	−23.295	2.295
12	7.355	−14.886	18.15	−23.795	1.795
14	7.355	−15.286	18.65	−24.295	1.295
16	7.355	−15.686	19.15	−24.795	0.795
18	7.355	−16.086	19.65	−25.295	0.295
20	7.355	−16.486	20.15	−25.795	0.205
22	7.355	−16.886	20.65	−26.295	−0.705
24	7.355	−17.286	21.15	−26.795	−1.205

TABLE VI
COMPARISON OF PARAMETERS BEFORE AND AFTER USING FBGS AND OA FOR DOWNSTREAM AND UPSTREAM CONFIGURATIONS

Parameters	Downstream before using FBG and OA	Upstream before using FBG and OA	Downstream after using FBG and OA	Upstream after using FBG and OA
Q-factor	6.87953	41.9221	89.5832	180.068
BER (dB)	$2.99513e^{-012}$	10^{-9}	0	0
Received power (dBm)	−22.103	−26.304	−12.486	−7.394
Transmitted power (dBm)	6	8	10	12

CONCLUSION

Noble network designs of the FTTH device using GPON with FBGs and optical amplifier for optical communication systems based on the OptiSystem simulator are constructed and investigated in this study. Main components of OLT, ONU or ONT, and ODN in the GPON system are widely used in FTTH device applications. The developed models are analyzed using the parameters BER, Q-factor, and power link budget in downstream and upstream configurations. The FTTH device is used with an optical fiber cable length of 20 km and wavelength of 1490 and 1310 nm for downstream and upstream configurations, respectively. The value of power budget link for downstream and upstream configurations is obtained on the basis of the simulation results. High Q-factor values of 89.58 and 181.3 are obtained for downstream and upstream configurations, respectively, with a BER value of 0. In addition, the power link budget of total damping is 25.50 dB, Rx sensitivity is -25.59 dBm, and optical receiver is –12.486 dB. The results indicate a highly efficient performance without interference. Finally, passive optical networks can be applied in college campuses and business environments to provide cost-effective solutions.

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