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Performance Optimization of Optical Access Networks Using Two Optical Amplifiers EYDWA and SOA in Cascade

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Abstract—This work aims to evaluate the contribution of cascaded optical amplifiers in improving the performance of optical communication systems in optical access networks. This study is thus carried out by a system simulation software which presents results concerning the characteristic parameters of two optical amplifiers, EYDWA (Erbium Ytterbium Doped Waveguide Amplifier) and SOA (Semiconductor Optical Amplifier) used in cascade, namely their gains, the length of the guide, and the concentration of ions.

1. INTRODUCTION

DWDM (Double Wavelength Division Multiplexing) technology is used to increase the capacity of the bandwidth for optical telecommunications, which allows intensive use of multimedia applications [1]. Optical access network technology such as the concept of Passive Optical Networks or PON (Passive Optical Network) leads us to the economical implementation of access networks via fiber capable of transferring services that are greedy in terms of bandwidth, which offers a different network architecture that allows essentially unlimited bandwidth to be used from fiber to the home FTTH (Fiber To The Home) technology [2]. The use of optical fiber in computer cabling is a safe and beneficial means, although sometimes certain regions such as suburbs require interconnection by microwave links for issues of network mobility and differences in geographical areas. Wireless transmission of the optical signal through the atmosphere, or in more colloquial terms, Free Space Optics (FSO) optical transmission can further reduce the cost of installing fiber in FTTH [3].

In international systems, GPON (Gigabit Passive Optical Network) has a maximum length of 35 km for 64 divisions. However, fiber optic link can exceed 65 km with the use of optical amplifiers. Several methods have been used involving Erbium-doped fiber amplifiers or EDFA (Erbium Doped Fiber Amplifier) and Ytterbium or EYDWA (Erbium Ytterbium Doped Waveguide Amplifier).

GPON is new generations that can reach physical speeds that go beyond 2.5 Gbit/s of bandwidth [4]. Several links also used Erbium-doped fiber amplifiers (EDFA), or Erbium-doped waveguide amplifiers (EYDWA), or two cascaded amplifiers. The latter, have been the subject of great attention in recent years in optical communications, as they form an interesting solution for the compensation of the loss introduced by passive components [5, 6].

In our case, the proposed solution is a TDM-PON (Trans Division Multiplexing-Passive Optical Network) two-way access network architecture for a practical implementation of the WDM-PON (Wavelength Division Multiplexing-Passive Optical Network) system in access networks [7]. The wide bandwidth of optical amplifiers makes it possible to simultaneously amplify several wavelengths of the same multiplexed signal [5, 8].

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2. MATERIALS AND METHODS

2.1. Amplification by Doped Fiber

In recent years in order to improve the transmission quality in access networks, Ytterbium-doped amplifiers have given satisfactory results around 1.55 µm which coincides with a minimum of fiber attenuation. Also in order to have better results, the use of another amplifier in series is necessary like so that with semiconductors of the SOA (Semiconductor Optical Amplifier) type. Doped optical fiber is naturally an amplifying medium, while the pumping laser which provides powerful light energy and passive optical components remains crucial [9]. It is by pumping precisely at this wavelength that one will obtain an optimal optical amplification phenomenon [10]. Figure 1 shows the operation principle of an optical amplifier.

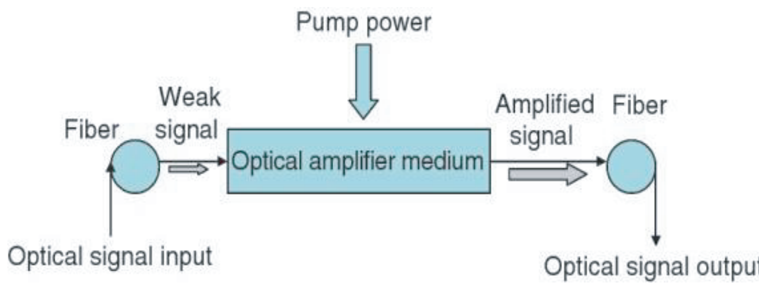


Figure 1. Operation principle of an optical amplifier [11].

3. YTTERBIUM OPTICAL AMPLIFIER (EYDWA)

Adjustment is done by introducing a modifier or co-dopant into the fiber core. For example, germanium increases the index of the medium in order to adjust the numerical aperture while aluminum modifies the gain band and allows a higher concentration of Er^{3+} ions before the cooperative luminescence appears. But it is co-doping with Ytterbium that introduces important and very interesting modifications and that will considerably improve the characteristics of the fiber [Bar89], [Fed95] [12]. Ytterbium is an Erbium sensitizer, hence the fact that the Ytterbium ions make it possible to better catch the energy of the pump before sending it to the Erbium ions. These ions are very close; thus several Yb^{3+} ions can surround an Er^{3+} ion, which facilitates the transfer of energy between both dopants. This phenomenon allows an energy transfer that exceeds 95% for adaptation with the emission spectrum of Ytterbium.

Ytterbium optical amplifiers are often used in telecommunications networks to amplify optical signals over long distances. They are also used in signal processing, spectroscopy, optical sensors, and scientific research applications. Ytterbium optical amplifiers have high efficiency, wide gain range, and low sensitivity to temperature variations [13].

The diagram in Figure 2 shows that the ytterbium ions (Yb^{3+}) are excited from the ground state $^2F_{7/2}$ to the excited state $^2F_{5/2}$ by absorption of a photon with a length of wave around 980 nm. These Yb^{3+} ions can be pumped from a laser source or a laser diode, at a wavelength of 980 nm, allowing high pumping efficiency.

4. SEMICONDUCTOR OPTICAL AMPLIFIER (SOA)

These amplifiers are divided into two categories: semiconductor or semiconductor optical amplifiers and fiber amplifiers depending on the medium that contains them. Fiber amplifiers are of great interest given their very high gain and saturation power as well as their low noise figure [15]. However, SOA, although less efficient in terms of gain and saturation power, has, on the other hand, a wider optical bandwidth, as well as a small size and above all the ability to be integrated with other optical amplifiers. In general, SOAs have a fairly wide operating spectral range, which can range from the wavelength of

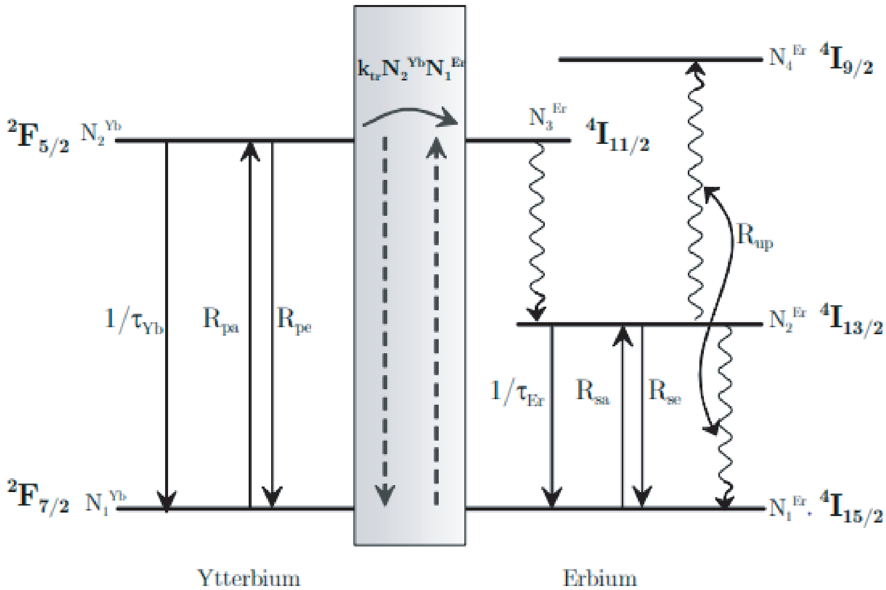


Figure 2. Energy levels diagrams of an Er^{3+}/Yb^{3+} system [14].

1300 nm to that of 1600 nm. It means that they can amplify optical signals in the C-band (1530–1565 nm wavelength) and L-band (1565–1625 nm wavelength), which are commonly used for optical communications [16].

Electronic components: semiconductor optical amplifiers require electronic components to control the excitation current and the temperature of the SOA chip. These components can include laser diodes, transistors, and resistors.

Figure 3 shows the presentation of peak gain and bandwidth of SOA.

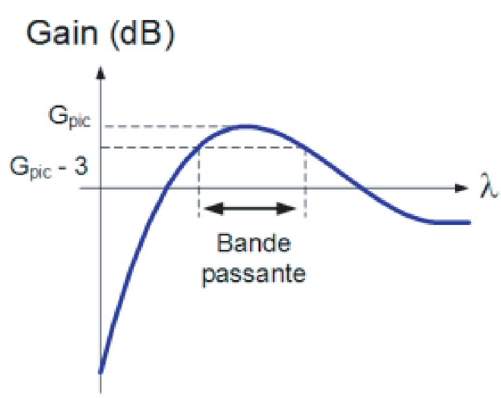


Figure 3. Presentation of peak gain and bandwidth of SOA [17].

5. OVERALL SYSTEM CONFIGURATION

Figure 4 shows a proposed hybrid long range and GPON (Gigabit Passive Optical Network) wireless system. This architecture explains the routing of data to subscribers.

The main work of this article is based on a comparative study with the results obtained when using an optical amplifier doped with Ytterbium and a configuration of a system comprising two optical amplifiers mounted in cascade, one doped with Ytterbium and the other based on semiconductor. This link is spread over a fiber length of 250 km with a wavelength of 1550 nm for a pseudo-random bit rate

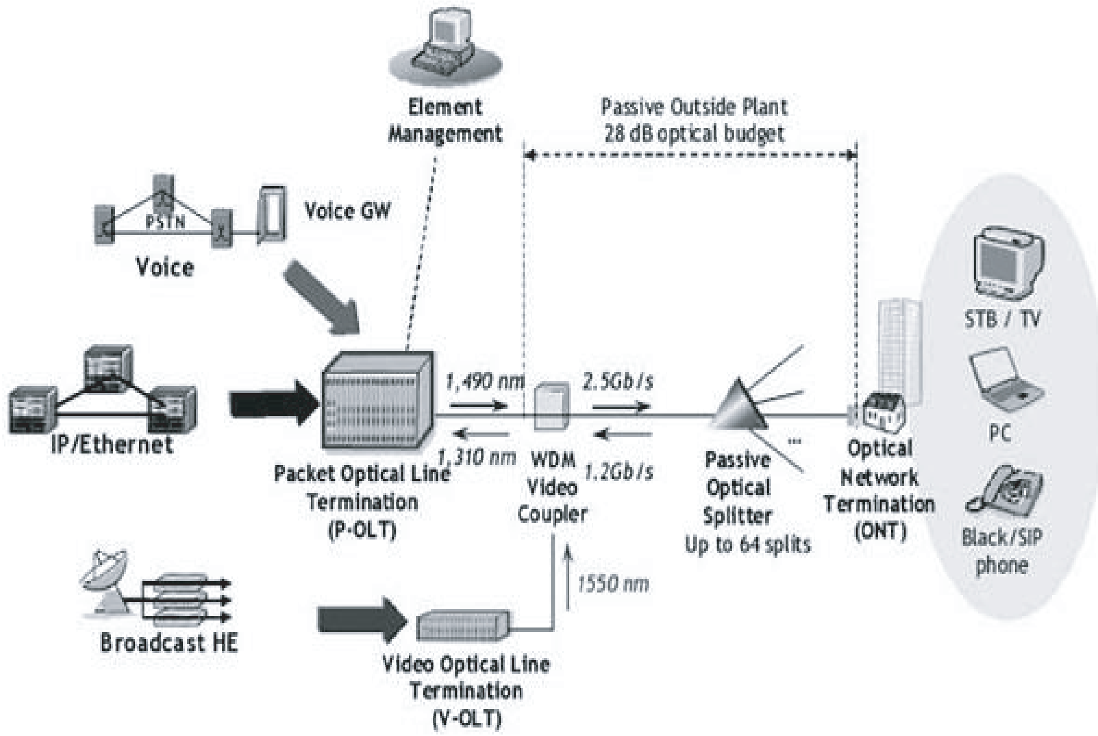


Figure 4. System setup for 2.5 Gbit/s of GPON-FSO system [18].

of 2.5 Gbit/s. The information was distributed before transmission via a receiver equipped with an optical network unit or ONU (Optical Network Unit). For the detection, we used an optical receiver formed by an avalanche diode or APD (Avalanche Photodiode) combined with a Bessel filter and a 3R regenerator. The APD photodiode has a dark current = 10 nA and a reactivity = 1 A/W. The Bessel low pass filter gives both Q values of the quality factor and eye diagrams. For amplification, we used two optical amplifiers in series, one EYDWA and the other SOA, whose physical parameters are given in the following table.

Table 1. EYDWA "Dense wavelength division multiplexing", optical amplifier.

Hybrid Amplifier	**Ion density (m^{-3})**	**Numerical Aperture**
EDFA	$1e^{+026}$	0.24
YDFA	$5.1e^{+027}$	0.2

6. RESULTS AND DISCUSSION

For the Ytterbium-based optical amplifier, Erbium and Ytterbium ion concentrations are $1e^{+026}$ ions/m^3 and $5.1e^{+027}$ ions/m^3, respectively. The pumping power is of 250 mW, and the wavelength is of 980 nm. The semiconductor amplifier has a gain of 25 dB at a wavelength of 1550 nm.

After mounting the bricks of the GPON link, one tries to transmit a rate of 2.5 Gbits/s by putting the two optical amplifiers in cascade with the parameters indicated in Tables 1 and 2.

In order to properly configure the system, an input power value has been fixed, then it has been proceeded to vary the power according to the quality factor Q, and the curve of Figure 5 has been obtained.

For a GPON of 65 km length, the curve above tells us that the more the input power increases, the

Table 2. Characteristics of SOA.

Characteristics	SOA (Semiconductor Optical Amplifier)
Maximum Gain	20–35 dB
Wavelength Range	1280–1650 nm
Band Width at −3 dB	30–80 nm
Insertion losses	3 dB
Output Saturation Power	5–15 dBm
Noise Factor	7–12 dB
Insertion Easiness	Oui
Gain Recovery Time	< 1 ns
Polarization Sensitivity	> 2 dB
Power Supply	Electrical

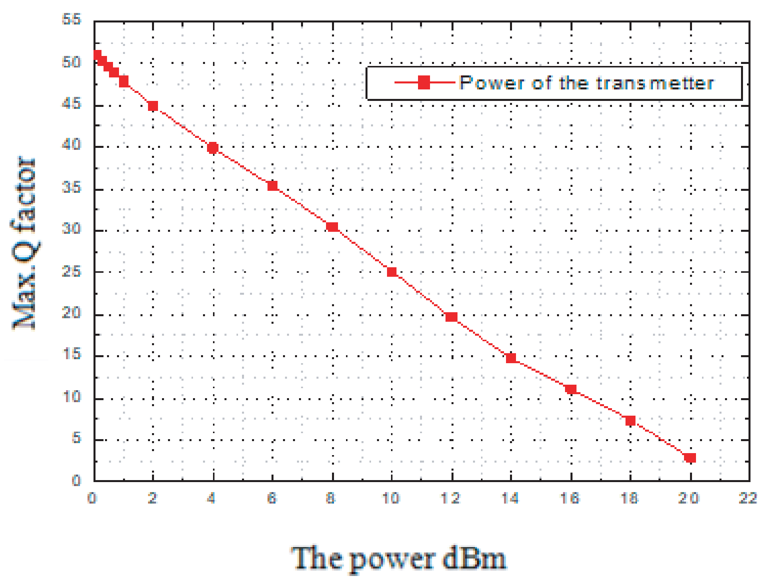


Figure 5. Input power variations related to Q factor.

more the quality of the system decreases, because for an input power of 0.1 dBm we obtained a quality factor of 51.05, while at the value of 20 dBm the Q factor fell to 2.9.

Mathematically, the quality factor Q can be expressed in several ways, but the most common one is: $Q = 2\pi\times$ energy stored/energy dissipated per cycle. The quality factor can also be expressed as a function of the bandwidth Δf and resonant frequency f_0 of the circuit: $Q = f_0/\Delta f$.

In a GPON link containing a single optical amplifier, the one based on Ytterbium in this case, we obtained a quality factor Q of 19 for a high power of 18 dBm as shown by the curve in Figure 6.

To have good results, it would be necessary to fix the parameters of the elements which constitute the amplifier in cascade. Thus, for the SOA and by fixing the value of the input power at 0.1 dBm, it must always be placed downstream of the EYDWA. By varying its injection current between 0.1 A and 1 A, the curve in Figure 6 shows that a quality factor Q of 65.9 can be reached for a current of 0.4 A.

During this configuration, we are looking at the impact of the Ytterbium-based optical amplifier and the performance of the system, so as to have a better quality of the system. The curve in Figure 7 shows this response, from which we obtained a Q factor value equal to 19.0365 for a length of 0.6 m, which allowed us to know the importance of the optimal physical parameters of each component of the

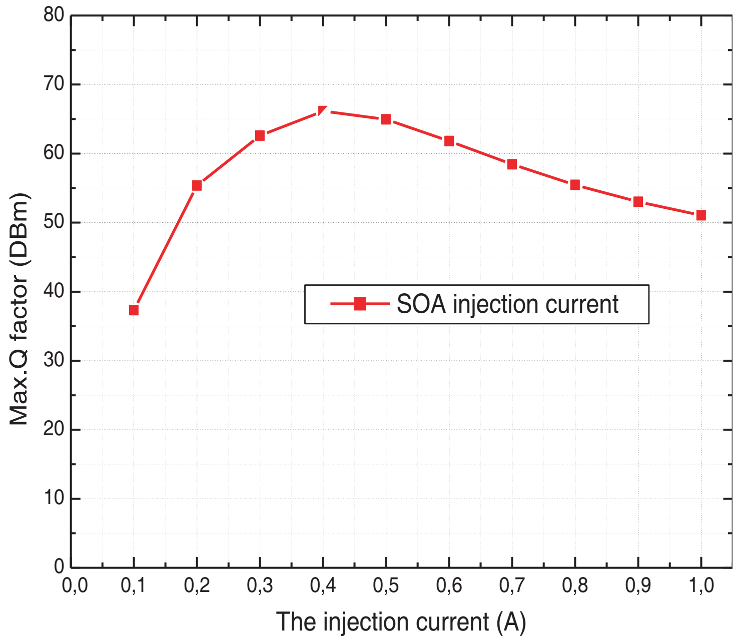


Figure 6. Injection current variations related to Q factor.

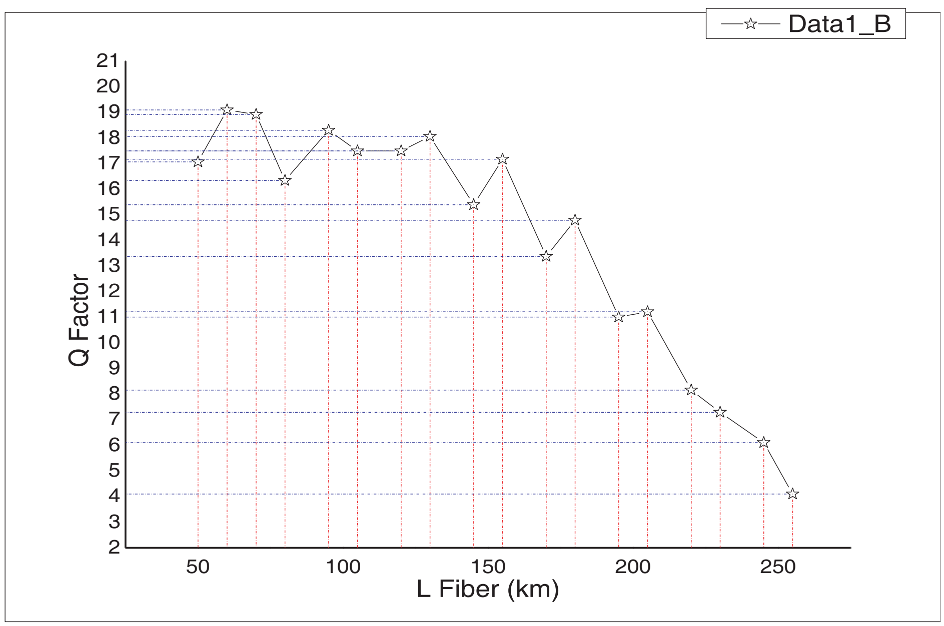


Figure 7. Variation of the Q factor as a function of fiber length L with EYDWA amplifier [19].

system.

Figure 8 shows that the link of the proposed GPON system uses EYDWA and SOA in series, while the results are obtained by varying the length of the optical fiber from 20 to 240 km and by fixing the range FSO at 5 km.

Note that for this configuration, a Q factor around 85 can be reached for a distance of 65 km, which is much better than those which only use a single amplifier, either Ytterbium or Erbium doped. Even, for a length of the GPON of 20 km we obtained the impressive value of 252.6 of quality factor.

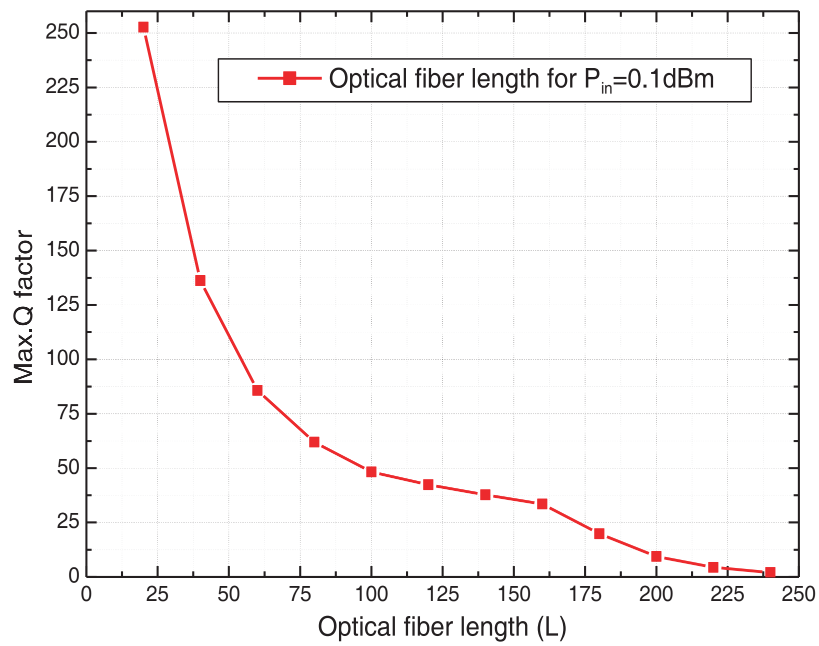


Figure 8. Q factor variation related to GPON length.

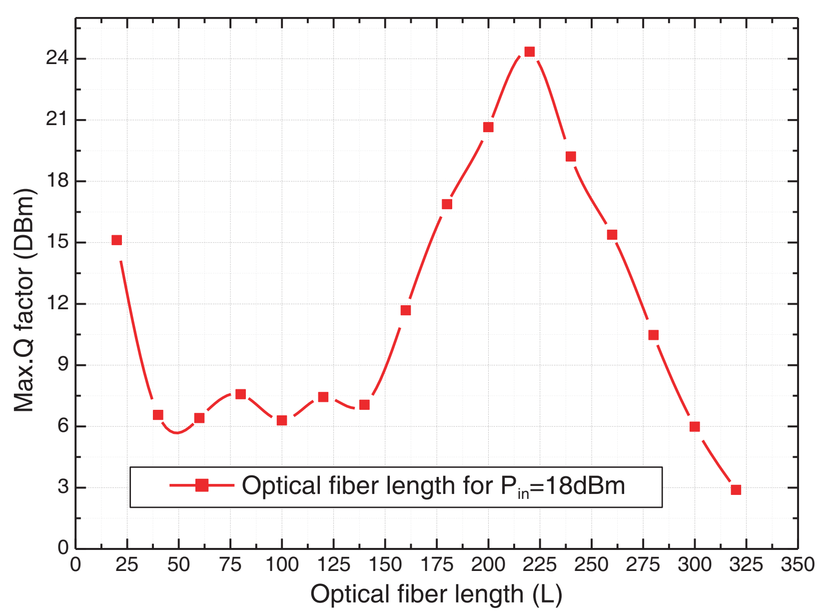
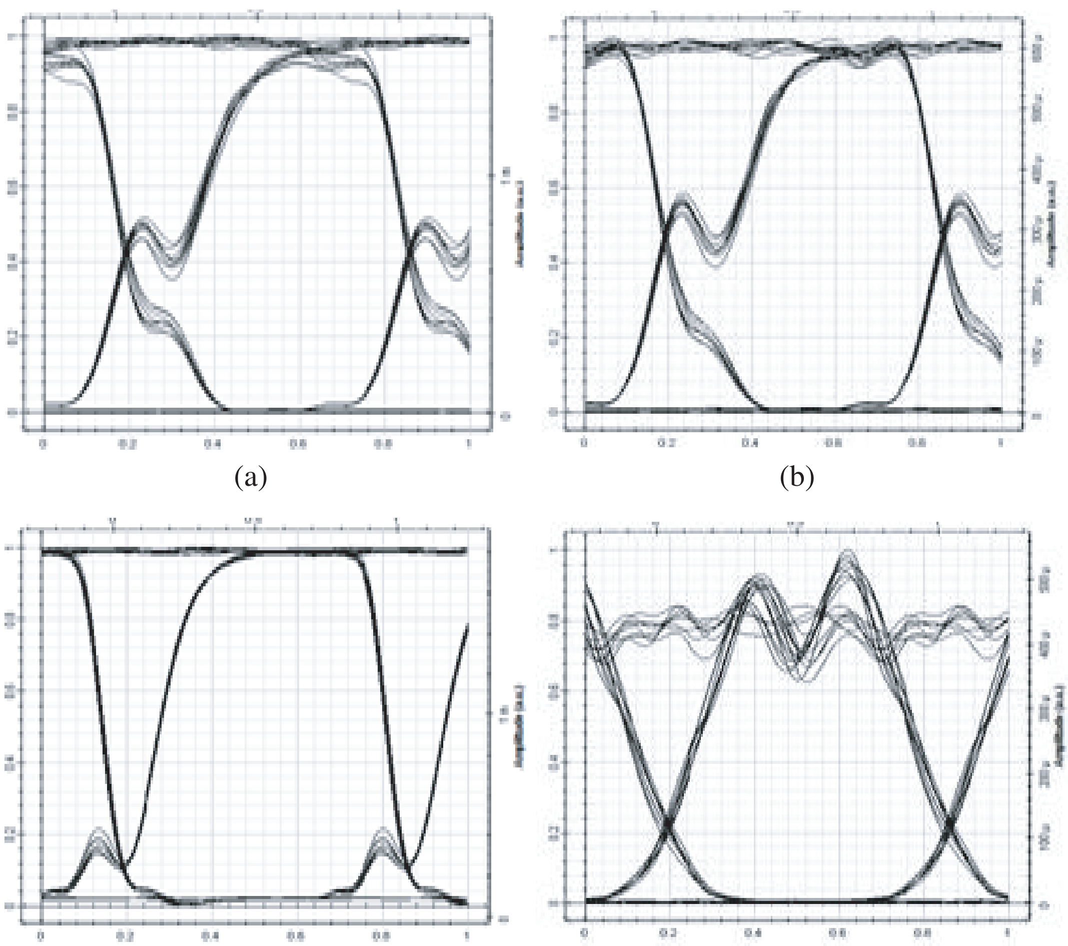


Figure 9. Variation of the Q factor as a function of the length of the optical fiber for an input power of 18 dBm.

Figure 9 presents the effect of the fiber length L varying from 20 km to 320 km always by using the two optical amplifiers in series, EYDWA and SOA. Nevertheless, this time we fixed the input power at 18 dBm in order to compare it with the results obtained with a single amplifier of the EYDWA type.

This curve shows that the quality factor Q can reach the value of 24.34 at the distance of 224 km, which remains a very satisfactory value.

Figure 10 represents the different eye diagrams for different powers over a GPON length of 65 km, where we note that the value of the input power affects the proper functioning of the system.



(a) (b) (c) (d)

Figure 10. Eye diagrams. (a) $L = 65\,\text{km}$, $Pin = 0.1\,\text{dBm}$, (b) $L = 65\,\text{km}$, $Pin = 0.4\,\text{dB}$, (c) $L = 20\,\text{km}$, $Pin = 3\,\text{dBm}$, (d) $L = 20\,\text{km}$, $Pin = 18\,\text{dBm}$.

In practice, the eye diagram is obtained by displaying a large number of consecutive bits of the received optical signal on an oscilloscope. The bits are layered on top of each other to form an eye-shaped pattern. Eye width is the amount of time the signal remains in a valid state, while eye height indicates the noise margin between logic 0 and 1 levels. The eye diagram is a useful tool for evaluating optical signal quality, as it helps detect distortions and disturbances that can affect data transmission. In particular, it can be used to measure optical amplifier pulse distortion, jitter, and noise. Optical communication engineers often use the eye diagram to optimize the design of optical receivers and optical communication networks [20].

The followed objective was the evaluation of the impact of the location of the EYDWA and SOA in series, on the performance of the simulated GPON system, depending on the length of the transmission fiber, the optical power input, and physical parameters of these two amplifiers for the four configurations, including that of in-line amplification and the quality factor of each over 65 km of transmission fiber.

A comparison of the four amplifier links was made to determine the best configuration for the targeted performance of $Q = 252$, which corresponds to a bit error rate or $\text{BER} = 10^{-9}$.

For the four configurations, the amplifier used remains characterized by the opto-geometrical parameters cited in Tables 1 and 2.

7. CONCLUSION

By comparing this simulation work with other works carried out in recent years, it appears that the different variations of the characteristics of the EYDWA and SOA have brought certain improvements. This study gave us an overview on the choice of the parameters of the optical amplifiers, their association, and their location because the quality of the latter is clearly improved since we were able to reach distances beyond 200 km.

These parameters appear very important in the optical fiber transmission system, i.e., in the practical domain of EYDWA and SOA which have a wide bandwidth in the [1530 nm–1560 nm] range for which the gains are practically identical, which makes these amplifiers important when one wants to simultaneously amplify several wavelengths multiplexed by the WDM technique.

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