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The Islamic University of Gaza
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Performance Improvement of Wavelength Division Multiplexing Passive Optical Networks (WDM PONs)

"تحسين أداء الشبكات الضوئية الخاملة متعددة الأطوال الموجية"

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بسم الله الرحمن الرحيم

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نتيجة الحكم على أطروحة ماجستير

بناءً على موافقة شئون البحث العلمي والدراسات العليا بالجامعة الإسلامية بغزة على تشكيل لجنة الحكم على أطروحة الباحث/ محمود يوسف خليل الحلبي لنيل درجة الماجستير في كلية *الهندسة* قسم الهندسة الكهربائية – أنظمة الاتصالات وموضوعها:

تحسين أداء الشبكات الضوئية الخاملة متعددة الأطوال الموجية

Performance Improvement of Wavelength Division Multiplexing Passive Optical Networks (WDM PONs)

وبعد المناقشة العلنية التي تمت اليوم الثلاثاء 10 جمادى الأولى 1435هـ، الموافق 2014/03/11م الساعة التاسعة صباحاً بمبنى طيبة، اجتمعت لجنة الحكم على الأطروحة والمكونة من:

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واللجنة إذ تمنحه هذه الدرجة فإنها توصيه بتقوى الله ولزوم طاعته وأن يسخر علمه في خدمة دينه ووطنه.

والله ولي التوفيق ،،،

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Abstract

Passive Optical Network (PON) introduces a good data transmission rate and large bandwidth. We have demonstrated a bidirectional PON system based on a Fabry-Perot laser diode (FP-LD) with two cascaded array waveguide gratings (AWGs). The downstream data rate equals to 10 Gbps and the upstream data rate equals to 2.5 Gbps. This network is classified to 10GPON Standard. FP-LD is used at optical network unit (ONU) as transmitter so it can re-modulate the downstream signal with upstream data, and then re-sent upstream towards the central office (CO). FP-LD is considered as low cost optical source, it is less costly than other sources like distributed feedback (DFB) laser, vertical cavity surface emitting lasers (VCSELs) and reflective semiconductor optical amplifier (RSOA). The main idea for using AWGs in the system is to increase the capacity, security and privacy. AWGs are used to multiplex and demultiplex different wavelengths in wavelength division multiplexing PON (WDM-PON). Our proposed systems is effective low cost system and the injection locked FP-LD is used as low cost colorless transmitters for high speed optical access exploiting WDM technology.

ملخص الرسالة

تتزايد أهمية الشبكات الضوئية الخاملة بشكل ملحوظ في عالم الاتصالات نظرا لأنها تقدم سرعة نقل عالية للبيانات وتزود نطاق عرض البيانات, من هنا قمنا ببناء نظام ارسال ثنائي للشبكات الضوئية الخاملة اعتماداً على مصدر ضوئي يسمى (Fabry Perot laser) مع اثنتين من مصفوفة الدليل الموجي المشبك AWG. وتم رفع معدل نقل البيانات التي أصبحت لاشارة التحميل (downstream) تساوي 10جيجابت في الثانية ولاشارة الرفع (upstream) تساوي 2.5 جيجابت في الثانية. هذه الشبكة الضوئية تصنف من ضمن شبكات الضوئية التي تنقل البيانات بسرعة 10 جيجابت في الثانية. تم استخدام FP-LD في منطقة المشترك كمصدر ضوئي حيث يمكنه تعديل اشارة التحميل المرسلة من جهة المقسم لاعادة ارسال هذه الاشارة مع دمجها ببيانات الرفع وارسالها الى جهة المقسم مرة أخرى. يعتبر FP-LD مصدر ضوئي رخيص الثمن مقارنةً بالمصادر الضوئية الأخرى مثل DFB laser و VCSELs و RSOA. الفكرة الأساسية من استخدام AWG في الشبكة هي زيادة عدد المشتركين والأمن والخصوصية. تستخدم AWGs لتجميع وتوزيع أطوال موجية مختلفة في الشبكات الضوئية الخاملة متعددة الأمواج.

في عملنا هذا تم تصميم ثلاث شبكات ضوئية مقترحة باستخدام برنامج Optisystem ، الشبكة الأولى لا تحتوي على مصفوفات الدليل الموجي المشبك AWGs ، الشبكة الثانية تحتوي على مصفوفة الدليل الموجي المشبك AWG في منطقة التوزيع بينما الشبكة الثالثة تحتوي على اثنتين من مصفوفة الدليل الموجي المشبك AWGs إحداهما داخل المقسم والآخر في منطقة التوزيع القريبة من المشترك . وقد تم عرض نتائج تحليل الشبكات الثلاثة المقترحة مثل حساب معدل خطأ البيانات (BER) لاشارة الرفع والتحميل وأيضا تصور طيف الإشارة عند كل نقطة في الشبكة ورسم تخطيط العين لكل من إشارة الرفع والتحميل. هنا تم ملاحظة أن جميع نتائج التحليل للشبكات السابقة مقبولة في أنظمة الاتصالات الضوئية مقارنةً بكثير من الأوراق البحثية السابقة ومعدل خطأ البيانات لاشارة الرفع في حالة استخدام FP-LD أقل بكثير من معدل الخطأ في حالة استخدام المصدر الضوئي RSOA.

من مميزات الشبكة المقترحة أنها شبكة قائمة على استخدام المصدر الضوئي FP-LD الذي يعتبر منخفض التكلفة وذو سرعة عالية في نقل البيانات مستغلاً تقنية تعدد الأمواج.

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Last, but not the least, very special thanks to my mother, my family and my friends for their constant encouragement and best wishes. Their patience and understanding without which this study would not have been in this present form, is greatly appreciated.

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Abbreviations

ASE	Amplified Spontaneously Emission
AWG	Array Waveguide Grating
BER	Bit Error Rate
BPF	Bandpass Filter
CO	Central Office
CPE	Customer Premises Equipment
CW	Continuous Wave
dB	Decibels
DFB	Distributed Feedback
DWDM	Dense WDM-PON
FEC	Free Error Correction
FP-LD	Fabry Perot Laser Diode
FSAN	Full Service Access Network
FSK	Frequency Shift Keying
FSR	Free Spectral Range
FTTB	Fiber-to-the-Building
FTTC	Fiber-to-the-Curb
FTTH	Fiber-to-the-Home
FWHM	Full Width Half Maximum
GE-PON	Gigabit Ethernet PON
GPON	Gigabit PON
LED	Light Emitting Diode
LPBF	Low Pass Bessel Filter
MZM	Mach-Zehnder Modulator
NGA2	Next Generation Access 2

NRZ	Non-Return to Zero
ODN	Optical Distribution Network
OFDM	Orthogonal Frequency Division Multiplexing
OLT	Optical Line Terminal
ONU	Optical Network Unit
OOK	On-Off Keying
P2MP	Point-to-multipoint
P2P	Point-to-Point
PIN PD	P-type Intrinsic N-type Photodetector
PRBS	Pseudo Random Binary Sequence
PSK	Phase Shift Keying
PON	Passive Optical Network
RIN	Relative Intensity Noise
RN	Remote Node
RSOA	Reflective Semiconductor Optical Amplifier
SCM	Subcarrier multiplexing
SMF	Single Mode Fiber
TDM/TDMA	Time Division Multiplexed/Time Division Multiple Access
VCSELs	Vertical Cavity Surface Emitting Lasers
WDM-PON	Wavelength Division Multiplexing PON
WGR	Wavelength Grating Router

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Chapter 1 – Introduction

1.1 An Introduction

This chapter discusses the architecture of passive optical network (PON) and its types. It presents the advantages and disadvantages of various PON models. It mentions details of the development of PON for last years. It shows the architecture of wavelength division multiplexing PONs (WDM-PONs) with using important devices in these topologies like array waveguide grating (AWG) and low cost transmitters like reflective semiconductor optical amplifier (RSOA) and Fabry Perot laser diode (FP-LD). Then, it discussed the benefits and drawbacks for using these devices. There are many sources that are used as transmitter in optical network unit (ONU). So, this chapter presents the advantages, the disadvantages for using these devices and its effect on the upstream signal from ONU. Section four in this chapter shows the literature review, Section five discusses the research problem and finally section 6 shows the scope of implementation.

1.2 Background

PON is a network that modulates the optical wave from optical line terminal (OLT) that locates at central office (CO) and sends it through fiber to ONUs that locates at end user, it is designed to provide virtually unlimited bandwidth to the subscriber. The system can be described as fiber-to-the-curb (FTTC), fiber-to-the-building (FTTB), or fiber-to-the-home (FTTH). The FTTx models are based on either a physical point-to-multipoint (P2MP) or point-to-point (P2P) topology [1], as illustrated in Figure 1.1.

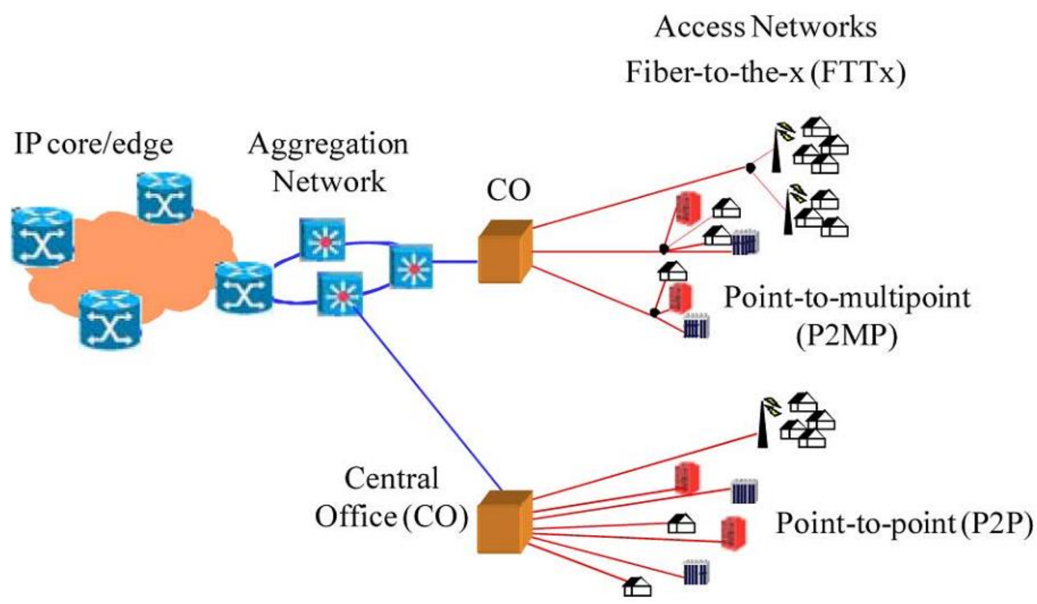


Figure 1.1: Network structure by showing the physical topology options of access networks [5]

Most FTTx models are built on the PON due to its cost effectiveness and low energy consumption per bit [2]. PON has a physical P2MP topology and it has many benefits stemming from its passive power splitter based optical distribution network (ODN). For *N* subscribers, a PON requires a single transceiver at the CO, giving rise to *N+1* transceivers overall. The shared feeder fiber saves CO space and allows for easy termination but PON based on optical power splitter at ODN has many disadvantage such as the limitation of bandwidth, reach and user count due the power splitting nature of the ODN. Power splitter has varied loss as a number of users is increased. The specific bandwidth and fiber between the CO and each user in the P2P topology overcomes this limitation as well as it provides other advantages such as data privacy and security. The main drawback of P2P is the large fiber count and terminations at the CO so this network requires high density fiber management [3].

There are different types of PON models that achieve both low loss passive optical splitters and high-speed burst mode transceivers. Gigabit PON (GPON) is now being used in North America and Europe but Gigabit Ethernet PON (GE-PON) has emerged as the dominant PON system in Asia. Both GPON and GE-PON are classified as time division multiplexed/time division multiple access (TDM/TDMA) PONs. In the downstream direction, encoded information is broadcast to all end users in timeslots at a line-rate of 2.5 Gbps for GPON and 1.25 Gbps for GE-PON as illustrated in figure 1.2.

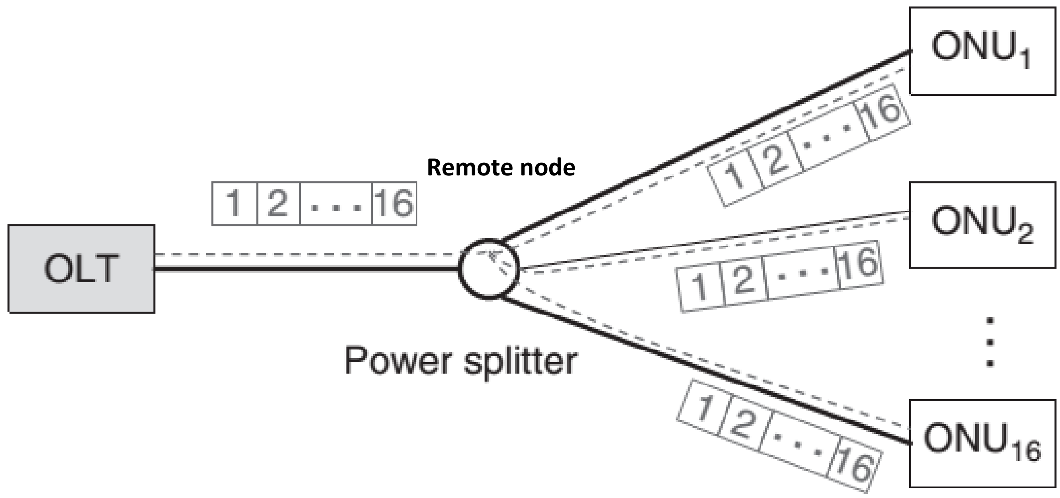


Figure 1.2: TDM-PON architecture [1]

Each ONU receives all timeslots but selects data addressed only to it. In the upstream direction, burst mode TDMA is used between network users to share the overall 1.25 Gbps upstream bandwidth for GPON and GE-PON. A special radio frequency on a wavelength channel differs from the upstream and downstream wavelength channels can be added for broadcast TV/video transmission. The main disadvantage of these networks that it have optical splitter at the remote node (RN) as shown in figure 1.2 so it limit the number of users. So, 10 Gbps PON systems and WDM-PONs have been developed to support future high bandwidth business, residential, and backhauling services. Figure 1.3 illustrates the development of next generation PONs, it shows a number of competing access technologies that are complementary to the WDM technology.

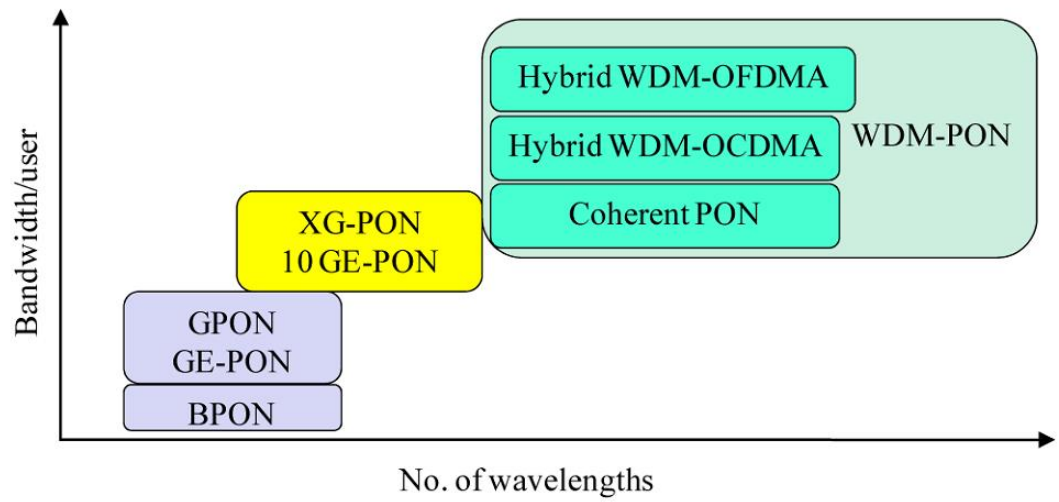


Figure 1.3: Development of next generation PONs [5]

1.3 WDM PONs

WDM PON is the desired solution for next-generation PON systems in competition with 10G-EPON. It is being considered by the Full Service Access Network (FSAN) group as a possible base technology for Next Generation Access 2 (NGA2). The main focus of NGA2 is on a long term access solution behind the 10 Gbps TDMA system with an option of a totally new optical network type [6]. The use of WDM in access networks was invented in the late 1980s [7]–[9]. Many devices has been developed in WDM PONs such as the AWG, WDM filter, RSOA and FP-LD. These devices are resulted a number of commercialized systems that are now used for business and wireless/wireline backhaul markets [10], [11].

1.3.1 WDM PON Architecture

Figure 1.4 illustrates a typical WDM PON architecture that consists a CO, two cyclic AWGs, a trunk or feeder fiber, a series of distributions fibers, and ONUs at the end users.

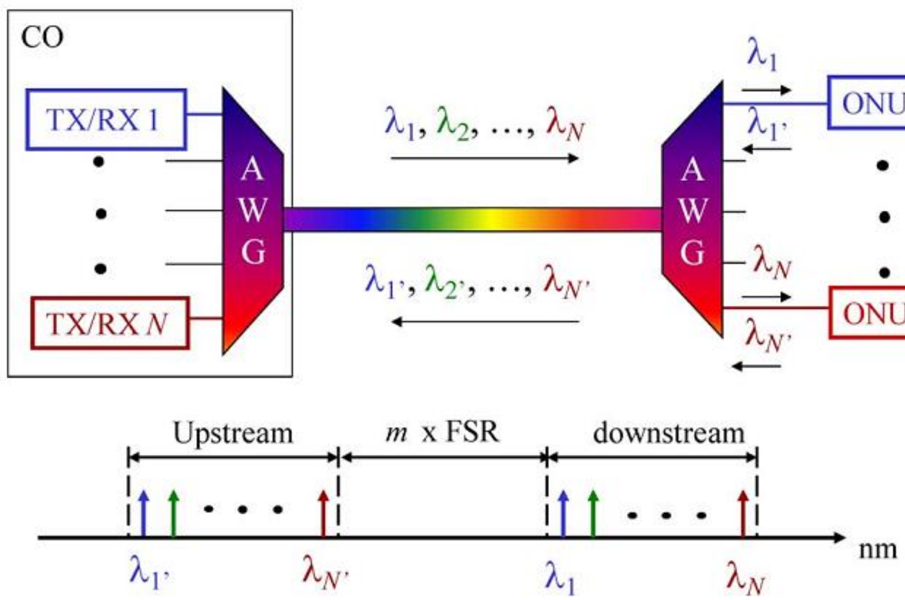


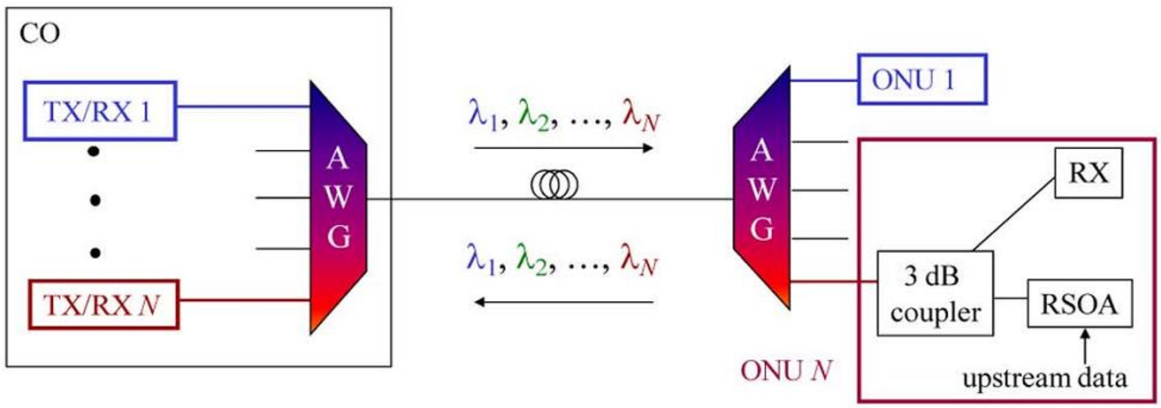
Figure 1.4: WDM-PON architecture. Inset: Allocation of upstream and downstream wavelength channels into two separate wavebands [5]

The first periodic AWG that locates at CO multiplexes downstream wavelengths to the ONUs and demultiplexes upstream wavelengths from the ONUs. The trunk fiber carries the multiplexed downstream wavelengths to a second periodic AWG that locates at RN. The second AWG demultiplexes the downstream wavelengths and guides each into a distribution fiber for transmission to the ONUs. The downstream and upstream wavelengths allocated to each ONU are separated by a multiple of the free spectral range (FSR) of the AWG, allowing both wavelengths to be directed in and out of the same AWG port that is connected to the destination ONU. In Figure 1.4, the downstream wavelengths assigned for ONU_1, ONU_2, and ONU_N are symbolized λ_1, λ_2… and λ_N respectively. Also, upstream wavelengths from ONU_1, ONU_2, and ONU_N that are destined for the CO are symbolized $\lambda_{1`}$, $\lambda_{2`}$… and $\lambda_{N`}$ respectively. In a WDM PON, wavelength channels are spaced 100 GHz (0.8 nm) apart. In systems classified as dense WDM-PON (DWDM), a channel spacing of 50 GHz or less is used. Although a WDM PON has a physical P2MP topology in reality, logical P2P connections are facilitated between the CO and each ONU. In the example shown in Figure 1.4, ONU_N receives downstream signals on λ_N and transmits upstream signals on $\lambda_{N`}$. The capacity on these wavelengths is especially assigned to that ONU. The benefits of WDM PON include protocol and bit-rate transparency, security and privacy, and ease of upgradeability and network management.

1.3.2 Low-Cost Optical Sources

ONUs use a unique upstream wavelength, different wavelength transmitters must be used at the end users but the simplest solution is to use fixed wavelength transmitters so long transmission distances and high speed transmission can be achieved with this solution. So, a network deployment would be expensive with increased complexity in network operation, administration, and management. Otherwise, identical tunable lasers can be used in all ONUs with each laser tuned to the pre-assigned transmission wavelength [11], [12]. Many sources such as a tunable distributed feedback (DFB) laser [12] and tunable vertical cavity surface emitting lasers (VCSELs) [13] can be used. The DFB laser can be modulated directly for a WDM-PON deployment, where the distance is often less than 20 km and it has good high-speed modulation property because of its narrow line width of less than a few MHz. In spite of all these advantages, the DFB laser diode is regarded as a costly device in a WDM-PON because a number of DFB laser diodes would usually be required, and each of them should be managed separately. VCSEL cannot be used as a WDM-PON source today but it can be used as an upstream source in PON. If this source in the 1550 nm DWDM range becomes stable and cheap, it will be strongly integrated with other electronics.

Other schemes like wavelength reuse as proposed in [14] and [15], the optical source is eliminated completely in the ONUs. Downstream wavelengths are remodulated with upstream data, and then re-sent upstream towards the CO. Figure 1.5 describes a WDM PON that uses the wavelength reuse scheme. The downstream wavelength also is used to wavelength seed RSOA located at the ONU. Each RSOA is operated in the gain saturation region such that the amplitude squeezing effect can be used to remove the downstream modulation on the seeding wavelength [16]. The resulting amplified RSOA output has a wavelength identical to that of the downstream wavelength and can be directly modulated with upstream data. The downstream and upstream wavelengths specified to and from an ONU are identical as illustrated in Figure 1.5,



TX: Transmitter RX: Receiver

Figure 1.5: WDM-PON architecture by showing colorless sources based on the wavelength reuse scheme [5]

The advantages of the wavelength reuse scheme include the remodulation of the downstream wavelength, elimination the need for seeding sources, less costly than using tunable lasers, and direct modulation of the RSOA. However, upstream performance can be decreased by the interference between the remaining downstream and upstream data at the CO. A solution to minimize remaining downstream modulation is to ensure that the upstream and downstream modulation formats are orthogonal. In [17], phase modulation and frequency shift keying (FSK) modulation are used for the downstream modulation with upstream being modulated with the on-off keying (OOK) format.

In yet another type of colorless sources, the transmitted optical light from the CO is fed into the ONUs to injection-lock FP-LDs [18]–[20] or to wavelength-seed RSOAs [21]–[23]. The injection-locking or wavelength seeding light may be provided by spectrally-sliced light from a centralized broadband light source located at the CO as illustrated in Figure 1.6,.

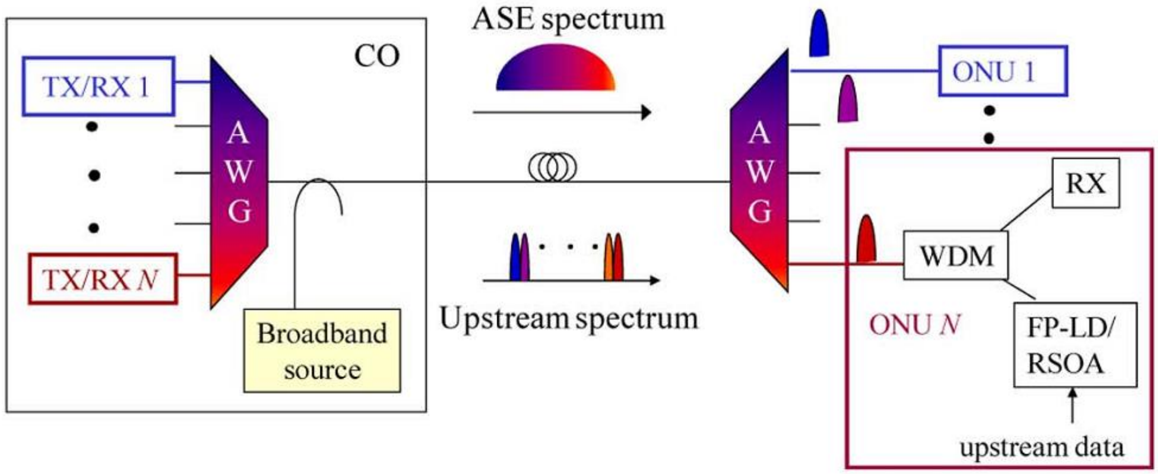


Figure 1.6: WDM-PON architecture by showing colorless sources based on injection-locking/wavelength-seeded scheme [5].

The wavelength seeding scheme is similar to the injection-locking scheme but RSOA is used to amplify and modulate the incoming continuous wave (CW) light. As the transmitting wavelength of a colorless ONU is determined externally by the wavelength of the incoming light, all ONUs may be designed with identical FP-LDs or RSOAs. The disadvantage of these schemes that require the use of additional broadband light sources so the transmission performance is limited by fiber dispersion and broadband amplified spontaneously emission (ASE) noise from the broadband light source and the colorless source. The upstream transmission bit rate is also limited by the modulation bandwidth of the colorless source used which in turn is dependent on the carrier lifetime of these semiconductor devices. In addition, wavelength control is required in injection-locking the FP-LD to ensure that the incoming ASE light at each ONU is locked with the upstream wavelength.

In the self-seeding scheme as proposed in [24], the RSOA in each ONU is self-seeded by its own spectrally-sliced CW light. ASE light transmitted from each RSOA is spectrally-sliced by the cyclic AWG that locates at the RN as illustrated in Figure 1.7. The wavelengths $\lambda_{1`}$, $\lambda_{2`}$… and $\lambda_{N`}$ in Figure 1.7 represent the upstream self-seeding wavelengths while the downstream wavelengths are symbolized λ_1, λ_2… and λ_N.

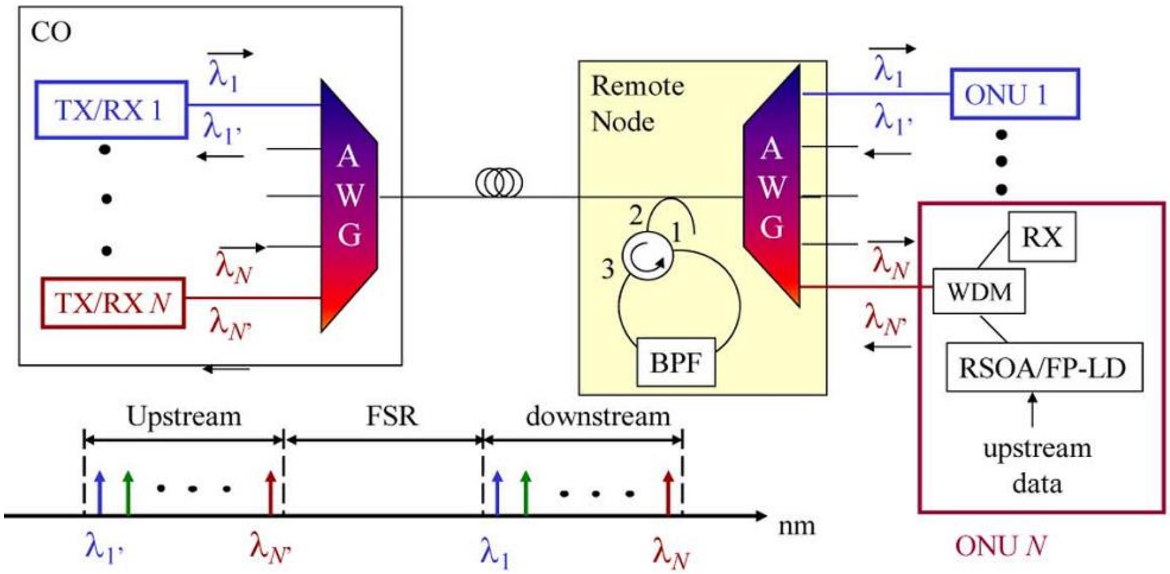


Figure 1.7: WDM-PON architecture by showing colorless sources based on the self-seeding scheme [5].

Mirrored reflector is used at RN and it consists from an optical circulator and a bandpass filter (BPF) with a passband similar to the FSR of the AWG, each RSOA will be self-seeded by only one spectrally-sliced light. For example, ASE light transmitted from the RSOA in ONU_1 as shown in Figure 1.7 is spectrally sliced by the AWG at the RN. This spectrally sliced light is sent back via the reflector to seed the RSOA in ONU_1. The reflected spectrally sliced seeding light, forms self-seeding of the RSOA with measurements in [24] showing the self-seeded output to be incoherent with low relative intensity noise (RIN).

1.4 Literature Review

Many PON systems have been studied. For initial deployment, a simple and low cost ONU design is desirable. In addition, a variety of WDM-PON systems have been studied to increase the channel capacity in existing optical fibers.

A bidirectional Subcarrier multiplexing–WDM PON (SCM-WDM PON) is demonstrated using a reflective filter and cyclic AWG where up/downlink data could be provided using a single optical source. In the proposed scheme, the signal for downstream was modulated by a single CW laser diode and re-modulated in the ONU as an upstream, the proposed WDM–PON scheme can offer the SCM signal for broadcasting service. A 1Gbps signals both for upstream and downstream were demonstrated in 10 km bidirectional optical fiber link [25].

Due to its unprecedented offered bandwidth, GPON is the ideal technology for large-scale FTTH applications where multiple end-users are requiring an ever-growing bandwidth. Moreover, in areas populated by both business and residential customers, GPON is the most cost-effective solution. This paper presented the downstream transmission performance of 1.25Gbps GPON bit rate. All the ODN classes are simulated separately. Multiple customers who are connected to the PON share the OLT costs. While EPON allows only 16 ONTs per PONs, GPON standard allows the OLT PON card to support up to 128 ONTs. This makes the GPON solution 4 to 8 times more cost effective. In this simulation, number of users (ONTs) of 18, 50 and 128 are obtained for classes A, B and C [26].

Designs of low cost ONU for WDM-PON are presented and evaluated. RSOAs are proposed to be used as core of the ONU in a bidirectional single-fiber single-wavelength topology. Forward error correction (FEC) is employed to mitigate crosstalk effects [27].

Wavelength Re-use model is written with RSOA for WDM-PON transmission, among the various solutions to the optical subscriber network realization, the WDM-PON has been considered as an ultimate next-generation solution. The wavelength re-use model with the RSOA has recently been developed for application to the WDM-PON. The wavelength re-use scheme has a common feature that the optical signal modulated with downstream data is re-used to carry the upstream data through the RSOA in the subscriber-side equipment by a series of processes such as being flattened out, reflected at the rear facet of the RSOA, and then re-modulated with upstream data. The major advantage with the wavelength re-use scheme would be the possibility of realizing the simplest WDM-PON optical link structure, which is directly reflected on cost-effectiveness of the network both in equipment and maintenance costs. The gain saturation scheme is presented. It uses the fact that the optical gain of RSOA declines as the injection power into RSOA increases. Experimental results show that it is possible to achieve error-free bidirectional transmission with 1.25 Gbps for upstream and 2.5 Gbps for downstream data rates over 20 km transmission distance [28].

An upstream-traffic transmitter based on FP-LD as modulator is proposed and demonstrated for WDM access networks. By injection-locking the FP-LD with the downstream wavelength at the ONU, the original downstream data can be largely suppressed while the upstream data can be transmitted on the same injection-locked wavelength by simultaneously directly-modulating the FP-LD [29].

Error-free colorless WDM-PON downstream over 25 km for 16 channels with 85 GHz channel spacing is experimentally demonstrated at 2.5 Gbps, using an injection-locked FP-LD and a quantum dash mode-locked laser as a coherent seeding source [30].

Error-free transmission over 20 km of 8-channels for both downstream and upstream in colorless WDM-PON based on injection-locked FP-LD is experimentally demonstrated at 2.5 Gbps, using a single quantum dash mode-locked laser as multi-wavelength seeding source [31].

A 10Gbps upstream transmission using FP-LD remotely injection-locked by coherent feed light from the CO. Experimental results show that transmission over a 10 km single mode feeder fiber incurs power penalty of 1.1 dB and up to 16 cavity modes of the FP-LD can be injection-locked [32].

A hybrid WDM/TDM PON construction applied by means of two cascaded AWGs is presented. Using the FSR periodicity of AWGs we transmit unicast and multicast traffic on different wavelengths to each ONU. The OLT is equipped with two laser stacks, a tunable one for unicast transmission and a fixed one for multicast transmission. The ONU is proposed to be reflective in order to avoid any light source at the Customer Premises Equipment (CPE). Optical transmission tests demonstrate correct transmission at 2.5 Gbps up to 30 km [33].

1.5 Research Problem

The ancient PONs were used in the channel passive splitter to support many users around 32 users and these system used power splitter at RN but this device has variable loss which increases by increasing number of users so it limits data rates. These systems operate as broadcast systems because it transmit all data to the user so we will need tunable filter at the end user to choose the desired signal (wavelength) but this mechanism considered drawback due to low security and expensive. And these systems do not support high data rates because there is a lot of losses. Proposed system contains AWG at both CO and end user to increase capacity and to support high data rates. AWG is considered an efficient device due to its low cost and has many advantages, we will discuss the characteristic of AWG later. FP-LD is used at the end user so it is the main factor to reduce the overall cost of the system. FP-LD is less costly than RSOA but it is used for short distance transmissions. Downstream signal and upstream signal are sent over a long distance up to 10Km. 10Gbps downstream data rate and 2.5Gbps upstream data rate are achieved in this proposed system.

1.6 Scope of Implementation

The ideas in this work can be applied for many networks. The main purpose of the work is to provide more capacity and economic system. The use of PON system integrated with FP-LD reduces installation and maintenance costs while offering more capacity than the present copper-based infrastructure.

PON is a network used to carry optical signal from CO to customers, it is passive that means no power requirement and it transmits signals over a long distance up to 10Km, development on this system is still based at the moment as increase data rate at both CO and ONU as well as increase the distance between them. WDM-PON with AWG gives the system some of advantages as low cost, high wavelength selectivity, low insertion loss, small size and cyclic wavelength routing. When FP-LD is used at ONU, it will give the system another advantage by using the same wavelength to achieve wavelength reuse scheme as discussed in last sections so this form is called (colorless ONU). Optisystem software is used to model and analyze the proposed networks.

1.7 Outline of thesis

This is written to bring the reader step by step going in the main core of the content. Chapter 1 Provides the introduction to this thesis where brief background of the study problem and to the statement of the problem, followed by the objective and the scope of the study.
Chapter 2 includes introduction to WDM-PON, the benefits, and applications of WDM-PON technology in communication fields. In addition various types of sources also have been covered. AWG and FP-LD characteristics will be discussed in this chapter.
Chapter 3 describes the analysis and design of three PON networks. The first network does not include AWG at both CO and end user with FP-LD. The Second network includes AWG at RN with FP-LD at end user. The third network includes two cascaded AWG, one of them is located in CO and the other is located in RN as well as FP-LD is used as transmitter for upstream signal. The relation between BER and the received optical power is drawing for every network in this chapter. Upstream and downstream eye diagrams for every network are illustrated. Comparison between RSOA and FP-LD is discussed in this chapter.
Finally; Chapter 4 introduces the conclusions of the study, as well as some suggestions for future work.

Chapter 2: WDM-PON

In this chapter, we will discuss the advantages and challenges of WDM-PON, the operation concepts of AWG and FP-LD. These devices are very important in WDM-PON.

2.1 WDM-PON

A WDM-PON is characterized by a WDM coupler, which replaces the power splitter at the remote terminal [34].

2.1.1 Advantages and Challenges of WDM-PON

WDM-PON offers the following advantages such as the RN is still passive and therefore has the same low maintenance, each user receives its own wavelength so WDM-PON offers excellent privacy and security**,** the connection between CO and ONUs look P2P connections and it are realized in wavelength domain, there is no P2MP media access control required and easy pay-as-you-grow upgrade because each wavelength in a WDM-PON can run at a different speed as well as with a different protocol. Individual user pays for his or her own upgrade.

The challenges of WDM-PON include high costs of WDM components. However, the costs of WDM components have reduced extremely in recent years which made WDM-PONs economically more applicable. Another challenge is Temperature control, WDM components' wavelengths tend to drift with environmental temperatures so many devices are developed to remove the need for temperature control such as athermal WDM devices. Another challenge is Colorless ONU operation, each ONU needs a different wavelength for upstream transmission in a WDM-PON so there are many schemes are proposed to overcome this problem such as wavelength reuse and injection locking schemes.

2.1.2 AWG router

The AWG router is an important element in many WDM-PON architectures. A conventional *N*-wavelength WDM coupler is a 1×N device as shown in Figure 2.1 (a).

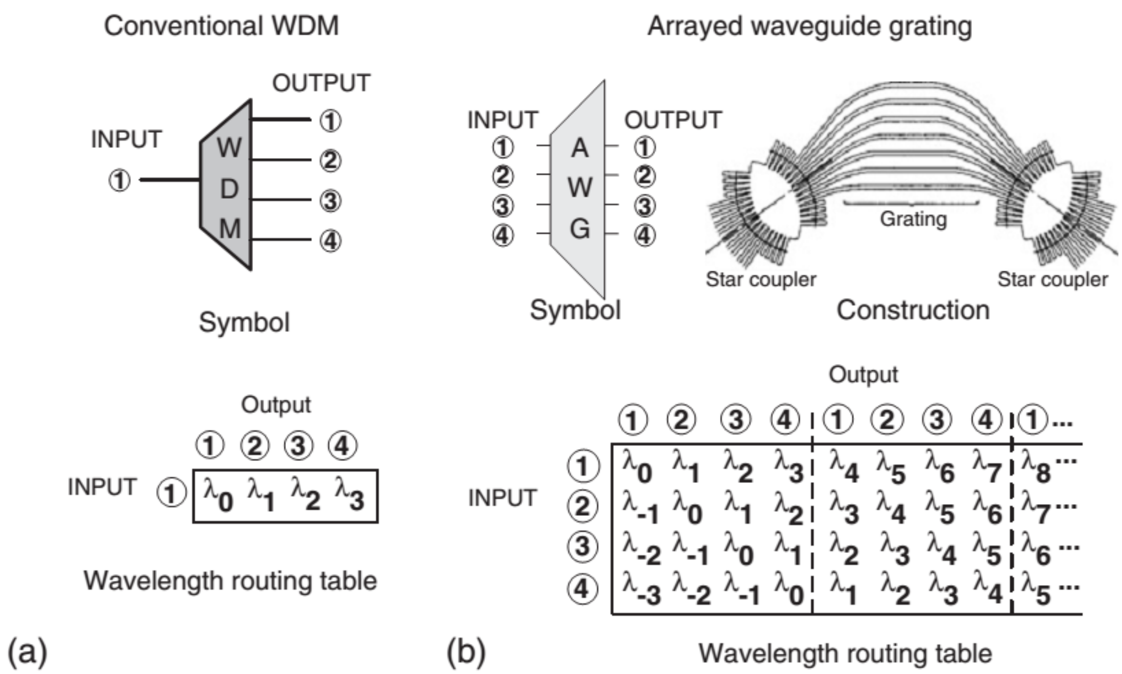


Figure 2.1: Conventional WDM coupler versus AWG.

AWGs have multiple input and multiple output as indicated in Figure 2.1(b) but the conventional WDM has one input and multiple output as shown in figure 2.1(a). A general AWG router includes two star couplers joined together with arms of waveguides of unequal lengths as shown in Figure 2.1 (b) [35]. Each arm is related to the adjacent arm by a constant length difference. These waveguides function as an optical grating to disperse signals of different wavelengths. The optical path length difference ΔL between adjacent array waveguides is set to be

$$\Delta L = \frac{m \times \lambda_o}{n_{eff}} \tag{2.1}$$

Where m is an integer number, λ_0 is the central wavelength, and n_{eff} is the effective refractive index of each single mode waveguide [36]. An AWG has another name which is called wavelength grating router (WGR) as well as it has a very important and useful characteristic which is called cyclical wavelength routing property illustrated by the table in Fig. 2.1 (b) [37]. With a normal WDM multiplexer in Fig. 2.1 (a), if an ‘‘out-of-range’’ wavelength, (e.g. λ_{-1} or λ_4, λ_5) is sent to the input port, that wavelength is simply lost or ‘‘blocked’’ from reaching any output port. An AWG device can be designed so that its wavelength demultiplexing property repeats over periods of optical spectral ranges called FSR. Moreover, if the multi-wavelength input is shifted to the next input port, the demultiplexed output wavelengths also shift to the next output ports accordingly. Cyclical AWGs are also called colorless AWGs. The wavelength-cyclic property of AWG can be exploited to enable many clever architectural inventions. For example, by using two adjacent ports for upstream and downstream connections, the same wavelength can be ‘‘reused’’ for transmission and reception at an ONU. An important property of the AWG is the FSR, also known as the de-multiplexer periodicity, the periodicity comes from the fact that constructive interface at the output free propagation range can occur for many different wavelengths .The FSR denotes the wavelength or frequency spacing between the maximum of the interface pattern, and can be obtained as follows:

$$FSR = \frac{\lambda_0 n_c}{m\, n_g} \tag{2.2}$$

Where m is an integer number, λ_0 is the central wavelength, n_g is the group refractive index of arrayed waveguides and n_c is the effective index in the arrayed waveguides [36]. The maximum number of I/O wavelength channels N_{max} depends on the FSR. The bandwidth of the multiplexed light (product of the channel spacing and the maximum number of wavelength channels) $N_{max}*\Delta\lambda$ must be narrower than FSR in order to prevent the overlapping of orders. Therefore, N_{max} can be derived as:

$$N_{max} = integer\ \left(\frac{FSR}{\Delta\lambda}\right) \tag{2.3}$$

In which, $\Delta\lambda$ is the channel spacing [36].

2.2 FP-LDs

The FP-LD is considered a light emitting diode (LED) with a pair of end mirrors. The mirrors are needed to create the right conditions for lasing to occur. The FP-LD is also called "a Fabry-Perot resonator" [38].

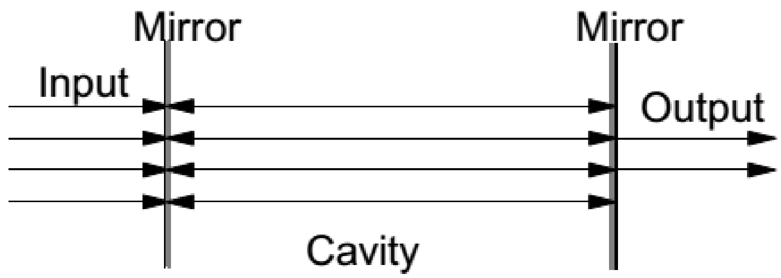


Figure 2.2: Fabry-Perot Filter structure

The input light will enter the cavity through the mirror on the left and will leave it through the mirror on the right. Some wavelengths will resonate within the cavity and it can pass through the mirror on the right but the other wavelengths will strongly attenuate as shown in figure 2.2. The operation of the FP-LD is similar to the operation of the Fabry-Perot filter. As the distance between the mirrors is increased, the more wavelengths will be produced within the cavity. Wavelengths produced are related to the distance between the mirrors by the following formula:

$$C_l = \frac{\lambda \times X}{2 \times n} \tag{2.4}$$

Where:

λ = Wavelength

C_l = Length of the cavity

X = an arbitrary integer 1, 2, 3…

n = Refractive index of active medium

The length of the cavity, the refractive index of the active medium and the center wavelength are constant but the integer (X) is a variable. So, the wavelength produced are directly proportional with the cavity length. This example shows the relation between the cavity length and the number of produced wavelengths. Assume that the center wavelength equals 1500 nm and the refractive index equals 3.45. If the cavity length equals 100 μm, the number of produced wavelength equals 7. If the cavity length equals 200 μm, the number of produced wavelength equals 13. Figure 2.3 illustrates the above the example of typical resonances.

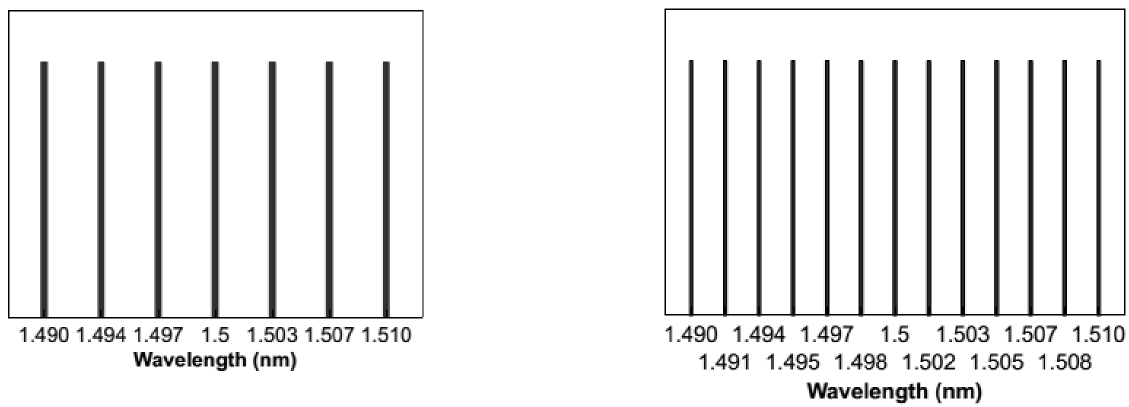


Figure 2.3: Resonance examples when the center wavelength equals 1500 nm and the refractive index equals 3.45.

If a random wave travels from the left-hand mirror to the right-hand mirror as shown in figure 2.4 (on the right). At the right-hand mirror, this wave is reflected; hence, the wave experiences a 180 degree phase shift so this resonator does not support this wave. The lateral modes will be formed in this situation.

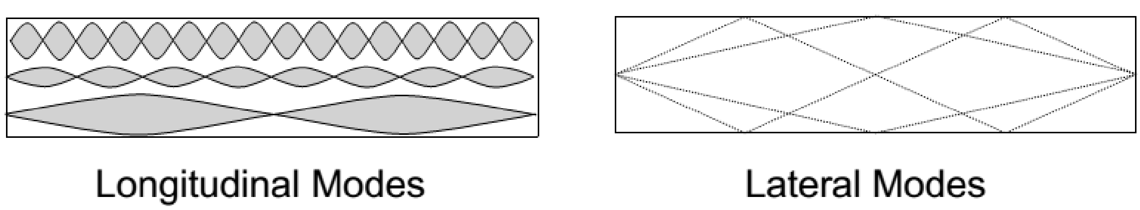


Figure 2.4: Longitudinal modes versus lateral modes

If a random wave travels inside a resonator as shown in figure 2.4 (on the right). At the right-hand mirror, the wave experiences a 180° phase shift and continues to propagate. At the left-hand mirror, this wave again has the same phase shift and continues to travel. Thus, the second wave produces a stable pattern called a standing wave. The only difference between the two waves is their wavelengths. Thus, a resonator can support only a wave with a certain wavelength, the wave that forms a standing-wave pattern. This resonator supports many wavelengths that can form a standing wave. Wavelengths selected by a resonator are called longitudinal modes. A resonator can support an infinite number of waves as long as they form a standing wave. However, the active medium provides gain within only a small range of wavelengths as shown in figure 2.5 (on the left). Since a laser radiation is the result of the interaction of a resonator and an active medium, only several resonant wavelengths that fall within the gain curve might be radiated as shown in figure 2.5 (on the right).

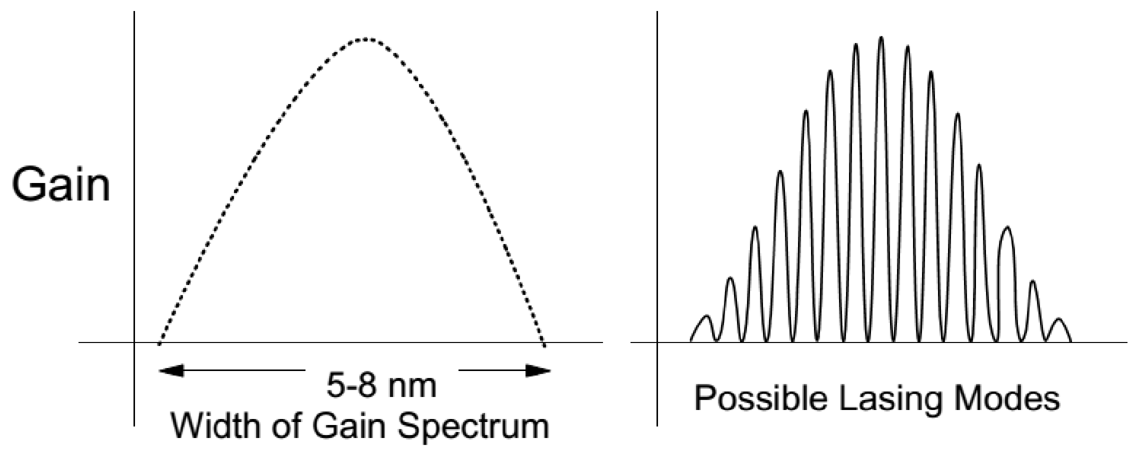


Figure 2.5: The width of gain spectrum and possible lasing modes in FP-LD

The laser output of each possible lasing mode is called a "line". A simple gain guided FP-LD produces a number of lines over a range of wavelengths called the "spectral width" as shown in figure 2.6. Full Width Half Maximum (FWHM) is usually measured as the width at half the maximum signal amplitude as shown in figure 2.6.

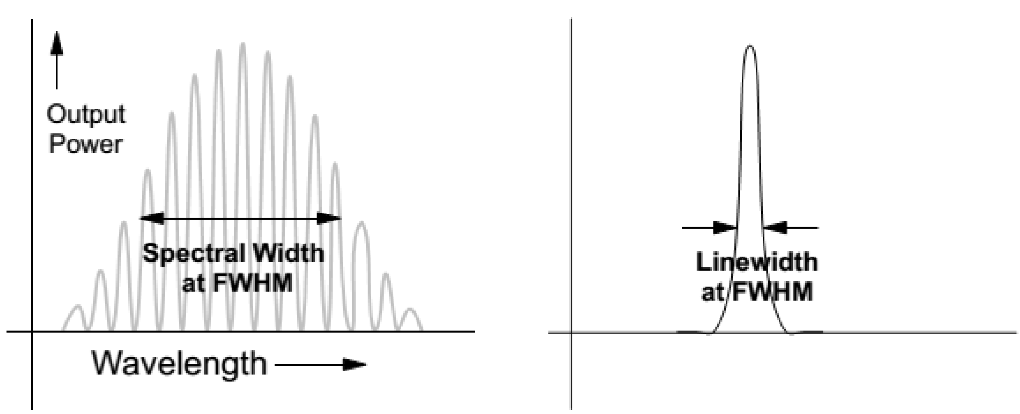


Figure 2.6: Spectral width and linewidth in FP-LD

2.3 Construction of a FP-LD

A FP-LD is similar to an edge-emitting LED with mirrors on the ends of the cavity in its basic form. A surface of FP-LD should be easier than a surface of LED to construct. In a LED, a lot of attention is taken into account to collect and guide the light within the device towards the exit aperture. In an ideal laser, the problem of guiding the light is not taken into account. Lasing happens only between the mirrors and the light produced is exactly guided but it is not as simple as this. All types of FP-LD contain electrical contacts on the top and on the bottom to supply it by injection current. A simple double hetero-structure laser is shown in figure 2.7. Mirrors are formed at the ends of the cavity by the "cleaved facets" of the crystal from which it is made.

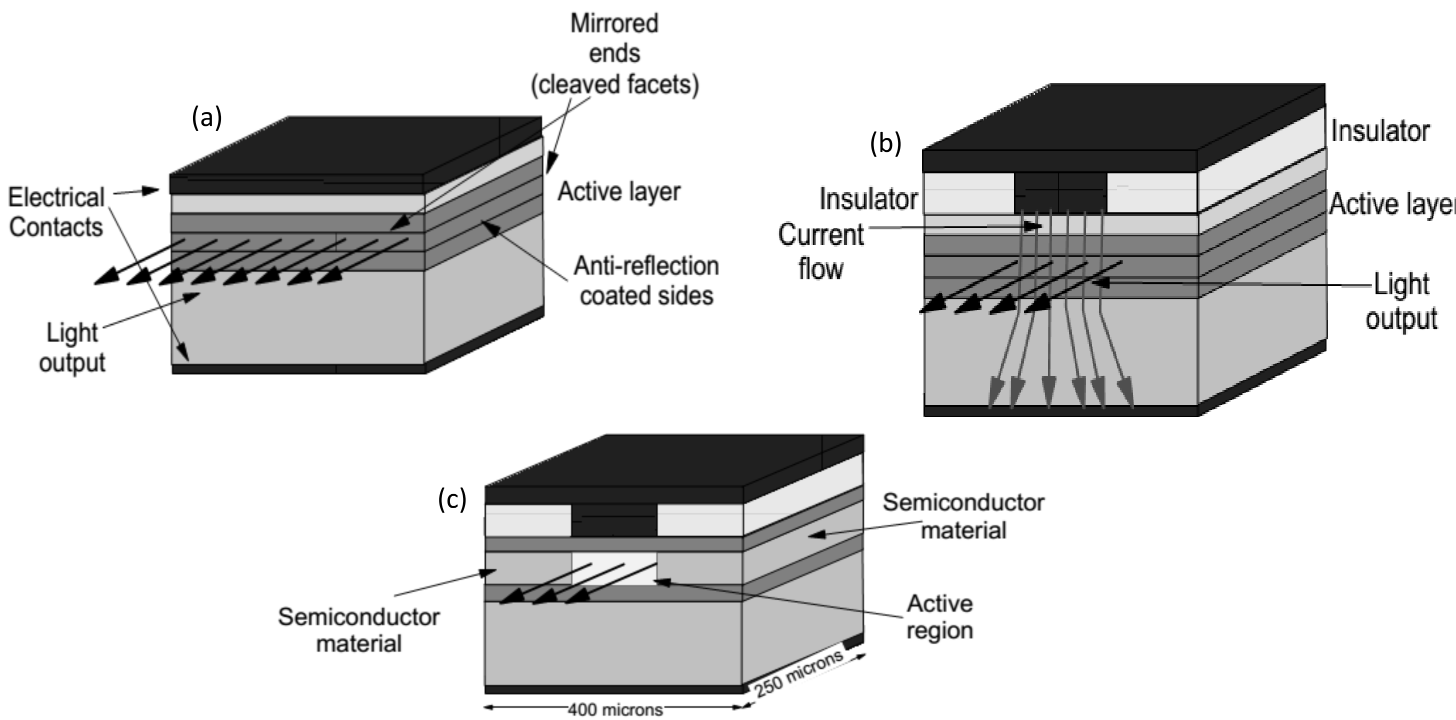


Figure 2.7: Unguided FP-LD (a), gain guided FP-LD (b) and index guided FP-LD (c).

These devices are made from a single semiconductor crystal and the planes of the crystal are exactly parallel. The interface of the semiconductor medium and air forms a mirror. The active layer is very thin and the refractive index difference between the material of the active layer and the surrounding material is not great. Thus, lasing is not occurred in the vertical mode. Lasing is appeared in the lateral mode but this is minimized by either coating the sides with an anti-reflection material or just making sure the sides are rough. In unguided FP-LD, lasing is appeared in the longitudinal mode across the full width of the device so the device will produce many different wavelengths as shown in figure 2.7(a). A more major problem is that it becomes very difficult to guide the light into a fiber. The solution to this problem that two devices are invented and are called “Gain guidance” and “Index guidance”.

The operational principle of gain guided FP-LD is to guide the power to active region so a strip line is connected with the active layer as shown in figure 2.7(b). The current will pass through the strip line with least path and minimum resistance as shown in figure 2.7(b). Standing waves will be produced but the lateral modes will not be increased. Thus, a narrow beam of light is emitted from the center of the active region. It produces a spectral width of between 5 nm and 8 nm consisting of between 8 and 20 or so lines. Linewidth is typically around .005 nm.

The operational principle of an index guided FP-LD differs from the operational principle of gain guided FP-LD. If strips of semiconductor material are put beside the active region as shown in figure 2.7(c), an index guided FP-LD are created. So, the active region is surrounded on all sides by material of a lower refractive index. Mirrored surfaces are formed and this is easy to guide the light much better than gain guidance alone. Any light strikes the edges of the cavity is captured and guided it to the cavity. Additional modes reflecting from the sides of the cavity are eliminated. This is not too much of a power loss since lasing cannot occur in these modes and only spontaneous emissions will leave the cavity by this way. It produces a spectral width of between 1 nm and 3 nm with usually between 1 and 5 lines. Linewidth is generally around .001 nm. It is better than the gain guided FP-LD.

2.3 Summary

This chapter mentions the advantages and challenges of WDM-PON then it shows the characteristic of AWG. AWG is a very important element in WDM-PON, it operates as multiplexer and demultiplexer, AWG is considered colorless device and passive element. This chapter shows the main characteristics of FP-LD and it discusses how FP-LD works. The operation of FP-LD is similar to Fabry Perot filter because it filter the undesired wavelengths. The construction of FP-LD is showed such as an Unguided, guided and an index guided FP-LD.

Chapter 3 –System Analysis

In this chapter, we review the implementation details of a bidirectional PON system architecture. Firstly, it describes three proposed system models, the first system does not include AWGs, the second system includes AWG at RN and the final system includes two cascaded AWGs at both CO and RN. It explains the implementation environment and then the final results are discussed. As well as, the chapter compares main measurements such as BER versus received power for each system model.

3.1 System Models

In this chapter, three main parts of the system model are discussed. It contain modulator, AWG, PON link, demodulators and the FP-LD. The first proposed PON architecture is shown in Figure 3.1. In downstream, CW laser with frequency (193.1THz) is modulated by Mach-Zehnder modulator (MZM) using 10 Gbps non-return to zero (NRZ) downstream data to generate the desired downstream signal. The generated signal is sent over the bidirectional Optical Fiber. A circulator is used in the CO to separate the downstream and upstream traffic. The modulated signal is sent to ONU. At the ONU, using optical splitter/coupler, portion of the modulated signal is fed to a balanced receiver. For upstream, the other portion of the downstream modulated signal from the splitter/coupler is re-modulated using 2.5 Gbps NRZ upstream data by FP-LD in the ONU. The re-modulated OOK signal re-pass through the bidirectional Optical Fiber. By using the circulator to avoid influencing the downstream signal, the upstream signal is sent to a P-type Intrinsic N-type photodetecor (PIN PD) which is used to receive the upstream signal in the CO.

The system model is categorized into three main parts which are CO, single mode fiber channel and ONU and the main components used in the system are as follows:

Pseudo Random Binary Sequence (PRBS): Generates bit stream an according to different operation modes. The bit sequence is designed to approximate the characteristics of random data.

NRZ generator: Generates an electrical NRZ coded signal.

MZM: Modulators are the devices used to modulate the beam of light according to the modulating signal which is the electrical signal that will be carried over the light.

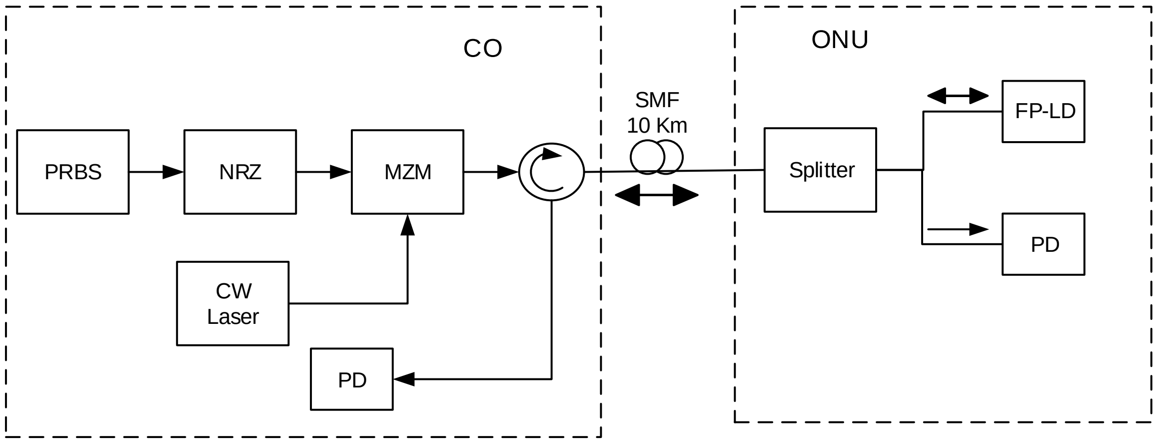


Figure 3.1: Block diagram of the first bidirectional PON system model

PIN-PD: It is used to convert the optical signal to electrical signal.

Bidirectional single mode fiber (SMF): The cable simulates the bidirectional propagation of arbitrary configuration of optical signals in a single-mode fiber.

FP-LD: This source simulates the modulation dynamics of a FP-LD using multimode rate equations. It has two inputs, one of them electrical input for modulation and the other is optical input for incoming optical signal. It has one output and it is optical port to send the remodulated signal.

Splitter 1×2: This device splits evenly the signal input power to two output ports.

CW laser: it is used to convert electrical signal to optical signal and it generates CW optical signal.

The second proposed PON architecture is shown in Figure 3.2. In downstream, CW laser with 193.1THz frequency is modulated by MZM using 10 Gbps NRZ downstream data to generate the desired downstream signal. The generated signal is sent over the bidirectional Optical Fiber then it passes through AWG which multiplexed the input signal. The multiplexed signal is sent to ONU. At the ONU, using optical splitter/coupler, portion of the multiplexed signal is fed to a balanced receiver. For upstream, the other portion of the multiplexed downstream signal from the splitter/coupler is re-modulated using 2.5 Gbps NRZ upstream data by FP-LD in the ONU. The re-modulated OOK signal re-pass through the AWG then it enters into bidirectional Optical Fiber. By using the circulator to avoid influencing the downstream signal, the upstream signal is sent to a PD is used to receive the upstream signal in the CO.

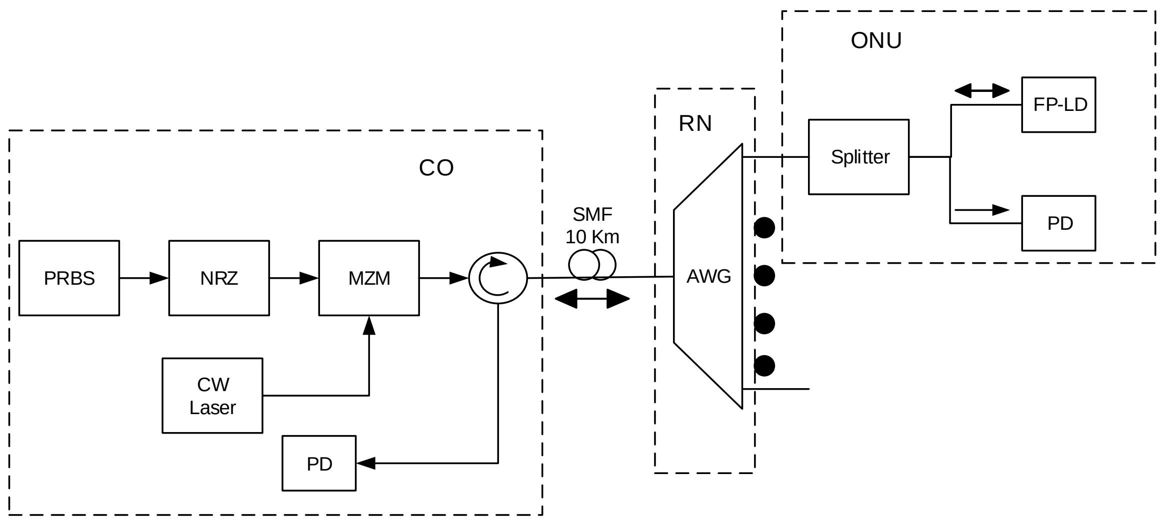


Figure 3.2: Block diagram of the Second bidirectional PON system model

This system includes AWG which is an optical device based on interferential phenomena, and it has a periodic behavior in the wavelength domain. The input optical signals in each port are routed to a specific output port depending on the signal wavelength and the input port number. Conventional WDM multiplexer can be used in CO to transmit multiple downstream wavelengths and AWG at RN will distribute these wavelengths to ONUs. For the system in figure 3.2 a tunable laser can be used in CO to transmit different wavelengths to ONUs.

The third proposed PON model architecture is shown in Figure 3.3. In downstream, CW laser with 193.1THz frequency is modulated by MZM using 10 Gbps NRZ downstream data to generate the desired downstream signal. The generated signal is sent to the first AWG at CO which multiplexed it then it is sent over the bidirectional Optical Fiber. It passes through the second AWG at RN which multiplexed the input signal again. The multiplexed signal is sent to ONU. At the ONU, using optical splitter/coupler, portion of the multiplexed signal is fed to a balanced receiver. For upstream, the other portion of the downstream multiplexed signal from the splitter/coupler is re-modulated using 2.5Gbps NRZ upstream data by FP-LD in the ONU. The re-modulated OOK signal re-pass through the AWG which demultiplexed the upstream signal then it is sent over bidirectional Optical Fiber. The upstream demultiplexed signal passes through the first AWG then it is received in CO. By using the circulator to avoid influencing the downstream signal, the upstream signal is sent to a PD is used to receive the upstream signal in the CO.

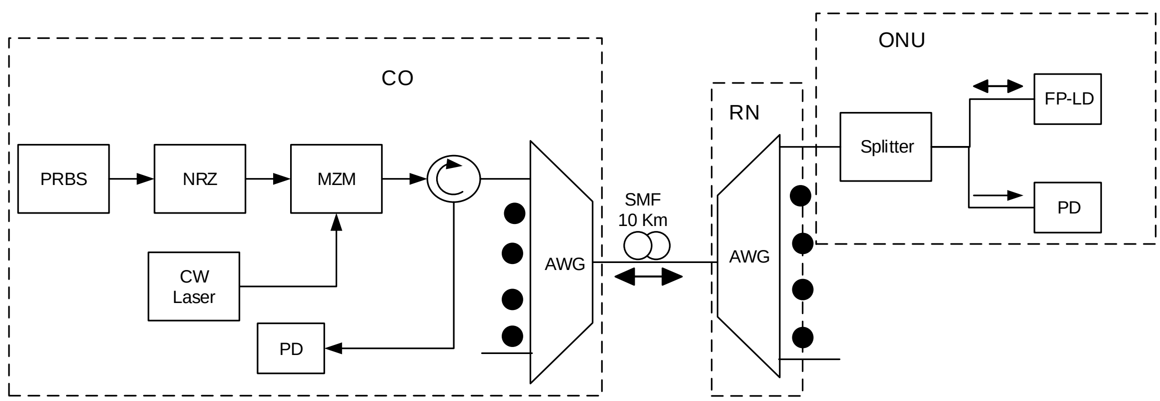


Figure 3.3: Block diagram of third bidirectional PON system model

3.2 Simulation Parameters:

From previous section, we can summarize the parameters that used in our system. These parameters are listed in table 3.1.

Table 3.1: Simulation parameters

Parameter	Value
Layout Parameter	
Bit rate (downstream)	10 Gbps
Bit rate (upstream)	2.5 Gbps
Sequence length	128 bits
Samples per bit	64
Number of Samples	8192
Optical Transmitter (CW laser)	
Laser Power input, P_{in}	1mW (0 dBm)
Frequency/Wavelength	193.1 THz / 1550 nm
Laser line Width	10 MHz
Optical link	
Length	10 km
Attenuation	0.2 dB/km
Dispersion	16.75ps/(nm×km)
Optical Attenuator	
Attenuation	10 dB
Optical Receiver (PIN PD)	
Responsivity	1 A/W
Dark Current	10 nA
Filter type	
Low Pass Bessel Filter (LPBF) for downstream	4 GHz
LPBF for upstream	1.7 GHz

3.3 Bidirectional GPON System based on FP-LD without AWG:

3.3.1 CO Part:

Transceiver in CO is shown in figure 3.4. Transmitter includes PRBS generator, NRZ generator, CW laser and MZM. Receiver contains PD, LPBF, 3R regenerator and BER analyzer.

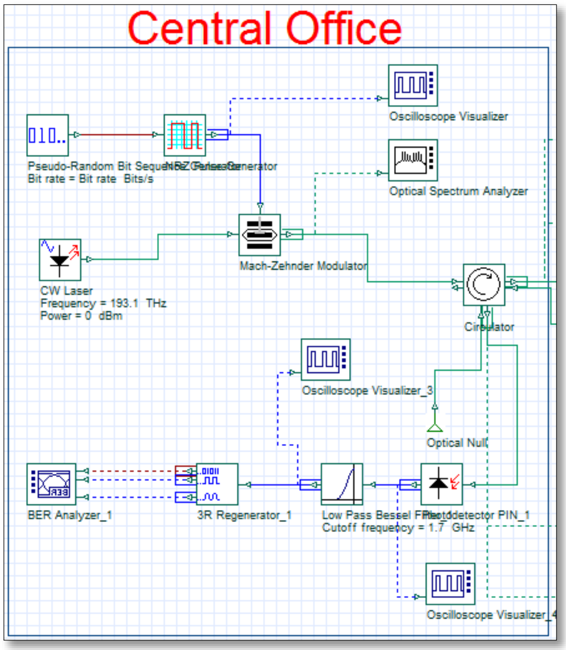


Figure 3.4: CO part in GPON without any AWGs

PRBS generator is used to generate random bit stream at bit rate equals to 10Gbps then the bit stream enters to the NRZ pulse generator that can convert the bit stream to pulse waveform as shown in figure 3.5.

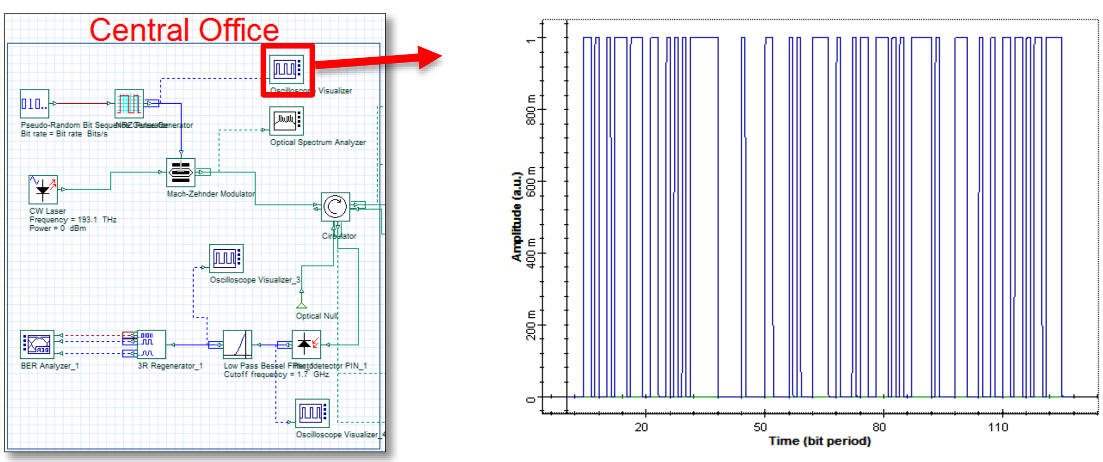


Figure 3.5: NRZ generator output at CO in GPON without any AWGs

NRZ generator output is electrical signal which has amplitude equals to 1 volt and bit sequence length equals to 128 bit. The parameters of CW laser are configured as shown in table 3.2. Frequency indicates the central frequency of the laser and determines the wavelength of the emitted light wave. Average power specifies the power of output light wave. Line width characterizes the width of the frequency interval of the total emission area. Initial phase gives the initial phase of oscillation to generate wave light.

Table 3.2: CW laser parameters in GPON without AWG

Parameter	Value
Frequency	193.1 THz
Power	0 dBm
Line width	10 MHz
Initial Phase	0 degree

The output power from MZM equals to -3.148 dBm so it is decreased due to loss in modulation. Optical Spectrum analyzer is used to display the signal in frequency domain, the output signal spectrum from MZM is shown in figure 3.6.

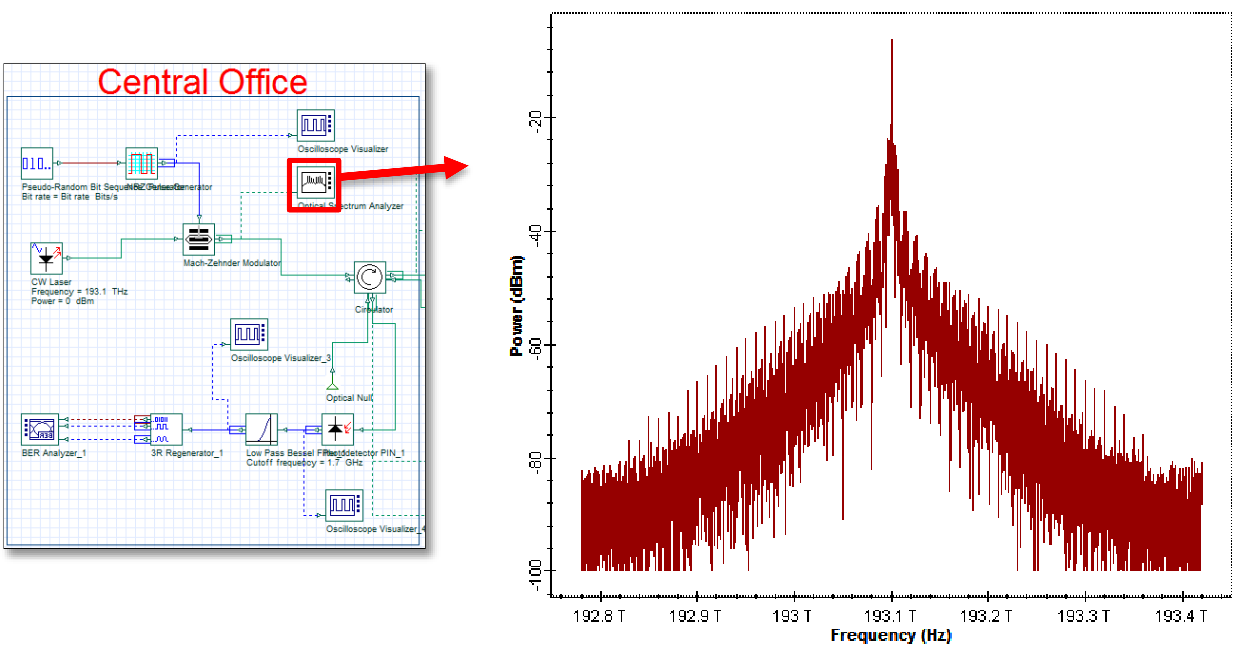


Figure 3.6: Output signal Spectrum from MZM at CO in GPON without any AWGs

The circulator is used to direct the transmitted signal into the Bidirectional SMF and at the same time is used to direct the upstream signal from ONU into receiver at CO. The upstream receiver at CO contains PIN PD and LPBF and BER analyzer. The incoming optical signal from ONU part and its total power equals to -63 dBm as shown in figure 3.7.

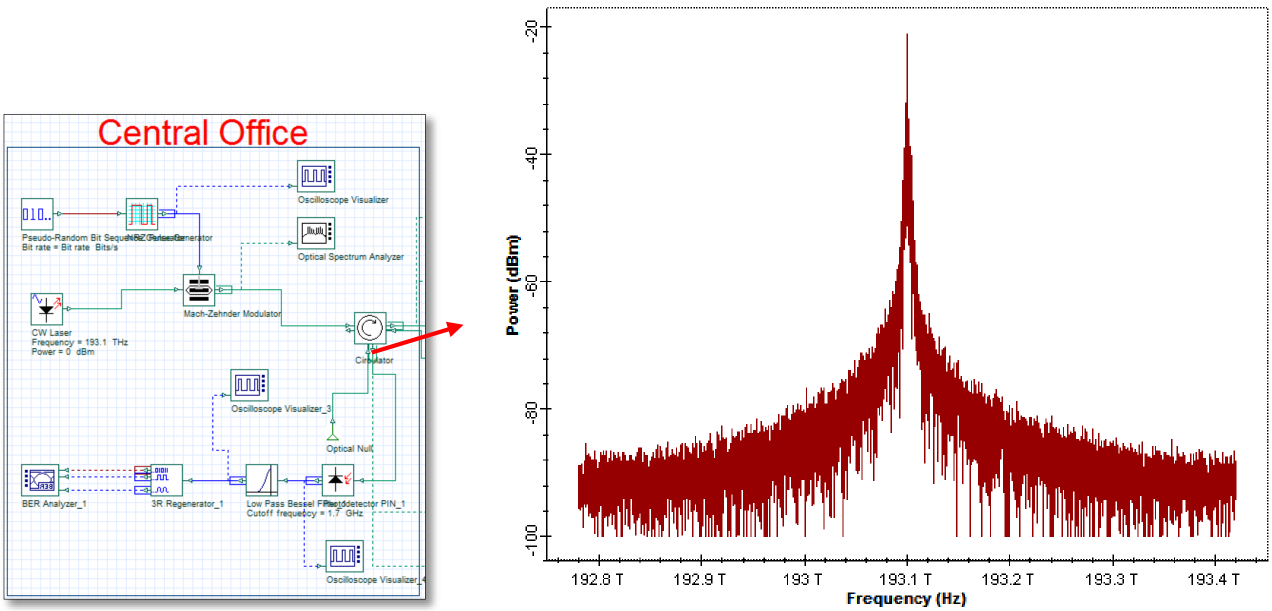


Figure 3.7: Incoming optical signal spectrum from ONU to CO in GPON without any AWGs

This incoming optical signal is detected by PIN PD which converts optical signal into electrical signal as shown in figure 3.8. The dark color signal is labeled for the desired signal but the light color signal is labeled for noisy signal.

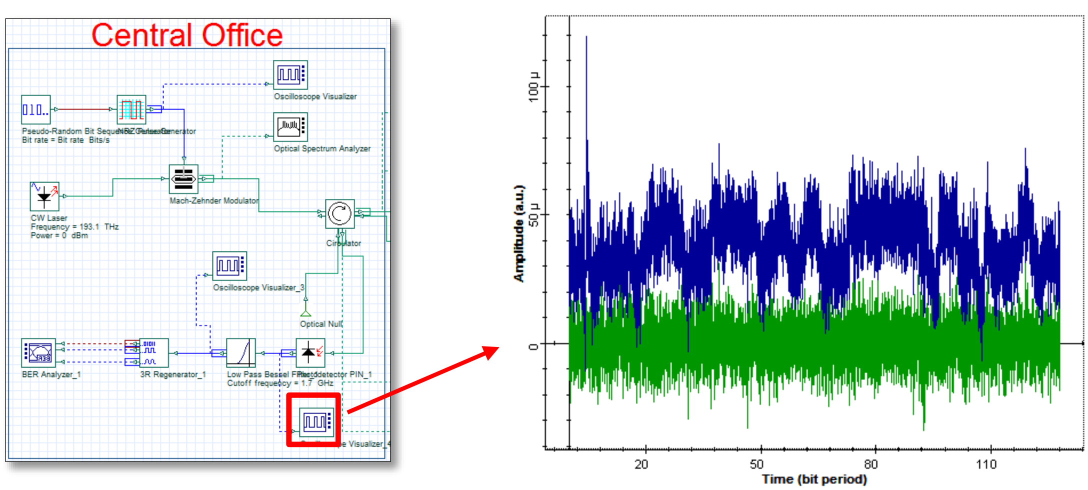


Figure 3.8: Upstream received signal from ONU to CO in GPON without any AWGs

The upstream received signal is filtered by LPBF at cutoff frequency of 1.7 GHz. Figure 3.9 illustrated transmitted signal from ONU and received signal at CO.

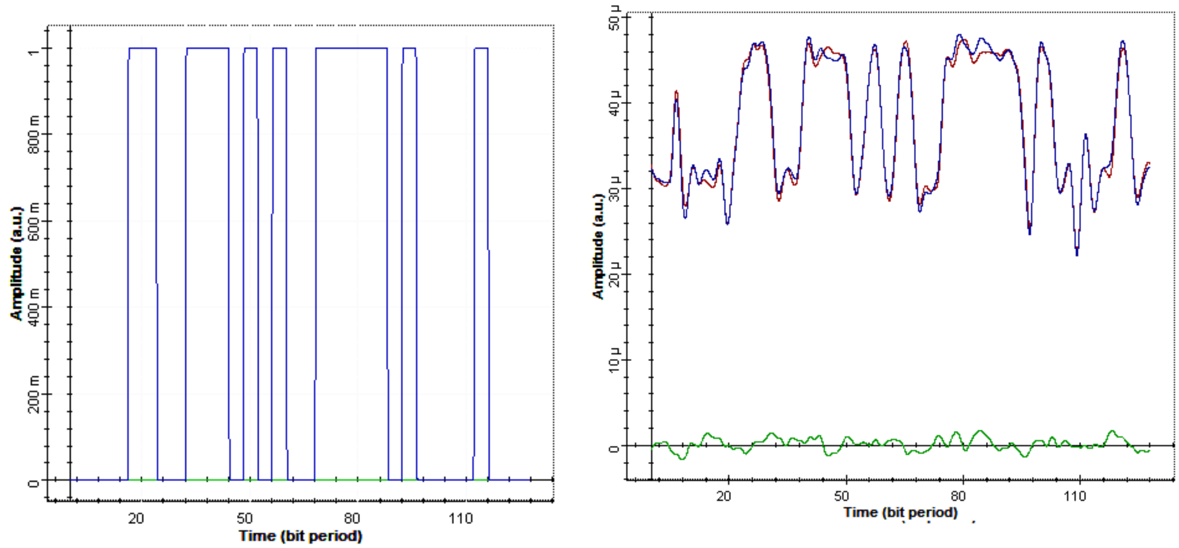


Figure 3.9: Upstream transmitted signal versus upstream received signal in GPON without any AWGs

The main parameter to determine the performance of any system in optical communication is evaluation of BER in this system so BER analyzer is used to display the eye diagram of Upstream BER. Minimum BER of Upstream received signal equals to 8.9×10^{-10} as shown in figure 3.10, this value is accepted in optical communication systems.

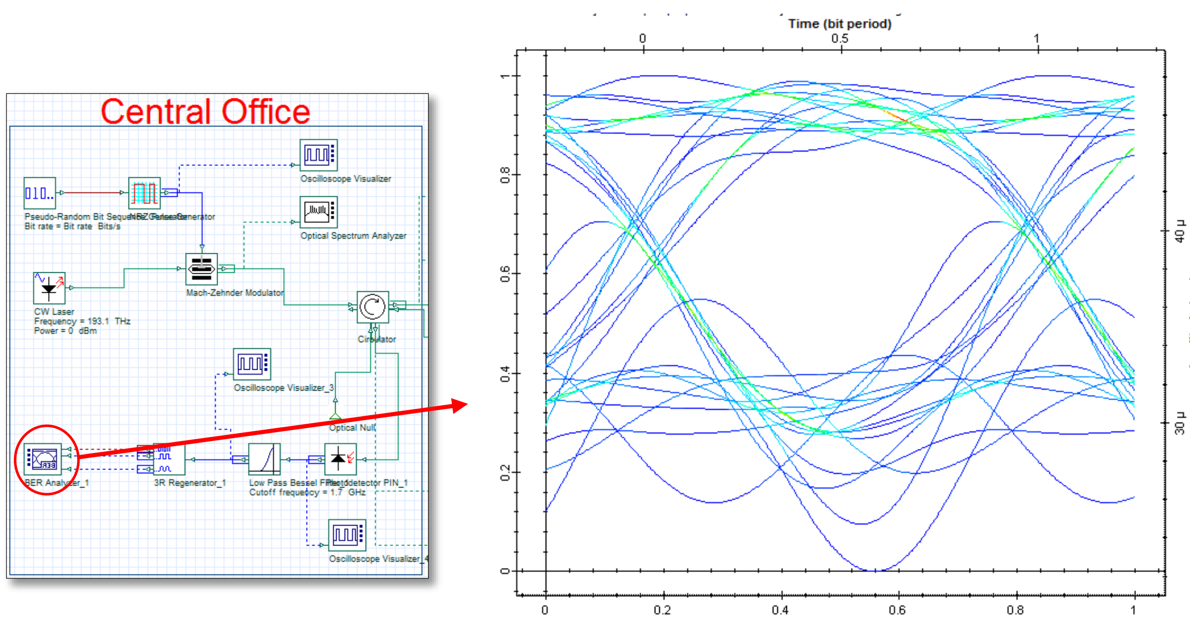


Figure 3.10: BER of Upstream received signal at CO in GPON without any AWGs

3.3.2. Bidirectional channel Part:

The channel includes bidirectional optical fiber as shown in figure 3.11.

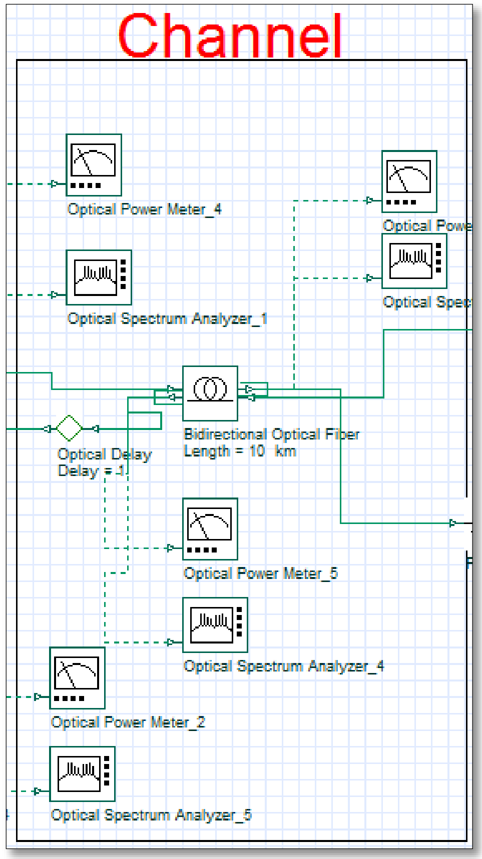


Figure 3.11: Bidirectional channel in GPON without any AWGs

A bidirectional single mode fiber of 10 km is used to forward the signal and to backward it with an optical delay of 1 unit in order to separate the upstream and downstream signals. Table 3.3 shows the main parameters of a bidirectional optical fiber.

Table 3.3: Bidirectional optical fiber parameters in GPON

Parameter	**Value**
Reference wavelength	1550 nm
Length	10 km
Attenuation	0.2 dB/km
Dispersion	16.75 ps/(nm×km)
Dispersion slope	0.075 ps/(nm^2×km)

The fiber cable has an attenuation loss of 0.2 dB/km and length of 10 km, this means there is a 0.2 dB/km×10 km which equals to 2 dB power loss. Output downstream signal power and output upstream signal power from optical fiber equals to -5dBm, -14.2dBm respectively. Figure 3.12 illustrated output downstream signal spectrum and output upstream signal spectrum.

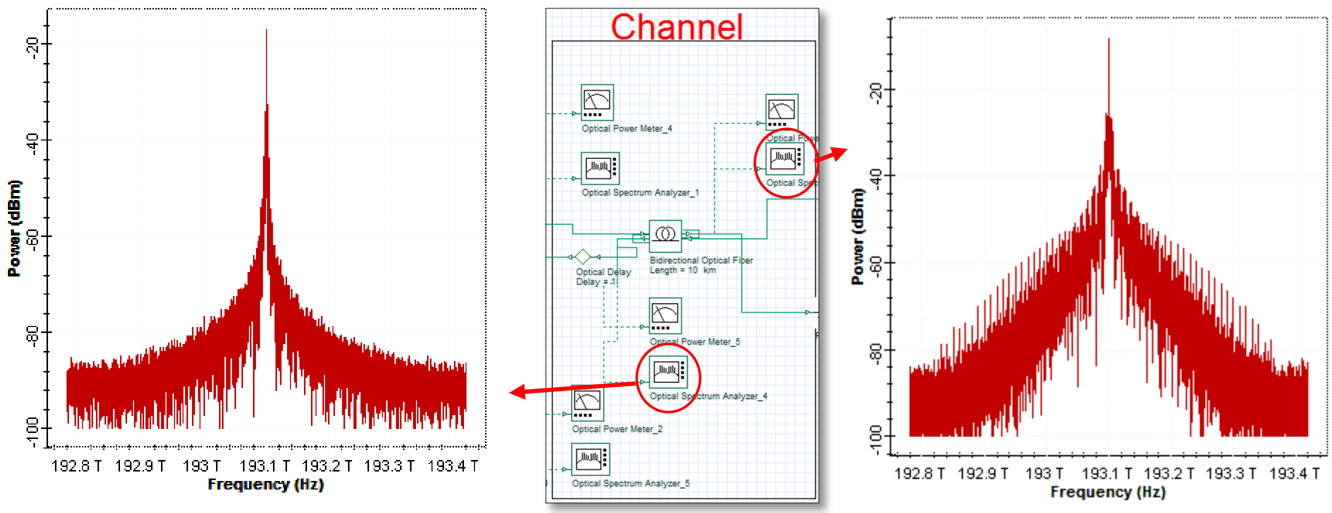


Figure 3.12: Downstream optical spectrum (right side) and upstream optical spectrum (left side) in the channel

3.3.3 ONU Part:

The transceiver at ONU includes two parts, first part is used to receive the signal from CO as discussed previously and second part is used to send signal to CO. Figure 3.13 illustrated ONU part.

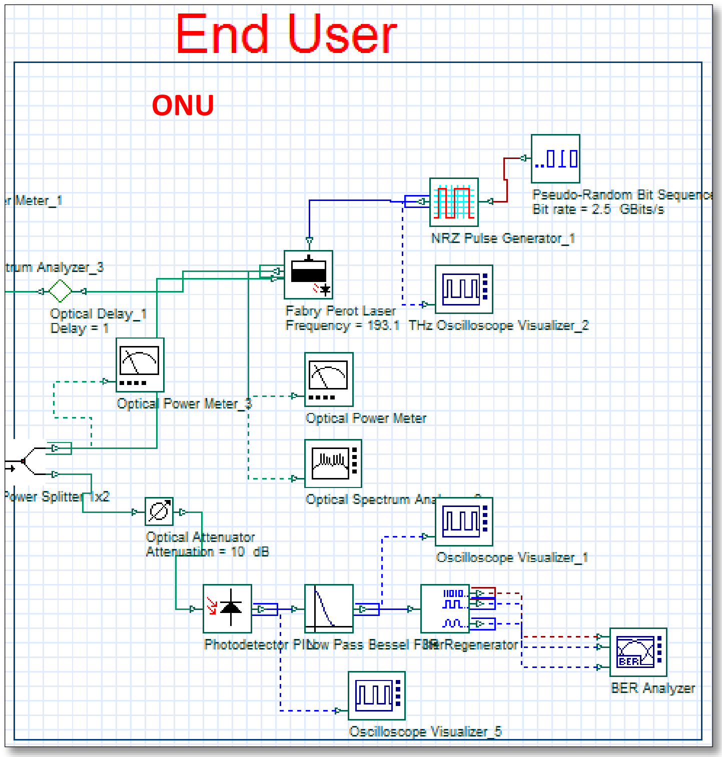


Figure 3.13: ONU part in GPON without any AWGs

ONU includes many components for receiving downstream signal and for transmitting upstream signal. Received signal components include Splitter, optical attenuator, PIN PD, LPBF, 3R regenerator and BER analyzer, transmitted signal components include FP-LD, NRZ generator and PRBS generator. Splitter is used to split the downstream signal into two partitions, one of them is received by PIN PD and the other portion is passed to FP-LD. Splitter has two output port so it will decrease the power of received signal by 3dBm, output optical power from Splitter equals to -8 dBm. Optical attenuator is used to account for other losses in the AWGs and it is adjusted to 10dB (5 dB for AWG in CO and 5 dB for AWG in RN). The output signal power from optical attenuator equals to -18 dBm and received optical signal spectrum is shown in figure 3.14.

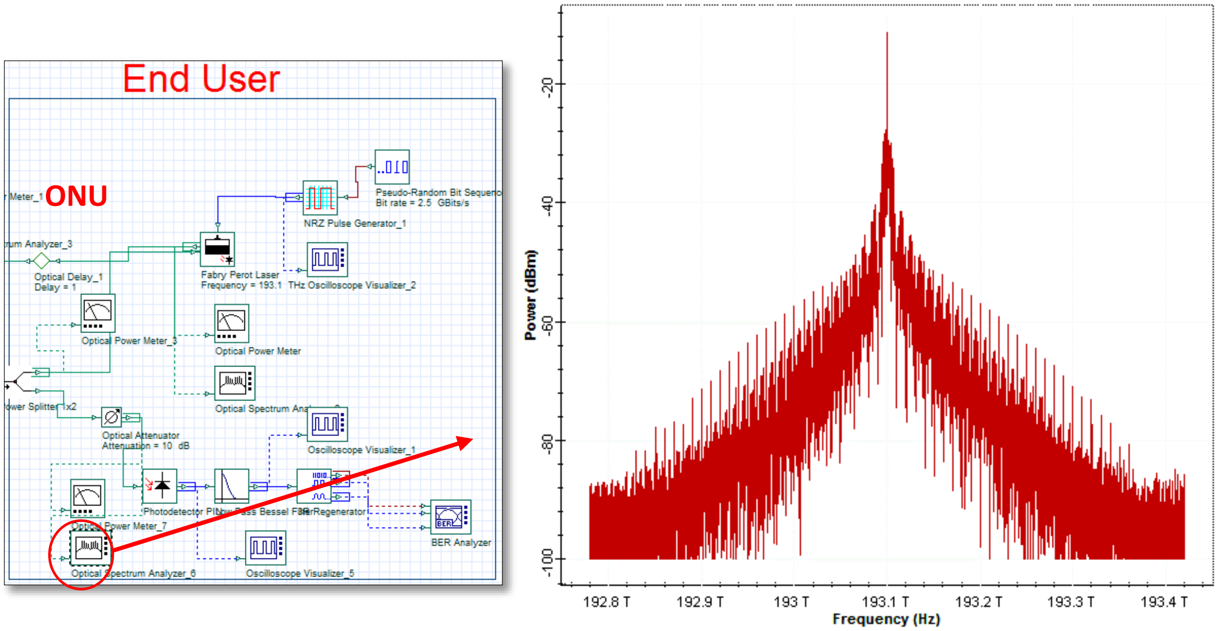


Figure 3.14: Received optical spectrum at ONU in GPON without any AWGs

The optical signal is received by PIN PD operating at 193.1 THz frequency to convert it back to electrical pulse wave, the received signal after PD is illustrated in Figure 3.15.

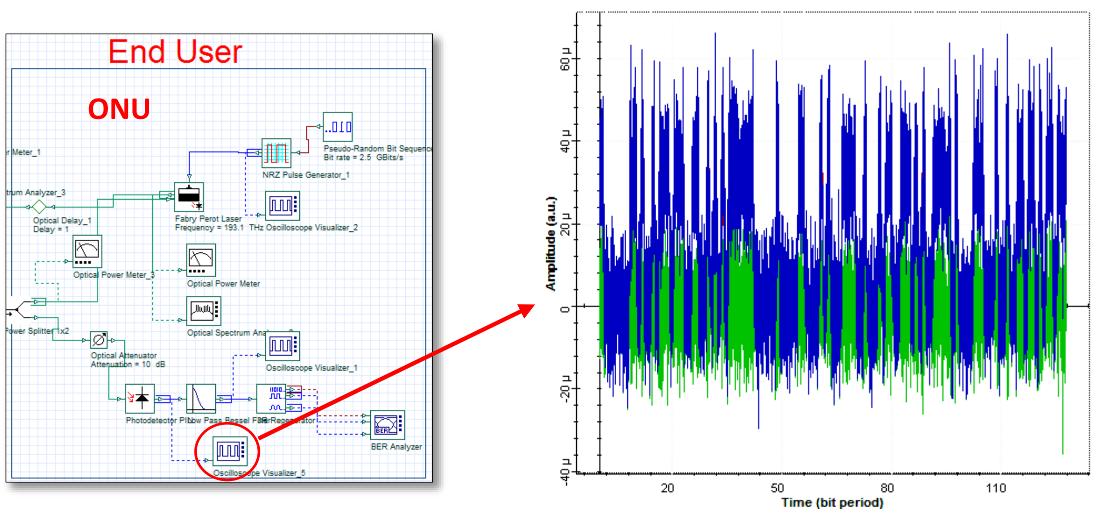


Figure 3.15: Received downstream electrical signal after PD in GPON without any AWGs

This signal needs a filter to recover the transmitted signal from CO so LPBF is used to filter the signal and it has cutoff frequency of 4 GHz. Figure 3.16 illustrated the received downstream electrical signal versus the transmitted downstream electrical signal.

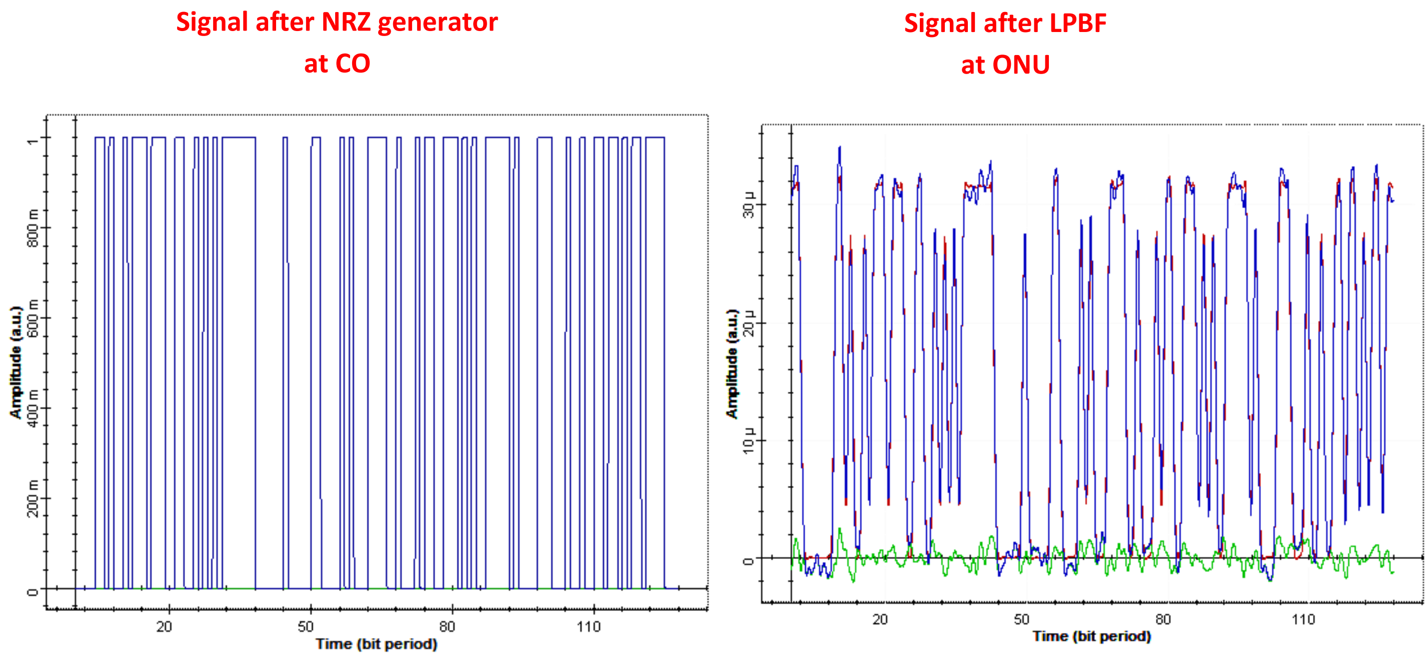


Figure 3.16: Received downstream electrical signal after LPBF in GPON without any AWGs

The filter order is fourth to increase the sharpness of filter edges and to decrease the transition area, more parameters for LPBF are included in Table 3.4.

Table 3.4: LPBF parameters at ONU

Parameter	Value
Frequency	4 GHz
Insertion loss	0 dB
Depth	100 dB
Order	4

BER analyzer is used to evaluate the downstream BER so the value of min. BER equals to 7×10^{-15} and the eye diagram of downstream signal is shown in figure 3.17.

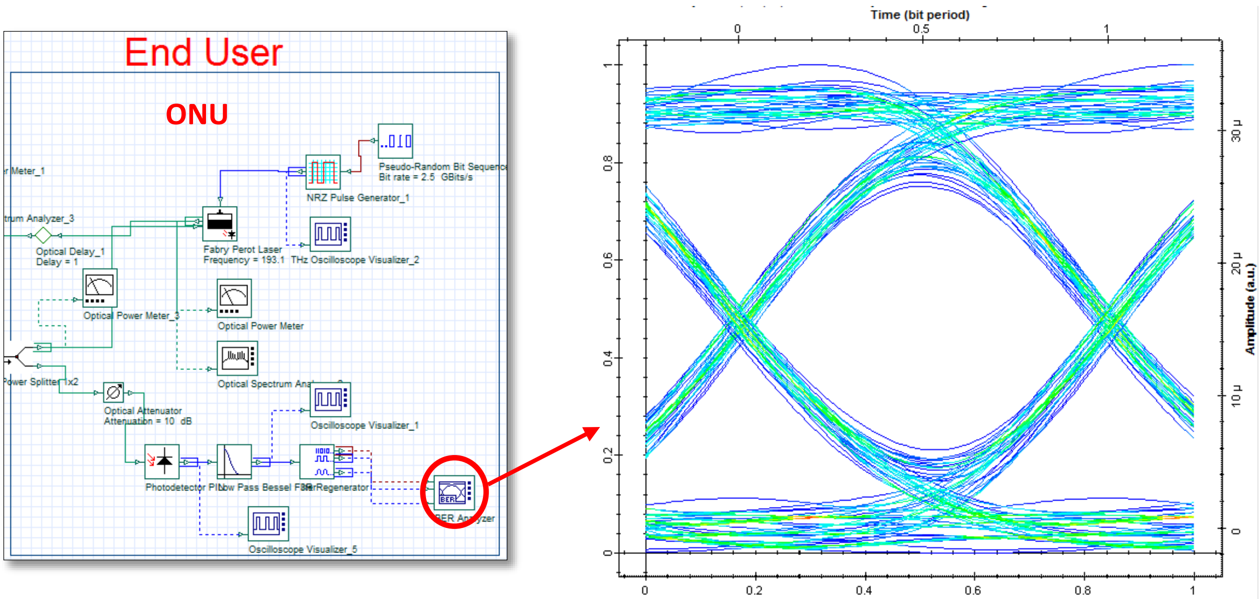


Figure 3.17: Eye diagram for downstream signal at ONU without any AWGs

FP-LD is used as transmitter at ONU and it is called colorless ONU because it is operated at the same transmitted frequency from CO. PRBS generator and NRZ generator is used to re-modulate the downstream signal and the upstream signal is shown in figure 3.18.

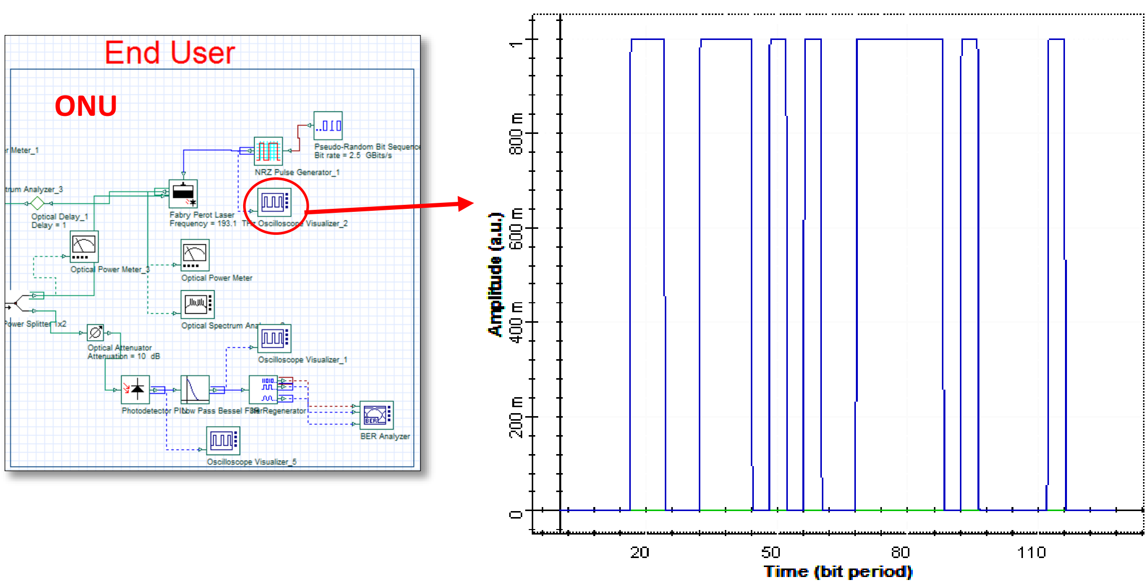


Figure 3.18: Upstream electrical signal at ONU in GPON without any AWGs

The optical power after splitter equals to -8dBm and after injection to FP-LD equals to -12 dBm so this device does not amplify the input signal unlike RSOA. The main parameters of FP-LD are shown in Table 3.5.

Table 3.5: FP-LD parameters

Parameter	Value
Frequency	193.1 THz
Bias current	40 mA
Modulation peak current	10 mA
Front facet reflectivity	0.99
Rear facet reflectivity	0.9

Upstream optical signal spectrum after injection is shown in figure 3.19.

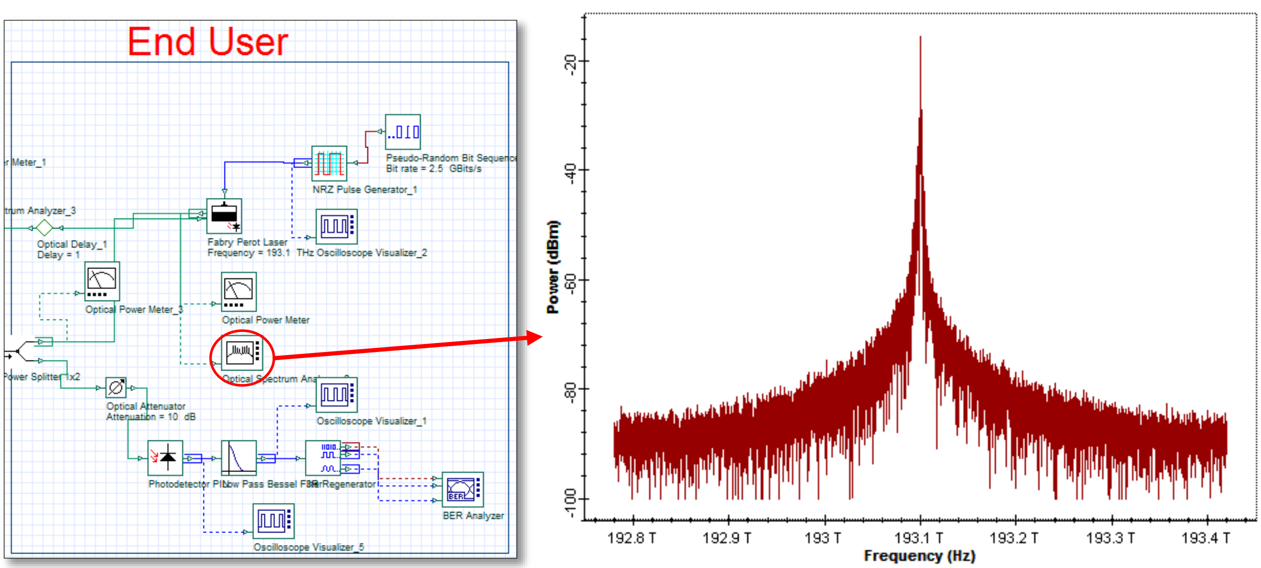


Figure 3.19: Output signal spectrum from FP-LD in GPON without any AWGs

3.3.4 BER versus Received power for the first system (No AWGs):

In this section, we will show the influence of the received power variation on the BER in both upstream signal and downstream signal, According to the previous section, our system includes three main parts such as CO part, Bidirectional SMF and ONU part. The BER versus downstream received power P_d curves for the downstream and upstream are shown in Figure 3.20.

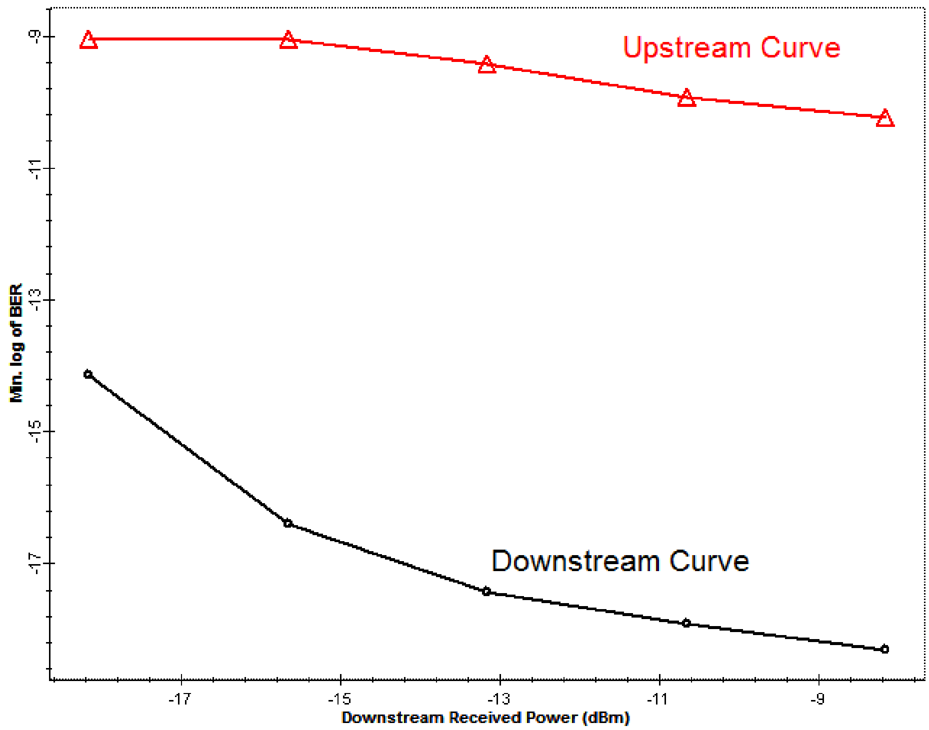


Figure 3.20: Min. log of BER versus Downstream received power at ONU for downstream and upstream in GPON without any AWGs

It is noted from the figure that the BER versus the downstream received power P_d (injected power) at ONU for the upstream signal goes down with increasing P_d from -18 dBm to -8 dBm. When P_d = -18 dBm, the BER $=8.9\times10^{-10}$. When P_d = -8 dBm, the BER $=5.8\times10^{-11}$. For the downstream signal, the BER curve goes down with P_d from -18 dBm to -8 dBm. When P_d = -18 dBm, the BER = 7.2×10^{-15}. When P_d = -8 dBm, the BER = 4.8×10^{-19}. Figure 3.21 is illustrated BER versus upstream received power P_u at CO.

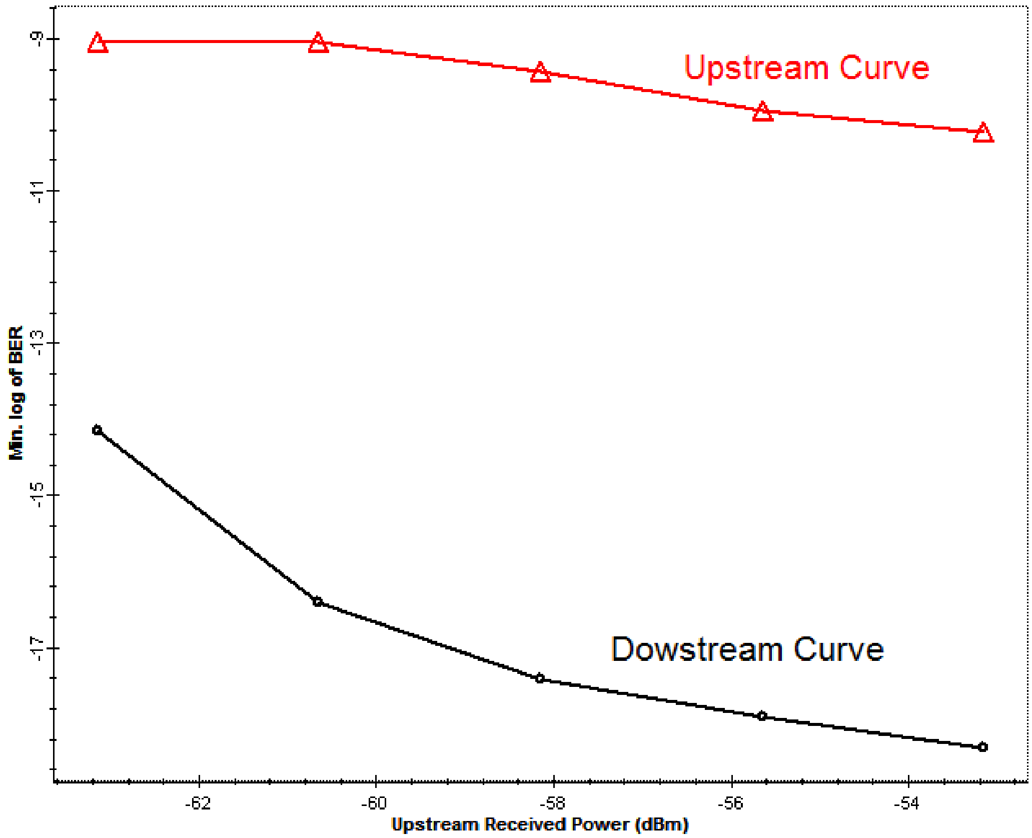


Figure 3.21: Min. log of BER versus upstream received power at CO for downstream and upstream in GPON without any AWGs

It is noted from the figure that the BER versus the upstream received power P_u at CO for the upstream signal goes down with increasing P_u from -63 dBm to -53 dBm. When P_u = -63 dBm, the BER =8.9×10^{-10}. When P_u = -53 dBm, the BER =5.8×10^{-11}. For the downstream signal, the BER curve goes down with P_u from -63 dBm to -53 dBm. When P_u = -63 dBm, the BER = 7.2×10^{-15}. When P_u = -53 dBm, the BER = 4.8×10^{-19}.

3.4 Bidirectional WDM-PON System based on FP-LD with AWG at RN:

3.4.1 CO Part:

The transceiver is the same as discussed in section 3.3.1 and the results are shown in figure 3.22 and the upstream received power is equal -14dBm. Two peaks spectrum are appeared as shown in figure 3.22 because AWG filter has Gaussian shape at 193.1 THz.

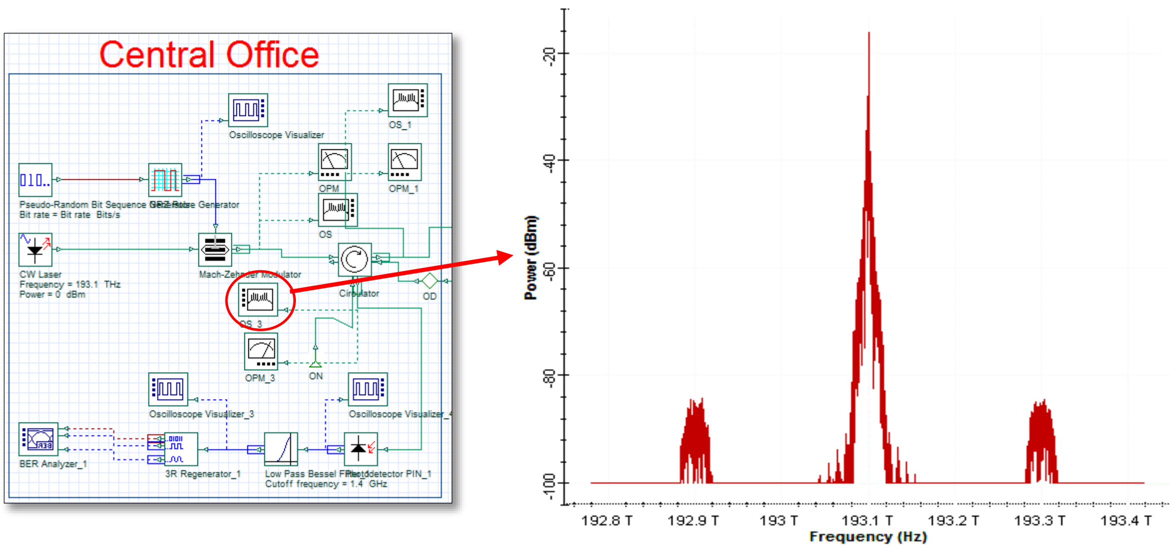


Figure 3.22: Received optical spectrum at CO in WDM-PON with AWG at RN

The min. BER equals to 3.6×10^{-12}. The eye diagram of upstream received signal at CO is shown in figure 3.23.

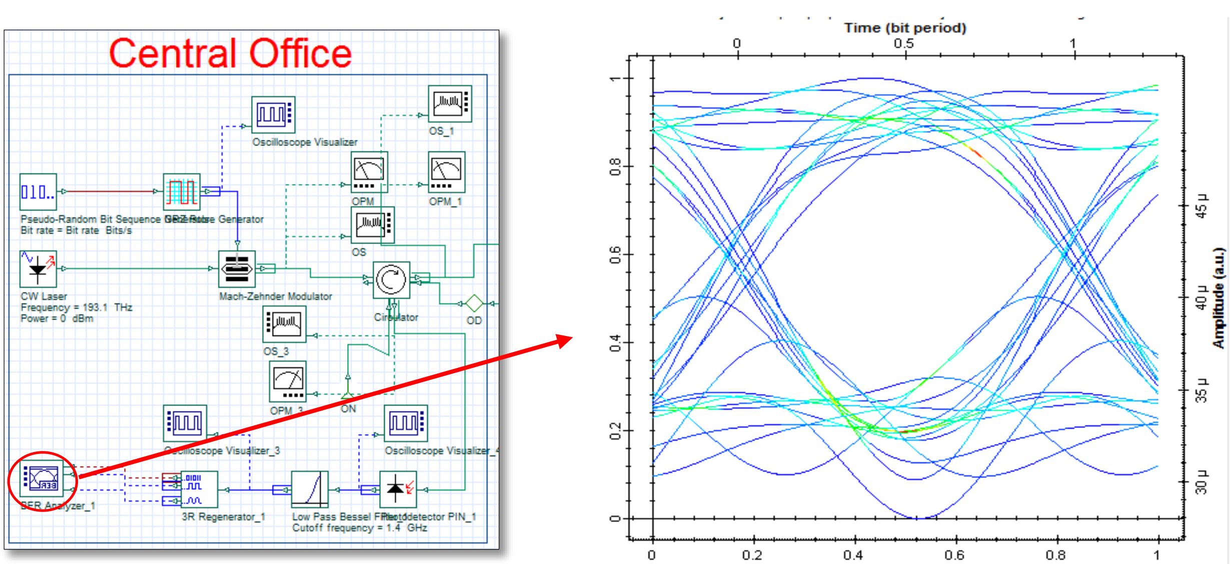


Figure 3.23: Eye diagram for upstream signal at CO in WDM-PON with AWG at RN

3.4.2. Bidirectional channel Part:

The channel includes bidirectional optical fiber and AWG as shown in figure 3.24.

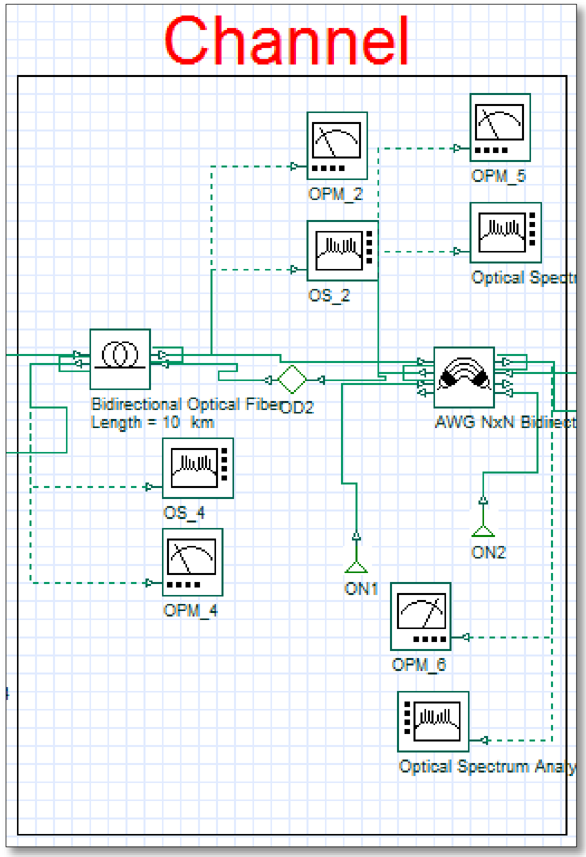


Figure 3.24: Bidirectional channel in WDM-PON with AWG at RN

The parameters of Bidirectional optical fiber does not change in this model and it is still the same parameters as illustrated in section 3.3.2. The downstream output spectrum and the power from optical fiber are illustrated previously. The upstream optical spectrum from optical fiber is shown in figure 3.25 and the upstream power equals to -13.9 dBm.

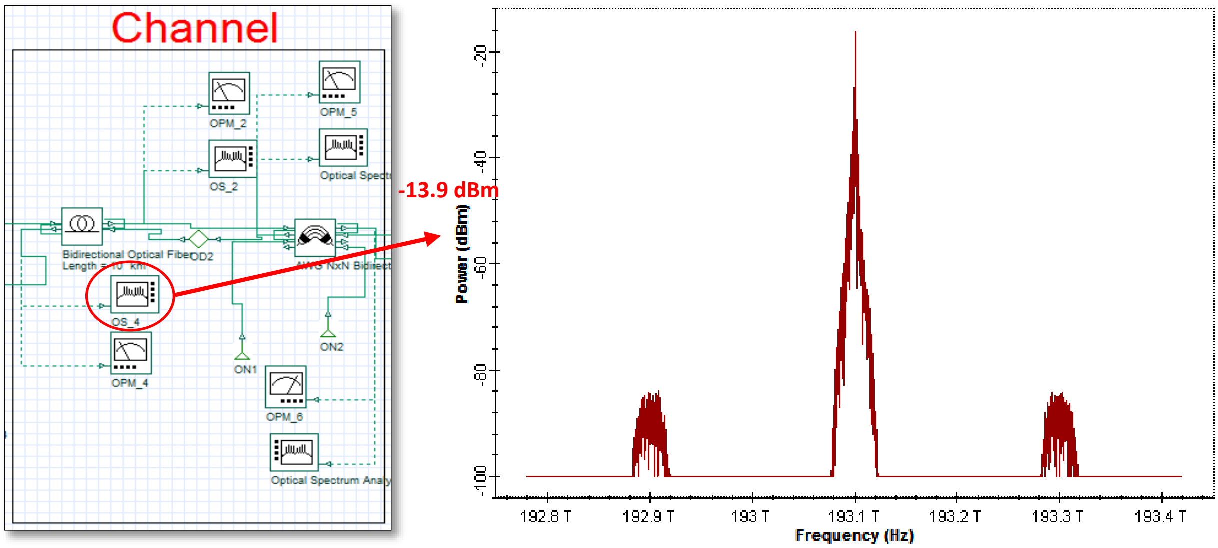


Figure 3.25: Output upstream signal spectrum from optical fiber at channel in WDM-PON with AWG at RN

The downstream optical signal will pass through AWG which is used as demultiplexer in the downstream direction and as multiplexer in the upstream direction. The main parameters of AWG are listed in table 3.6.

Table 3.6: AWG parameters at RN

Parameter	**Value**
Size	2 (two input port and two output port)
Frequency	193.1 THz
Bandwidth	25 GHz
Frequency spacing	100 GHz
Insertion loss	0 dB
Return loss	65 dB
Depth	100 dB
Filter type	Gaussian
Filter order	2

The output downstream signal power of AWG equals to -5.3 dBm and its spectrum is shown in figure 3.26.

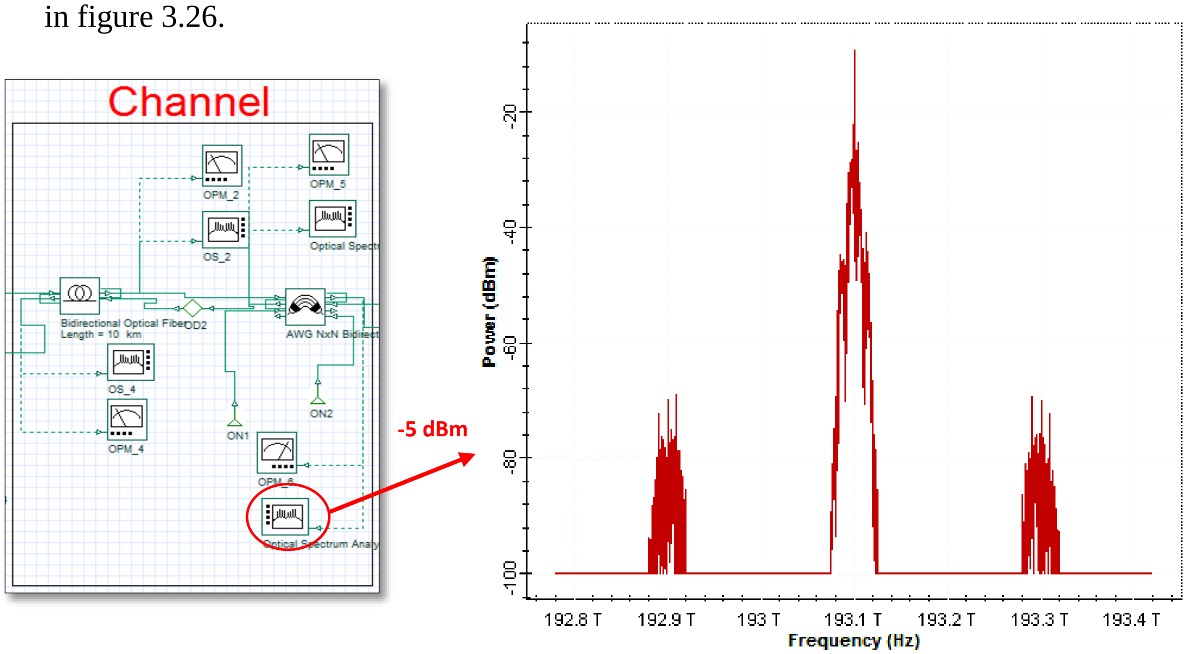


Figure 3.26: Output downstream signal spectrum from AWG at channel in WDM-PON with AWG at RN

The upstream optical spectrum from AWG is shown in figure 3.27 and its power equals to 11.9 dBm.

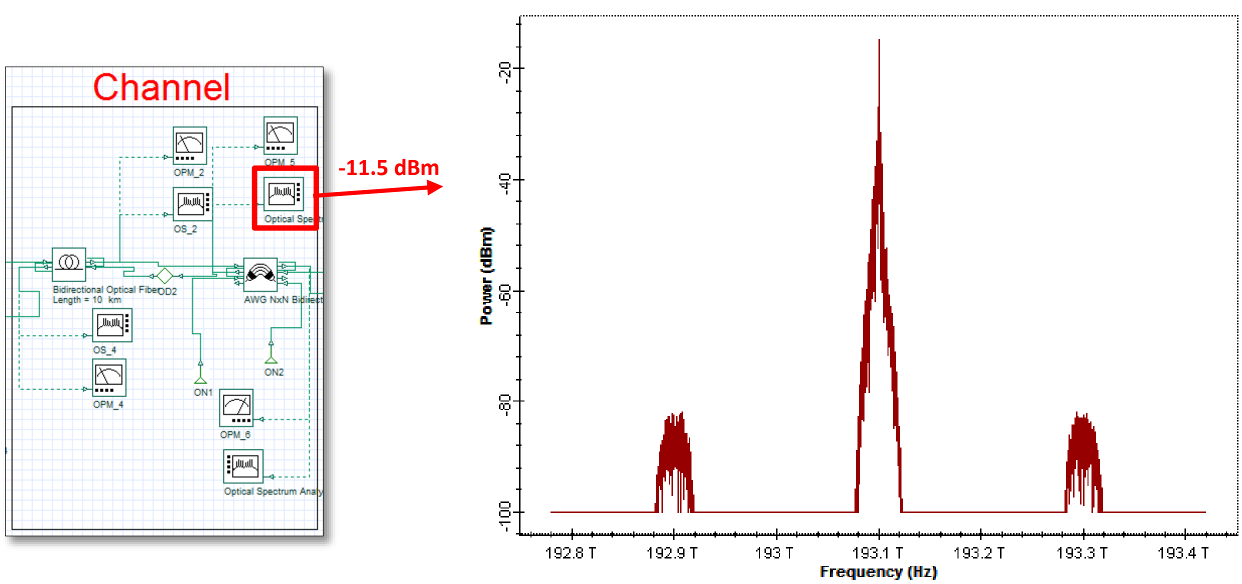


Figure 3.27: Output upstream signal spectrum from AWG at channel in WDM-PON with AWG at RN

3.4.3. ONU Part:

The receiver diagram is the same as discussed in section 3.3.3, the downstream signal power after splitter equals to -8.3 dBm and the received signal is shown in figure 3.28.

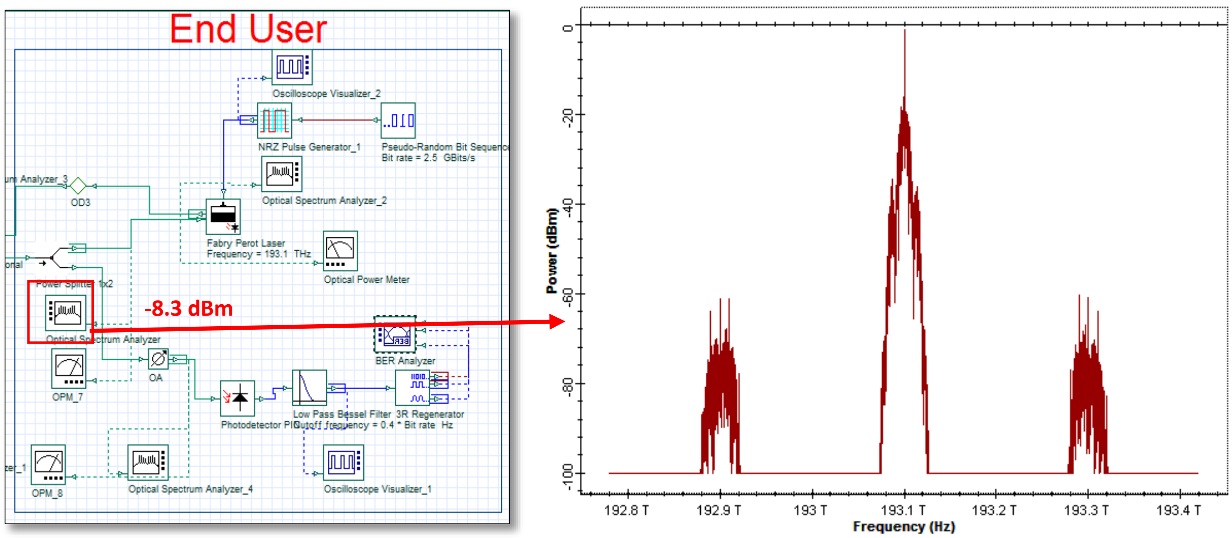


Figure 3.28: Output downstream signal spectrum after splitter at ONU in WDM-PON with AWG at RN

The downstream signal will attenuate by optical attenuator which has insertion loss equals to 10 dB, the downstream signal power becomes equals to -18.3 dBm and its spectrum is shown in figure 3.29.

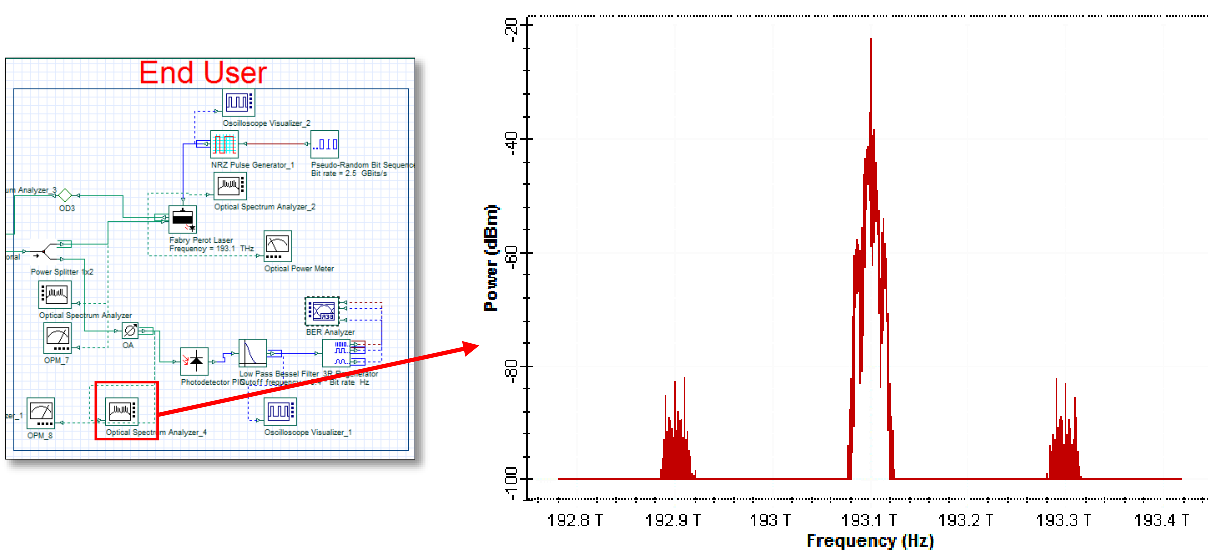


Figure 3.29: Output downstream signal spectrum after attenuator at ONU in GPON with AWG at RN

PD and LPBF have the same parameters as discussed in section 3.3.3. Min. BER for downstream signal is shown in figure 3.30 and it equals to 4.9×10^{-13}.

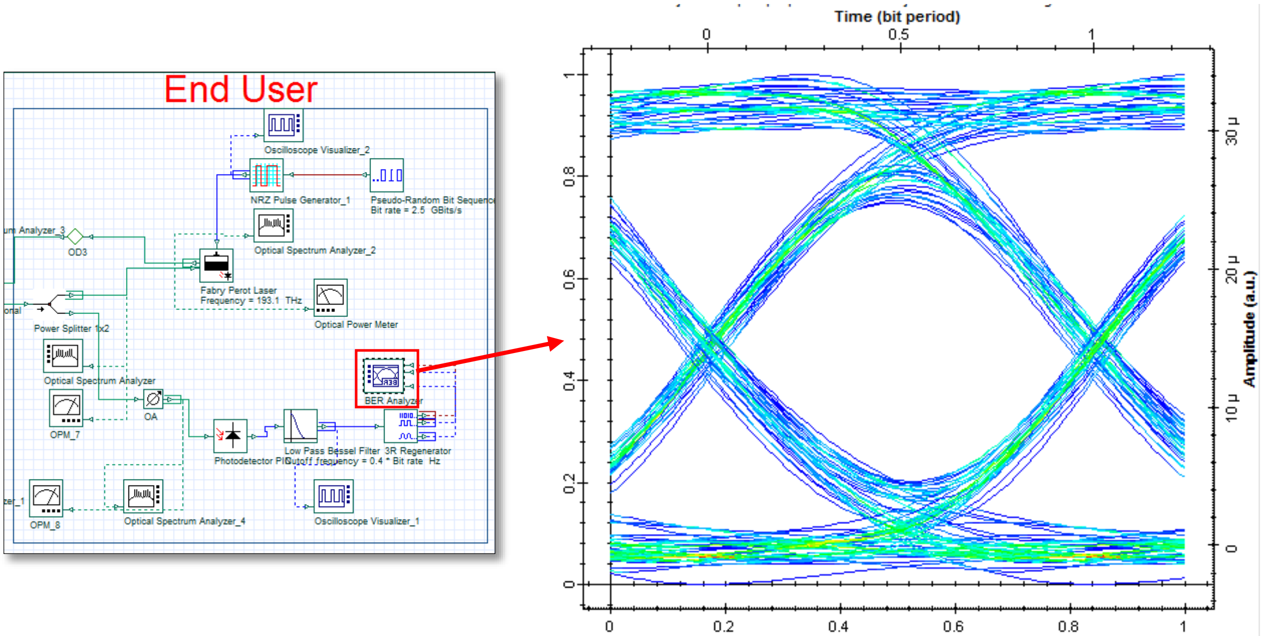


Figure 3.30: Eye diagram for downstream signal at ONU in WDM-PON with AWG at RN

The parameters of FP-LD is the same as discussed in section 3.3.3. The output optical power from FP-LD equals to 11.8 dBm and its spectrum is shown in figure 3.31.

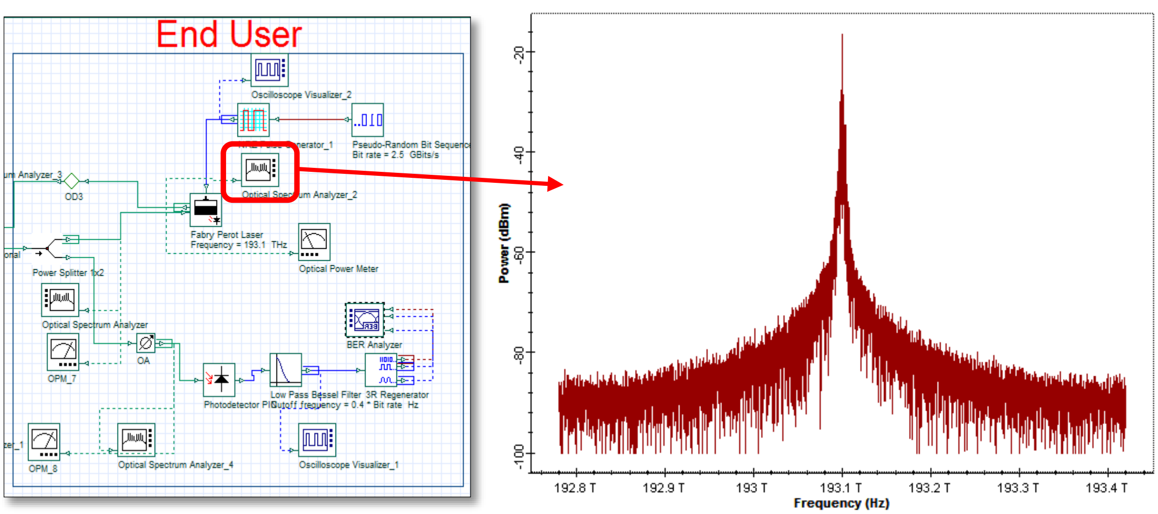


Figure 3.31: Output upstream signal spectrum after FP-LD at ONU in WDM-PON with AWG at RN

3.4.4 BER versus Received power for the second system with an AWG at RN:

In this section, we will show the influence of the received power variation on the BER in both upstream signal and downstream signal, According to the previous section, our system includes three main parts such as CO part, Bidirectional SMF and ONU part. The BER versus downstream received power P_d curves for the downstream and upstream are shown in Figure 3.32.

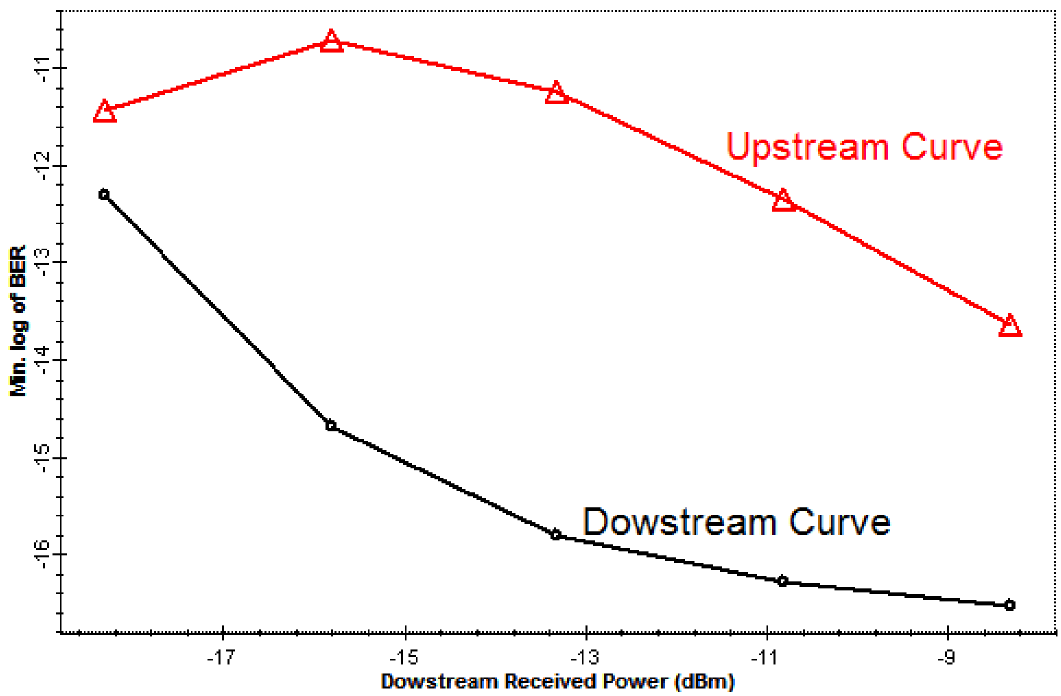


Figure 3.32: Min. log of BER versus Downstream received power at ONU for downstream and upstream in WDM-PON with AWG at RN

It is noted from the figure that the BER versus the downstream received power P_d (injected power) at ONU for the upstream signal goes down with increasing P_d from -18 dBm to -8 dBm. When P_d = -18 dBm, the BER = 3.6×10^{-12}. When P_d = -8 dBm, the BER =2.2×10^{-14}. For the downstream signal, the BER curve goes down with P_d from -18 dBm to -8 dBm. When P_d = -18 dBm, the BER = 4.9×10^{-13}. When P_{in} = -8 dBm, the BER = 2.9×10^{-17}. Figure 3.33 is illustrated BER versus upstream received power P_u at CO.

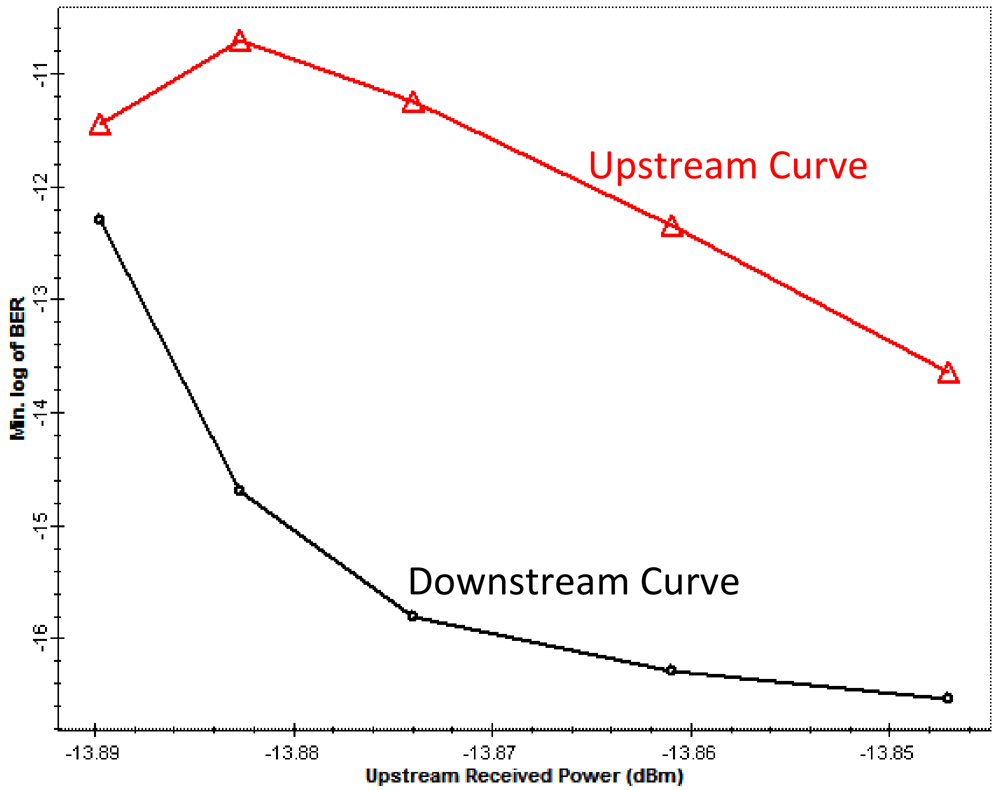


Figure 3.33: Min. log of BER versus upstream received power at CO for downstream and upstream in WDM-PON with AWG at RN

It is noted from the figure that the BER versus the upstream received power P_u at CO for the upstream signal goes down with increasing P_u from -13.89 dBm to -13.847 dBm.

When P_u = -13.89 dBm, the BER =3.6×10^{-12}. When P_u = -13.847 dBm, the BER =2.2×10^{-14}. For the downstream signal, the BER curve goes down with P_u from -13.89 dBm to -13.847 dBm. When P_u = -13.89 dBm, the BER = 4.9×10^{-13}. When P_u = -13.847 dBm, the BER = 2.9×10^{-17}.

3.5 Bidirectional WDM-PON System based on FP-LD with two cascaded AWGs:

3.5.1: CO Part:

The transceiver at CO is shown in figure 3.34. This model includes AWG after circulator as shown in the figure, it is operated as multiplexer in the downstream direction and like demultiplexer in the upstream direction. The output of circulator is the same as discussed in section 3.3.1.

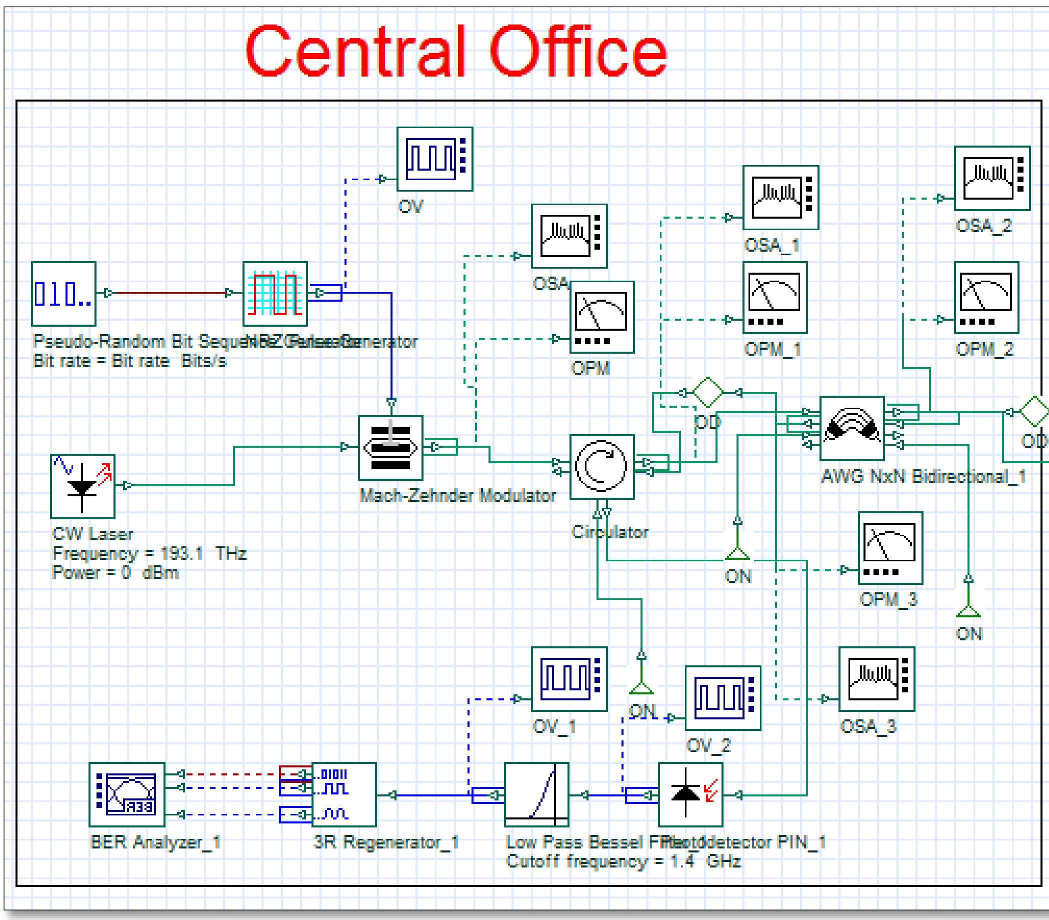


Figure 3.34: CO part in WDM-PON with two cascaded AWGs

AWG parameters in CO are similar to AWG parameters in RN. The downstream multiplexing signal spectrum is shown in figure 3.35 and its power equals to -3.3 dBm.

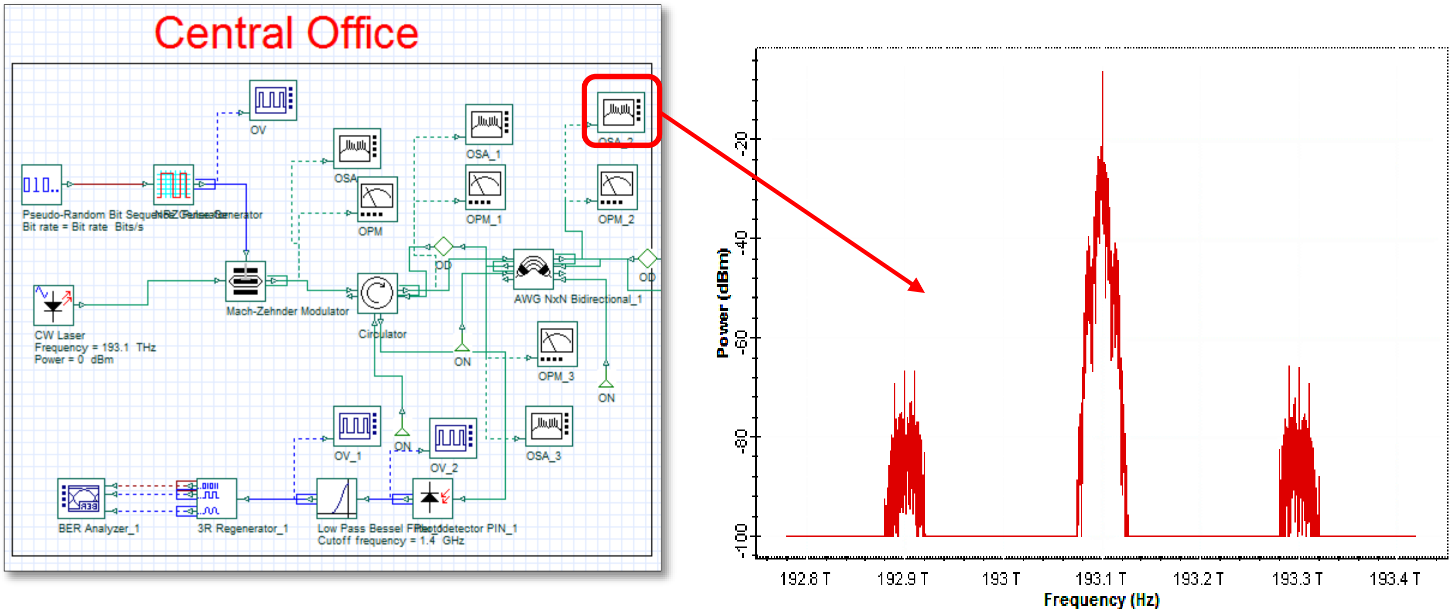


Figure 3.35: The downstream signal spectrum after AWG at CO in WDM-PON with two cascaded AWGs

The output upstream signal spectrum from AWG is shown in figure 3.36 and its power equals to -13.9 dBm.

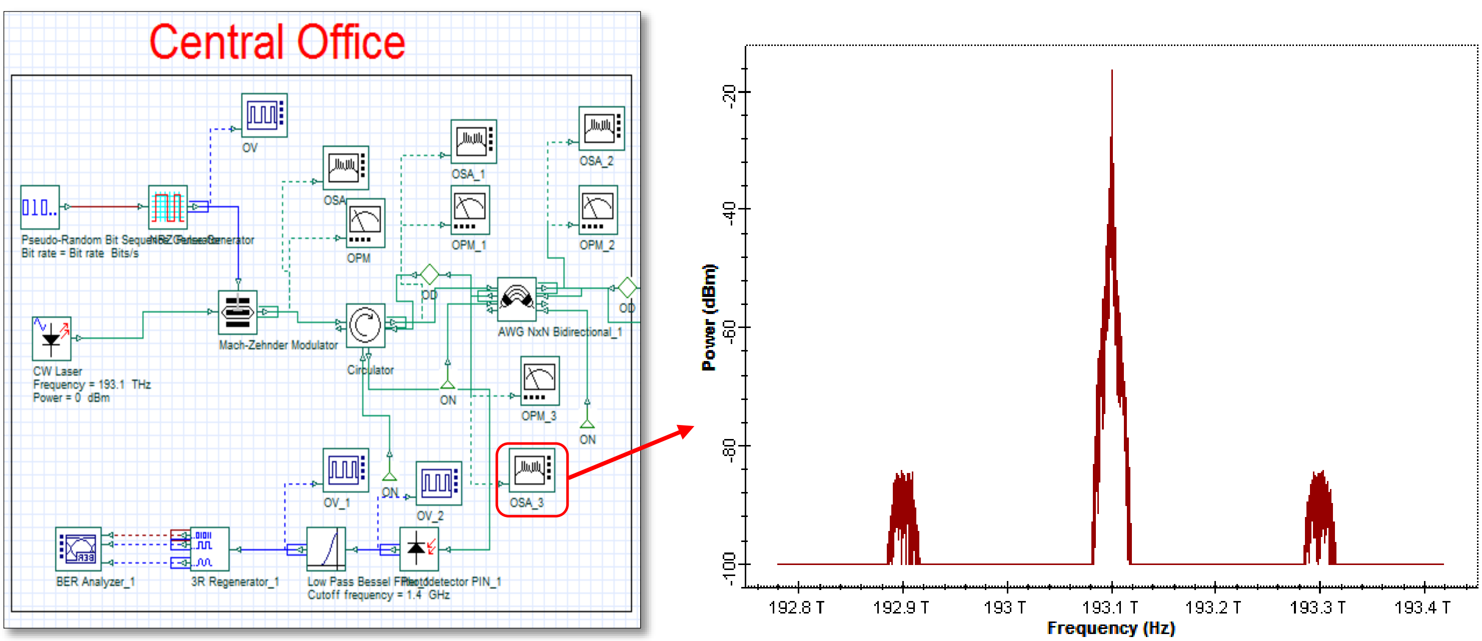


Figure 3.36: the output upstream signal spectrum from AWG at CO in WDM-PON with two cascaded AWGs

Min. BER equals to 6×10^{-11} and the eye diagram of upstream signal is shown in figure 3.37.

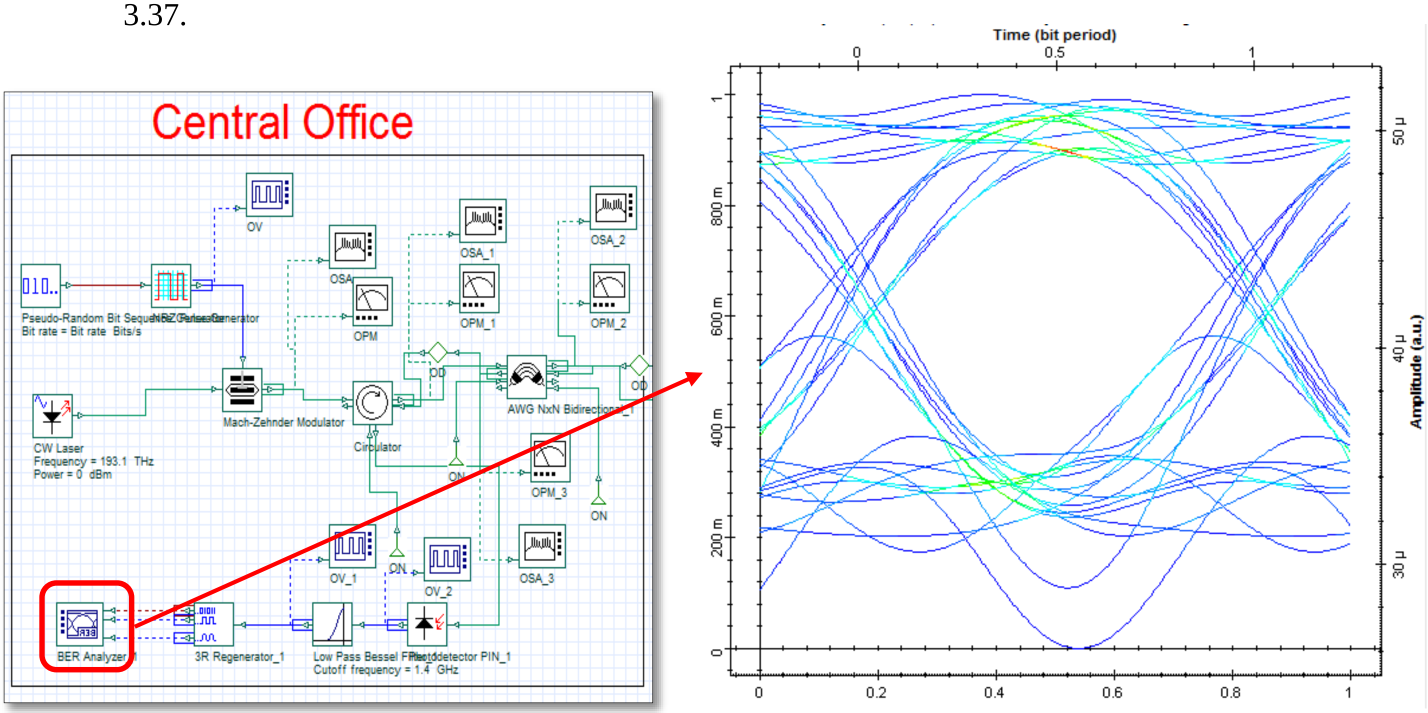


Figure 3.37: Eye diagram of upstream signal at CO in WDM-PON with two cascaded AWGs

3.5.2. Bidirectional channel Part:

The channel includes bidirectional optical fiber and AWG as shown in figure 3.38.

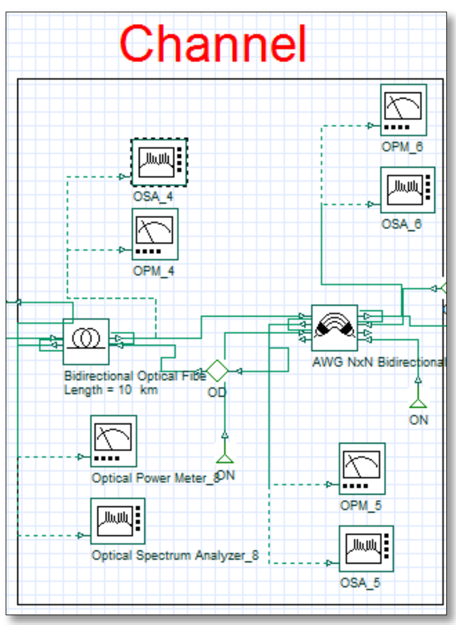


Figure 3.38: Bidirectional channel in WDM-PON with two cascaded AWGs

The parameters of Bidirectional optical fiber does not change in this model and it is still the same parameters as illustrated in section 3.3.2. The output downstream spectrum from optical fiber is shown in figure 3.39 and its power equals to -5.3 dBm.

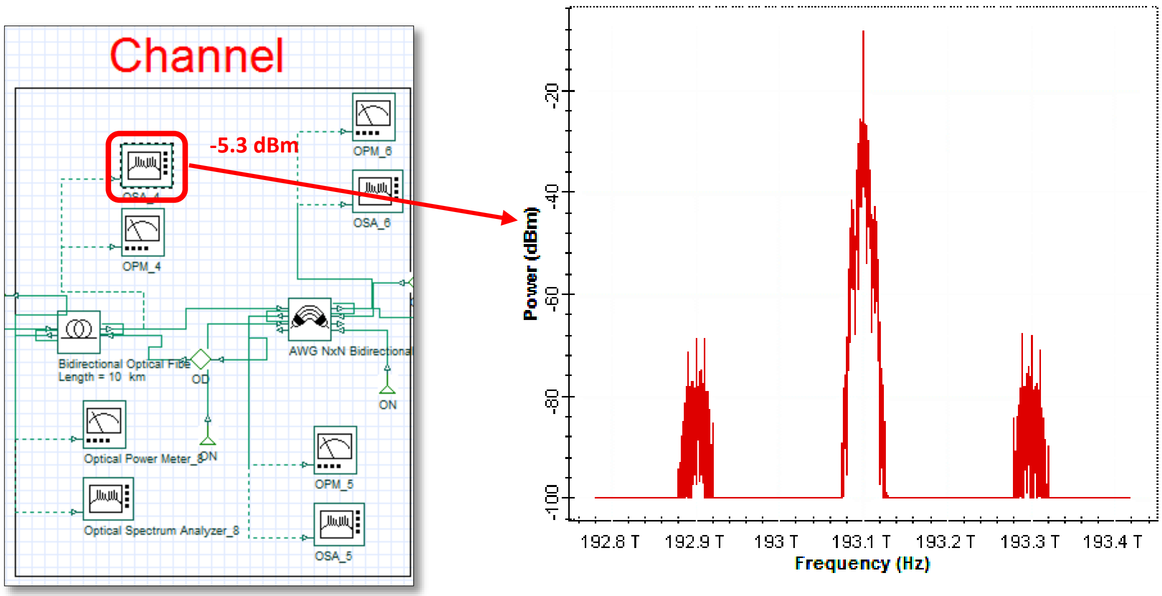


Figure 3.39: Downstream signal spectrum after optical fiber in WDM-PON with two cascaded AWGs

The downstream optical spectrum after AWG is shown in figure 3.40 and the downstream power equals to -5.3 dBm.

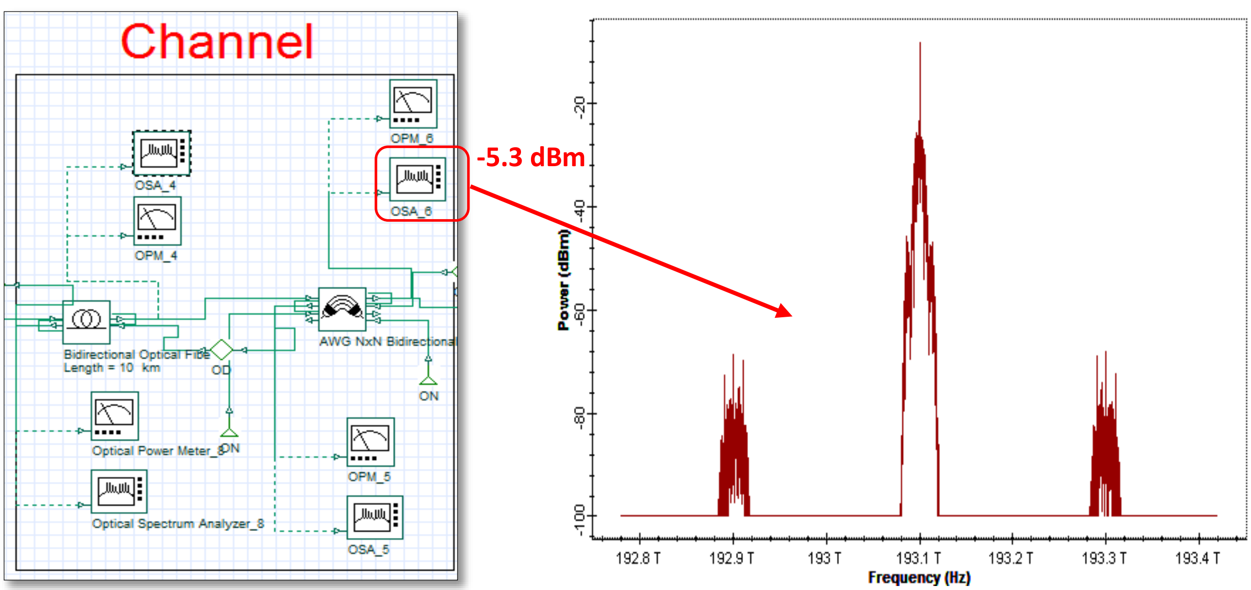


Figure 3.40: Output downstream signal spectrum after AWG in the channel with two cascaded AWGs

The upstream signal power after AWG in the channel equals to -11.9 dBm and the upstream signal power after optical fiber equals to -13.9 dBm due to the loss existing in optical fiber.

3.5.3: ONU Part:

The receiver diagram is the same as discussed in section 3.3.3, the downstream signal power after optical attenuator equals to -18.3 dBm and the received signal is shown in figure 3.41.

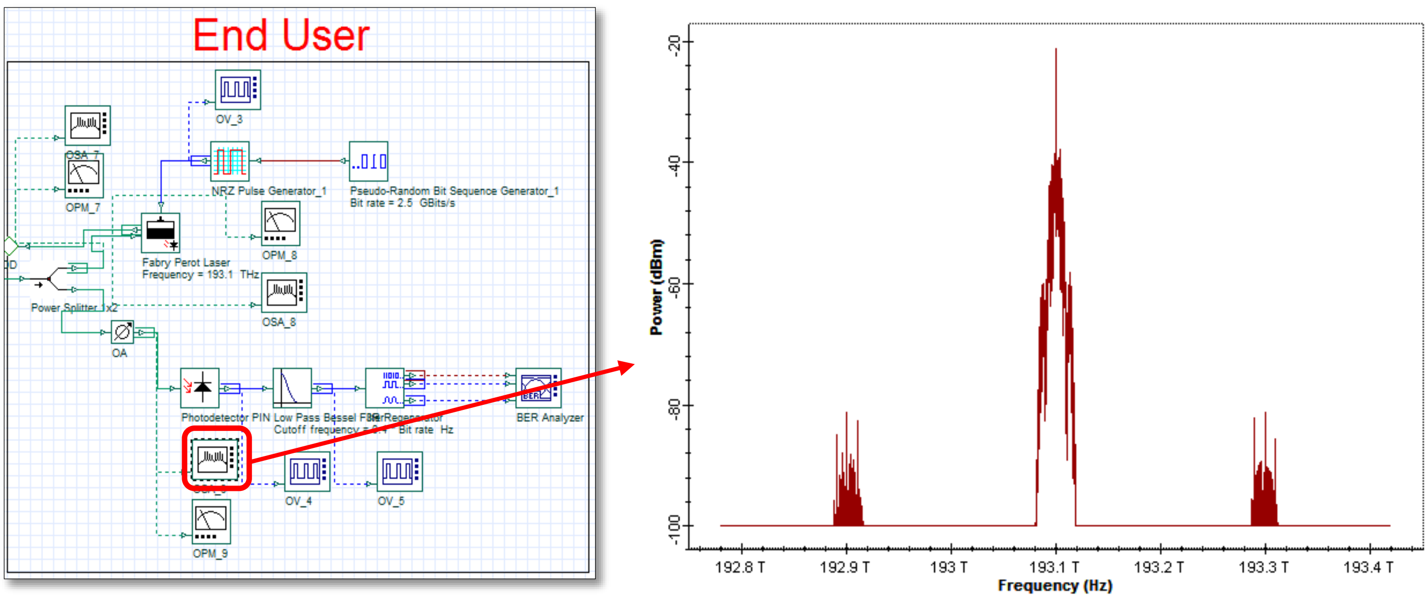


Figure 3.41: Downstream received spectrum after attenuator at ONU with two cascaded AWGs

BER analyzer is used to measure the BER of downstream signal so the value of min. BER equals to 1×10^{-13}. The eye diagram of downstream signal is shown in figure 3.42.

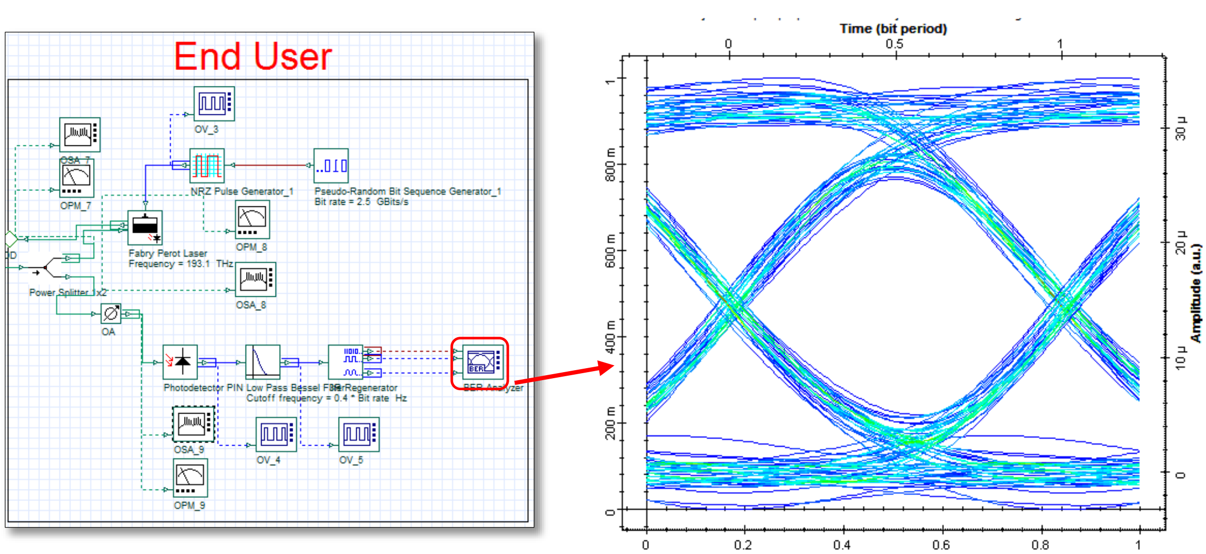


Figure 3.42: Eye diagram of downstream signal at ONU in WDM-PON with two cascaded AWGs

The injection power in FP-LD equals to -8.3 dBm and the output optical power equals to -11.8 dBm and its spectrum is shown in figure 3.43.

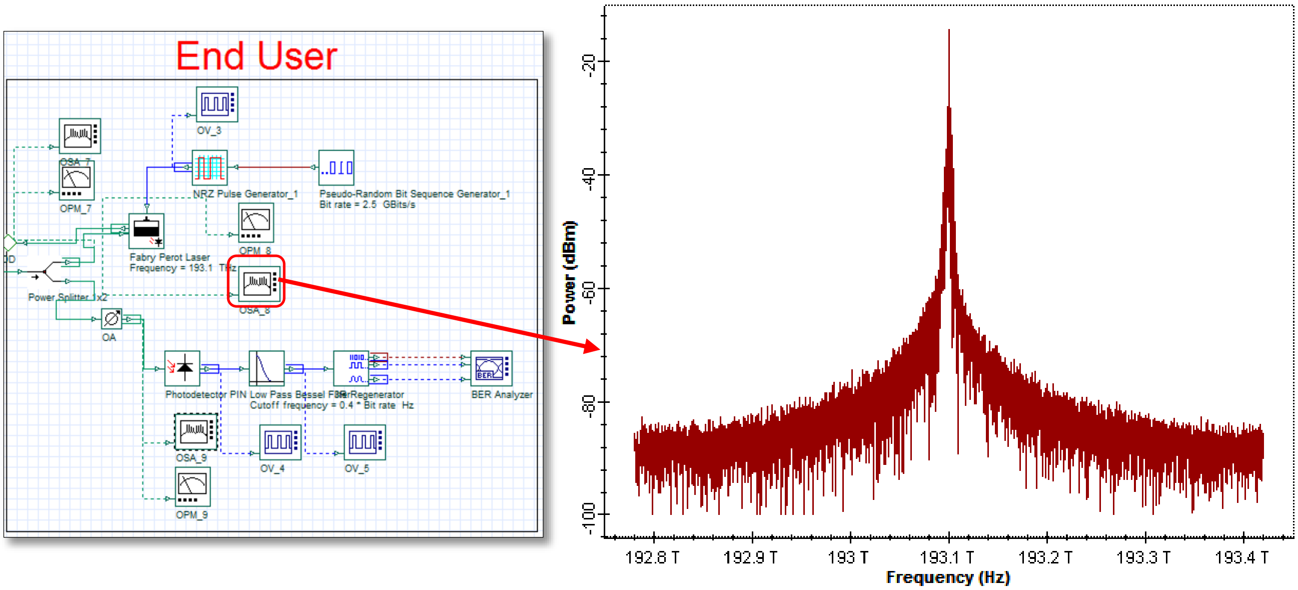


Figure 3.43: Output optical spectrum from FP-LD at ONU in WDM-PON with two cascaded AWGs

3.5.4 BER versus Received power for the third system with two cascaded AWGs:

In this section, we will show the influence of the received power variation on the BER in both upstream signal and downstream signal, According to the previous section, our system includes three main parts such as CO part, Bidirectional SMF and ONU part. The BER versus downstream received power P_d curves for the downstream and upstream signals are shown in Figure 3.44.

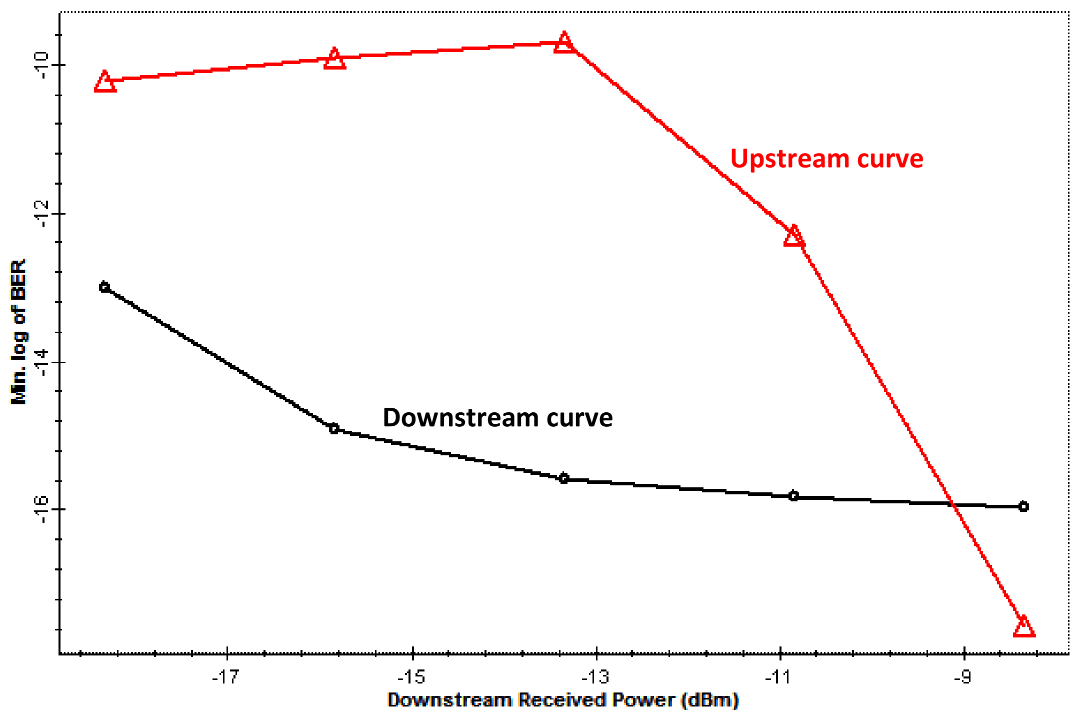


Figure 3.44: Min. log of BER versus Downstream received power at ONU for downstream and upstream in WDM-PON with two cascaded AWGs

It is noted from the figure that the BER versus the downstream received power P_d (injected power) at ONU for the upstream signal goes down with increasing P_d from -18 dBm to -8 dBm. When P_d = -18 dBm, the BER = 6×10^{-11}. When P_d = -8 dBm, the BER =2.7×10^{-18}. For the downstream signal, the BER curve goes down with P_d from -18 dBm to -8 dBm. When P_d = -18 dBm, the BER = 1×10^{-13}. When P_d = -8 dBm, the BER = 1×10^{-16}.

Figure 3.45 is illustrated BER versus upstream received power P_u at CO.

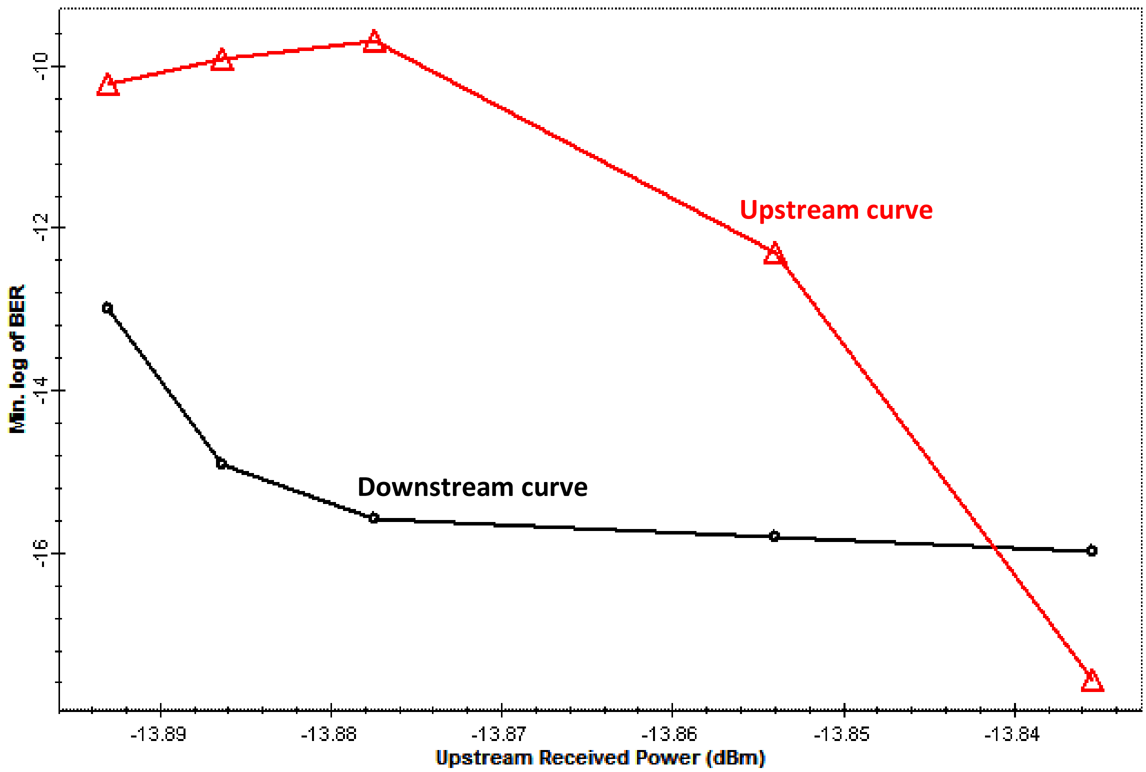


Figure 3.45: Min. log of BER versus upstream received power at CO for downstream and upstream signals in WDM-PON with two cascaded AWGs

It is noted from the figure that the BER versus the upstream received power P_u at CO for the upstream signal goes down with increasing P_u from -13.89 dBm to -13.835 dBm. When P_u = -13.89 dBm, the BER $=6\times10^{-11}$. When P_u = -13.835 dBm, the BER $=2.7\times10^{-18}$. For the downstream signal, the BER curve goes down with P_u from -13.89 dBm to -13.835 dBm. When P_u = -13.89 dBm, the BER = 1×10^{-13}. When P_u = -13.835 dBm, the BER = 1×10^{-16}.

3.5.5 Upstream BER versus FP-LD bias current for the third system with two cascaded AWGs:

In this section, we will explain the effect of FP-LD bias current on upstream BER at CO for the third model. Input power of CW laser is fixed at CO and it equals to 0 dBm. Figure 3.46 shows upstream BER versus the bias current of FP-LD.

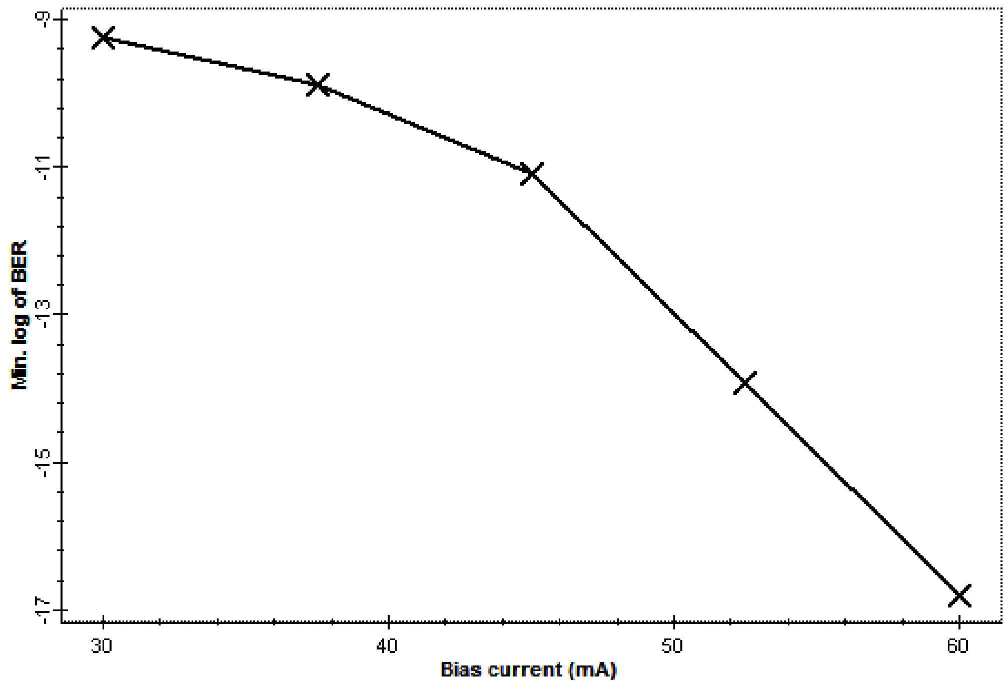


Figure 3.46: Upstream BER versus bias current of FP-LD

Bias current range is from 30 mA to 60 mA. Table 3.7 shows the relationship between upstream BER and bias current.

Table 3.7: Upstream BER versus bias current (I_b)

I_b(mA) / BER	30	37.5	45	52.5	60
Upstream BER	5.7×10^{-10}	1×10^{-10}	8×10^{-12}	1×10^{-14}	1.5×10^{-17}

We can conclude from table 3.7, upstream BER is decreased and it became better as bias current of FP-LD is increased.

3.6. Comparison on the results of the three models:

We will study the effect of CW laser power on the BER at CO and end user for the three systems when the input power is fixed and it equals to 0 dBm. All systems include FP-LD at end user for sending upstream signal. First model does not include any AWG, min. BER of downstream signal equals to 4.8×10^{-15} while Min. BER for downstream signal when using AWG at RN equals to 4.9×10^{-13} and min. BER of downstream signal using two cascaded AWGs equals to 1×10^{-13} . Now we will show the effect of using FP-LD and AWGs on the upstream signal at CO, min. BER of upstream signal without AWGs equals to 8.9×10^{-10} while min. BER for upstream signal when using one AWG at RN equals to 3.6×10^{-12} and when using two cascaded AWGs equals 6×10^{-11}. The system based on FP-LD without AWGs has better value of min. BER than the system based on FP-LD with AWGs in the downstream case due to more losses. We will show the comparison on the below table 3.8.

Table 3.8: Comparison between three proposed PON models

PON models	Min. BER for downstream	Min. BER for upstream	Received power in downstream	Received power in Upstream
WDM-PON based on FP-LD without AWGs	4.8×10^{-15}	8.9×10^{-10}	-18.1 dBm	-14.2 dBm
WDM-PON based on FP-LD with AWG at RN	4.9×10^{-13}	3.6×10^{-12}	-18.3 dBm	-13.8 dBm
WDM-PON based on FP-LD with two cascaded AWG	1×10^{-13}	6×10^{-11}	-18.3 dBm	-13.8 dBm

3.7 WDM-PON based on FP-LD versus WDM-PON based on RSOA with two cascaded AWGs:

We will study the effect of CW laser power on the BER at CO for the two systems when the input power is fixed and it equals to 0 dBm. Figure 3.47 shows the architecture of these colorless systems.

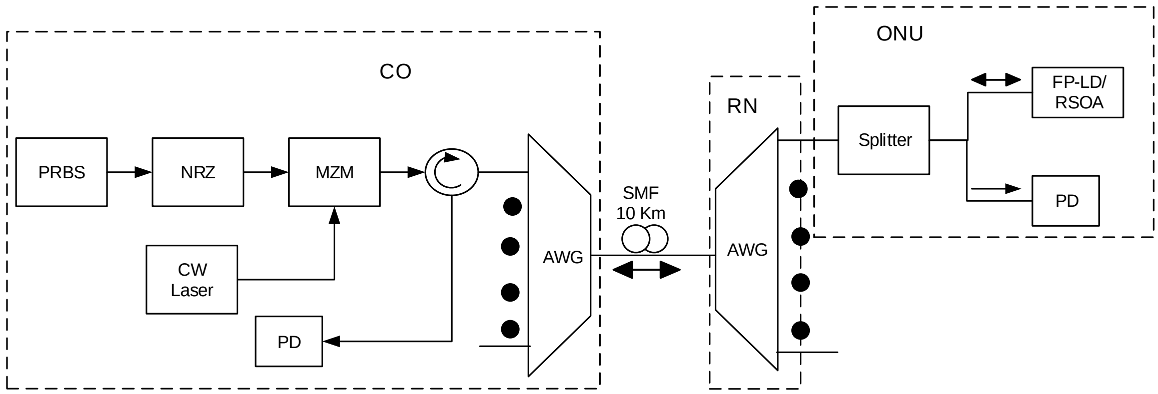


Figure 3.47: Architecture of WDM-PON showing colorless sources based on RSOA or FP-LD with two cascaded AWGs.

FP-LD and RSOA are used at ONU to remodulate the downstream signal with upstream data (2.5 Gbps) which is sent to CO. We will show the effect of using FP-LD on the upstream signal at CO, min. BER of upstream signal equals to 6×10^{-11} while min. BER for upstream signal when using RSOA equals to 1×10^{-6}. Upstream received power when using FP-LD equals to -13.89 dBm and upstream received power when using RSOA equals to -3 dBm. Now we will conclude the difference between RSOA and FP-LD in table 3.9.

Table 3.9: Comparison between using FP-LD and RSOA on WDM-PON

PON type	Min. BER for upstream signal at CO	Received power at CO for upstream signal	Cost	Amplify the incoming signal
WDM-PON based on FP-LD	6×10^{-11}	-13.89 dBm	low	No
WDM-PON based on RSOA	1×10^{-6}	-3 dBm	high	Yes

RSOA is operated in the gain saturation. It amplifies the upstream signal with noise so upstream BER has a bad value when RSOA is used as shown in table 3.9. RSOA parameters are summarized in table 3.10.

Table 3.10: RSOA parameters

Parameter	Value
Input coupling loss	3 dB
Output coupling loss	3 dB
Input facet reflectivity	5e-5
Output facet reflectivity	0.99

Figure 3.48 is shown the comparison between upstream BER for both WDM-PON based on RSOA and FP-LD when input power CW laser is increased from 0 dBm to 10 dBm.

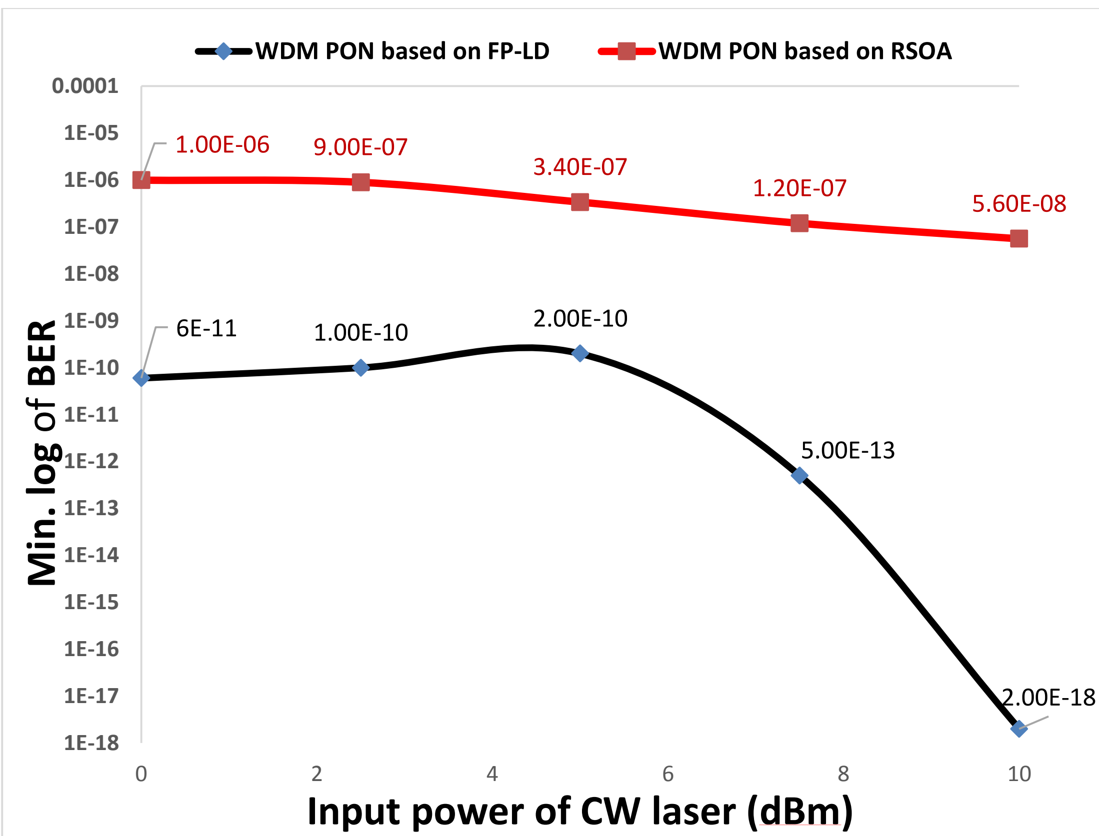


Figure 3.48: WDM PON based on RSOA versus WDM PON based on FP-LD in the results of upstream BER when input power of CW laser is increased.

Now we will conclude the difference between RSOA and FP-LD in table 3.11 when the input power of CW laser at CO is varied from 0 dBm to 10 dBm.

Table 3.11: WDM PON based on RSOA versus WDM PON based on FP-LD in the results of upstream BER and upstream received power when CW laser power is varied.

Input power of CW laser (dBm)	**WDM PON based on FP-LD**		**WDM PON based on RSOA**	
	Upstream BER	Upstream received power (dBm)	Upstream BER	Upstream received power (dBm)
0	6×10^{-11}	-13.89 dBm	1×10^{-6}	-3 dBm
2.5	1×10^{-10}	-13.88 dBm	9×10^{-7}	-2.4 dBm
5	2×10^{-10}	-13.87 dBm	3.4×10^{-7}	-1.9 dBm
7.5	5×10^{-13}	-13.85 dBm	1.2×10^{-7}	-1.6 dBm
10	2×10^{-18}	-13.83 dBm	5.6×10^{-8}	-1.5 dBm

WDM PON based on FP-LD is better than WDM PON based on RSOA in the results because the upstream BER values are good in our proposed system as illustrated in table 3.10.

Chapter 4 –Conclusion

4.1 Summary

This work includes four chapters. The first chapter shows the architecture of PON in general and mentions the development of PON, it discusses the different types of PON and it shows the architecture of WDM-PON with low cost optical sources. The second chapter discusses the advantages and challenges of WDM-PON and it shows the structure of AWG and FP-LD. Chapter 3 discusses the different types of proposed models by showing the results.

In chapter 3, we have designed and implemented a bidirectional PON system based on FP-LD for upstream stage with two cascaded AWGs and different proposed models have been used. Our system is a very effective solution for wired systems due to increasing the demand for multiservice operation and hence broadband access, it is a reliable and cost effective communication system that can support anytime, anywhere, and any media are needed. It is able to alleviate the increasing demand for high-bandwidth services.

The first proposed model in our work includes a bidirectional PON based on FP-LD without any AWG at both CO and RN by using a 10 Gb/s signal for downstream in CO and a 2.5 Gb/s OOK signal for upstream in ONU. FP-LD at ONU has been used for re-modulation of a downstream signal over 10 km SMF. Moreover, the FP-LD is cost-effective since it performs the functions a modulator (no need for local laser source) and it depends on bias current. The results are good in optical communication systems as discussed previously.

The second proposed model has been designed as a solution for increasing bandwidth demand. The combination of AWG and FP-LD has been performed to provide high data rates and to increase bandwidth in PON. Downstream data rates equal to 10 Gbps and upstream data rates equal to 2.5 Gbps. The modulation used in this model is OOK for both downstream and upstream. All results were good in this model like BER for downstream and upstream.

The third proposed model includes two cascaded AWGs and FP-LD. This model contains two AWGs to increase the number of ONU, the multiplexing and demultiplexing channels and support more security and privacy. Downstream and upstream data rates is similar to the downstream and upstream data rates for the second proposed model. FP-LD is very effective device in this model due to its low cost optical source. All results in this model are shown, it compare with the results of previous models and it compare with a model that is used RSOA at ONU and we note FP-LD is better than RSOA because the upstream BER with FP-LD is lower than the upstream BER with RSOA.

4.2 Suggestion for Improvement

The design in our work can be upgraded to give good performance. Future systems may include low cost optical sources at ONU. There are different types of optical sources that can be used in ONU to decrease upstream BER and to increase received power. In our system we use a 10 Gbps downstream data rate and 2.5 Gbps upstream data rate with OOK modulation but it can be attempt to increase these data rates for more than 10 Gbps. Also the design can be modified to operate with other modulation techniques such as Phase Shift Keying (PSK), FSK and Orthogonal Frequency Division Multiplexing (OFDM). This system can be improved by changing its parameters to get better results and the bidirectional SMF channel can be reconstructed with other components which may give low loss. A relation between the distance (optical fiber length) and BER can be discussed for both downstream and upstream signals.

4.3 Recommendations and future work

Continuing research in this field which will offer more bandwidth for every user to provide him by multi-services like high definition TV and high data rates of internet. In future, FP-LD can be replaced by other optical sources with low cost, narrow linewidth and high output power. AWG can be replaced by other devices with lower insertion loss. Another recommendation is to complete the third proposed model in order to use more downstream wavelengths and to use different types of modulation. Another recommendation is to increase data rates up to 40 Gbps with better BER.

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