Universidade de Aveiro Departamento de Electrónica, Telecomunicações e Informática,
2017

Eduardo Vala Franco

Circuitos óticos integrados para PONs de futura geração

Photonic integrated circuits for next generation PONs

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Dissertação apresentada à Universidade de Aveiro para cumprimento dos requisítos necessários à obtenção do grau de Mestre em Engenharia Eletrónica e Telecomunicação, realizada sob a orietação científica do Dr. Mário Lima , Professor do Departamento de Eletrónica, Telecomunicações e Informática da Universidade de Aveiro e do Engenheiro Francisco Rodrigues da PIC Advanced S.A.

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agradecimentos / acknowledgements

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Palavras chave Comunicações Óticas,Vídeo Overlay, XG-PON, NG-PON 2, multi-tecnologia, Circuito integrado fotónico, Transrecetor

Resumo

Vivemos numa época em que as comunicações se tornaram essenciais para grande parte da nossa vida, seja no mundo empresarial, seja nas nossas habitações. A crescente necessidade de aumento de largura de banda inviabiliza outras redes que não baseadas em fibra ótica.

Atualmente as comunicações são responsáveis por uma percentagem substancial dos nossos gastos energéticos, justamente por este facto Passive Optical Networks(PON) são as principais candidatas ao próximo passo no desenvolvimento de redes. Estas apresentam menor consumo energético, pois entre o emissor e o recetor todo o sinal permanece no domínio ótico.

Apesar da necessidade de largura de banda estar a aumentar de um modo transversal no mundo das telecomunicações, certos serviços/entidades necessitam de maiores velocidades tanto em termos de download como em termos de upload. É então fácil de perceber que consumidores diferentes têm necessidades diferentes.É necessário encontrar uma arquitetura que agrade a quem necessita de maiores larguras de banda mas também a quem não necessita de um aumento significativo e que, não está disposto a pagar por este. Existem neste momento tecnologias que ainda não foram implementadas em grandes escalas, como o caso de Next Generation Passive Optical Network (NG-PON2), porque não simbolizam um retorno financeiro para as grande operadores, uma vez que o número de potenciais consumidores de tais velocidades ainda não é substancialmente grande. É necessário encontrar uma solução que não só englobe as novas tecnologias como também as já existentes.

Com o objetivo de se encontrar um solução para os problemas acima referidos, este trabalho assenta na elaboração de um Circuito integrado fotónico que visa ser um transrecetor de uma arquitetura multi-tecnologia em que irão ser incorporadas tecnologias como Video-Overlay, 10 Gigabit-capable Passive Optical Network (XG-PON) e NG-PON2. Esta dissertação apresenta uma abordagem às Redes Óticas Passivas e também um estudo feito aos componentes usados no transreceptor usando os programas Aspic™e VPI Photonics™. Por fim será apresentado o desenho final do transreceptor que será usado numa Optical Network Unit(ONU).

Keywords Optical communications,Video Overlay, XGs-PON, NG-PON2, Multitech, PIC, Transceiver

Abstract We are living in a time where communications became essential for most of our lives, whether it's in the business world, or in our own homes. The increasing need of higher bandwidth inhibits other networks other than optical fiber based ones.

Nowadays communications are responsible for a substantial percentage of our energetic footprint, hence Passive Optical Network(PON) are a strong contender for the next step of network implementation. These networks present a low energy consumption because between the transmitter and the receiver the signal stays in the optical domain.

Although the increasing needs of bandwidth is almost across the communication world, certain services/identities need more bandwidth whether is download or upload. It's easy to understand that different consumers have unique needs. It's necessary to develop an architecture that serves all the costumers, in other words, there is a need for a network that provides high bitrate traffic to the users that needs it but also a network that serves the low end user that is not interested in this increase of bandwidth and therefore price inflation.

There is today technologies yet to be widely implemented like NG-PON2 that were not implemented in a large scale because they dont represent a financial return to the telecom operators simply because there is not enough user that requires the high bandwidth delivered by NG-PON2. It's necessary to find a solution that includes not only the modern technologies but also the already implemented ones.

With the objective of finding a solution for the problems mentioned before, this dissertation has the objective of designing a Photonic Integrated Circuit(PIC) that aims to be a transceiver of a Multitech Network that will be composed by the following technologies: Video-Overlay, XG-PON e NG-PON2. This dissertation presents an approach on Passive Optical Networks(PON) and the standards of the said technologies as well as a study of the components needed to assemble the transceiver using the programs ASPIC™and VPI Photonics™. In the end, there will be presented an architecture for the transceiver to be used in a Optical Network Unit(ONU), and the respective mask Layout.

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Acronyms

3D-TV 3D-Television

10G-EPON 10 Gb/s ethernet passive optical network

AMP/BRC-U Amplifier/Branch-Units

AWG Arrayed waveguide grating

BER Bit Error Ratio

B2B Back-To-Back

BPON Broadband PON

CATV Coaxial Cable Television

CNR Carrier to Noise Ratio

CSO Composite Second Order distortion

CTB Composite Triple Beat distortion

CW Continuous wave

DRC Design rule check

DSL Digital Subcriver Line

EDFA Erbium Doped Fiber Amplifier

EPON Ethernet Passive Optical Network

ER Extinction Ratio

F-HHI Fraunhofer Heinrich Hertz Institute

FDM Frequency-Division Multiplexing

FM Frequency Modulation

FSR Free spectral range

FTTB Fiber to the building

FTTC Fiber to the curb

FTTCab	Fiber to the cabinet
FTTH	Fiber-to-the-Home
FTTN	Fiber-to-the-node, -neighbourhood
FTTx	Fiber to the X (home, business, etc.)
GPON	Gigabit-capable Passive Optical Networks
HDTV	High Definition Television
IEEE	Institute of electrical and electronics engineers
ITU-T	International Telecommunication Union - Telecommunication Standardization Sector
MMI	Multimode Interference
NG-PON2	Next Generation Passive Optical Network 2
NRZ	Non-return to zero
ODN	Opical distribution network
OEO	Optical to electrical to optical
OLT	Optical line terminal
ONU	Optical network unit
OOK	On-off keying
P2P	Point-to-Point
PRBS	Pseudo Random Binary Sequence
PDK	Process design kit
PIC	Photonic Integrated Circuit
PIN	*p-i-n* photodiode
PON	Passive Optical Networks
PMP	Point-to-multi-point
RE	Reach Extender
RIN	Relative Intensity Noise
SNR	Signal-to-noise Ratio
SOA	Semiconductor optical amplifier
SSC	Spot size converter

TDM Time-Division Multiplexing

TWDM Time and Wavelength Division Multiplexing

V-OLT Video-OLT

V-ONT Video-ONT

XG-PON 10 Gigabit-capable Passive Optical Network

XM Cross Modulation distortion

WDM Wavelength division multiplexing

Chapter 1

Introduction

This chapter is going to be a guide line to the work here presented. In the next sections will be presented the overview and motivations, the main objectives,the structure of the work itself and the contributions of this work.

1.1 Overview and motivations

The evolution of communications has been a global scale phenomenon. All over the world there is a need for more bandwidth. According to Nielsen's Law which says that a high-end users Internet connection increases by 50 percent every year[1], one can understand that the current standard, the Gigabit-Capable Passive Optical Network(GPON) will easily meet the short-medium term needs of residential consumers, but over the longer term it will struggle to answer the requirements of highly demanding services like High Definition Television (HDTV), 3D-Television(3D-TV), multiple image and analoge video services, growth in unicast video (versus multicast), cloud computing, telepresence, multiplayer HD video gaming and more[2].To face this problem new standards were created as the XG-PON or, more recent, the NG-PON2. XG-PON standard achieve bitrates higher then GPON, which has 2.5 Gbit/s downstream and 1.25 Gbit/s upstream[3]. XG-PON can reach approximately 10Gbit/s downstream and 2.50 Gbit/s[4] or even symmetrical 10 GBit/s[5], NG-PON 2 has bitrate rounding 40 Gbit/s downstream and 40 Gbit/s upstream[6].

We live in a world that is driven by economics, this said it's easy to understand that although there is already new and faster standards, there is no financial reason for a big network provider to implement such standards. Whatever technology is being used, ensuring a smooth upgrade path from existing fiber optic networks will prove to be essential.[7]Nowadays there are costumers wanting more bandwidth, but there is no need for a low end residential costumer to have 1 GBit/s download bitrate and pay for it when he only uses a portion of that. This is one of the aspect why new standards are not quickly implemented in large scale. To face these problems a solutions has to be created that satisfies all costumers. Addressing this, there is a plan for a network where XG-PON, RF Video Overlay and NG-PON2 can coexist, giving each costumer the bitrate he needs.

Other big problems that modern optical communications are facing are the space and energy consumption. With the increase of data and the sheer size of the networks some had to come up to stop the proportional growth of the physical layer: Photonic Integrated Circuits(PIC). In a single chip there are all components needed in photonics : lasers, modulators,

optical amplifiers and multiplexers[8]. With this integration, the size of the components drops drastically, and so the consumption of energy.
The design of a PIC for a ONU in a multitechnologies environment is the center point of this dissertation. This PIC will be a transceiver capable of receiving and emitting according the following standards: XG-PON, Video Overlay and NG-PON2.

1.2 Objectives

The following dissertation has the objective of present desing plan of a tranceiver for a multitech network. Bearing this in mind, this dissertation has the following objectives:

- Analyse the standards considered in the scope of the dissertation, XGs-PON, Video-Overlay, NG-PON2, to enable the correct dimentioning of the multitech transceiver.
- Present a proposal for the multitech architecture and produce a layout.

1.3 Structure

Apart from the present chapter this dissertation has 4 more chapters:

- **chapter 2- Passive Optical Networks: State of the Art**

  This chapter will visit the recent story of the Passive Optical Networks and why the choice for the standards to be implement on this project, aswell as an aproach about this technologies: XG-PON, RF-Video and NG-PON 2.There will be also a focus on photonic integrated circuits and thier possibilities.

- **chapter 3- Tranceiver desing using Aspic**

  In this chapter will be studied the possibilities of multiplexing/demultiplexing using Arrayed Waveguide Grating(AWG), and the simulations results using Aspic™. There will be presented also the principle of operation of some important optical components.

- **chapter 4- VPI Photonics™tests and simulations**

  This chapter will present tests and simulations done using the software VPI Photonics™.

- **chapter 5- PIC layout**

  This chapter will contain the explanation and all the steps that led to the final mask layout for the PIC .

- **chapter 6- Conclusion and Future work**

  This final chapter will summarize all the work done and will present the conclusions based on the objectives set in the beginning of the dissertation. In the end will be sugested some future work.

1.4 Contributions

The prime contributions of this work are:

- Design a layout for the a ONU's transceiver.

Chapter 2

Passive Optical Networks

In this chapter, important concepts will be presented about optical communications for the development of the transceiver. There will be presented the evolution of PON standards and the main requirements of the 3 technologies: XG-PON, Video-Overlay and NG-PON2. The chapter will conclude with a description about photonic integrated circuits and their possibilities.

2.1 Evolution of PONs

PON evolution have been tremendous since the beginning of the millennium. In 2001 the Broadband PON (BPON) was the first PON standard that was completed by International Telecommunication Union (ITU-T) . This standard was responsible to provide speed up to 622 Mbps downstream and 155 upstream with reaches of 20 km and with a maximum of 64 users[9]. Three years later (2004) the Institute of Electrical and Electronics Engineers (IEEE) introduced the Ethernet-PON (EPON). This standard had a significant difference from its predecessor apart from the better speeds, 1.25 Gbps symmetric[10], that was the fact that this standard used the ethernet as the transport protocol. EPON had in the follow years gained popularity in most Asia Countries. Along with this growth in demand in 2009 the E-PON evolved to 10 Gb/s ethernet passive optical network(10G-EPON), which had 10 Gbps downstream and 1 Gbps upstream bitrate[11]. In the same year that EPON was released, ITU-T responded with a a new standard of their own: GPON. This standard has encountered remarkable success in Europe and America. It supports various bitrate options but it typically provides 2488 Mbps downstream bitrate and 1244 Mb/s upstream bitrate, with 30 km available reach and up to 128 end-users[3]. Has it counterpart -EPON- evolved in 2009, GPON had to evolve into something that satisfied the high end users, so in 2010 a new standard appeared: XG-PON. This new standard can deliver speed up to 10 Gbps downstream bitrate and 2.510 Gbps upstream bitrate. The XG-PON has a capacity to 64-128 end users with 20-60 km available reach, however reach and number of user are conflicting parameters.

The next evolution of PON standards was the NG-PON 2 standard. This standard was release in 2014 and had at least a capacity of 40 Gbps downstream and 40 Gbps upstream, however it can support 80 Gbps in each direction[6]. This bit rate is achieved using Time and Wavelength Division Multiplexer Passive Optical Network (TWDM-PON). The maximum passive fiber reach will be 40 km, or up to 60 km by using Reach Extender (RE) and it will support more than 64 users. As it happened with the XG-PON, the maximum number of users and the maximum reach distance are dependents from each other.

2.2 PON Standards

To fulfill the need of bandwidth high data rates networks had to be developed. To achieve this goal optical communication was the way. The loss of modern silica-glass fiber is phenomenally low compared to that of an RF coax cable. A high-performance RF coax cable operating at 10 GHz has an attenuation of about 500 dB/km. Compare this to 0.25 dB/km for a fiber[12].

Currently, the optical communications are predominantly based on PONs.

Historically, the term PON was introduced to describe a point-to-multipoint fiber infrastructure composed of exclusively passive optical components. This strict-sense usage was soon naturally extended to include a fiber-in-the-loop communication system employing such an infrastructure and using Time-Division Multiplexing (TDM) to share the available digital bandwidth among many subscribers (TDM PON).

A PON architecture is a system that combines network elements based in access optical networks of the type Optical Distribution Network (ODN).

Figure 2.1 Show the reader a example of a setup of a PON.

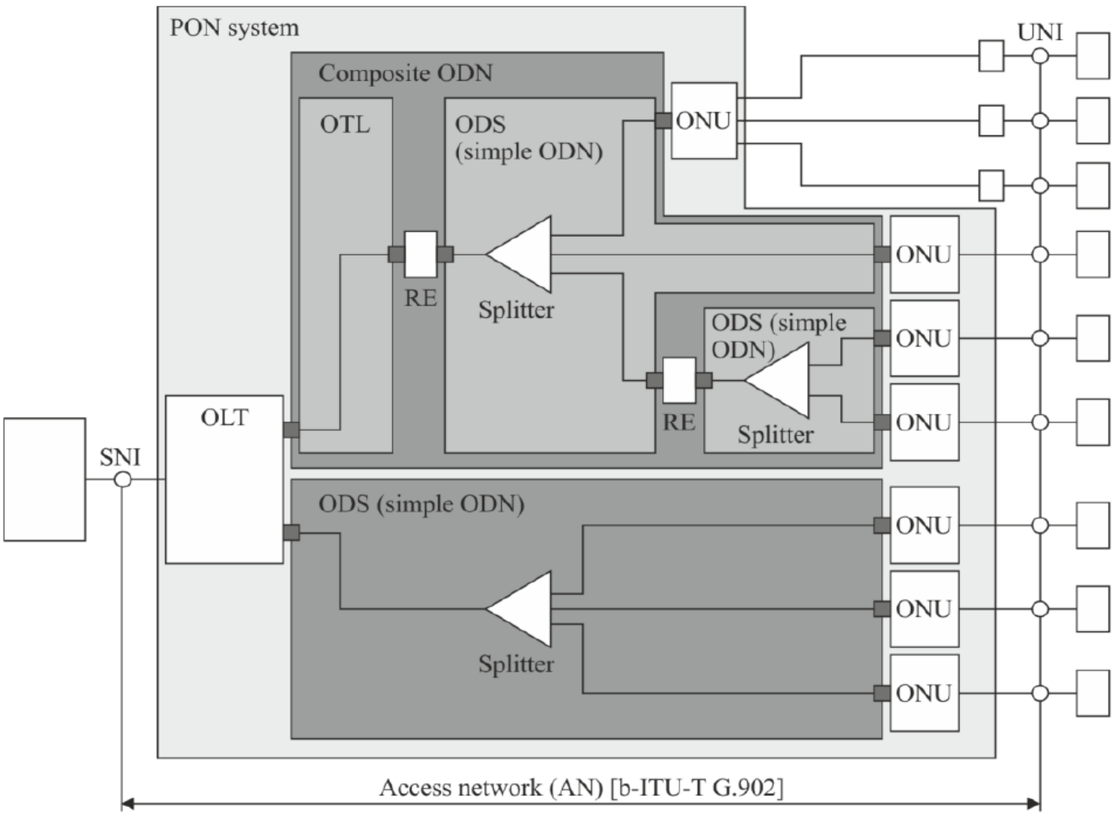

Figure 2.1: Example of a setup for a PON [6]

ODN is a point-to-multipoint optical fiber infrastructure that can be defined in two types:

- **Simple ODN**
  Composed only by passive elements and its represented single-rooted point-to-multipoint tree of optical fibers with splitters, and combiners.
- **Composite ODN**
  A network composed by 2 or more simple ODNs interconnected by active devices.

Its important to clarify some keywords that will be used in this dissertation in order for the reader understand the concepts:

- **Optical Line Terminal (OLT)**
  Its a device typically located in the telecommunications operator terminal that has the function of connecting the access network, witch in this case is the PON, to the service node(SN) of the core network.
- **ONU**
  As the counterpart of the OLT, ONU is a device that terminates the network in the user side.
- **Downstream**
  Is the direction which the signals are transmitted from the OLT to the ONU. In this case, the OLT is the transmitter and the ONU is the receiver.
- **Upstream**
  Is the direction which the signals are transmitted from the ONU to the OLT. In this case, the ONU is the transmitter and the OLT is the receiver.

A PON has a structure Point to Multipoint(PMP) that is called a PON tree. A single mode fiber(SMF) makes the link between the OLT and the passive optical splitter that further splits and share his content to, generally, 16, 32,64, or even 128 costumers without any switching or buffering. In other words, an OLT is connected and shared by ONUs via a passive optical splitter. Signals are sent from and to different ONUs with unique ONU identification in the frame header. To avoid collision between upstream and downstream communications a multiplexing scheme is used, where each subscriber receives their own time slot to transmit and receive. For this purpose TDM allows a coordinated communication and ONTs/ONU are responsible for the synchronization of the right user time slot.[15]

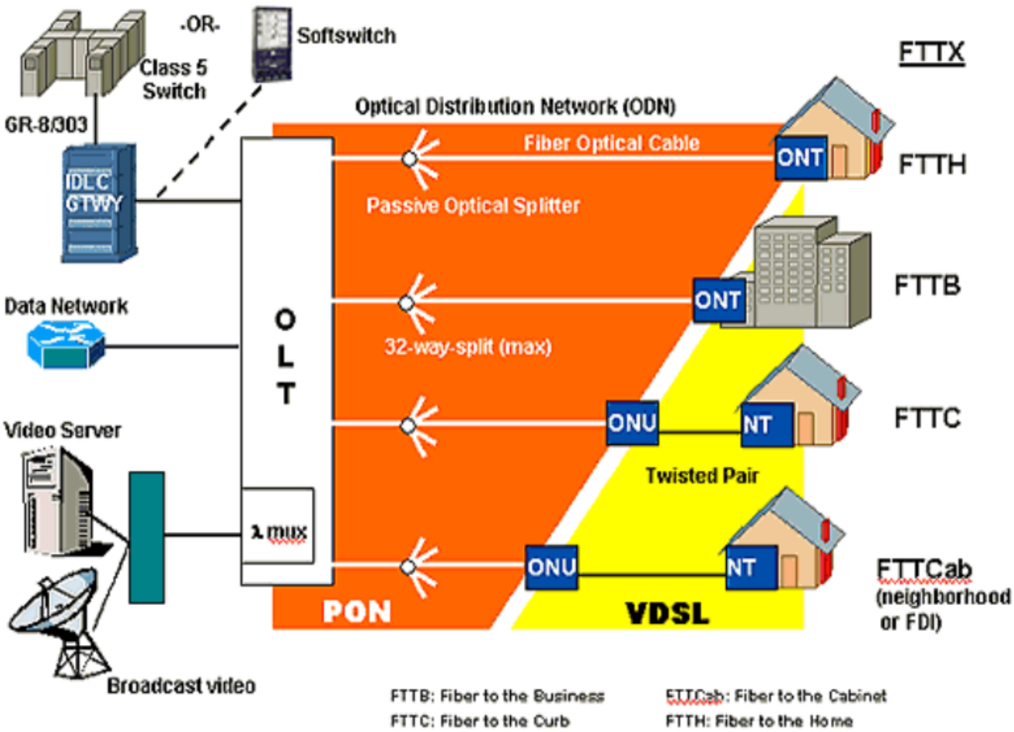

Figure 2.2: Variations of PON deployments[13]

As we can see on figure 2.2 a PON network can have different configurations, being the most important: Fiber to the Home(FTTH), Fiber to the Building(FTTB), Fiber to the Curb(FTTC) and Fiber to the Cabinet(FTTCab), or this last one also called Fiber to the Neighborhood(FTTN). This variation are due to the variations of the locations of the ONU. If the ONU is in the subscriber home or in the building we can call the ONU as Optical Network termination(ONT) and this describes FTTH and FTTB If the ONU is on the closet that houses the mounted communications device we call it FTTC, and Coaxial cables or twisted pairs then send the signals from the closet to the home. The last configuration is when the ONU serves a few hundred customers. The subscribers must be within a one mile radius. The remaining distance to the home, often referred to as the last mile, can use Digital Subcriver Lines (DSL) through existing telephone or cable company lines. Customer proximity to the node and delivery protocols determine data rates.[14]

2.2.1 XG-PON

In 2010, as a response to the need of faster connections, the GPON standard evolved to a 10G PON, which stands for 10 Gigabit Capable PON, or more commonly known as: XG-PON.

The term XGs-PON derives from XG-PON, the s stands for symmetrical, which means symmetric speeds for downstream and upstream, in this case 10 Gbps.

This technology was design to coexist with the previous one, GPON.

In figure 2.3 the reader can see the wavelengths that were chosen for XG-PON. At a basic level XG-PON appears to use the same spectrum as XG PON, that is 1260 to 1280nm upstream, and 1575nm downstream, with fixed wavelength allocation. This means we can improve from the asymmetric 10 Gb/s down, 2.5 Gb/s up to a fully symmetrical 10 Gb/s system. This is achievable without using the spectrum that is allocated to NGPON2.[16]

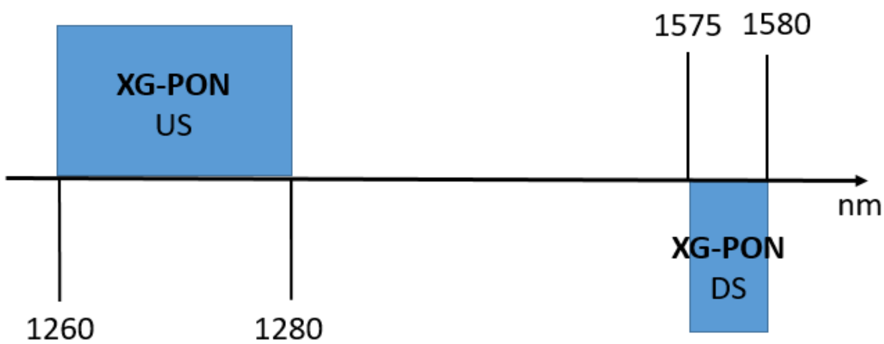

Figure 2.3: Wavelength plan for XG-PON

Now is going to be shown some of the more important parameters that had to me taken in for the design of the transceiver regarding XGs-PON technology. Its important to say that not all the standard's information is on this dissertation to simplify the reader's task. The following values are directly taken from the Physical media layer specification, [5].

OLT requirements:

OLT Transmiter					
Item	**Value**				**Unit**
Nominal line rate	9.95328				Gbit/s
Operating wavelength	1 575-1 580				nm
Line code	Scrambled NRZ				-
ODN class	N1	N2	E1	E2	-
Mean launched power MIN	+2	+4	+6	FFS	dBm
Mean launched power MAX	+5	+7	+9	FFS	dBm
Minimum extinction ratio	8.2				dB
Dispertion range	0-400				ps/nm
Minimum side mode suppression ratio	30				dB
Maximum differential optical path loss	15				dB

Table 2.1: Optical interface parameters of 9.95328 Gbit/s downstream direction for OLT

OLT Receiver					
Item	**Value**				**Unit**
Maximum optical path penalty	1				dB
Bit error ratio reference level	10e-3				-
ODN class	N1	N2	E1	E2	-
Minimum sensitivity at BER reference level	-26	-28	-30	FFS	dBm
Minimum overload at BER reference level	-5	-7	-9	FFS	dBm
Consecutive identical digit immunity	more than 72				bit

Table 2.2: Optical interface parameters of 9.95328 Gbit/s upstream direction for OLT

ONU requirements:

ONU Receiver					
Item	**Value**				**Unit**
Maximum optical path penalty	1				dB
Bit error ratio reference level	10e-3				-
ODN class	N1	N2	E1	E2	-
Minimum sensitivity at BER reference level	-28	-28	-28	FFS	dBm
Minimum overload at BER reference level	-9	-9	-9	FFS	dBm
Consecutive identical digit immunity	more than 72				bit

Table 2.3: Optical interface parameters of 9.95328 Gbit/s downstream direction for ONU

ONU Transmiter					
Item	**Value**				**Unit**
Nominal line rate	9.95328				Gbit/s
Operating wavelength	1 260-1 280				nm
Line code	Scrambled NRZ				-
ODN class	N1	N2	E1	E2	-
Mean launched power MIN	+4	+4	+4	FFS	dBm
Mean launched power MAX	+9	+9	+9	FFS	dBm
Minimum extinction ratio	6				dB
Dispertion range	0 to 140				ps/nm
Minimum side mode suppression ratio	30				dB

Table 2.4: Optical interface parameters of 9.95328 Gbit/s upstream direction for ONU

2.2.2 NG-PON2

NG-PON2 is defined as a PON system with a nominal aggregate capacity of 40 Gbit/s in the Downstream direction and 40 Gbit/sin the Upstream direction [6]. This technology is implemented based in a suite of protocols specified in the ITU-T G.989.x series Recommendations, specifically in G.989.2.
In figure 2.4 the reader can see the wavelengths that were chosen for NG-PON2. A NG-PON2 system is composed by a set of Time Wavelength Division Multiplexing (TWDM) channels and/or by a set of Point-to-Point(P2P) Wavelength Divison Multiplexing(WDM) channels.

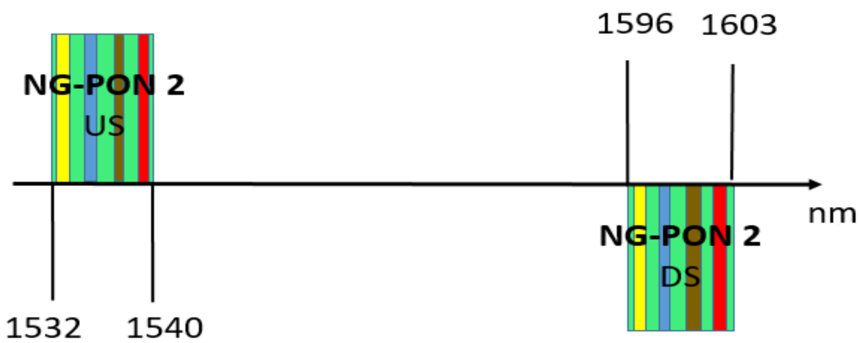

Figure 2.4: Wavelength plan for NG-PON2

Channel	Channel Frequency(THz)	Wavelength (nm)
1	187.8	1596.34
2	187.7	1597.19
3	187.6	1598.04
4	187.5	1598.89
5	187.4	1599.75
6	187.3	1600.60
7	187.2	1601.46
8	187.1	1602.31

Table 2.5: List of downstream channels for NG-PON2

Channel	Channel Frequency(THz)	Wavelength (nm)
1	195.6	1532.68
2	195.5	1533.47
3	195.4	1534.25
4	195.3	1535.04
5	195.2	1535.82
6	195.1	1536.61
7	195.0	1537.40
8	194.9	1538.19

Table 2.6: List of upstream channels for NG-PON2

Channels 1-4 are assigned to TWDM with four downstream wavelengths. Channels 5-8 are optionally assigned to TWDM and may be used by PtP WDM or other systems if not reserved for TWDM expansion. For the sake of this dissertation only the 4 first channels will be used.

TWDM-PONs

TWDM is a fusion between the technologies WDM and TDM. In the TWDM-PON architecture, four XG-PONs are stacked using four pairs of wavelengths. For simple network deployment and inventory management purposes, the ONUs uses colorless tunable transmitters and receivers. The transmitter is tunable to any of the upstream wavelengths, while the receiver can tune to any of the downstream ones[17].

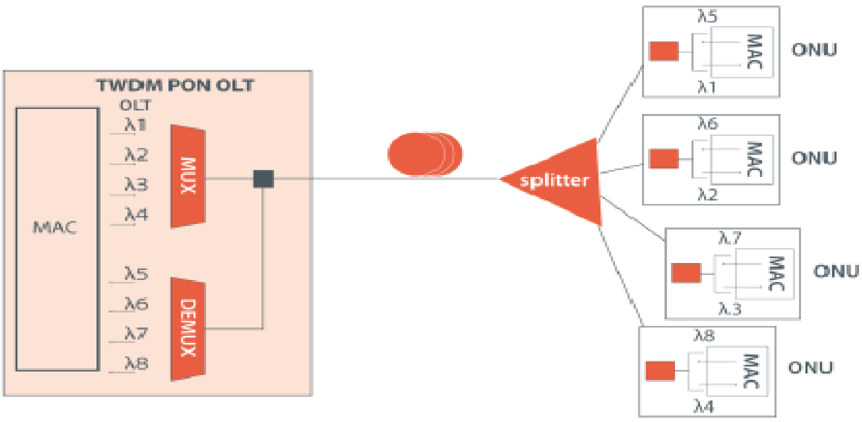

Figure 2.5: TWDM-PON architecture[26]

Figure 2.5 shows an example of a TWDM-PON architecture. Four 10 Gbit/s wavelengths are multiplexed in the Central Office and routed in the downstream direction. The ONU will select the corresponding operation wavelength, filtering one of the 4 downstream wavelengths.

In the upstream direction, the ONU/ONT will work in one of the 4 upstream wavelengths, previously selected by the OLT for that same ONUs operation[26]. Most of the TWDM-PON components are commercially available in access networks today. As compared to previous generations of PONs (e.g., G-PON, XG-PON), the only significantly new components in TWDM-PON are the tunable receivers and tunable transmitters at the ONU[27].

Standard's requirements

In this subsection is going to be shown some of the more important parameters that had to me taken in for the design of the transceiver regarding NG-PON2 technology. Its important to say that not all the standard's information is on this dissertation to simplify the reader's task. The following values for the standard are directly taken from the Physical media layer specification, [6].

OLT Transmiter					
Item	**Value**				**Unit**
Nominal line rate	9.95328				Gbit/s
Operating wavelength	1596-1603				nm
Line code	Scrambled NRZ				-
ODN class	N1	N2	E1	E2	-
Mean launched power MIN	+3	+5	+7	9	dBm
Mean launched power MAX	+7	+9	+11	11	dBm
Minimum extinction ratio	8.2				dB
Disperssion range	0 to 840				ps/nm
Minimum side mode suppression ratio	30				dB
Maximum differential optical path loss	15				dB

Table 2.7: Optical interface parameters of 9.95328 Gbit/s downstream direction for OLT

OLT Receiver					
Item	**Value**				**Unit**
Bit error ratio reference level	10e-3				-
ODN class	N1	N2	E1	E2	-
Minimum sensitivity at BER reference level	-26.5	-28.5	-31.0	NA	dBm
Minimum overload at BER reference level	-5	-7	-9	NA	dBm
In-band crosstalk tolerance	-30				dB
Consecutive identical digit immunity	more than 72				bit

Table 2.8: Optical interface parameters of 9.95328 Gbit/s upstream direction for OLT

ONU Transmiter					
Item	**Value**				**Unit**
Nominal line rate	9.95328				Gbit/s
Operating wavelength	1532-1540 (narrowband)				nm
Line code	Scrambled NRZ				-
ODN class	N1	N2	E1	E2	-
Mean launched power MIN	+4	+4	+4	NA	dBm
Mean launched power MAX	+9	+9	+9	NA	dBm
Minimum extinction ratio	6				dB
Dispertion range	0 to 710				ps/nm
Minimum side mode suppression ratio	30				dB

Table 2.9: Optical interface parameters of 9.95328 Gbit/s upstream direction for ONU

ONU Receiver					
Item	**Value**				**Unit**
Bit error ratio reference level	10e-3				-
ODN class	N1	N2	E1	E2	-
Minimum sensitivity at BER reference level	-28	-28	-28	-28	dBm
Minimum overload at BER reference level	-7	-7	-7	-9	dBm
In-band crosstalk tolerance	-35.3				dB
Consecutive identical digit immunity	more than 72				bit

Table 2.10: Optical interface parameters of 9.95328 Gbit/s downstream direction for ONU

2.2.3 Video-Overlay

Cable television is one network system today that is making a drastic step forward by spreading out from its long-established role as an entertainment service industry which includes on-demand video and broadcast television to a high-speed data service industry.

The original design of cable television systems was the one-way, analog transmission system using coaxial cable. Today, cable television companies have found that fiber is the perfect choice for transmitting signals to multiple customer locations.

Video Overlay is a solution for telecommunications operators who apply xPON technology or Ethernet P2P to insert television services (analogue TV/FM signal and digital television) over an extra parallel bandwidth without reducing the present capacity. While not using any subscribers devices e.g. Set-Top Box, the Video-Overlay reduces CAPEX spending[36].

In the next figure one can see the Video Overlay deployment scheme.

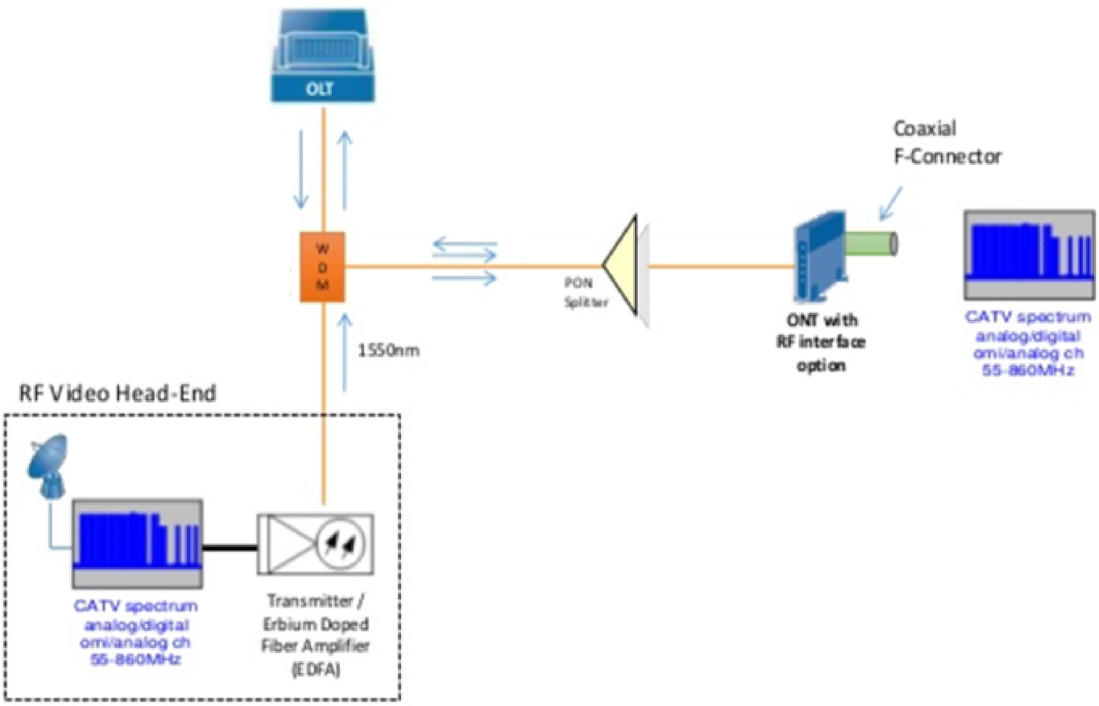

Figure 2.6: Video-Overlay deployment scheme[37].

Two separate parallel systems enable the operator to deliver more services thus increasing his offer and competitiveness[18]. Video-Overlay is a method of transmitting multi-channel television signals over an optical access network that utilizes frequency modulation (FM) conversion. In this FM transmission system, multi-channel frequency-division multiplexing (FDM) television signals are simultaneously converted into one single wideband FM signal. This FM signal is then transmitted through the optical access network by using the intensity modulation technique. The video-optical network terminal (V-ONT) at the customer premises converts the received single FM signal into the original multi-channel FDM video signals, i.e., coaxial cable television (CATV) signals[19].Figure 2.7 shows the wavelength plan for Video-Overlay.

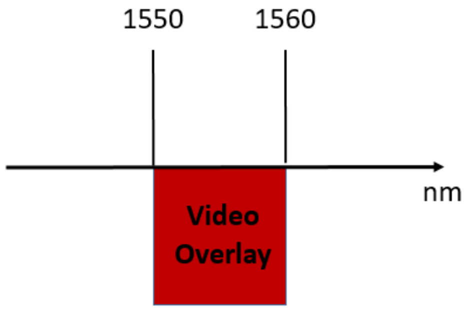

Figure 2.7: Wavelength plan for Video Overlay

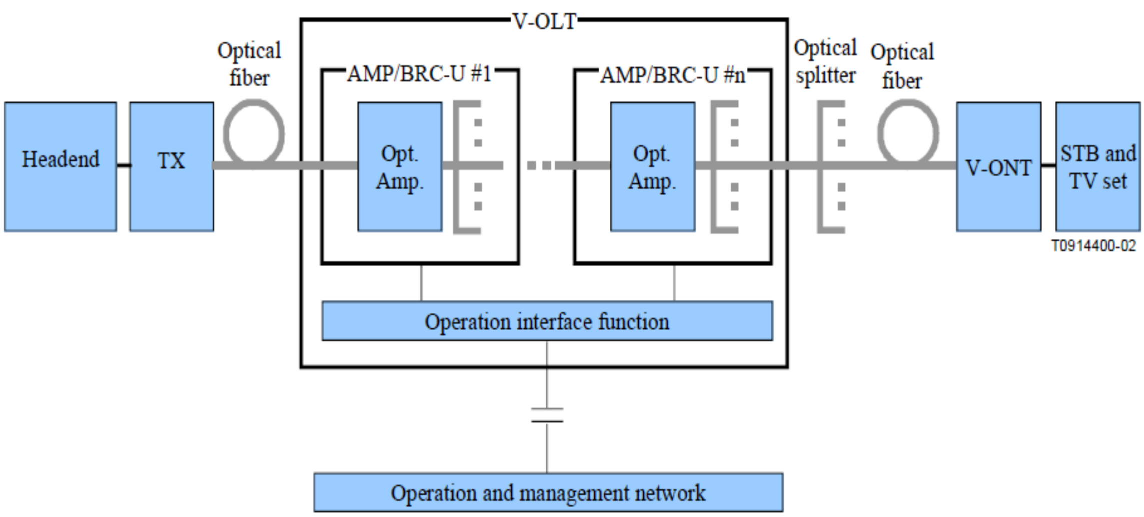

Figure 2.8: System configuration of an FM-converted multi-channel video signal transmission system[19].

A Video-OLT (V-OLT) consists of cascaded amplifier/branch-units (AMP/BRC-U), which amplify and branch the optical signal output by the TX. The operation interface collects alarms from the entire system and transmits them to the operation and management network. AMP BRC-Us can be cascaded in several stages provided the specified relative intensity noise (RIN) degradation is not exceeded. The optical signal output by V-OLT is further branched by optical splitters and transmitted to the V-ONT in the customer's premises. The V-ONT converts the optical input signal into a single electrical super-wideband FM signal in the optical/electrical converter, and the electric signal is then demodulated into FDM multi-channel video signals by the frequency demodulator. The demodulated signal output by the V-ONT is input to the STB and the TV set[19]. This transmission system is presented in figure 2.8.

In the table 2.11 the standard's most important requirements are summarized. Its important to say that the standard notes that the optical reaching the V-ONT must be greater than -15 dBm[19].

TV system	**M-system NTSC**	**B, G-system PAL**	**L-system SECAM**
Noise bandwidth	4.0 MHz	4.75 MHz	5.0 MHz
CNR	$\geq$ 43 dB	$\geq$ 44 dB	$\geq$44 dB
CSO	$\geq$ -53 dB	$\geq$ -52 dB	$\geq$-52 dB
CTB	$\geq$ -54 dB	$\geq$ -52 dB	$\geq$-52 dB
XM	$\geq$ -46 dB	$\geq$ -46 dB	$\geq$-46 dB

Table 2.11: System configuration of an FM-converted multi-channel video signal transmission system[19]

It's important to note that the output eletrical signal of the V-ONT must be grater then 75 dBμV(7.5dBm).

2.3 Photonic Integrated Circuits

The explosive Moore's Law growth of integrated electronics [23], along with the similarly explosive growth of the Internet, has contributed to growing demand for communications networks offering greater bandwidth and flexibility at lower cost. PICs are able to provide sufficient functionality, performance, and cost reduction, offer compelling solutions for such networks, while also providing the same inherent scalability that has benefited Si-based integrated electronics. However, since the early proposals for photonic integration [24], progress in Indium Phosphide(InP) PIC technology has been relatively slow.

There are myriad reasons for this slow rate of maturity. Numerous technological barriers associated with InP semiconductor processing have been one of the strongest inhibitorsincluding difficulty in achieving the requisite process uniformity and reproducibilityon a manufacturing scalein such processes as epitaxy, lithography, dry etching, etc.

It is also interesting to note that industry pull may have played a role in this slow development path. Since all-optical WDM networks based on Erbium doped fiber amplifier (EDFA) technology rose to prominence in the 1990s, meeting the demands of telecommunications bandwidth while in effect circumventing the need for optical-electronic-optical (OEO) conversion, the motivation for commercial development of large scale photonic integration that would enable such approaches was somewhat dampened [25].

Early examples of complex InP-based PICs remounts back to 1988 with the publication of the first AWG by Smit[28], and after this invention, the complexity of AWG-based devices with increasing circuit complexity was reported.In 1993 WDM receivers with 5-10 components by Amersfoortet al. [29] were published, and by the year 2010 the number of components in a chip rose to 400[30]. This evolution of chip complexity can be seen at the next figure(2.9)

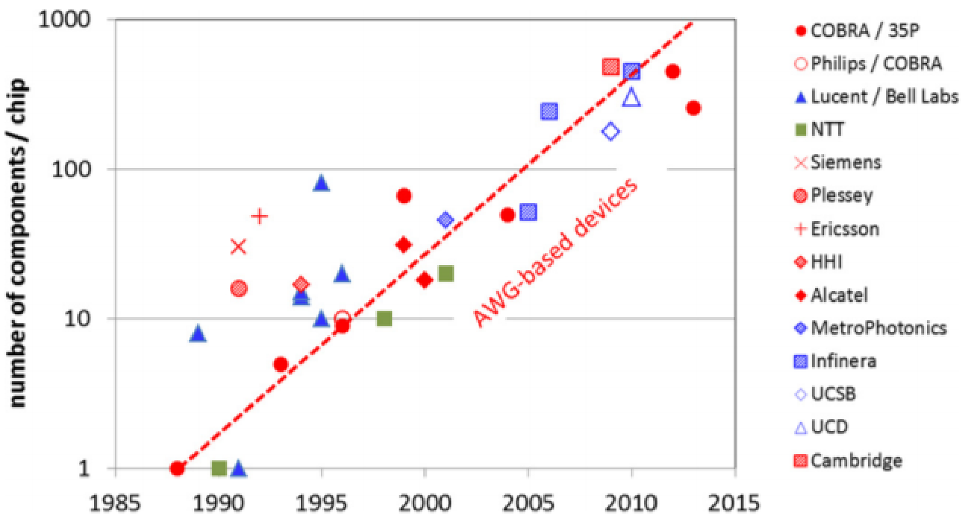

Figure 2.9: Development of chip complexity measured as the number of components per chip[25].

In micro-electronics, a broad range of functionalities is realized from a rather small set of basic building blocks, like transistors, diodes, resistors, capacitors and interconnection tracks. By connecting these building blocks in different numbers and topologies we can realize a vast variety of circuits and systems. In photonics, we can do something similar.

Most of the functionality of a PIC is realized from a rather small set of components: lasers, optical amplifiers, modulators, detectors and passive components like couplers, filters and (de)multiplexers.Some of this examples and more can be seen in figure 2.10. By proper design, these components can be reduced to an even smaller set of basic building blocks. As basic building blocks, we need passive devices for combining and splitting of light, both wavelength dependent (filters, wavelength multiplexers) and wavelength independent (power splitters, couplers and combiners). Most of these devices can be composed of a combination of passive waveguides of different widths and lengths, so in a proper integration process that supports integration of passive waveguides a variety of passive devices, such as MMI couplers and AWGs can be realized. In addition to these passive devices we need basic building blocks for manipulating the phase, the amplitude and the polarization of the light signal, in order to support a broad range of functionalities[25].

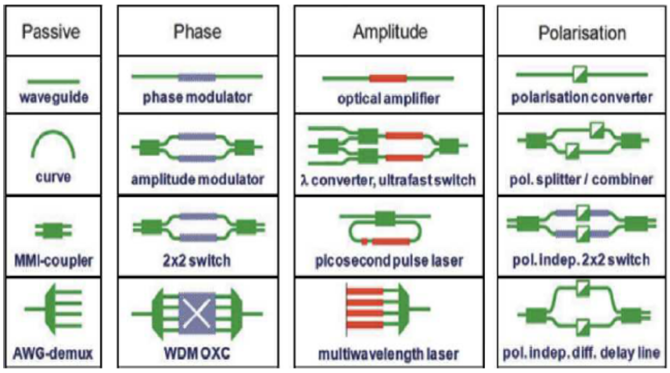

Figure 2.10: Example of the functionalities that can be realized in a generic integration technology [25].

So far, the use PICs has been mainly restricted to some niche areas in telecom applications, where their specific functionality cannot be met by competing technologies. With the expected cost reductions through a generic foundry approach they will also become competitive in high volume markets like the telecom access network, where they may be applied in the Central Office for integration of larger numbers of circuits that must be repeated for each subscriber or group of subscribers.

By applying the methodology of microelectronics to photonics we expect a dramatic reduction of the costs for R&D and manufacturing of photonic ICs and a breakthrough to a wide range of application fields, in telecommunications and data communications, but also for application in sensors, medical equipment, metrology and consumer photonics[25].

Chapter 3

Wavelength Multiplexer / Demultiplexer

Chapter 3 will be divided in four sections. In section 3.1 will be given a theoretical explanation about the operation principle of the AWG. Section 3.2 contain the information regarding the wavelength plan of the technologies that will be used. In Section 3.3 is explained the topology of the transceiver in terms of wavelength multiplexing/demultiplexing. Finally section 3.4 contains all the tests and results with Aspic™and VPI Photonics™regarding AWGs.

3.1 AWG

An AWG, also known as the optical phased-array[20] is an optical planar passive device whose applications can vary from wavelength routing to wavelength multiplexing. AWGs are also called wavelength routers which are nowadays used in several multiwavelength network applications [21]. With the development of technology and optical integration, AWGs capable of multiplexing up to 1080 channels with 25 GHz spacing have been reported [22]. AWGs offer many advantages for use such as compactness, fabrication stability, reliability and reduced cost of fabrication and packaging. They also offer high precision on the control of channel spacing enabling its compliance with the ITU-T. In the next figure(3.1) a block diagram of an AWG is presented.

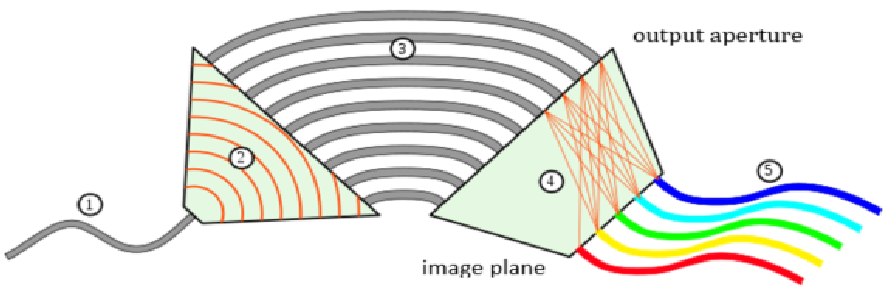

Figure 3.1: Diagram blocks of an AWG,1-ribbon fiber, 2-propagation region,3-waveguides, 4-second propagation region, 5- output fibers

As light from the ribbon fiber enter the propagation region, it gets diffracted. This light gets coupled to the waveguides of the array structure. This waveguides have different lengths intentionally, and because of this, the light inputs on the output of the second propagation region in such a way that different wavelengths get focused at different spots, and by this way we can isolate the different wavelengths from the main channel in different fibers.

The choice of the length of the array waveguides is such that the path length difference between adjacent waveguides is equal to an integer multiple of the central wavelength of the device. The divergent beam at the input aperture is transformed into a convergent one at the output.

An image of the input field at the object plane will be formed in the center of the image plane. Phase change induced by a change in the wavelength varies linearly along the aperture. This is due to the linear increase of the length of the array waveguides. Because of this fact, the outgoing beam is tilted and the focal point shifts along the image plane thus by placing receiver waveguides properly along the image plane one can obtain spatial separation of the different wavelength channels.

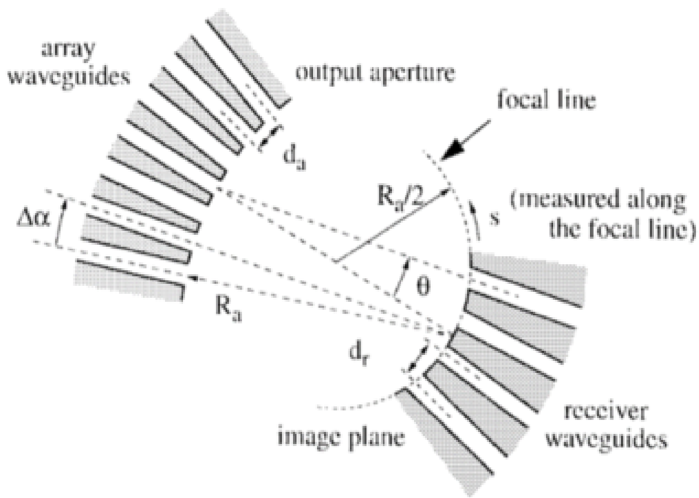

Figure 3.2: Geometry of the AWG at the receiver side [21].

The length difference between adjacent array waveguides enables focusing. As explained before it should be equal to an integer number of wavelengths and is given by [21]

$$\Delta L = m\frac{\lambda_c}{N_g} \tag{3.1}$$

where m is the order of the phased array, λ_c is the central wavelength and N_g is the effective index of the waveguide mode. By choosing this, the array acts as a lens with image and object planes at a defined distance of the array apertures. This distance is denoted by Ra in Figure 3.2. This figure depicts a Rowland-type mounting where the receiver waveguides should be positioned along a circle with radius half of R_a [21].

Another important property of the AWG is the Free Spectral Range(FSR), also known as the demultiplexer periodicity. This periodicity is due to the fact that constructive interference at the output star coupler can occur for a number of wavelengths and is easily calculated by[20]

$$\Delta\lambda_{FSR} = \frac{\lambda_c}{m} \tag{3.2}$$

3.2 Wavelength plan

One of the first tasks of this dissertation was to multiplex and demultiplex the several wavelengths of the network. In the following sections, all the steps for this goal will be explained.

The wavelength of the technologies are shown in figure 3.3.

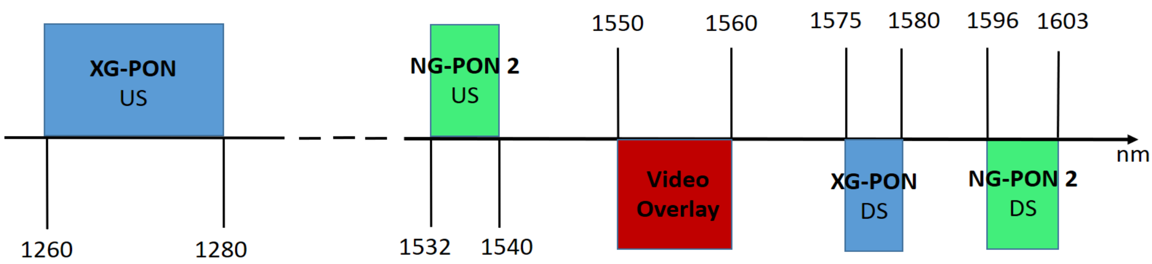

Figure 3.3: Wavelength plan for XG-PON, video-Overlay and NG-PON 2.

3.3 Transceiver topology

The first approach was to try to make an AWG that would separate the more wavelengths/channels as possible and then work from there. In theory, this would work but after some work with the software ASPIC using AWGs, was possible to reach the conclusion that in order to obtain this AWG, the lobes had to be too big because the XGs-PON upstream channel has 20 nm of width. In addition of last problem, the fact that there was a proximity between the upstream of NG-PON2 and the downstream Video-Overlay the crosstalk was hard to keep low.

To correctly design a AWG for this width of channel the lobes had to have a prohibitive size because in order to fit all the width of certain channels, the crosstalk between channels would be too high.

To void the previous problems the next approach was to split as soon as possible the downstream channels from the upstream ones. In order to accomplish such task an optical circulator was used as it would fulfill the needs for this block.

A circulator is a device that is used to direct the optical signal from one port to another port and in one direction only. This action prevents the signal from propagating in an unintended direction.The circulator implementation can be seen in the next figure(3.4).

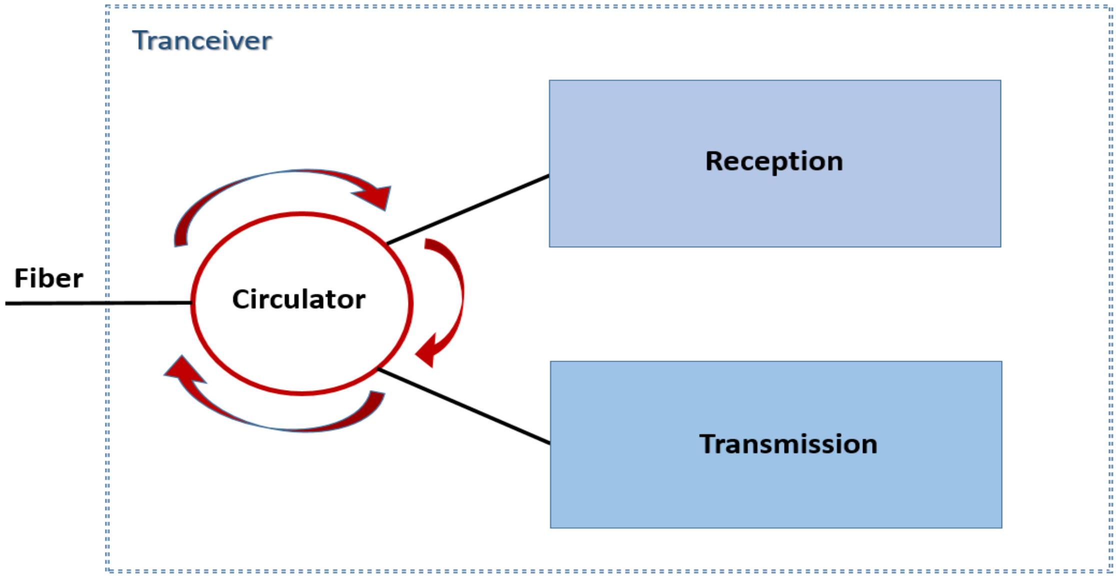

Figure 3.4: Circulator implementation

In this application, the light coming from the OLT is directed to the reception, and the light produced in the transmission block directed to the fiber. In this configuration, the path reception to transmission is available, however this fact is irrelevant as the reception part does not produce any light.

This design allows a looser modelling of the AWG for the reception block, because now the spectrum becomes simpler, composed by the 4 downstream channels of NG-PON2, Video Overlay and XGs-PON downstream.

The next figure shows a diagram of the transceiver's architecture.

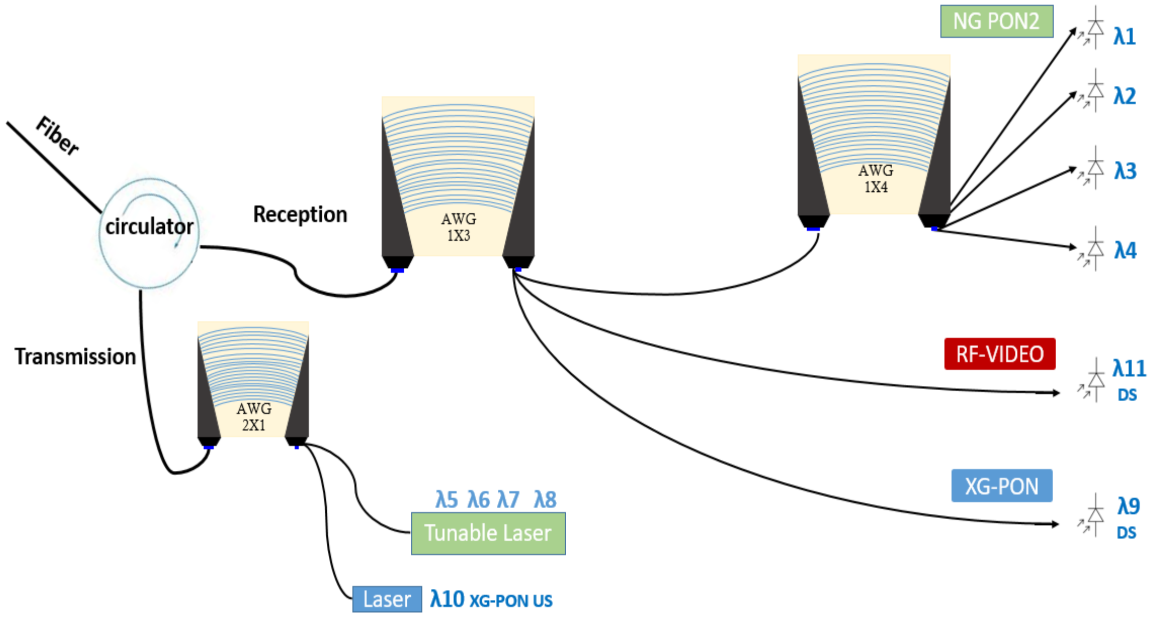

Figure 3.5: Overview of the transceiver's design

3.4 Design and modelling of AWGs with Aspic™

Now will be proposed 2 AWGs for the reception part that will demultiplex all the channels, leading the light to the correct photodiode.

Following the circulator,in the downstream block, was design a 1:3 AWG that separates the three technologies, one lobe for each one. The center frequency of the three technologies are: 187.50, 190.17 and 192.92 THz for NG-PON2, XGs-PON and Video-Overlay respectively. This AWG had to be design in a way that would compensate the fact that the channels are not equidistant. This was not a major problem since an increase in bandwidth of the lobes and a slight adjust of the center frequency of the AWG would compensate.This adjustment however increases the insertion loss on two of the NG-PON2 downstream channels in 1.1 dB.

The following table show the reader the parameters used to design such AWG.

Parameter	value
Number of inputs	1
Number of Outputs	3
Central waveleght	1.5775 um
Channel spacing	2.7 THz
Free Spectral Range(FSR)	8.0 THz
IO waveguide width	3.0 um
IO waveguide pitch	5.0 um
Array waveguide width	3.5 um
Gap between array waveguides at FPR	0.2 um
Array Acceptance Factor	3.0
Chirp factor	0.0

Table 3.1: AWG 1:3 desing parameters

In figure 3.6 one can see the full spectral response of the AWG. Starting from the right one can see that the first lobe is centered at 1598 nm exactly were the 4 downstream channels from NG PON2 are. The second in 1578 nm where is nearly were the downstream from XGs PON is. The third at 1550 is supposed to filter Video-Overlay.

To overcome the problem the width of the lobes was increased and the loss of the wavelength that are not in the center of the lobe is almost neglectable - the insertion loss never increases above 3dB.

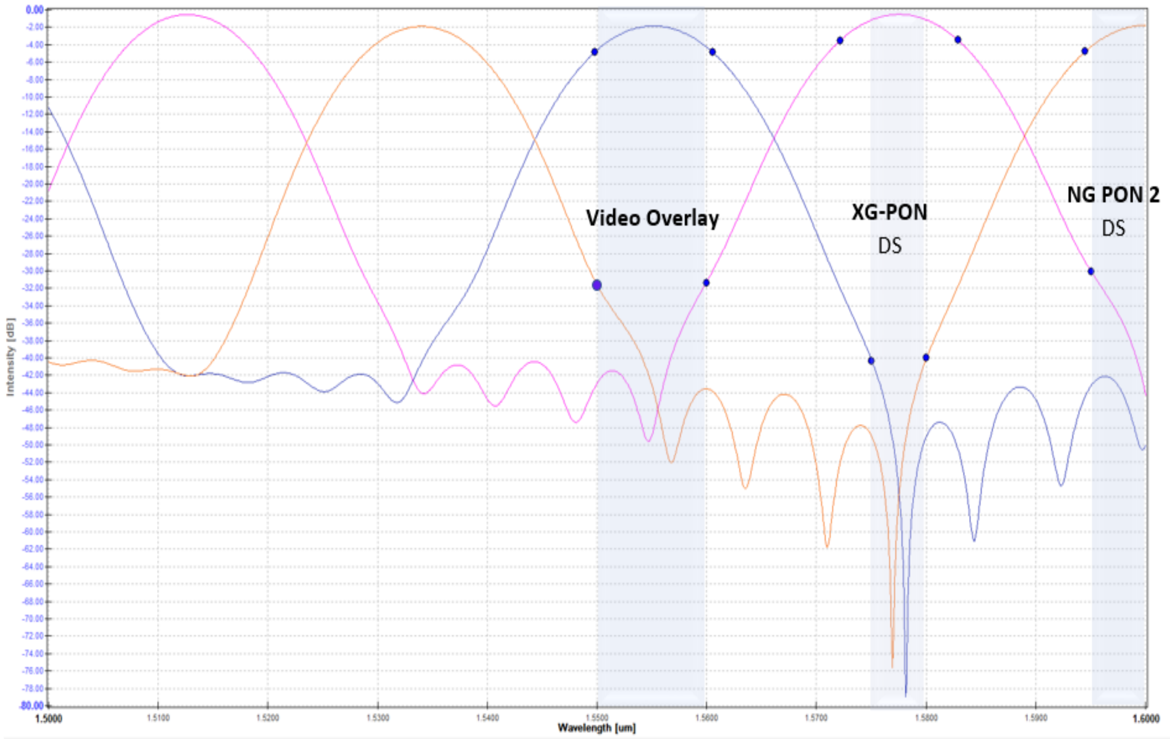

Figure 3.6: Spectrum of the 1:3 AWG

One can see that the insertion loss its not the same for the 3 lobes, the middle lobe has around 2 dB of insertion loss whereas the side ones have around 2.8 dB of insertion loss, this differences are present because there is non-uniformity of the AWG. It's important to mention that the AWG in terms of PIC's size, with all the waveguides, it's the prime component to take in account. Knowing that the FSR was kept as reduced as possible in order keep the AWG as small as possible. The reader can see that the blue stripes represents the width of the 3 bands, and the interception of that bands with the adjacent lobe marks the crosstalk between technologies. The maximum crosstalk presented is -30 dB. The upper points mark the cutoff frequencies for each lobe.

Now it's easy to see that the channels are splitted except the 4 downstream channels from NG-PON2, for this matter a 1 :4 AWG was design. The next table shows the parameters used to design the AWG.

Parameter	value
Number of inputs	1
Number of Outputs	4
Central waveleght	1.597615 um
Channel spacing	100 GHz
Free Spectral Range(FSR)	3 THz
IO waveguide width	3.0 um
IO waveguide pitch	6.0 um
Array waveguide width	1.5 um
Gap between array waveguides at FPR	0.1 um
Array Acceptance Factor	3.0
Chirp factor	0.0

Table 3.2: AWG 1:4 desing parameters

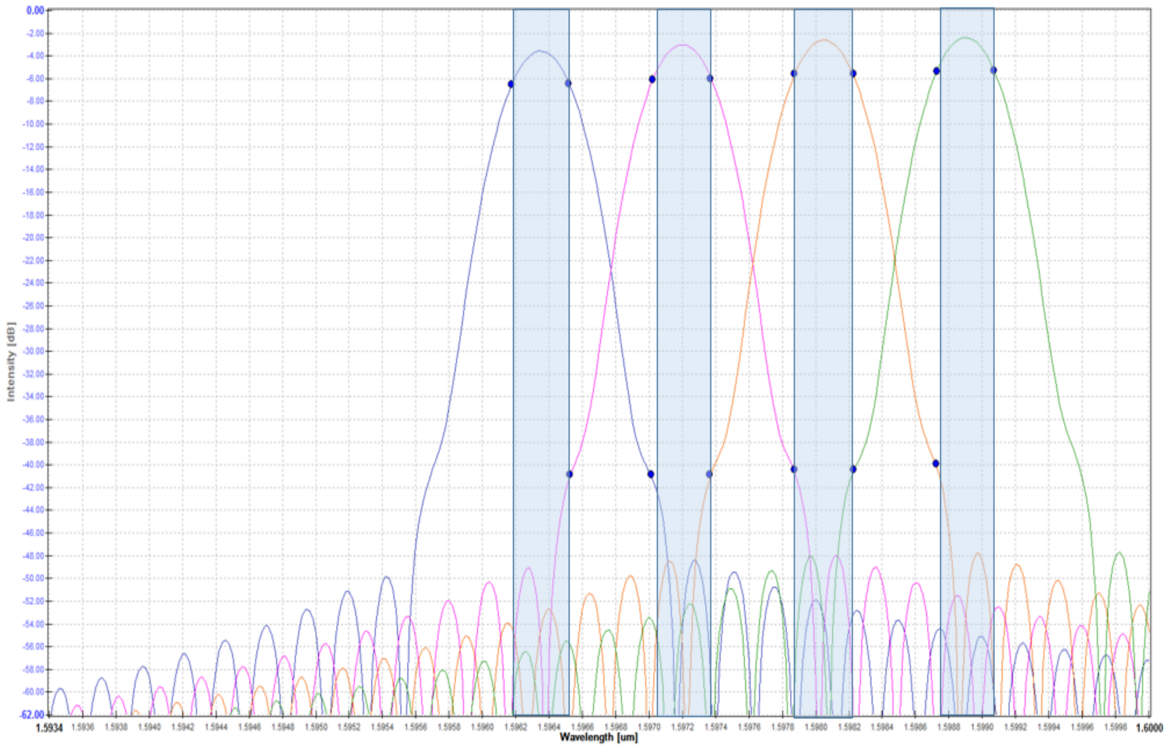

Figure 3.7: Spectrum of the 1:4 AWG

This AWG was needed to separate the four NG-PON2 channel for downstream. The lobes had 40 GHz bandwidth, between 2.4 and 3.5 of insertion loss and approximately -40 dB crosstalk between them. Note for the fact that the tight bands made this AWG one of the biggest components that the chip will have and it size will be limited by the size of this AWG (3 mm).

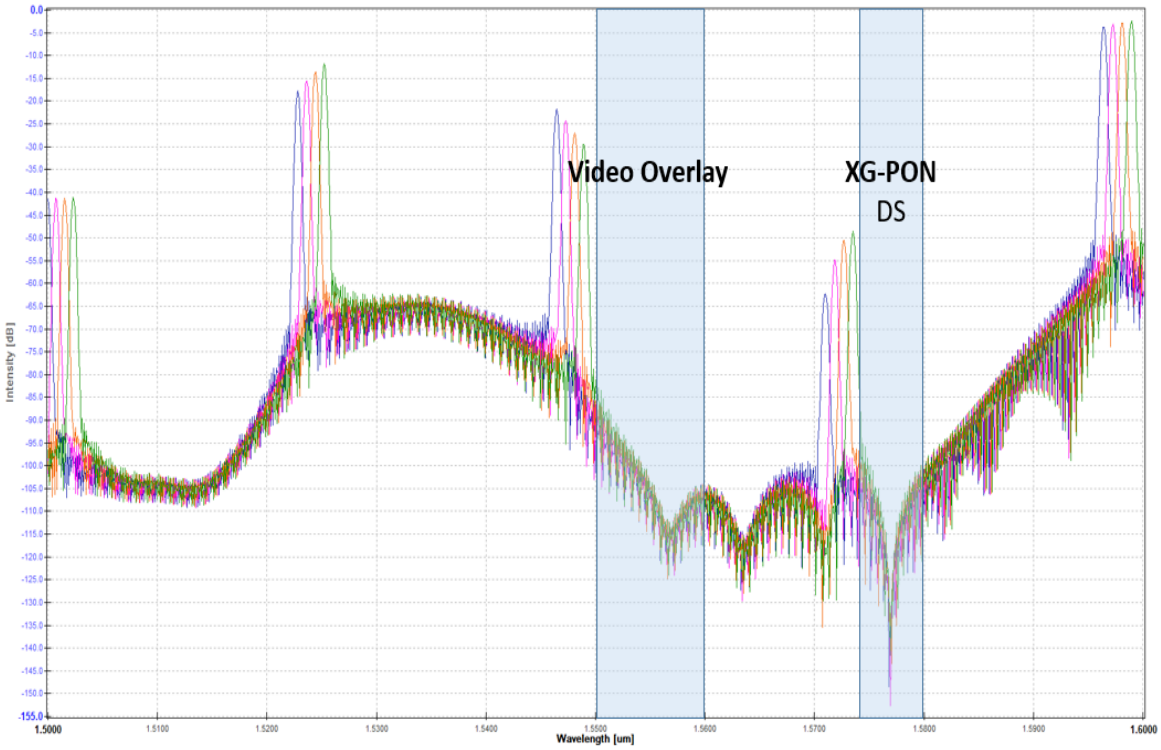

Figure 3.8: Spectrum of the 1:3 and 1:4 AWG

In figure 3.8 is shown the FSR had to be properly calibrated to not match any other band that was used in other channels. The minimum FSR possible was 3 THz.

With the reception part finished the next step was to address the upstream channels. The upstream channels are XGs-PON and 4 from NG-PON2. For the sake of the AWG design the 4 channels of NG-PON2 were treated as one big channel.

Was necessary to combine the 2 technologies, for that matter a 2:1 AWG was design. The next table shows the reader the parameters used to design said AWG.

Parameter	value
Number of inputs	2
Number of Outputs	1
Central waveleght	1.55 um
Channel spacing	3.7 THz
Free Spectral Range(FSR)	3 THz
IO waveguide width	2.0 um
IO waveguide pitch	3.0 um
Array waveguide width	1.5 um
Gap between array waveguides at FPR	0.6 um
Array Acceptance Factor	3.0
Chirp factor	0.0

Table 3.3: AWG 2:1 desing parameters

This last AWG was simulated not only with ASPIC™but also with VPI Photonics™. The reason to change software was that the ASPIC™had a major flaw - the simulation windown was only between 1500 and 1600 nm. In the upstream channels, this was a major issues due to the fact that the upstream channel of XGs-PON is outside of this range(1260-1270nm). The next figure shows the simulation of the AWG using VPI Photonics™.

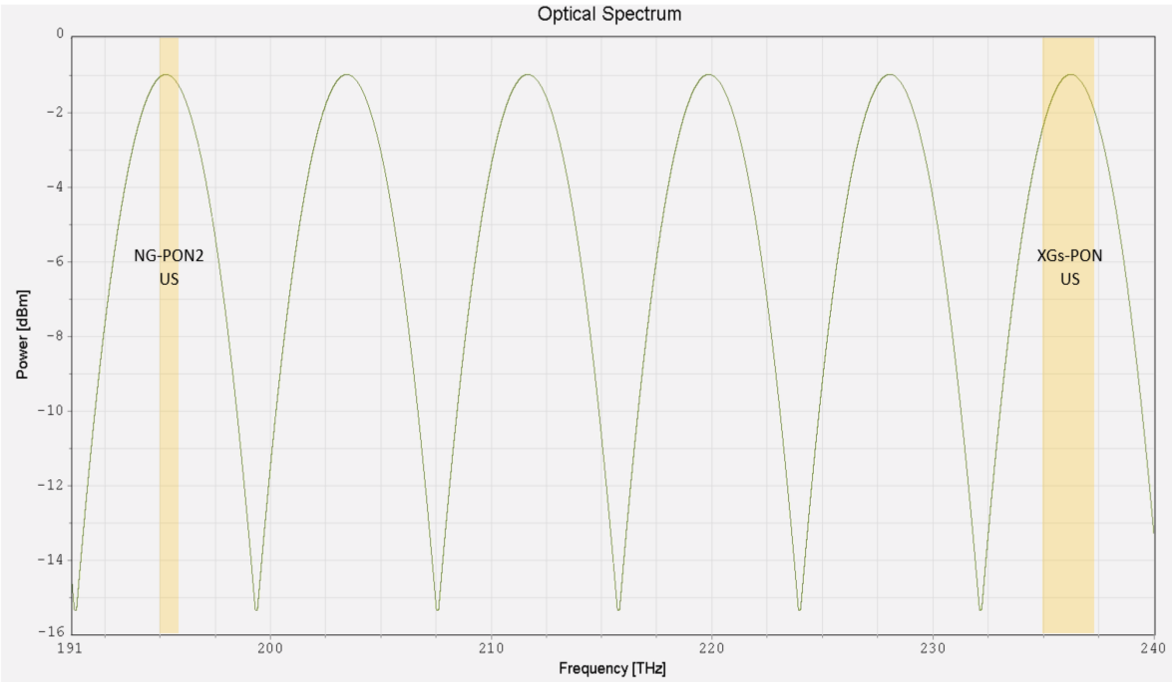

Figure 3.9: Spectrum of the 2:1 with VPI

The AWG was design in a way that one of the lobes would be centered on the NG-PON2 channels and using the third FSR the AWG would filter the XGs-PON channel with the other lobe. This way is possible to combine both bands in a single fiber without major loses. Its important to mention that in figure 3.9 the insertion loss is not realistic, the expected value is around 2 dB.

3.5 AWG in VPI™

To validate the study made previously in ASPIC™regarding the AWGs, on the next setup the AWGs that were design are tested. In this section, its not presented the upstream channels because they are at Figure 3.9. Is noteworthy to mention that the spectrum of the AWGs in VPI is slightly different from the ones in ASPIC™, this is due to the fact that ASPIC™is more realistic tool to model AWGs. The crosstalk levels are on VPI are lower, but again, not very realistic comparing to ASPIC™. In the follwoing figures the shadowed area represents the band ocupied by the channel or channels on scope.

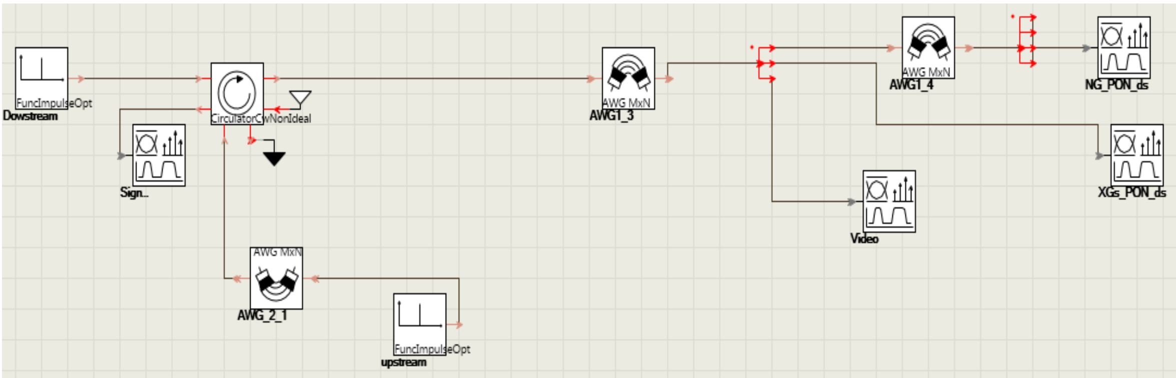

Figure 3.10: Setup for inicial AWGs tests on the VPI Photonics™

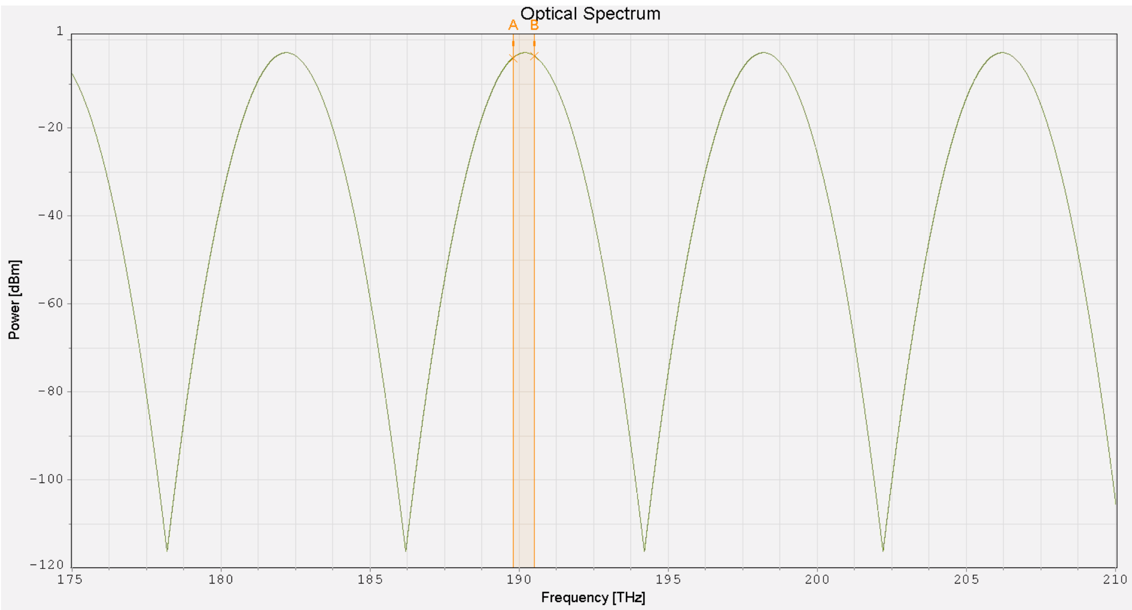

Figure 3.11: XGs-PON downstream channel

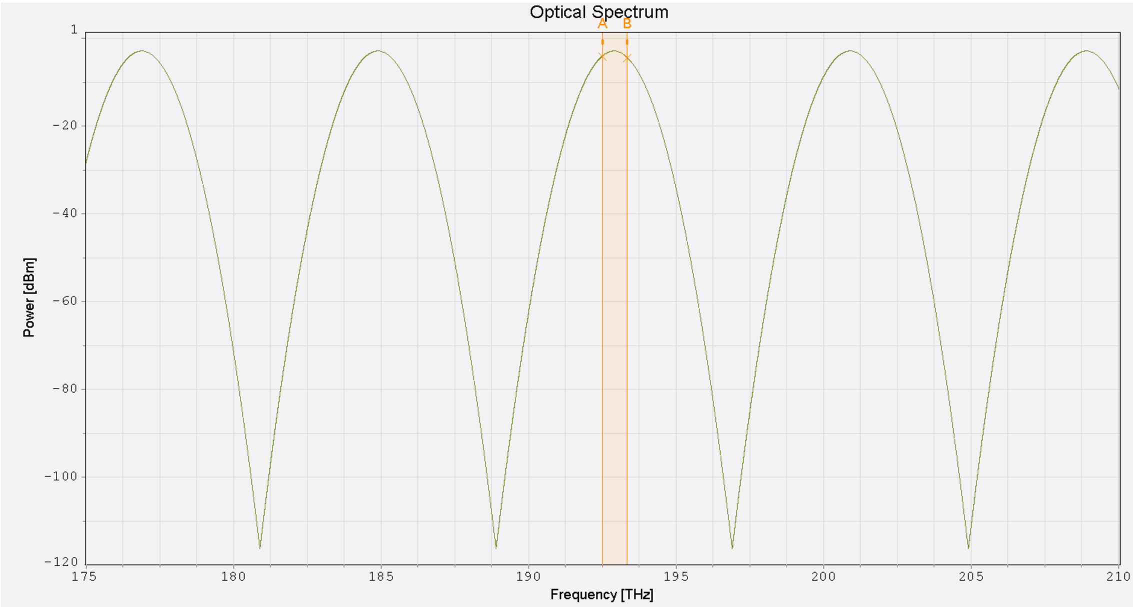

Figure 3.12: Video-Overlay channel

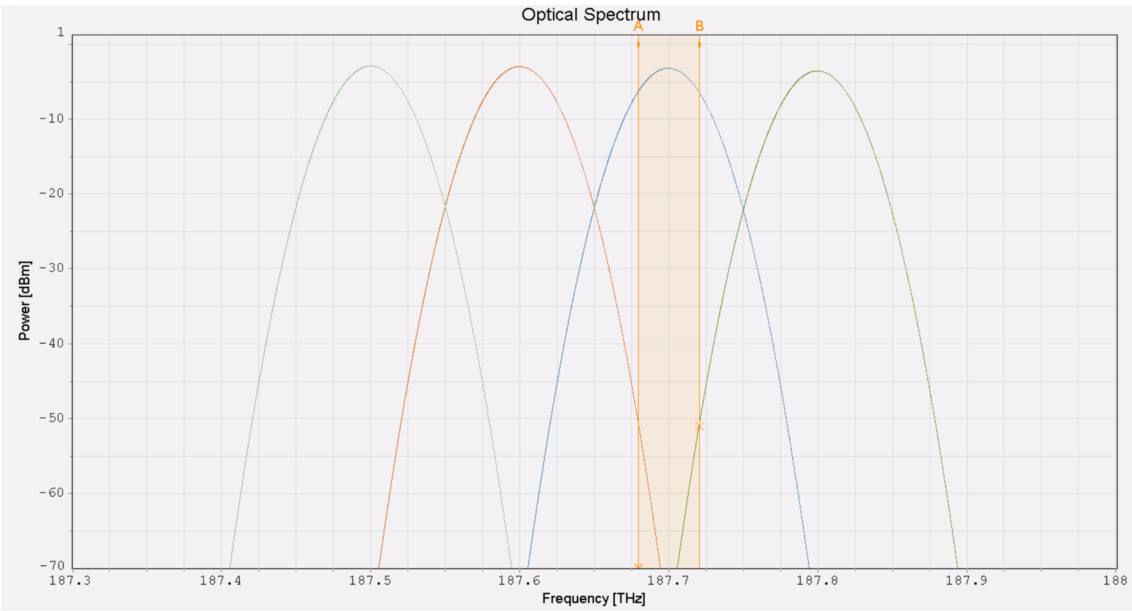

Figure 3.13: NG-PON2 downstream channels

Chapter 4

Transceiver simulation

This chapter contains all the tests, simulations and setups that lead to the simulation of the transceiver using VPI Photonics™. There is also introduced some concepts needed to the reader understand the tests made.

Initially are exposed tests made on some components and settings. Right after is shown the simulations with the full transceivers blocks. It is noteworthy to mention that the components tested and used are generic VPI components and, therefore, ideal in certain aspects. More on this matter will be explained in the following section.

4.1 Components modelling

The next figure (4.1), shows the reader the setup used to test some factors that affect the system sensitivity such as bit rate, extinction ratio and fiber length. This setup was meant to simulate as close as possible to the interaction between the OLT and a ONU.

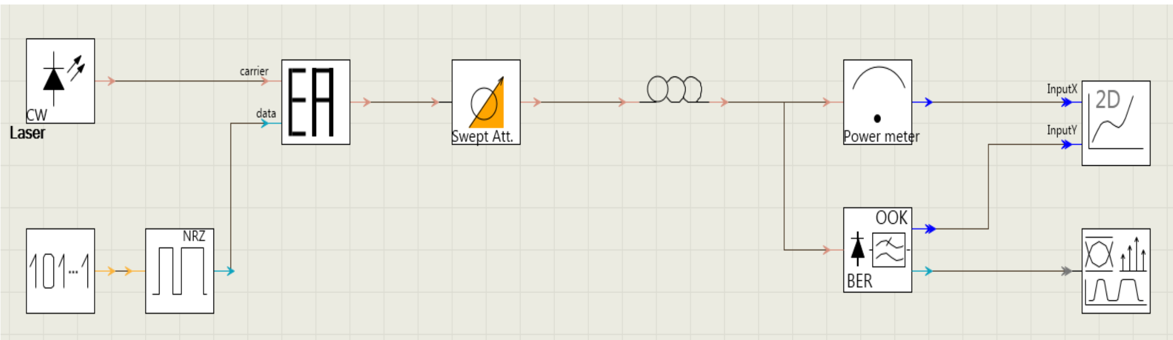

Figure 4.1: Setup for receiver sensivity tests

Laser

The laser used was a Continuous Wave(CW) laser with an emission frequency of 193.1 THz, with a output power of 10 mW, equivalent to 10 dBm, and with a linewidth of 10 MHz.

Data generator

To simulate a stream of data, was used a Pseudo Random Binary Sequence(PRBS)and followed by a Non-Return to Zero(NRZ) coder, both with a Bitrate of 10 Gbps. The PRBS was set to a Mark probability of 0.5, this means that the generator had a equal probability of generating either a logical '1' or a logical '0'.

External modulator

The external modulator used allowed the manipulation of the extinction ratio through the variable m, that can be seen in figure 4.2.

The variable m, the modulation index, controls the extinction ratio(ER) by controlling the power of the '0'. The output signal of this external modulator is:

$$P_{out}(t) = P_{in} * ((1 - m) + m * data(t)) \tag{4.1}$$

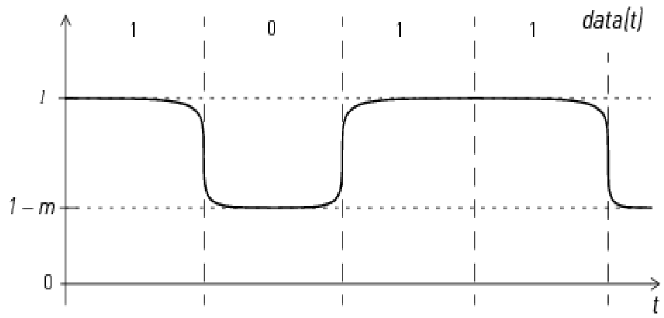

Figure 4.2: An example of the power transfer function of the modulator for the rectangular-like modulation signal varying in the range from 0 to 1 [35].

knowing that the ER is given by:

$$ER = 10log_{10}\left(\frac{P_1}{P_0}\right) \tag{4.2}$$

as P_0 is P_1(1-m),

$$ER = 10log_{10}\left(\frac{P_1}{P_1(1 - m)}\right) \tag{4.3}$$

it's easy to understand that with the desired ER and knowing the power of the laser, one can calculate the modulation index m.

Attenuator and fiber

To simulate the attenuation present on a PON network, is used a Sweep attenuator that was set to sweep between 14 and 29 dB. This values were selected in order to simulate the same attenuation present in a ODN class N1[6]. To simulate the fiber itself was used a universal fiber, and it was set to 40 km. This fiber was used with the following parameters: attenuation of 0.2 dB loss per kilometer and a dispersion parameter equal to 16ps/(nm*km).

The Chromatic dispersion is an important phenomenon to take in account. Chromatic dispersion is, in a basic explanation, an enlargement of the bits of data, hence their overlap and consequently, causing error at the receiver. Chromatic dispersion can be divided in 2 components: material dispersion and waveguide dispersion. The first one is due to the fact that the silica reflectivity vary with the frequency thus causing different spectral components to propagate with different group velocities, leading to enlargement of the signal. The dispersion in waveguide is due the different components of frequency associated with the traveling mode have different velocities[32].In figure 4.3 one can see the two components of chromatic dispertion.

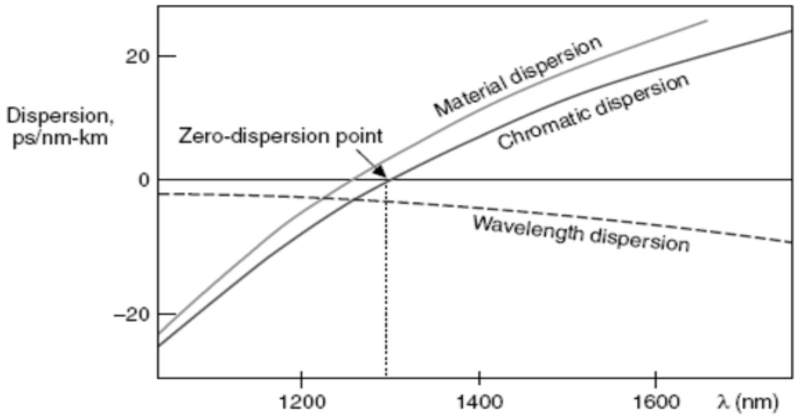

Figure 4.3: The two contributors to chromatic dispertion: material and wavelength[33]

It's easy to understand that dispersion increases with the fiber length, thus there is a limit of distance imposed by the chromatic dispersion:

$$L < \frac{c}{2B^2\lambda_0^2|D|} \tag{4.4}$$

Where L is the fiber length, c is the speed of light, B the symbol rate (which is the same as the bitrate in case of NRZ On-off keying(OOK)), λ_0 the wavelength and D the chromatic dispersion.

Photodiode

To simulate a ONU receiver was selected a receiver with detector Type *p-i-n* photodiode(PIN), with a responsivity of 1 A/W, a bandwidth of 75 percent of the Bitrate and a Thermal Noise of $10^{-12}A/\sqrt(Hz)$.

4.2 P2P system simulations

To understand the impact of some parameters like fiber length, bit rate or ER the following tests were made using the setup present on figure 4.1.

Fiber length tests

The figures 4.4 and 4.5 show the results of a simulation, where the sensitivity was tested for the following fiber length: back to back(B2B), 10 ,20 and 40 kms. The simulation was made with a speed of transmission of 10 Gbit/s. The first test was made using a 8.2 dB extinction ratio and the second with 6 dB. This values where chosen knowing they are the lower limits for downstream and upstream respectively, for NG-PON2 and XG-PON [6][16].

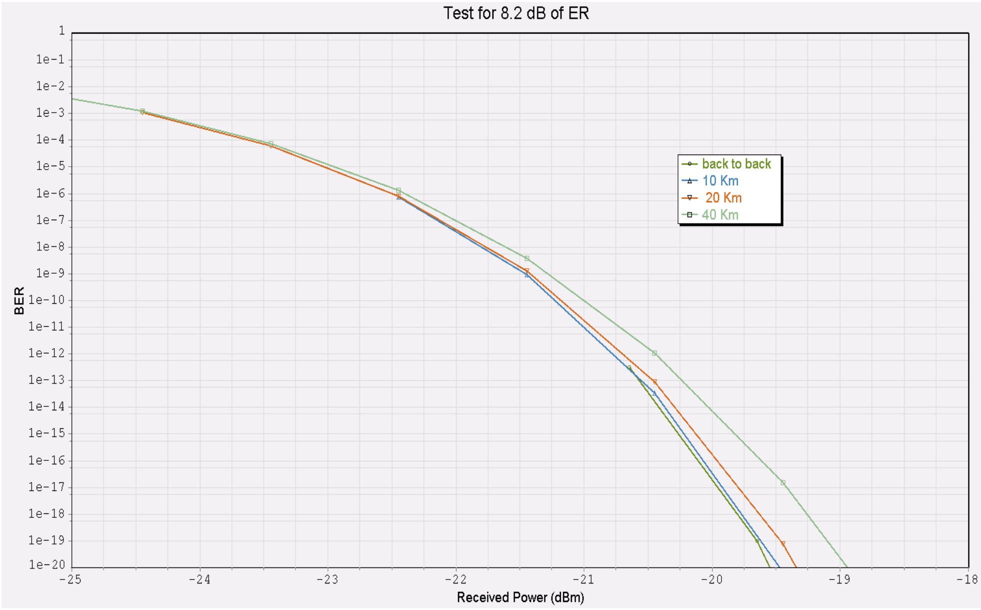

Figure 4.4: BER vs Received power for 8.2 dB extintion ratio

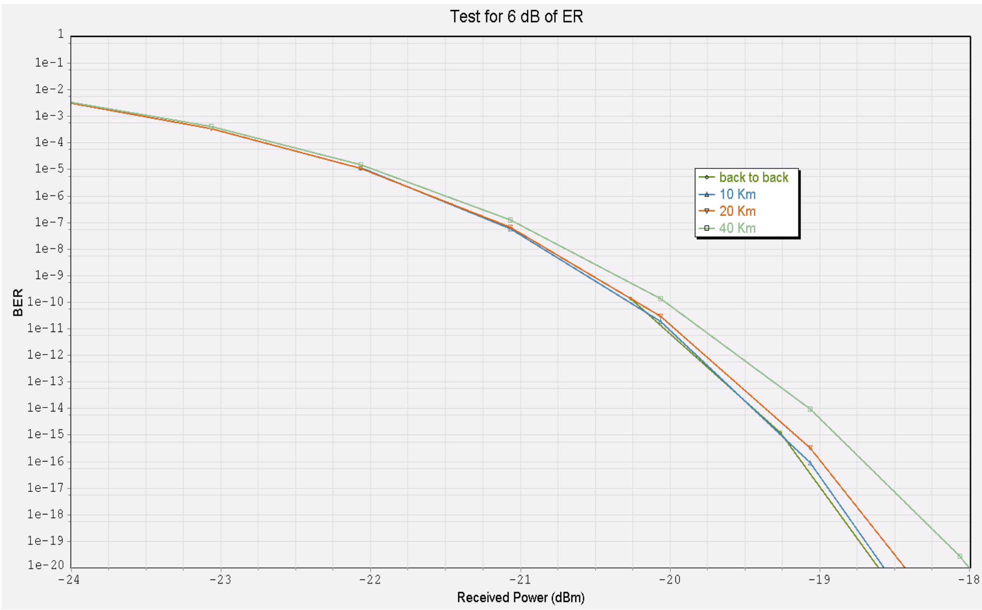

Figure 4.5: BER vs Received power for 6 dB extintion ratio

As one can expect, the fiber length influences the power needed to achieve a certain Bit-Error-Rate(BER). For the values 0, 10 and 20 km the differences are minimal and this is due to the fact that for this length chromatic dispersion have a small impact on the signal. Using the formula 4.4 can be calculated the transmission limit imposed by the dispersion, 38.8 km. So, its expected for that set of lengths, that just the 40 km would be different. The difference despite not being that much is noticeable. In terms of ER, its easy to see that the behavior its exactly the same if we alter the ER. The only difference is that, for a smaller ER, a bigger power is required to achieve the same BER level. For $10^{-}3$ on the test with 8.2 dB ER the BER was achieve with -24.6 dBm. For the same conditions with 6 dB ER is necessary -23.5 dBm. This result is expected because a lower ER means a lower eye opening and by extention more reception errors. To overcome this factor is needed a higher received power . After this test is noticeable that when constructing the final simulation a Amplification will be required in order to follow the standards for NG-PON2 and XGs-PON in terms of reception sensitivity: -28 dBm.

Bitrate and ER tests

For testing the receiver in terms of bitrate of the transmission was used the setup presented in figure 4.1. The conditions for this test are the same as explained in the beginning of this subsection, apart from the fiber length that was set to 0, in order to do the test in B2B mode.

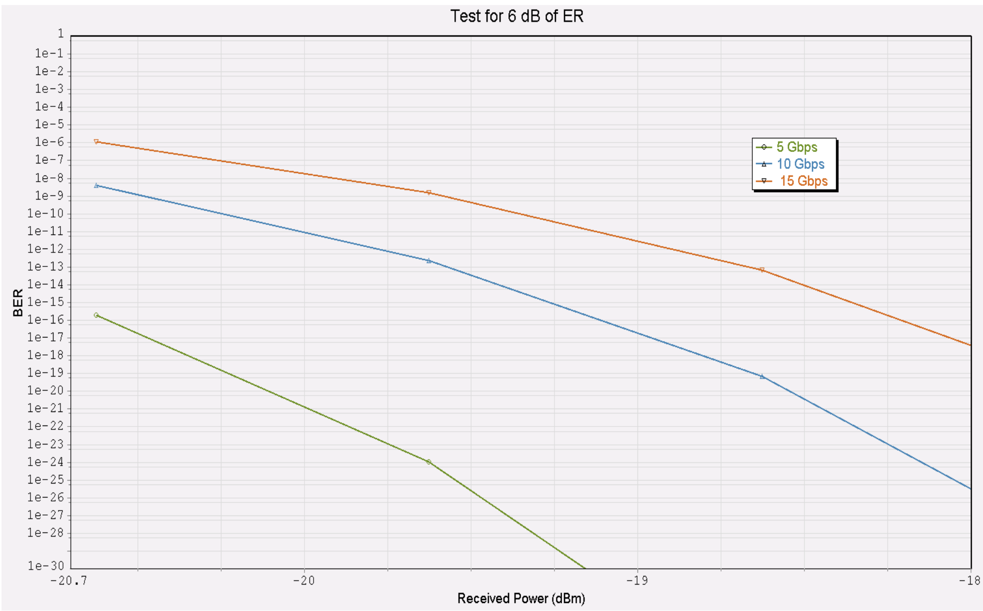

Figure 4.6: BER vs Received power for 6 dB of ER

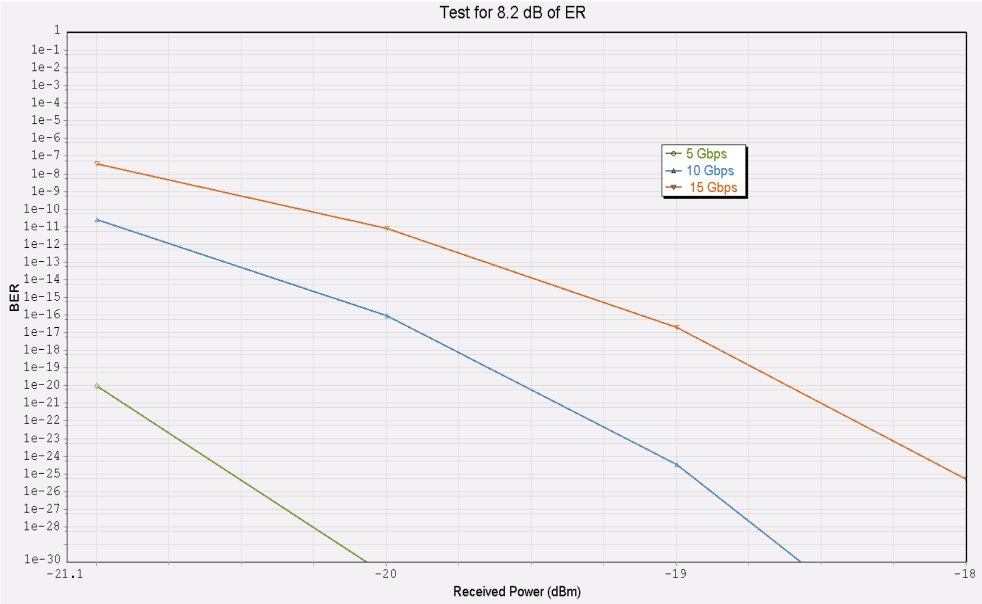

Figure 4.7: BER vs Received power for 8.2 dB of ER

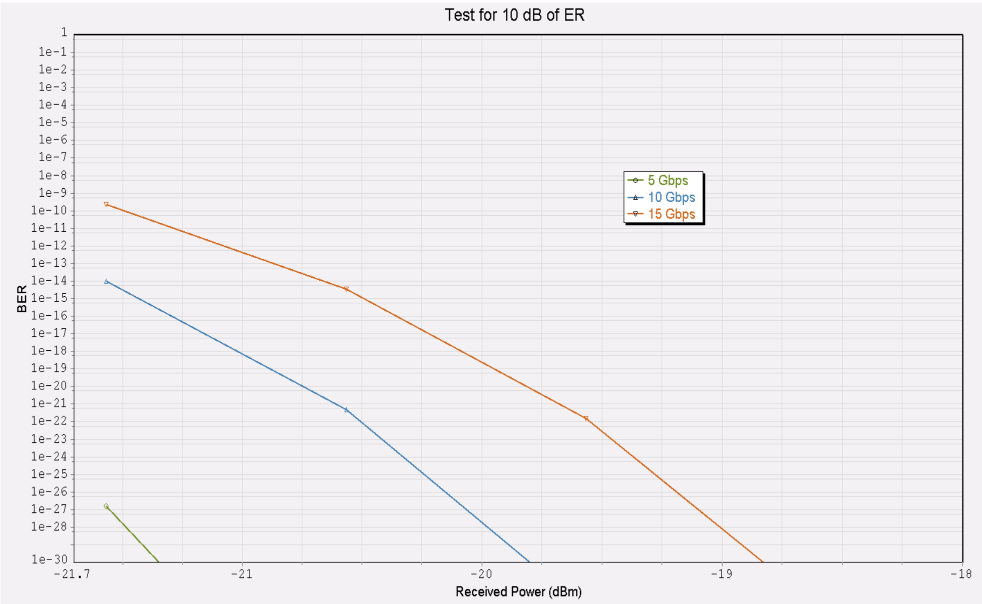

Figure 4.8: BER vs Received power for 10 dB of ER

In all the 3 tests,figures 4.6, 4.7 and 4.8, is easy to see that as we increase the bitrate the sensitivity decreases independently of the ER. This results are expected because for higher bitrates the signal to noise ratio(SNR) decreases and this way the photodiode perform worse.

4.3 Multitech simulations and results

The next figure, (4.9), presents the setup that was used to simulate the whole ONU and, for simulation purposes, the OLT. This simulation was done using a bitrate of 10 Gbps and a length fiber of 40 km. The sweep attenuator was set between 14 and 29 dB, to simulate a ODN N1 type. The lasers and modulators were set using the minimums of output power and ER mentioned on the standards summarized on Chapter 2. The figures 4.10, 4.11 and 4.12, are the results of this simulation.

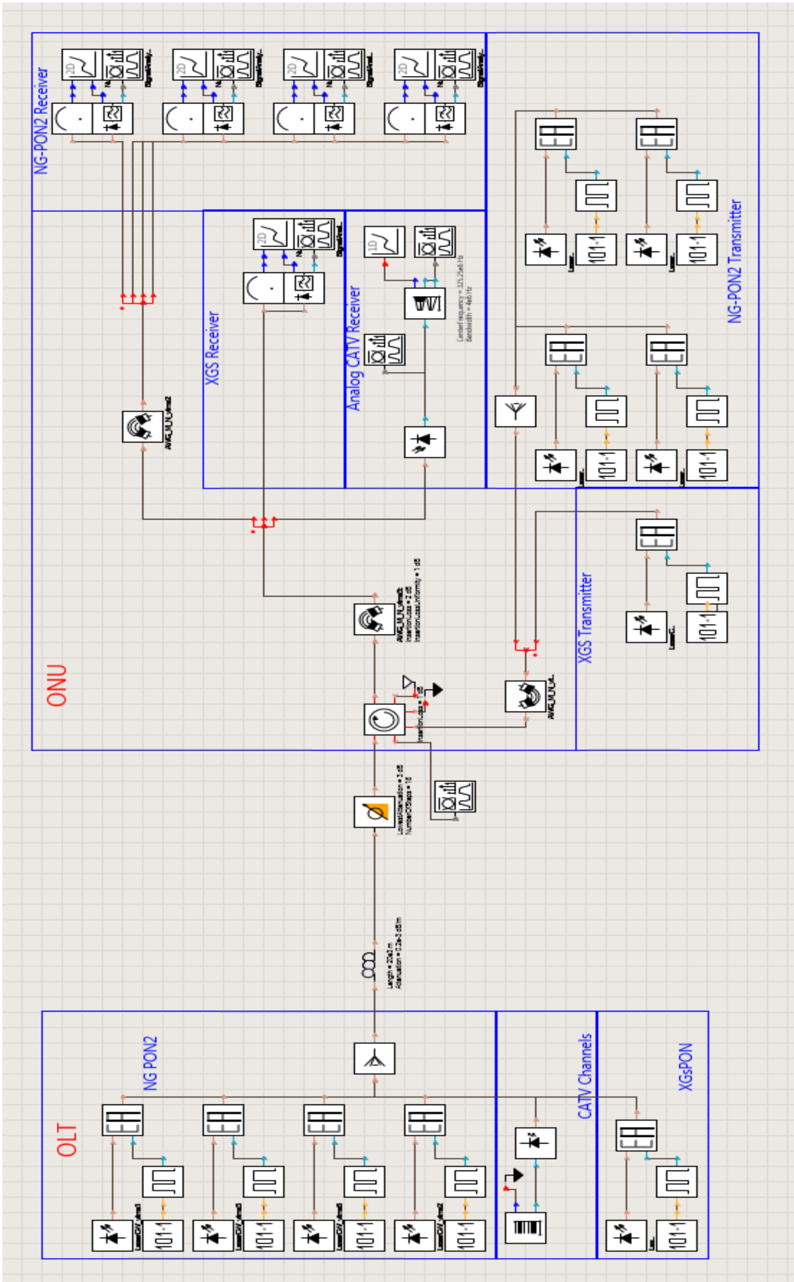

Figure 4.9: Full VPI Seput for the OLT/ONU

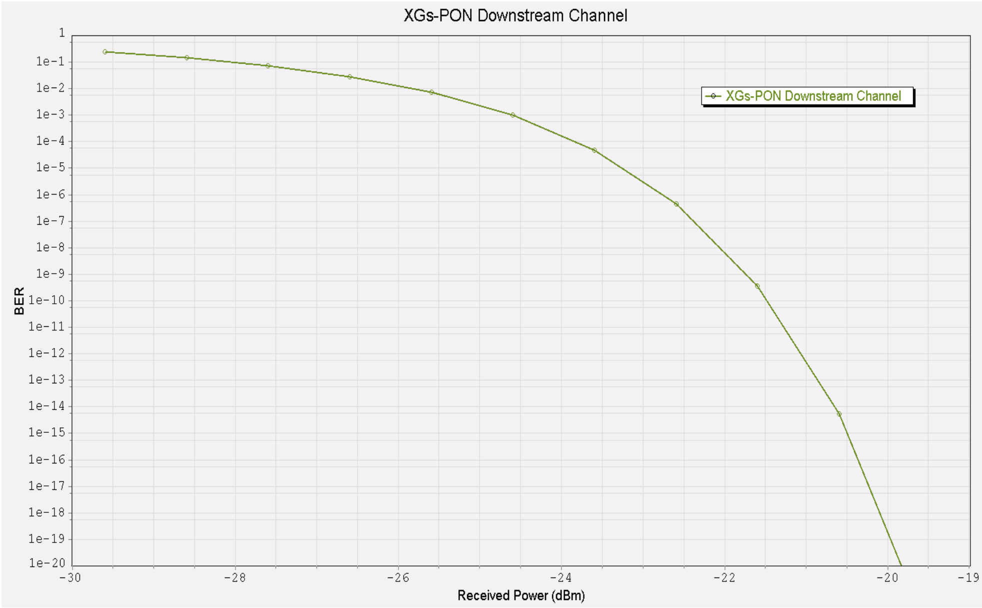

Figure 4.10: XGs-PON downstream channel

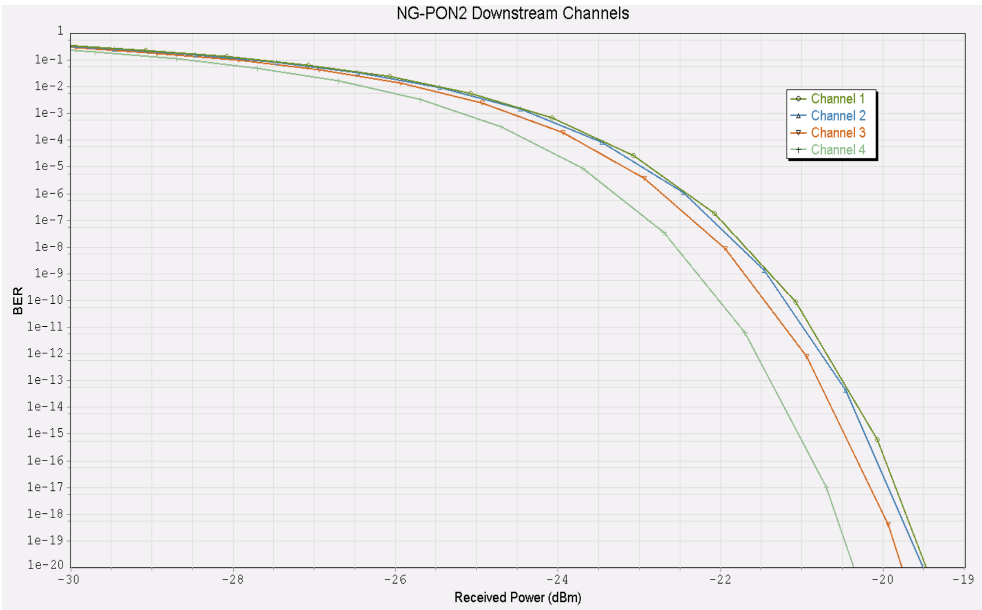

Figure 4.11: NG-PON2 downstream channels

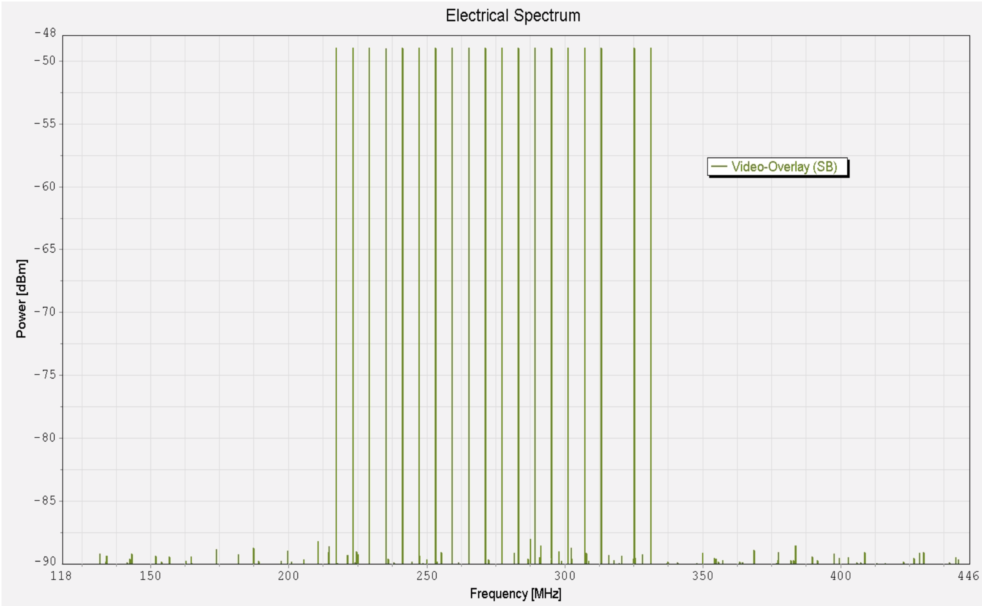

Figure 4.12: Video-Overlay eletrical signal

After a careful examination of the results it's easy to understand that across all channels there are not enough power to guarantee a good operation on this network in terms of sensitivity. On XGs-PON downstream channel to obtain a BER of $10^{-}3$ is necessary 24.6 dBm. In order to follow the XGs-PON standard a amplification of the received signal will be required to reach the -28 dBm mark [16]. As the XGs-PON channels, the NG-PON2 downstream channels will need amplification. Despite the difference between the 4 channels, which is caused by the lobe of the AWG not being centered on the 4 channels as it was explain on chapter 3, all of them present powers above the -28 dBm mark explicit of the standard[6]. The values of power needed to get a BER of $10^{-}3$ presented by the NG-PON2 downstream channels are: -24.2, -24.3, -24.6 and -25 dBm.

Regarding the Video Overlay one can see that the CNR mentioned on the standard is bigger - 44 dB -[19] then what was get on this simulation, 40 dB. To obtain the required CNR the signal needs to be amplified.

4.3.1 Multitech simulation with amplification

In figure 4.13 the reader can see the seput used on the last section, but now with Semiconductor optical amplifiers(SOA) doing optical amplification of the channels of NG-PON2 and XGs-PON. For the Video Overlay part was used a normal Bipolar Transistor to make the amplification on the eletrical domain. This simulation was done in the same conditions as the first simulation on this section. The following figures shows the reader the results of such setup: 4.14, 4.15, 4.16, 4.17, 4.18 and 4.19.

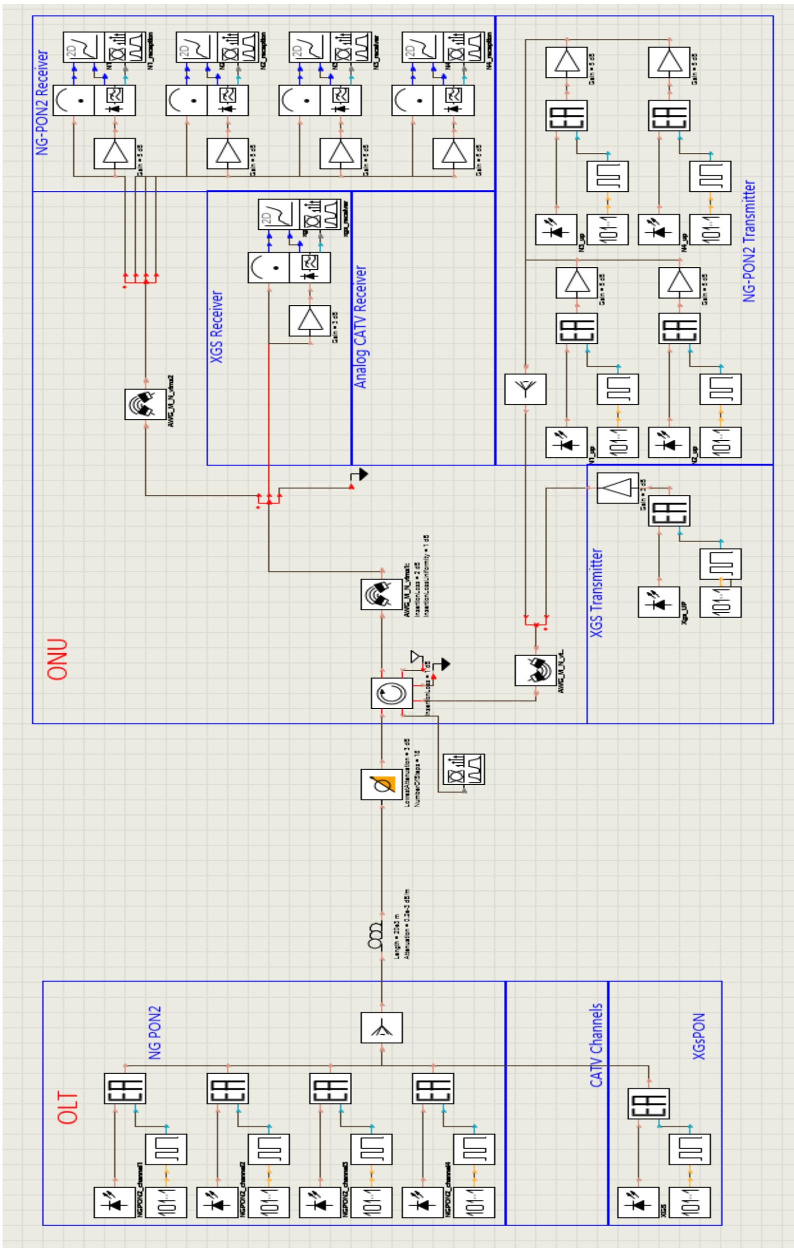

Figure 4.13: Full VPI Seput for the OLT/ONU with amplification

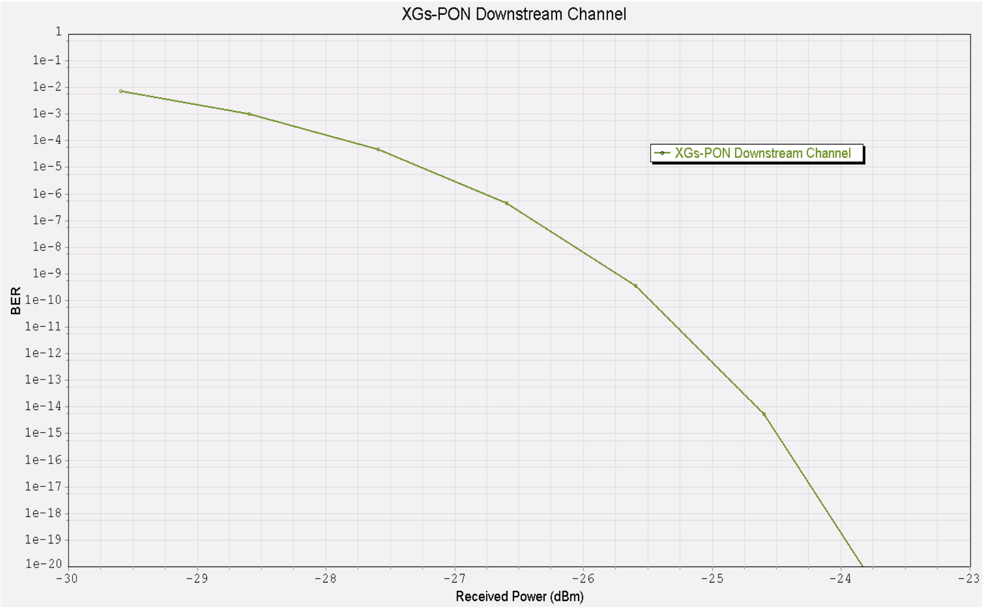

Figure 4.14: XGs-PON downstream channel with SOA

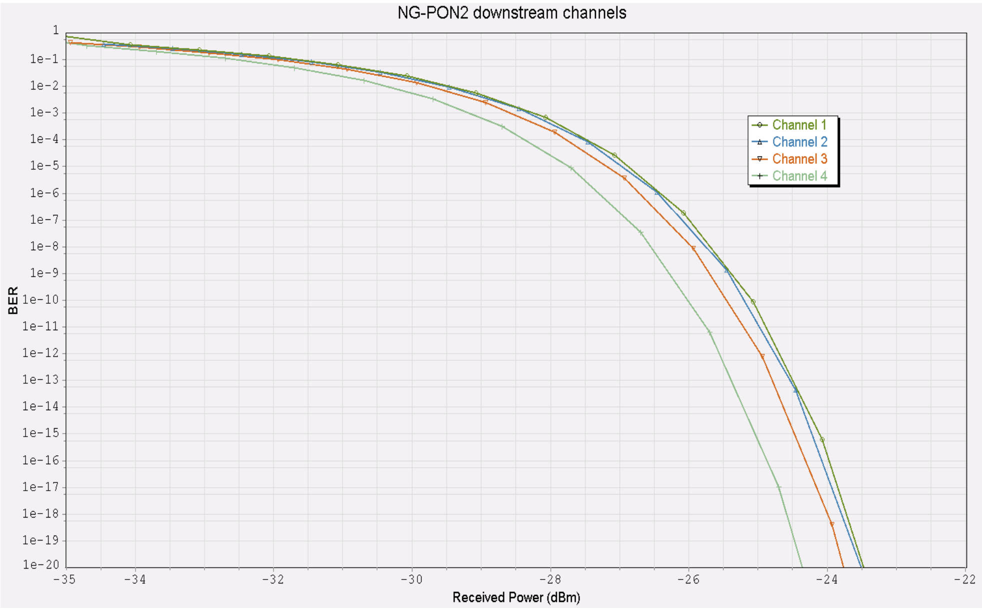

Figure 4.15: NG-PON2 downstream channels with SOA

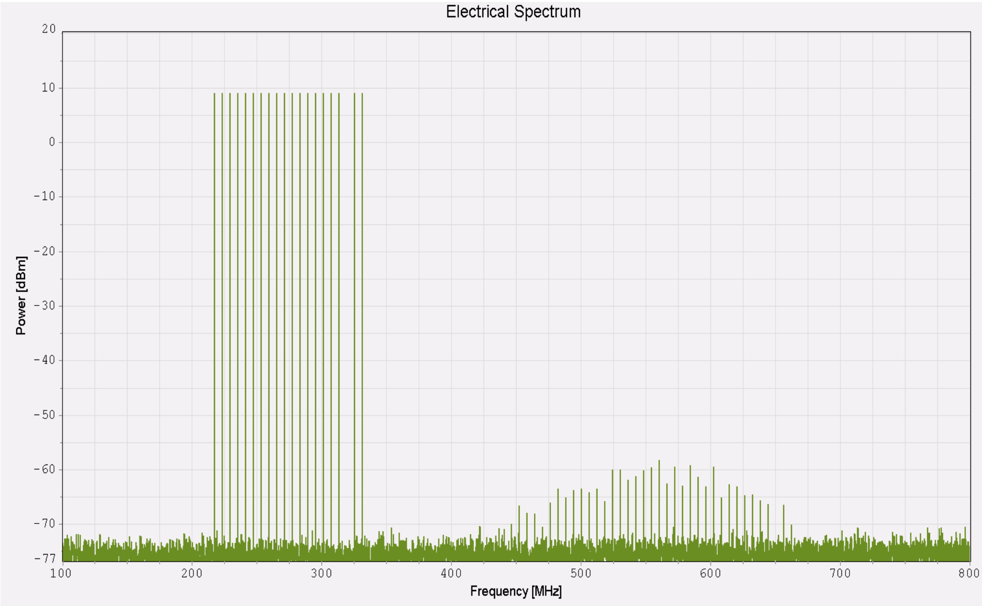

Figure 4.16: Video Overlay eletrical signal with eletrical amplifier

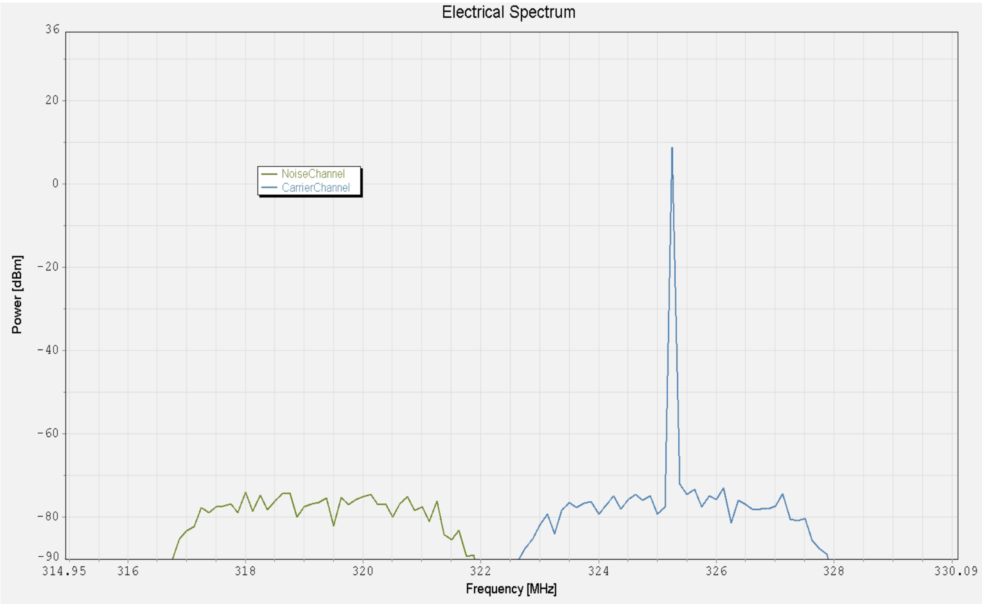

Figure 4.17: Spectrum of Carrier channel and Noise channel

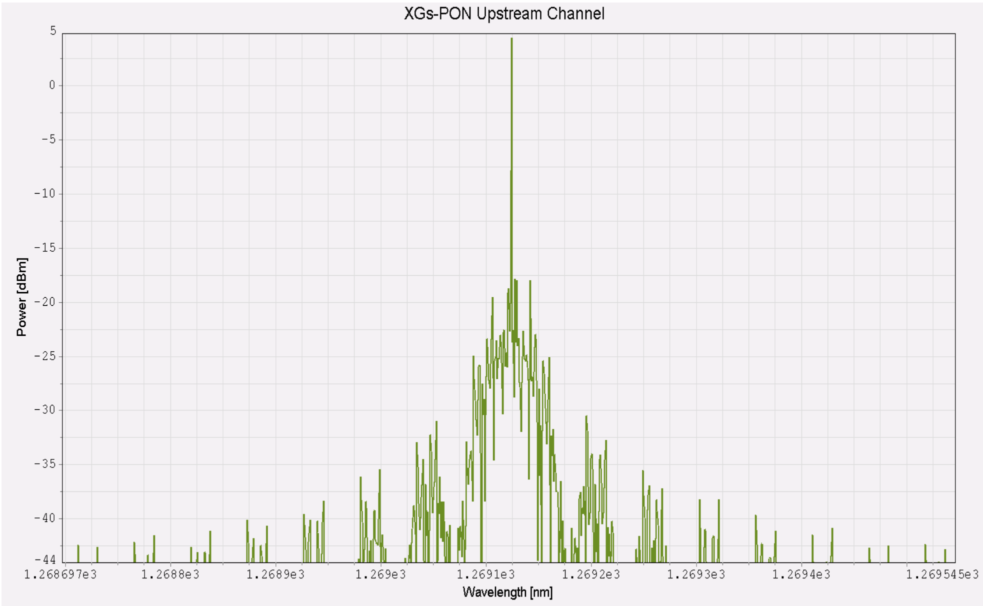

Figure 4.18: XGs-PON Upstream channel's spectrum

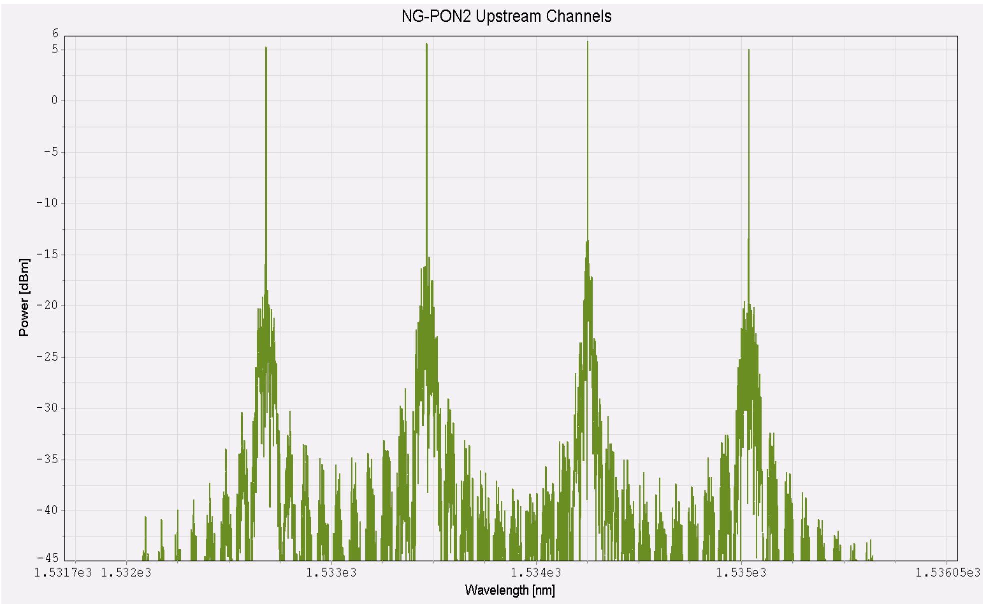

Figure 4.19: NG-PON2 Upstream channel's spectrum

After including some amplification on the reception block of the ONU the standards are all being respected. For the NG-PON2, a SOA was introduced in all the channel with a gain of 4 dB. In figure 4.19 the reader can see that the channel need less than -28 dBm to reach a BER of $10^{-}3$. Their values of sensitivity are -29.2, -28.6, -28.3 and -28.2 dBm.

For XGs-PON was also introduced a SOA with a gain of 4 dB, making the channel's sensitivity now of -28.6 dBm which also goes along with the sandards that states a minimum sensitivity of -28 dBm for a BER of $10^{-}3$ [16].

For the Video Overlay, as it was mentioned before, was introduced a Bi Polar transistor as a electrical amplifier. The gain was set on 60 dB in order to achieve the CNR of 44 dB and. After the amplification the CNR is 49.82 dB. The eletric output power is now 9 dBm, which is higher then the lower limit imposed by the standard, 7.5 dBm [19].

Regarding the upstream channel must be said that the output power of the lasers could had been set to any value in this simulation. However, the available laser on the Fraunhofer Heinrich Hertz Institute(F-HHI) foundry had a 4 dBm[34] output power upper limit. As it was explained on Chapter 2, for XG-PON and NG-PON2 the minimum output power of the ONU is 4 dBm. If no amplification was used the output power of the ONU for these technologies would be 3 dBm, caused by the 1 dB of insertion loss of the 2:1 AWG. Because of this, SOAs were used in the upstream channels as well.

Chapter 5

Tranceiver layout

This chapter presents all the steps towards building the design implementation of the architecture that was presented in chapters 3 and 4. This implementation was made using the software Optodesigner, provided my Phoenix. This software supports the Process design kit(PDK) of F-HHI foundry, so it contains libraries with the necessary building blocks to construct the transceiver.

In order to do send the PIC to production, some rules had to be followed. This rules are dictated by the Design Rules of the chosen foundry, in this case, F-HHI.

There are several rules one has to take in account when designing the PIC. Initially must be understood that there is a limit in area available for the user of 6 mm x 4 mm. Some components like lasers, amplifiers, and other active components have to be placed on the chip perpendicularly to the major flat. After this, there is a minimum distance between waveguides of 1.5μm.

Regarding the waveguides themselfes they have a minimum width of 1μm, and when using waveguides with a curvature, there is a minimum for the radius of 100μm when using the type E1700. The waveguides can be of the following three types: E200, E600 and E1700, for this design mainly will be used the waveguide E1700 because for a width bigger the 2μm it's the best in terms of propagation loss, with 0.75 dB/cm [34]. There are more rules on the design rules but they will be explained in the next sections.

5.1 Reception Block

The reception block part is shadowed in figure 5.1. In the top right corner there is the Spot size converter(SSC) which is the entrance/exit of the light of the chip. This block, following the design rules, had to be design in a way that the fiber has an angle of 7 degrees and had to be used E200 waveguide. Right after there is a transition between E200 and E1700, because, as is was explained before the E1700 are the best waveguide for the design. After that there is an MMI.

On the previous chapters the separation between reception and transmission is made with a circulator, unfortunately the foundry doesn't have a circulator on the set of optical components available, and, in order to make this separation between block was decided to use a MMI. This MMI was used almost as a coupler 1:2, separation the light in the 2 output ports. The downstream signal was this way splited into 2 ways. The downstream signal loses this way 3 db. The downstream signal which goes to the lasers of the upstream channels is absorved by a couple of isolator placed in front of the lasers. After the MMI there is the 1:3 AWG with 2 of the output ports connected to the Video Overlay PIN and the XGs-PON SOA + PIN. Note that the video has no amplification in optical domain and so the Video Overlay block (left upper corner) is just a transition between E1700 and E200, because PINs need to be connected to E200 only, and the PIN itself. After this two output ports, there is a third output port on the AWG which is connected to the 1:4 AWG. This AWG is responsible for demultiplex the 4 NG-PON2 downstream channels, and can be seen below the SSC. The four output ports are equally connected to 4 sets of SOA+PIN, with the transition between E1700 and E200 because like the PINs the SOAs need to be connected to E200 waveguides. Note that a butt-joint was used between the transition and the SOA itself to make a transition between passive elements and active ones.

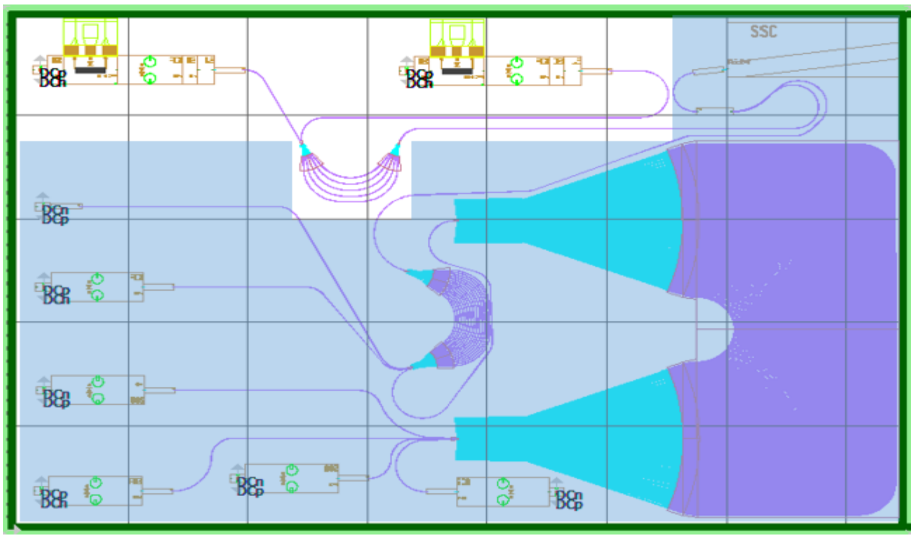

Figure 5.1: Reception block of the mask layout (shadowed).

5.2 Transmission Block

The reception block part is shadowed on figure 5.2. After the MMI one can see the 2:1 AWG that puts together the upstream channels from NG-PON2 and XGs-PON. Connected to each input port of the AWG there is a set of components. Each set is composed by a absorbent PIN, a laser, a SOA, a Butt-Joint, a isolator and a transition between E200 and E1700. Its important to mention the absence of a modulator, and this is due to the fact that F-HHI foundry does not have a external modulator like the one simulated in chapter 4. The best way to modulate the signal was to use lasers with direct modulation. Despite being worst in many aspects then the external modulation direct modulation was the closest design to the one presented in chapter 4 that was available on the foundry. For the NG-PON2 upstream channels was decided to use a Tunable laser, as just one of the upstream channels will be transmitting at a given time. This way the complexity of the PIC is kept low and is saved some space.

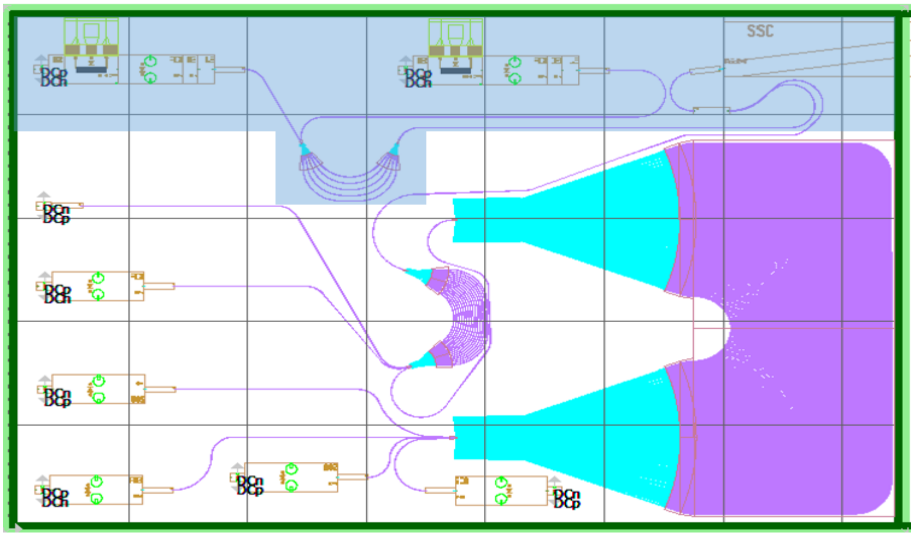

Figure 5.2: Transmission block of the mask layout (shadowed).

5.3 Final Design Considerations

The overall transceiver mask layout was completed in the previous sections, but for the final mask, it was necessary to introduce some electrical connections in particular components.

These electrical pads were done using DC interconnects whose form is like a square and the size is 100 μm^2. Was important to place this pads apart from each other at least 100 μm ir order to make possible the task of professional that will do the wire bonding. For the laser were two DC pads and two RF pads since this architecture is intended to support 40 Gb/s (20 GHz), so there are RF pads support high frequencies. For each SOA were placed two DC pads as for each PIN. This pads were carefully placed in the edges of the PIC in order to make the bonding as short as possible.
In figure 5.3 there is the final layout with the electrical DC pads and all the metal routing.

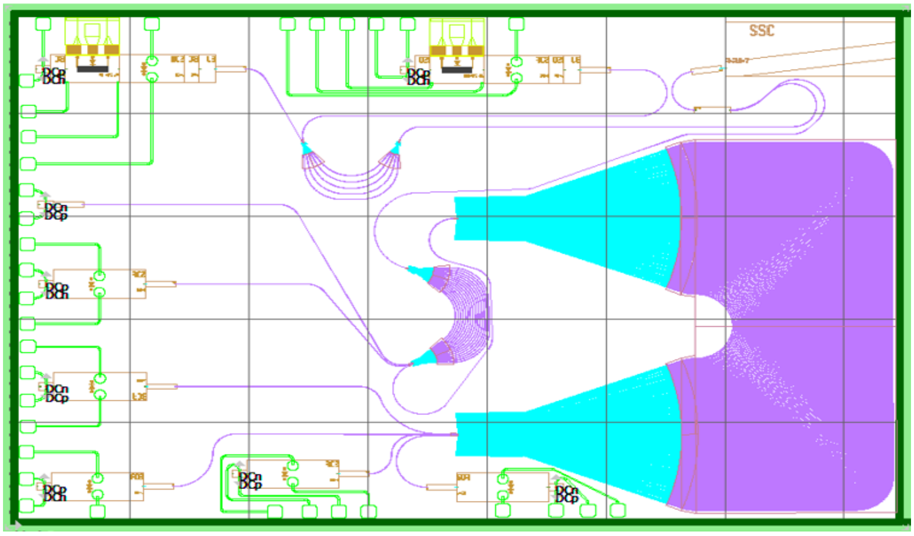

Figure 5.3: Final design of the transceiver

After running the Design Rules Check(DRC) the final mask layout was generated and can be seen at figure 5.4. This PIC is ready to send to F- HHI foundry to produce.

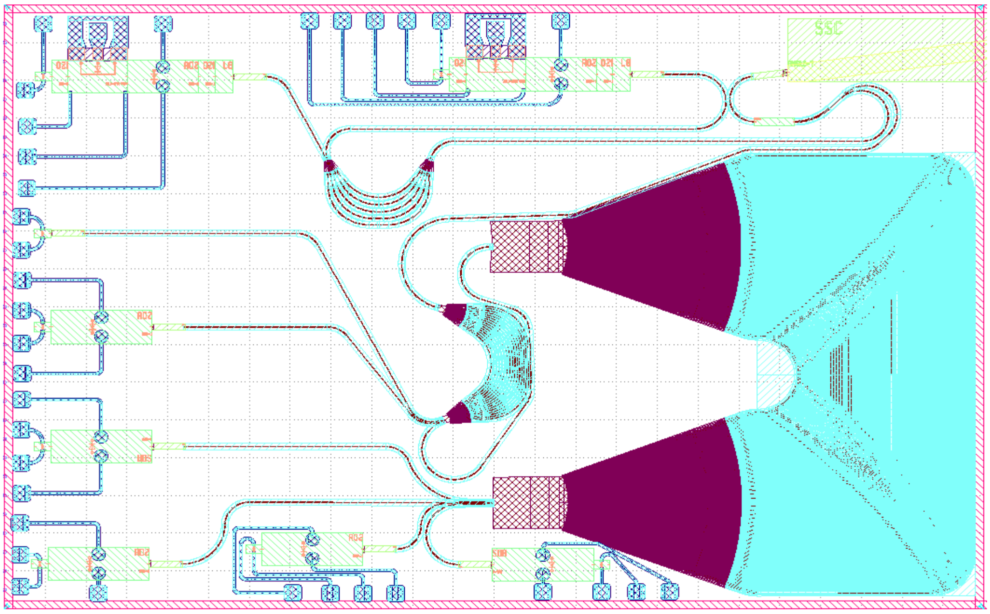

Figure 5.4: Mask layout of the ONU transceiver

Chapter 6

Conclusion and Future work

This is the last chapter of this dissertation and contains all the conclutions of the work done. This document terminates in section 6.2, where suggestions of future work to complement this dissertation are presented.

6.1 Conclusion

The future of telecommunications lays on the optical fiber, thats why in the last decade the investment on this area as being increasing exponentially. Optical networks are the only ones that can follow the demands for the future networks. In chapter two of this dissertation a overview of PON networks was made as a brief explanation of the standards used on this dissertation.

Ever-emerging requirements, such as the growing bandwidth demands and supporting mobile access traffic, increase spectral efficiency, reduce capital/operational expenditures (CAPEX/OPEX), and application versatility are adopted as enablers driving network marketability and potential convergence with wireless technology. Coexistence with legacy PON technologies is another vital point of discussion, as wavelength distribution faces the challenge of spectral availability in low-loss fiber bands growing exceedingly scarce. Such requirements are largely motivated by the commercial aspects. Namely, relevant challenges faced by companies in general are largely related to the need to create globally accessible products with a high degree of service diversification. Chapters 3 and 4 are a contribution for the area of TDWM networks as for the development of Multitech PON networks and a step towards developing such coexisting scenario.

The chapter 3 starts the design of the transceiver. In this chapter is presented all the work regarding the wavelength multiplexing and demultiplexing using AWG as the component of choice. This AWGs were simulated using Aspic and VPI and was possible to see their behavior and impact on the transceiver design.

Chapter 4 was devoted to a characterization and study of generic VPI components. In this chapter was shown a full simulation of the transceiver's design as well as all the steps taken in order to fulfill the requirements of the technologies used .

Another trend that needs to be followed in optical communications is the PICs. From the service providers perspective, the cost per client and application is very important. The fact that a single chip can comprise the functions of several discrete components is a major step towards reducing not only costs but also power and shelf space. This dissertation is a contribution towards this integration goal. In Chapter five was achieve one of the majors goals for this dissertation: the transceiver design mask layout.

The final result of this dissertation was a transceiver that functions as a ONU in Multitech PON Network. The PIC is ready to produce in a foundry.

6.2 Future work

As future work, the following topics are suggested to be explored:

- Continue to study the various existing optical components in order to obtain the best possible feature for the specific use.
- Rather then using VPI generic components as laser, SOAs, modulators and PINs, is recommended to test and simulate using the building blocks of a foundry, and that way obtain behavior models for that components.
- When designing the layout was not possible to use the same components as the ones used on the simulations. Moving forward, is advised to try to replace the MMI for a Circulator and use external modulation rather then direct modulation.
- A laboratory work is recommended to test how the chip's architecture works as a system.
- Production of the chip should be done, in order for it to be characterized. A design and implementation of its packaging can be addressed.

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.1 Appendix A

Bit Error Rate

In telecommunication transmission, the bit error rate (BER)is the percentage of bits that have errors relative to the total number of bits received in a transmission. For example, a transmission might have a BER of 10^6, meaning that, out of 1,000,000 bits transmitted, one bit was in error[31]. An incorrect identification of a bit by the decision circuit of the receiver may be caused by transmission channel noise, interference, distortion, attenuation bit or even synchronization problems.

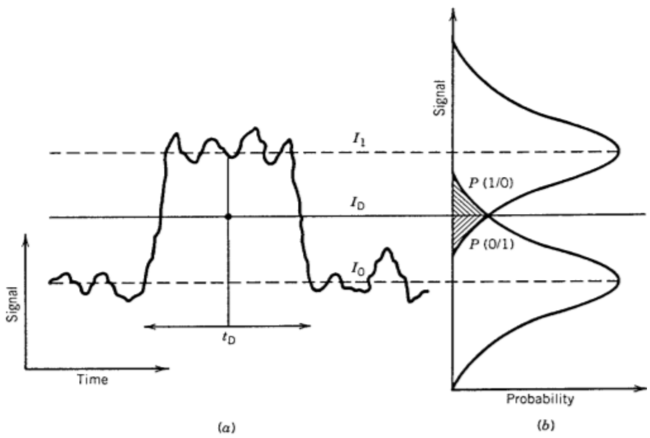

Figure 1: (a)Fluctuating signal generated at the receiver. (b)Gaussian probability densities of 1 and 0 bits. The dashed region shows the probability of incorrect identification.[32]

Considering a Gaussian noise distribution, like the one at figure 4.5, in 1 and 0 bits is possible do a BER estimation. The BER is obtained by[32]:

$$BER = \frac{1}{2} ercf(\frac{Q}{\sqrt{2}}) \tag{1}$$

where[32],

$$BER = \frac{I_1 - I_0}{\sigma_1 + \sigma_0} \tag{2}$$

where P_1 is the power of bits at level 1, P_0 the power of bits at level 0, σ_1 is the standard deviation of the power of bits 1 and σ_0 for the bits 0. BER is the prime factor when characterizing a receiver in terms of sensitivity. By definition, sensitivity is measured by the receive power needed to achieve a certain BER.