Universidade de Aveiro Departamento de Eletrónica, Telecomunicações e Informática
2018

Samuel de Jesus Marques

Plataforma de desenvolvimento de transceivers optoelectrónicos – implementação em XFP OLT NG-PON2

Optoelectronic transceivers development platform - XFP implementation OLT NG-PON2

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Dissertação apresentada à Universidade de Aveiro para cumprimento dos requisitos necessários à obtenção do grau de Mestre em Engenharia Eletrónica e Telecomunicações, realizada sob a orientação científica de Dr. Mário Lima, Professor do Departamento de Eletrónica, Telecomunicações e Informática da Universidade de Aveiro e Engenheiro Francisco Rodrigues, PICadvanced, SA.

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palavras-chave Redes Óticas Passivas, TWDM-PON, NG-PON2, OLT, Transceiver

resumo

No passado recente, houve uma clara evolução no desenvolvimento e implementação de fibra ótica até ao utilizador final. As redes FTTH foram desenvolvidas e normalizadas em todo o mundo, mas os requisitos de largura de banda por parte dos utilizadores e serviços exigidos por essa tecnologia foram evoluindo, de GPON para XG-PON e agora para NG-PON2.

Para os componentes óticos da próxima geração, é relevante criar soluções que permitam testar e calibrar estes componentes, no entanto isto apenas é possível se numa primeira fase for realizado um varrimento manual dos parâmetros, trabalho esse que será feito nesta dissertação.

Neste trabalho, são apresentados transceivers óticos e foram realizados vários testes visando a caracterização de transmissores e recetores, com o objetivo de serem posteriormente implementados num XFP da OLT para NG-PON2.

Com esta dissertação, foi possível concluir que tanto o transmissor como o recetor que foram testados apresentam uma resposta compatível com os comerciais, e relativamente às figuras de mérito abordadas vão de encontro às exigidas na norma ITU-T G.989.2, abrindo assim boas perspetivas para o desenvolvimento num futuro próximo de XFP da OLT *compliant* e de custos reduzidos por parte da PICadvanced, SA.

keywords Passive Optical Network, TWDM-PON, NG-PON2, OLT, Transceiver

Abstract

Over the recent past, there has been a clear evolution in the development and implementation of fiber optics to the end user. FTTH networks were developed and standardized across the world, but the bandwidth requirements by users and services demanded by this technology evolved, from GPON to XG-PON, and now to NG-PON2. For the next generation optical components, it is relevant to create solutions that allow the testing and calibration of these components, however this is only possible if a manual sweep of the parameters is carried out in a first phase, which will be done in this dissertation.

In this work, some optical transceivers are presented and several tests for characterizing transmitters and receivers were performed, intended to be implemented in a OLT XFP for NG-PON2.

With this dissertation, it was possible to conclude that both the transmitter and the receiver tested present results compliant to the commercial ones, and which regards the figures of merit addressed, they meet the requirements of ITU-T G.989.2 standards. This leaves good prospects for the development of an OLT XFP compliant and low cost by PICadvanced, SA.

Contents

List of Figures

List of Tables

Acronyms

APC	*Angled Physical Contact Connector*
APD	*Avalanche Photodiode*
BER	*Bit Error Rate*
BOSA	*Bidirectional Optical Sub-Assemblies*
CDR	*Clock Data Recovery*
CE	*Coexistence Element*
CML	*Chirp Managed Laser*
CO	*Central Office*
CW	*Continuous Wave*
DFB	*Distributed Feedback Laser*
DML	*Direct Modulated Laser*
EML	*External Modulated Laser*
EPON	*Ethernet Passive Optical Network*
ER	*Extinction Ratio*
FC	*Ferrule Connector*
FEC	*Forward Error Correction*
FSAN	*Full Service Access Network*
FTTH	*Fiber-to-the-Home*
GPON	*Gigabit Passive Optical Network*
HDTV	*High-Definition Television*
ITU-T	*International Telecommunications Union - Telecommunication*
LA	*Limiting Amplifier*
LASER	*Light Amplification by Stimulated Emission of Radiation*
MSA	*Multi-Source Agreement*
NG-PON2	*Next Generation Passive Optical Network 2*
NRZ	*Non-Return-to-Zero*
ODN	*Optical Distribution Network*
OFDM	*Orthogonal Frequency Division Multiplexing*
OLT	*Optical Line Terminal*

ONT	*Optical Network Terminal*
ONU	*Optical Network Unit*
OSA	*Optical Spectrum Analyzer*
OSR	*Optical Spectrum Reshaper*
PIN	*Positive-Intrinsic-Negative*
PON	*Passive Optical Network*
PtP	*Point-to-Point*
P2MP	*Point-to-Multipoint*
ROP	*Required Optical Power*
ROSA	*Receiver Optical Sub-Assemblies*
SC	*Subscriber Connector*
SFF	*Small Form Factor*
SFP	*Small Form-factor Pluggable*
SFP+	*Small Form-factor Pluggable plus*
SMA	*SubMiniature version A*
SNR	*Signal-to-Noise-Ratio*
TDMA	*Time Domain Multiple Access*
TEC	*Thermoelectric Cooling*
TIA	*Transimpedance Amplifier*
TOSA	*Transmitter Optical Sub-Assemblies*
TWDM	*Time and Wavelength Division Multiplexing*
UDWDM	*Ultra Dense Wavelength Division Multiplexing*
UPC	*Ultra Physical Contact Connector*
VOA	*Variable Optical Attenuator*
WDM	*Wavelength Division Multiplexing*
WM	*Wavelength Multiplexer*
XFP	*10 Gigabit Small Form Factor Pluggable*
XGPON	*10 Gigabit Passive Optical Network*

Chapter 1

Introduction

This chapter introduces the major targets of this work. Section 1.1 presents the context of the current technology and the motivation for this dissertation. In Section 1.2 the main objectives of this work are indicated. Next, Section 1.3 presents the structure of the document and at the end, Section 1.4 lists the major contributions from this dissertation.

1.1 Context and Motivation

With the recent required increase in data transmission rates, the transport of information through coaxial cables became unviable since these present large attenuation and low bandwidth. Thus, the optical fiber has gained a prominent role, since, it was able to overcome the disadvantages previously mentioned for coaxial cable, allowing connections at greater distances and with higher data rates. These are indispensable parameters for FTTH (Fiber-to-the-Home) architectures based on PONs (Passive Optical Networks). Although the existing optical networks can meet current needs, they will have to be designed to keep up with the continuous evolution of technologies, and for that it is necessary to create other solutions that are essentially aimed for increasing data rates, reducing investment and operating costs.

Nowadays, GPON (Gigabit PON) is the most widely deployed technology for FTTx (home, business, etc.) in western countries, and can present data rates of 2.5 Gbit/s for downstream and 1.25 Gbit/s for upstream directions.

The increase of bandwidth has been a constant over the years, due to IoT (Internet of Things), clouds and other services, and with this the ITU-T (International Telecommunication Union - Telecommunication Standardization Sector), that was responsible for the standardization of GPON, realized that data rates would soon be insufficient to meet demands, and started working on a new PON standard called XG-PON (10 Gigabit PON) that can achieve 10 Gbit/s downstream and 2.5 Gbit/s in upstream, and being able to coexist with GPON.

For the same reasons above, FSAN (Full Service Access Network) group planned NG-PON2 (Next Generation Passive Optical Network) deployment, also coexisting with the previously referred technologies, and with the capacity of achieving 40 Gbit/s and 10 Gbit/s, respectively in upstream and downstream directions, or symmetrical 40 Gbit/s in both directions, according to ITU-T norm G.989.2 standards. Figure 1.1 illustrates the described evolution in PON standards.

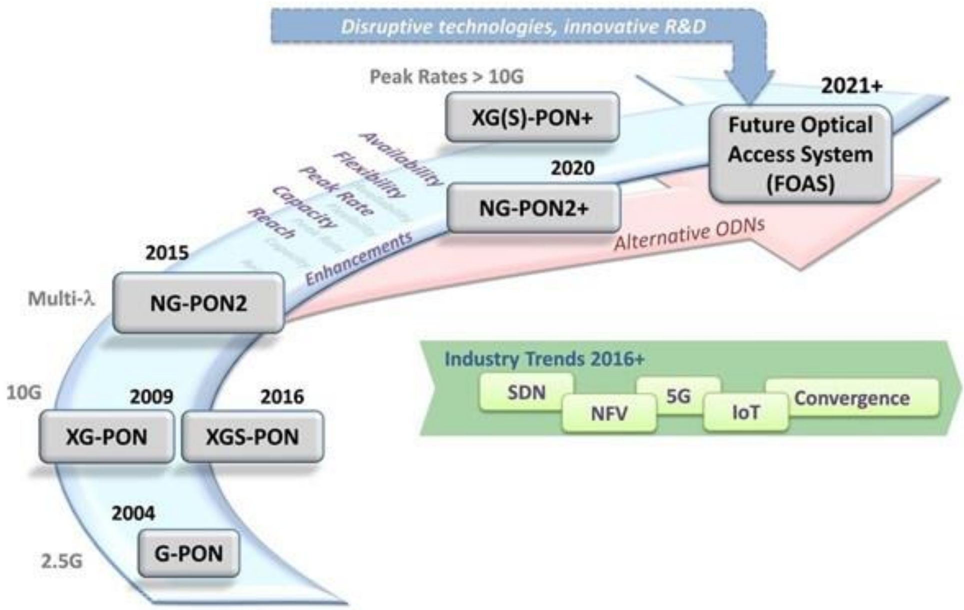

Figure 1.1: PON roadmap by FSAN. Adapted image from the reference. [1]

This dissertation focuses then on the study and characterization of a XFP (10 Gigabit Small Form Factor Pluggable) transceiver, intended to be implemented at the OLT (Optical Line Terminal) in a future generation PON.

1.2 Objectives

The main objective of this dissertation is the study and characterization of a XFP transceiver for OLT to NG-PON2. For this, the first hardware prototype developed by PICadvanced, SA of a OLT XFP for NG-PON2 will be tested in order to conclude about its feasibility. Other objectives for this works are:

- Manual sweep of relevant parameters essential for a future automatic calibration of OLT XFP for NG-PON2.
- Characterization of OLT XFP transmitters for NG-PON2.
- Characterization of OLT XFP burst mode receivers for NG-PON2.

1.3 Structure

This dissertation, excluding the present chapter, is divided in 4 chapters as follows:

- **Chapter 2 - Transceivers for next generation passive optical networks** introduces passive optical networks and some relevant previous deployed technologies. This chapter addresses TWDM-PON architecture, associated to NG-PON2, also some relevant figures of merit, and the main optical components that will be considered in this dissertation, some of them used in the optical transceivers. Finally, we will present the OLT XFP for NG-PON2 developed so far at PICadvanced, S.A and the improvements aimed in the scope of this work.
- **Chapter 3 - Characterization of OLT XFP transmitters for NG-PON2** presents the study of two OLT TOSAs and one commercial OLT XFP, addressing the major differences between them, so it can be concluded if the most relevant requirements from ITU-T G.989.2 are met, eye diagram opening penalty, extinction ratio, BER measurements are the principal focus.
- **Chapter 4 – Characterization of OLT XFP receiver for NG-PON2 in burst mode** presents in a first step important figures of merit regarding the ONU transmission (upstream) in burst mode, so it is possible to introduce the OLT receiver part. After, the study of two OLT ROSAs, one commercial and the other a sample test for a burst mode

receiver, and compare the general performance of them. Finally, is shown a comparison between the ROSAs and some conclusions taken.

- Chapter 5 – Conclusions and future work presents a description of what was achieved, as well as the main conclusions taken from this work. Suggestions for more work in this topic are also presented.

1.4 Contributions

The main contributions of this work are:

- Prove the feasibility of the first OLT XFP prototype from PICadvanced, SA.
- A manual sweep of parameters fundamental to a future automatic calibration of OLT XFP for NG-PON2.

Chapter 2

Transceivers for next generation passive optical networks

In this chapter, a generic architecture of a passive optical network will be presented, as well, some relevant previous technologies before NG-PON2. Also, the TWDM architecture and figures of merit will be addressed, with emphasis on the OLT side. Finally, we will present an overview on the main optical components and transceivers that are used nowadays in the access network technologies.

2.1 PON architecture

A PON is a network with a P2MP (Point-to-Multipoint) architecture and is composed essentially by three fundamental blocks: OLT (Optical Line Terminal), ODN (Optical Distribution Network) and ONU (Optical Network Unit).

An OLT broadcasts the information for all the ONUs and is responsible for controlling and synchronizing the data associated to the communications in the network.

An ODN consists of fiber and a splitter, placed between an OLT and each of the optical fibers that connects to the ONUs, and has the major function of grouping or splitting the optical signals coming/going from/to the ONUs. In upstream direction, the optical splitter works as a coupler gathering all the information coming from the ONUs. In opposite direction, in downstream, it is responsible for splitting the signal that is coming from the OLT and forwarding for each of one the ONUs. Figure 2.1 present a generic PON architecture. [2]

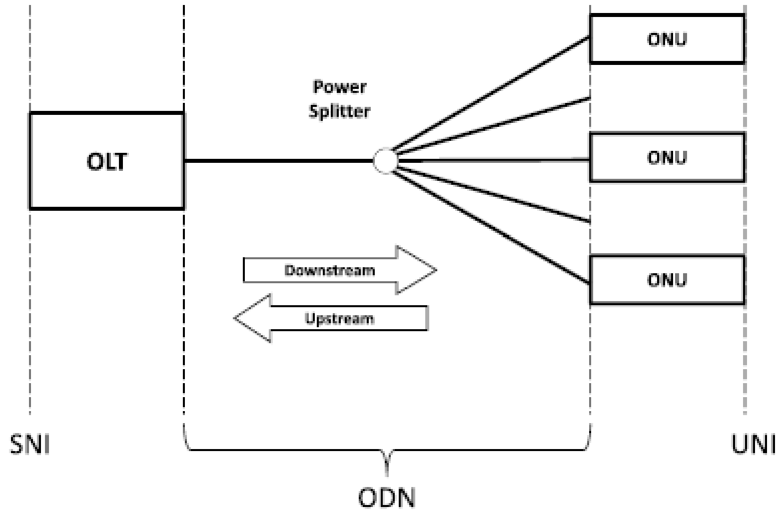

Figure 2.1: Generic PON Architecture. [2]

2.1.1 Previously deployed technologies

In this section, several technologies prior to NG-PON2 are presented, namely EPON, GPON and 10GPON, indicating their main characteristics.

2.1.1.1 Ethernet PON

In 2000, EPON technology was created by IEEE (Institute of Electrical and Electronics Engineers), with the purpose of broadening Ethernet access areas and, allowing the transport of information in packets of different lengths, lead to a more efficient technology compared to the developed until then. [3]
The EPON architecture is based on the remaining PONs, more concretely one single-mode fiber and optical splitters in order to distribute the information traffic. It is characterized by a transmission rate of 1.25 Gbit/s in upstream and downstream directions, a splitting capacity of 1:16, a reach of 10 km, and by the use of WDM (Wavelength Division Multiplexing) to multiplex the several optical carriers in a single fiber, using a wavelength plan of 1260 to 1360 nm for upstream and 1480 to 1500 nm for downstream.

2.1.1.2 Gigabit PON

The GPON technology was created in 2001 by FSAN (Full Service Access Network) with the purpose of increasing the transmission rate in the access networks.
Regarding the transmission, this topology can have symmetric and asymmetric rates, 2.5 Gbit/s for upstream and downstream directions or 1.25 Gbit/s for upstream and 2.5 Gbit/s for downstream respectively. The wavelength plan for this technology is 1480 to 1500 nm for downstream and 1290 to 1330 nm for the upstream direction. [3]

2.1.1.3 10 Gigabit PON

In 2010, the XG-PON was also created by FSAN, in order to respond to the continuous demand for bandwidth allocation and data rates by users. This technology has an extremely important feature, especially for operators, that is the capacity of coexistence with the previous technologies, allowing to provide customers different services, without major changes in ODN. It also has the possibility to, as in GPON, present symmetric and asymmetric rates, 2.5 Gbit/s for upstream direction and 10 Gbit/s for downstream, or 10 Gbit/s for both directions (XGS-PON). Its splitting capacity is between 1:32 and 1:256, and distance ranging between 20 and 60 km, depending on the transmission rates and the number of users. Regarding the wavelength plan, it is between 1260 to 1280 nm for upstream and 1575 to 1581 nm for downstream. [3]

2.1.2 Next Generation Passive Optical Network

In recent years the development and implementation of fiber-based technologies has increased exponentially, more specifically in the provisioning of FTTH (Fiber-to-the-Home) services at end customer. This growth is inherent to the increasing offer of services that consume large bandwidths such as HDTV (High-Definition Television) and 3D television, online games among others, leading to the search for new alternatives to those previously deployed.

This new standard is characterized by 40 Gbit/s aggregate capacity for downstream and 10 Gbit/s for upstream, exploring both the time and wavelength domains, TWDM architecture. Each channel allows 10 Gbit/s for the downstream direction and 2.5 Gbit/s for the upstream typically, for the case of 4 channels, but also achieving 80 Gbit/s for downstream and 40 Gbit/s upstream in the case of 8 channels. [4]

Comparing to GPON technology nowadays deployed, NG-PON2 faces a difficult challenge, inherent to the lower bandwidth available per channel, which is a narrow band (1532 -1540 nm), making channel tuning much tighter and harder to do. Figure 2.2 presents the spectrum of different PON wavelength plan.

Regarding the wavelength plan for the upstream, it was chosen the C band, 1525 to 1544 nm, corresponding to a range where the attenuation is the lowest, and for the downstream the band used is L band, from 1596 to 1625 nm, also with low attenuation.

Another relevant characteristic related to NG-PON2 is the spectral flexibility, which means that when some optical spectrum is not being used by TWDM, may be used by systems PtP WDM (Point-to-Point Wavelength Division Multiplexing), favoring the support of different clients in the same ODN. This system was also developed to achieve increments in its capacity, known as “pay-as-you-grow”, allowing channels with a different wavelength to be added over time and thus enabling new services in the system. Therefore, it has the necessity to use new components in transmitters and add tunable receivers to each ONU, allowing a selection of channels for transmission and reception. [5]

Nevertheless, one of the major obstacles for a smooth migration to NG-PON2 is that the ODN represents about 70% of the investment of operators in a PON, thus, one of the main requirements for this new technology is the coexistence with the previously deployed technologies, being able to reuse equipment previously installed.

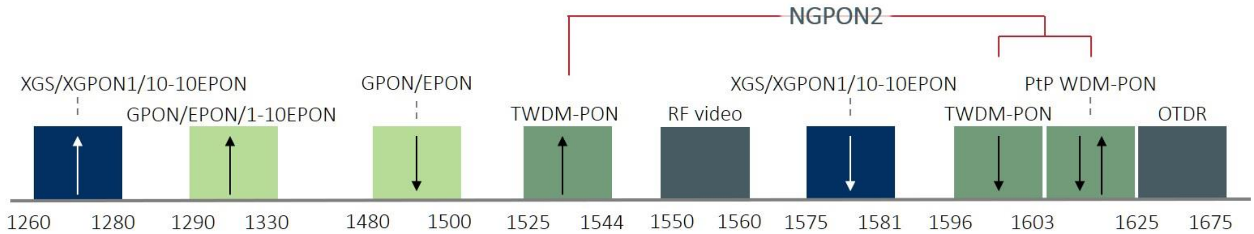

Figure 2.2: Spectrum of different PON wavelength plan. [6]

In accordance to the imposed requirements by ITU-T, several options were considered for the architecture to be implemented in NG-PON2, such as WDM-PON (Wavelength Division Multiplexing), UDWDM-PON (Ultra-Dense Wavelength Division Multiplexing), OFDM (Orthogonal Frequency Division Multiplexing) and the already referred TWDM.

The one that was considered the best solution by FSAN was the TWDM-PON, since from the operator's point of view it is considered the one with lower risk, less disruptive and cheaper, helping in a very effective way to the standardization of NG-PON2. This technology is characterized by having an aggregate capacity of 40 Gbit/s as previous referred, for this, four wavelengths were stacked, with 10 Gbit/s each. It allows a distance up to 40 km, a splitting capacity of 1:64 ONUs and the ability of reusing the previously installed ODNs.

In such a system, multiple wavelengths coexist in the same ODN using wavelength division multiplexing, and each wavelength serves multiple ONUs with time division multiple access, as shown in figure 2.3.

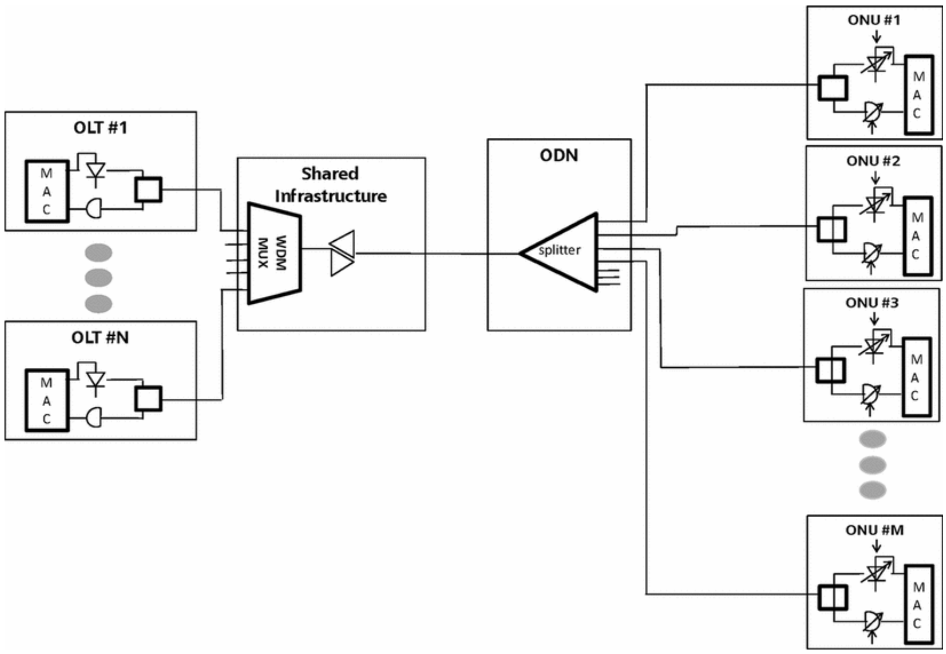

Figure 2.3: TWDM architecture. [7]

An ONU in TWDM PON is equipped with a tunable transceiver, so it can selectively transmit/receive in upstream/downstream respectively. This system can coexist with

GPON/EPON and XG-PONs, thus the evolution of optical access toward TWDM PON is very smooth with little service interruption. [5]

As already referred, a big concern with deployment of this technology lies on the fact of enabling coexistence with the previous implemented technologies in the same ODN, and these are divided in classes depending on the losses in the optical path as shown in Table 2.1.

	Class N1	Class N2	Class E1	Class E2
Minimum optical path loss (dB)	14	16	18	20
Maximum optical path loss (dB)	29	31	33	35
Maximum differential optical path loss (dB)	15			

Table 2.1: Different ODN classes. [4]

2.2 Optical components

In this section the main components existent in optical networks will be presented. First, the lasers, with particular focus on the directly modulated ones. After that, are presented the types of optical receivers and a comparison between them. Finally, the study of major impairments for transmission through optical fiber and a brief discussion on some characteristics of fiber connectors types most used.

2.2.1 Transmitters

With the increase of data rates transmitted daily and supported by the advance of electric and optic technologies, the use of light, through optical fiber, for the transport of information became very advantageous, not only on transmission rates but also achieving larger distances. One important functionality of optical systems relies on the modulation operation, which allows to send digital information through an optical carrier.

2.2.1.1 Externally Modulated Lasers

In EML (Externally Modulated Laser), a continuous wave CW (Continuous Wave) laser is used to emit light and the power is constant over time. A second component, known as modulator, is then used as a switch to let the light pass whenever the data corresponds to a logic level '1' and to block it whenever the signal is a logic level '0'.

Note that here, the key point is that the physical process that allows the switch to toggle between its two states 'open' and 'closed', should be fast enough to allow proper operation at the desired bit rate. The principle of these two types of laser modulation is presented in figure 2.4. [8]

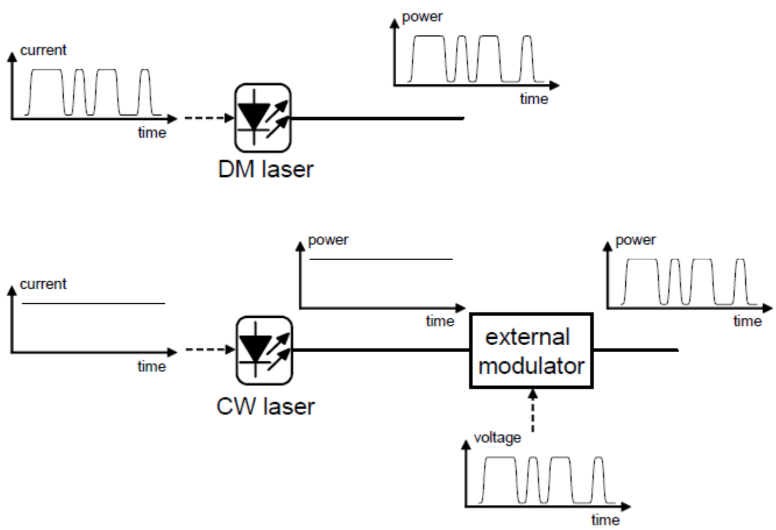

Figure 2.4: Directly and External modulation principle. [8]

2.2.1.2 Directly Modulated Lasers

In DML (Directly Modulated Laser), the information is directly modulated through a control current, making the laser turn 'on' and 'off', according to the logic level that is supposed to be sent, therefore a simple and cheaper method, but for shorter distances.

The output power in this case, is dependent on the current that is injected on the laser according to its transfer function. Increasing the bias current, the laser goes from spontaneous to stimulated emission, when the referred current is higher than a defined threshold that is different for each laser.

Thus, the output power of a laser increases with the bias current until a saturation point, leading to a lower ER, however, as the bias current is further away from the threshold current, there is less distortion once induced chirp is lower, also the intensity noise presents lower values, thus improving the SNR (Signal-to-Noise-Ratio) relation and thereafter the quality of signal.[8]

For that, this value must be carefully chosen according to the final purpose, as shown in figure 2.5.

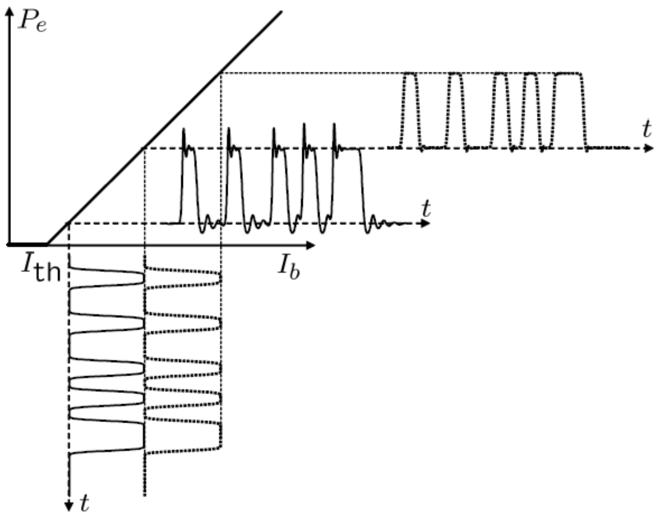

Figure 2.5: Direct modulation concept of a semiconductor laser. [8]

In table 2.2, are briefly presented some of the most relevant figures of merit in a non-quantitative but qualitative comparison between the DML and EML.

	DML	EML
Price	$	$$$
Chirp	higher	lower
ER	lower	higher
Output power	higher	lower

Table 2.2: Most relevant parameters comparison for DML vs EML. [9]

2.2.1.3 Chirp Managed Laser

In DML the bias current increase further than the threshold current leads to an approximately linear increase on the output power, and the direct consequences from that are the lower ER, and less distortion, once induced chirp is also lower. There are two types of chirp, the transient chirp, which occurs in the bit transition and increases the scattering of the pulse in the fiber and the adiabatic chirp, which causes the logic level bits '1' to be offset from the logic level bits '0'. In the case of direct modulation, where the LASER is polarized near the threshold current the dominant chirp is the transient. [10]

CML (Chirp Managed Laser), allows lasers directly modulated to be used for high transmission rates and at high distances. This laser is composed by a DML, followed by an OSR (Optical Spectrum Reshaper), and is biased quite above the threshold value, in this way the transient chirp is reduced but leading to a lower ER. The small ER problem is solved by the OSR, that will attenuate the bits from the logic level '0', thus allowing obtain a higher ER and a better eye diagram.

This CML solution, is very useful since it is less complex than the external modulated technologies. Figure 2.6 illustrates the CML principle. [11]

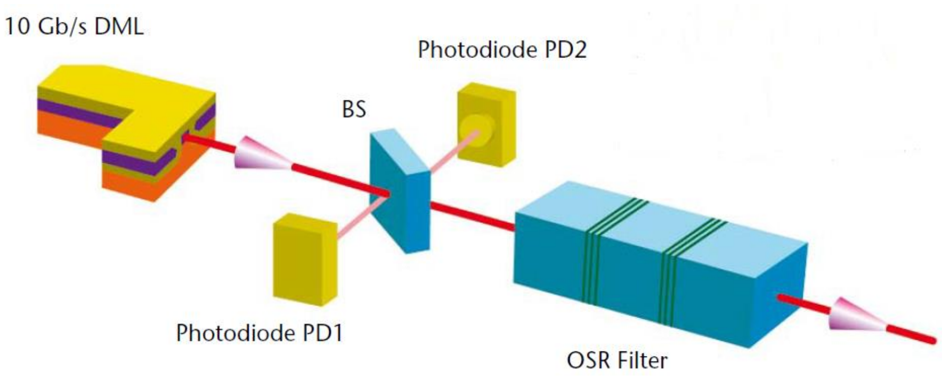

Figure 2.6: Chirp Managed Laser principle. Adapted image from the reference. [11]

2.2.2 Receivers

The optical receivers are devices used for the detection of light and are the responsible for transforming an optical signal into an electrical one. The basic requirements for choosing an optical receiver are the wavelength, bandwidth, noise, sensitivity and price. Thus, in the next sections are presented two optical receivers, PIN and APD photodetectors.

2.2.2.1 PIN photodetector

A PIN photodetector is based on a pn junction with an intrinsic material placed between the two types of semiconductor. In these diodes the intrinsic region is bombed with p and n load carriers, that are inversely polarized opening the gap. Thus, light strikes and given the characteristics of the intrinsic material a gap becomes an electron (or more) creating current, although sometimes occurs spontaneous conversions that in practice are the thermal noise of the receptor. The sensitivity is limited by the doping of the semiconductor, lead to an impossibility of convert more electrons than the ones that are doped there.
These photodetectors are widely used and cheap, however, intrinsically they are not able to reach low values of sensitivity which is a block for applications such as access networks.

2.2.2.2 Avalanche photodetector

Although Avalanche photodetectors (APD) are more complex and expensive than the previous ones, they present some advantages, such as, associated gain, therefore they can detect a weaker signal, although they need a higher reverse voltage.
The avalanche process happens due to the strong electrical field that causes the electrons to gain sufficient energy, thus causing an avalanche effect. This will be the receiver that better suits for NG-PON2 purposes, once longer distances are required and the received signals are very weak, justifying in this way the increase on cost for a better performance.

2.2.3 Optical Fibers

Optical fiber is used on information transport for longer distances, since, unlike of electrical cables its losses are approximately 0.2 dB/km, for the operating wavelength range in which this dissertation focus, wavelengths near 1550 nm, allowing the information to travel longer distances without any signal amplification.

There are two principal types of optical fibers, the mono-mode and the multi-mode, differing in the number of modes that are propagated in each fiber, one in the first case and multiple for the other one. Regarding the propagation distance, the mono-mode is used for longer distances and bit rates, while multi-mode fiber is used for lower distances and bit rates. In the scope of this work, it will be used mono-mode fiber due to the bit rate and distance considered.

2.2.3.1 Attenuation

Attenuation is a factor inherent of optical fiber and represents the reduction of optical power with propagating distance. Power loss depends on the distance as shown in expression 2.1 and depends on the type of fiber and wavelength that are used, since the attenuation coefficient associated will be different. The power variation through a fiber can be expressed as follows:

$$P(L) = P_0 . 10^{-\alpha L/10} \tag{2.1}$$

where P_0 is the input power, α is the attenuation coefficient (dB/km), and L represents the travelled distance in the fiber (km). [12]

2.2.3.2 Chromatic Dispersion

Chromatic dispersion is associated to differences in group velocity for different frequencies, leading to pulse spreading as light travels through the fiber, and thus to inter-symbol interference.

For the wavelength range that will be used in this work, 1550 nm, the chromatic dispersion parameter is about 17 ps/(nm.km). This parameter causes a transmission limit that can be estimated using expression (2.2), considering external modulation and OOK-NRZ (On-Off Keying Non- Return-to-Zero):

$$L < \frac{c}{2B^2\lambda_0^2|D|} \qquad (2.2)$$

where c is the light velocity in vacuum, B the bit rate, λ_0 the wavelength of the pulse and D the chromatic dispersion parameter.

In NG-PON2, the bit rate per channel is 10 Gbit/s, the wavelength is near 1550 nm and chromatic dispersion as previously referred about 17 ps/km.nm. With these values and using the expression 2.2 above, the limit imposed by dispersion will be around 36.7 km. [13]

2.2.4 Fiber connectors

Optical fibers connectors have a dedicated structure for holding the fiber in correct place, called ferrule, which can be made in different materials like metal, plastic or ceramic.

There are several types of connectors, with different characteristics and applications with correspondent advantages and disadvantages, but in this dissertation only the most used connectors used at PICadvanced, S.A are taken into account, the SC and FC connectors, with two sub-categories: UPC (Ultra Physical Contact), also called PC, and APC (Angled Physical Contact). The major difference between these two types of fiber connectors is that the APC presents less reflections than the PC fiber connectors, reflections that can interfere with the signal itself and are very important to mitigate, since the wavelength plan is near de RF video 1550 nm (PICadvanced, S.A ONU XFP uses APC optical fiber connectors and not UPC as most vendors do).

2.2.4.1 Subscriber

The Subscriber Connector (SC) is a fiber optic connector with a push-pull latching mechanism that provides quick insertion and removal while ensuring a good connection. The subscriber connectors are inexpensive, trouble-free, and robust, so they are very appealing for enterprises purposes. [14]

2.2.4.2 Ferrule

The FC connectors is a fiber optic connector designated for high-dense and very unstable environments, as screw type coupling makes it very hard to have problems in the connection. They are mainly deployed in single mode optical fibers in Datacom and Telecom applications. [14]

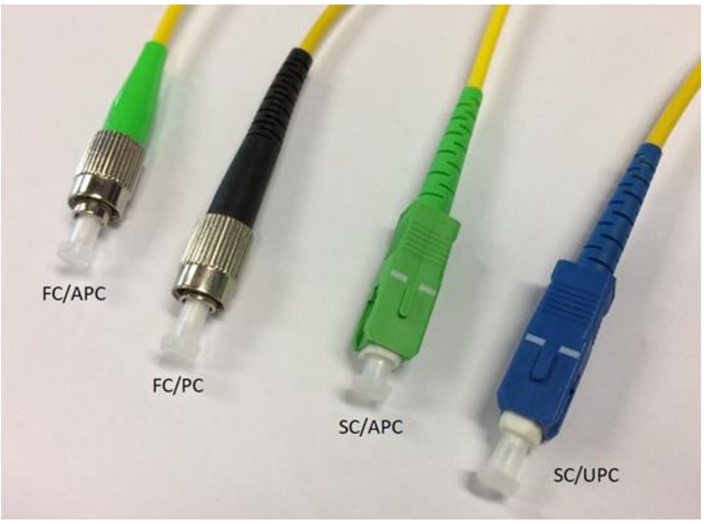

Figure 2.7: Fiber connectors used at PICadvanced, SA.

2.3 Optical transceivers

A transceiver is a device characterized by having a transmitter and a receiver in the same encapsulation, due to the presence of a BOSA (Bidirectional Optical Sub-Assemblies) composed by one laser on the transmitter and one photodetector on the receiver or in duplex transceivers one TOSA and one ROSA separately, thus enabling devices made in this compact way be simpler to standard, actualize and maintain.

These transceivers may be divided according to its encapsulation. Nowadays the most used are SFP (Small Form Factor Pluggable), SFP+ and XFP (10 Gigabit Small Form Factor

Pluggable). They are used for communications at high bit rate and are a flexible equipment with the ability and capacity to support several data rates and protocols.

One of the most important parameters to take into account is the desired propagation distance. For communications until 400 m and with the purpose of establishing Ethernet connections, Short-Reach are used. For communications between buildings with mono-mode fibers and 10 km distance, Long-Reach transceivers are used, and for communication between localities or cities, with distance until 40 km, Extended-Reach transceivers are used. Finally, also designated Extended-Reach (ZR acronym), very similar to the last transceiver but with the capacity to reach 80 km. The main enterprises that massively sold this type of devices are Hisense Broadband (previous Ligent photonics), Finisar and Lumentum.

After this brief characterization of some types of transceivers available in the market, it is possible to verify that the ones that better fit NG-PON2 technology are the Extended-Reach transceivers.

2.3.1 SFP

The SFP transceivers are used for communications among devices, respectively, switches, routers and optical fiber cables and are responsible for the conversion of electrical signals in optical and vice-versa. These devices support transmission rates up to 5 Gbit/s, are very compact, easy to handle and cheap. [15]

Figure 2.8: Commercial Hisense SFP. [16]

2.3.2 XFP

XFP modules were the first to support connections of 10 Gigabit Ethernet, once the SFP limit is 5 Gbit/s. This device is physically compact, easy to handle and allows switching modules easily. The main features of this module are: to support data rates between 9.95 Gbit/s and 10.5 Gbit/s, assuring communication up to 40 km, in mono-mode connections, with easy switches and updates. Its common operation wavelengths are 850, 1310, 1550, 1577 nm, and contrarily to SFP and SFP+, its dimensions are higher, and the optical power varies diverging form the objective of standardization. [17]

For these reasons above this transceiver is the best candidate for OLT in NG-PON2, once it can achieve the goal parameters in ITU-T G.989.2 standards, it is more robust for the control of all switches of data in a passive optical network. For this, the cost may be higher since this device is localized at CO (Central Office), and the target for power dissipation that enterprises try to achieve normally according to the MSA standard is to stay lower than 3.5 W. [18]

Figure 2.9: Commercial PICadvanced, SA ONU XFP.

2.3.3 SFP+

Although XFP already achieves high bit rates, 10 Gbit/s typically, the SFP+ modules can achieve this kind of data rate also, but this one with the same dimensions of the old module, allowing reuse of the previous slots. Nevertheless, internally this module requires more circuits and has a bigger footprint than the last one. [19]

2.4 Implementation of OLT XFP for NG-PON2

Currently the line of products present at PICadvanced, S.A, count with XFP for ONU in phase of small series production and XFP for OLT in final stage of development. With the experience acquired in the already developed products, it is important to create a layer of abstraction in the development, allowing the creation of a generic platform for XFP in access networks.

With this thesis the major goal is to fully characterize a XFP for OLT and conclude in which parameters it is compliant with ITU-T G.989.2, NG-PON2 standards. It is important to develop a generic approach to be simpler to standard and test this OLT XFP, so it can be soon available together with the ONUs at PICadvanced, S.A, allowing the company to deliver the “entire network”.

2.4.1 Figures of merit in NG-PON2

This section will approach some figures of merit defined by ITU-T G.989.2 standard regarding NG-PON2. The following tables 2.3 and 2.4 present the most relevant parameters for the transmission in downstream, for the two data rates 2.5 Gbit/s and 10 Gbit/s, respectively. [4]

	Value		Unit	
Nominal line rate	2.48832		Gbit/s	
Operating wavelength band	1596-1603		nm	
Line code	NRZ			
Operating channel spacing	100		GHz	
Minimum extinction ratio	8.2		dB	
ODN class	N1	N2	E1	E2
Mean channel launch power minimum (dBm)	0	2	4	6
Mean channel launch power maximum (dBm)	4	6	8	10

Table 2.3: Optical interface parameters of 2.5 Gbit/s downstream direction. [4]

	Value		Unit	
Nominal line rate	9.95328		Gbit/s	
Operating wavelength band	1596-1603		nm	
Line code	NRZ			
Operating channel spacing	100		GHz	
Minimum extinction ratio	8.2		dB	
ODN class	N1	N2	E1	E2
Mean channel launch power minimum (dBm)	3	5	7	9
Mean channel launch power maximum (dBm)	7	9	11	11

Table 2.4: Optical interface parameters of 10 Gbit/s downstream direction. [4]

Regarding the operating channel spacing it may be in a range of 50 GHz to 200 GHz, although the 100 GHz is the most common in current optical systems, since 50 GHz rises crosstalk problems between neighbor wavelengths and the 200 GHz solution would create, in the 4 channel case a 800 GHz grid which can be an obstacle for the ONU tunable technology.

Next, two tables 2.5 and 2.6 are presented like the previous ones for downstream, but now with the most relevant parameters for the upstream, with 2.5 Gbit/s and 10 Gbit/s data rates respectively.

	Value		Unit	
Nominal line rate	2.48832		Gbit/s	
Bit error reference level	10^{-4}			
ODN class	N1	N2	E1	E2
Sensitivity type A (dBm)	-26	-28	-30.5	-32.5
Sensitivity type B (dBm)	-30	-32	-34.5	-36.5
Maximum OPP excluding Raman (DD20)	0.5		dB	

Table 2.5: Optical interface parameters of 2.5 Gbit/s upstream direction. [4]

	Value		Unit	
Nominal line rate	9.95328		Gbit/s	
Bit error reference level	10^{-3}			
ODN class	N1	N2	E1	E2
Sensitivity type A (dBm)	-26	-28	-30.5	NA
Sensitivity type B (dBm)	-28	-30	-32.5	-32.5
Maximum OPP excluding Raman (DD20)	0.5		dB	

Table 2.6: Optical interface parameters of 10 Gbit/s upstream direction. [4]

The sensitivity types, A and B, referred in the previous two tables 2.5 and 2.6 are related to the required optical power on the receiver and the minimum launch power on the transmitter, thus type A and B refers to the cases that lead to more effort on the ONU and OLT side, respectively.

NG-PON2 allows, as mentioned, four channels of operation, with the standard allowing eight channels as well. For this, the transceiver must be able to change the laser parameters allowing the wavelength to shift and change to another channel. Table 2.7 shows the four wavelength channels in NG-PON2 upstream and downstream directions.

Channel	Upstream Wavelength (nm)	Downstream Wavelength (nm)
1	1532.68	1596.34
2	1533.47	1597.19
3	1534.25	1598.04
4	1535.04	1598.89

Table 2.7: NG-PON2 upstream and downstream wavelengths. [4]

For the tuning of wavelengths in transceivers, typically the device that is used is a TEC (Thermoelectric Cooler), which is based on the Peltier effect, applying a voltage on a junction of electrical conductors. By the flow of current between junctions, heat is transferred from one to another. TECs are capable of transferring heat to a conductor, to set and maintain a desired temperature, although for this to happen, it will be required a certain time, which may exclude this device from certain applications which are time sensitive.

In the OLT case, the receiver does not need to be tunable since the filtering is done in the WM present in the central office on the upstream direction after the Coexistence element (CE).

A figure of merit that can evaluate the quality of transmission and is requested by the ITU-T is the ER (Extinction Ratio), and is calculated by the expression:

$$\mathrm{ER\ (dB)} = 10\log\left(\frac{\mathrm{P_1}}{\mathrm{P_0}}\right) \tag{2.3}$$

This expression represents the ratio between P_1 that is the power of logic level ‘1’and P_0 that is the power of logic level ‘0’. For the downstream direction, which means from OLT to ONU communication, the minimum ER is 8.2 dB. [4]

Another very relevant figure of merit is the BER (Bit Error Rate), given by:

$$BER = \frac{Bits\ with\ errors}{Total\ number\ of\ bits} \tag{2.4}$$

Another figure of merit is the sensitivity, that is the power required for the defined BER level (for NG-PON2 at 10 Gbps application that reference is 10^{-3}). The sensitivity levels are, -28 dBm for downstream and -26 dBm for upstream. An additional requirement is that the OPP (Optical Path Penalty), the difference between sensitivity with or without fiber at BER 10^{-3}, must be lower than 2 dB for downstream and 0.5 dB for upstream. [4]

The BER measurements can also evaluate the efficiency of FEC (Forward Error Correction). FEC is a process in which a transmitter of digital data adds extra information known as check bits to the data stream, and the receiver analyzes the check bit information to locate and correct errors. The check information is then removed from the data stream and the remaining data is converted to its original voice, data, or video form. Hence, in an FEC system, the receiver detects and corrects errors in real time as the data is being received. FEC is an important advantage in digital communication technologies. The exact methods used for detection and correction depend on the type of information being transmitted and the form in which it was transmitted.

The main advantages of FEC use are: it reduces the number of transmission errors, extends the operating range, and decreases the power requirements for communications systems. FEC also increases the effective systems throughput, even with the extra check bits added to the data, by eliminating the need to retransmit corrupted data.

BER value for OLT XFP is 10^{-3}, for 10 Gbit/s data rates, as present in ITU-T standards G.989.2. The pre-FEC BER of 10^{-3} corresponds to 10^{-12} in post-FEC, this is, after FEC only one in 10^{12} bits transmitted is an error, leading to a very robust digital communication system but decreasing the available bandwidth, since not all transmitted bits were data bits.

Chapter 3

Characterization of OLT XFP transmitters for NG-PON2

In this chapter, two OLT TOSAs and a commercial OLT XFP transmitter will be characterized, all provided by PICadvanced, S.A. The first OLT TOSA is used in the first hardware prototype of the company, for OLT XFP, used for NG-PON2 purposes, the other one was welded and tested in a board internally developed.

These OLT TOSAs present a main difference from the commercials ones, that are used as OLT transmitters currently, and it is the fact of using a DML with an optical filter, operating in a similar way to the already described in the previous chapter section 2.2.1.3 for the CML, instead of using a EML like the majority of vendors.

3.1 Characterization of the first OLT XFP hardware prototype for NG-PON2

This OLT transmitter is composed essentially by a DML plus optical filter, and a monitoring LD that with the help of a thermistor can read and control the temperature of laser through a microcontroller. This one communicates to a TEC driver in order to increase or decrease the temperature of the TEC and consequently shift the laser to a desired wavelength. Next, it will be presented in figure 3.1 a schematic with this OLT transmitter and the several components that compose it.

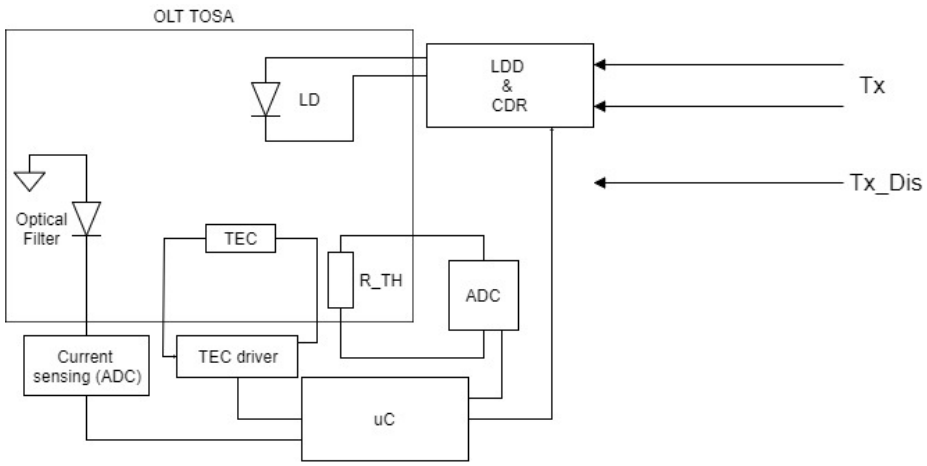

Figure 3.1: OLT XFP transmitter schematic.

CDR (Clock Data Recovery) is responsible, in a first stage, and with the help of a PLL (Phase-Locked Loop), to detect and trigger the transmission data rate. XFP is connected to a host board and this implies some losses in the electrical paths that will degrade the signal due to the distance between them at 10 Gbit/s operation rate. Therefore, CDR is so important, because, after the data rate is discovered, and the signals phase aligned, a precise trigger will be made to deliver the eye diagram free of noise and distortion, as much as possible.

3.1.1 Set-up used for the study of OLT XFP transmitter

In the initial part of the characterization of the OLT XFP and to acquire some knowledge regarding the components, the following set-up was assembled. In this schematic, for sake of simplicity, it is missing the connection of the Pattern Generator sending 10 Gbit/s, NRZ modulation data out (positive and negative), to OLT XFP board, using two SMA (SubMiniature version A) cables with 20 GHz bandwidth each to the T_x^+ and T_x^- respectively.

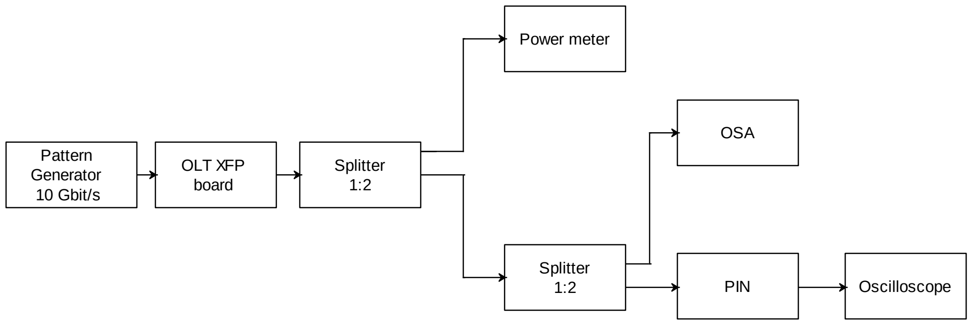

Figure 3.2: Initial set-up used for characterizing the OLT XFP transmitter.

This set-up allows to measure the characteristic curve of the DML, output power as a function of the biasing current and observe the eye diagram and measure ER. The OSA allows to check the spectrum, the wavelength and the power at PIN input.

3.1.2 Characteristic curve of DML used for OLT XFP transmitter

As previously referred in the last chapter section 2.2.1.2, for DML, as the biasing current increases above the threshold the output power also increases (approximately) linearly until a saturation point. The bias current establishes the operation point of the laser, and the modulation current, in this case AC coupled, leads to power variations of the optical signal. Figure 3.3 and 3.4 present the characteristic curve of the laser, output power as function of Ibias current.

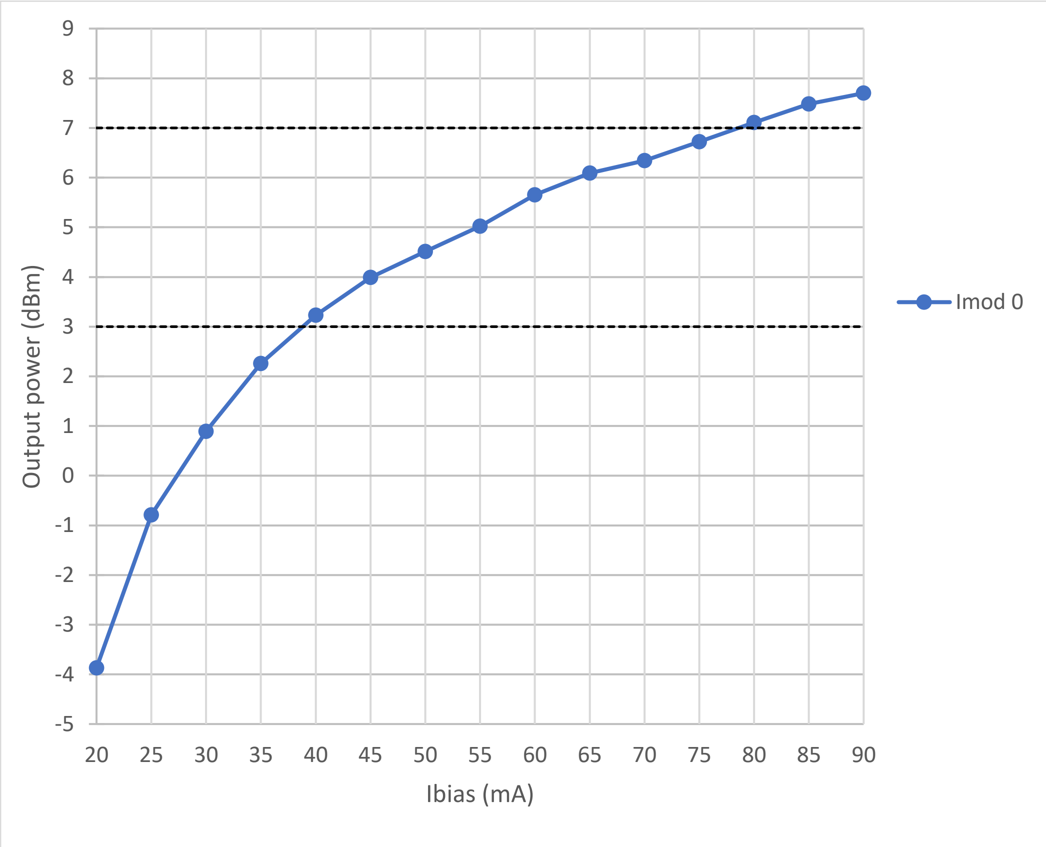

Figure 3.3: Characteristic curve for OLT XFP DML transmitter in dBm.

The dashed lines presented at this figure, represent the required output power for ITU-T, G.989.2 norm for NG-PON2, and the DML should operate in this region, above +3 dBm and lower than +7 dBm, for a N1 link. The values for bias and modulation currents should be carefully chosen to meet the mentioned requirements, but also considering the figures of merit referred on chapter 2 for 10Gbit/s transmission in downstream, for example the minimum 8.2 dB for ER. The next figure 3.4, presents the characteristic curve with higher Ibias excursion and the output power in mW.

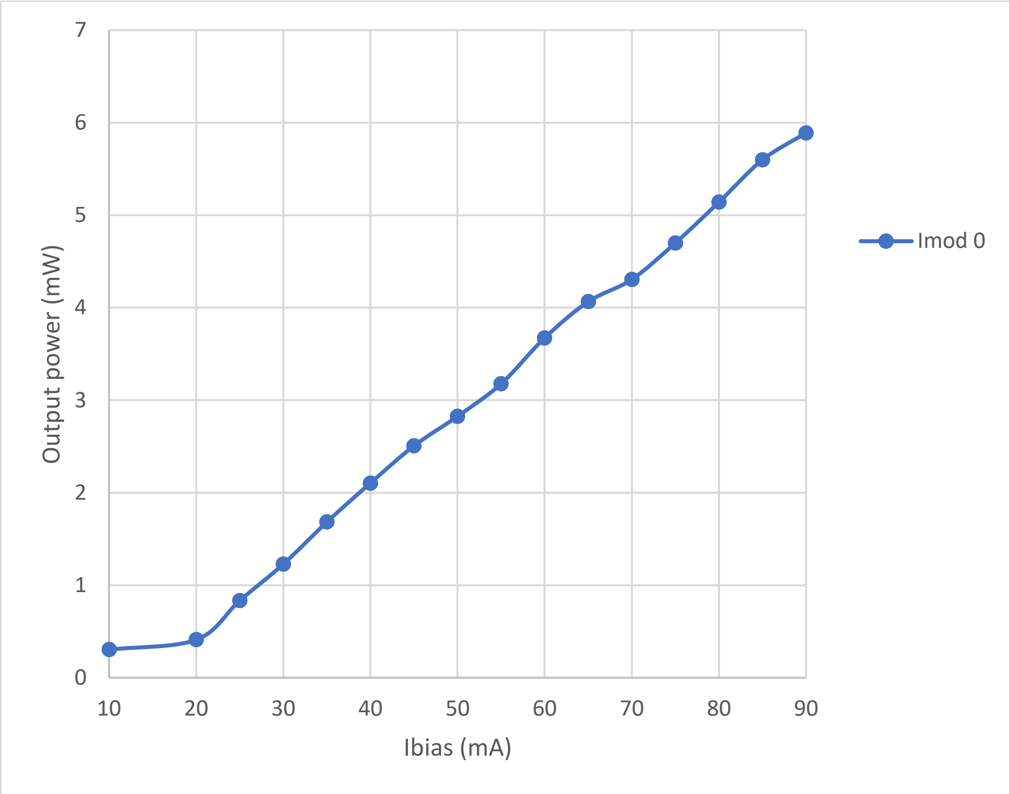

Figure 3.4: Characteristic curve for OLT XFP DML transmitter in mW.

From figure 3.4, it is possible to conclude about the threshold region. The values that should be chosen for Ibias and Imod must be away from this zone in order to reduce the degradation (chirp, intensity noise) induced by this laser.

3.1.3 Eye diagram and BER measurements

After the characteristic curve is known, an optimization was done for different sets of bias and modulation currents, and the TEC temperature, based on eye diagram opening, value of ER and BER.

3.1.3.1 Set-up for eye diagram and BER measurements

In this part, it will be presented the set-up used to obtain the eye diagram and BER. This is an upgrade of the set-up illustrated in Figure 3.2, but now with the possibility of measuring the required optical power (ROP) in back-to-back or with 20 km of SSMF for a BER of 10^{-3}, thus using an APD in the optical transceiver model Gryphon XFP from JDSU.

The VOA (Variable Optical Attenuator) allows to change the attenuation in the network, to obtain the ROP at 10^{-3} BER, as the ITU-T G.989.2 standard imposes. As in the previous set-up it was neglected the connection of Pattern Generator to OLT XFP board by two SMA cables with 20 GHz bandwidth each, and the connection between the Gryphon XFP from JDSU and the Pattern Generator, also through two SMA cables with the same bandwidth, to data in (positive and negative). The set-up is presented in figure 3.5.

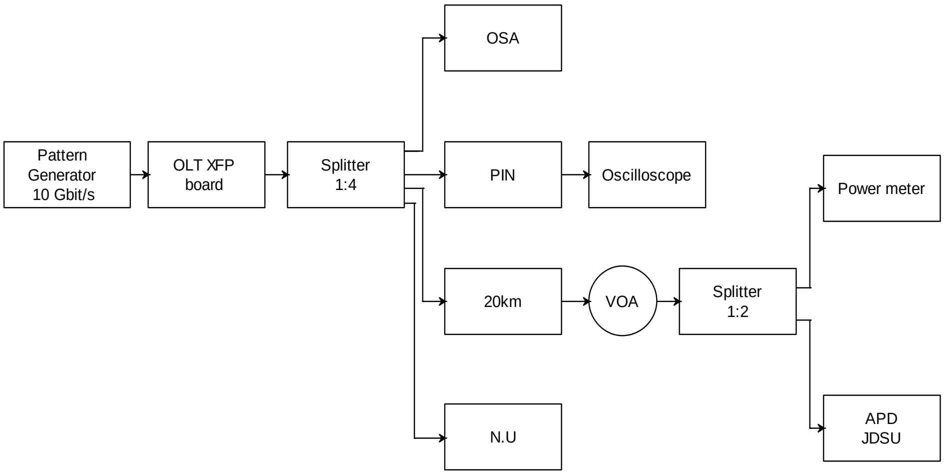

Figure 3.5: Set-up for eye diagram and BER measurements.

3.1.3.2 Experimental results for OLT XFP transmitter

Using the previous set-up and with the results taken so far, TEC temperature and some sets of bias and modulation currents, that lead to a better eye diagram and output power, inside the range required, are characterized. This is done using an application developed by PICadvanced S.A, that makes possible to change the bias and modulation currents and also TEC temperature, to be set in the Laser and TEC drivers respectively. The user interface is presented in figure 3.6.

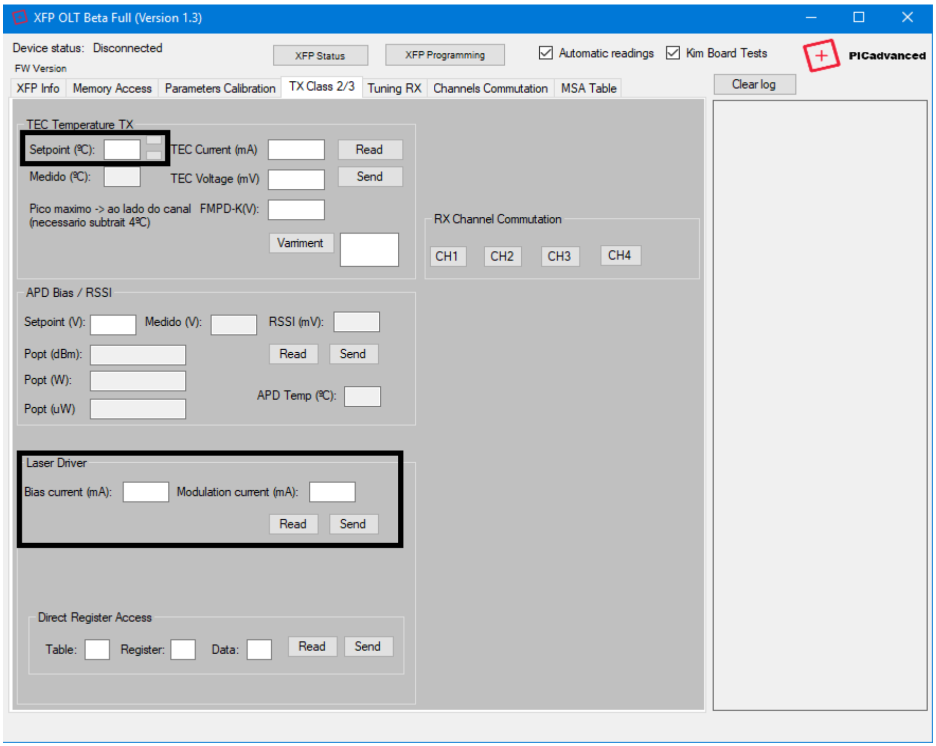

Figure 3.6: PICadvanced user interface used to configure parameters.

In table 3.1 are presented the results for downstream. The ROP value is taken for the required 10^{-3} BER, with and without fiber, and the associated OPP is then obtained.

Ibias (mA)	Imod (mA)	ER (dB)	TEC (ºC)	Required Optical Power B2B (dBm)	Required Optical Power 10km (dBm)	Required Optical Power 20km (dBm)	OPP 10km (dB)	OPP 20km (dB)
45	15	8.0	51.9	-30.1	-29.4	-29.0	0.7	1.1
45	20	10.7	51.9	-31.3	-30.5	-29.3	0.8	2.0
50	15	6.6	50.9	-30.0	-29.3	-28.8	0.7	1.2
50	20	9.1	50.9	-31.2	-30.5	-29.8	0.7	1.4
50	25	11.2	50.9	-31.8	-30.7	-30.0	1.1	1.8
55	20	8.2	49.4	-31.3	-29.6	-28.8	1.7	2.5
55	25	10.3	49.4	-31.6	-31.1	-30.6	0.5	1.0
55	30	11.9	49.4	-31.9	-30.5	-29.7	1.4	2.2
60	20	8.4	48.4	-31.3	-31.1	-30.2	0.2	1.1
60	25	10.2	48.4	-32.0	-31.7	-31.1	0.3	0.9
60	30	11.7	48.0	-32.2	-30.1	-29.9	2.1	2.3

Table 3.1: Results for different Ibias and Imod in downstream direction.

From table 3.1 there are several pairs of bias and modulation currents that meet the requirements from G.989.2 standard from ITU-T regarding NG-PON2, such as ER above 8.2 dB, sensitivity higher than -28 dBm and an OPP lower than 2 dB. From the results, it was possible to observe that with the increase of the modulation current the ER also increases, for the same biasing current. As we move away from the threshold the required B2B ROP is lower. Also, it would be expected that with the increase of the ER, the required ROP would be lower, since the logical levels ‘1’ and ‘0’ difference is higher. However, in some cases this does not happen which can be explained by the fact that the OLT transmitter is AC coupled, thus, in some of the presented cases, they operate near the threshold zone leading to a degradation of the ROP and consequent OPP results. The cases that present a better performance are the 55 and 60 mA for Ibias and the 25 mA for Imod. Figures 3.7, 3.8, 3.9 and 3.10 present the eye diagram and the BER curves for such cases.

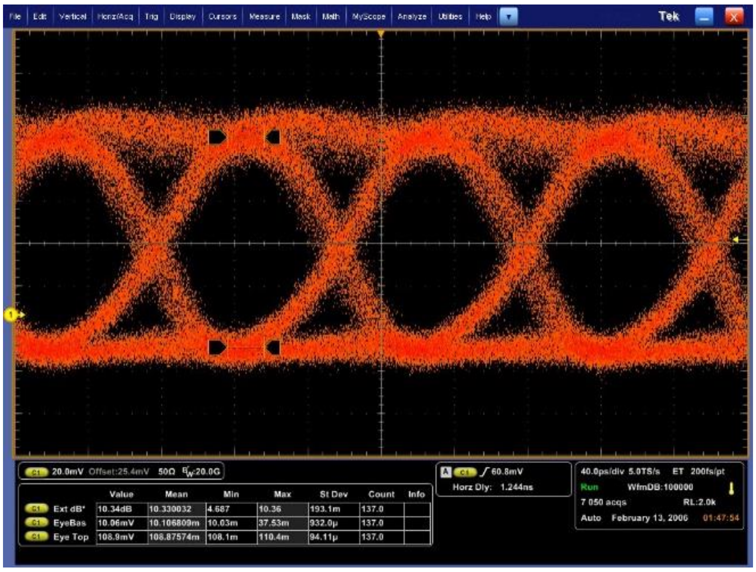

Figure 3.7: Eye diagram for Ibias 55 mA and Imod 25 mA in B2B.

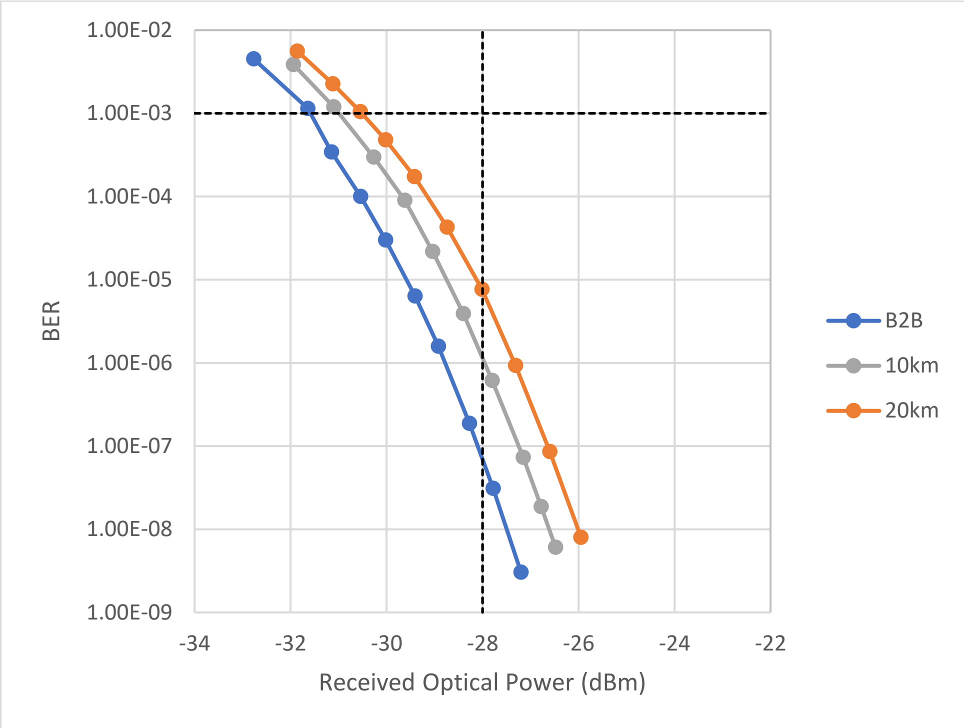

Figure 3.8: BER curves with Ibias 55 mA and Imod 25 mA.

Observing figures 3.7 and 3.8 it may be concluded that the indicated bias and modulation currents used, lead to a system performance with required ROP margin from the imposed by ITU-T. In B2B the value is -31.6 dBm and for 20 km increases to -30.6 dBm, thus lower than -28 dBm required by the standard.

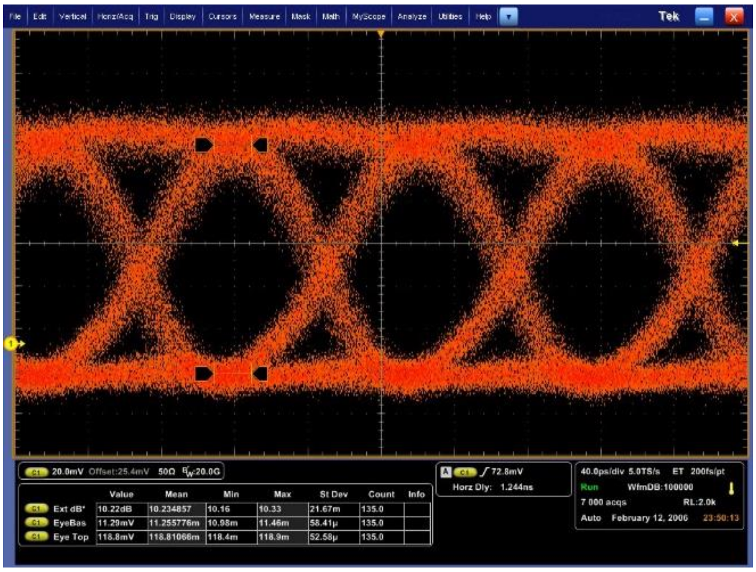

Figure 3.9: Eye diagram for Ibias 60 mA and Imod 25 mA in B2B.

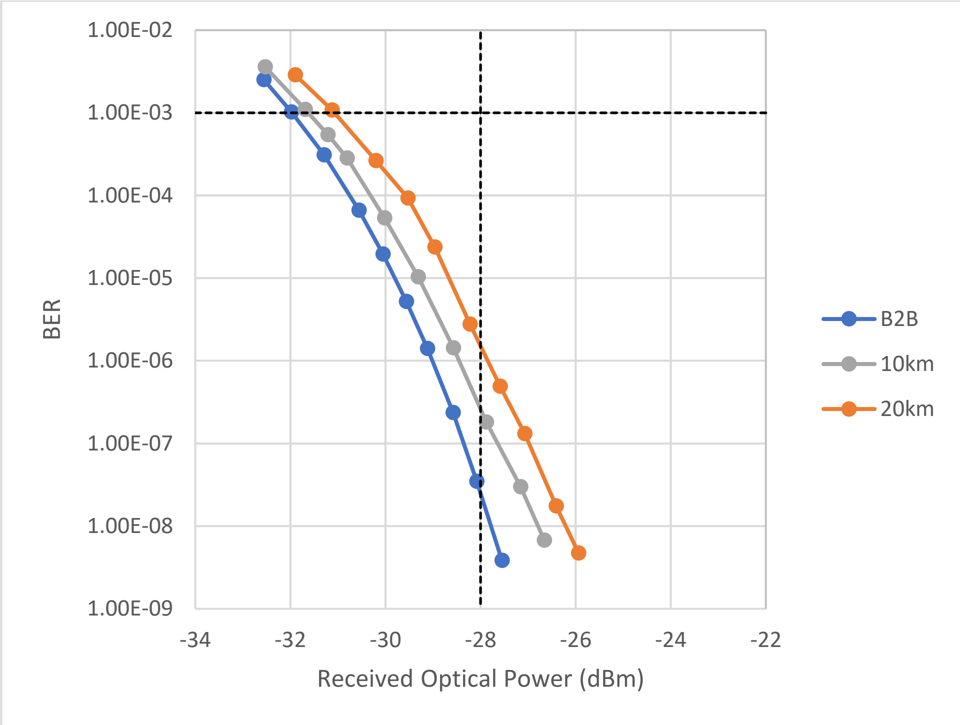

Figure 3.10: BER curves with Ibias 60 mA and Imod 25 mA.

Regarding the OPP, with 10 km of fiber the value is 0.5 dB and with 20 km the signal degrades more and the value increase for 1.1 dB which is still inside the 2 dB maximum penalty for losses on optical path for 20 km.

Regarding, the second pair of currents, the major requirements are met. The ROP value in B2B is -32.0 dBm and with 20 km of fiber increases to -31.1 dBm. Meeting the standard spec of -28 dBm. The table 3.2, present the best cases studied until this point and some of their neighbors.

Ibias (mA)	Imod (mA)	ER (dB)	TEC (ºC)	Required Optical Power B2B (dBm)	Required Optical Power 10km (dBm)	Required Optical Power 20km (dBm)	OPP 10km (dB)	OPP 20km (dB)	Output Power (dBm)
50	20	9.1	50.9	-31.2	-30.5	-29.8	0.7	1.4	3.1
55	25	10.3	49.4	-31.6	-31.1	-30.5	0.5	1.1	3.6
60	20	8.4	48.4	-31.3	-31.1	-30.2	0.2	1.1	4.1
60	25	10.2	48.4	-32.0	-31.7	-31.1	0.3	0.9	4.0

Table 3.2: Results from different Ibias and Imod in downstream direction with output power.

Table 3.2 presents the results of the previous pairs of Ibias and Imod study and some neighbor values. It is also indicated the output power, according to the range referred at section 3.1.2, minimum +3 dBm and +7 dBm maximum from N1 ODN class.

3.2 Characterization of a second OLT TOSA

In this section it will be characterized an OLT TOSA provided by PICadvanced, S.A with the main objective of complementing the study of the previous OLT XFP transmitter. With this new TOSA, also a DML, it is expected a better eye diagram, but in terms of output power it may fall short of the ITU-T G.989.2, due to the intrinsic optical alignment of the laser.
Using the same set-up of figure 3.5, the only change was the use of a new OLT XFP board, where this TOSA was soldered. Some pairs of bias and modulation currents were tested to conclude which lead to better eye diagrams and required ROP results. In table 3.3 are presented the results obtained.

Ibias (mA)	Imod (mA)	TEC (ºC)	ER (dB)	Required Optical Power B2B (dBm)	Required Optical Power 10km (dBm)	Required Optical Power 20km (dBm)	OPP 10km (dB)	OPP 20km (dB)
23	25	19.5	8.4	-31.9	-30.1	-28.9	1.8	3.0
23	25	30.3	8.5	-31.4	-29.9	-28.6	1.5	2.8
25	30	19.3	9.4	-32.0	-31.0	-30.1	1.0	1.9
25	30	30.0	9.5	-31.4	-30.1	-29.5	1.3	1.9
28	25	19.0	6.4	-30.9	-30.2	-29.9	0.7	1.0
28	25	40.4	8.2	-31.2	-30.0	-28.2	1.2	3.0
33	25	29.1	6.3	-29.1	-28.4	-27.5	0.7	1.6

Table 3.3: Results for different Ibias and Imod in downstream direction for OLT TOSA.

From table 3.3 it can be shown that are a few pair of currents that lead to a better performance. These currents, are very close to the threshold, once in this region the ER can achieve higher values. The ROP value is taken on the required BER of 10^{-3}, with and without fiber for the calculation of OPP.
Figures 3.11 and 3.12 present the eye diagram and BER curves of the chosen pairs of Ibias and Imod from table 3.3, that obey the NG-PON2 ITU-T G.989.2 standard.

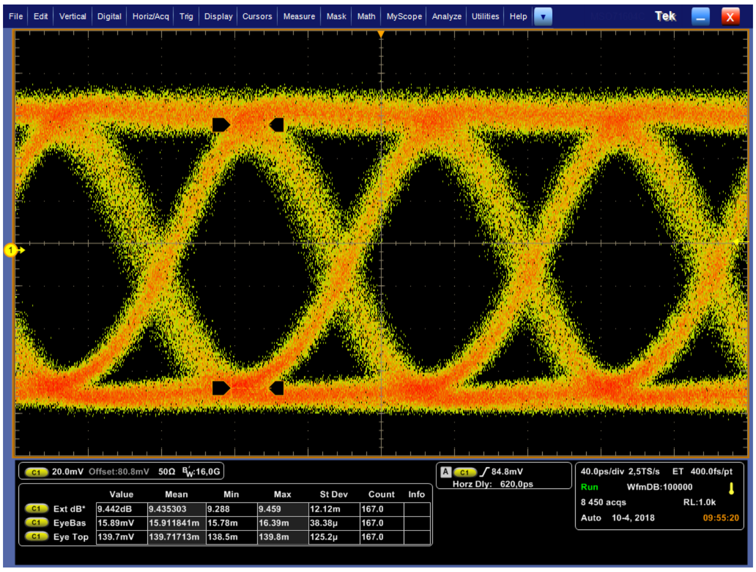

Figure 3.11: Eye diagram for Ibias 25 mA and Imod 30 mA in B2B with TEC at 19.3 ºC.

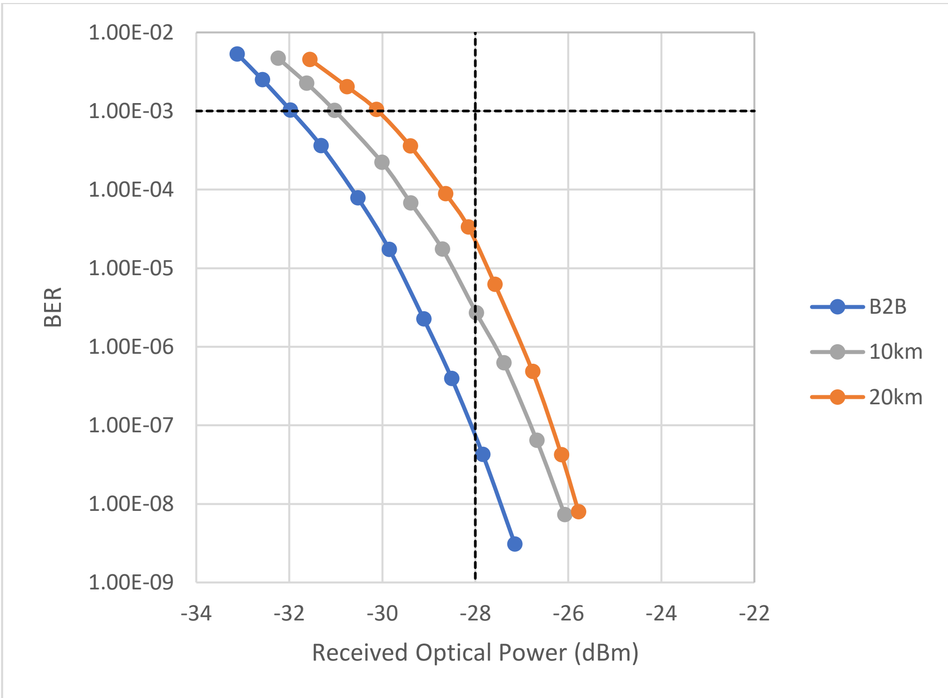

Figure 3.12: BER curves with Ibias 25 mA and Imod 30 mA.

As it can be observed in figure 3.11 the eye diagram opening is better in comparison with the presented for the OLT XFP transmitter at section 3.1. The ROP is also lower than the required in G.989.2 standard, and in this case also the ER meets the requirements. The output power in this OLT TOSA is lower than the +3 dBm minimum, but as previously referred, it is inherent to the coupling of the laser itself. At this part of the work the eye diagram and ROP were the principal test focus. In the next figures, it is shown the eye diagram and BER curves of OLT TOSA for Ibias 28 mA and Imod 25 mA. In this case, the ER is, as the output power, lower than the standards but ROP and OPP meet the standard specifications.

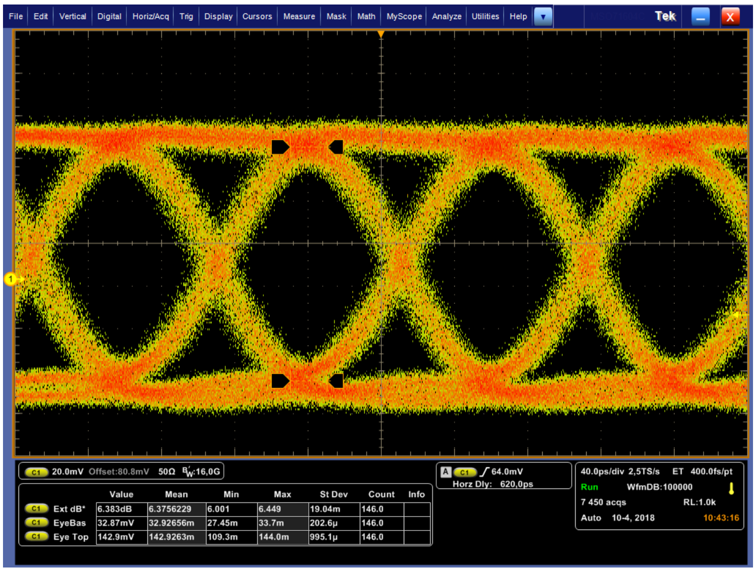

Figure 3.13: Eye diagram for Ibias 28 mA and Imod 25 mA in B2B with TEC at 19 ºC.

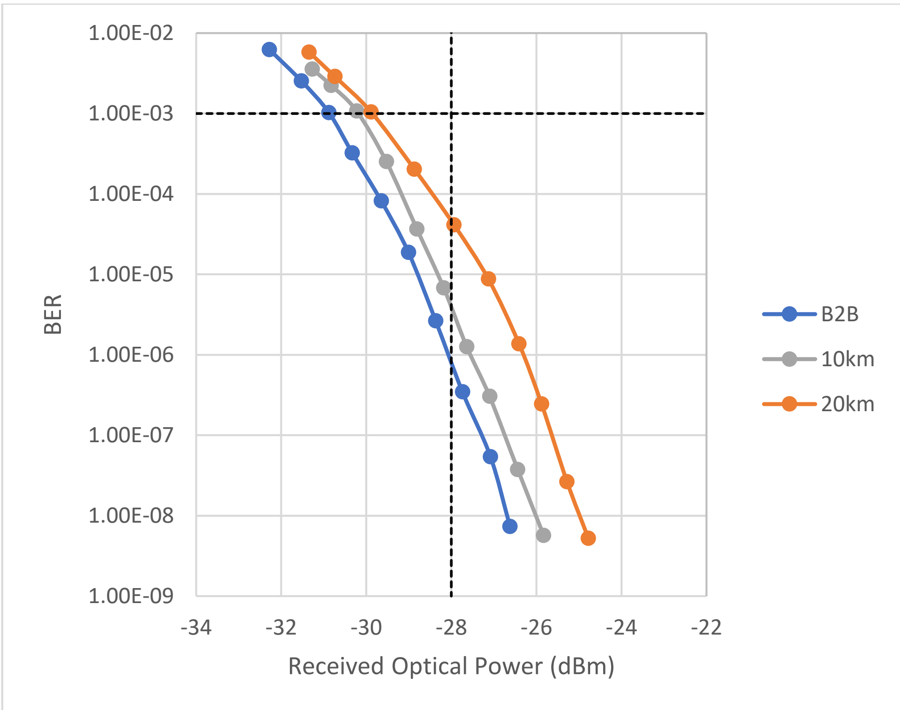

Figure 3.14: BER curves with Ibias 28 mA and Imod 25 mA.

These two previous cases show, improvements on the quality of eye diagram and ROP. Regarding the output power and ER this OLT TOSA falls short and do not meet the standards, however this is not a major issue since the optical coupling was not improved and the main objective of this study was to observe if the overall RF performance was improved when compared to the OLT XFP transmitter on section 3.1.

3.3 Characterization of a commercial OLT XFP transmitter

In this section a commercial OLT XFP transmitter available at PICadvanced, SA will be characterized for reference with the products under development. Characterization of the eye diagram, BER curves and output power are presented. Regarding the set-up used for taking these measurements, it is the same as the presented in section 3.1.3.1, figure 3.5.

The commercial OLT transmitter under study is based on an EML. When compared to the DML presented and characterized on the previous sections, one should expect higher ER and less jitter in the eye diagram.

In the figure 3.15 it can be seen the eye diagram with an ER of 10.7 dB and output power near +7 dBm.

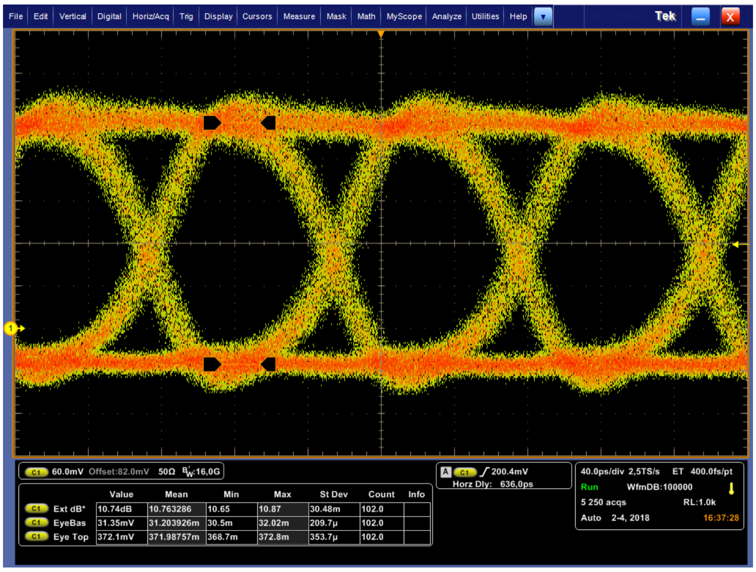

Figure 3.15: Eye diagram for commercial OLT XFP channel 1.

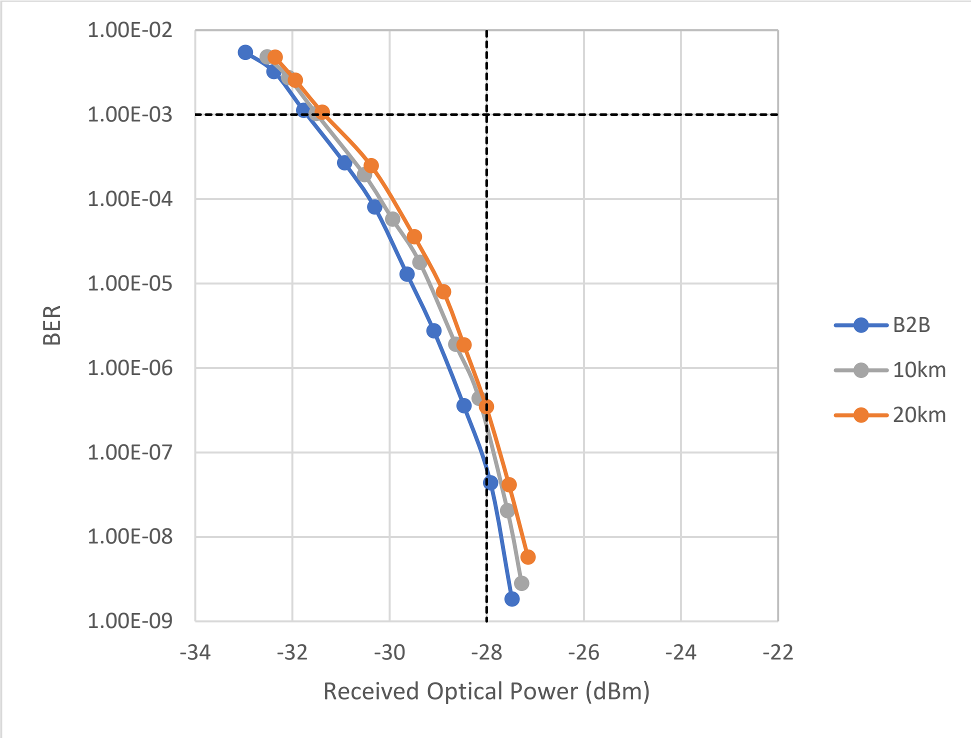

Figure 3.16: BER curves for commercial OLT XFP channel 1.

Regarding the ROP values in B2B and worst case with 20 km of fiber are -31.8 dBm and -31.4 dBm respectively. The OPP value for 10 km of fiber is 0.3 dB and for 20 km is 0.4 dB, accommodating margin for the 2 dB maximum OPP of ITU-T G.989.2 standard. The following table 3.4, presents the summary results.

Ibias (mA)	Imod (mA)	TEC (ºC)	ER (dB)	Required Optical Power B2B (dBm)	Required Optical Power 10km (dBm)	Required Optical Power 20km (dBm)	OPP 10km (dB)	OPP 20km (dB)
NA	NA	NA	10.7	-31.8	-31.5	-31.4	0.3	0.4

Table 3.4: Most relevant parameters obtained with commercial OLT XFP channel 1.

The Ibias and Imod, as well TEC temperature, were not made available (NA) by the vendor. For the remaining parameters, the same procedures of previous sections were followed.

3.4 Conclusions

For the first transmitter present on the OLT XFP prototype, several tests were done, optical power, ER, OPP and BER curves in order to know the values of TEC, Ibias and Imod that would improve the transmission performance of this laser. For the OLT TOSA a similar study was made, nevertheless in this case the TOSA was tested soldered directly to a board also designed in PICadvanced, S.A that allows, with the application previous mentioned, to manipulate the parameters referred above. It should be noted that in both cases it was not possible to place the laser emitting within the wavelength plan specified for one of the OLT channels described in section 2.4.1, table 2.7, due to the intrinsic specified wavelength of the laser itself.

The main objective of the OLT TOSA study was to optimize the transmitter characteristics by optimization of the transmitter eye diagram. There was an improvement in the characteristics of the eye diagram, lower jitter and consequent inter-symbol interference and clear decision levels. Finally, a commercial OLT XFP transmitter was characterized for reference and comparison with the OLT TOSAs studied. In table 3.5 are presented the comparison results.

Ibias (mA)	Imod (mA)	TEC (ºC)	ER (dB)	Required Optical Power B2B (dBm)	Required Optical Power 10km (dBm)	Required Optical Power 20km (dBm)	OPP 10km (dB)	OPP 20km (dB)	Output Power (dBm)
55	25	49.4	10.3	-31.6	-31.1	-30.5	0.5	1.1	3.6
60	25	48.4	10.2	-32.0	-31.7	-31.1	0.3	0.9	4.0
25	30	30.0	9.5	-31.4	-30.1	-29.5	1.3	1.9	2.2
28	25	19.0	6.4	-30.9	-30.2	-29.9	0.7	1.0	2.4
NA	NA	NA	10.7	-31.8	-31.5	-31.4	0.3	0.4	7.0

Table 3.5: Comparison results for the transmitters studied.

As seen in table 3.5, the first transmitter presents better results than the second as far as optical power, ER, ROP and OPP are concerned. In terms of transmission conditions, the general parameters are achieved in both OLT TOSAs, although the second one presents eye diagram improvement.

The results obtained with these two prototype OLT TOSAs, when compared to the commercial one, present similar performance, which leaves good prospects for the possibility of integrating this transmitter in a OLT XFP for NG-PON2 purposes, with significantly lower costs.

Chapter 4

Characterization of OLT XFP receivers for NG-PON2 in burst mode

As the PONs are P2MP, in the upstream direction the transmitter has to "speak" in burst mode, thus the architecture chosen was the TDMA (Time Division Multiple Access), allowing different ONUs to transmit in the same frame. All this switch of data is controlled and managed by the OLT which assigns a temporal slot to each ONU.

The burst mode transmission is an efficient method to share a common channel by exploiting time domain, although in NG-PON2 with the reduced available channel bandwidth in the range of 100 GHz or below, the burst mode induces frequency-drift that need to be considered. As it can be seen in figure 4.1, in NG-PON2 upstream direction, and once the bandwidth is very narrow and practically without margin when compared for example with GPON, these burst mode transmissions need to be carefully compensated so the spectrum shift is controlled, especially if a DML laser is used. [20]

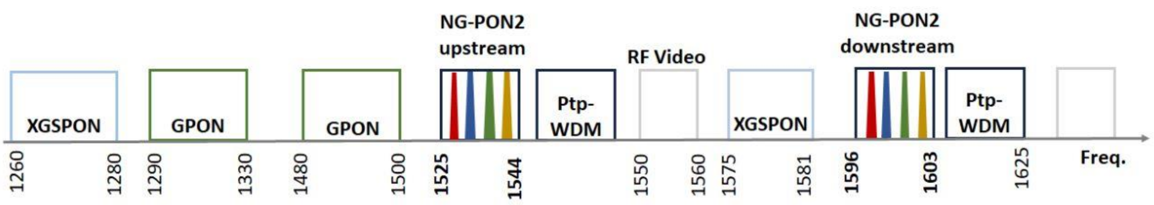

Figure 4.1: PON roadmap spectrum comparison. [21]

Challenges in the upstream path of TWDM passive optical networks arise mainly from frequency drifts due to self-heating of the laser and the existence of highly different power levels from the different ONUs. In general, the use of the wavelength domain to increase the aggregated bit rate of the system is a well-known technique, extensively exploited in core and metro networks. TDM-PON systems such as GPON or the 10-Gbit/s XG-PON are both operated on a single wavelength channel, in upstream and downstream directions, respectively. Contrarily, when the wavelength domain is exploited too, for the first time in access networks with the next-generation of passive optical network stage 2, the challenge in terms of power dynamic is strongly increased and this process must be transparent, which means without any type of processing. [22]

In the present chapter two burst mode receivers will be characterized, one used in a commercial OLT XFP and the other a test sample of a burst mode ROSA, both provided by PICadvanced, SA.

4.1 Burst mode transmission in NG-PON2 ONU

Burst mode transmission consists basically in sending all the information in very small time windows, in NG-PON2 different ONUs transmit in different time slots attributed by the OLT. In one frame of 125 µs length one can have several ONUs transmitting. This frame is essentially composed by 3 slots: Preamble, Delimiter and the Payload, as shown in figure 4.2.

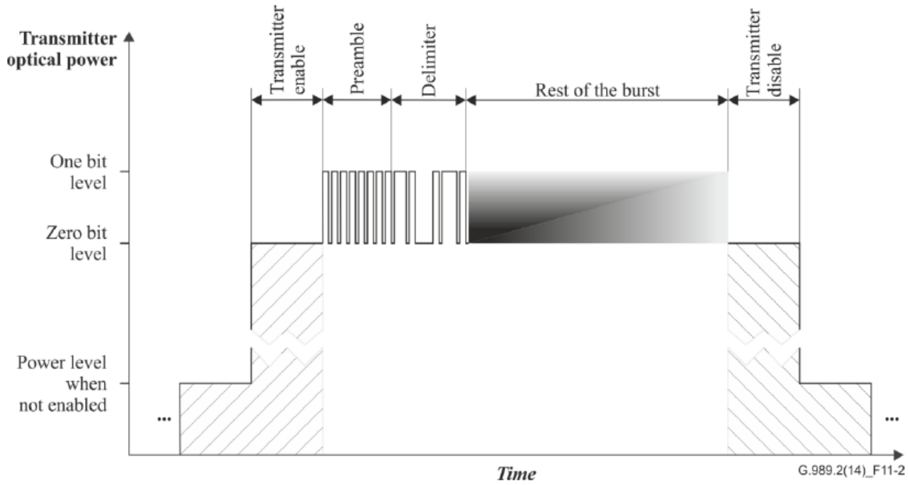

Figure 4.2: Burst mode frame. [4]

The preamble is typically around 800 ns (80 bits) and serves for the stabilization of the power levels, so it can easy the reception by the OLT receiver. The delimiter is a well known sequence of 2 bytes and it is using this slot that the receiver knows where the preamble ends and where the payload begins. The remaining frame can be used for payload.

4.2 OLT XFP receiver for NG-PON2

The OLT XFP receiver block diagram is depicted in figure 4.3: a circuit to bias the APD photodetector, a TIA (Transimpedance Amplifier) and a LA (Limiting Amplifier).

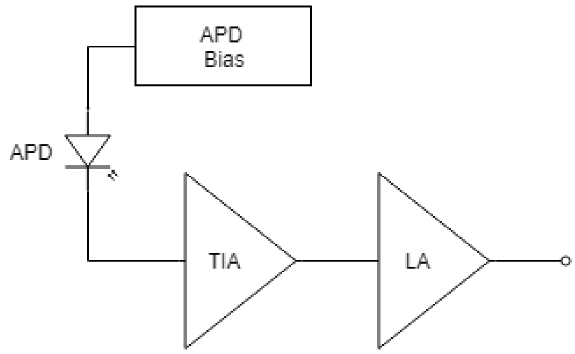

Figure 4.3: OLT XFP receiver schematic.

The APD bias, based on a DC-DC step-up converter is responsible to providing the necessary reverse voltage to bias the APD photodetector so it can properly collect the light coming from the ONUs and deliver a proportional current (order of µA). This voltage depends on each APD and normally the value that is used is 2 V below the breakdown voltage (provided by manufacturer). This current, that depends directly from the collected light power and the responsivity of the APD, pass through a TIA that will transform it into an amplified voltage once this current will pass through a resistor (typically in order of MΩ). Finally, these different voltages are amplified, with the LA normalizing the voltage to predefined '0' and '1' voltage levels.

4.2.1 OOC and MSE of ONU

The out-of-channel power spectral density (OOC-PSD) mask and MSE (Maximum Spectral Excursion) are important figures of merit, and the purpose of the transmitter mask, presented at figure 4.4, is to define the maximum power spectral density that an NG-PON2 transmitter is allowed to send outside the spectral interval corresponding to its current operating wavelength channel.

This kind of mask exists also for the OLT, however, and as it is quite similar it is only addressed in the ONU side, since, as it operates in burst, the challenges for compensation are strongly increased. [23]

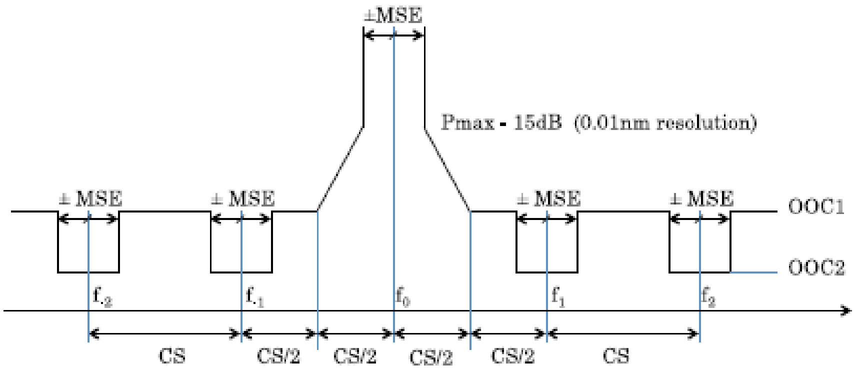

Figure 4.4: OOC power spectral density mask. [23]

This mask presented at figure 4.4 serves for two very important tests, that costumers generally demand, once they are presented on the standards, respectively the OOC and MSE measurements. These mask values are sized so that in the PON there is no channel interference when all impairments occur simultaneously. This mask from ITU-T, that the ONU needs to comply, required a OOC1 lower than -40.5 dBm for 100 GHz CS and OOC2 in this case using 4 channels lower than -44.8 dBm, this last one according to recent news will suffer a relaxation of 3 dBm. [4]

The figure 4.5, presents these measurements on a PICadvanced, SA commercial ONU (S/N:1010000481) used in posterior upstream tests and BER measurements. The blue and red spectrums, represent respectively the OOC (with 0.127 nm resolution) and MSE (0.01 nm resolution), and are obtained with a OSA in a range 1532 to 1536 nm, in order to observe all 4 channels in upstream for NG-PON2 wavelength plan.

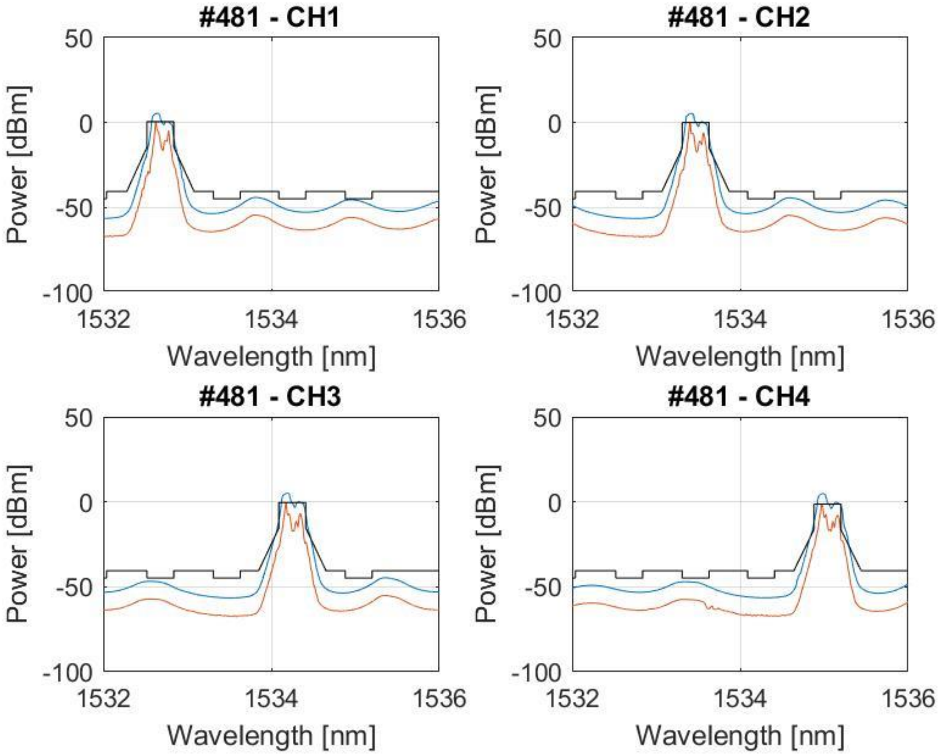

Figure 4.5: OOC power spectral density and MSE mask for PICadvanced, SA ONU Tx.

The wavelength stability of an NG-PON2 system is qualified through the MSE. MSE is specified for two main reasons, prevent optical power in one wavelength channel from leaking into an adjacent wavelength channel causing cross-talk induced degradation, and to ensure that the transmitter operates within the desired wavelength. The spectral excursion of a Tx in a stationary wavelength channel state is defined as the absolute difference between the nominal central frequency of the wavelength channel and the −15 dB point of the Tx spectrum furthest from the nominal central frequency. For the upstream (US), the CS is not fixed and can range from 50 to 200 GHz, with the MSE specified for three specific values as shown in table 4.1. [23]

Channel Spacing (GHz)	50	100	200
MSE (GHz)	+/- 12.5	+/- 20	+/- 25

Table 4.1: MSE values for NG-PON2 US direction. [24]

The value that is mostly used for CS is 100GHz and corresponding +/- 20 GHz of MSE mainly due to crosstalk issues.

4.2.2 Burst compensation

The wavelength drift can cause the upstream signal to drift out of its channel and fall into the adjacent channels, thereby causing power loss and interference in the adjacent channels.

There are several methods described in the literature to mitigate the burst mode drift. One is, the use of a dummy waveguide in the same chip of the laser itself that when the laser turns 'off' and consequently lowers its temperature the dummy laser turns 'on' and heat the "neighbor environment" causing lower temperature drifts, and a stable operating temperature. Another one, consists on using a heating compensation method, operating in opposite way of the laser, when laser is turn 'off' this heating compensation method is 'on', and vice-versa. [25]

Figure 4.6, illustrates this last operation method, in which the curves represent the temperature of the laser, heating compensation method and the wanted operation temperature, respectively. [26]

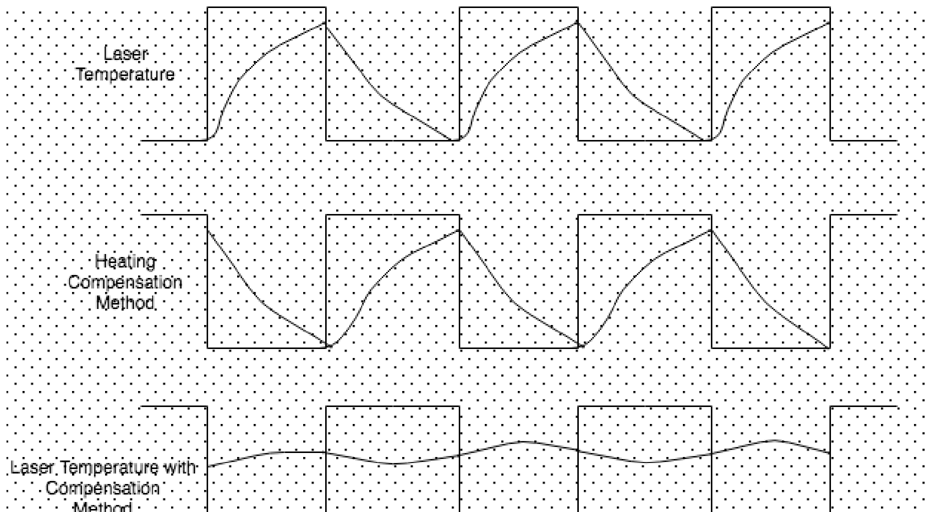

Figure 4.6: Burst compensation principle.

For the practical results that will be presented next, the channel chosen was the 1535.04 nm (ch4), once it is the most challenge one to compensate due to the higher operating temperature. It is desirable to reduce the wavelength drift in order to satisfy the MSE requirement specified in ITU-T G.989.2. [4]

Figure 4.7, shows the burst compensation of ch4 from a PICadvanced, SA commercial ONU.

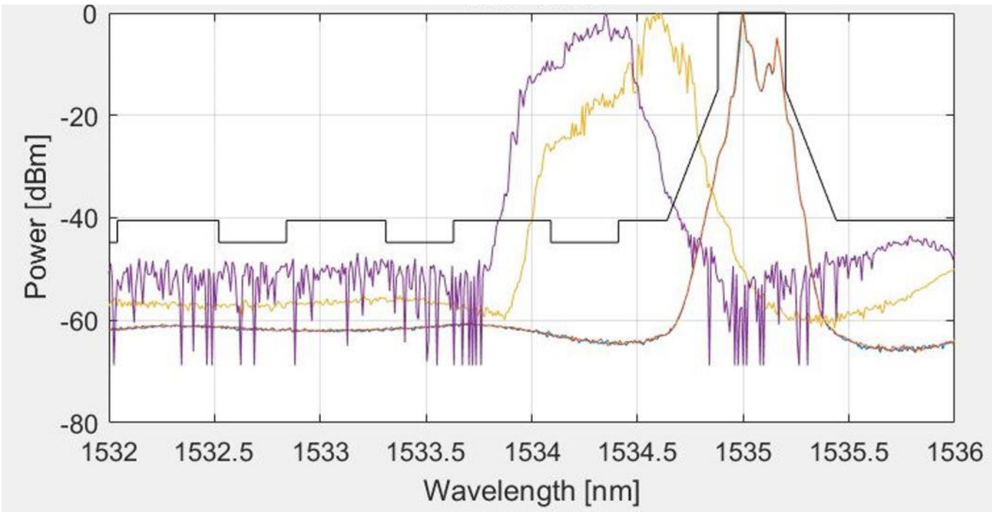

Figure 4.7: Burst compensation for PICadvanced, SA ONU Tx ch4.

In figure 4.7, the red trace is the burst compensation at the maximum, and as can be seen it is inside the mask, in opposition to the yellow and purple traces, that represent approximately half and a low burst compensation, respectively.

The spectrum of these last ones is very broad and out of channel, since when the laser temperature decreases, the heating compensation method acts, but not enough. What one can observe is the averaging by the OSA of the compensation with the shift leading to broader spectrum results.

4.3 Characterization of a commercial OLT XFP burst mode ROSA for NG-PON2

This section presents the characterization of a commercial OLT receiver using the ONU transmitter presented in the previous section.

4.3.1 BER measurements on a commercial OLT ROSA

The set-up includes a VOA, 1:2 coupler, a commercial OLT XFP ch4 and the ONU XFP transmitter approached, both in a BER tester board, as shown in figure 4.8.

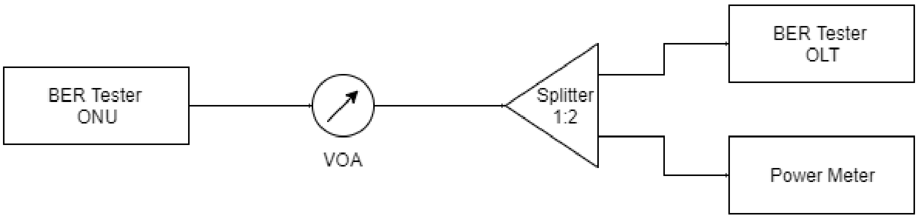

Figure 4.8: Set-up used for burst mode BER measurements.

Figures 4.9, 4.10 and 4.11 present the BER curves in three tests performed: one is to change the preamble maintaining the payload, the other is to change the length of payload and maintain preamble, and finally the scenario with a payload length of 1 µs. With this, it is expected to observe how the change of this previously referred parameters of burst frame affect the system performance. Figure 4.9, presents the BER curves for different preamble lengths with the same payload.

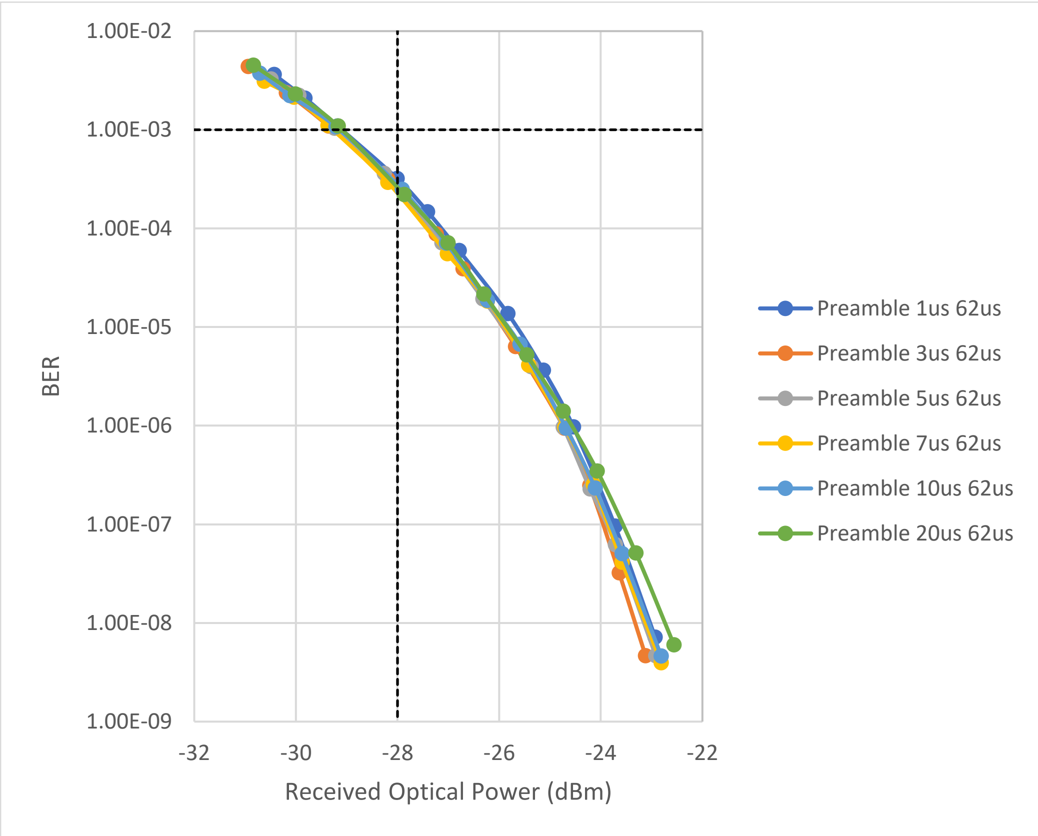

Figure 4.9: BER curves for different preamble lengths and 62 µs payload.

It is expected that with the increase of the preamble, once the system has more time to stabilize, to achieve better results.

Figure 4.9 shows that the system performance is quite similar for the preamble length ranging from 1 µs to 20 µs for a payload of 62 µs where 1 µs is the minimum preamble/payload available in the BER tester used. This is the closest possible to implemented in the systems: 800 ns.

The increase of preamble, cannot bring significant improvements on the performance, so the best value to use is the lowest, thus allowing the payload to be the biggest possible, which is advantageous since it is there that data is transmitted. Next table presents the ROP for BER of 10^{-3}.

Preamble (us)	Payload (us)	Required Optical Power B2B (dBm)
1	62	-29.2
3	62	-29.4
5	62	-29.2
7	62	-29.4
10	62	-29.2
20	62	-29.2

Table 4.2: ROP values for different preamble and payload of 62 µs.

Table 4.2 shows that the maximum difference on ROP for different preambles is 0.2 dB, which is within the error measurement of the system. Thus, one can conclude that changing the preamble length does not affect the general system performance for a fixed payload of 62 µs.

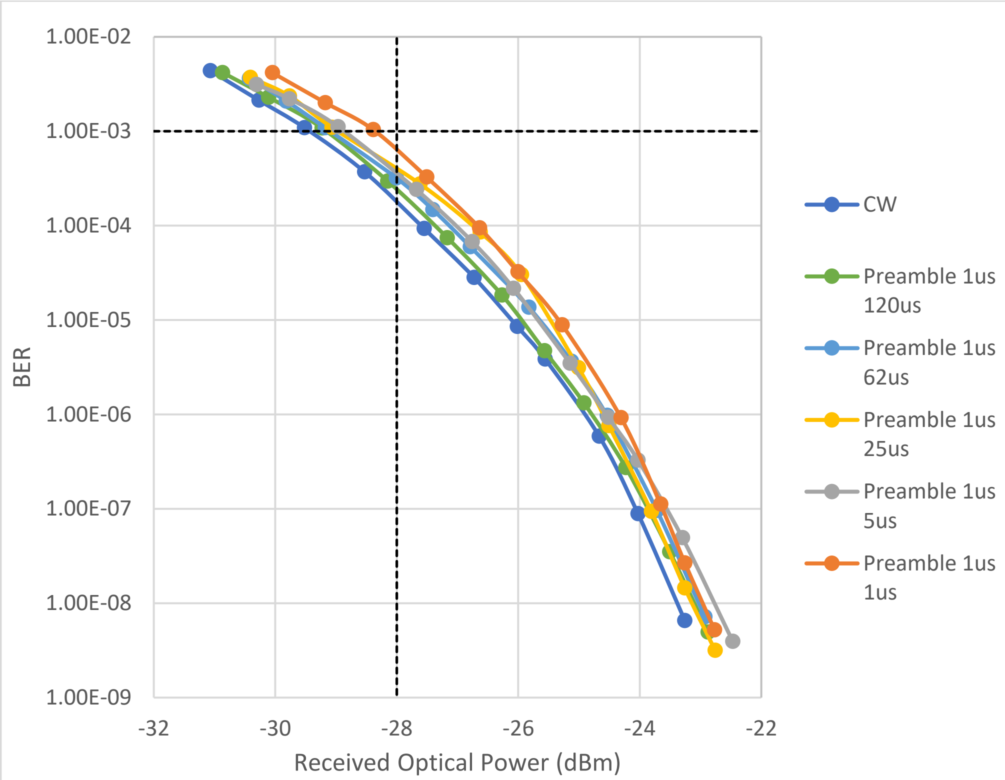

Figure 4.10: BER curves for different payloads lengths and preamble 1 µs.

Figure 4.10 presents the BER curves for the same preamble and different payloads lengths and one for continuous wave (CW) operation. What can be observed in most of the measurements is that when the payload increases, the curve approaches the CW curve, but this can be due to the fact that the system was already stabilized from previous transmissions, and the impact of increasing the payload is not observed. Next table presents the ROP for 1 µs considering different payloads.

Preamble (us)	Payload (us)	Required Optical Power B2B (dBm)
CW		-29.5
1	1	-28.4
1	5	-29.0
1	25	-29.1
1	62	-29.2
1	120	-29.2

Table 4.3: ROP values for different payloads with 1 µs preamble.

The worst case is when the preamble is 1 µs and the payload is also 1 µs, once the transmitter and the receiver must respond very fast, since in this case the capacitors are already unloaded from the previous transmission. Figure 4.11 presents the BER curves for different preambles, with 1 µs of payload.

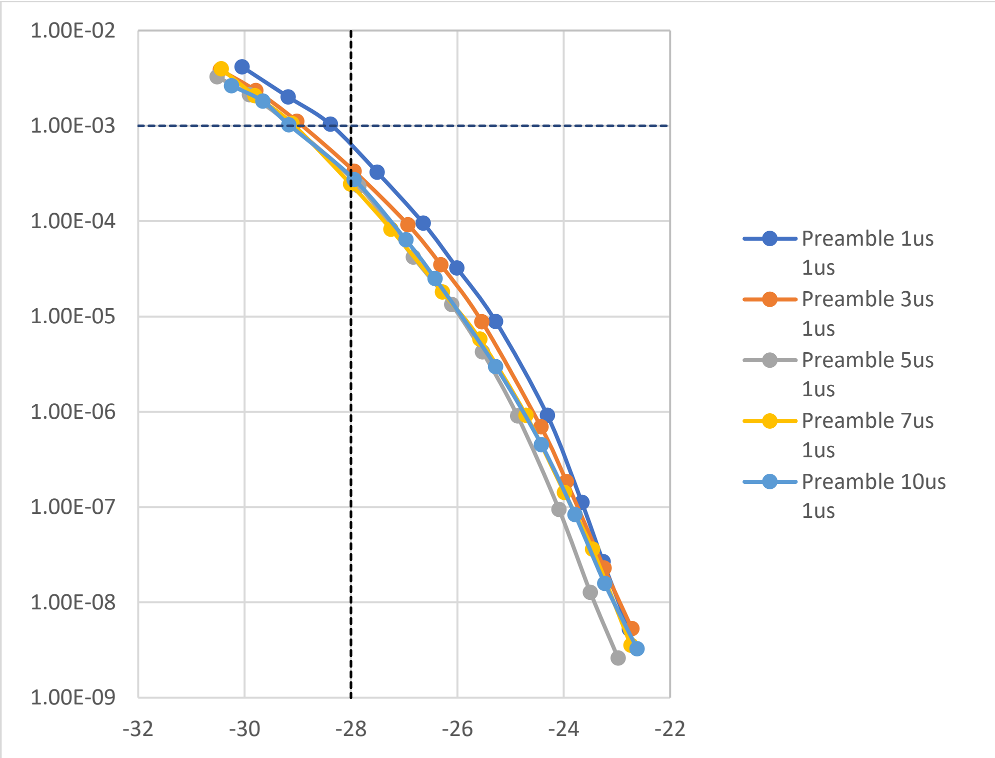

Figure 4.11: BER curves for worst case different preamble and 1 µs payload.

As expected, the one that present poor performance is when preamble is 1 µs and the payload is also 1 µs. The others present similar results and is not possible to observe a clear increase or decrease tendency on the impact of preamble, with the payload length of 1 µs (maximum deviation 0.2 dB). Table 4.4 presents the ROP for 1 µs and payload for different preambles.

Preamble (us)	Payload (us)	Required Optical Power B2B (dBm)
CW		-29.5
1	1	-28.4
3	1	-29.0
5	1	-29.2
7	1	-29.1
10	1	-29.2

Table 4.4: ROP values for different preambles with 1 µs payload.

From table 4.4, it was possible to observe that the ROP, excluding the worst case referred above, present similar results, what was expected, since the performance should not be affected, whatever are the length of preamble and payload, excluding limit cases as the mentioned.

4.4 Characterization of a test sample burst mode OLT ROSA for NG-PON2

At this part of work, a similar characterization was made, compared to section 4.3, so it can be possible conclude on the performance of the burst mode receiver in analysis.

4.4.1 BER measurements on test sample OLT ROSA

The set-up used for the BER measurements is the same used in section 4.3.1, figure 4.8, the only change was the OLT receiver on the BER tester. Figure 4.12 presents the obtained BER curves with payload of 62 µs and changing the preamble from 1 to 20 µs.

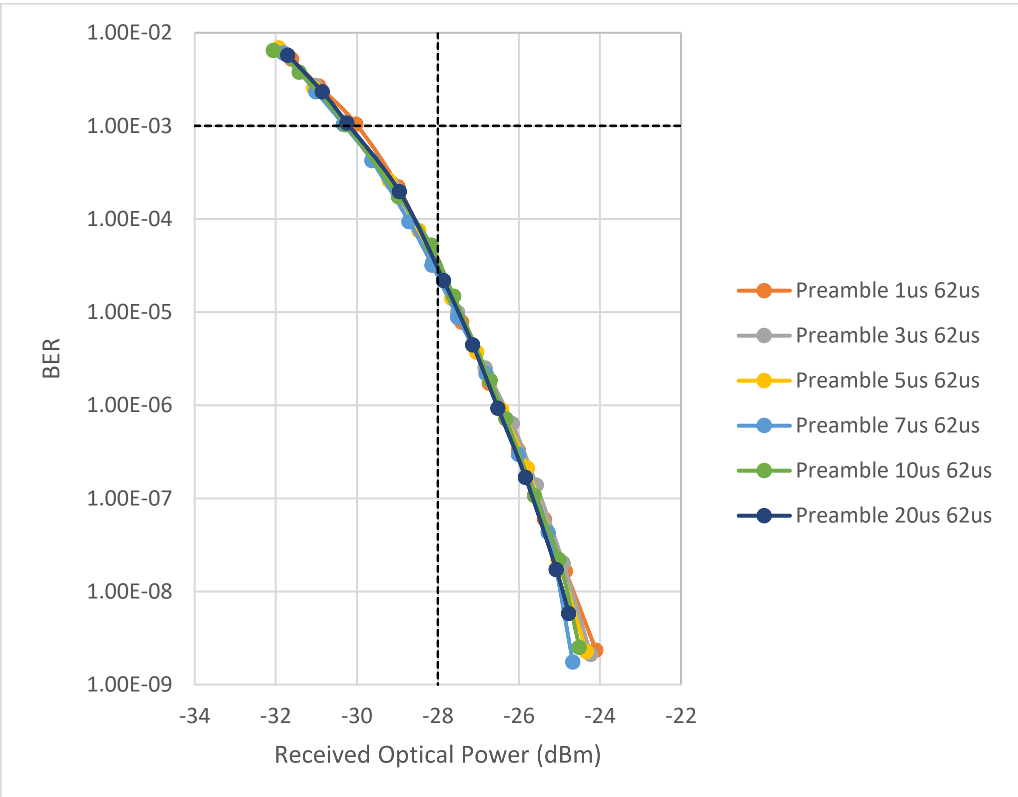

Figure 4.12: BER curves for different preambles and 62 µs payload.

From figure 4.12, it is possible to observe that the system performance is practically the same with this payload, for several preamble lengths, which is expected and observed also in the same test made in the commercial ROSA. Table 4.5 shows the results obtained for the ROP with these lengths of preamble and payload.

Preamble (us)	Payload (us)	Required Optical Power B2B (dBm)
1	62	-30.1
3	62	-30.3
5	62	-30.3
7	62	-30.3
10	62	-30.3
20	62	-30.2

Table 4.5: ROP values for different preambles with 62 µs payload.

Table 4.5, follows the previous test made with the commercial ROSA, and as it is expected, the shortest preamble 1 µs lead to worst results, and the remaining preamble values presented very similar values. The maximum difference observed was 0.2 dB which is within the error measurement of the system, and one can conclude that the system was not affected by the change of the preamble for a payload of 62 µs. As in the previous study, figure 4.13 will presents the BER curves of the closest preamble used in systems of 1 µs, for different payloads.

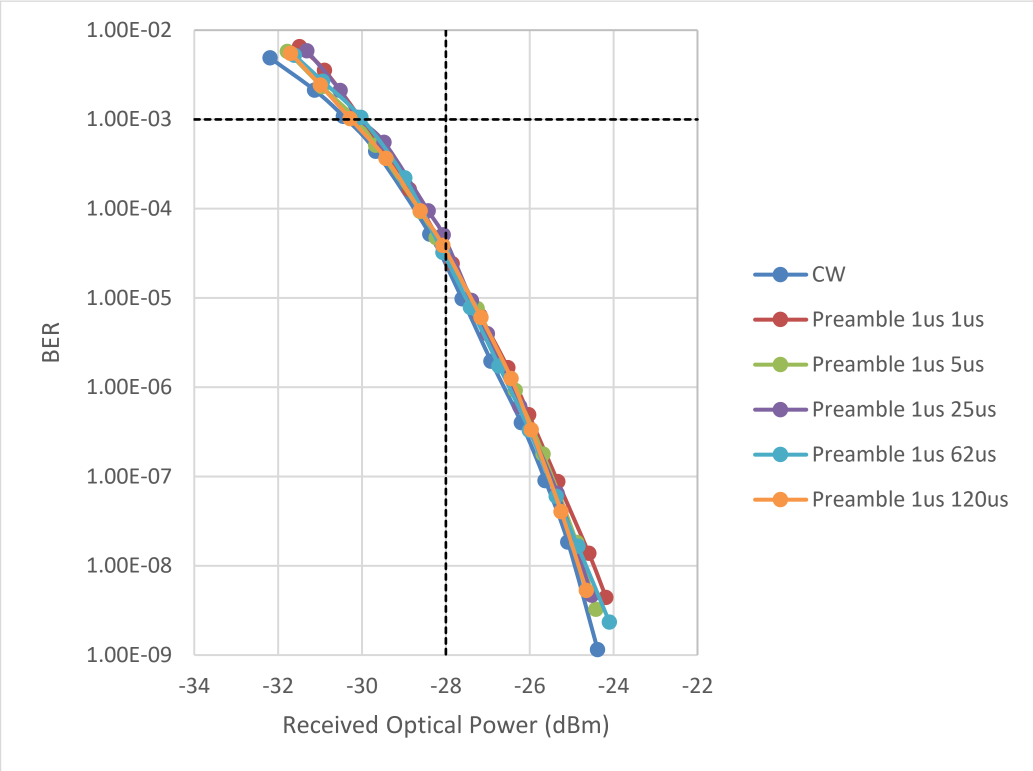

Figure 4.13: BER curves for different payloads and 1 μs preamble.

Supported by the figure 4.13, the general performance of system maintains approximately the same, inclusively when compared to the CW. Showing that the BOSA can operate evenly in CW and burst mode as desired. Table 4.6, presents the results taken for ROP in this previous case different payloads maintaining the preamble at 1 μs.

Preamble (us)	Payload (us)	Required Optical Power B2B (dBm)
CW		-30.4
1	1	-30.0
1	5	-30.2
1	25	-30.1
1	62	-30.1
1	120	-30.3

Table 4.6: ROP values for different payloads with 1 μs preamble.

From table 4.6, the values for ROP are very similar and the cases that seem to present worst results are the preamble of 1 μs and payload also 1 μs. This was expected, due to the already referred time for charge and discharge the capacitors, and with this very short burst the receiver time response is demanding.

The curves obtained in figure 4.14 were obtained for the minimum payload possible that the used system can achieve, so it was possible to conclude if the global performance was affected or not with decrease of payload length.

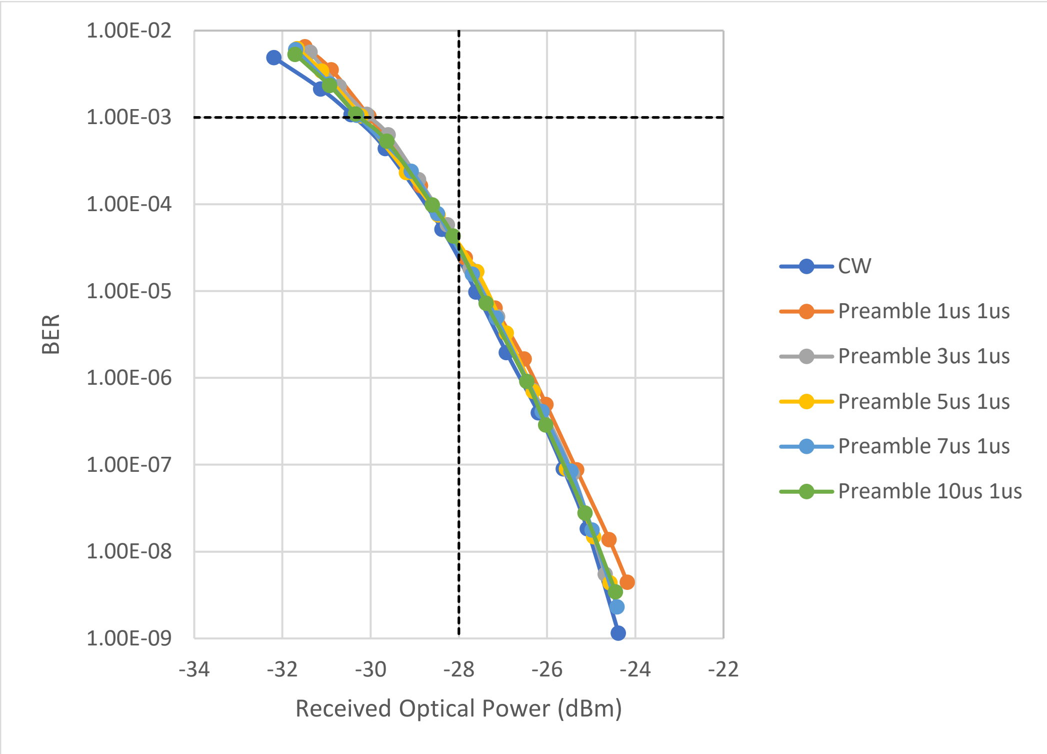

Figure 4.14: BER curves for different preambles and 1 µs payload.

As observed in figure 4.14, the curves are practically overlapped. As already referred, the expected worst case was when the preamble and the payload are 1 µs, since the receiver has to respond in a very short time window, the remaining cases should present identical required optical powers.

Table 4.7, presents the summary results for the previous BER results, analyzed with different preambles and payload 1 µs.

Preamble (us)	Payload (us)	Required Optical Power B2B (dBm)
CW		-30.4
1	1	-30.0
3	1	-30.1
5	1	-30.2
7	1	-30.3
10	1	-30.3

Table 4.7: ROP values for different preambles with 1 µs payload.

From table 4.7, it is seen that a maximum difference between CW and the anticipated worst case scenario is 0.4 dB which is acceptable.

It is possible to conclude that, as there is no performance degradation with the decrease of the preamble length, the system should operate at the lowest case to deliver maximum bandwidth to the subscriber. Meaning that this ROSA does not limit the system performance.

4.5 Conclusions

At this section it will be done a comparison between the two ROSAs studied in this chapter, the commercial and the test sample burst mode receiver. Figure 4.15, presents the BER curves from these two ROSAs, in which CR and TR stands for commercial and test ROSA respectively.

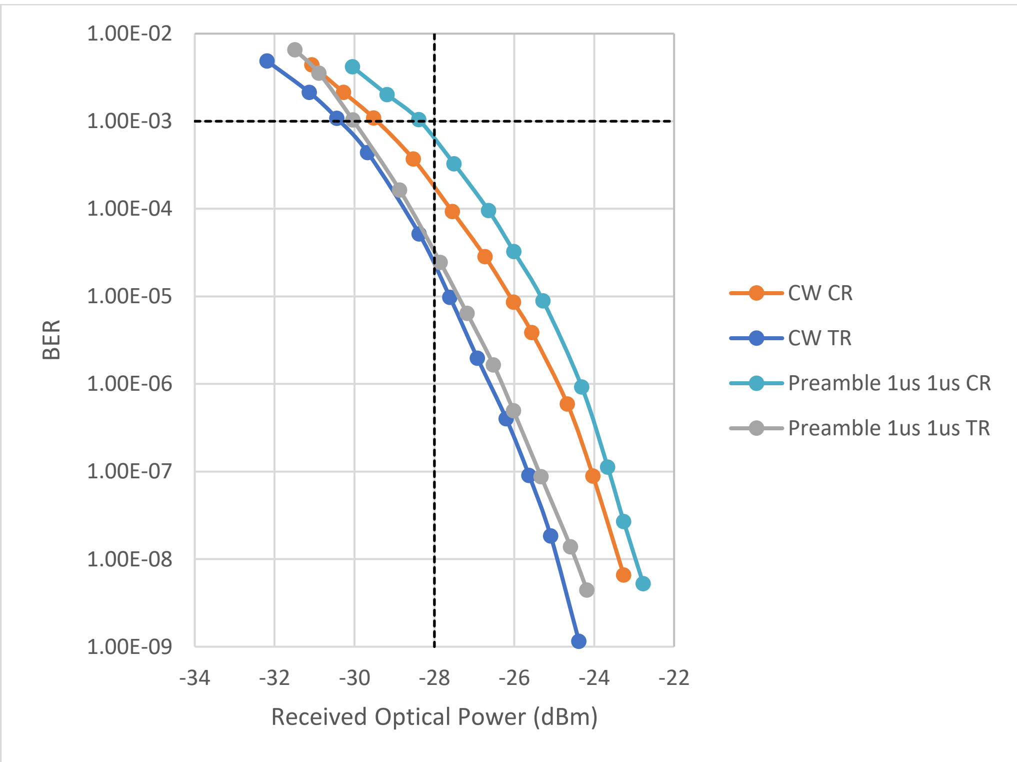

Figure 4.15: BER curves comparison between the two studied ROSAs.

From figure 4.15, it can be seen that exists a clear penalty between the two ROSAs, although the performance in each ROSA is similar from CW to worst case of the preamble and the payload 1 µs. It is only presented the cases of CW and 1 µs for preamble and payload in each ROSA, once these are the extreme cases. Table 4.8 presents the inherent penalties associated between the ROP in different cases addressed, the commercial and test sample ROSAs.

Burst Frame (us)		Required Optical Power B2B (dBm)		Penalty (dB)
Preamble (us)	Payload (us)	Commercial ROSA	Sample Test ROSA	
CW		-29.5	-30.4	0.9
1	1	-28.4	-30.0	1.6
1	5	-29.0	-30.2	1.2
1	25	-29.1	-30.1	1.0
1	62	-29.2	-30.0	0.8
1	120	-29.2	-30.3	1.1

Table 4.8: ROP comparison between the two presented ROSAs.

Table 4.8, shows the ROP for the two ROSAs, for CW the penalty was 0.9 dB, and the maximum penalty observed was 1.6 dB between the receivers in the worst case scenario. Supported by these results, the TR presented better sensitivity results than CR showing that the former is, in one hand compliant with the specifications targeted and on the other hand has margins to be taken into mass production.

Chapter 5

Conclusions and future work

5.1 Conclusions

This dissertation had as objective the study and analysis of the NG-PON2 technology, more concretely the optical transceivers for OLT to NG-PON2. Chapter 2, introduces the PON roadmap, as well the main optical components and figures of merit for NG-PON2 technology. Thereby, the scope of this dissertation was, in a first phase to conclude about the feasibility of the first OLT XFP prototype from PICadvanced, SA, what was achieved, and perform a manual sweep of parameters for a future automatic calibration of OLT XFP. Taking the previously mentioned, in chapter 3, a characterization of OLT XFP transmitters for NG-PON2 was done. A comparison between a commercial OLT transmitter and two OLT TOSAs was made, in order to conclude if the ITU-T G.989.2 standards are met, regarding power, eye diagram opening, ROP and OPP. It was possible to verify that, although the second TOSA studied brings improvements on the eye diagram, as it was expected the general performance its better with the TOSA that was already assembled in the XFP prototype for OLT.

In chapter 4, it was introduced the burst mode operation of an ONU, and as in the case of transmitter, several figures of merit are presented and measured. One of the major difficulties on the OLT reception is the thermal compensation. Regarding the tests, several BER curves were obtained, changing the length of slots that compose the burst frame, in order to conclude if the system performance varies, and how. Finally, in the same chapter, it was done a comparison between the two ROSAs. The test sample burst mode ROSA lead to better results than the commercial one, which is quite positive, since it opens up great possibilities, together with the transmitter discussed in chapter 3, to develop an XFP for the

OLT, with costs significantly lower (mainly from transmitter) than those proposed by OLT XFP sellers nowadays, opening up good perspectives for PICadvanced, SA , that already produces a significant number of ONUs, to start thinking about engineering samples to XFP OLT for NG-PON2.

5.2 Future work

The following topics present relevant points to pursue in future works regarding this subject:

- Do similar tests than the ones presented in this dissertation, with improved RF performance on the testing boards (still prototypes).
- Test the OLT TOSA and ROSA in a XFP encapsulation.
- Test different OLT TOSAs that meet the wavelength plan for NG-PON2.
- Firmware implementation for automatic calibration of OLT XFPs.

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