**Universidade de Aveiro** Departamento de
Electrónica, Telecomunicações e Informática,
**2016**

**Sérgio António
da Costa Coelho**

# Mecanismos de tuning em redes de acesso óticas

# Tuning mechanisms in optical access networks

**Universidade de Aveiro** Departamento de Electrónica, Telecomunicações e Informática,
**2016**

**Sérgio António da Costa Coelho**

# Mecanismos de tuning em redes de accesso óticas

# Tuning mechanisms in optical access networks

Dissertação apresentada à Universidade de Aveiro para cumprimento dos requisitos necessários à obtenção do grau de Mestre em Engenharia Electrónica e Telecomunicações, realizada sob a orientação científica do Prof. Dr. António Teixeira e do Prof. Dr. Mário Lima, ambos do Departamento de Electrónica, Telecomunicações e Informática (DETI) e do Instituto de Telecomunicações (IT) da Universidade de Aveiro

**o júri / the jury**

presidente / president — **Prof. Doutor Nuno Borges de Carvalho**
Professor catedrático da Universidade de Aveiro

vogais / examiners committee — **Professor Doutor António Luís Jesus Teixeira**
Professor associado da Universidade de Aveiro (orientador)

**Prof. Doutor Pedro Tavares Pinho**
Professor adjunto do Instituto Superior de Engenharia de Lisboa

**agradecimentos**

Esta dissertação marca o final de um capítulo da minha vida. Foi um percurso moroso e difícil, com momentos altos e baixos, dos quais levo recordações que ficaram comigo para o resto da vida. Aproveito para deixar alguns agradecimentos as pessoas que mais me marcaram neste percurso.

Em primeiro lugar, não poderia deixar de ser, um agradecimento especial aos meus pais, Cristina e Nelo, aos meus irmãos, Patricia, Manuel e Margarida, pelo seu apoio incondicional. Certamente sem eles tudo isto não seria possível. A minha afilhada, Luana, por ser uma fonte de alegria constante na minha vida.
Gostaria também de agradecer aos meus amigos de infância, Marcel, Cátia, Virgínia, Carla, Joel e Coralie, fomos criados juntos e muito aquilo do que sou hoje devo também a vocês.

Gostaria de agradecer ainda a todos amigos e colegas de vida académica, Carlos Salgueiro, Rui Puga, Samuel Moreira, André Faceira, João Gonçalves, Tiago Urze, Hugo Veloso, Luís Pinheiro, João Andrade, Luís Matos e Miguel Leite tanto pelos momentos de diversão como pelas noites de estudo. Todos vós, de uma maneira ou de outra me ajudaram a moldar e expandir os meus horizontes, certamente me tornaram uma pessoa melhor. Um abraço especial ao José Maricato, companheiro de longa data tanto em Portugal como em Erasmus.
Não podia deixar de mencionar também os, poucos mas bons, amigos que fiz em Erasmus: Mladen, Nikola, Bojan, David, Branka, Ida, Heinrich, Felipe, Milica.
Uma menção ainda para a Eng. Ana Tavares pela sua incansável ajuda no laboratório, um muito obrigado pela paciência disponibilizada.

Por fim, um agradecimento especial aos meus orientadores, Prof. Dr. António Teixeira e Prof. Dr. Mário Lima, pela ajuda dispendida, mas principalmente pela motivação que me deram para finalizar este trabalho

**Palavras-Chave**

NG-PON2, TWDM-PON, PtP WDM-PON, redes de acesso, redes óticas passivas, lasers sintonizáveis, mecanismos de tuning, receptores sintonizáveis, tempo de sintonização, precisão de tuning.

**Resumo**

O principal tema abordado neste trabalho é a tecnologia a ser utilizada em redes passivas óticas de nova geração, nomeadamente o TWDM e o PtP WDM, com um foco em especial nos mecanismos de tunabilidade a ser usados nas arquiteturas de rede mencionadas. Começou por ser feita uma abordagem geral ao tema, um "overview" a recomendação para o NG-PON2 é apresentada, assim como uma revisão a transceivers incolores, componentes essenciais nas arquitecturas do NG-PON2. Tendo em conta o nível de precisão apresentada, três tipos de ONUs são definidas nos standards do NG-PON2, e os mecanismos de tuning necessários para lidar com os diferentes tipos de ONU são também apresentados.

Foi caracterizado um laser sintonizável (DFB) tendo em vista a sua utilização numa ONU do NG-PON2, os parametros avaliados foram: tempo de sintonização, excursão espectral e precisão de tuning. As técnicas de medição são apresentadas bem como os resultados obtidos.

**Keywords** NG-PON2, TWDM-PON, PtP WDM-PON, access networks, passive optical networks, tunable lasers, tuning mechanisms, tunable filters, tuning time, tuning accuracy.

**Abstract** The main issue addressed in this work are the technologies to be employed in the next-generation passive optical networks, including TWDM-PON and PtP WDM, with a particularly focus on the tuning mechanisms featuring the aforementioned network architectures. A general approach to the topics was carried out, by making an overview the NG-PON2 recommendation, a review to colorless transceivers is presented as well, essential components on the NG-PON2 architectures. Three types of ONUs are defined in NG-PON2 standards, by taking into account the accuracy level of the ONU Tx, tuning mechanisms necessary to to deal with the different kind of ONUs are presented as well

A tunable DFB laser was characterized, considering its utilization on a NG-PON2 ONU. The evaluated parameters are: tuning time, spectral excursion and tuning accuracy. The setups utilized for the measurements are presented as well as the results.

# Contents

# List of Figures

# List of Tables

# List of Acronyms

**AES** Advanced Encryption Standard

**AMCC** Auxiliary Management and Control Channel

**AN** Access Network

**APON** Asynchronous Transfer Mode-based Passive Optical Network

**ATM** Asynchronous Transfer Mode

**AWG** Arrayed Waveguide Grating

**BPON** Broadband Passive Optical Network

**CAPEX** Capital Expenditure

**CE** Coexistence Element

**CG** Channel Group

**CO** Central Office

**CS** Channel Spacing

**CT** Channel Termination

**DBA** Dynamic Bandwidth Allocation

**DCT** Dispersion Compensation Technique

**DBR** Distributed Bragg Reflector

**DFB** Distributed Feedback

**DML** Direct Modulated Laser

**DWBA** Dynamic Wavelength and Bandwidth Allocation

**EML** Externally Modulated Laser

**FEC** Forward Error Correction

**FSAN** Full Service Access Network

**FSR** Free Spectral Range

**FTTB** Fiber to the Building

**FTTC** Fiber to the Curb

**FTTH** Fiber to the Home

**IP** Internet Protocol

**ITU** International Telecommunication Union

**NG-PON2** Next-Generation Passive Optical Network 2

**OLT** Optical Line Terminal

**ONU** Optical Network Unit

**OPEX** Operating expense

**OSA** Optical Spectrum Analyzer

**P2P** Point to Point

**P2MP** Point to Multi-point

**PAYG** pay-as-you-grow

**PLOAM** Physical Layer Operations, Administration and Maintenance

**PON** Passive Optical Network

**PtP WDM** Point-to-Point Wavelength-division multiplexing

**QoS** Quality of Service

**RN** Remote Node

**Rx** Receiver

**SOA** Semiconductor Optical Amplifier

**SSW** Single-Side Spectral Width

**SW** Wavelength Channel Selector

**TEC** Thermo-Electric Cooler

**TFF** Thin Film Filters

**TDMA** Time Division Multiple Access

**TDM-PON** Time-Division Multiplexing Passive Optical Network

**Tx** Transmitter

**TWDM-PON** Time and Wavelength Division Multiplexed Passive Optical Network

**US** Upstream

**WM** Wavelength Multiplexer

**WR-ODN** Wavelength Routed ODN

**WS-ODN** Wavelength Selected ODN

**XG-PON1** 10×Gigabit Passive Optical Network

# Chapter 1

# Introduction

Nowadays we live in an era that might be called connected age. In contrast with its predecessor, information age in which the core business was and still is to develop monolithic intangible goods and profiting using licensing fees and strict control of software copying, connected age comes in the picture when enterprises started monetizing the human behavior on the web. [1] With the evolution and rise of technologies such as smart phones and tablets, and with the proliferation of network access points, to be or not connected is in the tip of your finger. Thus social networking became a huge thing, from Facebook to Youtube, and even Twitch TV (streaming service), all services that profit with the connectivity of people. Also the availability to buy and download products from the web (music, films, games) cause a ever increasing demand of network bandwidth, therefore the network it self must evolve in order satisfy the users needs, new future services and maintain a certain Quality of Service (QoS).

## 1.1 Context and Motivation

When it comes to select an ideal solution for an Access Network (AN) there is a continuous struggle to balance infrastructure investments against the need to deliver stronger financial returns. It is with this factors in mind that Passive Optical Networks (PONs) for access come in the picture.

In a PON, a single fiber between the Optical Line Terminal (OLT) and the Remote Node (RN) is shared by all users connected to it. The network between the OLT and the Optical Network Units (ONUs) is passive, which means that there is no need of any power supply in this path.

PON standardization started in the early 1990s, by the hands of the Full Service Access Network (FSAN) working group, and led to the creation of APON in 1995, which later was improved to Broadband Passive Optical Network (BPON) in 1998, redefining it in 2005 to allow higher bit rates. The maximum data rates achievable for this technology are 1.2 Gb/s and 622 Mb/s for downstream and upstream respectively. [2] [3]

In 2001, FSAN group started the development of GPON (Gigabit Passive Optical Network), standardized in 2003 by the International Telecommunication Union (ITU), to keep pace with the increasing demand for bandwidth. This later standard supports downstream bit rates up to about 2.5 Gb/s and upstream bit rates up to about 1.25 Gb/s. [2] [4]

All currently deployed PON based on the standards referred before are known as Time-Division Multiplexing Passive Optical Networks (TDM-PONs) architectures since they rely on TDM technology. Upstream transmission is accomplished by time sharing the available bandwidth between all subscribers (TDMA), while downstream operation is performed by sending all data to all ONUs, being these responsible to select the data destined to the subscriber(s) associated. [2] [4]

Due to progressive massification of new types of traffic (such as 3DTV and cloud-based services) the ITU has already ratified new standards. 10×Gigabit Passive Optical Network (XG-PON1) was standardized in 2010. It allows 10 Gb/s and 2.5 Gb/s bit rates for downstream and upstream transmissions, respectively. Next-Generation Passive Optical Network 2 (NG-PON2) specifications are being standardized, the first set of recommendations was issued in the start of 2013, G.989.1. [5], allowing 40 Gb/s symmetrical bandwidth, using a Time and Wavelength Division Multiplexed Passive Optical Network (TWDM-PON) based architecture, with a Point-to-Point Wavelength-division multiplexing (PtP WDM) PON overlay.

TWDM-PON increases the aggregate PON rate by stacking four XG-PON1 using four pairs of wavelengths. The only significantly new components in TWDM, and used for simple network deployment and management purposes, are colourless tunable transmitters and receivers.

The NG-PON2 specifications for wavelength plan, and channel spacing are covered by the well matured tunable devices technologies developed for core/metro networks, (full C-band or L-band with more than 80 channels). However, they require a considerably reduced number of wavelength channels. Although there is a need for low volume of TWDM downstream transceivers and costs will be shared across multiple subscribers, when it comes to choose an upstream Transmitter (Tx) low cost solutions are preferable. Taking this into consideration, NG-PON2 specifications defines three types of ONU Tx [5]: calibrated, loosely calibrated and uncalibrated. Therefore multiple tuning mechanisms must be enabled in the PON in order to activate and deal with the different kinds of ONUs.

NG-PON2 systems takes advantage of the tunable Tx and Rx, not only they provide colorless ONUs and pay-as-you-grow deployment, some advanced network functions resulting from in-service wavelength tuning techniques may feature in the system as well. The maximum service interruption required for in-service tuning in NG-PON2 is 50 ms [5] Therefore tuning time is an important ONU parameter, which will be decisive regarding the implementation or not of in-service tuning functionalities.

## 1.2 Structure and Objectives

This document is divided in 5 chapters, and the main objectives are the following:

- Overview of the NG-PON2 recommendation.
- Study the available tunning mechanisms in NG-PON2 systems.
- Overview on tunable transceivers.
- Testing of tunable lasers available in the laboratory, regarding the tunable characteristics.

In the first chapter are presented the context and motivation, structure and objectives, as well as the contributions according to the author's opinion.

The second chapter presents the state of the art, in that sense PON's preponderance in access networks is reviewed as well as the Legacy PONs structures and main features in order to introduce the NG-PON2 systems.

In the third chapter an overview of the NG-PON2 recommendation is presented, with a focus in the tunable characteristic of the network architecture. The relevant parameters of tunable ONUs are briefly described and a quick overview on tunable lasers' tuning mechanisms and receivers is also presented.

Fourth chapter features a characterization of tunable transceivers to be used in NG-PON2 as well as the experimental results on a transceiver tuning time measurement and accuracy.

Finally in the fifth chapter conclusions taken from the carried out work are presented as well and some future work related to this topic is suggested.

## 1.3 Contributions

In the author's opinion the main contributions of this work are as follows:

- Identification of the currently available tuning mechanism to be used in NG-PON2 deployment, distinguishing three types of tuning mechanisms regarding the use of calibrated, loosely calibrated and uncalibrated transmitters.
- Characterization of a tuning transmitter to be used in NG-PON2, tunable time measurement, and determination of tuning accuracy for a DFB laser.

# Chapter 2

# State of Art

## 2.1 Telecommunication Network

A modern telecommunication network general structure consists of three main sub networks: backbone or core network, metro or regional network, and the access network. Fig. 2.1 presents a simple scheme of a telecommunication network. The Backbone Network as the core, interconnects all metro/regional networks of a country. The Metro Networks aggregate the high traffic from access networks' (AN) Central Office (CO), transport the data at higher speed, pass that traffic addressed to other metro/regional areas to the core network and delivers to the respective central office the remaining traffic.

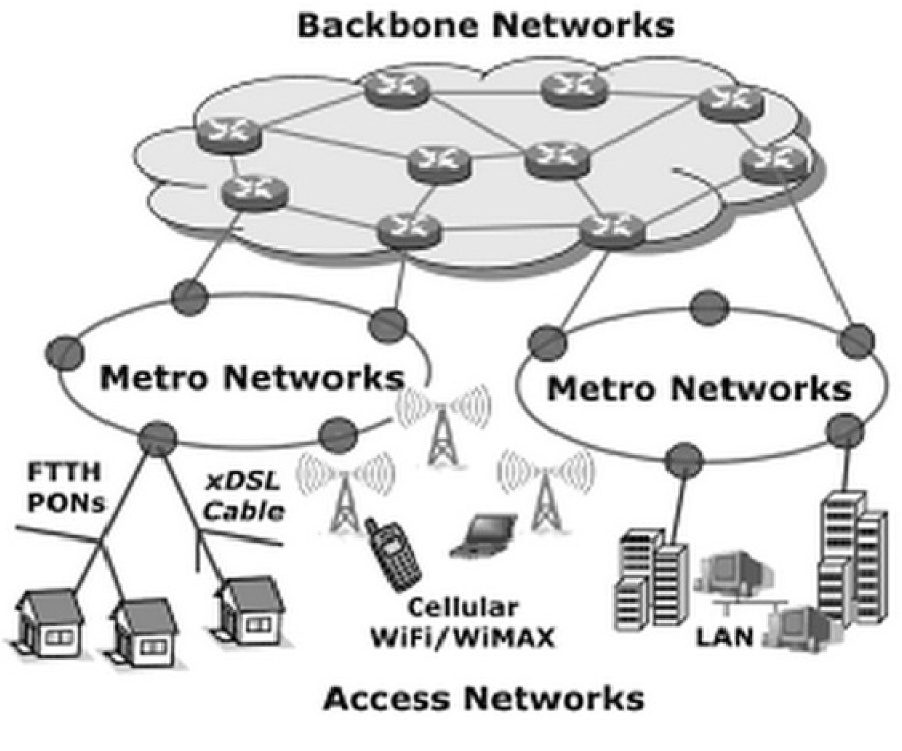



Figure 2.1: Architecture of a telecommunication network [2]

The core and metro networks structures are usually more uniform that the access network, and have their cost shared by a large number of users. Finally, the access network which provides end-user connectivity, e.g. AN is the bridge between the user and the service provider.

Table 2.1: Characteristics of the several types of a telecommunication network [6]

| **Network Type** | **Characteristics** |
|---|---|
| **Core** | Has active elements;<br>Low granularity;<br>Low variation in traffic flow;<br>Operate with a lower number of protocols than metro networks;<br>Transport traffic over long distances;<br>Use a irregular mesh topology; |
| **Metropolitan** | Has active elements;<br>Medium granularity;<br>Medium fluctuation in traffic flow;<br>Covers high density population areas;<br>Use ring topologies; |
| **Access** | Passive optical network (PON);<br>High granularity;<br>High fluctuation in traffic flow;<br>Operate with a variety of protocols (IP, ATM, Ethernet);<br>Covers small distances;<br>Have a wide variety of topologies implemented |

## 2.2 Optical Access Network

Nowadays the most cost efficient solution in access networks is the PON, which makes the fiber access one of the most important technologies in the next generation networks. Before overlooking the role of PON's in AN, is of the most importance to understand what an AN is. An AN provides the connection between subscribers and service providers, it is the last segment of an operator network which enables users to access the network itself, either to transmit or receive data, voice and so on. Optical AN are constituted of an optical line terminator (OLT) located at the CO, Remote Node (RN), and a Optical Network Unit (ONU) to terminate the fiber.

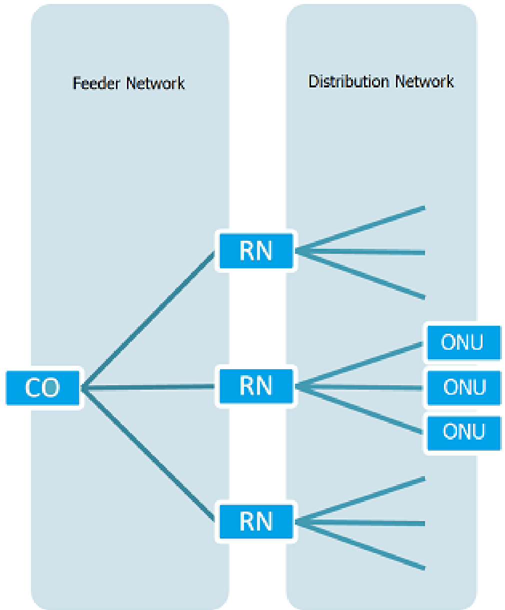



Figure 2.2: High-level architecture of an access network [6]

An AN can be perceived as two distinct networks, the distribution and the feeder network, as can be seen in Fig.2.2 The first one connects the RN with the respective ONUs, and the second one connects the CO with the RNs. The RN can be active or passive.

## 2.3 PON and the FTTx Network Models

According to Ovum [7] PON is, nowadays, the dominant FTTx technology due to the cost advantages of its point-to-multipoint architecture compared to other solutions. Ovum also forecasts that more than 90% of the expected 300 million FTTH subscribers in 2019 will be PON Networks. Fig. 2.3, represents the several applications models of an optical access networks, the so called FTTx. The different architectures are characterized by the fiber length and the ONU location relatively to the user end [4]. Citing, Fiber to the Curb (FTTC), Fiber to the Building (FTTB) and Fiber to the Home (FTTH).

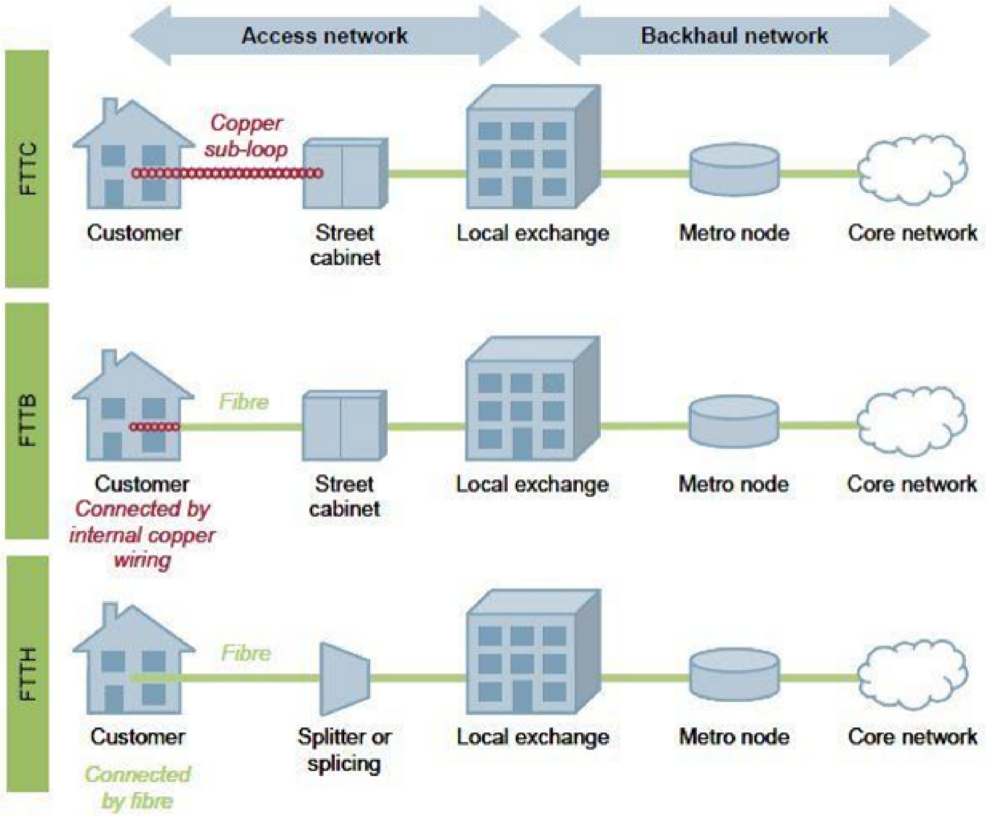



Figure 2.3: FTTx application model in PON [4]

PONs are the attractive solution for the FTTx due to the inherent characteristics of its passive RN, Fig. 2.4 represents the architecture of an FTTH PON, in contrast, and active RN requires constant power supply, backup power, and additionally, a cabinet for its placement, raising the Capital Expenditure (CAPEX) and Operating expense (OPEX).

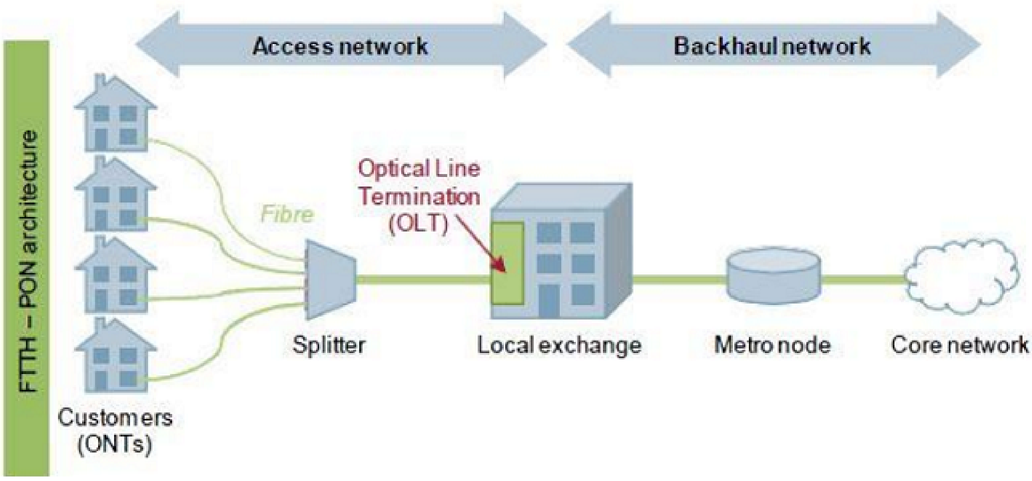



Figure 2.4: Passive optical network architecture [4]

PON is a Point to Multi-point (P2MP) system, as it is referred before. Some authors argue that P2P optical network can be considered a PON due to connection between the OLT and the ONU being completely passive. Nevertheless the most common and widespread definition to PON is P2MP.

The feature of passiveness makes the network deployment flexible and advantageous [6]:

- Both, equipment and fiber in the CO are shared (smaller number of fibers in feeder), providing lower cost than in a Point to Point (P2P) solution. Above all, power supply is not needed for the RN, greatly reducing the CAPEX;

- Trough the removal of the active equipment, there is a reduction in the electromagnetic interference, decreasing the failure rate of the line and the external equipment. This provides easy maintenance, lower CAPEX and also lower OPEX;

## 2.4 Legacy PON Systems

ITU Study Group 15 Q2 completed the recommendations that define a GPON (gigabit passive optical network) [ITU series G.948] in 2004, since then, FTTx based on PON have been largely deployed. Full Service Access Networks (FSAN), along with the ITU are the forum and the standardization entities with the greatest activity in study this type of networks. Their point of view on next generation networks divides the evolution on two stages, NG-PON1 and NG-PON2, the first one is known as 10×Gigabit Passive Optical Network (XG-PON1) and it is considered as short-term solution, a transition technology, standardized since 2010, while NG-PON2 technology is seen as a medium-term solution (2015) Fig. 2.5, its standardization was initiated on the beginning of 2013 [5].

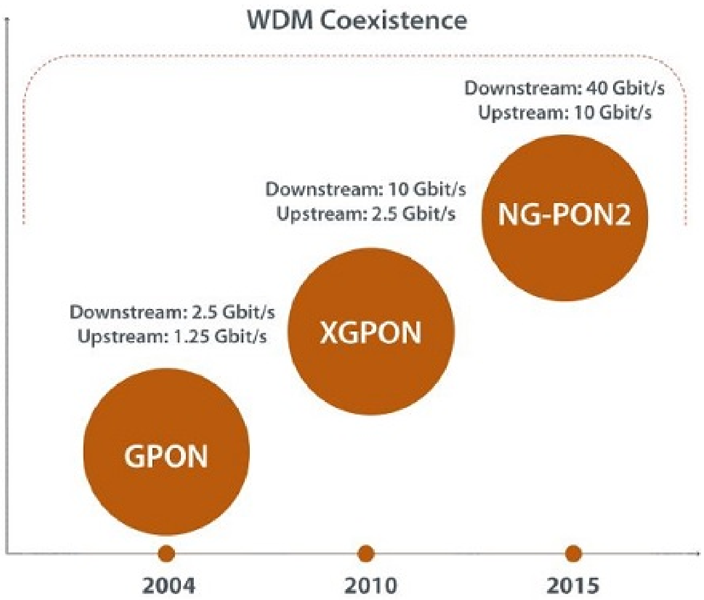



Figure 2.5: PON Evolution [8].

### 2.4.1 G-PON

Gigabit passive optical network (G-PON) is currently a mature technology, ITU started working on G-PON in 2002 and there is the G.984.x series of recommendations, standard series define general characteristics of GPON (G.984.1) as well as physical layer specification (G.984.2), transmission layer specification (G.984.3) and ONU (Optical Network Unit) management and control specification (G.984.4). G-PON has an enhanced capability comparing with its predecessors, APON and BPON (ATM PON which evolved in to Broadband PON), and is backward compatible. Being G-PON a passive network, only the OLT and the ONU are active equipments.

#### G-PON architecture

Sarting from the Central Office (CO), only one single-mode fiber strand is connected to a splitter near the users' end, Fig.2.6.

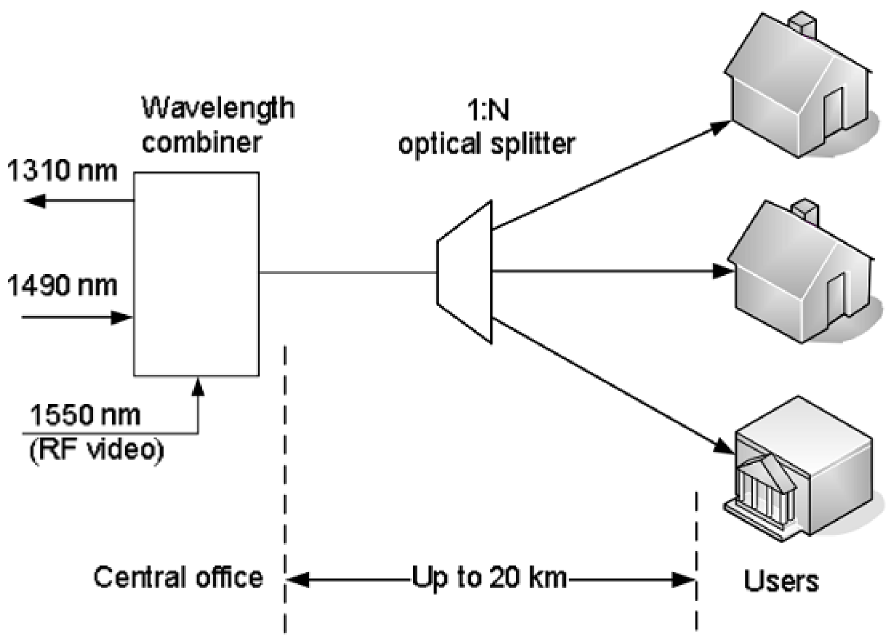



Figure 2.6: Typical GPON architecture [9]

The optical splitter simply divides the signal into N separate paths to the subscribers. From this point, the number of paths that the optical power can be divided into may vary from 2 to 64, thus the split ratio capability of a G-PON network is 1:128. After the splitting, individual single-mode fiber strand run to each user (home, businesses, etc.). The optical fiber transmission span from the central office to the each user can be up to 20 km [9].

The network is capable of supporting the bandwidth requirements of business and residential services and covers systems with lot of different line transmission rates for downstream and upstream direction.

Table 2.2: GPON Nominal bit rate [9].

| Transmission Direction | Bit Rate |
|---|---|
| **Downstream** | 1244.16 Mbit/s |
| | 2488.32 Mbit/s |
| **Upstream** | 155.52 Mbit/s |
| | 622.08 Mbit/s |
| | 1244.16 Mbit/s |
| | 2488.32 Mbit/s |

### G-PON trasmission and main features

The operating wavelength range is 1480-1500 nm for the downstream direction and 1260-1360 nm for upstream direction. In addition, the wavelength range 1550-1560 nm can be used for downstream RF video distribution, Fig.2.7.

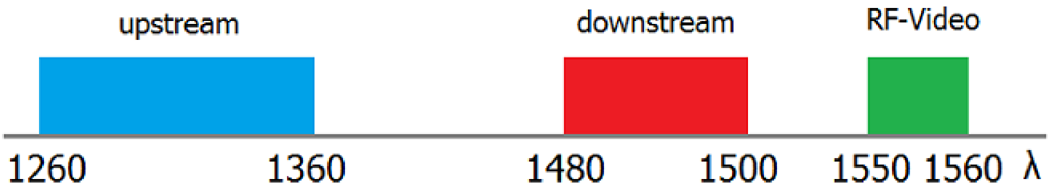



Figure 2.7: G-PON wavelength allocation

**Downstream** transmission, on G-PON, consists in broadcasting fixed frames of 125$\mu$s from the OLT to the ONUs. Although all the ONUs receive the same data, GEM port ID are imbued in the frames which allows them to be differentiated therefore a filtering process will occur in the ONUs, a respective ONU will only receive data that was aimed to it in the first place [10] [11].

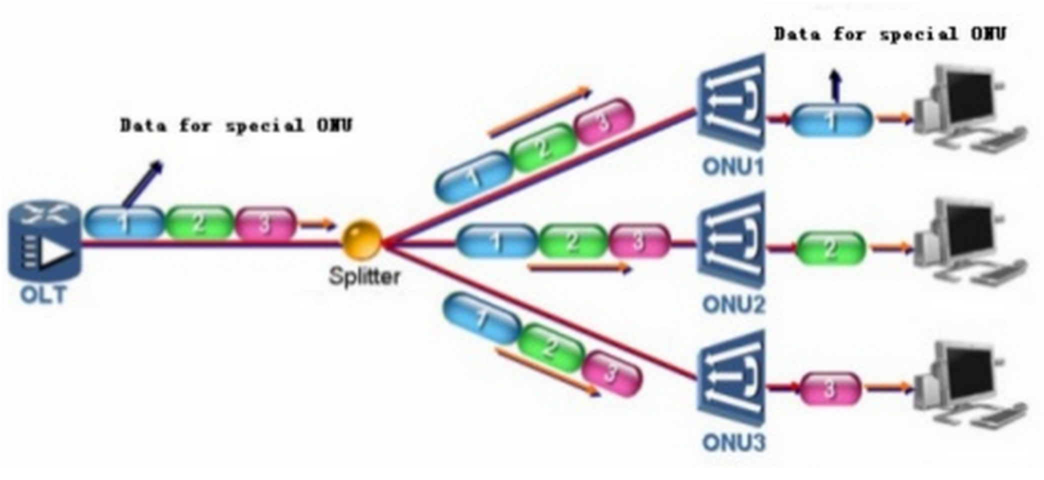



Figure 2.8: Downstream Transmission.
[12]

**Upstream** transmission, a multiple access protocol is used Time Division Multiple Access

(TDMA), Time Division Multiple Access in order to avoid packet collision. Each ONU has a respective time window when they are allowed to transmit upstream data. An Upstream Bandwidth Map is sent in the downstream frames which regulates time attribution to each ONU [10] [11].

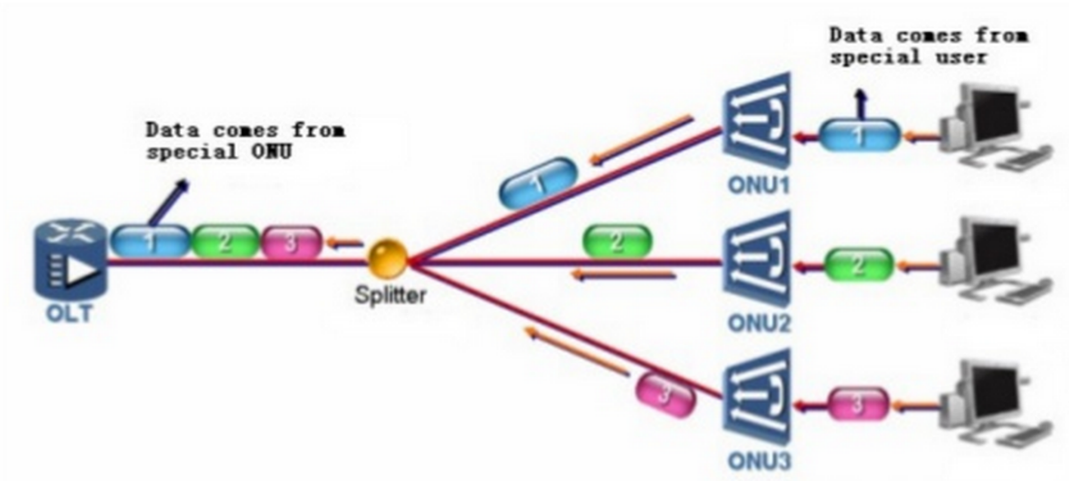



Figure 2.9: Upstream Transmission
[12]

Features such as Forward Error Correction (FEC) and Dynamic Bandwidth Allocation (DBA) are enabled .FEC is a mathematical signal-processing technique that encodes data so that errors can be detected and corrected. DBA is a methodology that allows quick adoption of users bandwidth allocation based on current traffic requirements [10] [13] [14].

#### Security and Protection

Regarding security, in the upstream direction G-PON uses point-to-point connection so all traffic is secured from eavesdropping. When it comes to downstream, the basic functionality of G-PON is that data is broadcast to all ONUs and every ONU have allocated time when data belongs to it (TDM). This could present a problem, since a malicious user could reprogram his own ONU to receive all downstream data belonging the other ONUs connected to that respective OLT. To prevent the referred security issues the GPON recommendation G.984.3 describes the use of an information security mechanism to ensure that users are allowed to access only the data intended for them. Advanced Encryption Standard (AES) is encryption algorithm that is used, it accepts 128, 192, 256 byte keys which makes the encryption extremely hard to compromise. Thus this key can be changed periodically, without disturbing the information flow, to enhance security [10].

There are two types of protection switching, Automatic switching and Forced switching. The first one is triggered by fault detection, such as loss of signal, loss of frame, signal degrade and so on. The second one is activated by administrative events, such as fiber re-routing, fiber replacement, etc. However, protection is considered as an optional mechanism because its implementation depends on the realization of economical systems.

### 2.4.2 XG-PON/NG-PON1

XG-PON (10-Gigabit-capable passive optical network) is a technology already standardized in the ITU Recommendations G.987.x, since 2010, and defines a mechanism migration to acquire transmissions of 10Gbit/s downstream and 2.5Gbit/s upstream. As it was referred before, XG-PON is viewed as a short-term solution, therefore, there are few technological suppliers, few interoperable equipment between manufacturers and few interested operators. XG-PON can be seen as the natural evolution of the G-PON Networks, nevertheless the need for larger bandwidth will lead operators to evolve directly into NG-PON2 [8], since its standardization is expected within this year, there are already the ITU Recommendation G.989.1 which defines the general requirements as well as physical layer specification G.989.2.

Wavelength plan is defined in ITU Recommendation G.987, Fig.2.10

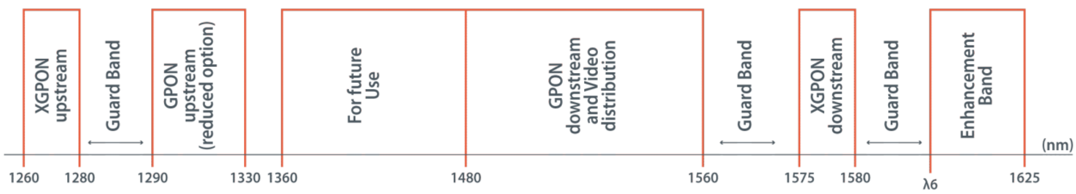



Figure 2.10: Allocation of G-PON XG-PON wavelengths
[8]

The operating wavelength range is 1575-1580nm for the downstream direction and 1290-1330nm for upstream direction. Coexistence of XG-PON with the G-PON technology is possible within the same fiber that requires a WDM filter in the CO to combine the users signal and the RF-Video [10] [13] [15], Fig.2.11.

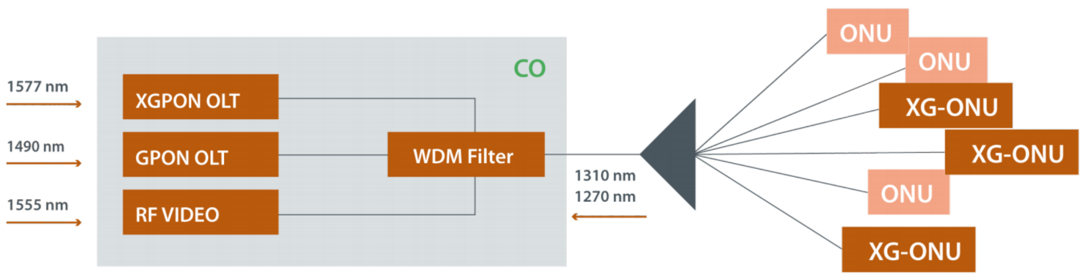



Figure 2.11: G-PON and XG-PON coexistence
[8]

## 2.5 Tunable Light sources

Semiconductor lasers have the potential to meet demands for next generation high speed optical networks. Their low cost, wide tunability, low power consumption, and very good spectral response make them ideal transmission sources. Colorless components will be essential in NG-PON2 deployment. In the this section we will review some characteristics of semiconductor lasers, in particular the tuning mechanisms behind such devices that provide a colorless mode of operation within a determined wavelength range.

### 2.5.1 Semiconductor lasers

Semiconductor lasers are popular optical communication light sources for high speed data transmission. They are accepted as “the laser of the future”, due to their compactness, easy integration, and high output powers. Coherent emission is produced in these lasers by stimulated emission, and the gain is achieved in the active medium of semiconductor by electrical injection [16]. Their gain material is usually a compound of elements from columns III and V of the periodic table. Typically they operate in the 1310-nm or 1550-nm region of the spectrum.

These diode lasers are compact, therefore, they are developed on a large scale using very mature fabrication technologies. Semiconductor lasers are very efficient in converting electrical power into optical power [17]. In order to study such type of device is important to first understand the basic structures and operations that comprise semiconductor lasers. From the simplest diode laser to the most complex one, all structures function on the same principle, an active medium (gain medium) is placed between two mirrors (Distributed Bragg Reflectors, High and Anti-reflector coatings or distributed grating), while the active medium is stimulated by injecting a current in order to produce emission, the mirrors provide a feedback and a selective function. When stimulated emission occurs, light from unwanted modes is reflected into the cavity in order to stimulate more photons. In short their wavelength is determined both by the properties of the III-V gain medium and by the physical structure of the laser cavity surrounding the gain medium [18].

### 2.5.2 Distributed Feedback Laser Diode (DFB)

In the DFB laser diode the active medium is periodically structured as a diffraction grating, figure 2.12 (bottom). The grating povides feedback and its wavelength (corrugation period) determines the wavelength emitted from the laser. The tunablity in this type of laser is achieved by thermally change the reflection index of the grating, thus this type of device is tunable in a narrowband, typically under 5nm. A conventional DFB laser’s emission wavelength can be tuned by heating or cooling with a gradient of about 0.08 nm/K. Widely tunable devices using DFB technology are available by incorporating various laser cavitys in the same device, DFB arrays, figure 2.12, coarse tuning is achieved by selecting the correct laser bar, and fine tuning is done thermally.

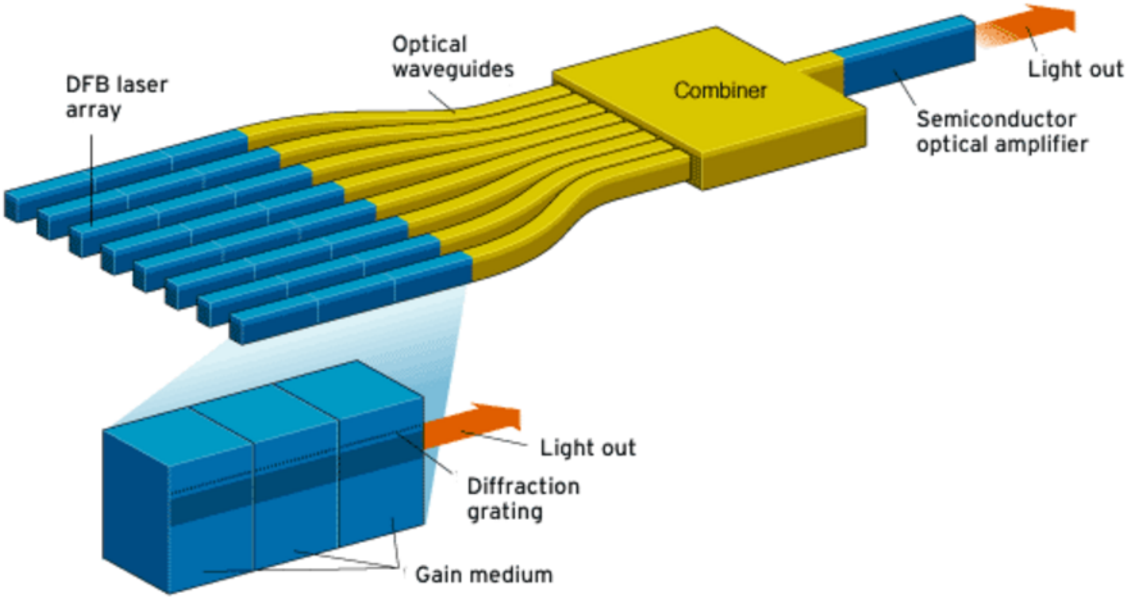
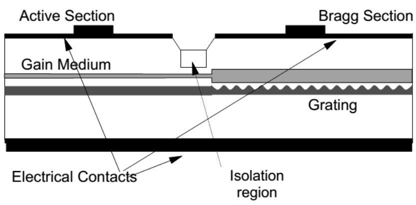


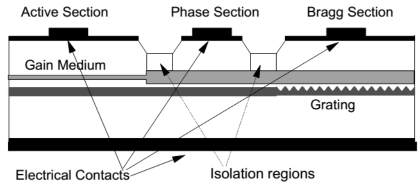

Figure 2.12: DFB Structure array [19].

### 2.5.3 Distributed Bragg Reflector laser (DBR)

The DRB laser structure lies within the placement of at least one Bragg Reflector outside the gain medium (active region) at one end of the resonator, and the other end may have another DBR, Figure 2.13a shows the schematics of a simply DBR laser. The gratings provides a wavelength-dependent feedback and thus a single-mode operation can be achieved. Although DBR lasers are usually a single-frequency laser, they present a small tunable range within the operating wavelength, this tuning is associated with the thermal characteristics of the Gratings, the reflection index of the grating can be changed by driving it with a current. Moreover a tuning within the free spectral range of the laser resonator may be accomplished with a separate phase section, which can be electrically heated, or simply by varying the temperature of the gain region via the drive current, wider tunning can be achieved by adding more sections, figure 2.13b.




(a) 2 section DBR Laser




(b) 3 section DBR Laser

Figure 2.13: DBR laser schematics [20]

DBR Tunable Lasers are electrically tunable, e.g., different modes are locked by injection current into one, or more existing sections of the laser, furthermore the lasing wavelength is a function of a multi-reflection-peak resultant of the feedback provided by the one or more DBR mirrors inside the cavity, lasers using this technology, such as, SG-DBR [21], SSG-DBR [22], GCSR [23], DS-DBR [24], DCG-DBR [25], have been widely reported in literature. In Table 2.3, some parameters and characteristics regarding this type of laser are presented.

Table 2.3: DBR Tunable Lasers [21] [22] [23] [24] [25].

| Laser-Parameter | Output Power | Tuning range | SMSR | Structure | Tuning Currents |
|---|---|---|---|---|---|
| Digital Supermode DBR (DS-DBR) | ~14 dBm | 45 nm | >40 dB | Front and Rear Gratings, Gain and Phase Section. | Front (0 - 200 mA) Rear (0 - 60 mA) |
| Sampled Grating DBR (SG-DBR) | ~4 dBm | 38 nm | >40 dB | Front and Rear SGDBR mirrors, Lever, Gain and Phase Sections. | N/A |
| Super Structure Grating DBR (SSG-DBR) | ~9 dBm | 40-60 nm | >35 dB | Rear and Front Reflectors, Gain and Phase Sections. | Front (0 - 15 mA) Rear (0 - 18 mA) |
| Digital Concatenated Grating DBR (DCG-DBR) | ~14 dBm | 60 nm | >30 dB | Rear and Front Concatenated Gratings,Gain and Phase Sections. | Front (0 -30 mA) Rear (0 -40 mA) |
| Grating assisted codirectional Coupler with rear Sampled grating Reflector (GCSR) | ~14 dBm | 40 nm | >30 dB | Rear Reflector, and Coupler in the Front Section, Gain and Phase Section | Front (0 - 16 mA ) Rear (0 - 16 mA) |

### 2.5.4 External Cavity Laser (ECL)

The ECL is based on a laser diode where the cavity is completed with external optical components and typically as one Anti-reflection coating end. The external components can vary, as well as the setup their set, nevertheless the external setup is made of a set of lens in order to provide a collimated beam, and some kind of diffraction grating in order to provide wavelength selectivity. Wavelength tuning is possible by including and adjustable element, a mirror or a diffraction grating, usually by mounting it on a structure such as a piezoelectric crystal. Figure 2.14 shows two types of configuration, a) Littrow configuration, b) is Littman–Metcalf configuration, the first one exhibits better output power, since the beam is reflected only once, in the other hand the second offers better wavelength selectivity.

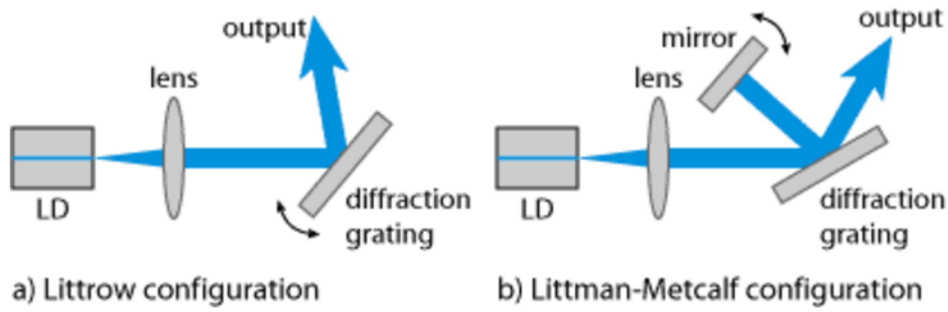



Figure 2.14: ECL Structure [26].

This type of structure provides a very wide tuning range, and a very narrow linewidth, but a relatively slow tunning.

### 2.5.5 Vertical Cavity Surface Emitting Lasers (VCSEL)

VCSEL achieve single longitudinal mode operation in different manner, the structures presented before are edge emitting lasers while the VCSEL a surface emitting laser. The cavity is placed between two highly reflective Bragg Reflectors (99.5% on the emitting surface and 99.9% on the other surface), one of the advantages of VCSEL lies within its structure, which provides a easier way to couple the emitted light into fiber. In the VCSEL tunability is achieved by including Micro-electro-mechanical (MEMs) part in the structure, the lasing wavelength is therefore selected by a combination of MEMs and thermal Tuning, figure 2.15.

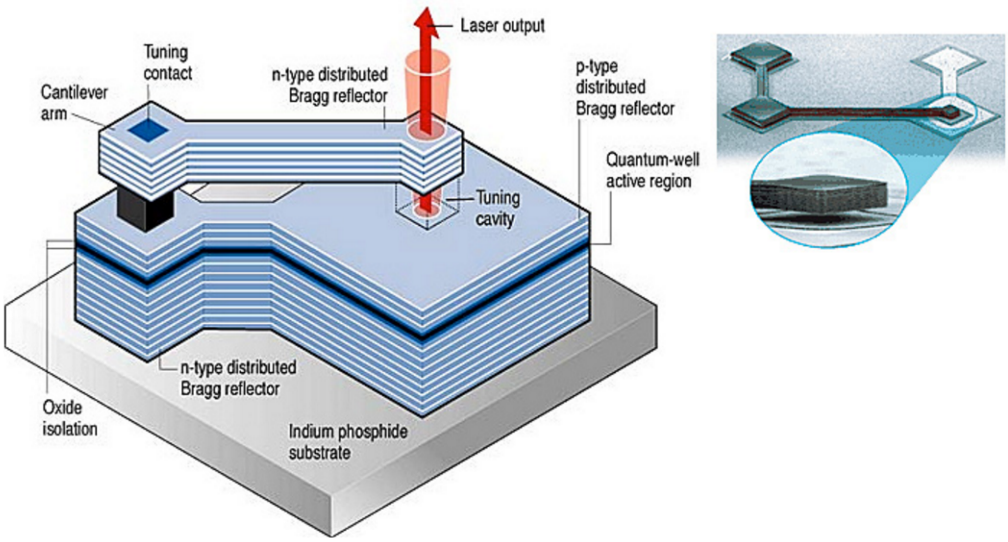



Figure 2.15: VCSEL Structure.

VCSEL/MEMs structures present relatively wide tunning, 30nm, but there is one concern in using MEMs, that lies within their long term mechanic reliability.

### 2.5.6 Lasers based on Hybrid III-V on SOI (Silicon-on-insulator)

Hybrid III-V on SOI devices integrates the advantage of III-V efficient light emission and amplification with the low loss and high index contrast waveguiding, for efficient spectrum filtering and tuning, of the silicon. The studied devices, are presented in [27, 28], use a set of extra-cavity ring resonators (RRs), and Bragg Reflectors (optional) in order to form two resonating structures with slightly different free spectral range (FSR), the RRs can thermally tuned, and the difference in the RR's FSR allows taking advantage of the Vernier Effect for wavelength selectivity and tunning. Also the FSR difference of the rings will determine the tuning range of the device. Such devices present wide tuning range 40 to 45 nm, and high values of SMSR, above 40 dB, and narrow linewidth, in the order of a few hundred kilohertz. Similar devices may be realized using at set of extra-cavity ring resonators on a Fabry-Perot cavity.

Based on the presented content above, it can be concluded that semiconductor lasing is associated with laser's cavity length, and intrinsic properties of the semiconductors used in the active sections. These properties rule the single-wavelength lasing characteristics of a laser. As far as tunability goes, three distinct categories can be distinguish: Temperature, Current Driven and Mechanical. The three are not mutually exclusive, since there are devices where a combination of at least two types are used. Table 2.4 summarizes the characteristics of the different tunning categories.

Table 2.4: Categories of tunability

| **Tuning Mechanism** | **Wavelength Range** | **Tuning Speed** |
|---|---|---|
| **Temperature** | NarrowBand 5nm | Slow (sub-s order) |
| **Mechanical (MEMs, piezoelectric transducer)** | WideBand<br>ECL - 100nm<br>VCSEL- 30nm | Very Slow (s-order) |
| **Current Driven** | Wideband - >30 nm | Fast (ns to $\mu$s order) |

## 2.6 Tunable Filters

In NG-PON2, a tunable wavelength selection device is required in the ONU, because each ONU should be able to get access to all wavelengths for dynamic bandwidth allocation. The wavelength selective filter is required to have wide tuning range to maximize the number of channels that can be selected, negligible crosstalk to avoid interference from adjacent channels, fast tuning speed to minimize the access time, small insertion loss, polarization insensitivity, stability against environmental changes (humidity, temperature, vibrations, etc.), and last but not the least, low cost [18]. Microring-resonator, thin film filter, Bragg gratings, Bragg reflectors, liquid crystal tunable filter, thermally tuned and angle tuned FP filters are the research focus. Several techniques will be introduced as example.

### 2.6.1 Microring resonator

Thermally tunable Si microring resonator (MRR)filter with flat-top passband is a promising candidate for WDM signal processing, because it is compact and easy to be integrated with other Si devices, including electro-optic modulators, optical routers and reconfigurable optical add drop multiplexers (ROADMs), etc. A thermally tunable Si 3rd order MRR filter has been proposed, which shows a box-like response with low intra-band ripple ( 0.65 dB), low insertion loss (less than 0.9 dB) and out-of-band rejection higher than 40 dB. By applying power to TiN heaters, the filter can be thermally tuned over the whole feedback shift register (FSR) of 3 nm with the tuning efficiency of 48.4 mV/nm [29].

### 2.6.2 Silicon Fabry-Perot filter (FPF)

FPF, also called as etalon, is realized by a silicon wafer with both sizes carefully polished. The incoming light experiences a multiple-beam interference. As a result, the wavelengths that match the resonant conditions are selected at the filter output as indicated in Eq 2.1

$$\lambda_m = (2nL_c \cos\theta)/m, \tag{2.1}$$

where $n$ is the etalon reflective index, $L_c$ is its length. By varying the reflective index or the length of the FP resonator, we can tune the output wavelength of the FP filter. For the reflective index tuning, we can use thermo optic effect, which is the refractive index variation induced by a temperature change. The thermo-optic effect is very strong and the thermally induced expansion of a silicon wafer is very poor, resulting in a large pre valence of the thermo-optic effect. A thermal tuning coefficient of 0.083nm/K is obtained at 1550 nm. The device can also be tuned by changing the optical path length in the cavity, which may be achieved mechanically, thermally, or electro-optically. Hence, the FP filter is a versatile and flexible component and a prime candidate for a wavelength selective filter in TWDM-PON systems. Furthermore the main advantage of fiber FP filters is that they can be integrated within the system without incurring coupling losses.

### 2.6.3 Thin Film Filter (TFF)

As a group, micro electro mechanical systems (MEMS) Fabry-Perot devices tend to possess wide tuning range, but have an serious limitation. They are structurally restricted to the simplest type of single-cavity etalon design. Plasma enhanced chemical vapor deposition (PECVD) is the preferred process for dense, compliant, homogeneous optical coatings of thin film silicon [30]. It is known that thin film narrowband filters may be tuned by mechanical rotation of the angle of incidence [31]. Nonetheless TFF including an integrated heater for thermal tuning were presented in [32]

### 2.6.4 Fiber Bragg grating (FBG)

FBG is also a technology to keep in mind due to its sharp spectral filtering characteristics and low insertion loss. Conventionally, the Bragg wavelength of FBGs can be shifted by imparting either the strain or temperature effect on a uniform FBG. Temperature change linearly shifts the Bragg wavelength through the refractive index variation of the grating induced by the thermo-optic effect [33]. Mechanically induced strain physically extends or compresses the grating period, which leads to a linear shift of the Bragg wavelength in conjunction with the refractive index change in the grating through the strain-optic effect. The excellent tolerance of silica-glass fibers to mechanical strain makes strain tuning preferable for achieving a wide tuning range.

Tunable receivers and tunable transmitters have been a research topic of optical transport networks for more than a decade, therefore there is a great deal of development practice in this area. The NG-PON2 system applications takes advantage of this component development effort in a couple of ways. Frist, the NG-PON2 tunable transceivers reuse mature tunable optical transport network components, if one technology does not perform to expectations, there is always other options to provide the required function. This versatility reduces the risk component availability. Second NG-PON2 can provide significant relief on the specifications of tunable optical transport network components. Because the NG-PON2 wavelength tuning performance could be relaxed from that of the optical transport network and NG-PON2 channel rates are widely used in the optical transport network, critical tuning requirements, such as wavelength tuning range, tuning speed, channel spacing, can be dramatically relieved. Such performance relaxation offers significant yield improvements during the mass production and cost reductions for tunable transceivers. [34]

# Chapter 3

# NG-PON2 General Requirements

The next generation passive optical network stage 2(NG-PON2) project was initiated by FSAN community in 2011. [35] The project's goal is to investigate optical fiber networks technologies enabling a bandwidth increase beyond the XG-PON's 10Gbit/s in the access network.

Next-Generation Passive Optical Network 2 (NG-PON2) is a multifaceted system, capable of meeting the different needs of a wide range of networks in a diverse market, and is deployable in several applications in a efficient manner. Taking in consideration that the ODN represents 70% of sum of the investments in the PON roll-out, NG-PON2 will not be a disruptive solution since re-utilizes the ODN infrastructure from previous PONs. Characteristics from legacy PON systems and ([ITU G.982], [ITU G.983], [ITU G.984], [ITU G.987]) are maintained as much as possible, as well as the re-use of established technical capabilities, to ensure some backward compatibility with the already exiting ODN's.

Many PON technologies have been proposed to provide broadband optical access beyond 10 Gb/s. There are the 40 Gigabit time-division multiplexed PON (40G TDM-PON) proposal [36] which increases the single carrier serial downstream bit rate of a 10 Gigabit PON (XG-PON) [15] to 40 Gb/s, the time- and wavelength-division multiplexed PON (TWDM-PON) proposal which stacks multiple XG-PONs using WDM [37], a group of WDM-PON proposals which provide a dedicated wavelength channel at the rate of 1 Gb/s to each ONU with different WDM transmit or receive technologies [38] [39] a set of orthogonal frequency-division multiplexed (OFDM)-based PON proposals which employ quadrature amplitude modulation and fast Fourier transform to generate digital OFDM signals for transmission [40] [41]. However, the requirement for backwards compatibility blocked of the way for WDM-PONs because they require wavelength selective ODNs. 40G TDM-PON is also out of consideration due to the cost pressure of 40G components in each user and the fiber chromatic dispersion would greatly limit transmission distance [42]. Other options are eliminated due to either technical immaturity or time-frame requirement. As result, all attentions turned to TWDM-PON, which attracted the majority support from global vendors and was selected among all of the aforementioned proposals by the FSAN community in April 2012 as a primary solution for NG-PON2, with PtP WDM overlay channels.

## 3.1 System Overview

NG-PON2 system requirements include support for [5]:

- Multiple wavelength channel TWDM architecture.
- 4-8 TWDM channel pairs (each channel pair comprising one downstream and one upstream wavelength channel), configurable for incremental growth starting from one deployed channel pair (i.e., not all channel pairs need to be active); for example, “pay as you grow” capability of TWDM populating in the OLT.
- Downstream and upstream nominal line rates per channel:
  - 10 Gbit/s downstream and 10 Gbit/s upstream
  - 10 Gbit/s downstream and 2.5 Gbit/s upstream
  - 2.5 Gbit/s downstream and 2.5 Gbit/s upstream
- Passive fiber reach of at least 40 km and maximum differential fiber distance up to 40 km with configurable maximum differential fiber distance as 20 km and optionally 40 km,
- Capability to reach 60 km, preferably with passive outside plant,
- Support for a split ratio of at least 1:256.

NG-PON2 systems require flexibility to balance trade-off in speed, distance, and split ratios for numerous applications. The set of parameter combinations that are supported by the system must include:

- 40 Gbit/s downstream capacity and 20 km reach with at least 1:64 split ratio,
- 10 Gbit/s upstream capcity and 20 km reach with at least 1:64 split ratio,
- Access to peak rates of 10/2.5 Gbit/s downstream/upstream,
- Longer distances with lower split ratios are also possible.

NG-PON2 systems may also support:

- 40 Gbit/s downstream capacity with 10 Gbit/s per upstream channel and 20 km reach with at least 1:64 split ratio,
- 2.5 Gbit/s per downstream channel and 2.5 Gbit/s per upstream channel with 40 km reach with at least 1:32 split ratio,
- 10 Gbit/s per downstream channel and 10 Gbit/s per upstream channel with 40 km reach with at least 1:32 split ratio,
- Acces to peak rates of 10/10 Gbit/s downstream/upstream,
- Tunable PtP WDM with capability to co-exist with other PON systems.

## 3.2 Architecture

The Basic NG-PON 2 architecture is shown in Figure 3.1. TWDM-PON increases the aggregate PON rate by stacking four XG-PON1 using four pairs of wavelengths (e.g, wavelength pairs of {λ1↑,λ1↓},{λ2↑,λ2↓},{λ3↑,λ3↓} and {λ4↑,λ4↓} in Fig.3.1). A TWDM-PON system with four pairs of wavelengths is able to provide 40Gbit/s downstream and 10Gbit/s upstream with 40 km reach and 1:64 split ratio. Each ONU can provide peak rates of 10Gbit/s and 2,5Gbit/s downstream and upstream, respectively, meeting the NG-PON2 requirements.

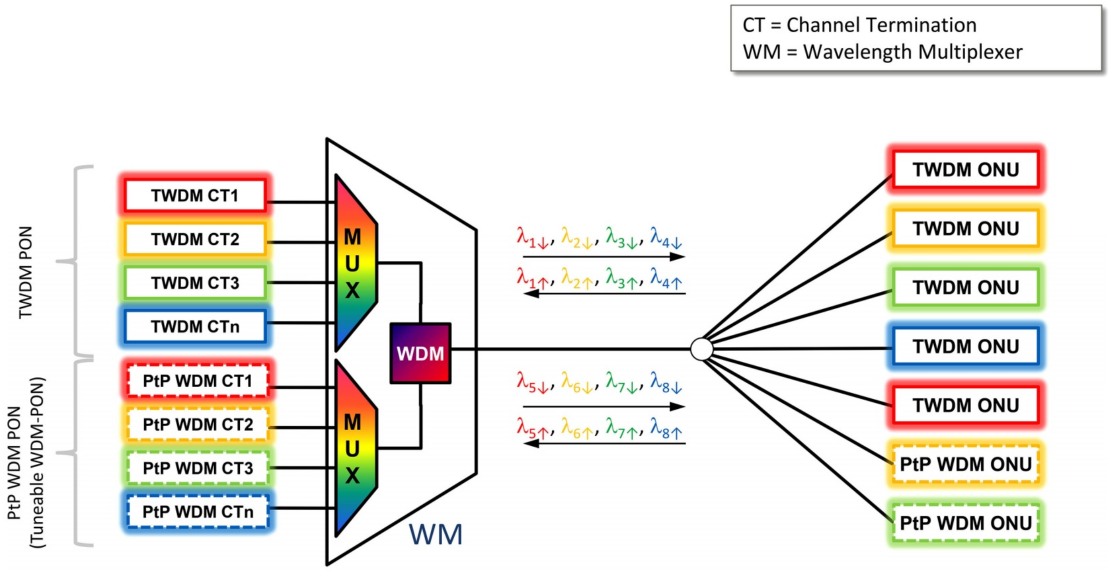



Figure 3.1: NG-PON 2 system diagram [43]

The PtP WDM overlay allows NG-PON2 to meet demanding operator requirements for business and back haul services. On the PtP WDM each ONU is served by a dedicated wavelength channel. In the baseline configuration, eight channels of PtP WDM are considered to allow full co-existence with legacy systems. Furthermore, depending on the particular deployment scenario, unused spectrum may be dedicated to additional PtP WDM channels.

## 3.3 Line Rates

The line rates defined for NG-PON2 systems are presented in Table 3.1.

Table 3.1: NG-PON2 Line Rate [5].

| **TWDM** | Downstream Line Rate (Gbit/s) | Upstream Line Rate (Gbit/s) |
|---|---|---|
| Basic Rate | 9.95328 | 2.48832 |
| Rate Option 1 | 9.95328 | 9.95328 |
| Rate Option 2 | 2.48832 | 2.48832 |
| **PtP WDM** | Downstream/Upstream Line Rate (Gbit/s) | |
| Class 1 | 1.2288–1.2500 | |
| Class 2 | 2.4576–2.6660 | |
| Class 3 | 9.8304–11.09 | |
| Class 4 | 6.144 | |

## 3.4 Wavelength Plan

As might be expected, with each generation of PON, the availability of unallocated spectrum diminishes. Co-existence with legacy PONs and RF Video relies on the NG-PON2 wavelength plan. Some considerations were made regarding the elaboration of two distinct wavelength plans, considering the presence or not of RF Video. However the idea did not move forward, a single wavelength plan is a more attractive approach since it would mean a world wide standard.

The Upstream bands fo TWDM (table 3.2) are located in the C-band where there is high availability in components which will facilitate lower costs in the ONUs. TWDM downstream is allocated in the L-band, although technology is not so matured, there is a need for low volume of TWDM downstream transceivers and costs will be shared across multiple subscribers.

Table 3.2: NG-PON2 Wavelength Plan [5].

| **TWDM** | Upstream Wavelength Band (nm) | Downstream Wavelength Band (nm) |
|---|---|---|
| Wide | 1524-1544 | |
| Reduced | 1528-1540 | 1596-1603 |
| Narrow | 1532-1540 | |
| **PtP WDM** | Downstream/Upstream Wavelength Band (nm) | |
| Shared | 1603-1625 | |
| Expanded | 1524-1625 | |

It may be noted that there are three upstream wavelength band options available, that were specified for TWDM-PON. These options are motivated by differing capabilities of the ONU transmitter to control its wavelength. A variety of techniques may be employed in order to control the wavelength in the upstream direction from the ONU to OLT. Nevertheless, temperature is the primary parameter of control. The wide option may be used by a "Wavelength-set" [44] approach to channel control, where the transmitter is allowed to drift in wavelength over a wide range, as the OLT de-multiplexer has cyclic pass bands. As for the narrow option a more precise transmitter is needed, since it will be of the utmost importance for it to precisely lock onto an assigned DWDM wavelength.

In downstream direction, eight channels have been specified with a fixed channel spacing

(CS) of 100Ghz from 187.1Thz to 187.8Thz. In the upstream direction CS of 50, 100 and 200GHz are to be supported, although no channel plan has been recommended it can be assumed that the ONU transmitter will adapt to whatever grid is employed by the OLT de-multiplexer.

It can be noticed as well that two bands were specified for the PtP WDM channels, the reasoning behind this fact will be further explained. The Shared Spectrum option, as it's name implies, is the wavelength plan to be applied in a scenario of full coexistence with legacy PON systems (G-PON, XG-PON1 and RF Video). The Expanded Spectrum option exploits the concept of spectral flexibility of NG-PON2 by enabling unused bands, in any particular deployment, to be utilized by PtP WDM. The Expanded Spectrum option may also be the option to go to in a Greenfield scenario, with no legacy coexistence limitations.

## 3.5 Advanced Network Functions

The wavelength agility of NG-PON2 systems allows network functionalities that were previously unavailable in Legacy TDM-PONs. By exploiting the wavelength agility inherent to the tunability of the NG-PON2 ONUs new use case scenarios are opened up. The attractive network functions resulting from the use of wavelength tunability in services are:

- Incremental upgrade of the system capacity, or pay-as-you-grow (PAYG)
- OLT power saving
- Load Balancing among OLT ports
- OLT-port protection
- Flexible bandwidth assignment such as Dynamic Wavelength and Bandwidth Allocation (DWBA)

Furthermore, a NG-PON2 architecture featuring the functionalities listed above as already been demonstrated [45]. Table 3.3 summarizes the relationship between network functions , tuning frequency and the required tuning time. Some of this function will be addressed in further sections.

Table 3.3: Network function and Tuning Frequency/Time [46]

| Function | Description | Tuning Frequency | Tuning Time |
|---|---|---|---|
| Colorless ONU | Eliminates complicated inventory management and improper connections between a colored ONU and an OLT. | **Low** (only initialization) | **Long** (s order) |
| Advanced Power Saving (OLT-port sleep) | For example, when there is less traffic, all ONUs are connected to one OLT-port and the other ports can be forced to sleep. | **Medium** (per hour or day) | **Medium** (ms order) |
| OLT-port Protection | When an OLT-port as failed, ONU can continue its communication to other OLT-ports by changing its wavelength. | **Low** (OLT-port Failure) | **Short** (ns - ms order) |
| Pay-as-you-grow (Incremental upgrade) | After installation of ONUs, the total bandwidth can be increased incrementally by istalling additional OLT-ports. | **Low** (only initialization) | **Long** (s order) |
| Load Balancing | When the traffic of one OLT-port is heavily congested, some ONUs are assigned to communicate to other vacant ports. | **Low** (per day or week) | **Medium** (ms order) |
| Flexible Wavelength Assignment | The optimized wavelength and timeslot are assigned to each ONU in order to improve the usage efficiency of the wavelength and provide bandwidth according to user demand (DWBA). | **High** | **Short** (ns - $\mu$s order) |

### 3.5.1 Spectral Flexibility

Spectral Flexibility is one of the key features introduced in NG-PON2, it will facilitate a diverse range of deployment scenarios, network applications and evolution paths. In a practical sense, and as it was explained before, whenever a particular subset of optical spectrum is unused by TWDM and/or Legacy PON systems PtP WDM may make use of that particular sub-band.

Such flexibility can facilitate the support of different customer types on the same ODN in a flexibly way. Additionally, spectral Flexibility facilitate a range os system coexistence scenarios and allows operators to "re-use" new wavelength bands when legacy systems are decommissioned.

## 3.6 Coexistence with Legacy PONs

The wavelength plan of NG-PON2 will facilitate its coexistence with Legacy PON systems. Regarding XG-PON1, NG-PON2 predecessor, the system uses wavelength overlay in order to permit each system to operate independently in a common fiber infrastructure. Not only simultaneous coexistence with legacy PON systems is achieved, but as well with 1555nm RF Video, figure 3.2 shows the NG-PON2 wavelength plan with inclusion of G-PON, XG-PON1 and RF Video.

The TWDM-PON downstream channels fit between XG-PON1 downstream and the monitoring band (labeled OTDR). On the other hand the TWDM-PON upstream channes work in the C-band which is expected to deliver lower cost optical transceivers at the ONUs.

The Shared Spectrum wavelength band for PtP WDM is shown in Figure 3.2, and it is configured as a mixed downstream and upstream plan, which will be assigned according to the network operator requirements.

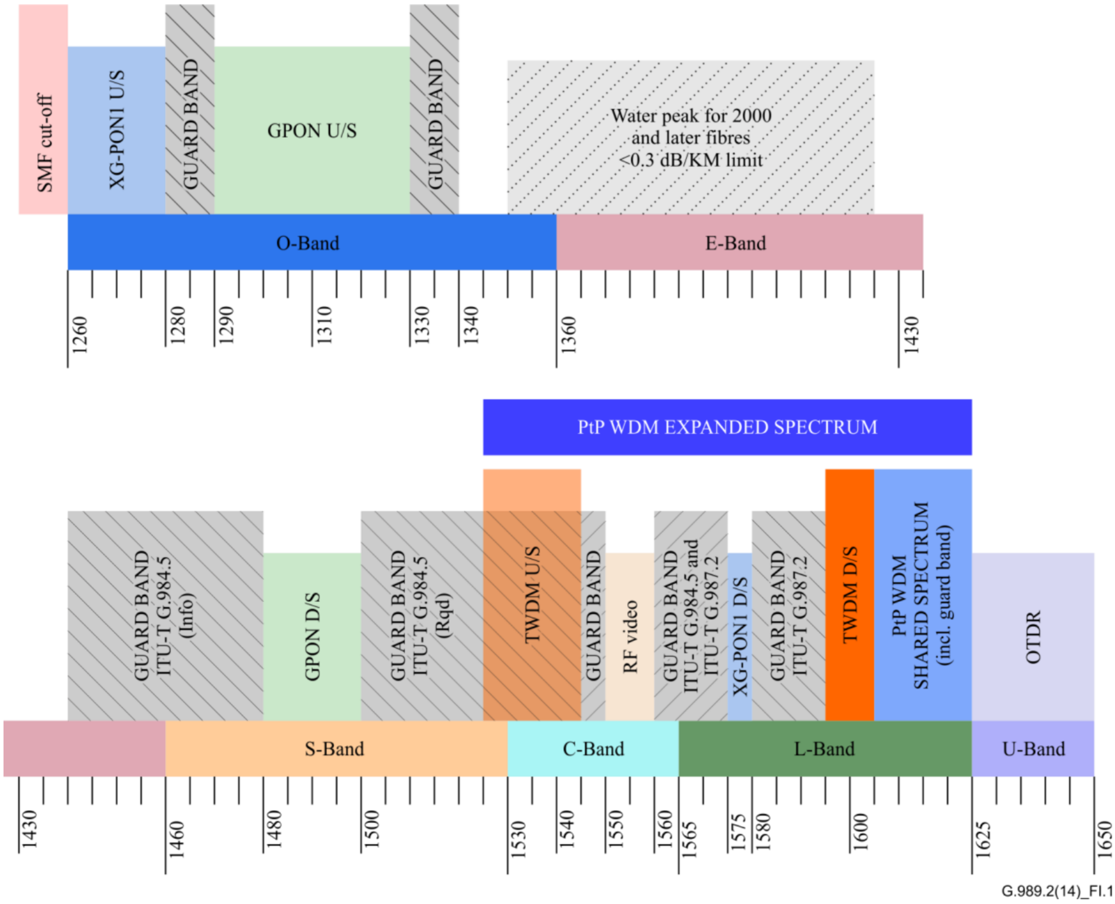



Figure 3.2: NG-PON 2 wavelength Plan [47]

## 3.7 ODN Considerations

One of the biggest challenges in NG-PON2 deployment relates to operator requirements on the ability to re-use already installed PON fiber-infrastructure, therefore NG-PON PMD has been designed to be compatible with power splitter based ODNs. In order to re-use power-splitter based ODNs, already deployed for Legacy PON systems, the optical path losses supported by NG-PON2 transceivers must also be compatible.

Furthermore, the need for coexistence with Legacy PONs driven the NG-PON2 standards to assign the same nomenclature and values of the optical path loss used in XG-PON1. These values and classification of ODN can be seen in Table 3.4, and as it can be seen, the requirement for compatibility with a 15dB ODN loss has been maintained. On further notice, the 40Km fiber distance from the OLT to the furthest and closest ONU respectively is also supported on NG-PON2.

Table 3.4: Classes for Optical Path Loss in NG-PON2 [5]

| ODN Class | N1 | N2 | E1 | E2 |
|---|---|---|---|---|
| Minimum Loss (dB) | 14 | 16 | 18 | 20 |
| Maximum Loss (dB) | 29 | 31 | 33 | 35 |

On a scenario where NG-PON2 needs to comply with Legacy PONs, and thus provide backward compatibility, the support of power-split only is mandatory. Two classes of PtP WDM ODN architectures are described in G.989: one requires tunable filters as the wavelength selection device, on the ONU, thus called Wavelength Selected ODN (WS-ODN). The other one, Wavelength Routed ODN (WR-ODN) uses wavelength splitters in the ODN, which allow a wavelength routing capability, figure 3.3. Nevertheless, the two are not mutually exclusive as PtP WDM ODN can be made as a combination of both, providing a hybrid solution which can take advantage of both configurations.

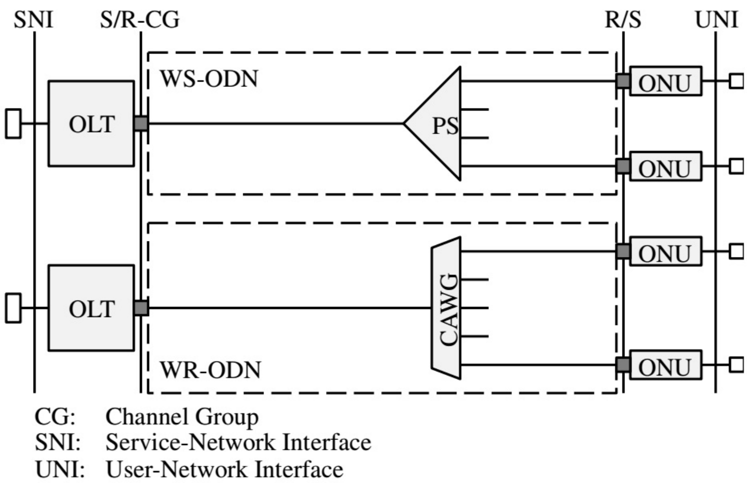



Figure 3.3: WS-OND with power splitter (top) and WR-ODN with lumped cyclic AWG (bottom). Relevant interface reference points are also shown [48]

### 3.7.1 Wavelength Selected ODN

NG-PON2 systems support single-stage splitting as well as multi-stage splitting, the required support for the maximum split ratio is of at least 1:64. For coexistence with legacy PON systems, a wavelength-band multiplexer, which is referred to as Coexistence Element (CE), enables them to be combined in a single ODN. Maximum Reach can be traded off against split ratio, since the power loss using splitter devices scales with the total split ratio.

### 3.7.2 Wavelength Routed ODN

NG-PON2 systems entirely based on a WR-ODN only make sense in a Green-field deploymente scenario, when the PtP WDM makes use of the Expanded Spectrum configuration. Due to the lower insertion-loss of the wavelength splitters compared with power splitters, WR-ODN can provide either a longer reach or the usage of transceivers with lower budget classes.

Note that NG-PON2 systems need a Wavelength Multiplexer (WM) in order to combine multiple wavelength channels into the same ODN. The WM is considered an integrated component of the OLT equipment, in that sense the extra loss from the WM is not part of the ODN loss, which is specified from the output of the WM (the S/R-CG reference point) to the input of the ONU (R/S reference point). S/R-CG refers to the location where the OLT sends/receives a set of DS/US wavelength channel pairs, called Channel Group (CG), to/from ONUs. At the OLT, a logical Channel Termination (CT) function terminates each individual TWDM or PtP WDM channel.

The WM, and the wavelength splitters for WR-ODN may be realized with Arrayed Waveguide Grating (AWG) or Thin Film Filters (TFF)

### 3.7.3 Hybrid ODN

As it was mentioned before, an NG-PON2 system can comprise a Hybrid configuration of WS and WR ODN types. Such approach, in comparison to WS-ODN, can provide a higher split ration for the same OPL Classes. Example shown in Figure 3.3, is relative to a two stage power splitting ODN with a 26-28 dB loss budget. Replacing the second stage power splitter with an AWG, results in a 16-18 dB loss budget, allowing a more reasonable power budget [48]. Other possible configuration would be to use a wavelength splitter in the first stage, and grouping wavelengths as wavelength sets on the second stage, all wavelengths are sent to the ONUs as a single set via power splitter. [44]

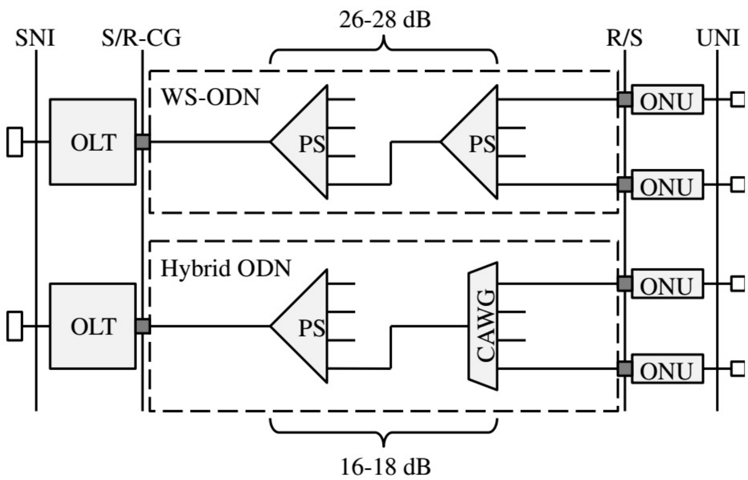



Figure 3.4: Hybrid ODN and WS-ODN in comparison [48]

In short, NG-PON2 can support a choice of ODNs, i.e, WS-ODN, WR-ODN or even a combination of both. WR-ODN offers the advantage of reduced splitting loss that may be used in order to achieve extended system reach or allowance for the use of lower specification transceivers, and is more attractive towards rural areas and Green-field scenarios. Also, some services could make use of the physical layer channel isolation offered by wavelength splitting to offer virtual private line services using wavelength channels. Whereas WS-ODN has a stronger affinity toward (dense) urban ares, in particular if legacy ODNs are already in place.

## 3.8 Key technologies

### 3.8.1 Transmitters

The NG-PON2 wavelength plan defines the C-band and L-band for US and DS respectively. Therefore the expected specifications for tunable Transmitter (Tx) in the ONUs are 4-channel tunability, respecting the chosen CS (50 GHz, 100 GHz or 200 GHz) in the C-band, a line rate of 2,5 Gbit/s (most likely for residential service) or 10 Gbit/s (most likely for business and mobile services), and burst-mode operation.

These specifications are covered by the well matured tunable devices technologies developed for core/metro networks, some of them were previously addressed in section 2.5 (full C-band or L-band with more than 80 channels). However, they require a considerably reduced number of wavelength channels and burst-mode capability [49]. Table 3.5 shows examples of possible tunable Tx to be employed in a NG-PON2 ONU.

Table 3.5: Possible Tunable transmitters in the ONU [49]

| Type | A | A' | B | C |
|---|---|---|---|---|
| Device | Heater-Integrated DFB-LD | EML (TEC inside) | DBR-LD (short cavity type) | 4h EML array + Selector (SW) |
| Tuning Control | Thermal | Thermal | Electrical | Electrical (SW) |
| Tuning Time | sub-s order | sub-s order | <ns (LD chip level) | <100 ns |
| Modulation | Direct mod. | External mod. | Direct mod. | External mod. |
| DCT for 10 Gbit/s | ✓ | ✗ | ✓ | ✗ |

**Type A** is a conventional uncooled direct modulated DFB, but needs an integrated heater and temperature sensor for an on chip tunabilty [50].

Advantages:

- Small size.
- Low cost.
- Easy burst-mode operation.

Disadvantages:

- Long tuning time.
- Needs Dispersion Compensation Technique (DCT) for 10 Gbit/s operation.

**Type A'** is similar to the DFB previously mentioned, has an integrated modulator and Thermo-Electric Cooler (TEC) inside the module.

Advantages:

- Small size.
- Low cost.
- Does not need DCT, due to external modulation.

Disadvantages:

- Long tuning time

**Type B** is a Distributed Bragg Reflector (DBR), one problem with this laser is that might suffer from mod-hop problem, but one solution is to adopt a short cavity design [**?**]

Advantages:

- Very short tuning time.
- Small size.

Disadvantages

- Needs DCT for 10 Gbit/s operation.
- More costly than previously solutions.

**Type C** is a composed of a 4-channel arrayed device, an optical multiplexer, and an electric Wavelength Channel Selector (SW), figure3.5 [51]

Advantages:

- Short tuning time.
- Mode hop free.
- Does not need DCT, due to external modulation.

Disadvantages:

- Bulky Size.
- Complex configuration for monolithic integration.

### 3.8.2 Receivers

Similarly to the T-Tx, tunable receivers in the ONU are expected to have a 4-channel tunability, with 100GHz channel spacing (CS for the NG-PON2 DS) in the L-band and line rates of 2.5 and 10 Gbit/s. Implementing Tunable Rx in NG-PON2 represents one of the major challenges in the system deployment. It will be the first time that a tunable Rx will be implemented in a practical manner in the telecom field [49], which is an indicator that tunable Rx technology is less mature than tunable Tx. Table 3.6 shows examples of possible technology solutions for ONU Rx.

Table 3.6: Possible solutions for ONU Rx [49]

| Type | X | Y | Z |
|---|---|---|---|
| Device | Heater-integrated TFF + PD | DeMUX + 4ch APD array + selector SW | DeMUX + SOA gates + PD |
| Tuning Control | Thermal | Electric SW | Optical Selector SW |
| Tuning Time | s order | <20 ns | <1.5 ns (chip level) |

**Type X** consists of a heater-integrated TFF pin-PD. The TFF is tuned by applying a current to the integrated heater, which shifts the central wavelength of the TFF. Thin film filters come in a small package, and offer a low cost solution, however they present a long tuning time, sub-s order.

**Type Y** is similar to Type C Tx, is composed of a 4-channel APD-arrayed device, an optical demultiplexer (DeMUX) and a SW, as shown in figure [51]. This Rx, was confirmed to have short tuning time <20 ns [49].

**Type Z** consists of a DeMUX, Semiconductor Optical Amplifier (SOA) gates, and a PD [52]. The SOA gates act as a wavelength selector, selecting the designated wavelength among the demultiplexed wavelengths with high speed tuning time of 1.5 ns. Although the use of the DeMUX is the same as the previous device, Type Z offers wavelength selection in the optical domain, while Type Y selects the wavelength at the electrical domain.

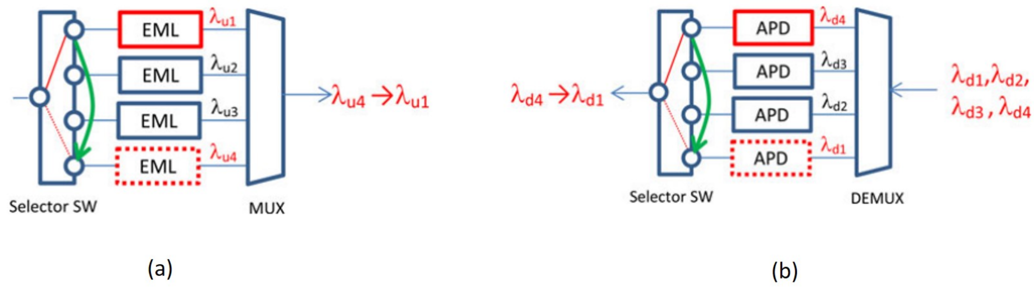



Figure 3.5: (a) 4 channel array EML (b) 4 channel array APD [51]

Table 3.7 presents which type of solutions can be achieved by employing the aforementioned Tx and Rx in an NG-PON2 system. ✗ marks the Tx and Rx that would be incompatible regarding the tuning time, from operation point of view does not make sense to have a fast Tx and a Slow Rx or vice versa.

### 3.8.3 Minimum Tuning Window

The minimum tuning window refers to the difference between the highest and the lowest operating frequencies/wavelengths of a tunable device, achievable by means of tuning control. Table 3.8 shows the minimum tuning window required for TWDM-PON ONU transmitters in NG-PON2 systems considering 50Ghz, 100Ghz and 200Ghz channels spacing and four and eight wavelength channel pairs. Regarding the PtP WDM-PON architecture in NG-PON2 systems, the minimum tuning window is based on the operating wavelength band.

Table 3.8: Minimum Tuning window for TWDM-PON ONU transmitters [5]

| Minimum Tuning Window | Channel Spacing | 4 channels | 8 channels |
|---|---|---|---|
| When using Cyclic Channel Grid | 50 Ghz | 250 Ghz | 450 Ghz |
| | 100 Ghz | 500 Ghz | 900 Ghz |
| | 200 Ghz | 1000 Ghz | 1800 Ghz |
| When not using Cyclic Channel Grid | 50 Ghz | 175 Ghz | 375 Ghz |
| | 100 Ghz | 340 Ghz | 740 Ghz |
| | 200 Ghz | 650 Ghz | 1450 Ghz |

Table 3.7: Use cases for with Tx and Rx solutions presented in tables 3.5 and 3.6

| Tx/Rx | Type X | Type Y | Type Z |
|---|---|---|---|
| Type A | Low cost Solution. Residential users. Might only provide Colorless ONU & PAYG | ✗ | ✗ |
| Type A' | Low cost Solution. Residential users. Might only provide Colorless ONU & PAYG | ✗ | ✗ |
| Type B | ✗ | Suits Resilient Services. Business users. Support all functions from table 3.3 | Suits Resilient Services. Business users. Support all functions from table 3.3 |
| Type C | ✗ | Suits Resilient Services. Business users. Support all functions from table 3.3 | Suits Resilient Services. Business users. Support all functions from table 3.3 |

## 3.9 ONU Tunablity

By employing the use of colorless ONUs for NG-PON2, it is essential for the ONU transmitter and receiver to have wavelength tunability. Therefore, it expected from NG-PON2 systems to have advanced network functions resulting from in-service wavelength tuning techniques. In-service tuning means that an ONU can tune its wavelength during service operation in addition to ONU's initializing process.

Regarding the ONU tunability it is then essential to have mechanism of wavelength assignment, tunning and maintenance. Thus, some necessary functions must be enabled:

- initiate the ONU discovery process, and recognize new ONUs on the PON and their tunability in a way that does not disrupt traffic;
- to assign a newly recognized ONU to an initial operating wavelength set, both upstream and downstream;
- to reassign an ONU's opertaing wavelength set during operation;

### 3.9.1 Wavelength Assignment and Tunning

Wavelength assignment is critical in order to bring inactive ONUs into operation. At the time a new ONU is installed initial downstream and upstream wavelength set have to be automatically and remotely assigned between the OLT and the new ONU. This wavelength assignment process has to be carried out as part of the ONU activation. In a case where there is a Mux Based ODN, wavelength assignment is done during the physical installation process.

In an analogous process, during activation, a newly activated Tunable ONU may need to tune its wavelength by following a OLT command. Furthermore, an OLT should be able to confirm ONU wavelength assignment in the MAC Layer, thus ONU wavelength are determined by physical infrastructure, and the TWDM and PtP WDM-PONs should inventory all working wavelengths.

In a process of wavelength assignment or tunning it is necessary for the OLT to synchronize with the downstream signal, to carry out ONU identification, and to adapt to the multiplexing technique present in the specified network. The procedures for wavelength assignment and tunning in multiple-wavelength PONs as defined in ITU-T recommendation G.9802 are as follows, figure 3.6:

1. Comunication on wavelength tuning capability
2. Wavelength assignment decision
3. OLT commands ONU of the downstream/upstream wavelength to be assigned
4. ONU wavelength adjustment
5. ONU response

**ONU tunablility information:** transmitter or receiver tunning range, tunning granularity, tunning time, channel spacing, calibrated or uncalibrated transmitter type. There are several ways that an OLT can issue a wavelength management and control message to an ONU, either by broadcasting to all downstream wavelengths or emit it in the downstream wavelength of the new ONU. The information elements in such type of message include: upstream and downstream wavelength ID, destination wavelength in nanometers or the corresponding frequency, wavelength tunning direction, wavelength tunning start time.

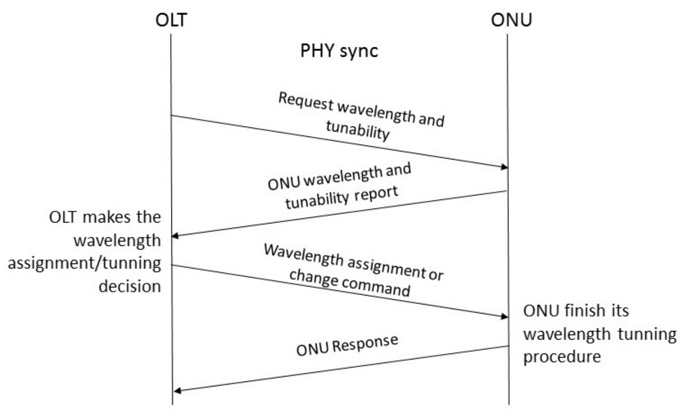



Figure 3.6: Wavlength assignment/tunning message exchange between OLT and ONU [53]

### 3.9.2 ONU Activation Process

The Process of bring an ONU into operation dwells with a certain number of factors. The tunable transmitter used as the ONU Tx characteristics plays an important role in carrying out an ONU activation, while having a calibrated ONU with sufficient accuracy might not bring any constrains in the ONU activation, and the process can be carried out with a straightforward downstream message from the OLT, issuing the desired channel in which the ONU will transmit. The process of activating an uncalibrated ONU might prove more difficut, requiring additional tuning mechanisms. The latter scenario shall have to deal with the additional constrains:

- Wavelength laser at the start is unknown
- New ONU activation must not interfere with traffic
- Several ONU may attempt an activation on the PON at the same time

We will start by describing the ONU activation process carried out in TDM-PON [10] in order to introduce the TWDM-PON ONU activation since there are mechanisms that will remain from the Legacy PONs.

At the start up an ONU is not synchronized with other ONUs, any transmission would be likely to disrupt regular data traffic. In order to deal with this problem, the OLT creates a quite window at regular intervals, during this time ONUs in service are not allowed to send upstream data. During this time the OLT broadcasts a raging request at the start of the quite window. In response to the broadcast signal, any new ONU in the PON recently powered up will respond with a short message in order to identify itself which will be its serial number. The quite window is at least as long as the maximum round trip in the PON, and after the reception of the ONU's serial number, the OLT is able to measure the real round trip time of the ONU requesting activation. An equalization delay is calculated based on the difference between the maximum possible round trip and the real round trip. The Serial number of the ONU is store on the OLT management system, and assigns a new ONU-identifier (ONU-ID), which is used for target physical layer process. In response to the ONU serial number message, the OLT will answer a message containing the ONU-ID and the equalization delay, thus the newly activated ONU will be on the same reference timeframe as the other ONUs, allowing the allocation of different time slots within that frame to prevent packets from colliding at the OLT.

In TWDM-PON scenario where the ONU Tx is not sufficiently calibrated in wavelength, transmission of the upstream discovery burst could occur in any upstream channel. It is then necessary that the OLT open the quite window simultaneously in all channels to avoid interference until a correct setting of the upstream wavelength is confirmed. Assuming that during the quite window, one of the OLT burst-mode receivers reads the serial number of an ONU pending activation, similarly to TDM-PON, the OLT would send and ONU-ID and equalization delay signaling the recognition of the serial number. Furthermore, a **coarse tuning mechanism** can be initiated, with the intent of steering the ONU Tx wavelength into another wavelength channel, even though we are assuming the use of an uncalibrated Tx, relative changes can be controlled in a reproducible way. The **fine tuning process** would then take place, in order to find the best tuning point for the ONU Tx, which would mean steering the wavelength to the maximum of the pass-band of the channel, typically the channel center. The fine-tuning mechanism is further explained in the section regarding wavelength locking.

However, if the OLT can't read the ONU's serial number because the ONU Tx starting wavelength is in a point where the SNR is insufficient to perform such measure. A first activation attempt from the ONU in the quit window would not receive a confirmation the OLT in the form of the ONU-ID and equalization delay. Therefore the ONU would, autonomously, shift its wavelength by a fraction of the of the channel spacing before and additional attempt in the next quite window. Note that this approach allows multiple ONUs attempting activation at the same time, simply because an unanswered request would trigger and autonomously wavelength shift and a subsequently attempt.

### 3.9.3 Tunning Time Classes

Three classes for the wavelength channels tunning time were specified for NG-PON2 and as shown in table 3.9,

Table 3.9: Wavelength channel tuning time classes for NG-PON2 [47]

| Tuning Time Class | Tuning Time |
|---|---|
| Class 1 | $<10\mu$s |
| Class 2 | $10\mu$s to 25ms |
| Class 3 | 25ms to 1s |

Devices falling into each of these three classes, open up multiple cases for wavelength tunability,e.g., dynamic wavelength assignment [54], advanced power saving [55], and channel-based protection mechanisms [48] that may require different tuning speeds.

Class 3, the tunable devices, characterized with the longest tuning time, could be thermally tuned DFBs. These devices are suited for applications that require infrequent tuning operations, or if short service interrupt is allowed. Furthermore, channel-based protection mechanisms can be adopted, but a typical sub-50 ms protection objective may not be achieved. Semi-static load sharing and power saving mechanisms may be of interest.

Class 2 components may be based on electronically tuned lasers (2sec. DBR), these a allow a faster channel switching and features such as sub-50 ms protection becomes possible, as well as dynamic load sharing and dynamic power saving.

Class 1 devices, characterized by the fastest tuning time, may include switched lasers, filter arrays or 3sec. DBR. Using this kind of tunable lasers may enable future dynamic wavelength and bandwidth allocation feature, and possible allow wavelength hopping between the transmission periods.

#### Tuning Time

The tuning time of an ONU, as shown in figure 3.7, does not begin when the laser begins to tune but when the laser exists the passband of the original wavelength, i.e, when the optical power drops of 0.5 dB compared to the initial value, after the change command issued by the OLT. Analogously the tunning time ends when the lasers enters the passband of the destination wavelength channel, i.e, when the optical power, in the destination wavelength, reaches and stays within the 0.5 dB of the initial (original channel) value. [47]

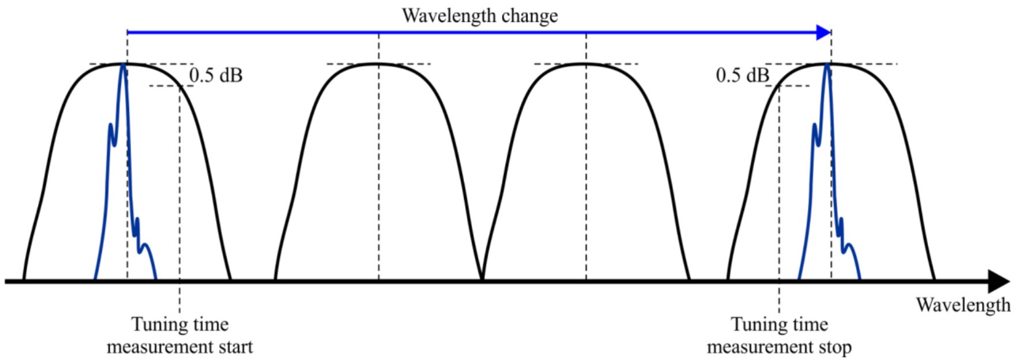



Figure 3.7: Laser tunning across the operating band [47]

### 3.9.4 Maximum Spectral Excursion (MSE)

MSE is specified as one-sided deviation from the nominal central frequency/wavelength, it is expressed in Gigahertz and it is illustrated in figure 3.8. MSE is a specified for to main reasons: first, to prevent optical power to leak from a wavelength channel to an adjacent wavelength channel, and second to endure that the transmitter operate within the desired WM channel passband.

Regarding tuning transmitters, the maximum spectral excursion requirement is only applied when those are in a stationary wavelength channel. Furthermore the referred requirement applies to both tunable transmitters which are under fine control of the OLT and tunable transmitters which are not under fine OLT control.

In the application to NG-PON2, MSE is the total allowable excursion due to:

- spectral width, tuning granularity, short-term wavelength drift (over one OLT-ONU tuning cycle) and tuning errors, when the ONU transmitters used are under fine OLT control;

- spectral width, tuning granularity and tuning accuracy, when the tunable transmitters used are not under fine OLT control.

The MSE values allowed for ONU transmitters in NG-PON2 systems are shown in table 3.10, and they depend on the CS used in the system.

Table 3.10: Maximum Spectral Excursion allowed in NG-PON2

| Maximum Spectal Excusion (Ghz) | Channel Spacing (Ghz) |
|---|---|
| 12.5 | 50 |
| 20 | 100 |
| 25 | 200 |

Regarding the OLT transmitter in a NG-PON2 system the channels have been specified with a fixed channel spacing (CS) of 100Ghz, thus a ±20GHz of MSE is allowed.

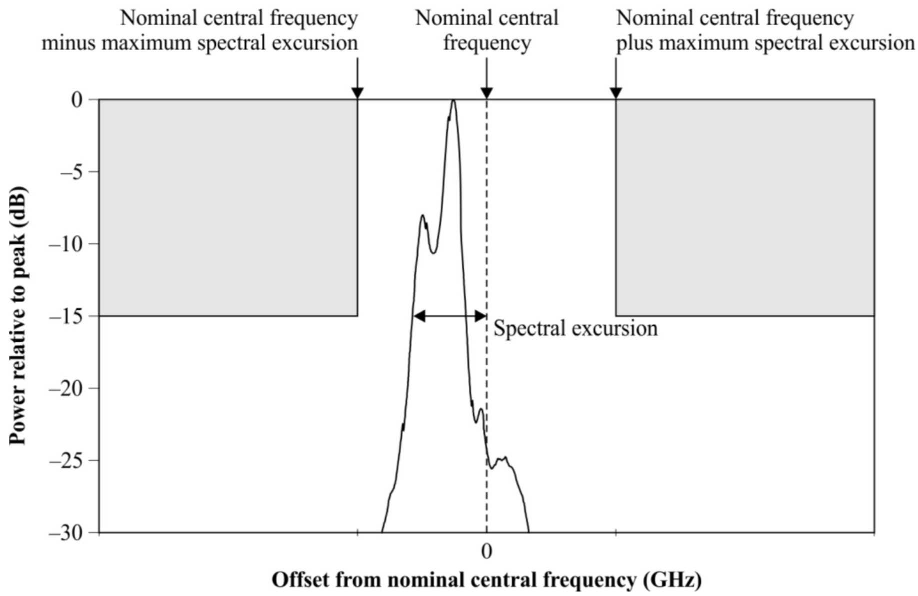



Figure 3.8: Illustration of the Maximum Spectral Excursion [47]

### 3.9.5 Wavelength Control

The three key aspects pertinent to control of multiple wavelength in an NG-PON2 system, are: wavelength stability, wavelength accuracy and wavelength locking. The related wavelength control parameters, specified in [47], are also introduced.

### 3.9.6 Wavelength Stability

The wavelength stability of an NG-PON2 system is quantified by the previously introduced parameter MSE.

For the TWDM-PON downstream, as referred before the channel spacing is fixed on the 100 GHz and the MSE required is ±20 GHz, it is relatively simple for a tunable filter to follow the maximum received power through a local feedback loop [56], therefore the ONU Receiver (Rx) filter does not require tight calibration.

For the upstream, the CS is not fixed, so three values of MSE were specified, Table 3.10, to each CS configuration. These MSE values were selected taking in consideration the need to avoid strictly requirements on wavelength calibration, in case where uncalibrated lasers are used, power variation over wavelength, tuning granularity, the loss and isolation of TFFs and AWGs and Tx spectral width [56]. Short-term spectral excursion caused by ONU laser switching on/off at the burst boundaries must comply with MSE limit.

### 3.9.7 Wavelength Accuracy

The wavelength accuracy, or the calibration accuracy of a Tunable ONU Tx refers to is capability of transmitting with a allowable spectral excursion and stay within the specified limits. There are three levels of calibration concerned to ONU tunable Tx defined in NG-PON2 standards: sufficient calibration, loose calibration and no calibration. Tunable ONU Tx with sufficient calibration will have no problems regarding wavelength accuracy, but are more costly. On the other hand loosely calibrated and uncalibrated ONUs, although a more attractive solution in terms of cost, can not be guaranteed to operate within the the specified MSE limits without additional mechanisms that ensure some kind of wavelength locking.

### 3.9.8 Wavelength Locking

As mentioned before, in downstream direction the ONU Rx can, by its own, look for the highest received optical power, thus locking to the best tuning point. In the upstream direction it may be more difficult for an ONU Tx wavelength locking relying on OLT feedback.

Assuming that an OLT Rx can perform an accurate power, but not wavelength, measurement, and that the ONU Tx launch power does not vary significantly for a small wavelength change. A closed wavelength control loop can be realized between the OLT and the ONU in order to reach and a maintain the optimal tuning point of the ONU Tx.

Under OLT control, the ONU transmits ate different times, two sightly different wavelengths ($\lambda^+$ $\lambda^-$) around the central wavelength $\lambda$. In the case that $\lambda$ is coincident with the WM channel center, then the OLT Rx would detect no power variation between the two different transmissions, thus no corrective action would be necessary. For the cases shown in Figure 3.9, the power change would revel both the magnitude and the sign of the wavelength misalignment. In such outcome the OLT would then instruct the ONU top apply appropriate corrections to rectify the tuning.

In order the previously explained closed loop method, which is described in [56] with more detail, the WM may need to comply with additional constraints with respect to filter, bandwidth, monotonicity and passband ripple, outlined in the Appendix VII of G.989.2 recommendations. Two factors must be guaranteed: first, a mistuning of the ONU Tx is correctly detected by the OLT power measurement, before MSE limit is exceeded. And second, power variations due to the WM filter shapes do not interfere negatively with the tuning. Furthermore a locking mechanism based on a BER measurement before the application on FEC, may be more convenient.

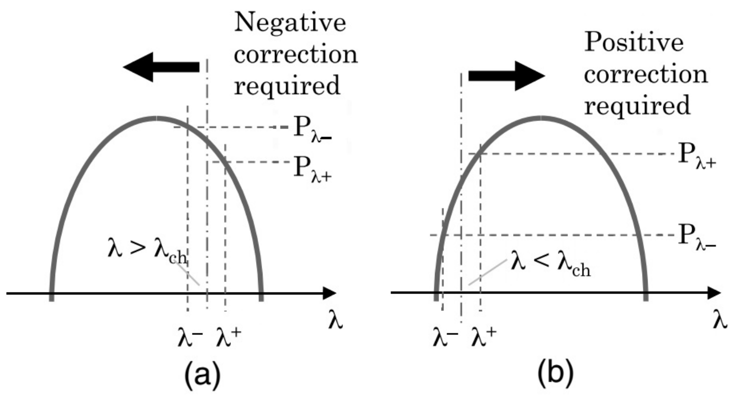



Figure 3.9: Result for a mistuned ONU, a) Negative correction required, b) Positive correction required. [56]

### 3.9.9 OLT-port Protection

A N:1 NG-PON2 fast protection by employing ONU wavelength tuning function was demonstrated in [57]. One backup wavelength pair is preconfigured (e.g, the blue wavelength pair figure 3.10) to protect traffic in other wavelength pairs if a failure is detected . The major steps of the N:1 protection are presented in table 3.11. Advantages of the presented scheme are: Protection time is reduced by avoiding sending the involved ONUs back to re-registration, and ONU configurations of logic connections and service managements are reserved.

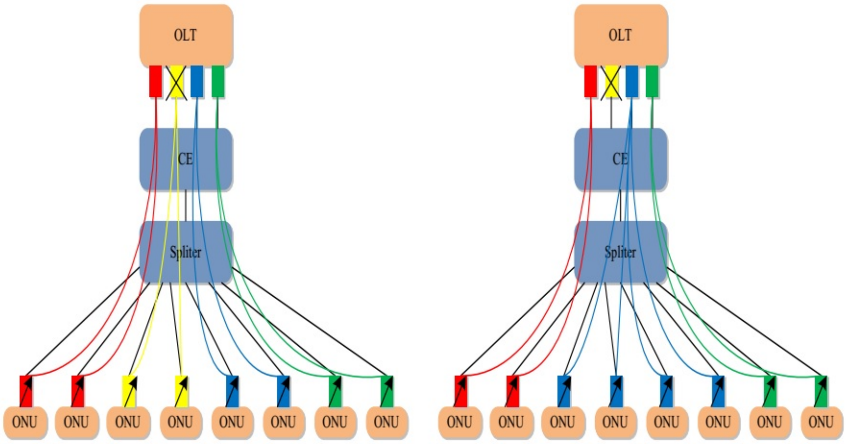



Figure 3.10: N:1 Protection Architecture [57].

Table 3.11: N:1 Protection Steps [57].

| | |
|---|---|
| Step 1 | OLT selects the backup wavelength pair. |
| Step 2 | When a new ONU registers, the OLT assigns a working wavelength pair, also configures it with the backup pair. |
| Step 3.a | When the ONU detects a loss of signal, it enters a wavelength tuning state and tunes wavelength to the backup wavelength pair. |
| Step 3.b | When the OLT detects a loss of signal of a wavelength pair, it switches the traffic to the backup wavelength pair. |
| Step 4 | The OLT and ONU continue traffic as soon as tuning ends. |

### 3.9.10 OLT-port sleep and Load Balancing

OLT-port sleep and load balancing are desirable functions in NG-PON2 systems, similarly to OLT-port protection, this function is provided by using the in service tuning capabilities of the NG-PON2 ONUs [55].

When the traffic is sufficient low, some of the OLT-ports enter a sleep state in order to provide power savings in the OLT, and decrease the OPEX. Figure 3.11(a) shows an example of the normal state of operation of an ONU. If it comes to a case when there is less traffic in a normal state operation of the OLT, figure 3.11(b), if the system uses the 4 wavelength channels, by using in in-service tunning of ONUs, all ONUs are then connected to a single port (Port #1) and the other ports can be made to sleep, as shown in figure 3.11(c).

Regarding the Load balancing, its an analogous process to OLT-port sleep. However it deals with the situation when an OLT-port has heavy traffic congestion. If this is to happen, some ONUs begin to communicate with other vacant ports, by changing their wavelength of operation.

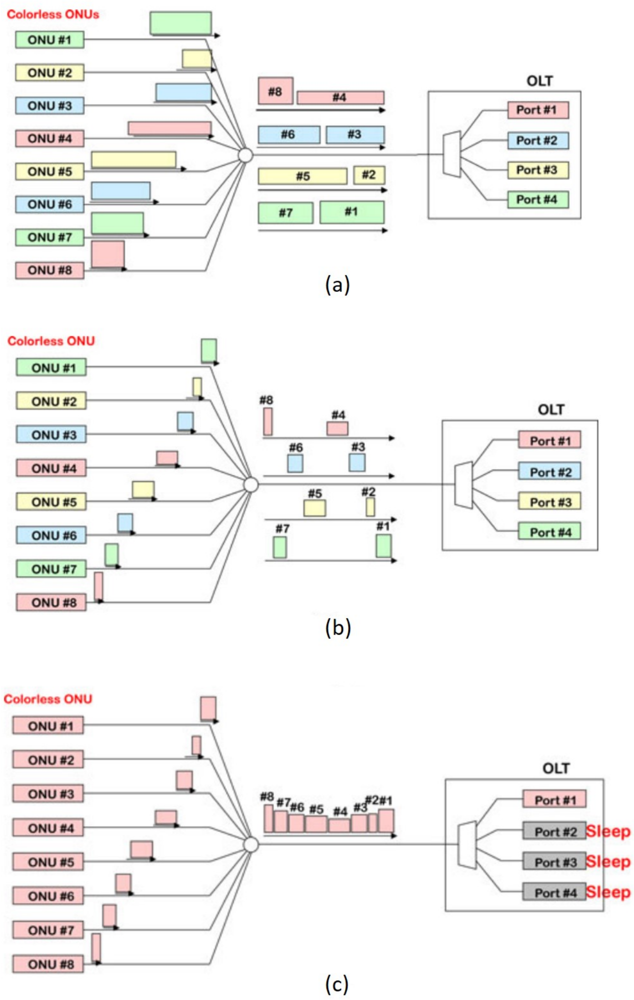


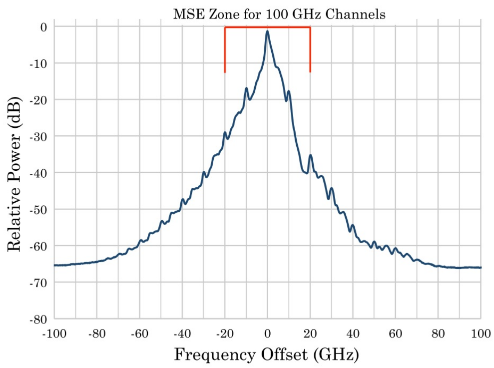

Figure 3.11: Exemple of OLT-port sleep. (a) Normal state (b) Normal state with less traffic (c) sleep state [49].

## 3.10 Externally Modulated Lasers versus Direct Modulated Lasers for ONU Tx transceiver

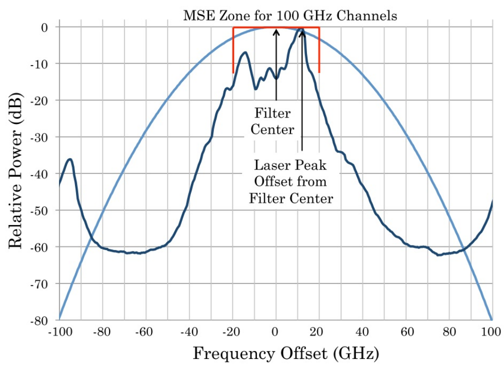
Maintaining the ONU Tx wavelength within the specified MSE values for upstream path presents several challenges. Further more for the 10 Gbit/s line rate.

Externally Modulated Laser (EML) Tx are well developed regarding high transmission data rates, over long fiber distances due to its low frequency chirp. Figure shows a EML Tx spectrum modulated at 10 Gbit/s. As can be observer the signal spectrum is about 14 GHz wide at -15 dB point, which means a single-side deviation of 7 GHz relative to the same point. In a case where the chosen CS is 100 GHz for the upstream channels, the allowed MSE is of ±20 GHz, the accuracy to wich the the spectral peak of the ONU Tx must be controlled, and stay within the MSE, is then ±13 GHz. Such EML Tx is considered to be feasible with acceptable cost with known technology and techniques. [56]

Direct Modulated Laser (DML) Tx face some problems when modulated at such hight date rate such as 10 Gbit/s, due to modulation induced frequency shift, the signal spectrum will broaden. Figure shows the DML spectrum and 2 distinct peaks can be observed, corresponding to the "0" and "1" logical levels respectively. The spectral with of the DML Tx is about 35 GHz at the -15 dB point, meaning a single-side deviation of about 17.5 GHz and its wider that the EML case. Therefore the accuracy to which this Tx must be controlled in order to stay within the specified MSE is ±2,5 GHz. Such tight control is generally impossible without adding a precise, meaning costly, wavelength locker in the Tx.




(a)




(b)

Figure 3.12: a) Optical spectrum of a 10 Gb/s EML Tx measured with a resolution bandwidth of 2.5 GHz. b)Gaussian-shaped filter and optical spectrum of a 10 Gb/s DML Tx measured with a resolution bandwidth of 2 GHz and tuned to fit within MSE [56]

From a transmission perspective, although DML is a good option for 2.5 Gbit/s upstream transmissions, it might not be for the 10 Gbit/s transmission due to the chirp induced. Nevertheless, several techniques have been developed [58, 59], in order to mitigate the chirp induced frequency shift, thus relaxing the tight wavelength control difficulties in order to take advantage of DML Tx

## 3.11 Wavelength Multiplexers (WM)

As extensively mentioned in previous sections, NG-PON2 systems employ WDM technology, e.g., multiple wavelengths are combined into the same ODN. To this end, a WM is used in the OLT to combine/split wavelengths for DS/US signals, respectively. The key components for WM can be AWGs and TFFs.

In general, AWGs are widely deployed for a large number of channels (>80) with narrow CS of 100 GHz, or less. AWGs have cyclic property of multiple passband wavelengths in a single port, with the Free Spectral Range (FSR) designating the space between wavelengths.

WMs using TFF are composed by a small number of individual filters in order to recreate the desired properties of the WM, they offer a small number of channels, typically four. TFF offer some advantages compared with AWGs, such as lower insertion loss, high isolation, and low cost when a small number of channels is needed. These advantages gradually fade away if the application requires a large number of channels

### 3.11.1 Cyclic Characteristics of AWG

The cyclic properties of AWGs consists of multiple passband wavelengths in one single port. Specific implementations of TWDM-PON make use of this characteristic in order to provide a low cost implementation, by allowing a wide variation in the US wavelength. [44,50]

Cyclic AWG designates an AWG with unique wavelength routing capabilities, this is illustrated in figure 3.13 . The referred AWG has 100 GHz CS, with enough channels to cover the C-band, used in US direction, in the wide option wavelength plan. Independently where the ONU Tx is tuned, it will be less that 50 GHz from the center of one of the AWG channels, that will route the wavelengths to one of the four OLT CTs. The routing is shown with different colors and repeats every 400 GHz. The employment of such device in a NG-PON2 system can translate into a low cost solution for the ONU Tx, by allowing the use of thermally tuned lasers with only a heating element, e.g., without the need for a TEC. To realize such implementation is necessary that the tunable laser can tune to any of the desired CT, to so heater must able to change the laser die temperature by 35 °C, meaning a tunning range of approximately 2.6 nm. The main disadvantage of the mentioned scheme is that high room temperatures fluctuations will require the laser to retune (jump 400GHz) in order to stay connected to the desired CT. If the tunning time of the laser is long, as it usually is with thermally tuned lasers, specially if high wavelength shift is needed such as 3.2 nm (400GHz), then the service outage from periodic retuning might not be acceptable.

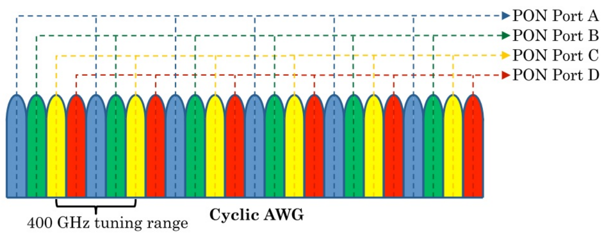



Figure 3.13: Cyclic AWG US wavelength routing, the colors represent the four different CT. [56]

## 3.12 OLT Configuration Options

In this section three possible use cases for AWGs and TFFs usage as WM on the NG-PON2 OLT are going to be presented.

Configuration I is composed by WM and transceivers that have single wavelength pair of US and DS signals. Configuration II contains a WDM filter, WMs, and transceivers that have dual optical interface ports, one for DS, and another for US. Lastly, configuration III consists of a WDM filter, WMs, a four channel Tx, and a four channel burst-mode Rx, figure 3.14.

Config. I is characterized by having single input/output interface port, which is a common feature of Legacy PONs, its main advantage is the use of a single WM that leads to a simple configuration. TFFs can not be used in this type of configuration. In config. II and III, both TFFs and AWGs are applicable. Configuration III is attractive because a small footprint can be expected if four-channel integrated transceivers can be used, however it may not support pay-as-you-grow. [56]

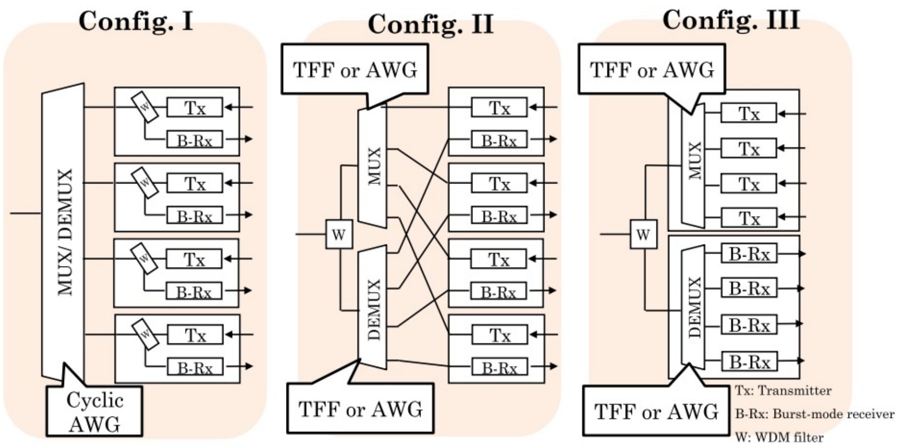



Figure 3.14: Example of OLT configuration [56]

## 3.13 Management and Control

Auxiliary Management and Control Channel (AMCC) was added as one of the NG-PON2 new feature. The motivation for the AMCC lies with the integration of the PtP WDM overlay in the system. While, in terms of management and control, the TWDM-PON is an end-to-end specification of a complete system in layers 1 and 2, and it extends the protocol specifications of Legacy PON systems. The PtP WDM is specified to transport client services with minimal or no payload modification, therefore the AMCC is required in order to deal with the management and control features of the PtP WDM Link. In short:

- NG-PON2 supports a wide range of PtP WDM devices transparently, so a new channel is defined AMCC. [60]
- AMCC is used for activation and control of the PtP WDM channels. Carries Physical Layer Operations, Administration and Maintenance (PLOAM) messages. [60]

The process of activating new uncalibrated ONU was described in section 3.9.2, however with the assumption that the OLT would simultaneously open a quite window in all channels. If this is not feasible, e.g., because the channels belong to separate systems or independent network operators or if the service in one channel can not be interrupted, a new approach must be followed. The TWDM-PON can take advantage of an AMCC approach, a very low-level low frequency signal on which an ONU can communicate US during activation phase, would be very useful on cases where the ONU cannot guarantee to start transmitting the correct wavelength. The ONU should transmit at a level low enough to not interfere with the working channels but detectable by the OLT [60]. Information to be transmitted must be minimal, e.g., serial number. Another advantage of such approach is that the detection of the AMCC signal does not require synchrony of the different wavelength channels [56].

## 3.14 Conclusion

In this chapter the NG-PON2 recommendation was discussed, it was started by presenting its general architecture, line rates and wavelength plan. NG-PON2 will not be a disruptive solution, it allows coexistence with previous PONs, and will re-utilize the already deployed infrastructure, if those exist. NG-PON2 will also feature attractive solutions for Green-field applications.

One of the requirements for NG-PON2 its the use of colorless transceivers, NG-PON2 may take advantage of the inherent tuning capabilities of such transceivers in order to allow in-service tuning functionalities.

While for downstream transceivers cost will be shared across multiple subscribers, this is not the case for upstream transceivers. The need for low cost solutions for upstream direction, mainly the ONU Tx, may push for the use of uncalibrated transmitters. Additional tuning mechanisms are then required in order to activate and deal with such ONUs. Some considerations are made regarding the use of DML, EML and cyclic AWGs.

The chapter is finalized with a reference to the AMCC, a control channel added manly to manage and control the PtP WDM channels transparently, e.g., with no payload modification. Considerations are made regarding the use of the AMCC in TWDM-PON to facilitate uncalibrated ONU activation.

# Chapter 4

# Tunable Laser Testing

## 4.1 Introduction

Tunable Distributed Feedback (DFB) with an integrated heater to perform tuning operation are a low cost solution for an NG-PON2 ONU Tx. In this chapter a device of this type is going to be characterized regrading the tunable aspects of operation. Tuning time is an important parameter of ONU Tx, it may limit the functionalities that an ONU provides. Specially when such functions require and in-service tuning, furthermore ITU-T NG-PON recommendation G.989.1 defines the service interruption time must be less than 50 ms in order to provide service continuation when and if ONUs are required to perform tuning. DFB lasers are known to a tuning time in the order of the sub-s, nevertheless, in this work tuning time of a DFB laser designed by PICadvanced is going to be evaluated. Implementation of network functions that require a tuning time in the order of $\mu$s to ms (such as: Load balancing, OLT-port protection and Power saving) are considered upon tuning time results. The accuracy of the tunable Tx is calculated as well.

## 4.2 DFB Characteristics

The Laser utilized in the following setups is DFB, integrated in a photonic circuit. The structure of a DFB laser was mentioned before, section 2.5.2, as well as the mechanism behind such device that allow a tunable operation in a narrow band. A conventional DFB laser's emission wavelength can be tuned by heating or cooling with a gradient of about 0.08 nm/K. The DFB works in the C-band, the operating wavelength is centered around 1552 nm at room temperature, and the laser has a tunning range of approximately 5 nm. This laser was design to operate in the NG-PON2 upstream direction, but due to a fabrication defect the operating wavelengths of the laser were shifted in 20 nm, as well as lower output optical power than expected. Nevertheless it will serve as a proof-of-concept in order to study the tuning mechanisms behind its operation and relevant characteristics for its use in a NG-PON2 ONU, such as spectral characteristics, tunning time. The laser can be seen in picture 4.1 and the setup utilized to characterize the laser can be seen in figure.

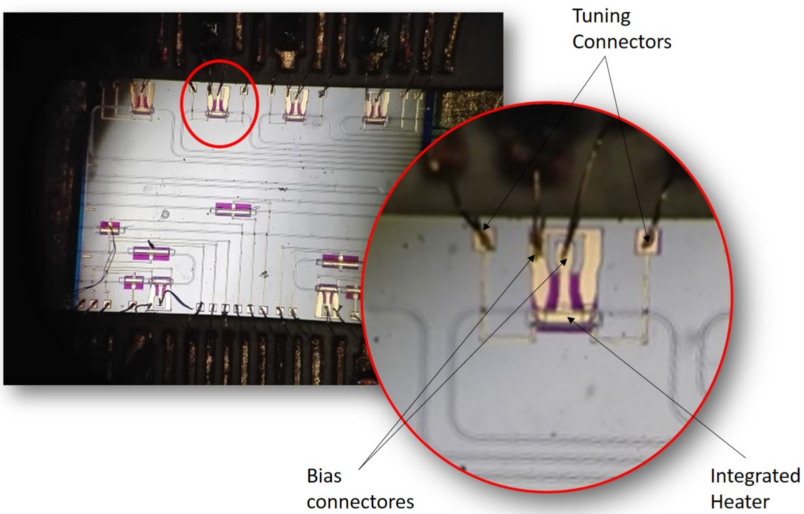



Figure 4.1: DFB laser

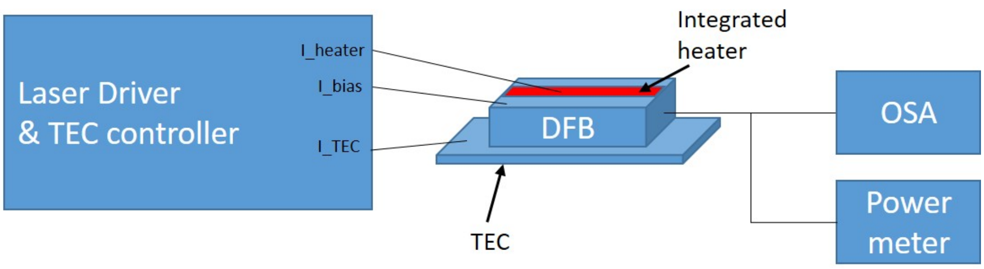



Figure 4.2: Setup used to characterize the DFB laser

The DFB laser has two control variables: bias current and temperature. Increasing bias current leads to an increase in the output power, whereas the temperature is used to adjust the laser to the desired wavelength. The laser as a fairly low output power, figure 4.3 and 4.4, although its threshold current is  20mA, it can be observed that for I_bias bellow 60 mA the laser as a significantly optical power drop. It can also be noted that the temperature does not have a significantly influence on the output power trait. Furthermore, regarding the optical output power of the laser, higher values could be measured by improving the fiber alignment with the laser.


Figure 4.3: Wavelength and Optical Power vs I_bias @ 25 °C

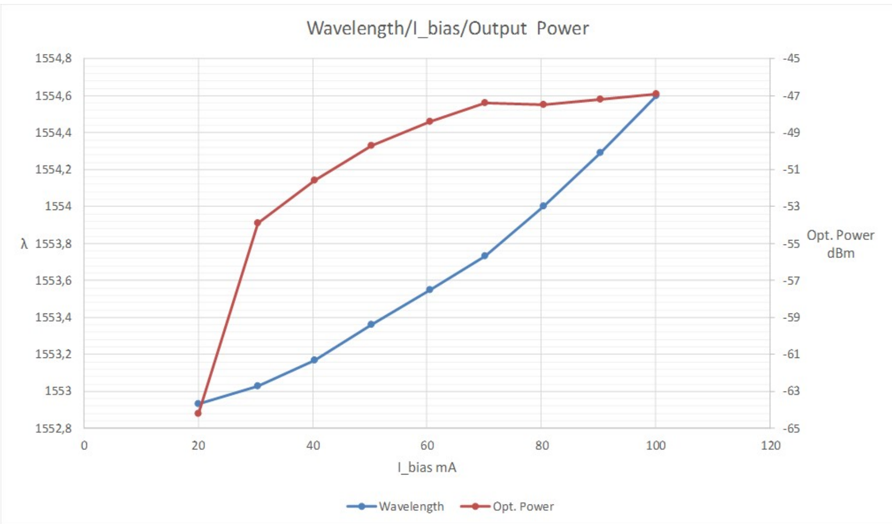
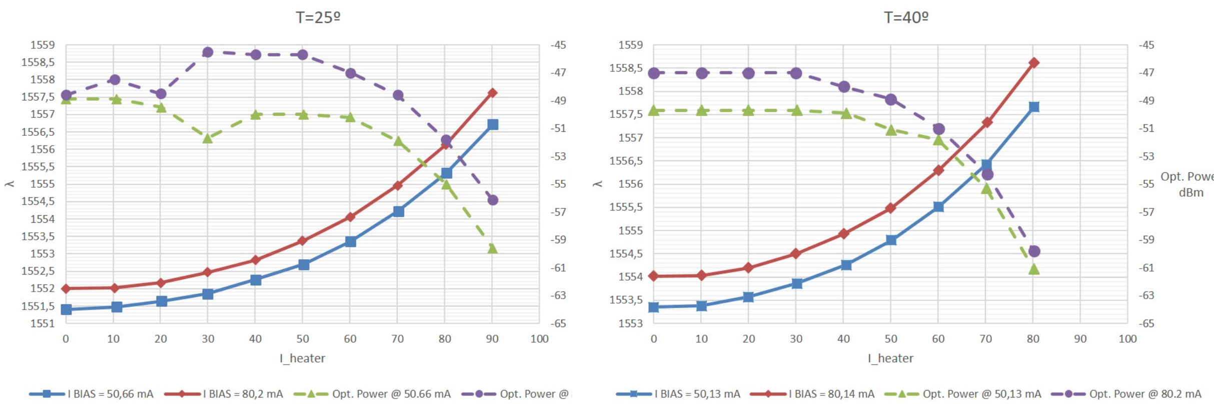



Figure 4.4: Wavelength and Optical Power vs I_bias @ 40 °C

### 4.2.1 DFB Tuning

A Thermo-Electric Cooler (TEC) is integrated with the system in order to maintain a stable temperature of operation, while the tuning is enabled by a monolithic integrated heater. The lasing wavelength of the DFB laser is a product of three factors: I_bias, I_heater and the temperature set by the TEC. First the I_bias used to drive the laser which has is own thermal effect withing the laser cavity, the influence of the I_bias over the lasing wavelength of the laser can be seen in figure 4.5, the wavelength is plotted versus I_bias for different temperatures. Note that a 0.8 nm tuning range can be obtained by varying I_bias, which, in a practical scenario where 100 GHz CS is chosen for the upstream direction, would mean the necessary variation to switch to a different channel. Second, by injecting a current on the integrated heater, which we will call I_heater, a change on the refractive index of the distributed grating along the cavity is produced, therefore changing DFB's lasing wavelength. And third the operation temperature of the laser which can be controlled with the TEC. The relationship of the lasing wavelength with I_bias and the temperature is plotted in figure 4.5, I_tunning was set to 0, and the temperature was controlled with the TEC. While the relationship between the wavelength and I_heater can be seen in figure 4.6a at 25 °C , and in figure 4.6b at 40 °C. Furthermore it can be seen that different I_bias will result in a different optical output power. For I_heater values greater than 70 mA can be noted a significant power drop, still for values bellow 70 mA of I_heater a tuning range above 2,4 nm can be maintained. Measurements regarding the characterization of the DFB can be seen in Appendix A.


Figure 4.5: Wavelength vs I_bias vs @ room temperature, 35 °C, 40 °C and 50 °C




(a) Wavelength vs I_heater @ 25 °C

(b) Wavelength vs I_heater @ 40 °C

## 4.3 Tuning Time

The tuning time of a tunable Laser was defined in section 3.9.3, it refers to a time it takes to a laser to exit the passband of the original channel and enter the passband of the destination channel, note that tunning time thus defined is related only to the tunable optical device characteristics. Being impossible to measure this time difference in the optical domain, it will be necessary to condition the optical signal in order to analyze the time it takes to change from one wavelength channel to another in the electric domain. In the further sections we will refer to the wavelength with lower value and to the wavelength with higher value the as $\lambda 1$, and $\lambda 2$ respectively. Furthermore, since the utilized laser is a DFB, a change from $\lambda 1$ to $\lambda 2$ requires heating, on the contrary, a change from $\lambda 2$ to $\lambda 1$ requires cooling, therefore the time it takes the laser to change from $\lambda 1$ to $\lambda 2$ will be defined as $t_{heat}$, on the contrary a change from $\lambda 2$ to $\lambda 1$ will be defined with $t_{cool}$. The method utilized for this end, as well as the obtained results will be presented in the following sections.

### 4.3.1 Setup

The Setup utilized to measure tuning time is shown in figure 4.7 (top), and is based on an example from G.989.2 Appendix VIII.

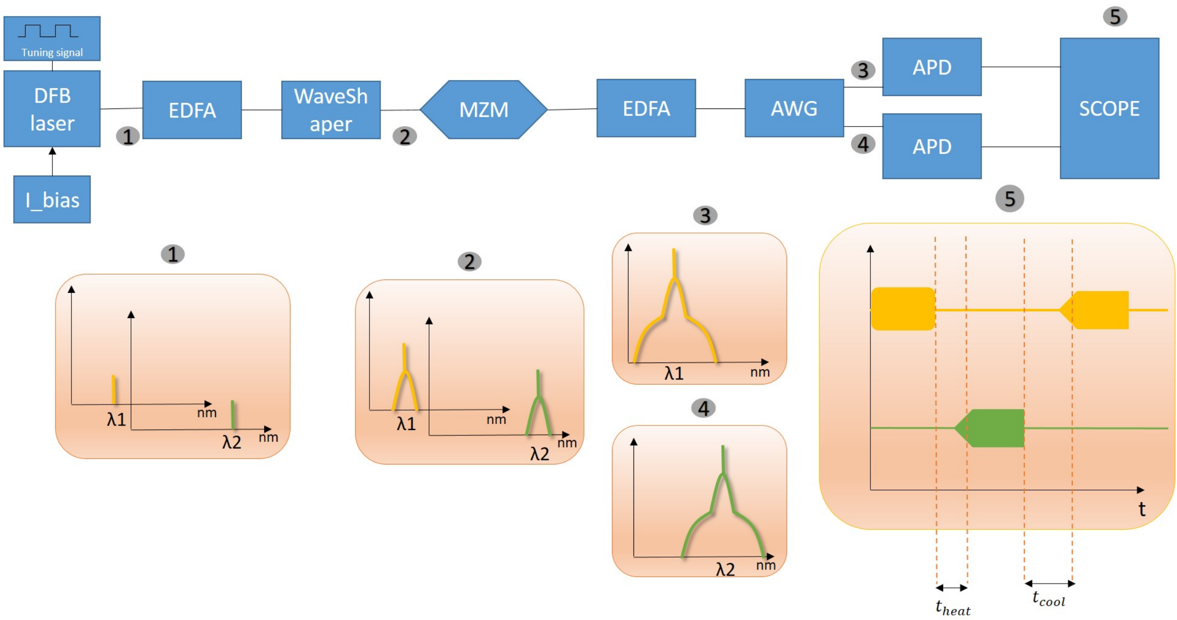



Figure 4.7: Tunning Time measurement setup (top), Expected Results (bottom)

The tunning signal used in the setup refers to I_heater, and the applied signal was a continuous pulse signal, the objective was to make the laser change from $\lambda 1$ to $\lambda 2$, and vice versa, multiple times, with the purpose to measure the $t_{heat}$ and $t_{cool}$.

The EDFA's and the waveshaper in the apparatus are used with the intent of boosting the signal's power, since the laser only debits a power around -45 to -50 dBm, without them it would be difficult to differentiate, in the electric domain, the actual signal from the noise.

The necessity to modulate the signal lies within the fact that the used scope blocks the DC component of the input signals, therefore a MZM is used to this end, otherwise, it would be impossible to watch the electric signal corresponding to the optical signal when using the laser in a CW operation.

The AWG used in the setup is set according to the 100 GHz ITU grid, and as two main functions. First acts as a wavelength splitter and enables the visualization of $\lambda 1$ and $\lambda 2$ in two different channels. Second, acts as filter, providing isolation for $\lambda 1$ and $\lambda 2$ and thus assuring that the measurements taken are effectively relative to a change from $\lambda 1$ to $\lambda 2$ and vice versa. At last we have two similar APD's, that convert the optical signal into electric domain to be further visualized in the oscilloscope, and thus observe the time relationship between $\lambda 1$ and $\lambda 2$. In short, the method is based on the observation of a power variation through a reference Wavelength Multiplexer (AWG), when the DFB laser tunes from wavelength to another.

### 4.3.2 Methodology

Considering that the DFB under test is to be used on a NG-PON2 ONU, 4 wavelength channels are going to be considered with a 100 GHz channel spacing, thus 3 different scenarios are going to be further studied, figure 4.8. Also $\lambda 1$ will always be considered as the lasing wavelength of the DFB without I_heater.

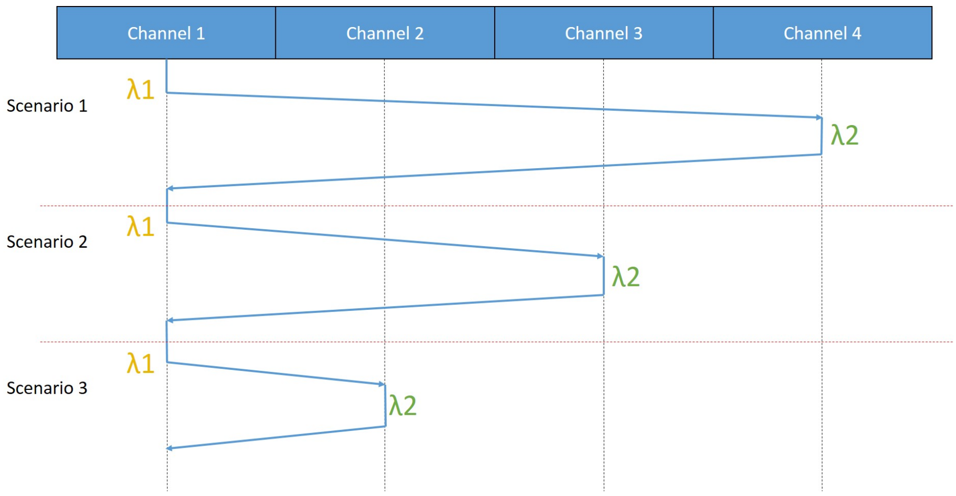



Figure 4.8: Different scenarios for a change from $\lambda 1$ yellow to $\lambda 2$ green

In a first approach to tuning time measurement, a uncooled scenario was studied, i.e., the TEC was not turned on, and all measurements were made at room temperature.

This experiment can be essentially divided in three steps:

1. Check $\lambda 1$, on a Optical Spectrum Analyzer (OSA), apply I_heater, and check $\lambda 2$, I_bias and I_heater are set accordingly so that both $\lambda 1$ and $\lambda 2$ fall withing the passband of two different AWG channels, figure 4.7(1, bottom).

2. Adjust the waveshaper to $\lambda 1$ and $\lambda 2$, and check the optical signal after the AWG to be sure that the lasing wavelengths is effectively going throw the AWG, a 50/50 coupler was used in order to check both channels simultaneously 4.7(bottom, 3&4).

3. Check $\lambda 1$ and $\lambda 2$ on the oscilloscope, figure 4.9, and measure $t_{heat}$ and $t_{cool}$.

The control signal utilized has a rise and fall time of 500 ns which is irrelevant on the tuning time scale for the DFB. On further notice, its clearly visible, figure 4.9, when the tuning time starts, as for when it ends, measurements where made on the point where the destination wavelength reaches its maximum output power. The three enumerated steps were thoroughly repeated for the different scenarios shown in 4.8. All measurements taken regarding the cases presented can be seen in Appendix B. To note that we are using a Flat-top AWG with a 100 GHz bandwidth in the setup, which means that $\lambda 1$ and $\lambda 2$ are not necessarily aligned with the AWG channel center. When performing a tunning time measurement, the tuning time ends when the the lasing wavelength enters the passband of the destination channel which does not necessarily coincide with the final $\lambda 2$.

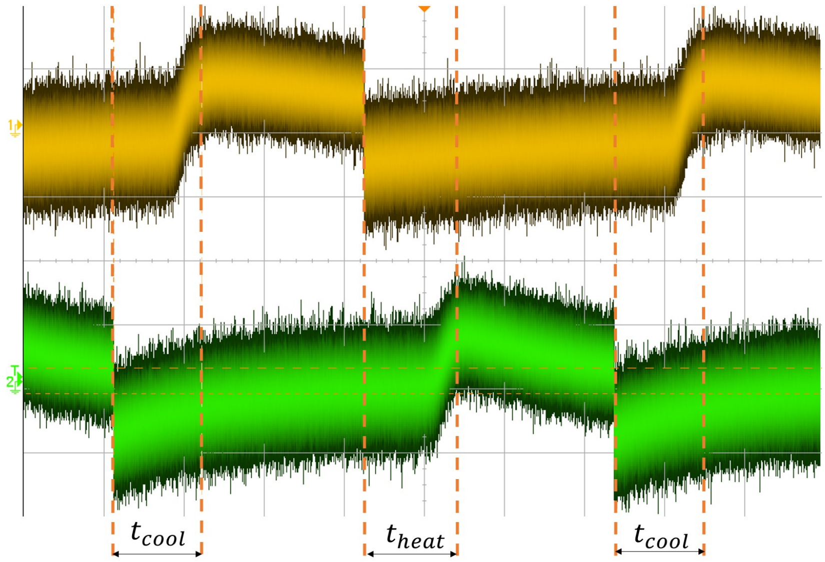
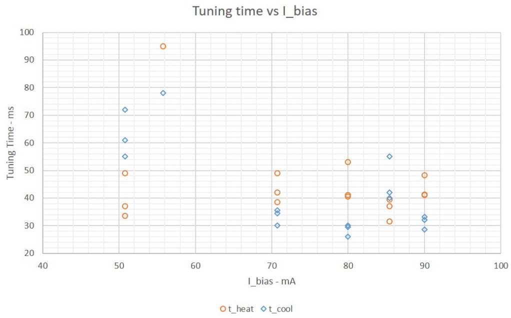



Figure 4.9: Oscilloscope picture of $\lambda 1$ yellow, and $\lambda 2$ green, 20 ms/div

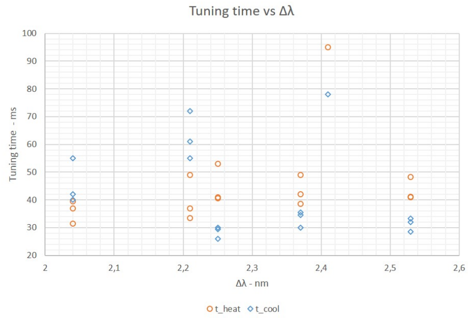
### 4.3.3 Results

#### Scenario 1

Scenario 1 refers to a tuning time from the first NG-PON2 wavelength channel (lowest $\lambda$) to the forth NG-PON2 wavelength channel (highest $\lambda$). In a practical sense, regarding the laser, this would mean a frequency shift around 300 GHz, or 2.4 nm, if the CS used is 100 GHz, which we will consider for all scenarios. The measurements for this scenario comprehend wavelength shifts in the order of 2.21 nm to 2.53 nm, which translate into 274.8 GHz to 314,1 GHz. The measured tuning time is plotted versus I_bias and $\Delta\lambda$ in figure4.10a and 4.10b, respectively. $t_{heat}$ presents a mean value of 44.8 ms, with a standard deviation of 14.1 ms. While $t_{cool}$ presents a mean value of 42.6 ms, with a standard deviation of 16 ms. Since the DFB laser is tuned by temperature, heating or cooling, which is a gradual process, higher wavelength shifts will require a higher tuning time, therefore we will analyze the tuning time per GHz in a further section.




(a) Tuning time versus I_bias



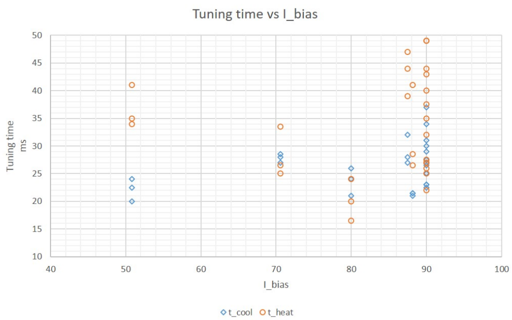

(b) Tuning time versus $\Delta\lambda$

Table 4.1: Tuning time summary Scenario 1

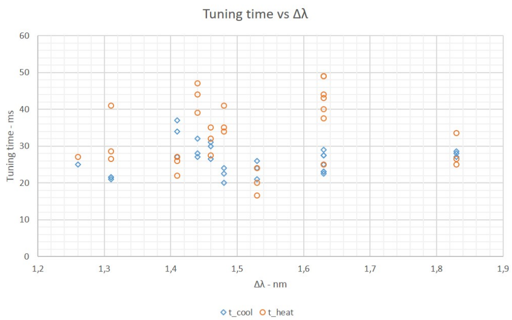
| | Average | Std. Deviation | Max | Min |
|---|---|---|---|---|
| $t_{heat}$ (ms) | 44.806 | 14.134 | 95 | 31.5 |
| $t_{cool}$ (ms) | 42.638 | 15.912 | 78 | 26 |
| $t_{heat}$/ GHz (ms/GHz) | 0.157 | 0.045 | 0.317 | 0.122 |
| $t_{cool}$/ GHz (ms/GHz) | 0.152 | 0.059 | 0.262 | 0.091 |

### Scenario 2

A wavelength shift from the first to the third NG-PON2 wavelength channel is represented by scenario 2. This would mean a frequency shift of 200 GHz, 1,6 nm, the measurements made for this scenario comprehend wavelength shifts in the order of 1.26 nm to 1.83 nm, that correspond to 156.6 GHz and 227.5 GHz. The average tuning time measured for $t_{heat}$ is 33.3 ms with a deviation of 9 ms, $t_{cool}$ presents a mean value of 26.2 ms with a deviation of 4 ms. The measured tuning time is plotted versus I_bias and $\Delta\lambda$ in figure4.11a and 4.11b respectively.




(a) Tuning time versus I_bias



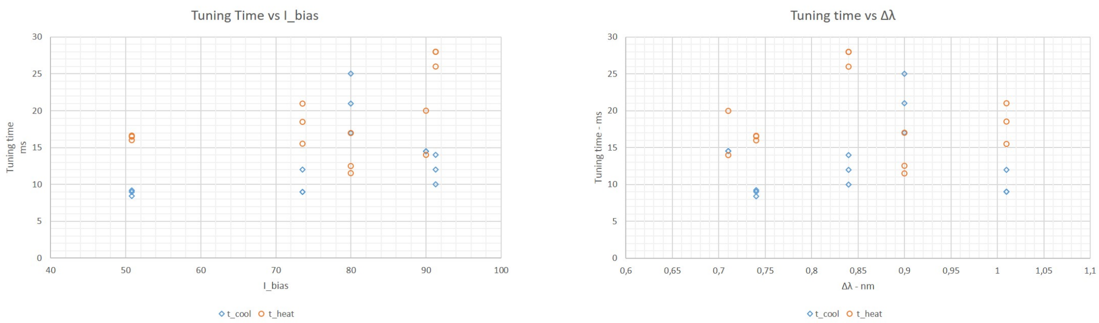

(b) Tuning time versus $\Delta\lambda$

Table 4.2: Tuning time summary Scenario 2

| | Average | Std. Deviation | Max | Min |
|---|---|---|---|---|
| $t_{heat}$ (ms) | 33.293 | 8.951 | 49 | 16.5 |
| $t_{cool}$ (ms) | 26.207 | 4.029 | 37 | 20 |
| $t_{heat}$/ GHz (ms/GHz) | 0.177 | 0.048 | 0.263 | 0.087 |
| $t_{cool}$/ GHz (ms/GHz) | 0.14 | 0.025 | 0.0211 | 0.109 |

### Scenario 3

Scenario 3 represents a wavelength channel change from the first NG-PON2 channel to the adjacent one, corresponding to a frequency shift of 100 GHz, 0.8 nm. The measurements taken for this scenario correspond to wavelength shifts in the order of 0.71 nm to 1.01 nm, which translate into 88.3 GHz to 125.6 GHz frequency shifts.The measured tuning time is plotted versus I_bias and $\Delta\lambda$ in figure4.12a and 4.12b respectively. The tuning time average for $t_{heat}$ is 18.65 ms with a deviation of 5.2 ms, as for $t_{cool}$ the mean value measured was 13.2 ms with a deviation of 4.8 ms.




(a) Tuning time versus I_bias

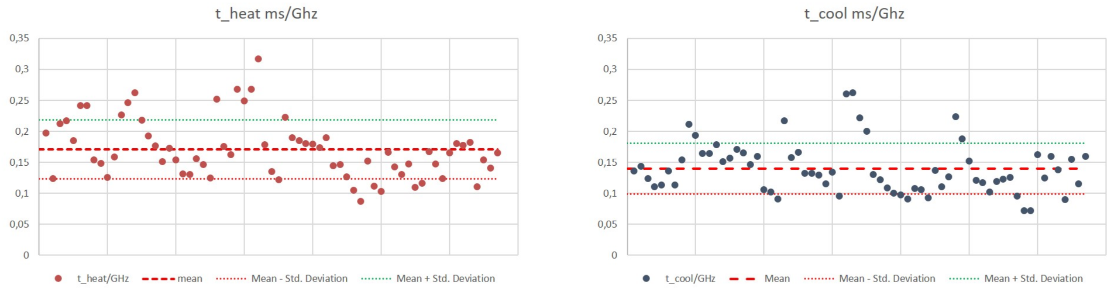
(b) Tuning time versus $\Delta\lambda$

Table 4.3: Tuning time summary Scenario 3

| | Average | Std. Deviation | Max | Min |
|---|---|---|---|---|
| $t_{heat}$ (ms) | 18.65 | 5.178 | 28 | 11.5 |
| $t_{cool}$ (ms) | 13.86 | 4.8 | 25 | 8.4 |
| $t_{heat}$ /GHz (ms/GHz) | 0.179 | 0.053 | 0.268 | 0.103 |
| $t_{cool}$ /GHz (ms/GHz) | 0.126 | 0.044 | 0.223 | 0.072 |

### 4.3.4 Statistic analysis

The tuning time per GHz, for heating and cooling is plotted in figures 4.13a and 4.13b, respectively. Figures 4.14 and 4.15 shown an histogram, with a bell curve, for $t_{heat}$/GHz and $t_{cool}$/GHz. The average value for $t_{heat}$/GHz is 0.172 and for $t_{cool}$/GHz is 0.142, and the respective standard deviations are 0.049 an 0.042 ms/GHz.




(a) (b)

Figure 4.13: (a)$t_{heat}$ and (b) $t_{cool}$ ms/GHz plotted with mean value and mean value $\pm$ standard deviation.

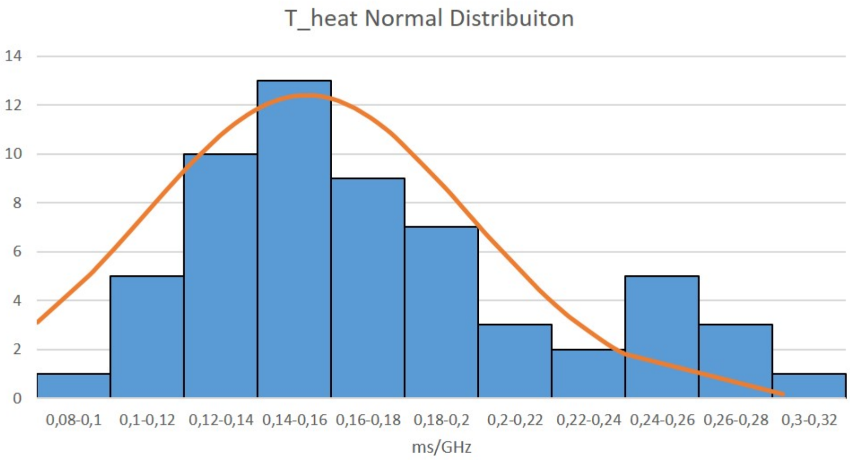



Figure 4.14: $t_{heat}$/GHz histogram and normal distribution

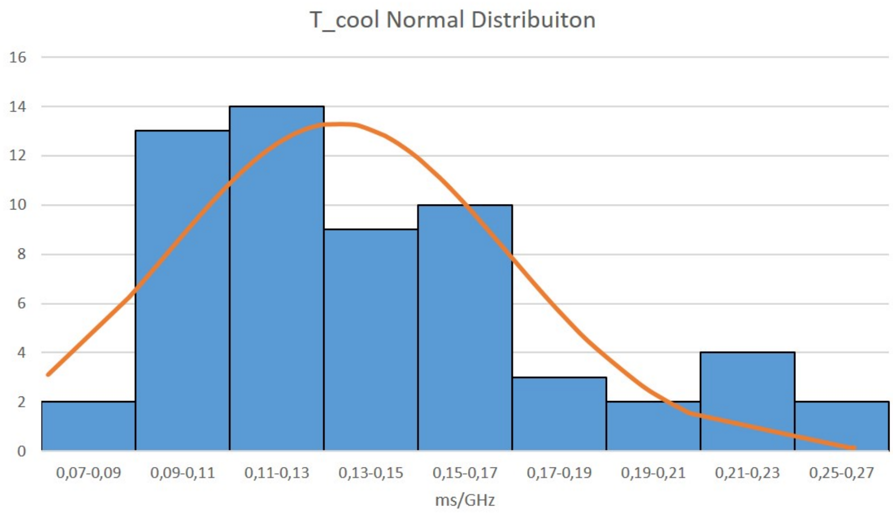



Figure 4.15: $t_{cool}$/GHz histogram and normal distribution

Analyzing the results of the tuning time measurements it can be seen high variance in the results, nonetheless it can also be seen that I_bias has no influence on the tuning time. The high divergence in the tuning time results can be caused by two factors: First the use of the waveshaper in the setup, because of the laser's low output power, which has a thinning effect on the pass-band of the original and destination channel. And second, the TEC was turned off, and measurements were made at room temperature. Few measurements were made with the TEC turned on and stabilized at 25 °C, due to a technical problem, results are summarized in table 4.4, Scenario 1,2 and 3 where evaluated to I_bias= 80 and 90 mA. The average value is slightly lower, and the standard deviation presents half of the value. To note the particular measurement, figure 4.4, referent to a wavelength change from 1552.247 nm to 1555.014 nm, meaning a 344 Ghz frequency shift. The elapsed time for heating and colling is 38.2 and 30.8 ms respectively.

We can conclude that the longest tuning time for the Tx is at maximum 27, 43 and 96 ms for 100, 200 and 300 GHz frequency shifts. Nevertheless by analyzing figure 4.14 and 4.15 it can be seen that 68,2% of the measurements point to a 0.12 to 0.21 ms/GHz heating time, and a 0.09 to 0.20 ms/GHz cooling time.

Table 4.4: $t_{heat}$/GHz and $t_{cool}$/GHz measurements with TEC

| | Average | Std. Deviation | Max | Min |
|---|---|---|---|---|
| $t_{heat}$/GHz (ms/GHz) | 0,1594 | 0,0213 | 0,1823 | 0,1111 |
| $t_{cool}$/GHz (ms/GHz) | 0,1380 | 0,0233 | 0,1624 | 0,0896 |

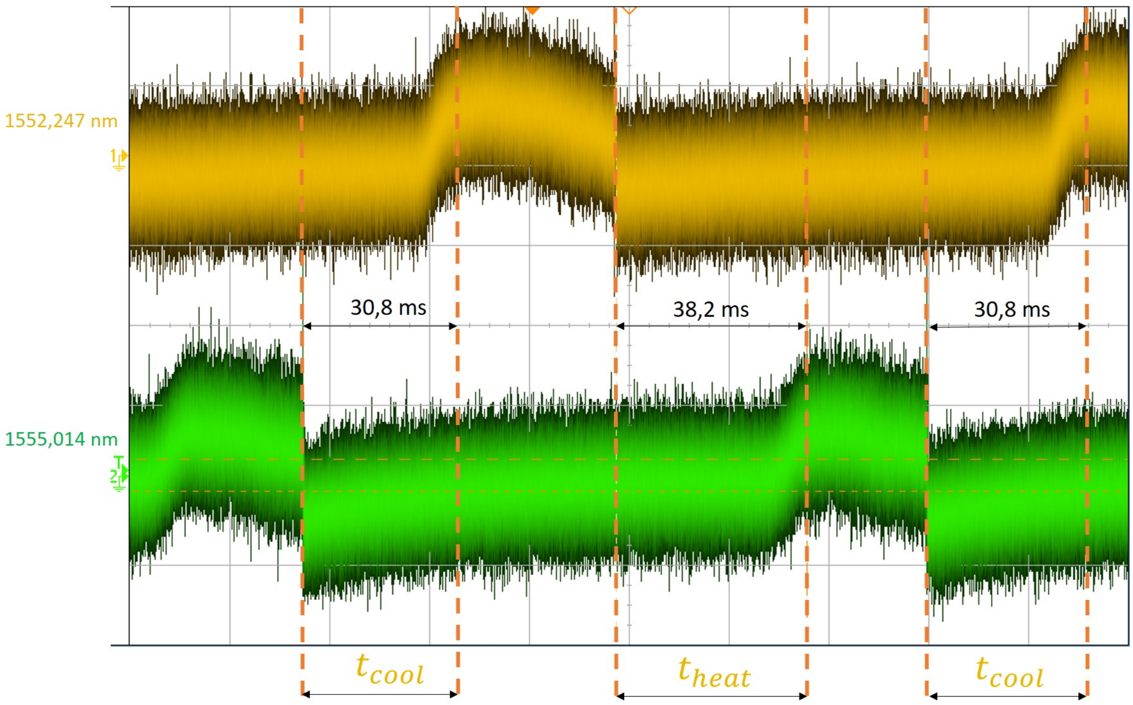



Figure 4.16: Tuning time measurement, 20 ms/div

## 4.4 Tuning Accuracy

Tuning accuracy of an ONU Tx is related to two factors: Single-Side Spectral Width (SSW) at -15 dB point, and MSE allowed imposed by Channel Spacing (CS) for Upstream (US) direction. SSW at -15 dB point was measured and found to be 0,038 nm, figure 4.17, which would mean around 5 GHz in terms of frequency. The specified MSE for 100 GHz US CS is ±20 GHz, so the accuracy to which the central peak of DFB laser must be controlled, and stay within the MSE, is then ±15 GHz. To note that the laser was externally modulated at 2.5 Gbit/s using a MZM. Direct modulation was not studied for this laser mainly because of the low output power, nevertheless using direct modulation in burst mode for this kind of Tx, would probably make it exceed the MSE values allowed.

In a case where CS for the US is 50 GHz, thus an MSE allowed of 12.5 GHz, the DFB would have to be controlled with an accuracy of ±7.5 GHz in order to stay withing the specified MSE.

Figure 4.18 shows the relationship between I_heater and the frequency shift produced, the red dashed vertical lines mark the ±15GHz around the channel center, whereas the blue dashed vertical lines mark the ±7,5 GHz. Assuming that for the laser to tune in the first wavelength channel (λ1, blue for 50 GHz CS, red for 100 GHz CS) a 50 GHz shift would be needed, it can be seen that the laser can be controlled accurately by I_heater, in order to tune to one of the other three wavelengths channels (λ2,λ3 or λ4) and stay within it, without exceeding the MSE limits, for both 50 and 100 GHz. In a practical scenario, the first wavelength channel would be set ideally with I_heater=0, being that the temperature stabilized by the TEC would define the US wavelength.

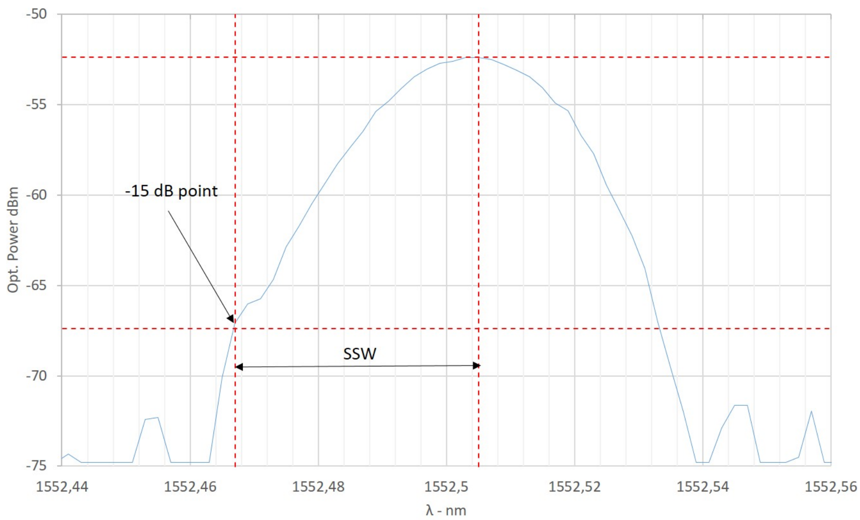



Figure 4.17: Optical Spectrum of the DFB, externally modulated at 2.5 Gbit/s, and measured with 33 pm accuracy.

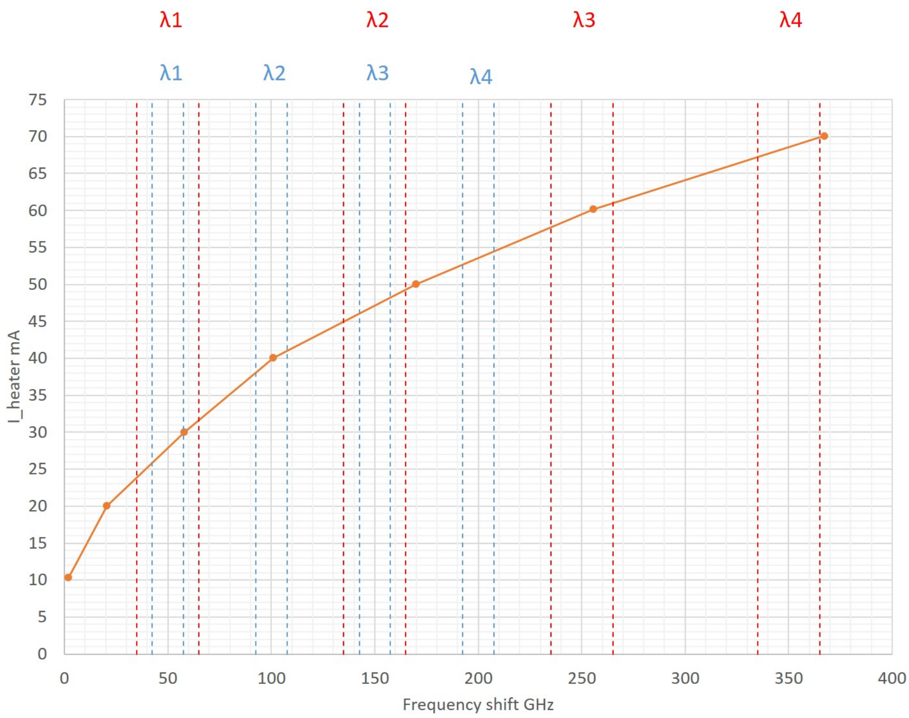



Figure 4.18: Relationship between I_heater and frequency shift @ 25 °C.

## 4.5 Tuning Mechanisms

The characterized DFB laser, operating in conjunction with a TEC, can be considered a loose calibrated Tx. By maintaining the temperature of operation constant, the lasing wavelength can be controlled by a stepped I_heater, with sufficient accuracy, in order to, change and stay within a desired wavelength channel, in short the ONU equipped with such transceiver would be capable of performing a **coarse tuning mechanism** autonomously. Nonetheless, such transmitter will not be able to tune its wavelength to the best tuning point on the wavelength channel, requiring an additional **fine tuning mechanism**, such as the one described in the previous chapter under section 3.9.8.

**OLT-port Protection**

The OLT-port protection presented in section 3.9.9 provides a fast solution for wavelength assignment in case of an OLT-port failure. The main feature of the referred tuning mechanism relies on a preconfiguration of a backup wavelength pair. In a case where the ONU Tx is characterized by a long tuning time, such as the transmitter under study, a good approach would be configuring the backup wavelength pair in an adjacent channel. If an OLT-port were to failure, the ONU would tune to the backup wavelength pair with a tunning time under 30 ms, nonetheless before resuming normal operation, the fine tuning mechanism previously mentioned would be necessary, to find the best tuning point for the ONU Tx. Regardless, the service interruption time would be less than the 50 ms defined in the ITU-T Recommendation G.989.1 [5]. For this purpose the OLT would not need to inventory the back up wavelength pair of each ONU, but just a flag signaling the direction of the adjacent wavelength channel pair which would serve as back up.

**Power Saving**

In a case where the low traffic on the PON justifies a sleep operation mode for one or more OLT-ports, and some of the ONUs are required to tune their wavelength to another OLT-port. The ONU featuring the presented DFB Tx would be capable of such operation under 50 ms if two conditions are meet. First the OLT should always have two ports in constant and normal operation. Second the ONUs required to re-tune their wavelengths, would do so, but to one of the adjacent channels, in order to meet the requirements of maximum tuning time allowed. Also, by making the OLT port #2 and #4 enter in sleep mode, ONUs would require to tune their wavelengths to port #1 and #3 (port #1 is the lowest wavelength, and port #4 is the highest), thus the Tx would require cooling to tune and take advantage of the shortest tuning time presented by the tunable DFB.

**Load Balancing**

An NG-PON2 ONU equipped with a Tx similar to the one presented in this chapter might support a semi-static load balancing functionality, with a in-service tuning capability that would not exceed the 50 ms. This network function could be achieved in an analogous way as the previously presented function. By ensuring that the ONU Tx would retune its wavelength to one of the adjacent channels.

Note that, in NG-PON2 Configuration where 50 GHz is used in US channel spacing the tuning time of the DFB laser can be drastically reduced, making it even more feasible the availability of the aforementioned network functionalities on the NG-PON2 ONU.

## 4.6 Further Considerations

Integrating a temperature sensor in the laser would enable its use on a NG-PON2 ONU, without the need for the TEC, in a case where a cyclic AWG is used, section 3.11.1. Such approach was described and studied in [50]. The DFB laser with an integrated heater and temperature sensor, would provide a lower cost solution than the DFB laser previously presented. Its operating wavelength could be maintained with a feedback control loop, using I_heater as a control signal, while the temperature sensor provides the needed feedback. Using such a type of Tx in ONU would be classified as an uncalibrated ONU. The tuning mechanism required for such approach are slightly different, the process of activation of uncalibrated ONU was described in section 3.9.2, so were the process of coarse and fine-tuning. An additional tuning mechanism must feature this kind of ONU Tx, and its related with the possibility of I_heater reaching its thresholds. Since there is not a TEC in order to stabilize the temperature of operation, temperature fluctuations might require the laser to retune its wavelength over 400Ghz to stay within the same channel termination.

# Chapter 5

# Conclusions and Future Work

## 5.1 Conclusions

This work as been presented on a set of 5 chapters, The first chapter included context, motivation, structure, objectives and the main contributions.

Second chapter features a state of the art regarding PON in access and legacy PONs. As well as a short review on colorless receivers and transmitters.

The third chapter presents an extensive overview on NG-PON2 system, which is the first standardized PON system to feature a multi-wavelength over the same ODN. Although harder to implement, this translates in the main advantage of NG-PON2, its spectral flexibility and wavelength agility. In order to provide a smooth transition from Legacy PONs, coexistence is enabled. The wavelength plan defined for NG-PON2 specifies three US options for TWDM-PON in order to provide relaxation regarding the ONU Tx control, furthermore since PtP WDM will be able to exploit unused wavelength bands, NG-PON2 will make efficient use of the spectrum.

The support for multiple ODN configurations (WS-ODN, WR-ODN and Hybrid ODN) can meet various operator and application needs, either for a deployment with need for coexistence or a green-field scenario, or a deployment in dense urban areas or rural areas.

Tuning mechanisms are addressed in order to deal with, calibrated, loosely calibrated and uncalibrated ONU. Calibrated ONUs do not need particular attention, loosely calibrated ONUs can perform a coarse tuning mechanism autonomously and uncalibrated ONUs are required to be under OLT fine control, either for coarse or fine tuning.

Regarding the choice for the tunable Tx for the OLT and ONU, a number of factors have to be taken into account, such as, tuning time, spectral excursion, tuning accuracy, as well if they can be directly modulated at the specified line rates or if external modulation is needed.

For the ONU tunable Tx, th choice depends on three factors, US wavelength plan, channel spacing and line rate. Wavelength plan and CS relate to the spectral and tuning characteristics of the laser. Using the wide wavelength plan option, in conjunction with an cyclic AWG allows transmitter to drift in wavelength over a wide range. Higher values of MSE allowed can enable the use of loose calibrated ONU, thus low-cost solutions as ONU Tx. While for lower values of MSE might require the use of calibrated Tx or ensure mechanisms of wavelength locking. The line rate might influence the choice for the tunable ONU Tx, DML are well developed when it comes to 2,5 Gbit/s data rate, which is not the case for 10 Gbit/s.

Regarding Chapter 4, the tunable transmitter under study, aligned with an external modulator (which can be monolithically integrated) and a TEC, might prove to be a low cost solution for an NG-PON2 TWDM-PON ONU. Tuning mechanisms are addressed in order to activate and tune loosely calibrated ONUs on the PON, which is the category at which the tunable DFB belongs. Tunable accuracy is deduced, and the Tx can be used in two configurations of US channel spacing, 50 and 100 GHz, although the former might easily enable network functions requiring tuning times of $\mu$s to ms order.

## 5.2 Future Work

The first proposal is to develop a controller for the studied transceiver in order to realize its implementation on a real ONU, with the release of ITU recommendation G.989.3 PLOAM messages were upgrade to deal with tuning performed by ONUs, so the main goal for such controller is to perform coarse tuning autonomously if issued by the OLT, and to deal with the OLT instructions in order to perform fine-tuning.

Second proposal, and still related to the former, is to extend the research on tunable receivers in order to find one that fits the tuning time characteristics of the DFB laser presented in this work, in order to build matched ONU in terms of tuning, that provides both a low cost solution and with some of the desirable network functions that require in-service tuning.

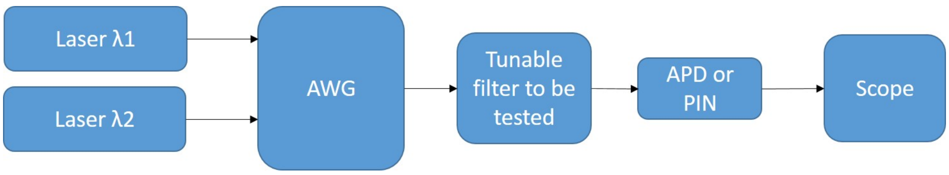



Figure 5.1: Proposed setup to measure tuning time of a tunable filter

# Appendices

# Appendix A

# Laser Characterization

Table A.1: $\lambda$ versus I_bias, I_heater=0 @ 25 °C

| I_bias mA | $\lambda$ nm | Optical Power dBm |
|---|---|---|
| 0,05 | N/A | N/A |
| 10,34 | N/A | N/A |
| 20,23 | 1551,067 | -60,5 |
| 30,34 | 1551,188 | -53,4 |
| 40,18 | 1551,276 | -51,7 |
| 50,29 | 1551,43 | -50,3 |
| 60,53 | 1551,606 | -49,2 |
| 70,15 | 1551,793 | -48,4 |
| 80,47 | 1551,969 | -48,9 |
| 90,21 | 1552,244 | -46,6 |
| 100,58 | 1552,563 | -47,1 |

Table A.2: $\lambda$ versus I_bias, I_heater=0 @ 45 °C

| I_bias mA | $\lambda$ nm | Optical Power dBm |
|---|---|---|
| 0,06 | N/A | N/A |
| 10,08 | N/A | N/A |
| 20,04 | 1552,93 | -64,2 |
| 30,41 | 1553,03 | -53,9 |
| 40,37 | 1553,17 | -51,6 |
| 50,29 | 1553,36 | -49,7 |
| 60,48 | 1553,55 | -48,4 |
| 70,24 | 1553,73 | -47,4 |
| 80,39 | 1554 | -47,5 |
| 90,28 | 1554,29 | -47,2 |
| 100,17 | 1554,6 | -46,9 |

Table A.3: $\lambda$ versus I_heater, I_bias=50.66 mA @ 25 °C

| I_heater mA | V_heater V | $\lambda$ nm | Optical Power dBm |
|---|---|---|---|
| 0 | 0 | 1551,405 | -48,9 |
| 10,68 | 0,624 | 1551,48 | -48,9 |
| 20,26 | 1,189 | 1551,645 | -49,5 |
| 30,01 | 1,778 | 1551,855 | -51,7 |
| 40,05 | 2,403 | 1552,26 | -50 |
| 50,28 | 3,089 | 1552,695 | -50 |
| 60,09 | 3,782 | 1553,355 | -50,2 |
| 70,19 | 4,56 | 1554,225 | -51,9 |
| 80,38 | 5,429 | 1555,32 | -55 |
| 90,16 | 6,374 | 1556,715 | -59,6 |

Table A.4: $\lambda$ versus I_heater, I_bias=80.2 mA @ 25 °C

| I_heater mA | V_heater V | $\lambda$ nm | Optical Power dBm |
|---|---|---|---|
| 0 | 0 | 1552,005 | -48,6 |
| 10,33 | 0,609 | 1552,02 | -47,5 |
| 20,04 | 1,189 | 1552,17 | -48,5 |
| 30,01 | 1,799 | 1552,47 | -45,5 |
| 40,05 | 2,438 | 1552,815 | -45,7 |
| 50,02 | 3,107 | 1553,37 | -45,7 |
| 60,16 | 3,835 | 1554,06 | -47 |
| 70,08 | 4,61 | 1554,96 | -48,6 |
| 80,19 | 5,487 | 1556,13 | -51,8 |
| 90,11 | 6,463 | 1557,63 | -56,1 |

Table A.5: $\lambda$ versus I_heater, I_bias=50.13 mA @ 40 °C

| I heater mA | V_heater V | $\lambda$ nm | Optical Power dBm |
|---|---|---|---|
| 0 | 0 | 1553,349 | -49,7 |
| 10,02 | 0,611 | 1553,376 | -49,7 |
| 20,01 | 1,228 | 1553,574 | -49,7 |
| 30,16 | 1,872 | 1553,862 | -49,7 |
| 40,59 | 2,56 | 1554,258 | -49,9 |
| 50,13 | 3,224 | 1554,789 | -51,1 |
| 60,05 | 3,965 | 1555,509 | -51,8 |
| 70,2 | 4,791 | 1556,427 | -55,3 |
| 80,22 | 5,698 | 1557,66 | -61,1 |
| 90,17 | 6,73 | N/A | N/A |

Table A.6: $\lambda$ versus I_heater, I_bias=80.14 mA @ 40 °C

| I_heater mA | V_heater V | $\lambda$ nm | Optical Power dBm |
|---|---|---|---|
| 0 | 0 | 1554,02 | -47 |
| 10,05 | 0,621 | 1554,03 | -47 |
| 20,01 | 1,242 | 1554,2 | -47 |
| 30,02 | 1,886 | 1554,5 | -47 |
| 40,03 | 2,556 | 1554,93 | -48 |
| 50,02 | 3,262 | 1555,48 | -48,9 |
| 60,16 | 4,031 | 1556,3 | -51 |
| 70,39 | 4,879 | 1557,33 | -54,3 |
| 80,24 | 5,787 | 1558,61 | -59,8 |
| 90,3 | 6,866 | N/A | N/A |

# Appendix B

# Tuning Time measurements

Table B.1: Measurements regarding tuning time

| I_bias mA | $\lambda 1$ nm | $\lambda 2$ nm | $\Delta\ \lambda$ nm | $\Delta\ \nu$ GHz | $t_{heat}$ ms | $t_{heat}/$ GHz | $t_{cool}$ ms | $t_{cool}/$ GHz | Vpp | I_heater mA |
|---|---|---|---|---|---|---|---|---|---|---|
| 90 | 1552,61 | 1553,32 | 0,71 | 88,3 | 14 | 0,159 | 14,5 | 0,164 | 2,2 | 37,49 |
| 90 | 1552,61 | 1553,32 | 0,71 | 88,3 | 20 | 0,226 | 14,5 | 0,164 | 2,2 | 37,49 |
| 50,81 | 1552,05 | 1552,79 | 0,74 | 92,1 | 16,6 | 0,180 | 9,2 | 0,100 | 2,6 | 44,30 |
| 50,81 | 1552,05 | 1552,79 | 0,74 | 92,1 | 16,5 | 0,179 | 9 | 0,098 | 2,6 | 44,30 |
| 50,81 | 1552,05 | 1552,79 | 0,74 | 92,1 | 16 | 0,174 | 8,4 | 0,091 | 2,6 | 44,30 |
| 91,24 | 1552,94 | 1553,78 | 0,84 | 104,4 | 28 | 0,268 | 12 | 0,115 | 2,5 | 42,60 |
| 91,24 | 1552,94 | 1553,78 | 0,84 | 104,4 | 26 | 0,249 | 14 | 0,134 | 2,5 | 42,60 |
| 91,24 | 1552,94 | 1553,78 | 0,84 | 104,4 | 28 | 0,268 | 10 | 0,096 | 2,5 | 42,60 |
| 80 | 1552,69 | 1553,59 | 0,9 | 111,9 | 17 | 0,152 | 25 | 0,223 | 2,8 | 47,71 |
| 80 | 1552,69 | 1553,59 | 0,9 | 111,9 | 12,5 | 0,112 | 21 | 0,188 | 2,8 | 47,71 |
| 80 | 1552,69 | 1553,59 | 0,9 | 111,9 | 11,5 | 0,103 | 17 | 0,152 | 2,8 | 47,71 |
| 73,55 | 1552,48 | 1553,49 | 1,01 | 125,6 | 21 | 0,167 | 12 | 0,096 | 2,8 | 47,71 |
| 73,55 | 1552,48 | 1553,49 | 1,01 | 125,6 | 18,5 | 0,147 | 9 | 0,072 | 2,8 | 47,71 |
| 73,55 | 1552,48 | 1553,49 | 1,01 | 125,6 | 15,5 | 0,123 | 9 | 0,072 | 2,8 | 47,71 |
| 90 | 1552,94 | 1554,2 | 1,26 | 156,6 | 27 | 0,172 | 25 | 0,160 | 3 | 51,12 |
| 88,19 | 1553,04 | 1554,35 | 1,31 | 162,8 | 41 | 0,252 | 21,5 | 0,132 | 3,25 | 55,38 |
| 88,19 | 1553,04 | 1554,35 | 1,31 | 162,8 | 28,5 | 0,175 | 21,5 | 0,132 | 3,25 | 55,38 |
| 88,19 | 1553,04 | 1554,35 | 1,31 | 162,8 | 26,5 | 0,163 | 21 | 0,129 | 3,25 | 55,38 |
| 90 | 1552,54 | 1553,95 | 1,41 | 175,3 | 27 | 0,154 | 27 | 0,154 | 3,22 | 54,87 |
| 90 | 1552,54 | 1553,95 | 1,41 | 175,3 | 26 | 0,148 | 37 | 0,211 | 3,22 | 54,87 |
| 90 | 1552,54 | 1553,95 | 1,41 | 175,3 | 22 | 0,125 | 34 | 0,194 | 3,22 | 54,87 |
| 87,52 | 1553,02 | 1554,46 | 1,44 | 178,9 | 44 | 0,246 | 32 | 0,179 | 4,25 | 72,42 |
| 87,52 | 1553,02 | 1554,46 | 1,44 | 178,9 | 47 | 0,263 | 27 | 0,151 | 4,25 | 72,42 |
| 87,52 | 1553,02 | 1554,46 | 1,44 | 178,9 | 39 | 0,218 | 28 | 0,156 | 4,25 | 72,42 |
| 90 | 1552,99 | 1554,45 | 1,46 | 181,4 | 35 | 0,193 | 31 | 0,171 | 3,5 | 59,64 |
| 90 | 1552,99 | 1554,45 | 1,46 | 181,4 | 32 | 0,176 | 30 | 0,165 | 3,5 | 59,64 |
| 90 | 1552,99 | 1554,45 | 1,46 | 181,4 | 27,5 | 0,152 | 26,5 | 0,146 | 3,5 | 59,64 |
| 50,81 | 1552,06 | 1553,54 | 1,48 | 184,1 | 41 | 0,223 | 24 | 0,130 | 3,4 | 57,93 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| 50,81 | 1552,06 | 1553,54 | 1,48 | 184,1 | 35 | 0,190 | 22,5 | 0,122 | 3,4 | 57,93 |
| 50,81 | 1552,06 | 1553,54 | 1,48 | 184,1 | 34 | 0,185 | 20 | 0,109 | 3,4 | 57,93 |
| 80 | 1552,69 | 1554,22 | 1,53 | 190,2 | 24 | 0,126 | 26 | 0,137 | 3,6 | 61,34 |
| 80 | 1552,69 | 1554,22 | 1,53 | 190,2 | 20 | 0,105 | 21 | 0,110 | 3,6 | 61,34 |
| 80 | 1552,69 | 1554,22 | 1,53 | 190,2 | 16,5 | 0,087 | 24 | 0,126 | 3,6 | 61,34 |
| 90 | 1552,86 | 1554,49 | 1,63 | 202,6 | 40 | 0,197 | 27,5 | 0,136 | 3 | 51,12 |
| 90 | 1552,86 | 1554,49 | 1,63 | 202,6 | 25 | 0,123 | 29 | 0,143 | 3 | 51,12 |
| 90 | 1552,86 | 1554,49 | 1,63 | 202,6 | 43 | 0,212 | 25 | 0,123 | 3 | 51,12 |
| 90 | 1552,86 | 1554,49 | 1,63 | 202,6 | 44 | 0,217 | 22,5 | 0,111 | 3 | 51,12 |
| 90 | 1552,86 | 1554,49 | 1,63 | 202,6 | 37,5 | 0,185 | 23 | 0,114 | 3 | 51,12 |
| 90 | 1552,86 | 1554,49 | 1,63 | 202,6 | 49 | 0,242 | 27,5 | 0,136 | 3 | 51,12 |
| 90 | 1552,86 | 1554,49 | 1,63 | 202,6 | 49 | 0,242 | 23 | 0,114 | 3 | 51,12 |
| 70,55 | 1552,69 | 1554,52 | 1,83 | 227,5 | 33,5 | 0,147 | 27 | 0,119 | 3,8 | 64,75 |
| 70,55 | 1552,69 | 1554,52 | 1,83 | 227,5 | 25 | 0,110 | 28 | 0,123 | 3,8 | 64,75 |
| 70,55 | 1552,69 | 1554,52 | 1,83 | 227,5 | 26,5 | 0,117 | 28,5 | 0,125 | 3,8 | 64,75 |
| 85,44 | 1553,04 | 1555,08 | 2,04 | 253,4 | 39,5 | 0,156 | 55 | 0,217 | 3,8 | 64,75 |
| 85,44 | 1553,04 | 1555,08 | 2,04 | 253,4 | 37 | 0,146 | 40 | 0,158 | 3,8 | 64,75 |
| 85,44 | 1553,04 | 1555,08 | 2,04 | 253,4 | 31,5 | 0,124 | 42 | 0,166 | 3,8 | 64,75 |
| 50,81 | 1552,06 | 1554,27 | 2,21 | 274,8 | 49 | 0,178 | 72 | 0,262 | 4 | 68,16 |
| 50,81 | 1552,06 | 1554,27 | 2,21 | 274,8 | 37 | 0,135 | 61 | 0,222 | 4 | 68,16 |
| 50,81 | 1552,06 | 1554,27 | 2,21 | 274,8 | 33,5 | 0,122 | 55 | 0,200 | 4 | 68,16 |
| 80 | 1552,69 | 1554,94 | 2,25 | 279,6 | 53 | 0,190 | 30 | 0,107 | 4 | 68,16 |
| 80 | 1552,69 | 1554,94 | 2,25 | 279,6 | 40,5 | 0,145 | 29,5 | 0,106 | 4 | 68,16 |
| 80 | 1552,69 | 1554,94 | 2,25 | 279,6 | 41 | 0,147 | 26 | 0,093 | 4 | 68,16 |
| 70,74 | 1552,69 | 1555,06 | 2,37 | 294,5 | 49 | 0,166 | 35,5 | 0,121 | 4,2 | 71,57 |
| 70,74 | 1552,69 | 1555,06 | 2,37 | 294,5 | 42 | 0,143 | 34,5 | 0,117 | 4,2 | 71,57 |
| 70,74 | 1552,69 | 1555,06 | 2,37 | 294,5 | 38,5 | 0,131 | 30 | 0,102 | 4,2 | 71,57 |
| 55,8 | 1551,97 | 1554,38 | 2,41 | 299,7 | 95 | 0,317 | 78 | 0,260 | 4 | 68,16 |
| 90 | 1553,31 | 1555,84 | 2,53 | 314,1 | 48,2 | 0,153 | 33,2 | 0,106 | 4,2 | 71,57 |
| 90 | 1553,31 | 1555,84 | 2,53 | 314,1 | 41,2 | 0,131 | 32 | 0,102 | 4,2 | 71,57 |
| 90 | 1553,31 | 1555,84 | 2,53 | 314,1 | 41 | 0,131 | 28,5 | 0,091 | 4,2 | 71,57 |

# Bibliography


[1] Anne Zelenka. https://gigaom.com/2007/10/06/from-the-information-age-to-the-connected-age/. website, October 2007.

[2] L.G. Kazovsky, N. Cheng, W.T. Shaw, D. Gutierrez, and S.W. Wong. *Broadband Optical Access Networks*. Wiley, 2011.

[3] M. Hajduczenia and J. A. da Silva. Next generation PON systems – current status. In *11th International Conference on Transparent Optical Networks*, 2009.

[4] Fibre capacity limitations in access networks. Technical report, Analysys Mason, Report of Ofcom, 2010.

[5] TELECOMMUNICATION STANDARDIZATION SECTOR OF ITU. *" 40-Gigabit-capable Passive Optical : Genreal requirements"*. International Telecommunication Union (ITU-T), March 2013.

[6] "Bárbara Salomé Ribeiro de Almeida". "Advanced passive optical networks and of extended coverage". Master's thesis, Universidade de Aveiro, 2011.

[7] White paper. "TWDM PON is on the Horizon". Technical report, Ovum, 2014.

[8] "Evolution of FTTH Networks for NG-PON2", 2013.

[9] Ivica Cale, Aida Salihovic, and Matija Ivekovic. Gigabit Passive Optical Network - GPON. In *ITI 2007 29th Int. Conf. on Information Technology Interfaces*, 2007.

[10] TELECOMMUNICATION STANDARDIZATION SECTOR OF ITU. *" Gigabit-capable Passive Optical : Physical Media Dependent (PMD) layer specification"*. International Telecommunication Union (ITU-T), March 2003.

[11] TELECOMMUNICATION STANDARDIZATION SECTOR OF ITU. *"Gigabit-capable Passive Optical : ONT management and control interface specification "*. International Telecommunication Union (ITU-T), February 2008.

[12] Pablo Guillen. " GPON-Fundamentals. Technical Team from FTTH Marketing Departement ". Technical report, HUAWEI TECHNOLOGIES, 2013.

[13] TELECOMMUNICATION STANDARDIZATION SECTOR OF ITU. *" Gigabit-capable Passive Optical : Genreal characteristics"*. International Telecommunication Union (ITU-T), March 2008.

[14] TELECOMMUNICATION STANDARDIZATION SECTOR OF ITU. *" Gigabit-capable Passive Optical : Transmission convergence layer specification"*. International Telecommunication Union (ITU-T), January 2014.

[15] TELECOMMUNICATION STANDARDIZATION SECTOR OF ITU. *"10-Gigabit-capable passive optical networks (XG-PON): General requirements "*. International Telecommunication Union (ITU-T), January 2010.

[16] V. P. Gribkovskii and G. I. Moiseenko. "a possible laser mechanism in thin semiconductor plates,". *Journal of Applied Spectroscopy*, 14:713–716, 1971.

[17] http://www.jdsu.com. "multiple application platform (map) fp laser,".

[18] G.P. Agrawal. *Fiber-Optic Communication Systems*. Wiley Series in Microwave and Optical Engineering. Wiley, 2012.

[19] Elizabeth Bruce. Tunable lasers. `http://spectrum.ieee.org/semiconductors/optoelectronics/tunable-lasers`.

[20] Harry J. R. Dutton. *Understanding Optical Communications*. 1998.

[21] J. Klamkin, J. M. Hutchinson, J. T. Getty, L. A. Johansson, E. J. Skogen, and L. A. Coldren. High efficiency widely tunable sgdbr lasers for improved direct modulation performance. *IEEE Journal of Selected Topics in Quantum Electronics*, 11(5):931–938, Sept 2005.

[22] G. Sarlet, G. Morthier, and R. Baets. Control of widely tunable ssg-dbr lasers for dense wavelength division multiplexing. *Journal of Lightwave Technology*, 18(8):1128–1138, Aug 2000.

[23] O. A. Lavrova and D. J. Blumenthal. Detailed transfer matrix method-based dynamic model for multisection widely tunable gcsr lasers. *Journal of Lightwave Technology*, 18(9):1274–1283, Sept 2000.

[24] A. J. Ward, D. J. Robbins, G. Busico, E. Barton, L. Ponnampalam, J. P. Duck, N. D. Whitbread, P. J. Williams, D. C. J. Reid, A. C. Carter, and M. J. Wale. Widely tunable ds-dbr laser with monolithically integrated soa: design and performance. *IEEE Journal of Selected Topics in Quantum Electronics*, 11(1):149–156, Jan 2005.

[25] Xiaoying He, Yonglin Yu, Shan Jiang, Dexiu Huang, and D.n. Wang. Widely tunable digital concatenated grating dbr laser. In *Optical Fiber Communication Conference/National Fiber Optic Engineers Conference*, page JWA46. Optical Society of America, 2008.

[26] Rp-photonics encyclopedia - external-cavity diode lasers. `https://www.rp-photonics.com/external_cavity_diode_lasers.html`.

[27] J. C. Hulme, J. K. Doylend, and J. E. Bowers. Widely tunable vernier ring laser on hybrid silicon. *Opt. Express*, 21(17):19718–19722, Aug 2013.

[28] A. Le Liepvre, C. Jany, A. Accard, M. Lamponi, F. Poingt, D. Make, F. Lelarge, J. M. Fedeli, S. Messaoudene, D. Bordel, and G. H. Duan. Widely wavelength tunable hybrid iii-v/silicon laser with 45 nm tuning range fabricated using a wafer bonding technique. In *The 9th International Conference on Group IV Photonics (GFP)*, pages 54–56, Aug.

[29] Hu T, Wang W J, Qiu C, Yu P, Qiu H Y, Zhao Y, Jiang X Q, and Yang Y. "Thermally tunable filters based on third-order microring resonators for WDM applications.". *IEEE Photonics Technology Letters*, 24(6):524–526, 2012.

[30] Domash L, Wu M, Nemchuk N, and Ma E. "Tunable and switchable multiple-cavity thin-film filters". *Journal of Lightwave Technology*, 22(1):126–135, 2004.

[31] Lequime M., Parmentier R., Lemarchand F., and Amra C. "Toward tunable thin-film filters for wavelength diision multiplexing applications.". *Appl Opt*, 41(16):3277–3284, 2002.

[32] Robert Murano, Wayne F. Sharfin, and Michael J. Cahill. Tunable 2.5gb/s receiver for wavelength-agile dwdm-pon. In *Optical Fiber Communication Conference/National Fiber Optic Engineers Conference*, page PDP32. Optical Society of America, 2008.

[33] Goh C S, Set S Y, and Kikuchi K. "Widely tunable optical filters based on fiber Bragg gratings". *IEEE Photonics Technology Letters*, 14(9):1306–1308, 2002.

[34] Yuanqiu Luo, Xiaoping Zhou, Frank Effenberger, Xuejin Yan, Guikai Peng, Yinbo Qian, and Yiran Ma. "Time- and Wavelength-Division Multiplexed Passive Optical Network (TWDM-PON) for Next-Generation PON Stage 2 (NG-PON2)". *Journal of Lightwave Technology*, 31(4):587–592, 2012.

[35] https://www.fsan.org/.

[36] E. Harstead and D. V. Veen and P. Vetter. "Technologies for NGPON2: Why I think 40G TDM PON (XLG-PON) is the clear winner". In *Proc. Opt. Fiber Commun. Conf./Nat. Fiber Opt. Eng. Conf. Workshop*, 2012.

[37] Y. Ma and Y. Qian and G. Peng and X. Zhou and X. Wang and J. Yu and Y. Luo and X. Yan and F. Effenberger. "Demonstration of a 40 Gb/s time and wavelength division multiplexed passive optical network prototype system". In *presented at the Opt. Fiber Commun. Conf./Nat. Fiber Opt. Eng. Conf.*, 2012.

[38] H. K. Lee and H. S. Cho and J. Y. Kim and C. H. Lee,. "A WDM-PON with an 80 Gb/s capacity based on wavelength-locked Fabry-Perot laser diode,". *Optics Express*, 18(17):18077–18085, 2010.

[39] K. Grobe and J. P. Elbers,. "PON in adolescence: from TDMA to WDM-PON,". *IEEE Communications Magazine*, 46(1):26–34, 2008.

[40] X. Hu and L. Zhang and P. Cao and K. Wang and Y. Su,. "Energy-efficient WDMOFDM-PON employing shared OFDM modulation modules in optical line terminal,". *Optics Express*, 20(7):8071–8077, 2012.

[41] W. Wei and C. Wang and T. Wang,. "Optical orthogonal frequency division multiple access networking for the future internet,". *IEEE/OSA Journal of Optical Communication Networks*, 1(2):236–246, 2009.

[42] Zhengxuan LI, Lilin YI, and Weisheng HU. "Key technologies and system proposals of TWDM-PON". *Front. Optoelectron*, 6(1):46–56, 2013.

[43] D. Nesset. Ng-pon2 technology and standards. *Journal of Lightwave Technology*, 33(5):1136–1143, March 2015.

[44] W. Pöhlmann and T. Pfeiffer. Demonstration of wavelength-set division multiplexing for a cost effective pon with up to 80 gbit/s upstream bandwidth. In *2011 37th European Conference and Exhibition on Optical Communication*, pages 1–3, Sept 2011.

[45] Zhengxuan Li, Lilin Yi, Meihua Bi, Jun Li, Hao He, Xuelin Yang, and Weisheng Hu. "Experimental Demonstration of a Symmetric 40-Gb/s TWDM-PON". In *Proceedings of Optical Fiber Communication Conference*, 2013.

[46] K. Asaka. What will be killer devices and components for ng-pon2? In *2014 The European Conference on Optical Communication (ECOC)*, pages 1–3, Sept 2014.

[47] TELECOMMUNICATION STANDARDIZATION SECTOR OF ITU. *" 40-Gigabit-capable Passive Optical : Physical media dependent (PMD) layer specification"*. International Telecommunication Union (ITU-T), March 2014.

[48] J. S. Wey, D. Nesset, M. Valvo, K. Grobe, H. Roberts, Y. Luo, and J. Smith. Physical layer aspects of ng-pon2 standards 2014 - part 1: Optical link design [invited]. *IEEE/OSA Journal of Optical Communications and Networking*, 8(1):33–42, January 2016.

[49] Kota Asaka. Consideration of tunable components for next-generation passive optical network stage 2. *J. Lightwave Technol.*, 33(5):1072–1076, Mar 2015.

[50] W. Pöhlmann, B. Deppisch, T. Pfeiffer, C. Ferrari, M. Earnshaw, A. Duque, R. L. Farah, J. Galaro, J. Kotch, M. F. Lau, D. T. van Veen, and P. Vetter. Low cost twdm by wavelength-set division multiplexing. *Bell Labs Technical Journal*, 18(3):173–193, Dec 2013.

[51] K. Taguchi, H. Nakamura, K. Asaka, S. Nakano, S. Kimura, and N. Yoshimoto. 100-ns wavelength-selective burst-mode transceiver for 40-km reach symmetric 40-gbit/s wdm/tdm-pon. In *Optical Communication (ECOC 2013), 39th European Conference and Exhibition on*, pages 1–3, Sept 2013.

[52] N. Kikuchi, Y. Shibata, H. Okamoto, Y. Kawaguchi, S. Oku, H. Ishii, Y. Yoshikuni, and Y. Tohmori. Error-free signal selection and high-speed channel switching by monolithically integrated 64-channel wdm channel selector. *Electronics Letters*, 38(15):823–824, Jul 2002.

[53] TELECOMMUNICATION STANDARDIZATION SECTOR OF ITU. *Multiple-wavelength passive optical networks (MW-PONs).* International Telecommunication Union (ITU-T), July 2015.

[54] H. Saito, H. Iwamura, N. Minato, S. Kobayashi, M. Sarashina, H. Tamai, K. Sasaki, and M. Kashima. Field trial and simulation of bandwidth allocation for efficient olt operation on virtualized pon. In *2012 38th European Conference and Exhibition on Optical Communications*, pages 1–3, Sept 2012.

[55] Shin Kaneko, Tomoaki Yoshida, Satoshi Furusawa, Masahiro Sarashina, Hideaki Tamai, Akiya Suzuki, Toshiaki Mukojima, Shunji Kimura, and Naoto Yoshimoto. First wavelength - tunable dynamic load-balancing operation enhanced by 3-msec bidirectional hitless tuning on symmetric 40-gbit/s wdm/tdm-pon. In *Optical Fiber Communication Conference: Postdeadline Papers*, page Th5A.4. Optical Society of America, 2014.

[56] Y. Luo, H. Roberts, K. Grobe, M. Valvo, D. Nesset, K. Asaka, H. Rohde, J. Smith, J. S. Wey, and F. Effenberger. Physical layer aspects of ng-pon2 standards 2013-part 2: System design and technology feasibility [invited]. *IEEE/OSA Journal of Optical Communications and Networking*, 8(1):43–52, January 2016.

[57] Yuanqiu Luo, Bo Gao, Ming Jiang, and F. Effenberger. N:1 fast protection in ng-pon2. In *Opto-Electronics and Communications Conference (OECC), 2015*, pages 1–3, June 2015.

[58] Y. Matsui, D. Mahgerefteh, Xueyan Zheng, C. Liao, Z. F. Fan, K. McCallion, and P. Tayebati. Chirp-managed directly modulated laser (cml). *IEEE Photonics Technology Letters*, 18(2):385–387, Jan 2006.

[59] H. Zhao, S. Hu, J. Zhao, Y. Zhu, Y. Yu, and L. P. Barry. Chirp-compensated dbr lasers for twdm-pon applications. *IEEE Photonics Journal*, 7(1):1–9, Feb 2015.

[60] Martin Carrol, Derek Nesset, and Peter Dawes. Fsan highlights and ng-pon2 standards update. In *FSAN and IEEE NG-EPON/1904 ANWG Joint Session*, 2015.