Universidade de Aveiro Departamento de Electrónica, Telecomunicações e Informática (DETI)
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Hugo Rodrigues Braz de Carvalho

Distribuição ótica de sinais vídeo

Video distribution over fiber

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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 Doutor António Teixeira e Doutor Mário Lima, ambos do Departamento de Electrónica, Telecomunicações e Informática e do Instituto de Telecomunicações, Aveiro.

Dedico este trabalho à minha mãe, ao meu pai e aos meus irmãos que sempre me apoiaram e guiaram no caminho do sucesso.

o júri / the jury

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palavras-chave

SMATV, distribuição de sinais video sobre fibra, amplificadores óticos, Coarse Wavelength Division Multiplexing, Dense Wavelenght Division Multiplexing, DVB-S/C.

Resumo

Apesar de serem hà muito uma realidade, os serviços de SMATV foram desde sempre fortemente limitados pelas perdas inerentes aos cabos de cobre. Hoje em dia, mais que uma empresa de serviços video implementa esta solução sobre fibra, contudo, as soluções presentes no mercado têm ainda por onde melhorar.

Ao longo deste trabalho foi levado a cabo um estudo tendo como objectivo criar um sistema de distribuição de vídeo sobre fibra capaz de melhorar os cenários existentes. Diferentes soluções foram testadas, recorrendo a CWDM e DWDM. Um breve estudo sobre as não linearidades do laser foi feito e o uso de um circuito de pré-distorção foi testado e avaliado, o seu uso foi considerado acessório. Finalmente, um cenário final, capaz de servir até 128 clientes, foi apresentado, testado e validado.

Keywords

SMATV, video distribution over fiber, Optical amplifiers, Coarse Wavelength Division Multiplexing, Dense Wavelength Division Multiplexing, DVB-S/C

Abstract

Despite being a reality for a long time now, SMATV has seen its service strongly limited by copper wire for a great amount of time. Nowadays, there is more than one solution available at the market that offers this solution over fiber; however, marketed solutions could be improved.

Throughout this work a study to provide an improving DVB-S and DVB-C distribution scenario over fiber was held. Different solutions are considered recurring to both CWDM and DWDM. A short study on the laser's non-linearities takes place and it is proven that a predistorter is unnecessary in a solution as the one presented. A final scenario capable of serving up to 128 users is presented, tested and validated.

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List of Acronyms

ASE	Amplified Spontaneous Emission
B2B	Back-to-Back
BS	Base Station
CATV	Cable Television
CBER	Code Bit-Error-Rate
CNR	Carrier-to-Noise Ratio
CWDM	Coarse Wavelength Division Multiplexing
DFB	Distributed Feedback laser
DVB-C	Digital Video Broadcast - Cable
DVB-S	Digital Video Broadcast - Satellite
DVB-T	Digital Video Broadcast - Terrestrial
DWDM	Dense Wavelength Division Multiplexing
EDFA	Erbium-Doped Fiber Amplifier
FP-SOA	Fabry-Perot Semiconductor Optical Amplifier
GEPON	Gigabit Ethernet Passive Optical Network
GPON	Gigabit Passive Optical Network
GVD	Group Velocity Dispersion
HD	High-Definition
IF	Intermediate Frequency
IMD	InterModulation Distortion
ISI	Intersymbol Interference

LED	Light Emitting Diode
LNB	Low Noise Block
MDU	Multi Dwelling Unit
OADM	Optical Add/Drop Multiplexer
ONA	Optical Network Analyzer
OSA	Optical Spectrum Analyzer
RAC	Real Application Cluster
RF	Radio Frequency
RoF	Radio over Fiber
SCM	Sub-Carrier Multiplex
SGM	Self-Gain Modulation
SMATV	Satellite Master Antenna TV
SMF	Single-Mode Fiber
SOA	Semiconductor Optical Amplifier
SPM	Self-Phase Modulation
SQRT	Square Root
STB	Set-Top Box
TEC	Thermoelectric Cooler
TV	Television
TW-SOA	Travelling-Wave SOA
VOA	Variable Optical Attenuator
WDM	Wavelength-Division Multiplexing
XGM	Cross-Gain Modulation
XPM	Cross-Phase Modulation

1. Introduction

1.1. Context and motivation

Television has been around for more than 80 years now. From the time when Cathode-Ray Tube televisions first appeared in 1922 till the latest high definition LED TVs, a long path has been traveled. Not only the physical device used to watch television has experienced major changes, but so did the way television is experienced by users, given the evolution of TV broadcasting systems. Television is part of almost every human being life. Nowadays users demand for more in terms of quality and quantity than they ever did.

Television has evolved from its first black and white images to its High Definition (HD) channels, from its analog signal to its digital one… The experience of watching television has also migrated from a passive to an interactive one with all the new available services: recording, video-on-demand, SMARTV… Most of these services rely on IPTV.

Television companies have struggled to offer the best services at the lowest price to the highest number of clients but this is not always easy. However digital television channels reach the end user, by cable (DVB-C) or by air (DVB-T/S), serving a new user always comes at a cost. If the user is within an area that already is served by cable (either coaxial cable or an optical fiber) the cost of connecting his/her house to the network is low. However, if the new user, or group of users, is/are isolated from the cable/fiber network, cable connection would probably come with a high price per user.

Distributing the same satellite TV signal received at a single satellite dish, system commonly referred as SMATV (Satellite Master Antenna TV), was widely used in Europe where SMATV systems were installed in blocks of flats [Prieto, 1995]. The concept was receiving the satellite signals, combine them (or not) with CATV signals and distributing them to a greatest number of users. The limit in the number of served users and distance between the satellite dish and users receiving device was imposed by coaxial cables' power losses.

The advent of optical fibers opened a new window on the topic of SMATV systems. State-of-the art SMATV systems already use optical fibers to broadcast Satellite TV to the users' houses. Overlaying the regular TV broadcast over fiber also allows for a better usage of the services over IP.

Systems where Radio Frequency signals are distributed over fiber (such as Video over Fiber) differ from common standard optical systems because signals are not necessarily at base-band. They can either be sent in the baseband, at an Intermediate Frequency or, ultimately, at the final RF frequency. The first two solutions require for more complex reception Base Stations (BS) since they must be up-converted to the original RF frequency. The last solution delivers the signal at the BS at the RF channel's exact frequency [Al-Raweshidy, 2002].

Sending the RF video channels over fiber represents some advantages [Al-Raweshidy, 2002]: Reduction in the BS complexity, size and cost with an increase in its liability; transparency to RF modulation, frequency, bitrate, protocols, etc. allowing multiple services, in the same fiber, which can be multiplexed in a Sub-Carrier Multiplex (SCM) scheme that has an easier implementation than TDM schemes while it can also be combined with WDM; the low fiber loss practically constant and a high bandwidth allows the use of high distance links with minimal CNR (Carrier-to-Noise Ratio) reduction. The best coaxial cables introduce between 30 to 70 dB/Km @ 850 MHz, hence, great degradation at the CNR values is introduced [Hunziker, 1998]. Using fiber optics is a cost effective approach for distributing video signals, therefore, this kind of solution deserves to be studied.

1.2. Structure and objectives

This document is divided in six chapters, and its main objectives are:

- Define which are the main impairments concerning a video distribution scenario over fiber;
- Describe state of the art solutions available at the market;
- Test different approaches to distribute DVB-S and DVB-C channels within the same optical fiber to 128 users;
- Propose a distribution scenario and certify its proper functioning.

In this **first** chapter the context of this work is presented with the motivation, main proposed objectives and the structure of the studies.

The **second** chapter describes the main concerns that should be accounted when designing a video distribution scenario over fiber. Issues related to the optical fibers themselves, the optical amplifiers and the optical sources are addressed.

In the **third** chapter a brief description of the solutions available in the market is done. It is crucial to understand what has been done so far to propose something new.

In the **fourth** chapter, by means of laboratorial experiments, tests were done to choose which type of WDM schemes should be used to send the 4 satellite polarizations: CWDM/DWDM. The amplifiers and their properties were also tested to assess the right one to use in order to serve 128 users.

Fifth chapter shows the results of the last tests performed. They were meant to evaluate the video channels Carrier-to-noise (CNR) and Code Bit-Error-Rate (CBER) values at the receivers' end. Some temperature tests were also performed.

At last, **sixth** chapter, presents the final conclusions drawn from the whole work, and proposes some work that may be carried out in the future.

1.3. *Main contributions*

The main contributions of this work are:

- Evaluation and comparison of amplification schemes to amplify the aforementioned quadrants (CWDM vs DWDM);
- Assess of the improvement introduced by a laser linearizer in a video distribution scenario as the one presented;
- Design and implementation of a new Video distribution scenario capable of serving up to 128 users.

Additionally to the already mentioned contributions, the following paper was published in the "X Symposium on Enabling Optical Networks and Sensors 2012".

- H. Carvalho, F. Parente, P. M. Monteiro, J. Rodrigues, L. Costa, J. Rodal, R. Pinero, M. Lima, A. Teixeira "DVB-S and DVB-C distribution over fiber", 2012.

2. Constraints associated to video distribution over fiber

2.1. Introduction

Before jumping into any proposal of solution, it is crucial to asses which are the main obstacles encountered when trying to distribute television signals through optical fibers. The system, as any other communication system, requires for a transmitter, a propagation mean and a receiver. In the particular case under study, there is a demand to serve as many users as possible; hence, amplification is also required.

Firstly, impairments in optical fibers were accounted. Since the video distribution scenario proposed only implies a kilometer long fiber, the grand concern on optical fiber goes to the attenuation and dispersion it introduces (as nonlinear effects will not occur given the fiber length and the optical powers travelling within it).

Secondly, a short study on optical amplifiers was held. Within it a superficial description on its operating basics and a characterization of both an EDFA and a SOA were done in order to help for a better understanding on its properties. A brief comment on their ability or disability to amplify more than one optical channel at a time is done.

Finally, optical sources impairments are described. Understanding their dependence with temperature and threshold condition is crucial to build for an adequate WDM system. Laser's linearity may also represent an issue, so it was also referred.

2.2. *Impairments in optical fibers*

This subsection gives an insight on linear effects which affect a light pulse when it travels throughout the fiber. The fiber will be regarded as a linear mean and nonlinear phenomena will not be described, since it will hardly represent an impairment: optical powers, spacing between channels and fiber length used in the suggested video distribution scenario, are too low to trigger Stimulated Raman or Brillouin Scattering (SRS or SBS respectively). Moreover, phenomena such as Self/Cross-Gain, Self/Cross Phase Modulation or Four Wave Mixing will not be a concern in the presented video distribution scenario.

When travelling through a fiber, and taking the optical fiber as a linear mean, the optical power of an optical pulse will decrease, due to attenuation, and will experiment broadening, resulting from dispersion. This broadening of the pulse will be considerably important as one pulse travels within many, and when it broadens so will its neighbors', leading to a growing interference between them, Intersymbol Interference – ISI. This ISI, adding to the attenuation, induces the receiver in making detection errors. [G. Keiser, 2000]

2.2.1. Attenuation

Among the impairments in video transmission over fiber, attenuation is one that should always be taken into consideration. The three basic attenuation mechanisms are absorption, scattering and radiation losses of optical energy. Both optical fiber material and its imperfections are responsible for the fiber's absorption and scattering. The radiation losses are usually due to micro and macro bending. [G. Keiser, 2000]

As previously stated, ISI and attenuation might contribute for errors in the reception side of an optical communication system. Therefore, a certain level of optical power must reach the receiver in order for proper reception of the sent signal, this makes it that, most of the time optical transmission is limited by fiber losses. In a general matter, changes in the average optical power P of a bit stream propagating inside an optical are described by Beers's law [Agrawal, 2002]:

$$\frac{dP}{dz} = -\alpha P$$

where α is the attenuation coefficient.

If P_{in} is the power launched at the input end of a fiber of length L, the output power P_{out} from Eq. (2.1) is given by

$$P_{out} = P_{in}\, e^{(-\alpha L)}$$

It is customary to express α in units of dB/km by using the relation

$$\alpha(dB/km) = -\frac{10}{L}\log_{10}\left(\frac{P_{in}}{P_{out}}\right)$$

In Figure 2.1, we can observe how fiber losses depend on the wavelength for a single mode fiber [Miya, 1979]. There is a loss around 0.2 dB/km around the wavelength region of 1550 nm. A loss slightly higher than 0.5 dB/km around the wavelength region of 1300 nm, being this region the one used for 2nd generation optical systems. For lower wavelengths the losses are considered to be too high, exceeding the 5 dB/km.

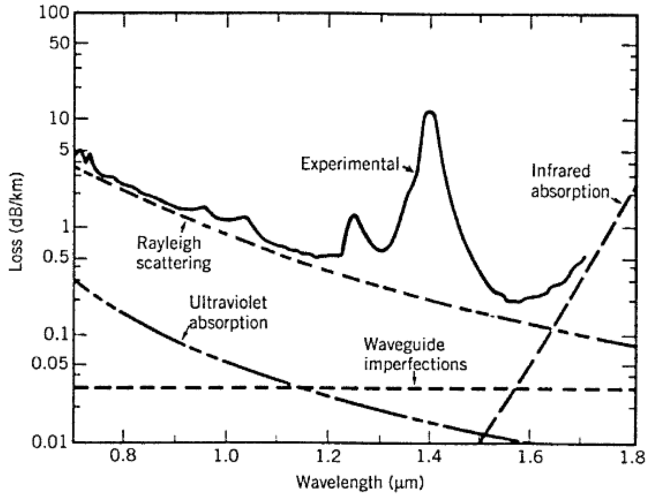


Figure 2.1 Experimental attenuation curve and its contributors [Fiber Optics, 2012]

As we can conclude from Figure 2.1, different factors contribute for the existing fiber losses. Among them three should be highlighted: Rayleigh scattering losses, absorption and losses due to waveguide imperfections.

2.2.2. Fiber dispersion in Single-Mode Fibers

In optical fibers two distinct dispersions can occur: intermodal and intramodal dispersion. As the name states, intermodal dispersion is related to the interaction between two or more modes, however, for this particular study only single-mode fibers will be used. Despite the fact that only intramodal dispersion, subdivided in material and waveguide dispersion, occurs in a single-mode fiber, pulse broadening does not disappear since the group velocity associated with the fundamental mode is frequency dependent because of chromatic dispersion. As a result, different spectral components of a pulse travel at different velocities, also known as Group Velocity Dispersion – GVD, intramodal dispersion or simply fiber dispersion [Agrawal, 2002].

2.2.2.1. Group Velocity Dispersion (GVD)

In a single-mode fiber – SMF, a light pulse carries information which is modulated and travels with a given group velocity, v_g:

$$v_g = (d\beta/d\omega)^{-1}$$

where β is the phase propagation constant of a plane wave travelling in the same frequency as the carrier wave ω0. Considering a given SMF with a length L, a specific spectral component at the frequency ω would arrive at the output end of the fiber after a time delay T=L/ vg. Being that β=n k0, k0 is the propagation constant in vacuum, we obtain vg=c/ ng, where ng is the group refraction index [Agrawal, 2002]:

$$n_g = n + \omega\left(\frac{dn}{d\omega}\right)$$

The frequency dependence of the group velocity leads to pulse broadening because different spectral components of the pulse disperse during propagation and do not arrive at the same time to the fiber's output. The extent of pulse broadening for a fiber of length L, where Δω the spectral width of the pulse, is given by [Agrawal, 2002]:

$$\Delta T = DL\Delta\lambda$$

where

$$D = -\frac{2\pi c}{\lambda^2}\beta_2$$

and $\beta_2 = d^2\beta/d\omega^2$, known as the GVD parameter, determines how much an optical pulse would broaden on propagation inside a fiber. D expressed in ps/nm km, is called dispersion parameter and defines the pulse broadening. It's a direct result of the material dispersion D_M and the waveguide dispersion D_W. D can be fairly approximated by adding the previous dispersions[Agrawal, 2002]:

$$D = D_M + D_W$$

Silica's refractive index changes with the optical frequency ω, causing the light pulse to suffer dispersion, material dispersion. Basically this dispersion phenomenon is due to the characteristic resonance frequencies at which the material absorbs the electromagnetic radiation.

In turn, waveguide dispersion results from the fact that part of electromagnetic wave's energy travels outside the core, within the cladding. This makes that group velocity changes with wavelength for a particular mode. Considering the ray theory approach, it is equivalent to the angle between the ray and the fiber axis varying with wavelength which subsequently leads to a variation in the transmission times for the rays, therefore, dispersion [Senior, 2009].

RoF systems, can have their RF signal degraded by fiber chromatic dispersion due to fading effects [J. Ma, 2007]. The fading effect can lead to cosine like fluctuation of the signal power along the fiber, Figure 2.2. This phenomenon happens because sidebands around the optical carrier, arising from modulation process, travel into the optical fiber with different group velocities, since they experience different values of chromatic dispersion.

Both attenuation and dispersion are directly connected with the fiber itself and the light wave as well; hence, they cannot be eliminated and so have to be accounted when calculating the optical link budget of the system. Attenuation will introduce a small loss in the system, around 0.2 dB (since regular monomode silica fiber, the one deployed in the final scenario has a loss of 0.2dB/Km), while dispersion could affect the system by RF power fading, however, given the transmission scenario and the fiber length, dispersion does not affect the presented solution.

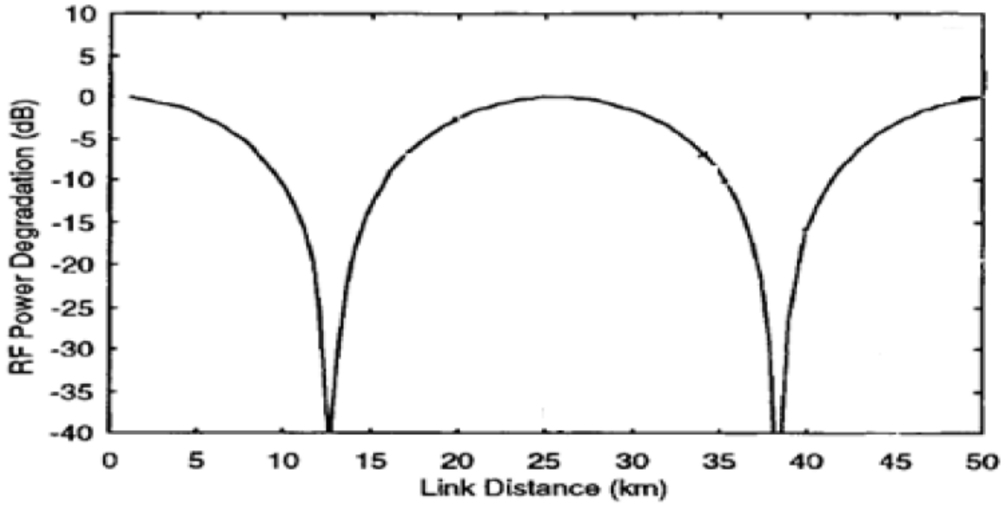


Figure 2.2 RF power fading effect with fiber length [Smith, 1997]

2.3. Amplification issues

In the beginning, for long-haul systems the solution was simply converting the signal into the electric domain, regenerate it (amplify it) and then continue its transmission in the optical domain. When WDM systems appeared, this solution became expensive and complex. Pure optical amplifiers gained momentum during the 90’s [Agrawal, 2002].

The following section of this work serves the purpose of studying two different types of optical amplifiers, Erbium-Doped Fiber Amplifiers (EDFAs) and Semiconductor Optical Amplifiers (SOAs), in order to understand which of them may be used in video distribution scenarios. The analysis of these optical amplifiers will be carried keeping in mind that video transmission occurs around the 1550 nm wavelength.

2.3.1. Erbium Doped Fiber Amplifier

As the name suggests, Erbium-Doped Fiber Amplifiers, EDFA, are amplifiers based on the doping of fibers with erbium, a rare-earth ion. As an introductory note, it is important to realize that there are some other rare-earth elements with which fibers may be doped, inducing amplification in wavelengths different than the C-band (1530-1570 nm), it’s the case of fibers doped with holmium or neondymium [Agrawal, 2002]. Only EDFAs will be studied, as the video distribution scenario, which will be studied, operates in wavelengths within the C-band.

2.3.1.1. Basic Principles of operation

As mentioned, the amplification medium in this kind of amplifier is a certain length silica fiber, doped with erbium ions (Er). These rare-earth elements, which lay in the ground state of energy, are optically pumped with a given amount of energy and wavelength (a wavelength lower that than the one of the incident signal) rising them into an excited state. In this excited state two different pathways of action may be taken by the excited ions, they can either suffer spontaneous or stimulated emission.

The amplification that is expected from an EDFA is due to stimulated emission. This occurs whenever a signal photon reaches the amplifier and makes an ion change from the excited state into a ground one. This energy level drop produces a photon with the same exact characteristics of the incident one – Figure 2.3 (b). As the process is repeated through the doped fiber more photons are created, hence, the signal gains power.

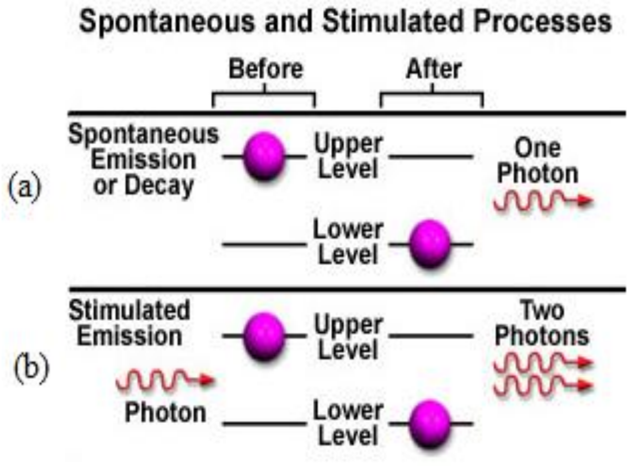


Figure 2.3 Spontaneous and Stimulated Processes [M. Expressions, 2006]

When a photon is generated without the need of an incident one, the process is called spontaneous emission – Figure 2.3 (a). The photon generated through this process does not have the same characteristics (phase, polarization and wavelength) of the signal and is, most of the times, prejudicial to the signal, it represents noise.

2.3.1.2. Characterization

Optical amplifiers, as any other device, are not perfect. In this section some characteristics and limitations of the erbium-doped fiber amplifier will be described, supported by the characterization of a bought EDFA. Some other tests varying the pump's wavelength and fiber length were also done. The spectrum gain, together with its dependence with both fiber length and pump emitting power and the EDFA saturation are some characteristics that will be accounted in this section.

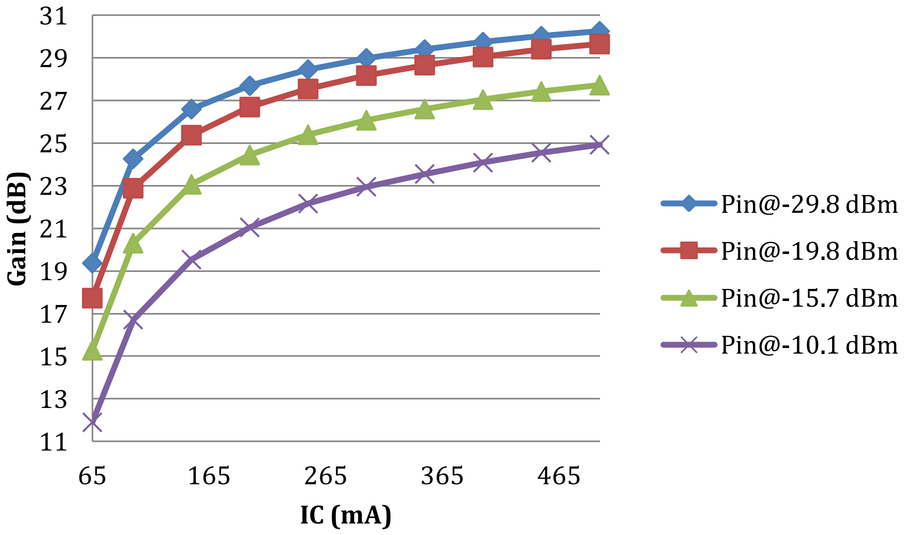


Figure 2.4 Signal gain vs biasing current at different input optical powers [Constelex]

The level of amplification varies from amplifier to amplifier, depending on fiber length and pump power and wavelength (for the first Figures of this subchapter the doped fiber length was kept constant since this is the characterization of a EDFA bought from CONSTELEX [Constelex]). In Figure 2.4, the signal input power was changed, Pin=-10.1dBm, Pin=-15.7 dBm, Pin=-19.8 dBm and Pin=-29.8 dBm and the pump wavelength was 980 nm. Pump's biasing current Ic was changed from 65 to 500 mA, corresponding to different pumping optical powers, which could not be assessed given the nature of the amplifier. A tendency towards an asymptotic value for both input powers -19.8 and -29.8 dBm, was registered, confirming saturation. To characterize an amplifier it is important to define what origins its gain saturation. There are two different contributors which may lead to gain saturation. The first, and more obvious one, is the total up conversion to the excited state of all the ions present in the ground state. This makes it that even if we increase the pump power, increased by the IC augment, no more ions will be transited to the upper level, and hence, no more ions will lose their energy to originate new photons.

The second contributor is the signal power, when it exceeds a certain value. However, the gain starts out to be constant for small signal powers it gradually experiments a decrease. This is a direct consequence of the lack of population in the excited state when compared to the incident photons of the signal. When this increase of photons, compared to ions in the excited state, occurs, there is no longer stimulated emission for all the signal photons and the gain increase, as stated, decreases. This is the reason why the gain for the input powers -19.8 and -29.8dBm is almost equal.

As aforementioned, regular EDFAs amplify between 1530 and 1560 nm, Figure 2.5, the so-called C-band.

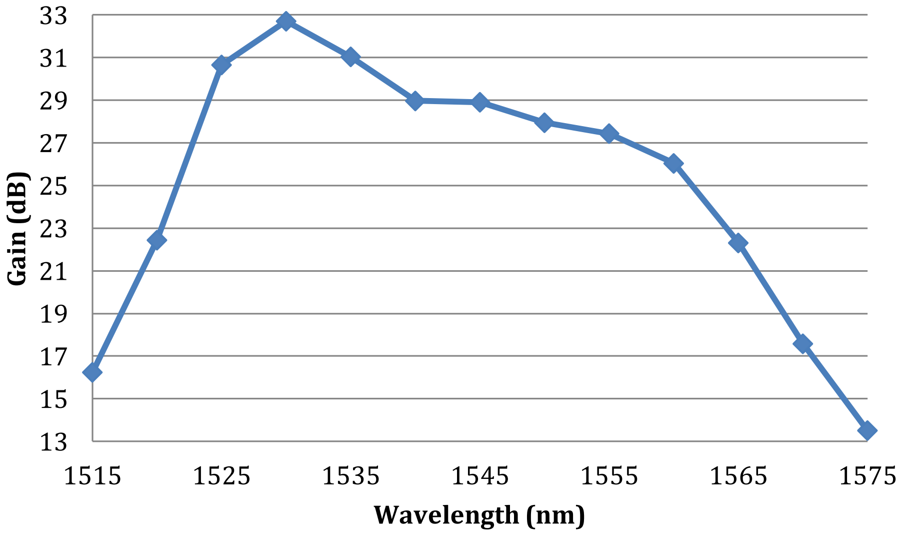


Figure 2.5 Optical gain for different wavelengths (Ic=350mA and Pin=-19,6dBm) [Constelex]

Another important characteristic of an optical amplifier is how it degrades the signal which is being amplified, quantified by the Noise Figure, F_n. It is a ratio between the Signal-to-Noise Ratio (SNR) of the input and output signals: $F_n = (SNR)_{in}/(SNR)_{out}$. An approximation of this degradation can be made so it depends solely on the $n_{sp} = \frac{N_2}{(N_2 - N_1)}$ factor [Agrawal, 2002]: $F_n = 2n_{sp}$. It is easy to conclude that even for the best case, when there is a total inversion of the atomic population from valence band, N_1, to the conducting band, N_2 ($N_1 = 0$), there is a 3dB amplified signal degradation, Figure 2.6.

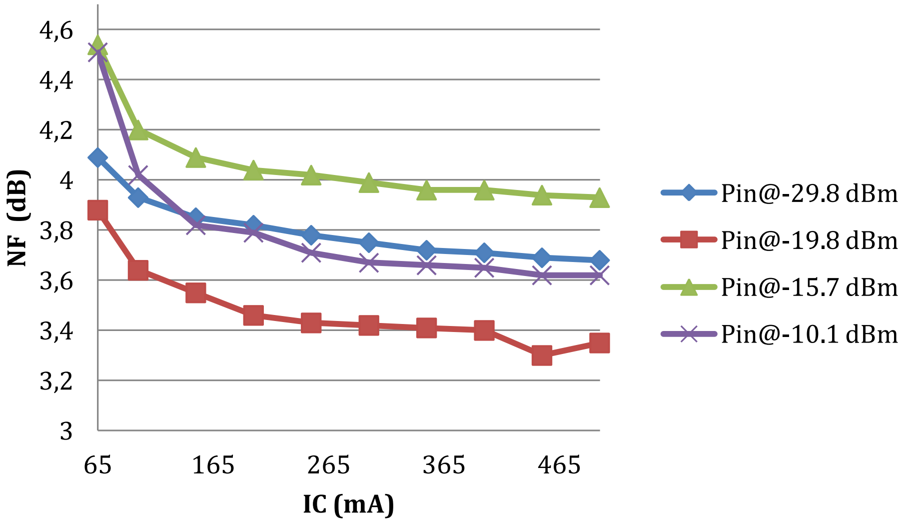


Figure 2.6 Noise Figure for different biasing currents and Pins (λ=1550nm) [Constelex]

The previous experiments were done using a bought EDFA. This made it impossible to check for the pump wavelength and doped fiber length influence on the gain experimented by signals passing through this amplifier. For the matter of proving this dependence, some results from the tests held to choose the optical channels spacing (later on chapter 4) are here presented.

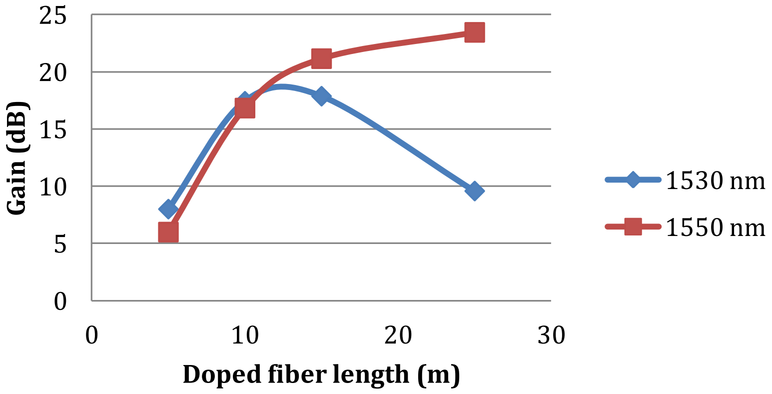


Figure 2.7 Optical gain vs. Doped fiber length for Ppump = 227mW, λ_p=1480nm, EDF input power = - 4 dBm

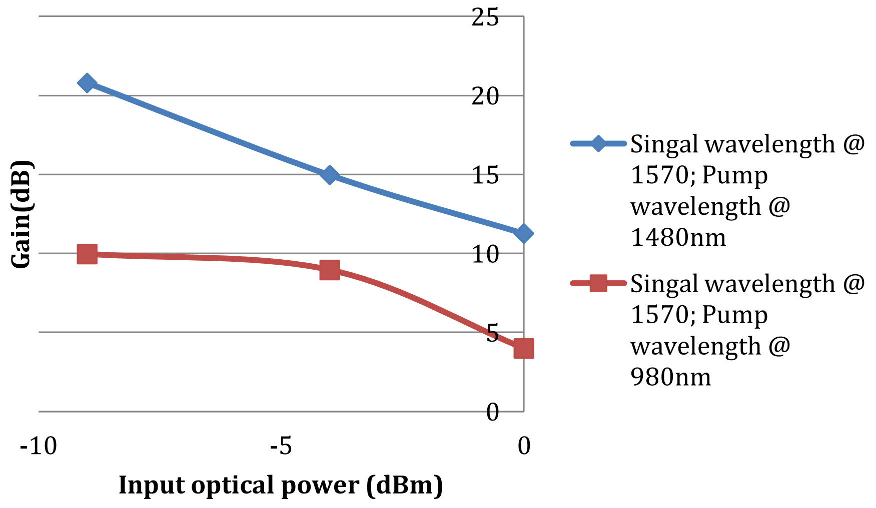


Figure 2.8 Optical gain vs. input optical power for Ppump = 227mW and 10 meter long doped fiber designed to amplify in the L band

Figures 2.7 and 2.8 allow us to understand how an EDFA gain varies with the doped fiber's length and pump wavelength, respectively. It is easy to conclude from Figure 2.7 that the doped fiber should be wisely chosen depending on the wavelength, for example. This gain variation, with fiber length, is reasoned by the fact that an increasing length makes it harder for a given pump power to excite the erbium ions throughout the all fiber. Figure 2.8 confirms that choosing different pumping wavelengths will lead to different gain results. The previous figures lead us to conclude that to obtain the best possible gain, the length of doped fiber as well as the pump wavelength must be reasoned.

2.3.1.3. EDFAs in WDM systems

EDFAs are the most suitable amplifiers for multichannel systems. Recombination time between electrons and holes, present in the conduction and valence bands, is very fast comparing to the time between each bit, providing immunity towards nonlinear phenomena [Agrawal, 2002]. EDFAs are not sensitive to most of interchannel crosstalk phenomena, which rises from carrier-density modulation from adjacent optical channels' beating, provided that the channel separation does drop below 10 KHz (which is true for any practical system) [G. Keiser, 2000]. Another reason that makes this kind of amplifier suitable for WDM, Wavelength-Division Multiplexing, is its polarization non sensitivity [Agrawal, 2002]. EDFAs, however, are not immune to one source of interchannel crosstalk which, in reality, affects all optical amplifiers, the cross-gain saturation, which happens whenever a channel is saturated, either by its own power (self-saturation) or by its neighbors'.

As it was seen in Figure 2.5 the EDF gain is not flat. This represents a crucial understanding for WDM systems using EDFA amplifiers. Channels in the region of 1530 nm will suffer higher amplification than the ones in the region of 1550 nm, for example. Despite how small the difference may be, this difference becomes significant whenever a cascade of EDFAs is used for long-haul transmissions. The difference would grow exponentially through the system [Agrawal, 2002].

2.3.2. Semiconductor Optical Amplifiers

In the beginning of the 60's, soon after the invention of semiconductor lasers, the first researches on Semiconductor Optical Amplifiers (SOAs) began, however, it was only in the 80's that they started to be produced to serve practical applications in lightwave systems [Agrawal, 2002].

Throughout this sub-section of this work, SOAs' basic principles as well as a brief characterization will be held, bearing in mind the need to serve a video distribution scenario.

2.3.2.1. Basic Principles of operation

SOAs are optoelectronic devices which amplify an optical input signal without converting it to the electric domain. The active region of this device is responsible for the amplification which is achieved thanks to an external electric current. There is an embedded waveguide which is responsible for keeping the input signal in the active region; however, part of it ends up being lost. [Connelly, 2002]

There are three types of semiconductor laser amplifiers: injection-locked, Fabry-Perot SOA (FP-SOA) and Traveling-Wave SOA (TW-SOA). The injection-locked is the least used one and operates based on a semiconductor biased above the lasing threshold. When the semiconductor is biased below the aforementioned threshold, we're in the presence of a FP-SOA and, finally, when the semiconductor has an anti-reflection coating, the SOA is a TW one [Shimada, 1994].

The difference between a FP and a TW-SOA is that in the second, with the antireflection coating added to the semiconductor, the signal will travel only once through the amplifier, while in the first it will suffer multi-reflection before exiting the amplifier. This can be observed in Figure 2.9.

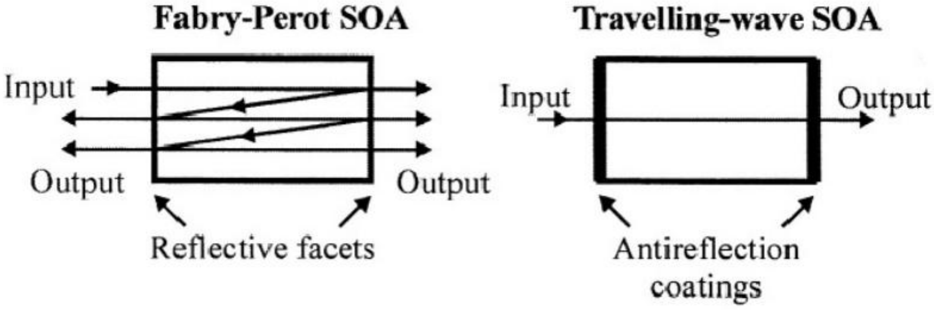


Figure 2.9 Operation schematic of both FP-SOA and TW-SOA [Connelly, 2002]

This structural difference between both types of SOAs makes yields that the TW-SOA has a much smoother gain spectrum, while the FP-SOA’s gain spectrum has ripples, due to the multiple reflections. Moreover, FP-SOA is much more sensitive to temperature, polarization and bias current changes [Connelly, 2002]. Because of this instability of FP-SOAs and also because of the ripples it presents in its gain spectrum, in SOA’s characterization, following subsection of this work, greater focus on the TW-SOAs is given.

The principle behind amplification in SOAs is relatively straightforward. SOA electrons, referred as carriers, are injected in the active region. These will be placed directly into the conduction band, originating holes in the valence band. The gain is obtained by radioactive transition between these two bands which end up in a electron-hole recombination. Transitions between the bands may be of three different types: spontaneous and stimulated emission, Figure 2.10 sections (a) and (b) respectively, and stimulated absorption Figure 2.10 section (c).

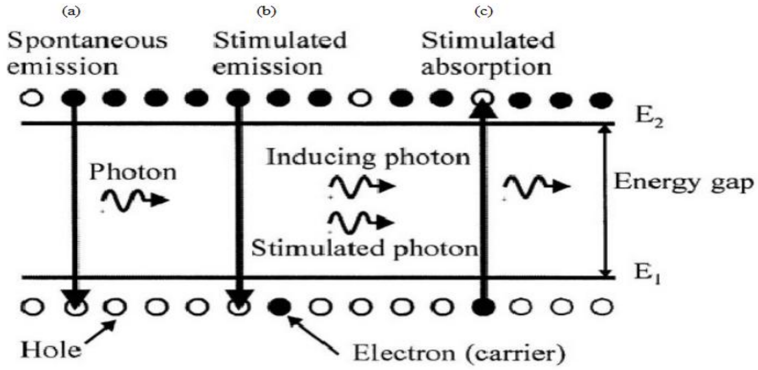


Figure 2.10 Different types of transition between bands: (a) Spontaneous and (b) Stimulated emissions, (c) stimulated absorption [Connelly, 2002]

As the name suggests, spontaneous emission can occur at any time, without the need of any trigger. It produces a random photon (with random frequency, polarization, etc…) that becomes simply noise to the output signal and represents a waste of photons which may have been used for amplification. This noise is called ASE, as it results directly from Amplified Spontaneous Emission. Spontaneous emission cannot be eliminated as it is a result of the amplification process.

When the population in the conduction band exceeds the one in the valence band, the conditions for amplification are gathered and stimulated emission overlaps the spontaneous one, resulting in optical signal amplification therefore, optical gain. Stimulated emission is the foundation of the amplification process. It occurs when a photon with a particular energy reaches the semiconductor instigating the carrier to drop from the conduction to the valence band. This drop originates a photon with the same characteristics of the incident one.

Finally, stimulated absorption happens whenever an electron makes the opposite path of the one described earlier, from the valence to the conduction band. This happens when the incident photon has more energy than the energy gap between both bands, which is a result of a low or inexistent biasing current.

2.3.2.2. Characterization

The gain spectrum of a SOA depends on its structure, materials and operation. SOAs have, of course, limitations which are critical for its performance. In the following paragraphs the most important characteristics and limitations are to be described based on a characterization of a SOA, more precisely a CIP SOA-S-OEC-1550 [CIP SOA]

As with EDFAs' characterization, the first measure to be made with the SOA is to check how gain varies with wavelength for a few, defined I_{bias}, in order to realize its bandwidth, Figure 2.11. The expected wide optical bandwidth, with a gain of approx. 20 dB for 60 nm, is observed.

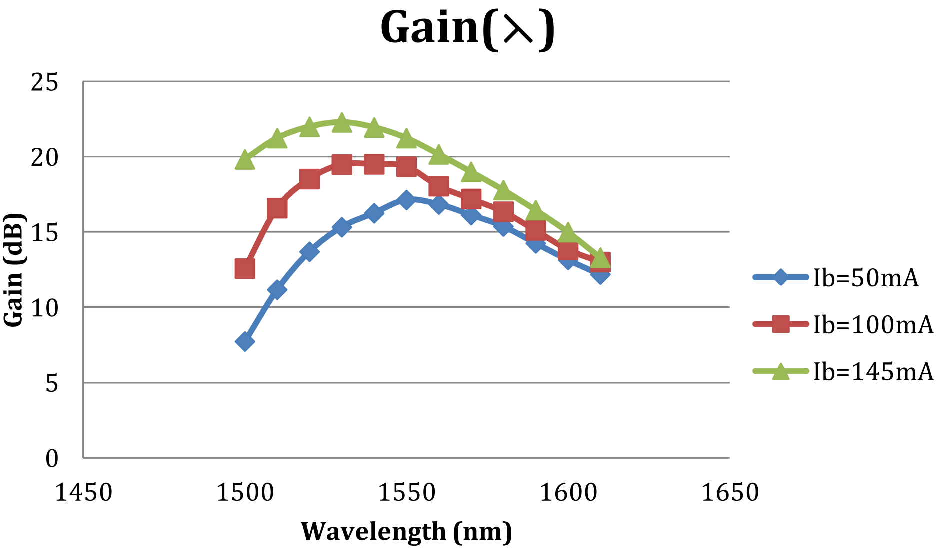


Figure 2.11 Signal gain as a function of wavelength for three different I_{bias} [CIP SOA]

The next important test to characterize a SOA is to understand how its gain varies with I_{bias} value. For this test a small signal input power of -20.1 dBm was used, Figure 2.12. As expected there is a minimum current which triggers the SOA into starting to amplify. This current is around the 15 mA. After this, the values of optical gain start to rise, till the 50 mA (approx.) abruptly, and after that, till 145 mA, in a more subtle way. Around 145 mA, which is very close to the value of maximum DC forward bias, 150 mA, [CIP SOA], the amplifier starts to enter the saturation region.

Saturation is achieved, in this case, since for an I_{bias} of 150 mA, there are no more electrons in the valence band to be moved to the conduction one. Even if the current is increased, this will only lead to a waste of energy.

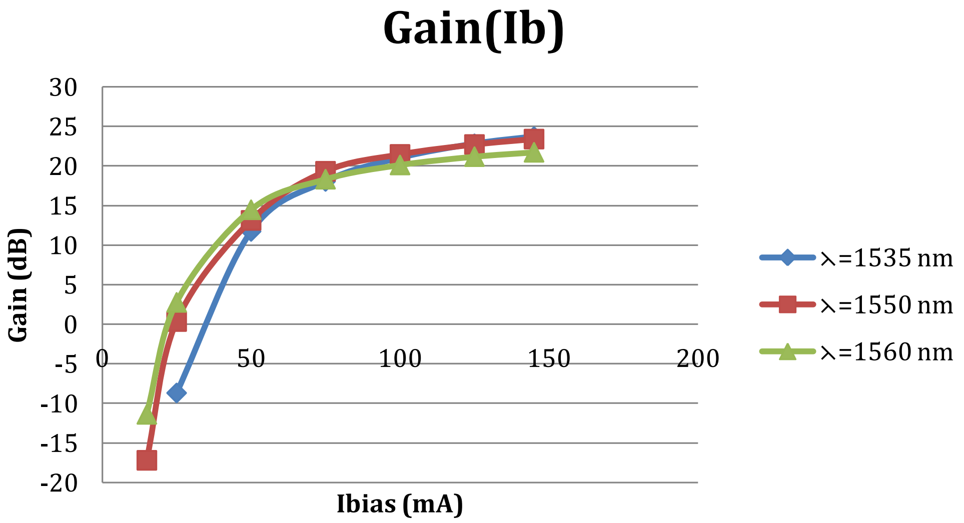


Figure 2.12 Signal gain as a function of I_{bias} for three different wavelengths (nm) [CIP SOA]

Saturation can also be achieved when the input optical power grows above a certain value. Saturation by excessive input optical power, observable in Figure 2.13, happens when the number of electrons, carriers, in the conduction band is not enough to amplify the amount of photons which are arriving to the semiconductor.

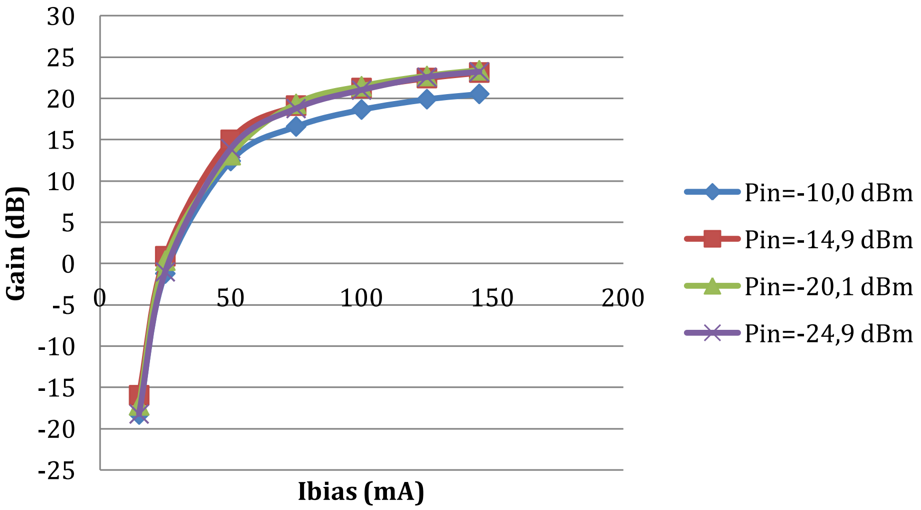


Figure 2.13 Signal gain as a function of I_{bias} for four different input optical powers [CIP SOA]

Regarding noise, and as aforementioned, it is impossible to eliminate noise from a SOA, since it is a direct consequence of the amplification process, Figure 2.14. It was observed that the Noise Figure assumes higher values for lower biasing currents and wavelengths, ending up reducing its value for around 4 dB near the saturation current.

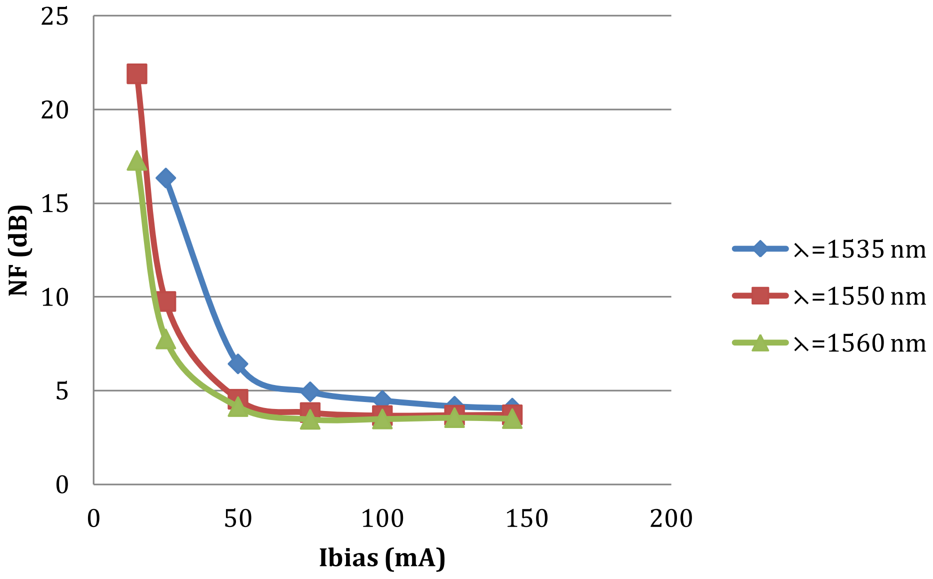


Figure 2.14 Signal's Noise Figure as a function of I_{bias} for three different wavelengths [CIP SOA]

To end this short SOA characterization, non linear effects must be accounted. Nonlinearities present in this type of amplifier are caused by the variation of the total density of carriers and their distribution. Interband transitions change carrier distribution in both bands, however, it does not change their distribution. These transitions are set off by stimulated emission, spontaneous emission and the non-radiative combination [Urquhart, 2011]. Interband transitions end up giving rise to intraband transitions which are responsible for a change in carrier distribution. The aforementioned transitions result in gain recovery times comparable to optical pulses' duration time. This leads to great bands population variations. Since these gain variations occur in a given time interval which has the same magnitude of signal variations', ultimately, nonlinear effects appear.

It is not the purpose of this work to study the nonlinearities in detail, it is however important, to understand that they can play a significant role in the video distribution setup, and justify certain results and options for the amplification scenarios. Therefore, the main nonlinear phenomena taking place in a SOA will be resumed in the following topics, based on [Connelly, 2002] and [Urquhart, 2011]:

- Self-Phase Modulation (SPM): reasoned by the nonlinear behavior of SOA's active region, which varies with carrier density. Carrier density changes, result of a signal pulse propagating through the amplifier, change the propagation coefficient. Since carriers have a finite life time, the leading edge of the pulse faces a different phase shift than the lagging one. SPM changes not only the pulse's shape but also its spectrum.

- Cross-Phase Modulation (XPM): is a nonlinear effect very similar to SPM, however, it can only happen when more than one signal are introduced in the SOA. XPM implies the phase modulation of a signal (travelling at the same time as one other signal inside the SOA structure), due to the refractive index change induced by the second signal. The signal suffering the change is often referred as the probe signal and the signal imposing the refractive index change is called the pump.

- Self-Gain Modulation (SGM): corresponds to the modulation gain which occurs due to the input signal power variation;

- Cross-gain Modulation (XGM): it is a nonlinear effect similar to SGM. It's explanation is similar to the one given for XPM. An optical signal modulates the gain of a co-propagating optical signal. It results, as aforementioned, from the fact that the response time of a SOA is usually around tens of picoseconds, comparable to pulse duration for actual optical systems (depending on the transmission rate).

These nonlinearities do not represent solely impairments, they also have a very practical usage, allowing SOAs to become wave modulators, receivers and wavelength converters, for example.

2.4. Optical sources' impairments

A crucial part of any communication system is its transmitter. For the purpose of this work it is not important to go into many details about the physics behind laser's operation. So, in this section, things such as energy bands, fabrication materials or pn junctions will not be spoken of. However, operating characteristics which may interfere directly with video over fiber distribution must be taken into account and described.

With exception to systems which require high RF frequencies (>10GHz), which use External Modulation, in order to achieve higher bandwidths and to fight laser chirp phenomena (described later), most of the systems sending Radio Frequency signals over fiber, Radio over Fiber systems (where Video over Fiber systems are included), use Direct Modulated optical sources. Cheap lasers are crucial for the solution proposed in this work [Al-Raweshidy, 2002]

Modulation consists, in simple terms, in shifting a base-band signal into the carrier's frequency in order to transmit this signal through different types of communication channels. At the receiver end, the signal is again converted, now to the baseband. Two methods are used to modulate the signal's carrier amplitude: direct and external modulation. Direct modulation consists on directly varying the laser drive current with the information stream, in order to produce a varying output power. External, in turn, uses an external modulator in order to modulate a steady optical power emitted by the laser, a continuous wave, CW, signal [G. Keiser, 2000].

The simplest way to modulate information into an optical signal is to vary the bias current of the laser which is generating the signal, however, this amplitude modulation induces a natural variation on the bit's current. Changing the current value leads to a variation of carriers, N, in the laser's cavity. This variation makes it possible for the number of photons being created to fluctuate, in order to transform the electrical pulses into optical ones with the desired modulated information.

For 1550nm lightwave systems, the chirp frequency imposes a limitation of 100 km @ $\mathrm{B} = 2{,}5\ \mathrm{Gb/s}$ [Agrawal, 2002]. Higher bit rates and distances may be achieved using dispersion management schemes to reduce the average dispersion to around null values [Agrawal, 2002].

All in all, direct modulation may not be able to transmit information at high bit rates, however, it is quite effective for low bit rates (till 10 Gb/s [Agrawal, 2002]) given its simplicity, thus, low cost. Direct modulated laser are, however, good enough for the purpose of this work. Optical signals do not travel longer than a kilometer fiber and a bandwidth of 2.5 GHz is enough.

Laser's threshold conditions, temperature effects and light source linearity will be discussed in the following subsections.

2.4.1. Laser's threshold condition and temperature dependence

In order for there to be light amplification the lasing condition has to be met. The requirement for lasing is that a certain level of population inversion in the semiconductor is met and it occurs when the gain of one or several guided modes is sufficient to exceed the optical loss during one roundtrip through the laser's cavity (one roundtrip is the path that a guided mode does from one reflective end of the laser to the other one and then again to the first one).

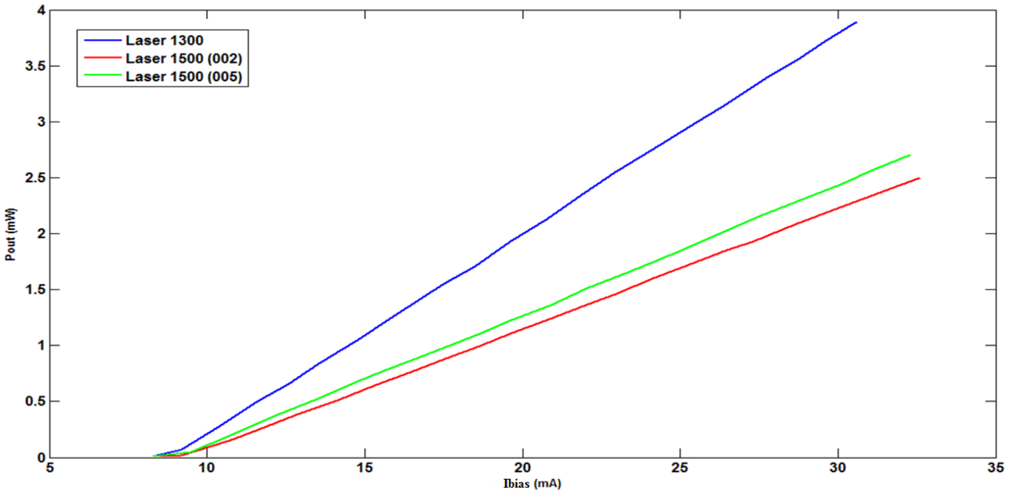


Figure 2.15 Optical output power vs. Laser driver current

At the lasing threshold a steady-state oscillation takes place, this means that the wave, in a certain guided mode, maintains its magnitude and phase through one roundtrip. From this point on, the laser's energy increase should represent a growth solely in the mode that has reached it first, however, in practice, more than one mode are excited.

At low diode current, only spontaneous emission is emitted, as expected, the spectral range is very broad, as if it were a LED. A pronounced increase in the output power goes on at the lasing threshold, as we can see in Figure 2.15 (which shows three different lasers tested at the lab). When the driving current increases, the spectral range and beam width narrow. The threshold current, $\mathrm{I_{th}}$, is conventionally defined by extrapolation of the lasing region of the P/I curve in Figure 2.15 [G. Keiser, 2000].

An important fact that should always be taken into consideration is the lasers' $\mathrm{I_{th}}$ variation with temperature. In all semiconductor laser devices, the threshold current augments with the increase of temperature, the relation between temperature and threshold current, however, depends on the laser's constituent material [Senior, 2009]. The aforesaid variation is observable in Figure 2.16.

The threshold current variation is a function of temperature, T, given by the following expression [Keiser, 2000]:

$$\mathrm{I_{th}(T) = I_z e^{T/T_0}}$$

where $\mathrm{T_0}$ is a measure of the relative temperature insensitivity, given for each laser, and $\mathrm{I_z}$ is a constant. $\mathrm{T_0}$ is usually a value between 40 and 75 K [Senior, 2009]

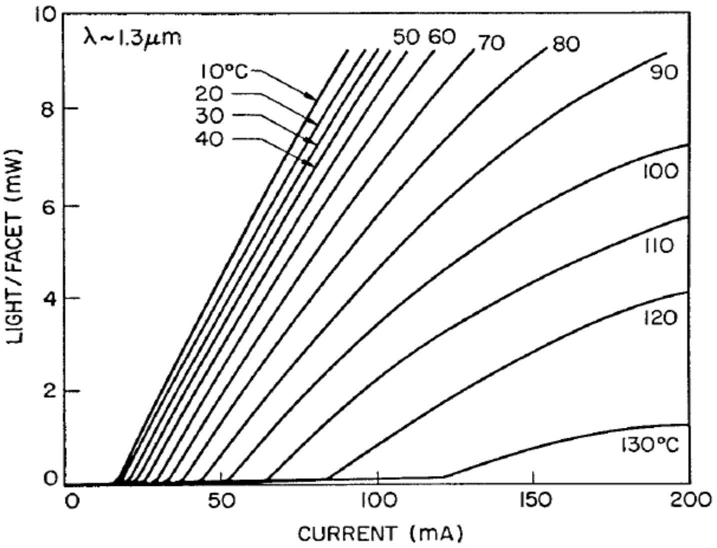


Figure 2.16 Variation in threshold current with temperature for a 1300 nm buried InGaAsp heterostructure laser [Agrawal, 2002]

It is important to bear in mind that to maintain a constant output optical power and wavelength, temperature must be kept constant. Temperature change ends up changing the wavelength emitted by the source, Figure 2.17.

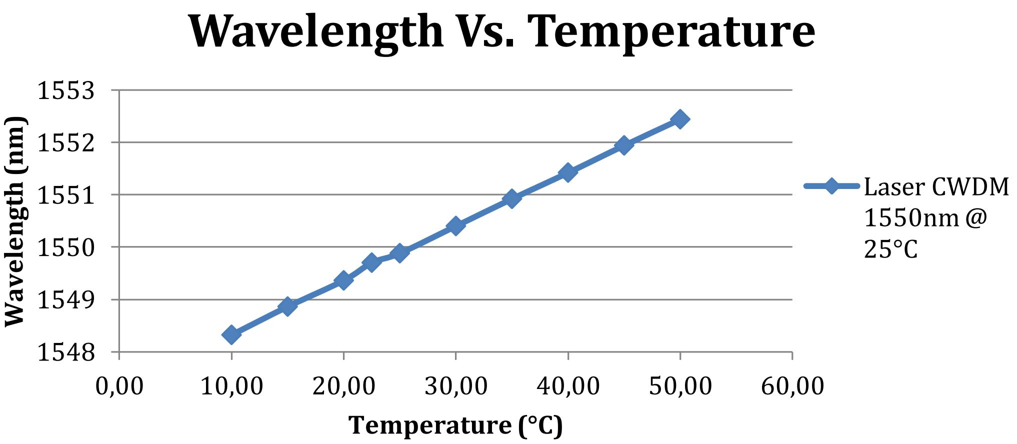


Figure 2.17 Laser's wavelength with temperature variation for a DFB CWDM laser

A very common type of circuit used to maintain the laser's temperature, hence performance, constant are Thermoelectric Coolers (TEC). TECs have the ability either to lower the temperature of a given object below the ambient temperature either to raise it above the ambient temperature.

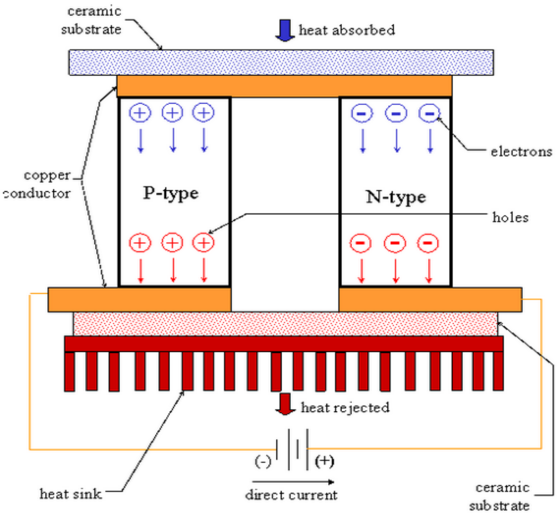


Figure 2.18 Schematic of a Thermoelectric Cooler [TE Tech]

Thermoelectric modules operate on the Peltier effect – *“if a current passes through the contacts of two dissimilar conductors in a circuit, a temperature differential appears between them”* [TEC basics]. TECs consist of p- and n-type semiconductor legs electrically connected in series (thermally in parallel) fixed between two ceramic plates, which constitute the TEC hot and cold sides – Figure 2.17. The ceramic plates provide mechanical integrity of a thermoelectric (TE) module. These plates must have good thermal conductance to provide heat transfer with little resistance. Electric conductors are made as thin multilayer structures containing copper as a conductor deposited onto ceramic plates [TEC basics].

TECs are used in many different areas. In the case of optics, the laser is mounted on top of the ceramic substrate, Figure 2.18 in blue. The heat is absorbed there and expelled by the heat sink connected to the red ceramic plate.

2.4.2. Laser’s linearity

When a laser is directly modulated a time varying electric signal, $s(t)$, is used to impose the data signal around a certain biasing point, I_b. The signal output with no modulation applied, continuous wave (CW) is P_l. When the signal $s(t)$ is applied to the laser the optical output power $P(t)$ is defined by [G. Keiser, 2000]:

$$P(t) = P_l\,[1 + ms(t)]$$

where m is the laser's modulation index, $m = \Delta I/(I_b - I_{th})$. ΔI is the variation in current about the bias point, whenever this value is greater than the difference $I_b - I_{th}$ the signal's lower portion gets cut off and severe distortion will result. To prevent output distortions' the laser must operate at the linear region of the curve in Figure 2.15, where lasing emission occurs.

For a better understanding of what the correct I_b choice represents, tests were run at the lab to trace the P-I curve of a given 1550 nm laser, Figure 2.19 (a), and then, recurring to *Matlab*®, laser's operation around different biasing points, modulated by a cosine with 4mA of amplitude was simulated, remaining subfigures of Figure 2.19.

The simulation ran on *Matlab*® showed that the laser's optical output was not linear before reaching the linear section of the curve (approx. I=10mA), Figure 2.19 $I_b = 8\text{mA}$ and $I_b = 9\text{mA}$. For bias currents of 15mA and 23mA a cosine response was obtained, the laser is biased within the linear region. Finally, for a higher I_b, 27mA, the response was once again distorted, this time due to the laser's saturation. The modulating signal has a maximum amplitude of 4mA, so, the output cannot surpass this value.

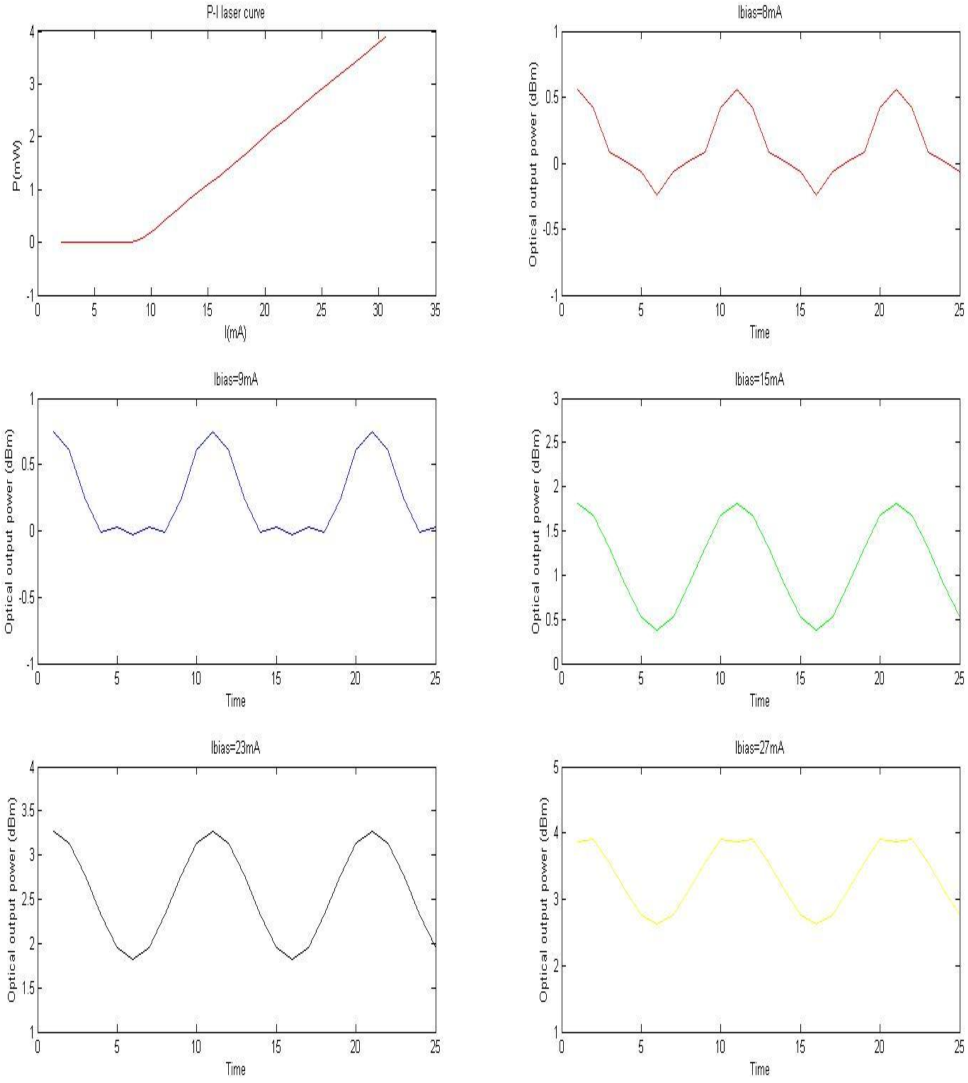


Figure 2.19 1550nm laser P-I curve and its optical output responses, with a cosine input, $x = 4 * \cos(2\pi \times 50E10 \times t)$, operating around different I_b

Laser nonlinearities are responsible for creating frequency components in the output that were not present in the input signal. These nonlinearities in the output signal, the extra frequency components, are divided in two assorted types: harmonic and intermodulation distortion. When the input signal is a cosine wave, $x(t) = A\cos(\omega t)$, the output signal will be, not only a component at the input frequency ω, but also another one at 2nd harmonic frequency 2ω, one at the 3rd harmonic frequency, and so on [G. Keiser, 2000]:

$$y(t) = A_0 + A_1\cos(\omega t) + A_2\cos(2\omega t) + A_3\cos(3\omega t)$$

To observe harmonic intermodulation, the input signal is not a simple cosine but a sum of two cosines.

Figure 2.21 presents the Fast Fourier Transform of the previous output signals. The difference between fundamental frequency’s magnitude and it’s second harmonic is greater when the laser is operated in the linear region, hence, the distortion at the output is smaller.

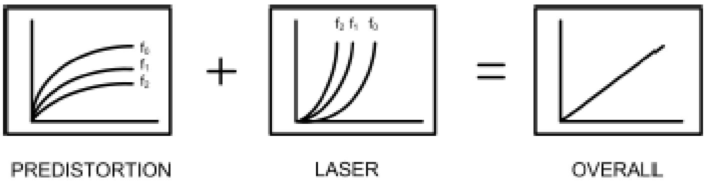


Figure 2.20 Graphical explanation of the idea behind predistortion

Different linearization techniques have been suggested to fight laser’s nonlinearities [Keiser, 2000]: complementary nonlinear distortion and photoelectric feedback and feed-forward techniques. Feedback and feed-forward techniques have been abandoned given the difficulty to properly adjust the circuits.

Predistortion consists on passing the RF signal through a device designed to generate distortion with equal amplitude and opposite in sign to the one introduced by the laser itself, Figure 2.20, which means, if the laser P-I curve behaves somehow like a sin function, the predistorter has to have a curve similar to an arcsin. The injected distortion ends up being cancelled by the laser’s distortion, a highly linear output signal is obtained [Avigdor, 2008]. An analog predistorter generally has two paths: one carries the fundamental components; the second one carries the distortion generator. The two paths are time-aligned and are combined before reaching the laser.

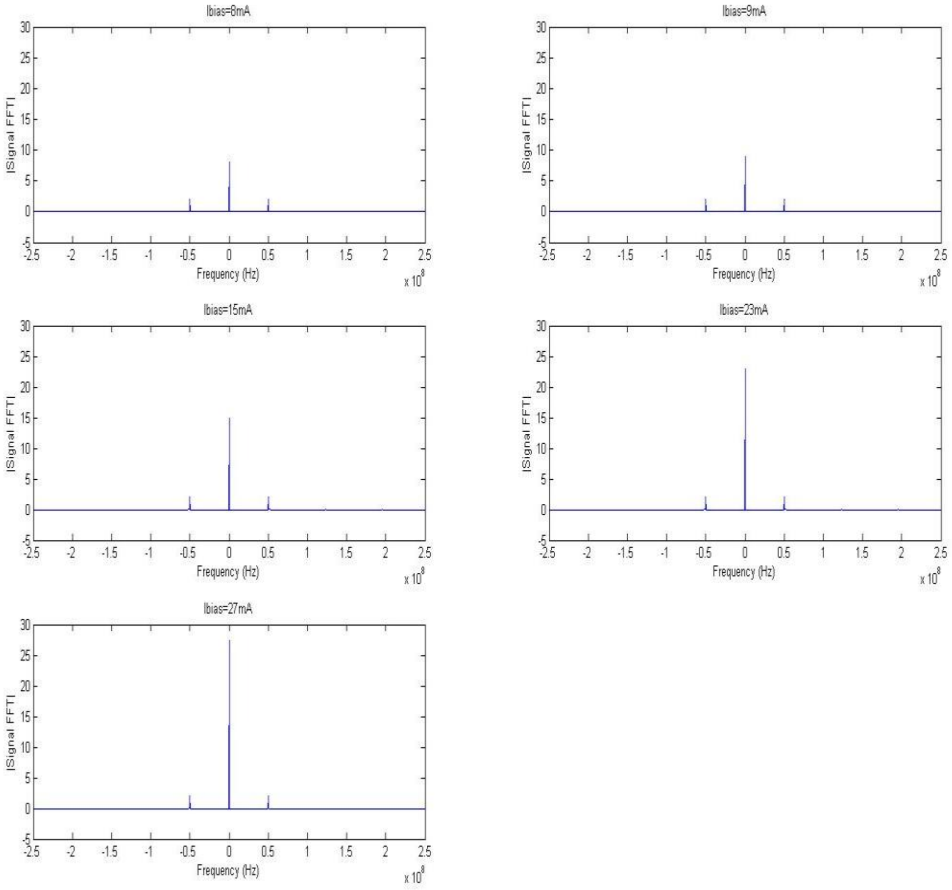


Figure 2.21 Harmonic distortion for the different operating I_b: (b)8mA (c)9mA (d)15mA (e)23mA (f)27.5mA. The dotted line is meant to set the same reference for all the different cases.

Since 1995 different predistortion circuits have been patented. Some examples are [GooglePatents]:

- Optical transmission system (US 5477367): consists of a circuit including a zener diode (Schottky) and other including an impedance element (1995);
- Lossy linearizers for analog optical transmitters (US 7208992): suitable for even or odd order nonlinear distortions, it distinguish itself from the others because it does not use delay lines or phase matching techniques (2007)

All in all, the biasing current choice represents a major concern for the system performance. It is easy to conclude that tightly controlling the temperature is, therefore, of crucial importance as well. Laser linearizer circuits were tested, section 4.3.3.1, but their improvement in the system’s performance was proven to be irrelevant, and their usage was proven not to be required.

3. Existing solutions of video distribution solution

3.1. Introduction

In the previous chapter the main problems affecting a possible TV broadcast fiber distribution scenario were identified. These problems have been targeted and solutions have been proposed by different companies throughout the world. Along this chapter a brief description/analysis of the available solutions will be held.

It would be impossible to present all the companies offering this type of service, therefore, three of them were chosen: Global Invacom, a British company, BKtel, a German one and, finally, 4CableTV, from North-America.

3.2. Global Invacom Solution

Global Invacom has recently developed a solution to distribute satellite TV over a PON within Multi Dwelling Units, MDUs, taking advantage of the various DBS satellite frequency plans throughout the world. Multi-Dwelling Unit is a classification of housing where multiple separate housing units for residential inhabitants are contained within one building or several buildings within one complex.

This British company has accepted that coaxial cable was the main set back in providing a better, with longer reach, service in distributing Intermediate Frequency, IF, satellite signals to more than one house. With coaxial cables, satellite's IF cannot be transmitted over more than 150 meters [Giving the coax the axe].

Figure 3.1 shows how this company's solution works in practice. It's functioning relies in two major devices developed by them: an Optical Output LNB and an Optical Converter (Twin/Quad or Quattro) at the receiver's end. The Radio Frequency signals arrive at the dish, were they are fed into the fiber LNB. Here the satellite IF signals, which come in four different polarizations, are stacked and then modulated onto a laser. The optical LNB's output is then connected to a conventional PON, with a single fiber feeding each 8-way optical splitter; we can interpret this splitter as a dwelling. Inside each dwelling there are Gateway Termination Units, GTU, responsible for re-converting the signal into RF and, subsequently, de-stacking the RF signal, in order to feed the Set Top Box, STB, with the original IF signal. For the STB, the signal is just as if it had been received straightly from a universal LNB. [FTTH, 2011]

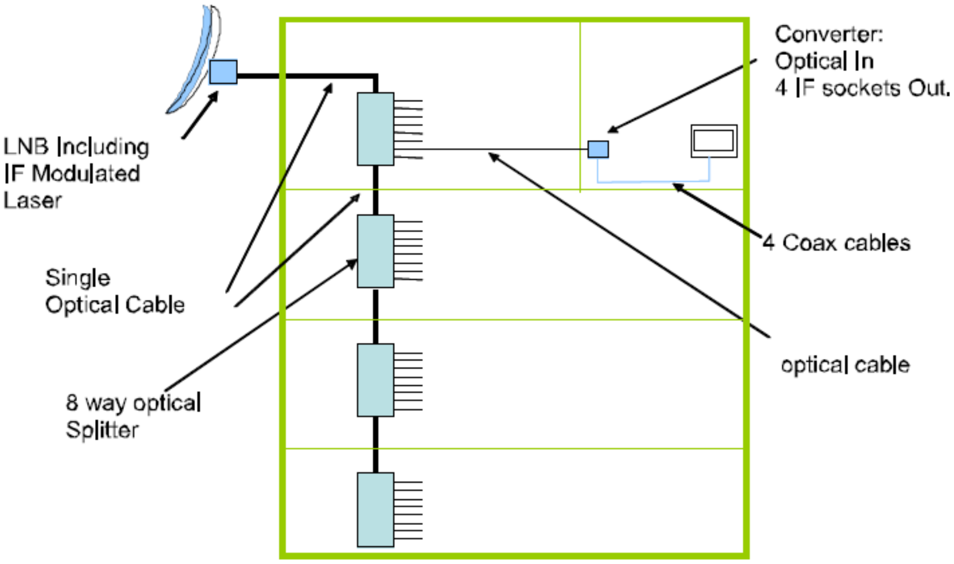


Figure 3.1 Principle of operation behind Global Invacom Solution [FTTH, 2011]

The main innovation in this approach is the fact that the four different polarization quadrants, Vertical High (VH) and Low (VL) and Horizontal High (HH) and Low (HL), are now possible to be transmitted all within the same cable, an optical fiber. Previous approaches were only sending a single polarization in each fiber, originating the need to deploy four fibers in case of four polarizations needed at the receivers end. Moreover, the system is purely optical: from the moment signals leave the optical LNB till they get to the customers end.

The conventional MDU deployed in Europe has two 2050 MHz bands leaving the satellite dish (divided in High and Low), with a total bandwidth of 4100 MHz. In order to distribute the four quadrants present at the two bands, VH, VL, HH, and HL within a MDU, these have to be fed into the various Multi-Switches responsible to feed the STB. Simply replacing the coaxial cables with fibers would not solve the problem; therefore, Global Invacom came up with a frequency stacking solution.

Despite this stacking technique being also based on a down-conversion of the incoming frequencies (10700-12750MHz) at the LNB, this is not done in a conventional way. The different polarizations are down-converted to subsequent frequencies, between 950 and 5450 MHz: VL and HL within the interval 950-3000 MHz and VH and HH within the interval 3000-5450 MHz. The stacked frequencies could not be sent all within the same coaxial cable, since its losses would make it impossible to transmit the signal for more than a few tens of meters [FTTH, 2011].

The Optical LNB output signal travels through an optical fiber, after being modulated onto a laser installed within it, with a wavelength of 1310 nm [Optical LNB, 2009]. At the receiver's end, a fiber GTU de-stacks the signal, recreating the original IF signal which is presented at the STB.

Some technical considerations are crucial to a proper understanding of this distribution system:

Firstly, regarding the Optical Output LNB: it is responsible for frequency stacking all 4 universal IF bands to a continuous one; it's output signal, as the name suggests, is an optical signal, with the aforementioned 1310 nm wavelength and an optical output power of +7dBm @ 25ºC; the fiber connection is made via a FC/PC connector, which feeds the single mode fiber; it requires an external power supplier with 12V and <450mA, connected through a standard female F type connector. The +7dBm optical output power makes it suitable to serve 32 users within a range of 10Km, given the GTU's sensibility [Optical LNB, 2009].

Secondly, concerning the optical converter, responsible for converting the Optical LNB optical signal into the IF radio frequency, there are three different types of converters. Twin and Quad optical converters provide 2 or 4 universal satellite feeds from a single fiber optic – Figure 3.2 – while Quattro optical converter provides 4 fixed polarities, making direct connection to a Multiswitch simple. These devices are power supplied by the STB and the input optical power that has to be guaranteed at the converter's input must lie between -13 and 0 dBm [Converters, 2009].

Thirdly, the company developed a special optical fiber for this solution, GI3.0, capable of handling near right-angles without affecting the signal and with losses around 0.3dB/Km. This fiber is the mean in which the light travels between the LNB and the optical converter [Giving coax the axe].

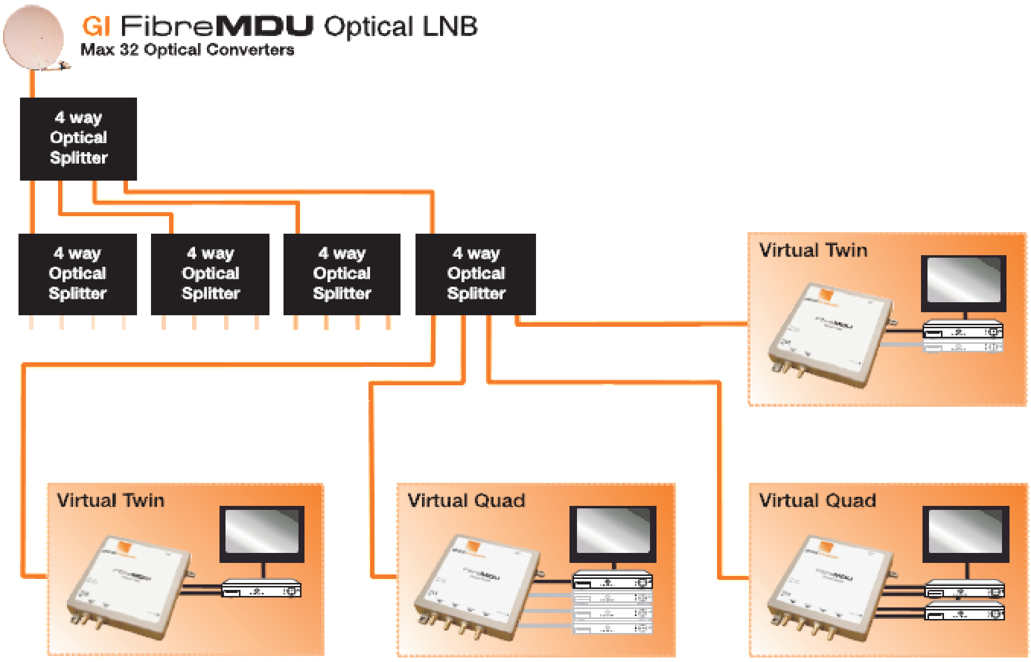


Figure 3.2 Twin and Quad converters application [Converters, 2009]

Global Invacom has presented more than one scenario where their solution might be used: for small MDUs (32 users), for standard MDUs (256 users) and, finally, for a large MDU or a Municipal System. The first one, and simplest, operates as described in the second paragraph of this subsection and is the only one operating purely on the optical domain. The other two are variations of the first and require whole-band LNBs, which are responsible for stacking the different polarization bands, but these LNBs have an RF output which, after passing through a RF splitter, modulate several lasers. The large MDU solution requires optical amplification [FTTH, 2011].

The choice for a C-band wavelength, 1310nm, was made in order to maintain wide open the possibility to integrate, through WDM, the television video with data services provided via GPON/GEPON systems, this integration would also favor a better usage of IPTV. GPON/GEPON upstream is made at 1310 nm, this might represent a constraint for this integration between this architectures and the video transmission over fiber. Allowing for a hybrid system where the broadcast would be held by the satellite fiber distribution and IPTV services would be less sought, allowing for a better quality of service. [FTTH, 2011]

This purely optical solution’s main drawback is its limitation to 32 users. If more users are to be served, a regular whole-band LNB must be used and the signal must be sent in the RF domain, pass through a RF splitter and, only then, they reach the lasers, modulating them.

3.3. BKtel Solution

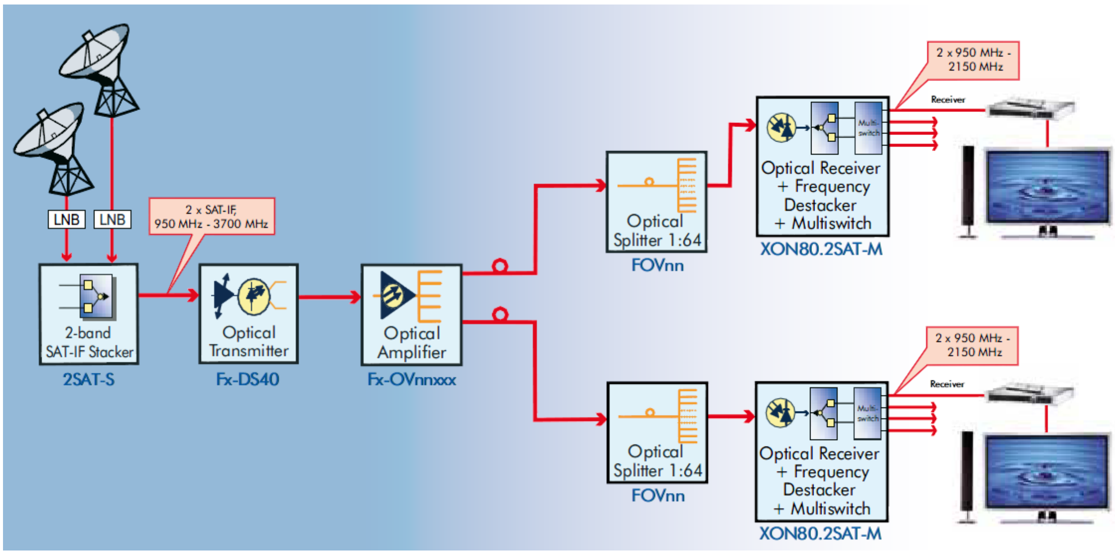


Figure 3.3 Fiber.2SAT system [Fiber.xSAT]

BKtel’s FTTx satellite TV distribution system, under the name Fiber.xSAT, has a big similarity with Global Invacom’s solution: both solutions stack the L-band frequencies before transmission. Global Invacom solution, however, modulates its IF onto the laser in the LNB, whereas BKtel’s solution uses more than one universal LNB to capture the different polarizations and only after sending them through separate RF cables into a L Band frequency stacker.

This solution is presented by the company as a resource for Direct-To-Home (DTH) satellite TV providers to take advantage of modern telecommunication networks in order to avoid installing a satellite dish per customer house. Moreover, this solution is also propitious to offer TV broadcast together with data services.

Figure 3.3 represents the company’s solution for optical transmission of 2 L band signals. There is also a solution which stacks the 4 L band signals with differences at the headend and also at the receiver’s end.

The system is based on the transmission of (DVB-S) TV signals consisting of various independent SAT IF satellite feeds. These are received in different LNBs and then passed on to a frequency stacker which, lately, modulates the 1550 nm optical transmitter. The frequency stacker up-converts one of the L bands to the frequency range from 2500 to 3700 MHz and multiplexes it with the L band in the baseband 950 to 2150 MHz. The optical transmitter is responsible for converting the electrical signal to the optical domain imposing the modulation. The optical signal is then transmitted, at 1550nm, enabling the usage of amplifiers (EDFAs or YEDFAs) as boosters or repeaters.

This specific transmitter, Fx-DS40, offers the possibility to also transmit CATV signals, as it bandwidth lies between the CATV interval, 5…870 Mhz, and the SAT-IF interval 950…3750 MHz.. Other company’s transmitters offer the opportunity to integrate DVB-T signals in the transmission instead of CATV. Succeeding the optical transmitter one optical amplifier is used. Two different amplifiers are suggested by the company for this purpose: a very high power optical amplifier (YEDFA) and a regular EDFA. The Yterbium-erbium Doped Fiber Amplifier is suggested as a booster amplifier for last mile transmission. The output powers go up to 25 dBm, while the minimum optical input level is -6 dBm [FX-EDFA].

After amplification the signal passes through one or more splitters before reaching the optical receiver. The receiver is responsible for the optical-to-electrical conversion and for de-stacking the SAT IF bands, moreover, there are some models which also serve as multiswitches, allowing for the connection of more than one STB. The input optical power must lie between -18 and -3 dBm [FX-receiver].

BKtel also offers equipment for RF overlay to be done in point-to-multipoint architectures such as GPON or GEPON. Concerning the TV broadcast part, this system, represented in Figure 3.4, works in the same way as the previously described (without GPON/GEPON integration) up till the optical amplifier. After the optical amplifier, a WDM equipment integrates the downstream signal (@ 1490 nm) coming from the Optical Linte Terminal (OLT) with the RF modulated signal, sending both through the same fiber up to each customer’s premises. At this point, an Optical Network Unit (ONU), with a WDM equipment responsible to separate TV broadcast and data, serves the different equipments present at each house.

Being responsible for the interchange of data between the final user and the OLT, this system has the ability to generate and send an upstream signal, through the same path of the downstream one. So in the same fiber, between the Point-of-Presence (POP), where the RF video modulated and the data signals are integrated, and the ONU, 1550 and 1490 nm wavelengths are sent in downstream direction and a 1310nm wavelength is sent in the upstream direction [BKTEL FTTH solution].

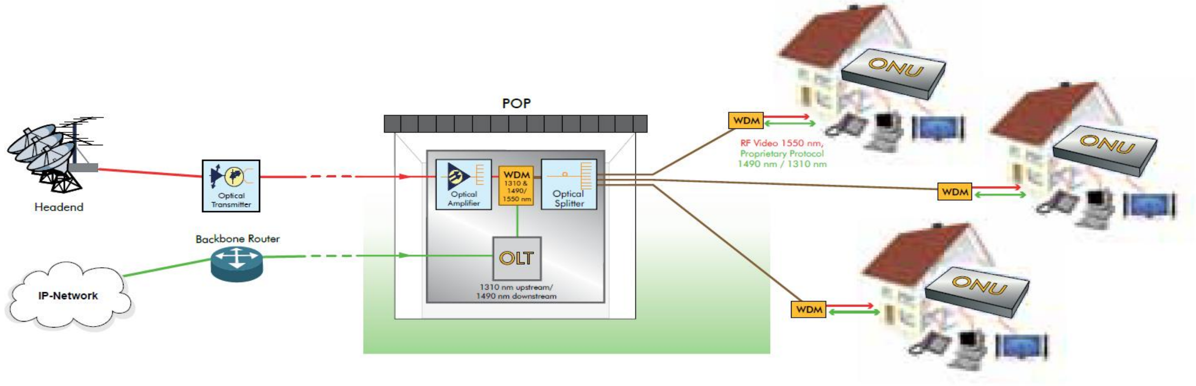


Figure 3.4 PON and RF video overlay [BKTEL FTTH solution]

Summing up the main features of BKtel's satellite TV distribution solution are: transparent fiber optic transmission of DVB-S SAT IF/CATV/DVB-T signals, stacking of multiple SAT IF signals, suitable for point-to-point and point-to-multipoint FTTx networks, low-cost headend equipments, integration with standard DVB-S/DVB-T STBs, multiswitch included in the customer premises unit [Fiber.xSAT].

3.4. 4CableTV solution

4CableTV came up with a solution for a problem other than the one targeted by the two previous presented companies. The problem targeted by 4CableTV was the so-called "last-mile problem". The company realized that by the end of each feeder CATV line there are a few more customers that could use the service if there was a service extension. This extension is unworthy of the money spent for its installation when we talk about doing it with coaxial cables only to serve an average of two customers per 610 meters [RF2F].

The company realized that serving last-mile clients with an optical system would be far cheaper, stating that deploying this kind of system cable TV operators could acquire new customers at prices below 1000$ and, in certain cases, even under 500$.

Figure 3.5 helps for a better understanding of how the solution works. The system within the green line represents a regular Hybrid Fiber-Coaxial (HFC) network, combining cable TV services and high speed data services (cable internet, VoIP, etc…). The innovation of this solution is presented inside the red line rectangle. At the end of the feeder line a RF2F Tx/Rx, developed by the company, is responsible for receiving a RF feed from the HFC and output a 1550nm signal over fiber, working as a transmitter. When working as a receiver, it has, as an input, a 1310nm optical signal that is reconverted to RF and sent back to the HFC plant.

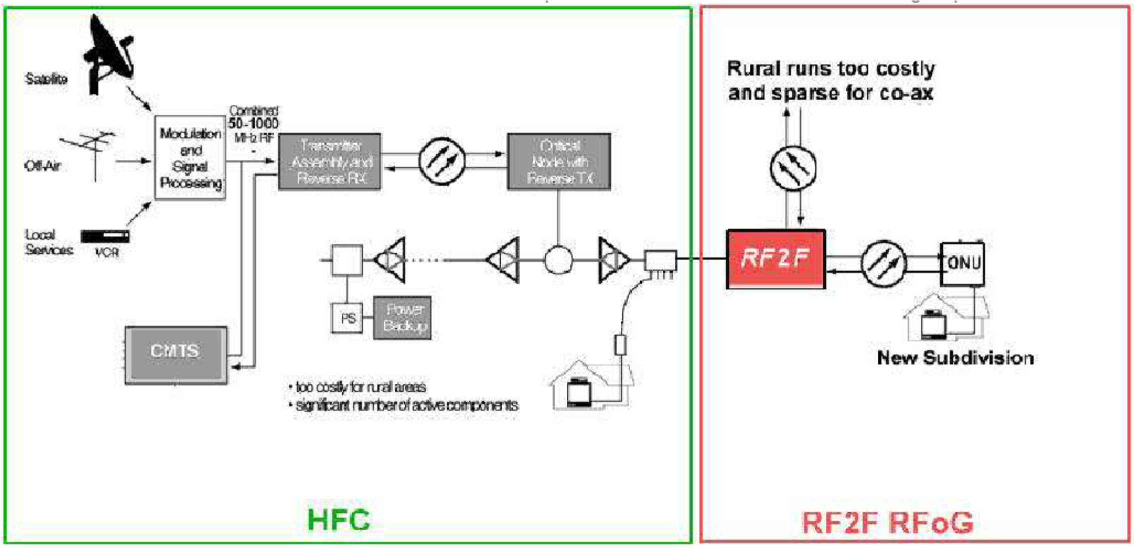


Figure 3.5 4CableTV video distribution solution [RFoG3]

On the side of the fiber fed home, a regular Radio Frequency over Glass (RFoG) home unit is used. This kind of unit is responsible for in-home content distribution over existing home coaxial cabling to cable STBs, modems and TV sets. It is also responsible to send the upstream signal back into the HFC plant through a modulated laser operating around 1310nm [RFoG ONU].

A deeper perception on the RF2F Tx/Rx is mandatory for a clear understanding of this solution. The laser used in this equipment is directly modulated, therefore, its output power is limited to 10 dBm, 18 if required, and the RF2F comes pre-configured to be connected with fiber lengths of 5, 10 and 15 km. The optical output power limitation has to do with the laser's chirp, direct consequence of direct modulation, interaction with the dispersion characteristics of the optical fiber under use. If the abovementioned lengths are to be exceeded, signal distortion most certainly occurs.

Still concerning the laser, its wavelength can be set between 1530 and 1563 nm and its optical output power can reach the 18 dBm. Since it is intended to transmit CATV channels, its bandwidth ranges within the interval 45-862 MHz and the minimum input power is 13 dbmV. The maximum output Carrier-to-Noise Ratio (CNR) is higher than 50 dB. When in receiving duties, this equipment has a minimum input CNR of 30 dB, guaranteed for -26 dBm. The maximum input optical power is -5 dBm [RFoG3].

Figure 3.6 explains the upstream and downstream signal paths inside the RF2F. The upstream signal, green line, is done at a wavelength of 1310 nm and the downstream, red line, uses 1550 nm wavelength.

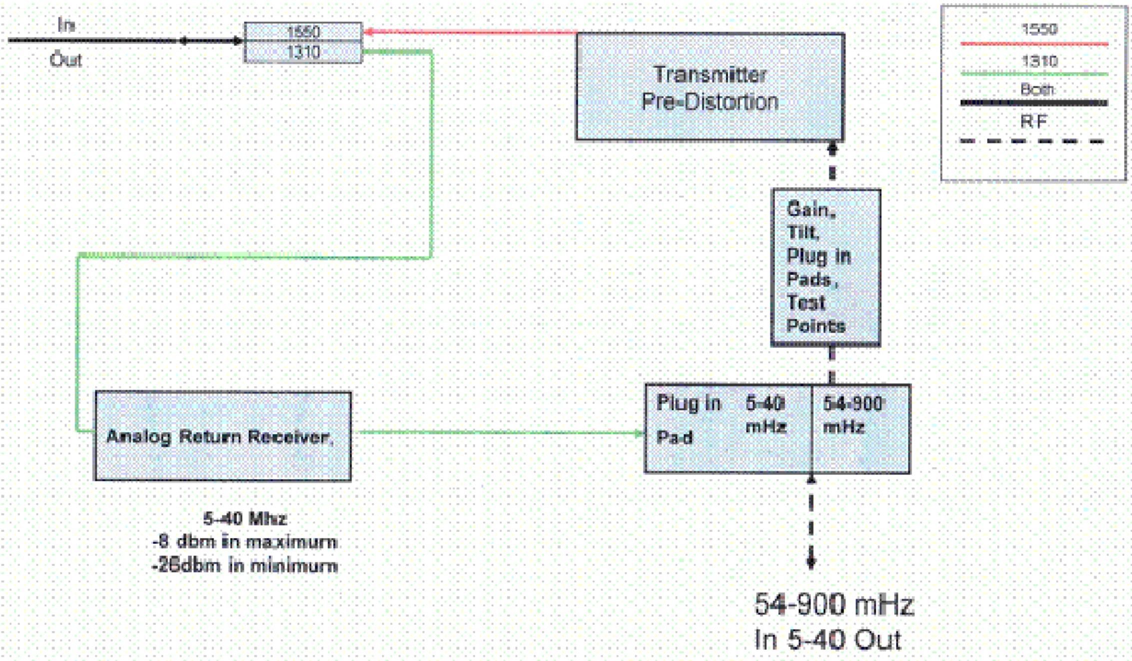


Figure 3.6 RF2F Transmitter/Receiver detailed [RFoG3]

For extending the solution reach the company has developed an extender. This extender is merely an EDFA working both up and downstream ways [4cable.tv].

4. Introducing a new video over fiber distribution scenario

4.1. Introduction

The previous chapters were meant to study which were the problems affecting video distribution, both satellite and CATV, in order to reach for a better solution. In chapter 2, general concerns about an optical system were described and analyzed. Major concerns for satellite TV distribution over fiber are attenuation, amplification, laser characteristics and how to modulate the laser (direct vs. external modulation).

In chapter 3 different solutions, already available in the market, were analyzed. This helped for realizing for yet another problem, sending the different satellite polarizations within the same fiber. Coarse Wavelength Division Multiplexing (CWDM) together with Dense Wavelength Division Multiplexing (DWDM) were thought as a solution to this problem.

Choosing between CWDM and DWDM had direct implication on the type of amplification used, given their wavelengths spacing. For CWDM the choice could either go for two DFAs, one amplifying the C band (common band) and the other one the L band (long band), or it could be done using a SOA. For DWDM a single EDFA could be used. Laboratorial tests were run to reach a conclusion.

It is important to make a preliminary note to state that the minimum CBER and CNR values at the receiver's end are, respectively, in the order of magnitude of 10^{-4} and 34 dB, for DVB-C channels and, in the order of magnitude of 10^{-4} and 11 dB, for DVB-S channels [DVB, 1997]. Both must be ensured at any time. It goes without saying that even if the CNR is higher than the minimum value but the CBER does not meet its minimum value, the signal is not good enough.

4.2. Sending 4 satellite polarizations (CWDM vs. DWDM)

Stacking the polarizations, as in BKtel's and Global Invacom's solution, would require for higher bandwidth lasers, with the satellite frequencies occupying 4.5GHz (950-5450 MHz), and adding the terrestrial frequencies, almost another GHz of bandwidth (45-862MHz). Stacking the 4 quadrants would, therefore, demand for a laser with a bandwidth of 5.5GHz, whereas if the different polarizations through different lasers, lower bandwidth lasers would be needed.

The challenge of sending all 4 polarizations, received at the satellite's dish LNB, through a single fiber was set and WDM, the multiplexing of several signals along the same fiber in the frequency domain, appeared as the perfect suggested solution. Two different solutions, within WDM and based on their granularity, were considered: CWDM and DWDM. Their main differences are the wavelengths used and the spacing between them.

In terms of number of multiplexed wavelengths, both solutions provide more than four, CWDM supports fewer than 16/18 and DWDM more than 32 (up to 320) [Ofcom, 2010], so both of them are suited for transporting satellite's four quadrants. Wavelengths are usually separated by 20nm in the coarse WDM system and by 0.8nm in the dense version. Figure 4.1 shows the channel spacing grid defined by ITU in G.694.2 for CWDM. 18 channels per fiber are available; however, they are only attainable if a low water absorption peak fiber is used, otherwise, two channels within the extended band, E band (1360-1460nm), would be severely attenuated, hence, unusable for transmission.

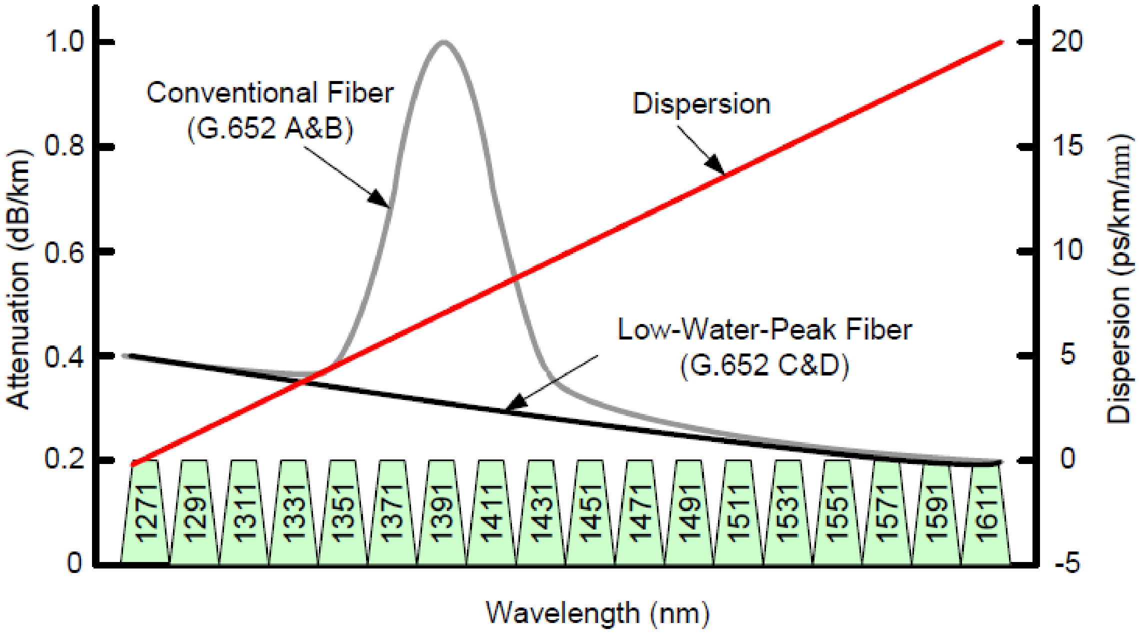


Figure 4.1 20nm CWDM grid [WDM-PON, 2005]

For this satellite distribution scenario a common fiber could be used, since only 4 channels are to be used.

DWDM tends to be used in more sophisticated systems since it has a wider capacity. G.692 ITU standard has defined a 0.8nm spacing (100 GHz between channels) but spacing of both 50 and 25GHz have already been used in order to extend system's capacity.

Channel spacing is a crucial factor when choosing both the type of laser and, considering that 4 channels will be used, the type of amplifier (given their bandwidths). Since DWDM uses a smaller channel spacing it is mandatory that its lasers are more stable, more robust. This need for better optical transmitters results in an increase on the price of the type of laser used in DWDM: a 2.5Gbps CWDM laser is currently retailed around 180 Euros while a 2.5Gbps DWDM retail price stands around 600Euros [oemarket.com]. Assembling the different laser parts may bring the prices to lower values, but DWDM lasers plus TEC controllers are always more expensive than a CWDM laser.

DWDM requires Distributed Feedback laser diodes (DFB), which are stable enough (an approximately 0.1 nm/°C) with a thermal-electric cooler (TEC) to maintain the temperature almost constant [WDM-PON, 2005].

Since CWDM channels are widely separated, they do not demand for lasers with the same stability as a DFB associated with a TEC. A simple DFB, not temperature controlled, or even a Fabry-Perot laser diode may be used, substantially reducing the price associated with the transmitter [Ofcom, 2010].

CWDM is cheaper in terms of transmitter, it can use cheaper lasers and does not require for a temperature control system (smaller transmitter), resulting in a lower electric power consumption. Although CWDM has, as its main disadvantages, the fact that its scalability is diminished, it operates within a lower range, both these characteristics do not represent a concern to our scenario. CWDM was designed, however, for systems that do not require amplification. This will represent a major setback in our distribution scenario, since it will require for amplification.

DWDM accounts for major system capacity even though this is not an issue in our system. DWDM is ready to be used with EDFAs and this will represent a huge advantage in the SAT TV distribution scenario.

In the upcoming subchapter different schemes of amplification will be used. This will be done for both CWDM and DWDM in order to test which one fits best the purpose of sending the 4 SAT polarizations. Despite the fact that CWDM laser prices are lower than the ones of DWDM lasers, it was concluded that for the studied scenario, which needs to recur to amplifiers with limited bandwidths, the dense solution is preferable. SOAs are not the best solution for this video distribution scenario, as they perform poorly for multi-channel wave systems. EDFAs, are suited both for the coarse and the dense WDM approach, however, in the first case there is the need for two different amplifiers, one for the C and one for the L bands. Another drawback associated with CWDM is the possibility of occurrence of Stimulated Raman Scattering.

4.3. Amplification schemes

As stated in the previous subsection, the spacing between the channels is crucial to pick the correct amplifier. SOA and EDFA solutions were covered. For CWDM a SOA and 2 EDFAs (of different types and arranged in different configurations) were tested, since one EDFA was not enough: EDFA's bandwidth is approx. 30nm, below the $3 \times 20nm$ needed to transmit 4 channels spaced by $20nm$. For DWDM a single EDFA solution was tested, given the results obtained during the SOA tests.

4.3.1. CWDM with SOA

When SOAs were studied in this work, section 2.3.2, it was discussed how they are susceptible to nonlinearities from different kinds: SPM, XPM, XGM, etc… It was also said that they account for wide band amplifiers, amplifying above 20 dB for about 60nm and above 15 dB for more than 80nm, Figure 2.10. This particular feature make SOAs look particularly attractive to amplify CWDM signals in order to transport the 4 SAT polarizations.

Anticipating possible signal degradation, due to SPM, a first setup with a single modulated laser was set. First of all, a back to back test was done. A laser working at a wavelength of 1550.137nm, directly modulated by the TV signal, was connected to a Variable Optical Attenuator (VOA) and then to a PIN photodiode. This VOA was present at this circuit to guarantee a certain input optical power throughout the subsequent tests. This optical power was defined as -3.20 dBm (this value was chosen according to the PIN characteristics).

Figure 4.2 SOA setup with one wavelength

Results presented in this subsection of this work are related to the results obtained with the back-to-back test. After entering the PIN in the optical domain, the signal was reconverted to the Radio Frequency (RF) domain and then fed to a H45. The H45 is a *Televes*® advanced HDTV system analyzer. It provides CNR, MER, CBER and electrical power measurements.

A final preliminary note to state that recurring to an electric circuit, once again provided by *Televes*®, it was possible to send through the optical signal both satellite and cable Digital Video Broadcast (DVB- S/C) signals. The DVB-S signal was received by a regular satellite dish and the DVB-C channels were generated in the lab with the help of this particular device.

A SOA was inserted into the first, and reference, setup together with another VOA, this one with the sole purpose of controlling the SOA input optical power, Figure 4.2. This setup allowed for the control of both PIN and SOA input optical powers. The purpose is, of course, to check the SOA's impact on a single channel.

The SOA input values tested were -5, -10 and -20dBm and the SOA was biased at different currents: 75, 100 and 145mA. A set of DVB-T and DVB-S channels were tested and the results were as follow in Figure 4.3.

The results were worse for DVB-C signals (frequencies up to 870MHz) than for DVB-S. This can only be explained given their modulation format difference, since their electrical powers were very similar when the back-to-back tests were performed: for the higher channels of both DVB-C and DVB-S the electrical power leaving the transmitter was 74.6 and 75.9 dBµV respectively. DVB-S is modulated using Quadrature Phase-Shift Keying (QPSK) whilst DVB-C is modulated recurring to Quadrature Amplitude Modulation (QAM), in this particular case, 256QAM.

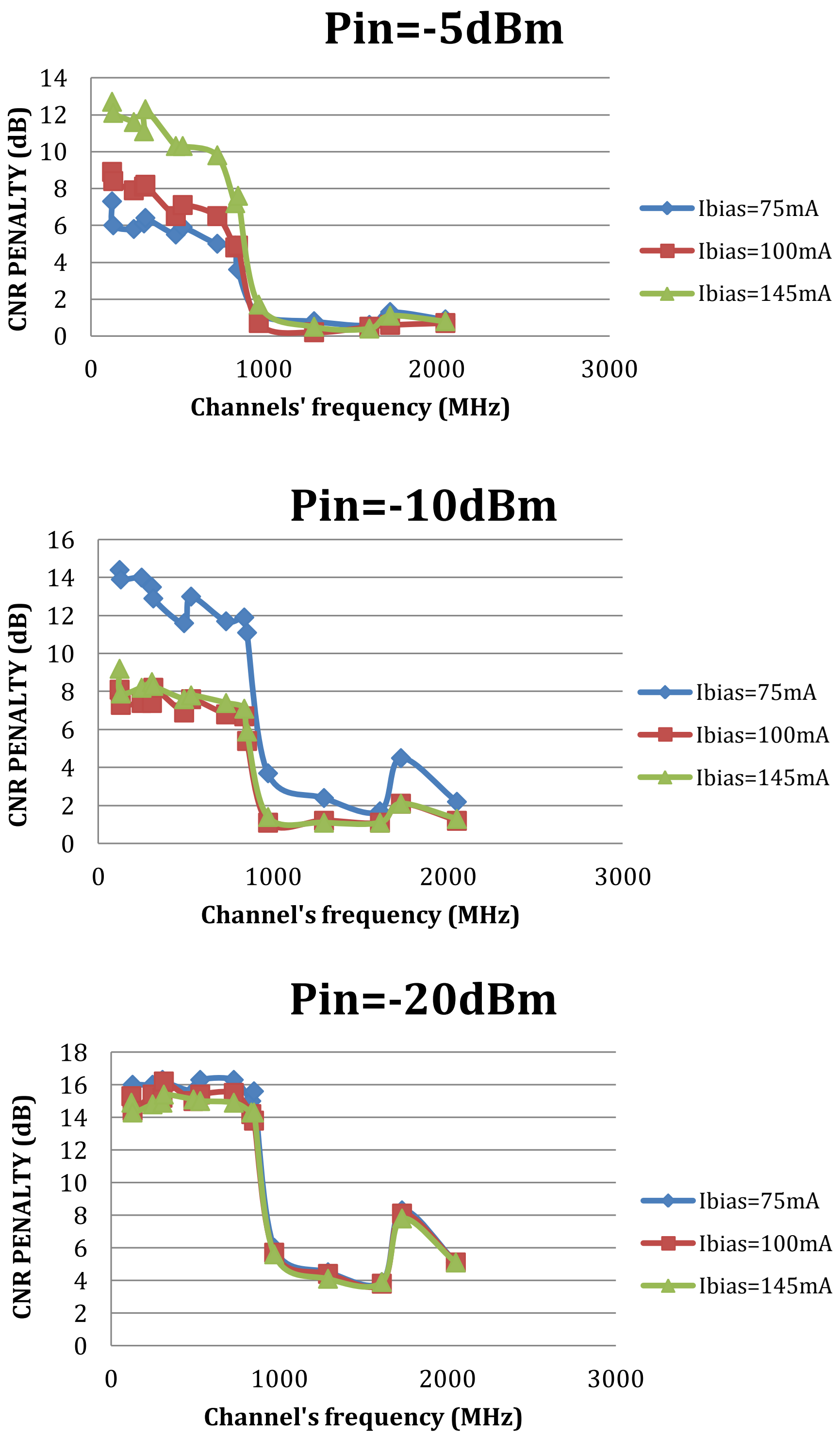


Figure 4.3 DVB-T/S Channels' CNR penalty when amplified by a SOA with different SOA input powers and biasing points (single laser test)

Modulating the signal with 256QAM implies that one can transmit more bits per symbol, however, the fact that 256QAM is a high-order constellation also reasons that symbols are very close to each other, demanding for a higher Optical Signal-to-Noise Ratio (OSNR) to achieve the same performance of QPSK, for example.

Satellite transmission occurs between points separated by hundreds of kilometers; hence, its modulation format must be very resistant to noise and has to be able to deal with non-linear phenomena. Its channels are characterized by limited downlink power and a relatively high bandwidth. QPSK does not have the problem of having its symbols too close since it only has 4 symbols and these are well spaced. This modulation format has a very good performance when facing noisy means of propagation [Seimetz, 2009].

The degradation experienced by the DVB-C channels, well evident in Figure 4.3, is explained by its modulation format which is susceptible to nonlinearities, in this case SPM. These experiments allowed to conclude that it would not be possible to transmit the DVB-C channels if they were to be amplified by a SOA. If a single wavelength produced such degradation in the Carrier-to-Noise Ratio and Channel Bit Error Rate (CNR and CBER respectively) values, the four wavelengths with the different SAT polarizations could only lead to worse results. The CNR values for the back-to-back test were around 40 dB hence, introducing degradation always superior to 6 dB, made the CNR equal or lower to 34 dB, the minimum value for DVB-C channels.

Despite how bad the DVB-C results were, it was important to understand if a SOA could fit a solution integrating solely DVB-S signals. The interaction between two different modulated signals had to be tested in order to see if it was or not possible to transmit all 4 polarizations and still get a proper DVB-S at the users end. Some changes had to be done to the previous setup: a mux and a demux had to be inserted as well as another VOA to control the new modulated laser’s output optical power – Figure 4.4.

After passing the demux the signal entering the PIN is the one modulated at 1550nm, this is because this laser is the one with video modulation and the second one is modulated with a random sequence of bits.

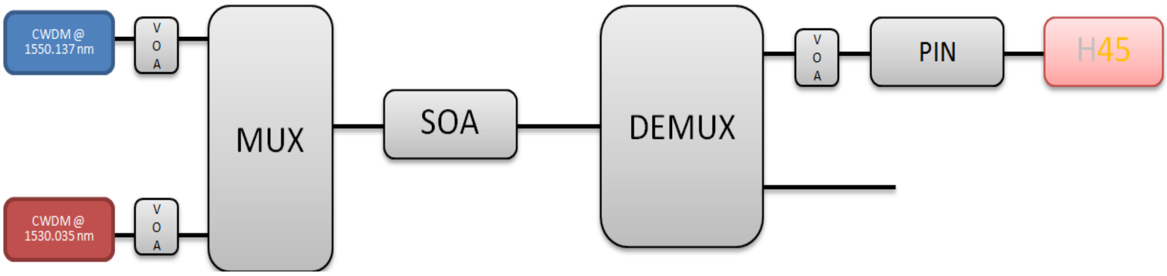


Figure 4.4 SOA setup with 2 wavelengths

Satellite video channels, even though their modulation format has the ability to face strong nonlinearities, succumb when in the presence of another modulated signal. The CNR drop was around 7 dB (from 17 to 10 dB) for DVB-S channels and 23 dB for DVB-C (taking as reference the back-to-back values), Figure 4.5. Taking as reference the values taken with the previous setup the DVB-S channels CNR penalty was, again, around 7 dB (DVB-S experienced little CNR penalty for a single wavelength) and around 15 dB for DVB-C channels, Figure 4.6. CBER's values also dropped to levels which are not suited for correct video signal reception.

This second round of experiments, with two wavelengths was done with the TV modulated signal input power of -5dBm (when entering the MUX) and a SOA bias current of 100mA. The choice of these parameters was done since they represented a combination which presented one of the best results for the single laser setup.

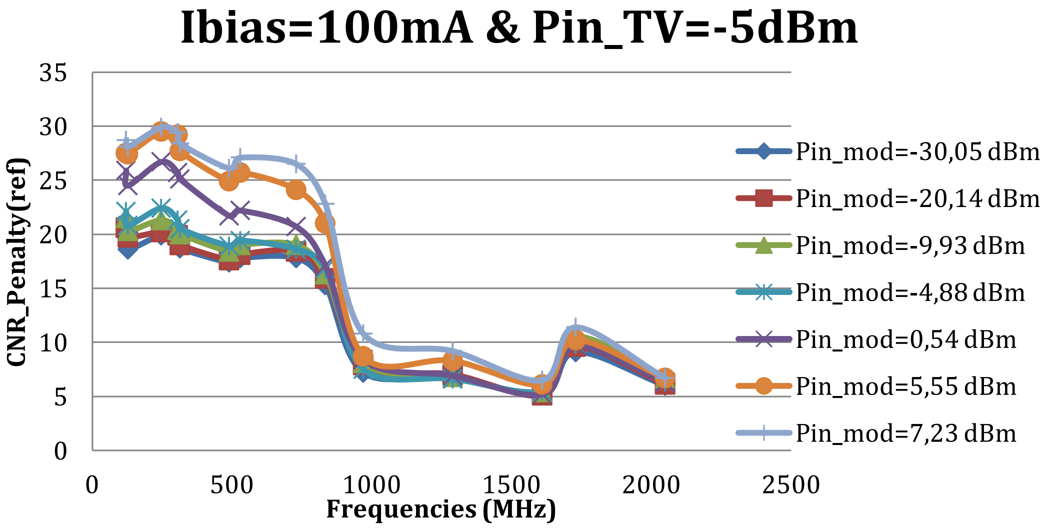


Figure 4.5 DVB-T/S Channels' CNR penalty when amplified by a SOA with different input powers of the second modulated laser (with back-to-back reference)

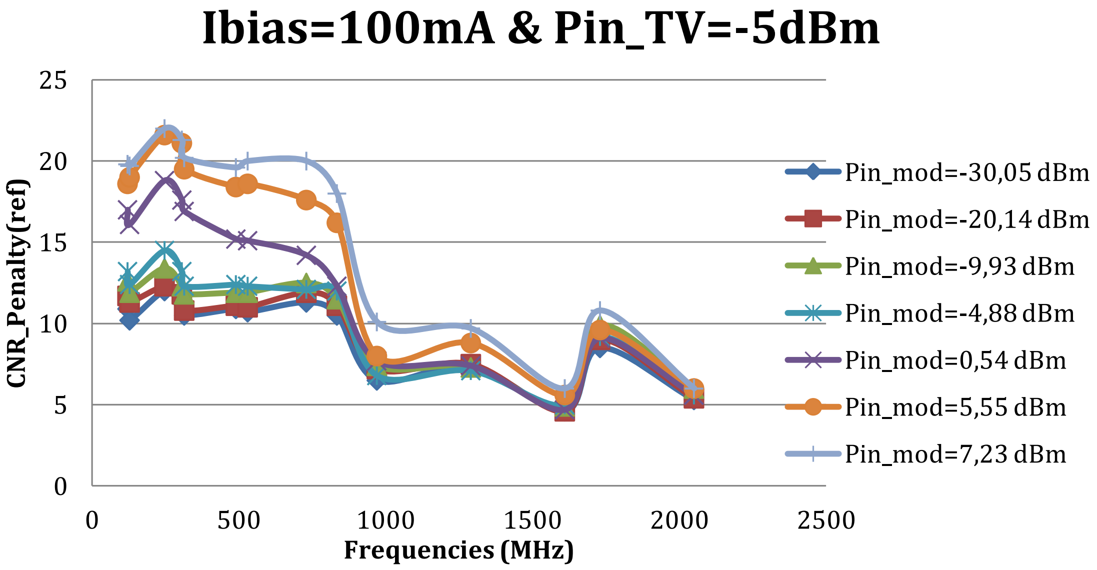


Figure 4.6 DVB-T/S Channels' CNR penalty when amplified by a SOA with different input powers of the second modulated laser (with 1 laser test as reference)

It was proven that SOAs are not fit for the proposed video distribution scenario. Signals travelling through the SOA see their CNR and CBER degraded to values well below the minimum required for a proper reception TV broadcast reception.

4.3.2. CWDM with 2 EDFs

Three different doped fibers were used together with three different configurations. The length of the fiber was also varied between 5 and 20 meters. The pumping power, P_p, was set for 227mW. This value was chosen since it was the one producing the best amplification results.

Tests were run at *Fibercore Limited's Gainmaster Amplifier Design Software*, to figure out what would be the best pumping wavelength for the available C and L bands EDFs (from the same company). Figure 4.7 shows the setup used in the software in order reach a decision. The pump's wavelength was set to be 980nm and then to be 1480nm. The type, and length, of doped fiber were also changed to amplify in the C-band and then on the L-band. 1480nm produced the best average amplification results, so this was the wavelength used throughout all the tests, even the ones with the C+L band EDF (produced by *LIEKKI*™).

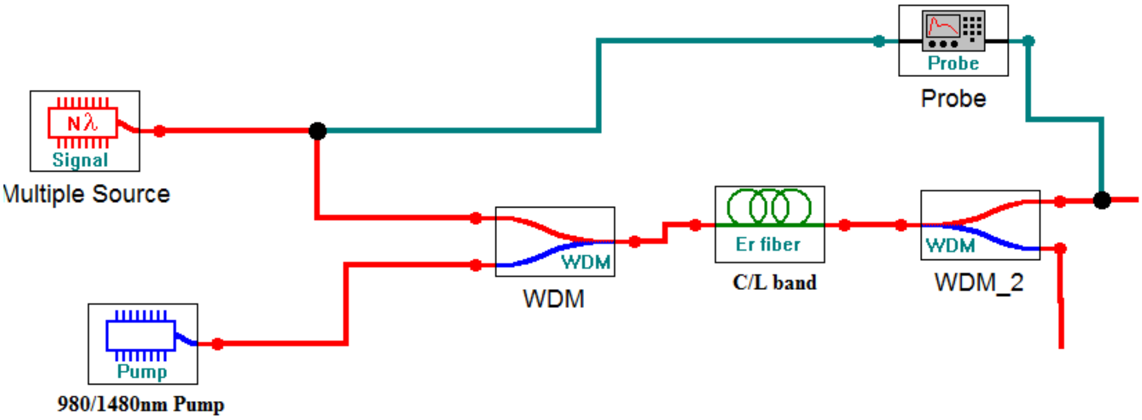


Figure 4.7 Setup used to define the pumping power

4.3.2.1. *Single-stage C+L EDF*

This setup, Figure 4.8, represents, ideally, the simplest way to amplify four channels around 1550nm transmitted with 20nm spacing: a single doped fiber and a single pump. The doped fiber developed by *LIEKKI*™ is set to amplify in both C and L bands (1530 to 1625 nm). Basically the 4 modulated channels, 1530-90nm, are multiplexed; they are coupled with the 1480nm pumping signal and sent through the highly doped fiber.

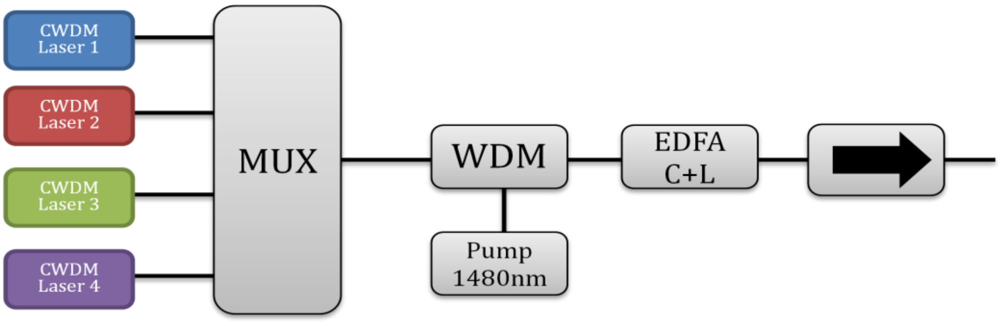


Figure 4.8 Single-stage C+L EDF

The challenge was to see if it was possible to obtain 12dBm of optical power at the amplifier’s output, for each wavelength. The 12 dBm line was set to model the provision of service for 32 users. Three different input powers (-9, -4, -1 dBm) were tested along with three different EDF lengths (5, 10, 15 meters). Figure 4.9 presents the results obtained with this setup.

The best results were obtained for a 5 meter long EDF, namely for a -9dBm input power. However, not even for this specific case were all the channels amplified sufficiently to exit the EDFA with an optical power of 12dBm. This solution, despite its simplicity, does not suit the purpose for which it was intended.

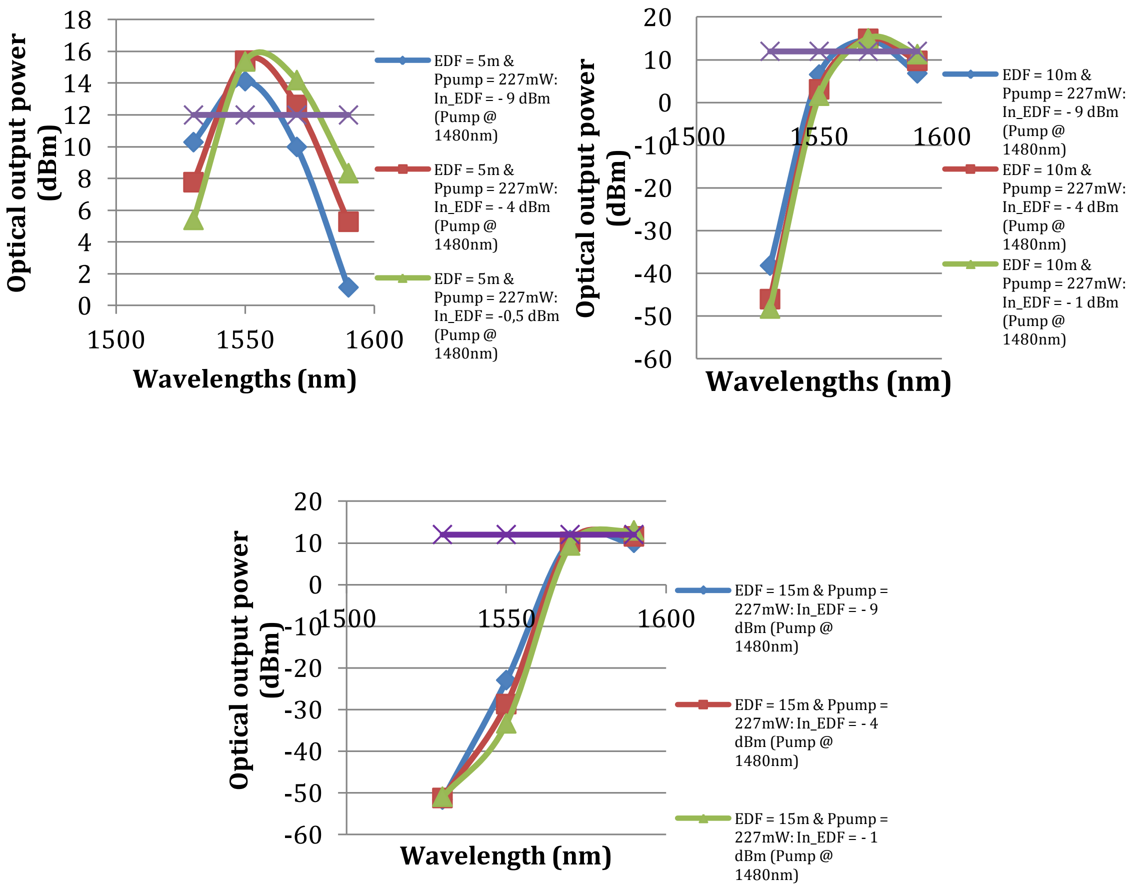


Figure 4.9 Optical output power vs. Wavelength for different EDF input powers and EDF lengths (the purple line defines the required 12dBm output)

4.3.2.2. Double-stage C and L EDFs in parallel

A second suggestion to achieve the 12 dBm of optical output power throughout the 4 CWDM channels was to amplify channels in the C-band separately from the ones in the

L-band and then, using a 50/50 coupler, get them together, Figure 4.10. This setup has the downside of requiring more hardware.

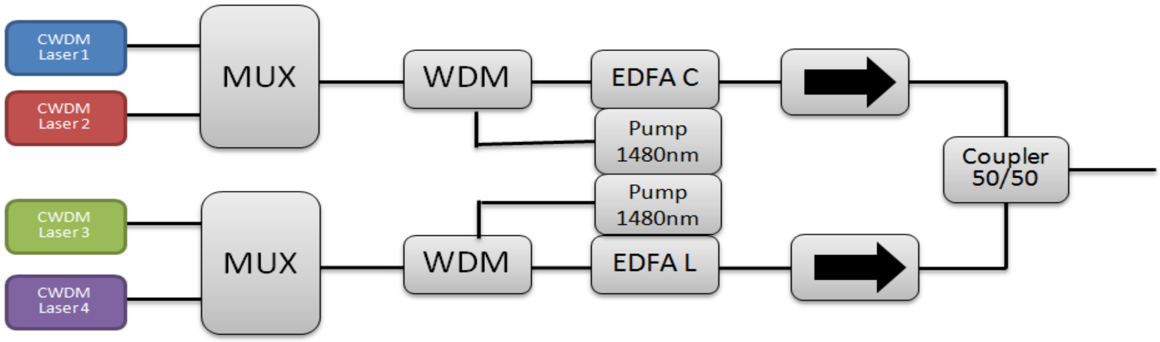


Figure 4.10 Double-stage C and L EDFs in parallel

The challenge and parameters changed were the same from the first configuration. The results in Figure 4.11 are for the C-band wavelengths amplified in the upper arm of the setup. Figure 4.12 shows the results for the L-band wavelengths. For the L-band a slight change on the pump's wavelength took place, 1487nm was tested since neither 980nm or 1480 produced the required results.

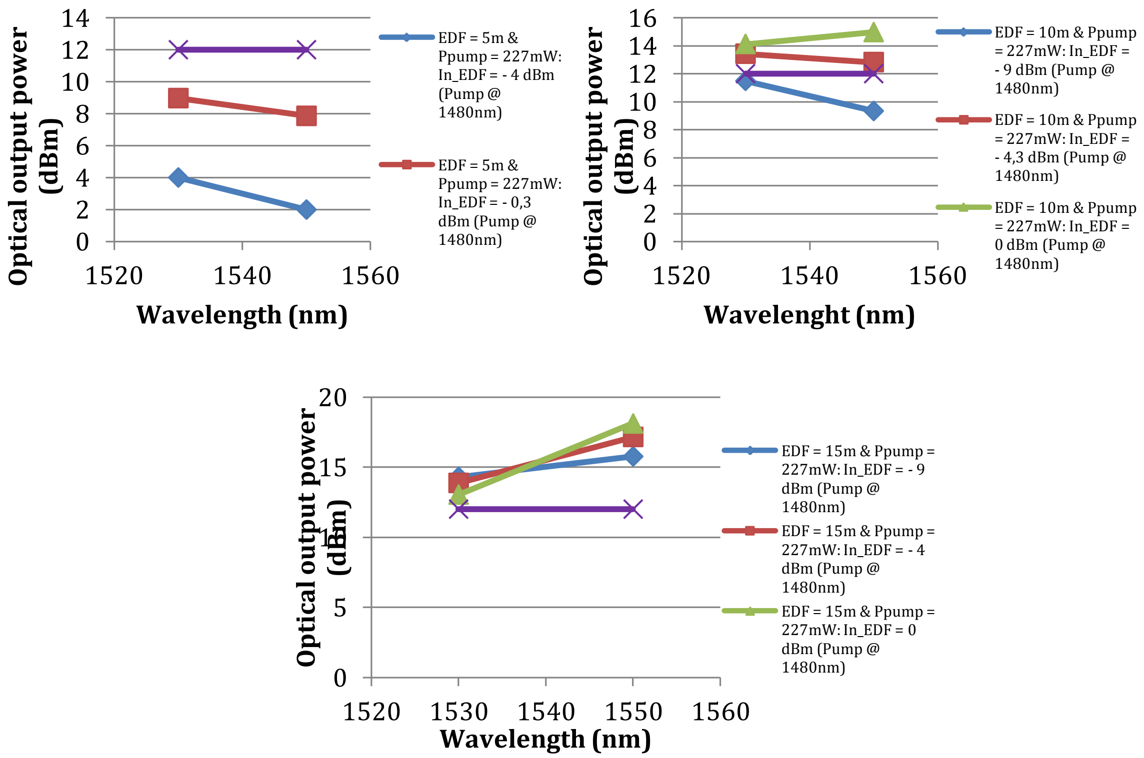


Figure 4.11 Optical output power vs. C-band wavelengths for different EDF input powers and EDF lengths (the purple line defines the required 12dBm output)

For the L-band only two tests with a 10m long doped fiber are presented. With lengths over or under 10 meters it was not possible to obtain the 12 dBm output for both 1570 and 1590 nm wavelengths. Pumping the doped fiber with a 1480nm wavelength also didn’t produce results to fit the requirements. For a 1480nm pumping and a 0 dBm input the gain settled for 11.27 dB. However, when the input power, the pumping wavelength and power were readjusted, the 12 dBm of optical output power were obtained.

This solution is well capable of tackling the problem. Granting the 12 dBm output power for more than one combination of EDF input power and length. This solution comes at a cost though, it demands for more hardware (the number of WDM couplers and the number of pumps has to be doubled; a 50/50 coupler has to be introduced, etc…).

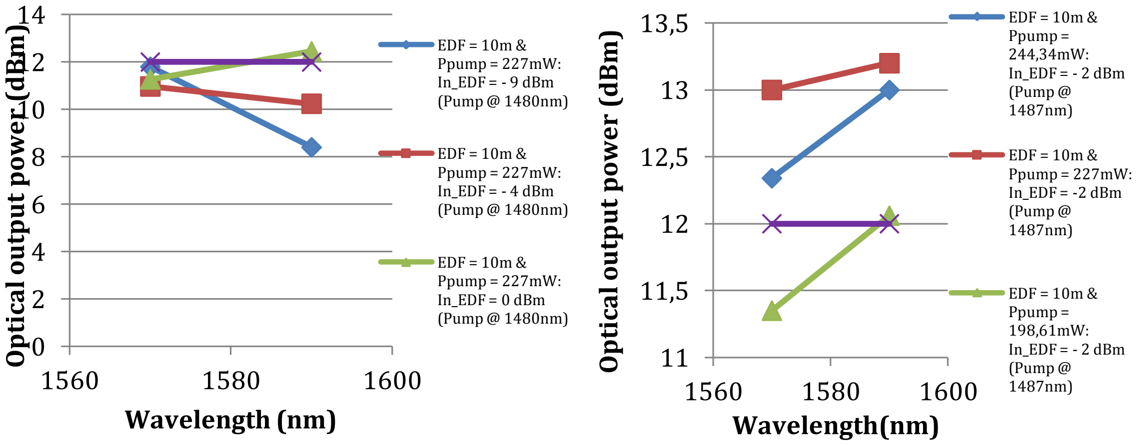


Figure 4.12 Optical output power vs. L-band wavelengths for different EDF input powers and 10 meters of EDF (the purple line defines the required 12dBm output)

4.3.2.3. Double-stage C+L EDF and C EDF in series

A final solution was tested recurring to both a L and a C-band EDF connected in series. It was then realized that better results were obtained using a C+L EDF instead of a simple L-band fiber, and since they come at very similar costs, the tests for this solution were done using a C+L and a C-band EDF, Figure 4.13.

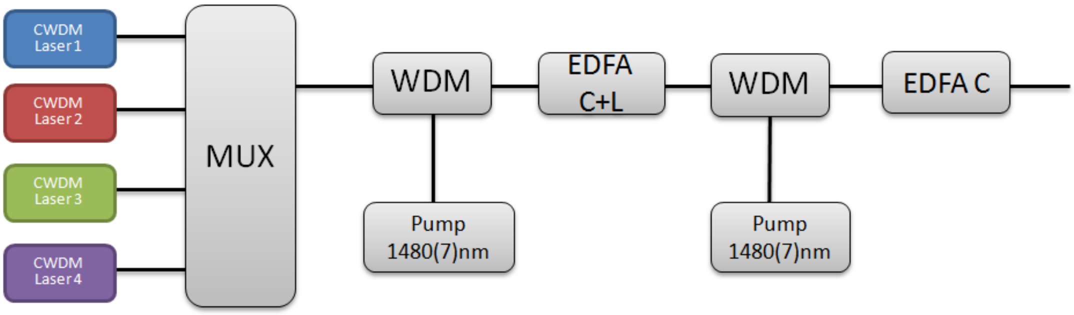


Figure 4.13 Double-stage C+L and C EDFs in series

Different length configurations for the C and the C+L doped fiber configurations were tested (15 meters of C and 5 of C+L, 10 meters of C and 5 of C+L, 10 meters of C+L and 5 of L, etc…). Figure 4.14 only depicts the best result obtained: 10/ 15 meters of C-band doped fiber and 5 meters of C+L fiber and pumping wavelengths of 1480 and 1487nm.

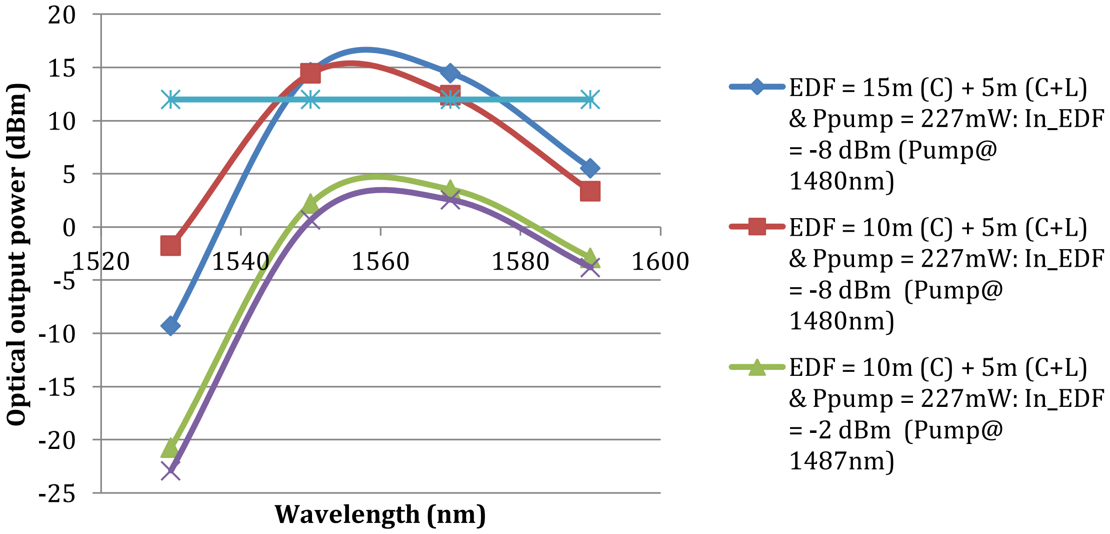


Figure 4.14 Optical output power vs. wavelengths for different EDF input powers and EDF lengths (the blue line defines the required 12dBm output)

The results produced by this setup were, once again not satisfactory. This solution does not meet the requirements of the satellite TV distribution scenario for 32 users.

4.3.3. DWDM with 1 EDFA (C-band)

Given that only the solution with 2 EDFAs in parallel, one amplifying the L and the other one the C bands, produced results which met the requirements, even though they were almost met in a minimal way, introducing doubts about the scalability of the system (the scenario with this two amplifiers would hardly serve 64 or 128 users), and taking in account the amount of hardware needed to implement this solution, DWDM was equated.

4 DWDM channels, with their 0.8nm spacing, are perfectly capable of being amplified by a single C-band EDFA. DWDM systems come, of course, with the problem of requiring a high degree of temperature control of their lasers.

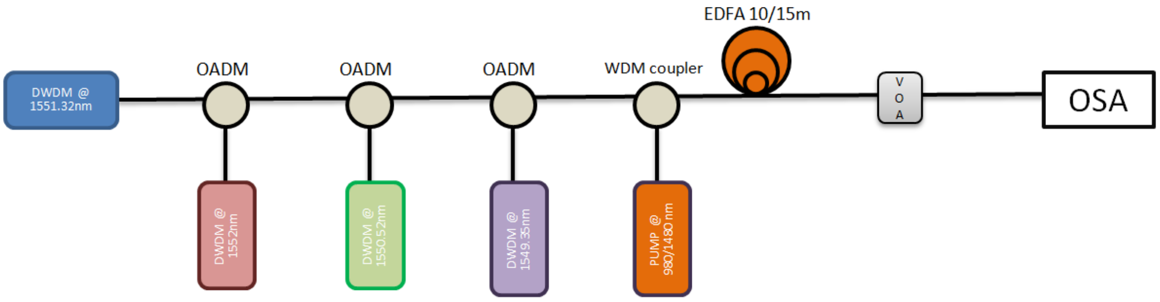


Figure 4.15 DWDM with 1 C-band EDFA experimental setup

Again, 12 dBm of optical output power were to be guaranteed at the amplifiers output for each wavelength. The optical input power at each Optical Add/Drop Multiplexer (OADM) was equalized for each wavelength. Two sets of wavelengths were tested: 1548.51, 1549.35, 1550.52, 1551.32nm and 1549.35, 1550.52, 1551.32, 1552nm. The second set of wavelengths accounted for the best results, hence, will be the one with its results shown in this work. The experimental setup can be seen in Figure 4.15.

Figure 4.16 shows the results obtained for a 0/-1dBm input power of each wavelength at each OADM, left and right sides of figure, respectively. The doped fiber was pumped with 980nm wavelength pump.

The results met the required minimums when the optical input power was 0dBm for any of Ppump and EDF length tested. For the second test, when the optical input power at the OADMs was -1dBm, the system behaved properly for measures with 10 meters long fibers but did not reach the minimum value for the amplifier with a 15 meters long fiber, 1549.35nm channel was not sufficiently amplified.

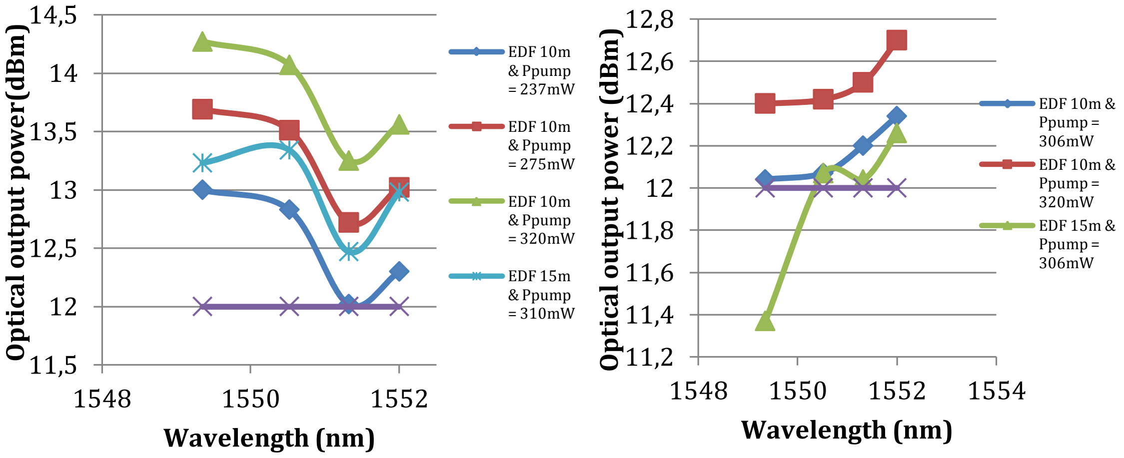


Figure 4.16 Optical output power vs. wavelengths for different EDF pumping powers (the purple line defines the required 12dBm output)

Figure 4.17 shows the results for the EDFA pumped at 1480nm. Results were particularly satisfactory for an input power of -0.5dBm. An augment of the pump power represents a rise in the output power.

Despite how cheaper CWDM might be when compared to DWDM, considering the amplification required in this scenario and its amplifier’s bandwidth limitations, the choice became obvious (after the described experiments) and fell for a DWDM solution with a single C-band amplifier. CWDM would require at least two amplifiers, and signals would not be free of being affected by Stimulated Raman Scattering. As abovementioned, DWDM lasers have the handicap of requiring very stable lasers. More than a TEC controller, they might benefit from using a laser linearizer, as described earlier.

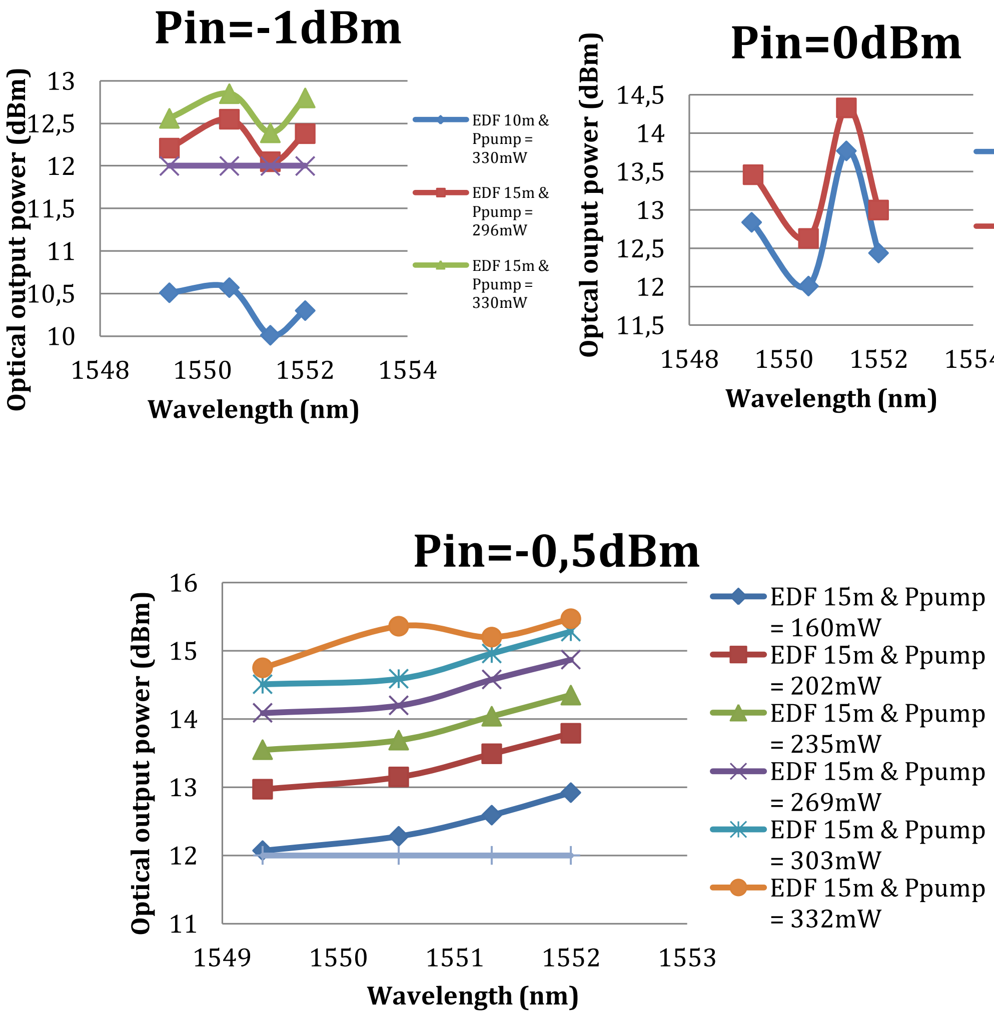


Figure 4.17 Optical output power vs. wavelengths for different EDF pumping powers (the purple/light blue (upper/bottom graph) lines define the required 12dBm output)

4.3.3.1. Benefits of using a laser linearizer

A small study on the usage of a linearizer is important in order to understand to which degree the introduction of this circuit may benefit the proposed video distribution scenario. Recurring to *Advanced Design System*, software by Agilent Technologies for electronic design automation for RF, the RF behavior of a linearizer was simulated and imported to *Matlab*®. Using *Matlab*®, two setups were tested: the first one to set reference values, a RF carrier modulated a laser and its response was registered, a second setup, setting up a predistorter, before the RF carrier enters the laser, Figure 4.18.

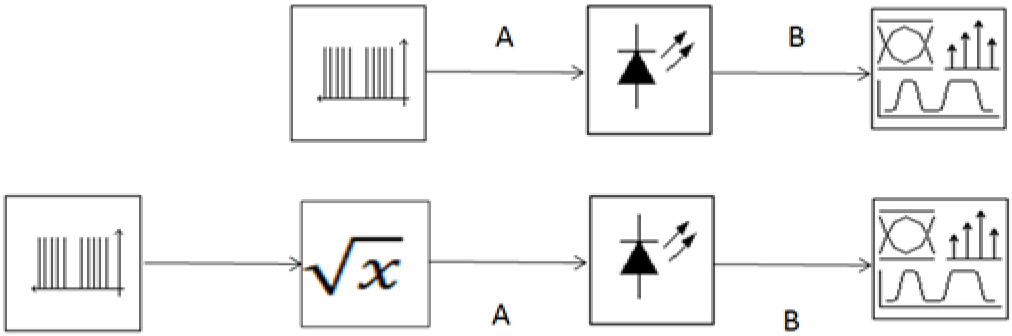


Figure 4.18 Setup to test a square root predistorter on the laser's behavior

As it was described in section 2.4.2, lasers introduce harmonic distortion when they are directly modulated by a RF carrier. This distortion is characterized by the appearance of 2nd and 3rd order harmonic distortions, in the case of this laser, which has a third order component (cubic) in its transfer function. The lower the magnitude of this 2nd and 3rd harmonics, the less they interfere (distort) the fundamental frequency (the frequency of the signal that in fact transports the information modulated at the laser).

Figure 4.19 shows us the input and output laser's signals, point A and B at Figure 4.18 respectively – point A represents the carrier generator output for the first setup and the output of the SQRT predistorter for the second one. The laser had a transfer function described by the following equation:

$$y = -0.0004x^3 + 0.0145x^2 - 0.0945x + 0.0005$$

and was modulated by a simple sin function with peak-to-peak power A_n and a DC voltage V_{DC}. Both A_n and V_{DC} where changed in order to reach a conclusion on the possible improvement of the laser's behavior in the presence of a linearizer.

$$y = A_n \times \sin(2\pi f t) + V_{DC}$$

For the case where no linearizer was used, the InterModulation Distortion (IMD) related to the 2nd harmonic, 2IMD, was 34.88 dB below the fundamental frequency laser's output power, while the 3IMD was 78.62dB below the same reference. When the Square Root predistorter was introduced the difference between the fundamental frequency and its harmonics increased: 2IMD was 37.66 dB and 2IMD was 84.07dB. This improvement tendency was verified for more than one A_n and V_{DC}, but always around this values.

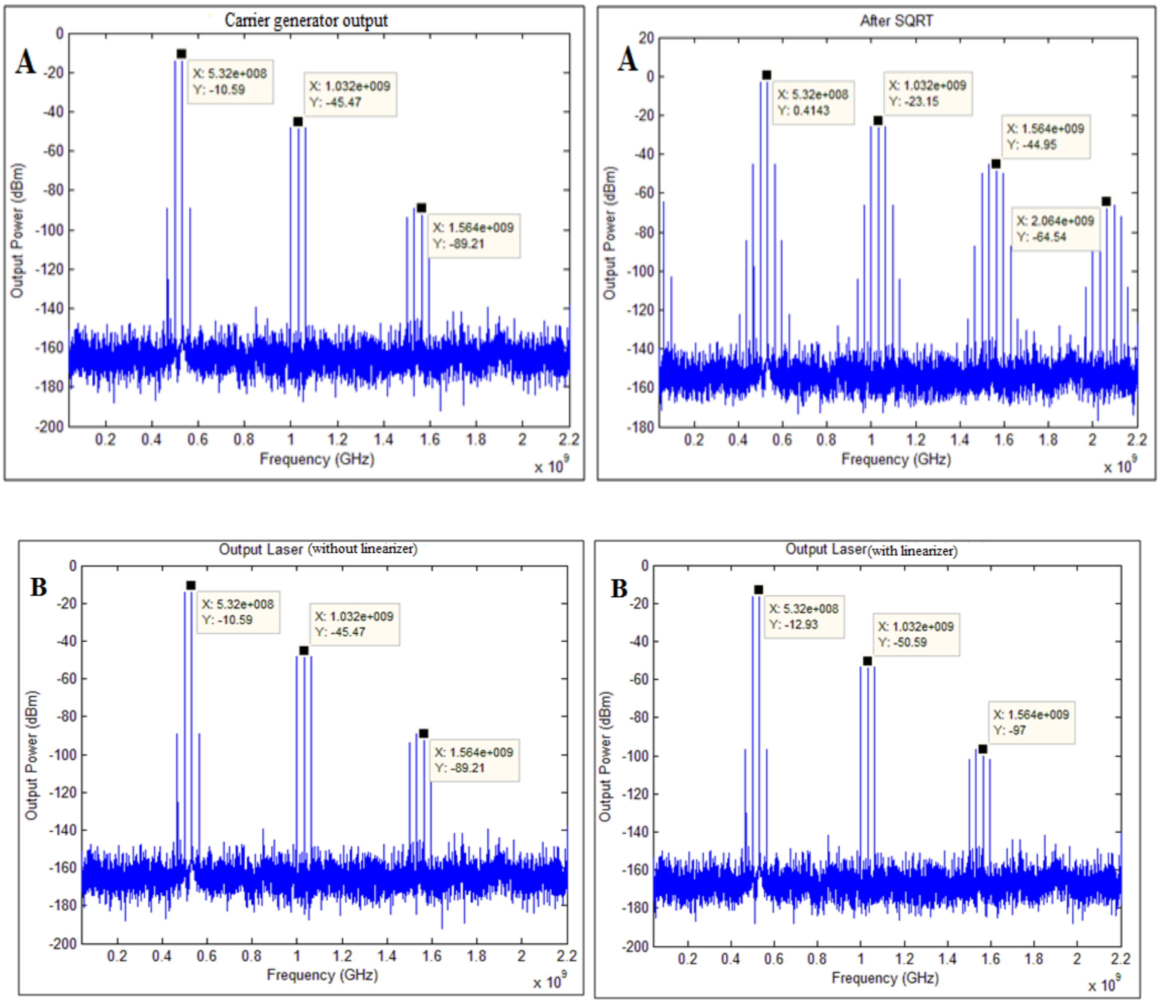


Figure 4.19 On the left: the input and output laser signals without linearizer. On the right: the input and output laser signals with the SQRT linearizer before the laser. $A_n = 100\text{mV}$ and $V_{DC} = 250$ mV

Despite the better results obtained for the tested values of A_n and V_{DC} (similar to the ones to be used by prototype lasers) by introducing the linearizer before the laser, their improvement, always between 1 and 4dB for 2IMD and between 1 and 7dB for 3IMD, is not worth of investing in a linearizer for each laser.

4.4. OADMs

It was decided that the final scenario was to be implemented with DWDM, a scenario similar to the one in Figure 4.3.3.1. As far as this scenario is concerned, the optical sources and the amplifier have already been discussed, however, the Optical Add/Drop Multiplexers are yet to be studied. This is the purpose of this subsection.

The transmitter's end of the proposed video distribution scenario is to be mounted within a single block, commonly termed Real Application Cluster (RAC). This fact makes it very important for the OADMs to keep their performance for a wide range of temperatures, that is to say, if they are intended to multiplex, into a fiber, a 1551.35nm wavelength, they should always exhibit their maximum gain for that wavelength.

To check for the possibility of a deviation of the normal performance of an OADM with temperature a very simple test was ran. Resorting to an Optical Network Analyzer (ONA), a series of wavelengths were sent to a 100GHz bandwidth OADM centered on 1551.35nm and then the OADM output was observed and registered for each wavelength. The OADM was placed in a thermal chamber in order to vary the temperature. The temperature variation range was from -40°C till 80°C.

Figure 4.20 exhibits the OADM's performance for the range of temperatures proposed. As it can be seen, Temperature does not affect the device's behavior. A final remark to state that the same type of OADMs was used at the DEMUX end of the circuit.

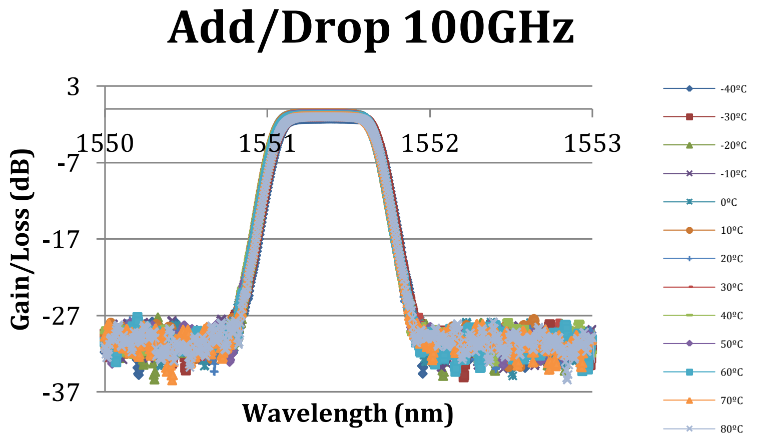


Figure 4.20 Add/Drop performance for a -40 to 80°C range of temperatures

4.5. *Conclusion*

This chapter started out with a brief discussion on which way were the 4 Satellite polarizations to be sent within a single fiber. CWDM and DWDM appeared as two solutions to be tested. Each one represented its own challenges: CWDM requires for a higher bandwidth, DWDM requires for more precise lasers. Experiments were ran to assess which was the best solution to amplify the 4 wavelengths at their different frequency spacing. To implement the CWDM solution four different approaches were tested, one resorts to a SOA and the remaining resort to EDFAs amplifying in different bands and arranged in different schemes.

The SOA was ruled out due to the nonlinear phenomena severely affecting the channels passing through it, leading to a major CNR degradation of TV channels being transported in the different wavelengths. The option of using two EDFAs was only suitable to meet the required minimum optical power at the output of the amplifiers, when a C-band and a L-band were used in parallel. This solution, despite its positive results, demanded for a lot of hardware, hence, it represented high costs of implementation. DWDM channels were then tested recurring to a single C-band EDFA. This solution granted the desired power at the amplifiers output for every wavelength, and, despite its laser's prices, appeared as fittest solution to be implemented in the final video distribution scenario.

Later in this chapter a brief analyses on whether or not to use a laser linearizer between the RF signal and the laser, to be modulated by this signal, was held. The benefits introduced by the linearizer, with an input signal similar, in terms of peak-to-peak power, to the one used to modulate the laser's output, were noticed, however, their improvement in the IMD of 2nd and 3rd order, were not that significant to justify using linearizers in our distribution scenario.

Finally, a temperature test was ran on the OADMs to be used in the add and drop of the wavelengths, at both the emitter's and receiver's end. The 100GHz OADM tested proved to keep its performance for a wide range of temperatures, proving to be suitable for the final prototype.

5. Final prototype

5.1. 64 users/128 users

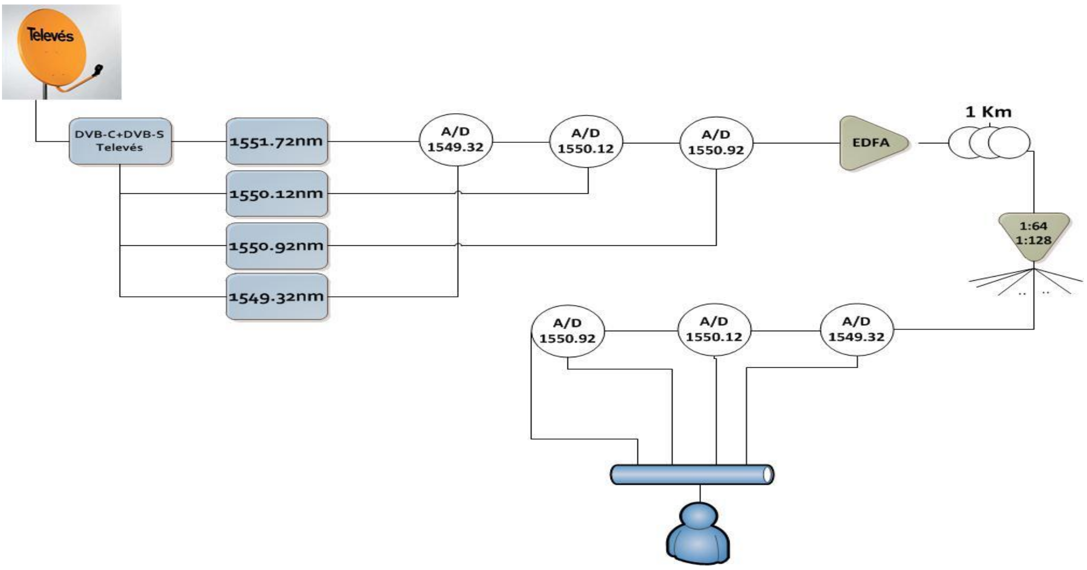


Figure 5.1 Final setup

After testing different solutions and approaches to design a prototype to distribute video to 64/128 users a final prototype came up, Figure 5.1. Tests were run on this setup to check if the minimum required CNR and CBER were guaranteed for both 64 and 128 users. It is important to notice that in this particular setup every laser is being modulated with the same Satellite polarization quadrant, plus DVB-C, channels, however, this solution extends to each laser being modulated with different polarization quadrant

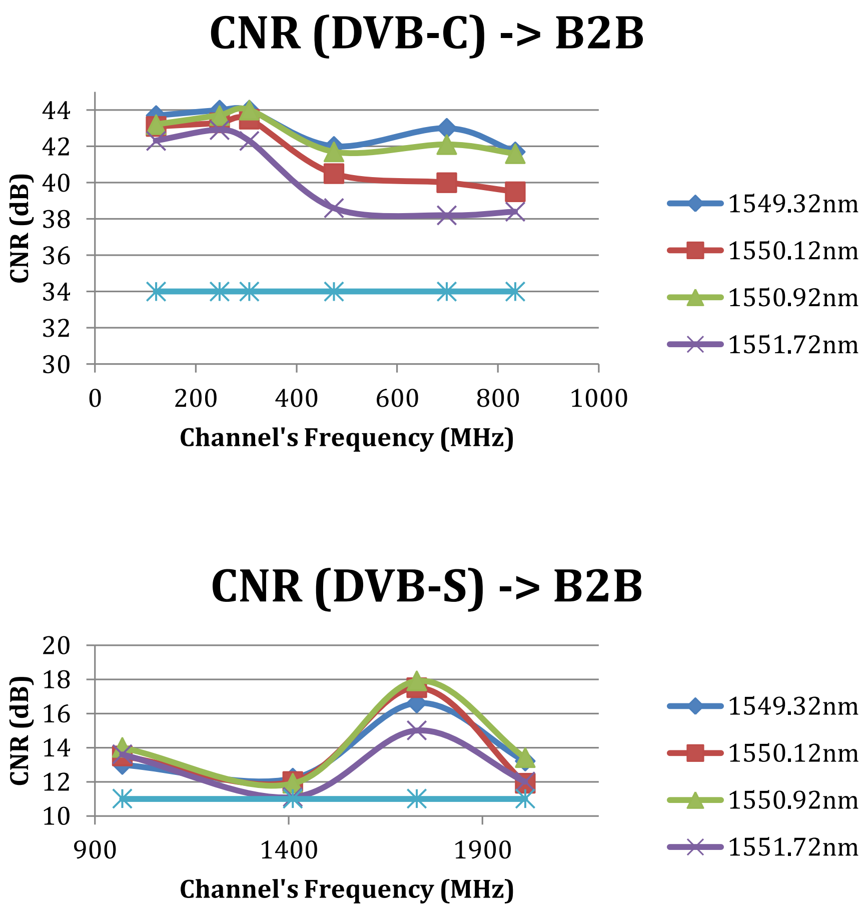
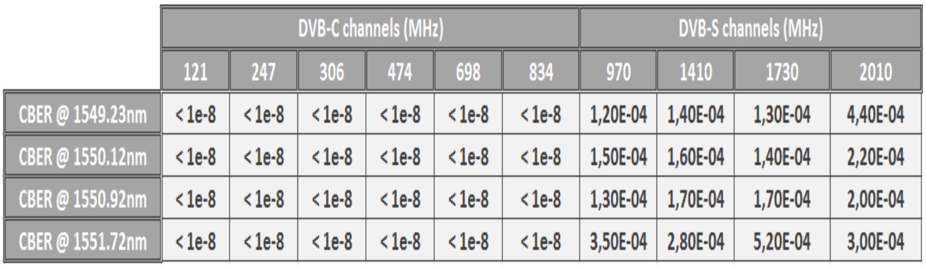


Figure 5.2 B2B CNR values at the receivers end for all 4 wavelengths: DVB-C channels on the upper graphic; DVB-S channels on the bottom graphic (the blue line defines the minimum CNR value for each group of channels)

TABLE I
CBER VALUES AT THE RECEIVER'S END, BACK-TO-BACK CONFIGURATION



	DVB-C channels (MHz)						DVB-S channels (MHz)			
	121	247	306	474	698	834	970	1410	1730	2010
CBER @ 1549.23nm	< 1e-8	< 1e-8	< 1e-8	< 1e-8	< 1e-8	< 1e-8	1,20E-04	1,40E-04	1,30E-04	4,40E-04
CBER @ 1550.12nm	< 1e-8	< 1e-8	< 1e-8	< 1e-8	< 1e-8	< 1e-8	1,50E-04	1,60E-04	1,40E-04	2,20E-04
CBER @ 1550.92nm	< 1e-8	< 1e-8	< 1e-8	< 1e-8	< 1e-8	< 1e-8	1,30E-04	1,70E-04	1,70E-04	2,00E-04
CBER @ 1551.72nm	< 1e-8	< 1e-8	< 1e-8	< 1e-8	< 1e-8	< 1e-8	3,50E-04	2,80E-04	5,20E-04	3,00E-04

Before jumping into the final tests a back-to-back (B2B) test, solely on the optical part of the system was performed (i. e, each laser was modulated and its output signal was directly connected to the PIN, and the PIN's output to a CNR/CBER measuring device provided by Televes S.A, the H45) were done. This way, the Code Bit Error Rate (CBER) and Carrier-to-Noise Ratio (CNR) degradations could be assessed. Figure 5.2 shows the CNR values for the various wavelengths and Table I the CBER values for the B2B test.

A set of channels of both DVB-C and DVB-S (representative of the remaining) were tested at each wavelength. The four wavelengths were sent with very similar optical powers around 0dBm: 1550.12 and 1550.92nm wavelengths both had 0dBm of optical output peak power; 1549.32nm wavelength had 1dBm of optical output peak power; 1551.72nm wavelength had -0.8dBm of optical output peak power. The choice for different output power values is explained by the intrinsic differences between lasers, which make them output better results for different optical powers.

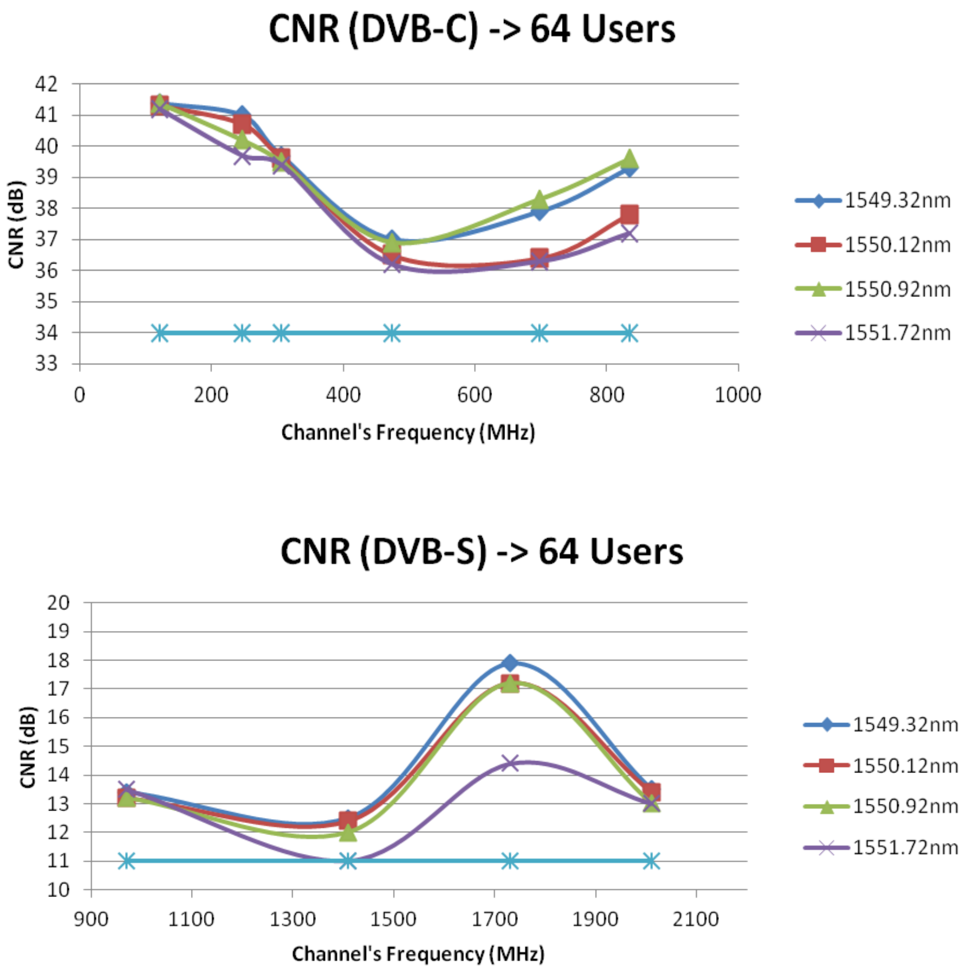


Figure 5.3 CNR values at the receivers end for all 4 wavelengths, 1:64 splitting: DVB-C channels on the upper graphic; DVB-S channels on the bottom graphic (the blue line defines the minimum CNR value for each group of channels)

Still regarding the four lasers, 1550.92 and 1551.72nm lasers were operating at 41°C (again different intrinsic characteristics of the laser made them operate at different temperatures to output the same wavelength), 1549.32nm at 18.3°C and 1550.12nm at 29.5°C.

Replacing the user's receiver by the H45 (at the final setup Figure 5.1), CNR and CBER values were measured after the various wavelengths passed through 1 km of fiber, the splitter and the demultiplexing OADMs. Once again, the minimum CBER and CNR values to guarantee video reception with signal quality are: values of 10^{-4} or lesser magnitude and 34dB respectively, for DVB-C channels; values of 10^{-4} or lesser magnitude and 11dB respectively, for DVB-S channels. [DVB, 1997]

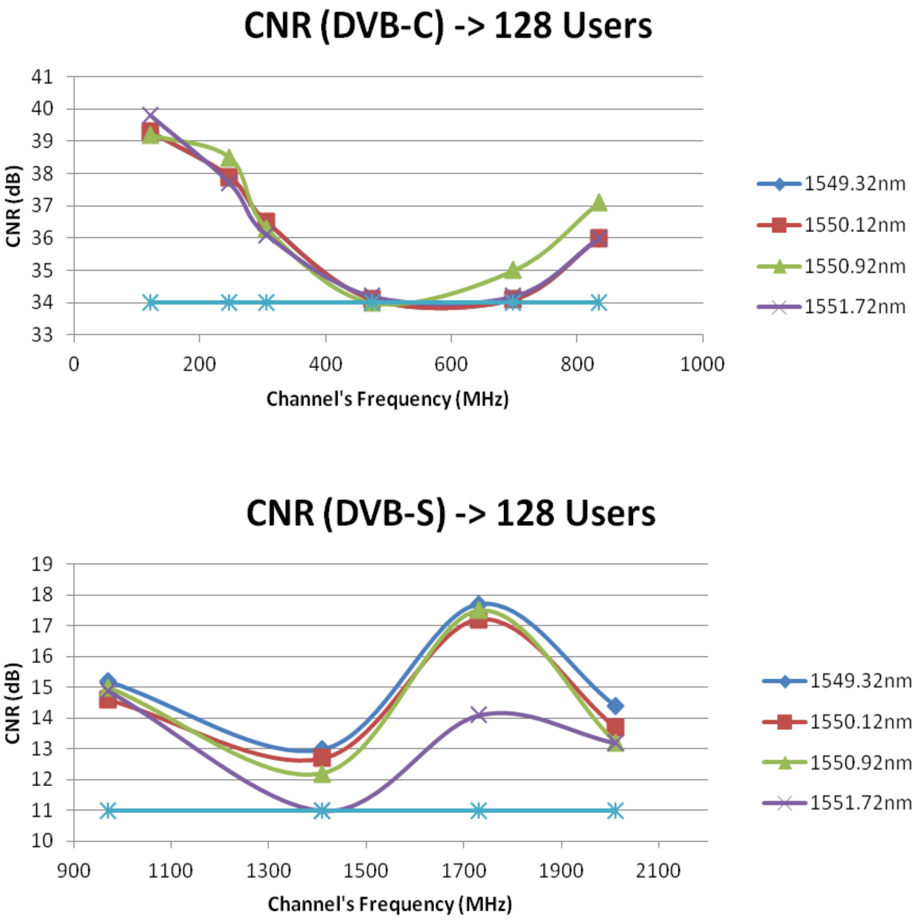
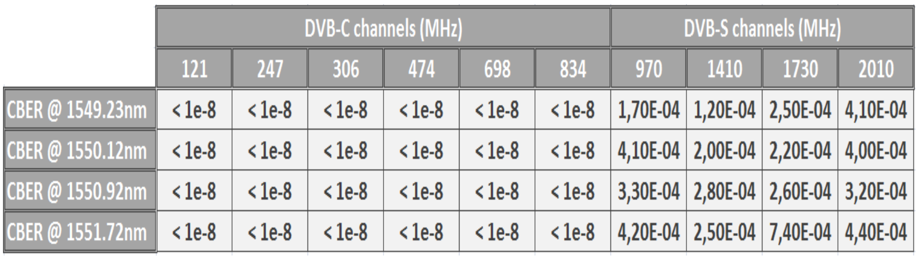


Figure 5.4 CNR values at the receivers end for all 4 wavelengths, 1:128 splitting: DVB-C channels on the upper graphic; DVB-S channels on the bottom graphic (the blue line defines the minimum CNR value for each group of channels)

CNR results at the user end of some DVB-C and DVB-S channels (the same ones measured on the B2B test) are shown in Figure 5.3 for 64 users and in Figure 5.4 for 128 users. It can be seen that every channel arrives at the final user with the required CNR value. The CNR variation between channels is attributed to the RF characteristics of the emitting board, this variation was also duly noted in the B2B test.

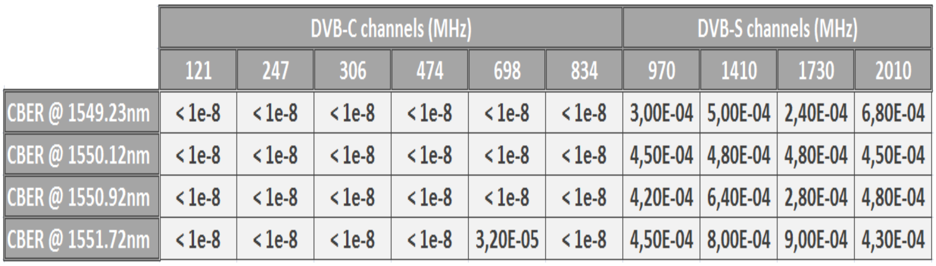
Tables II and III show the CBER results for both 64 and 128 users, respectively. Again, all the channels arriving at the end user's equipment kept an acceptable value, good enough to allow for a clear reception of the TV channels.

TABLE II
CBER VALUES AT THE RECEIVER'S END FOR ALL 4 WAVELENGTHS, 1:64 SPLITTING



	DVB-C channels (MHz)						DVB-S channels (MHz)			
	121	247	306	474	698	834	970	1410	1730	2010
CBER @ 1549.23nm	< 1e-8	< 1e-8	< 1e-8	< 1e-8	< 1e-8	< 1e-8	1,70E-04	1,20E-04	2,50E-04	4,10E-04
CBER @ 1550.12nm	< 1e-8	< 1e-8	< 1e-8	< 1e-8	< 1e-8	< 1e-8	4,10E-04	2,00E-04	2,20E-04	4,00E-04
CBER @ 1550.92nm	< 1e-8	< 1e-8	< 1e-8	< 1e-8	< 1e-8	< 1e-8	3,30E-04	2,80E-04	2,60E-04	3,20E-04
CBER @ 1551.72nm	< 1e-8	< 1e-8	< 1e-8	< 1e-8	< 1e-8	< 1e-8	4,20E-04	2,50E-04	7,40E-04	4,40E-04

TABLE III
CBER VALUES AT THE RECEIVER'S END FOR ALL 4 WAVELENGTHS, 1:128 SPLITTING



	DVB-C channels (MHz)						DVB-S channels (MHz)			
	121	247	306	474	698	834	970	1410	1730	2010
CBER @ 1549.23nm	< 1e-8	< 1e-8	< 1e-8	< 1e-8	< 1e-8	< 1e-8	3,00E-04	5,00E-04	2,40E-04	6,80E-04
CBER @ 1550.12nm	< 1e-8	< 1e-8	< 1e-8	< 1e-8	< 1e-8	< 1e-8	4,50E-04	4,80E-04	4,80E-04	4,50E-04
CBER @ 1550.92nm	< 1e-8	< 1e-8	< 1e-8	< 1e-8	< 1e-8	< 1e-8	4,20E-04	6,40E-04	2,80E-04	4,80E-04
CBER @ 1551.72nm	< 1e-8	< 1e-8	< 1e-8	< 1e-8	3,20E-05	< 1e-8	4,50E-04	8,00E-04	9,00E-04	4,30E-04

5.2. *Temperature tests*

Since the transmitting end of the system is to be mounted in a RAC and the lasers are separated by mere 0.8nm, it is important to perform some temperature tests to check the system's behavior.

The first one was done with a single laser board (composed by the laser itself and its RF and TEC systems). The chosen laser was the one operating at 1550.92nm, its TEC was defined to keep the laser at 41°C and the room temperature was 24°C. The test was done resorting to an Infrared Thermal Camera. During 5hours a value was registered each half an hour, Figure 5.5. Results showed a small variation around the 41°C. This tested assessed the proper functioning of the TEC controller system. The laser's temperature was kept practically constant.

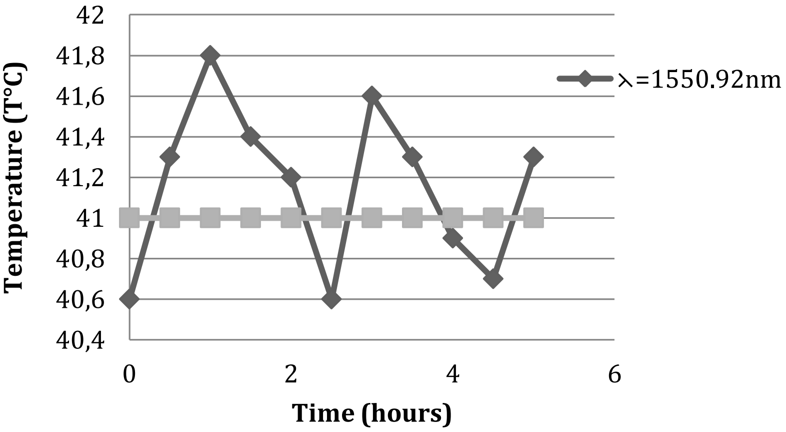


Figure 5.5 Laser board temperature vs. Time

A second test, to assess any unusual temperature variation of the RAC itself was also done. All the lasers, the OADMs, the EDFA amplifier and the power sources were mounted together and its temperature was registered for 5 hours as well (the room temperature was the same as in the previous test). The results confirmed that nothing unusual occurred: the temperature was kept around 36°C, Figure 5.6.

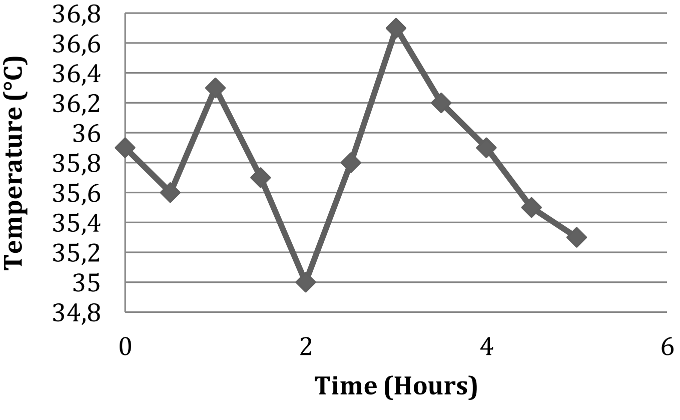


Figure 5.6 RAC temperature vs. Time

Finally, and probably the most crucial test, the room temperature was changed from 18 to 30°C and the system's performance evaluated. Even though it was probably important to check the system's behavior for higher temperatures, in our lab it was not possible to perform such tests.

Instead of checking for the RAC's temperature variation with the room's temperature variation, a different experiment was done. The EDFA's output (which is the RAC's output) was connected to the Optical Spectrum Analyzer (OSA) and the wavelengths in which the lasers were being emitted were checked. This way it is possible to assess if the TEC controllers are capable of maintaining the wavelengths at their expected values. The four original wavelengths were: 1549.32nm, 1550.12nm, 1550.92nm and 1551.72nm.

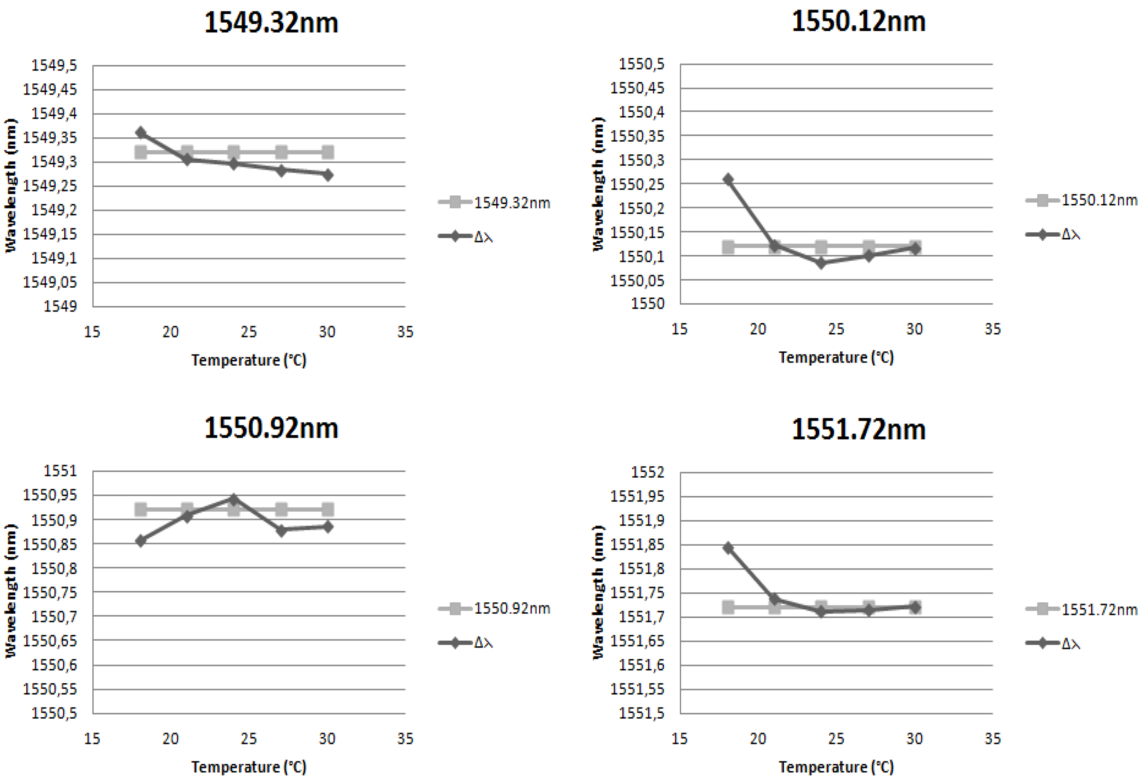


Figure 5.7 Wavelength variation vs. Room temperature variation for all wavelengths

Figure 5.7 shows us the satisfactory results of this experiment. The biggest wavelength deviation was registered for a room temperature of 18°C and was of 0,14nm for the 1550.12nm wavelength. For temperatures equal or above 21°C the wavelengths never deviated more than 0,045nm from their reference. It is concluded that the room temperature change will not have a severe impact on the system’s performance.

6. Conclusions and Future Work

6.1. Conclusions

This work has been presented in a set of 6 chapters. In the first one its context and motivation, structure and objectives along with its main contributions were presented.

In the second chapter the main concerns that should be accounted when designing a video distribution scenario, with the characteristics of the one presented in this work, were described. Optical fiber's impairments were described, namely, the ones related to linear effects which cause degradation in the transmitted signal – attenuation and signal dispersion. Nonlinear effects were left out from the discussion since they do not occur in a system operating with such low optical powers and fiber lengths. Both attenuation and dispersion are directly connected with the fiber itself and the light wave as well, hence, they cannot be eliminated and so have to be accounted when calculating the optical link budget.

The need to serve up to 128 users demanded for amplification of the signals being sent, for this purpose, and aware that 4 different wavelengths needed to be sent, a careful study and characterization of both EDFA and SOA amplifiers was done. This study led to the understanding that the SOA amplifier could introduce signal degradation due to its susceptibility to introduce nonlinear effects - this was latter confirmed in the fourth chapter. Finally, still on the second chapter, optical source's impairments were described in order to alert for the importance of properly tuning the emitting lasers. It was also concluded that for RoF systems direct modulation is used, in optical systems with bitrates below 10Gb/s, this is the case of the proposed video distribution scenario.

The third chapter presented an overall description of three different solutions to distribute digital television available in the market. The three had different flaws: the ones sending DVB-S 4 polarizations require for higher bandwidth lasers to transmit the four satellite polarization quadrants (since they transmit them frequency stacked); one of the solution is only capable of serving up to 32 users without the need for RF pre amplifiers; one of the solutions only distributes CATV channels.

The fourth chapter, and core chapter of this work, contains all the experimental work which led to the final setup presented at the fifth chapter. Two solutions, CWDM and DWDM, to transmit the four satellite polarizations within a single fiber, were presented and experiments were run to check which one was the fittest. The experiments consisted on sending, and amplifying, four different SAT polarization modulated in four wavelengths differently spaced, 20nm for CWDM and around 0.8nm for DWDM. The amplification was done with different types and configurations of amplifiers. The SOA proved itself to introduce great distortion in the DVB-C channels, therefore, useless for the proposed solution. A single C-band EDFA, amplifying 4 wavelengths in the DWDM configuration, was proven to be the fittest solution to the proposed distribution scenario. DWDM, however, requires for a tight control of the wavelength emitted by the laser. To control its temperature, TEC controllers were used in each laser. The laser's IMD could be an issue, so a small simulation was done in order to assess the benefit of introducing a laser predistorter between the RF signal and a laser. It was concluded that the benefits were not worthy of the investment.

Finally, chapter five presents the final video distribution scenario and the tests ran on it. It was proven that the proposed distribution scenario is capable of providing up to 128 users with proper quality DVB-C and DVB-S (in its four polarization quadrants) channels. A couple of tests to assess the correct functioning of the TEC controller were done. It was proven that at a room temperature of 24°C a single laser board and the RAC, with the entire transmitting system assembled (including lasers, EDFA, OADMs, power supplies), kept their temperature almost constant. A last experiment where the room temperature was changed between 18 and 30°C and the outputting wavelengths were monitored proved that the signals were outputted at a almost constant wavelength for temperatures between 21 and 30°C.

6.2. Future work

This work has presented a new solution to transmit all the 4 DVB-S polarizations' plus DVB-C channels within the same fiber. This broadcast overlay was done in the 1550nm wavelength in order to maintain wide open the possibility to be integrated with both EPON and GPON. These distribution standards have allocated the window involving the 1550nm wavelength to overlay video channels so the services over IP can benefit from a greater bandwidth [Ofcom2, 2010], [Kazovsky, 2011]. So this is one of the challenges for the future: integrate this solution with data services over fiber. Another challenge, and with the rising of next-generation video distribution standards such as 10G-EPON (which will downstream at wavelengths in the interval 1575-1580nm [Ofcom2, 2010], [Kazovsky, 2011]), is to test how the distribution scenario proposed with these next generation standards will work: will they be able to co-exist?

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