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"Optical CDMA transmission system simulations"

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Optical CDMA transmission system simulations

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Resumen

En primer lugar se estudiarán el funcionamiento de los códigos ópticos en escenarios de acceso múltiple. Se realizarán simulaciones con diferentes configuraciones y elementos de red usando el software de VPI. Se usarán arquitecturas PON de nueva generación con unidades de red capaces de transmitir información sin fuentes de luz propias. Finalmente, el objetivo principal del proyecto es aplicar técnicas que reduzcan la penalización por retrodispersión de Rayleigh en transmisiones bidireccionales en las que se usen códigos ópticos.

Palabras clave

OCDMA, Retrodispersión de Rayleigh, RSOA, SPM, transmisiones bidireccionales, ensanchamiento de espectro, difuminado de la bias

Abstract

First of all, the behaviour of optical codes in multiple access scenarios will be studied. Different simulations will be performed modifying various system parameters and configurations of the network elements using software from VPI. New generation Passive Optical Network architectures will be used, being capable of transmitting information without any light source. Finally, the main goal of this study is to apply techniques for Rayleigh scattering penalties reducing in bidirectional transmissions where optical codes are used.

Keywords

OCDMA, Rayleigh scattering, RSOA, SPM, Bidirectional transmissions, Spectral broadening, Bias dithering

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Glossary

ACR	Attenuation to Crosstalk Ratio
ASE	Amplified Spontaneous Emission
AWG	Array Waveguide Gratings
BER	Bit Error Rate
CAPEX	CAPital EXpenses
CDMA	Code Division Multiple Access
CMG	Chirped Moiré Gratings
CO	Central Office
DCF	Dispersion Compensating Fiber
DSL	Digital Subscriber Line
FBG	Fiber Bragg Gratings
FTTx	Fiber To The x
FWHM	Full Width at Half Maximum
HBR	Holographic Bragg Reflector
HDTV	High Definition TV
MAN	Metropolitan Area Network
OCDMA	Optical Code Division Multiple Access
OLT	Optical Line Termination
ONU	Optical Network Unit
OOK	On-Off Keying
OPEX	OPerational EXpenses
OSNR	Optical Signal to Noise Ratio
P2P	Peer-two-Peer
RBS	Rayleigh Back-Scattering

RSOA	Reflective Semiconductor Optical Amplifier
SDTV	Standard Definition TV
SMF	Single Mode Fiber
SOA	Semiconductor Optical Amplifier
SPM	Self Phase Modulation
TDM	Time Division Multiplexing
TFF	Thin-Film Filters
TBP	Time-Bandwidth Product
VoD	Video on Demand
WAN	Wide Area Network
PON	Passive Optical Network
WDM	Wave Division Multiplexing
WHTS	Wavelength Hoping Time Spreading

Chapter 1

Introduction

Consumer bandwidth demands are growing at an enormously high rate, and are projected to grow for years to come. This growth rate applies not only to the entire Internet, but to a large range of individual institutions.

59 % to 64 % of the downstream traffic is web media-related which is mainly because of photo and video communication and real-time streaming. Peer- to-peer (P2P) traffic covers over one fifth of downstream and over 60 % of upstream traffic. Services alternative to P2P like file hosting and remote storage are gaining more interest [1].

Also the growing interest in voice, video and data delivery on the same infrastructure (triple-play) has changed the common way of network usage, a necessity of running many applications on several devices connected simultaneously to a single access point has arisen [2]. Furthermore, when mature high-definition TV (HDTV) products become available the bandwidth demand will get even higher. Changing from the standard definition TV (SDTV) to HDTV, 1-3 Mbit/s to 8 Mbit/s per channel respectively, even not including services like video-on-demand (VoD), P2P and online gaming will exceed the capabilities of currently most popular digital subscriber lines (DSLs) drastically. Higher quality HDTV channels, where the information is less compressed, require a much higher bandwidth than the 8 Mbit/s.

Although the capacity offered by the asymmetric DSL (ADSL) technology has improved significantly from 512 Kbit/s (2001) up to 20 Mbit/s (2006), the most sophisticated protocols ADSL2+ and very high speed DSL 2 (VDSL2) are not able to satisfy the next-generation users' bandwidth hunger. This forces the efforts towards developing new generation networks that can offer enough bandwidth to satisfy the increasing needs of the users. Note that VDSL2 already needs the DSLAM to be closer to the user since the capacity decreases rapidly versus increasing distance.

This bandwidth-hungry scenario created by both content providers and consumers stimulates the development of novel components and network architectures which should not only be capable of transmitting data at high bit-rates but should also be cost-efficient. Latter is a necessity to make them particularly attractive to deploy for network operators and service providers. The physical layer of such network has to be capable of providing bandwidth on-demand, and, since the destination of the traffic load may change in time, the provision of the bandwidth should be made reconfigurable.

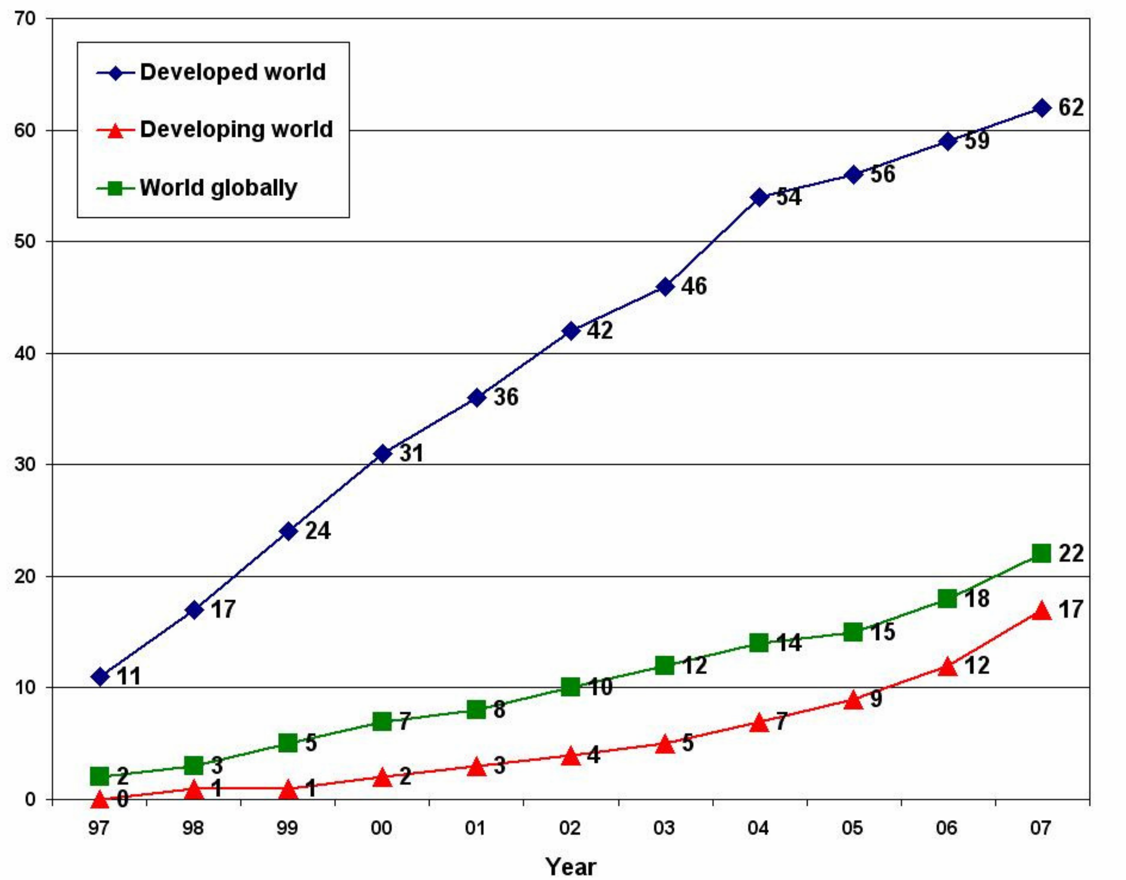

Fig. 1-1: Internet users per 100 inhabitants between 1997 and 2007 [3]

Also the international scenario is changing rapidly. The global economy doesn't stop growing pushed by the developing countries. These countries are experiencing a similar growth of internet users as the developed countries at the end of the last century.

Passive Optical Networks architectures

The great majority of current copper-based access installations can not guarantee the increasing bandwidth demand of future users and need to be changed into advanced fiber architectures. Installing optical fiber in the access area is a great challenge in terms of capital expenses (CAPEX) and operational expenses (OPEX). There are many risks that have to be evaluated, it is important to choose the right technologies to guaranty the success of the new network.

The decisions on the architecture should be made taking a low cost and low complexity point-of-view otherwise a large-scale commercial deployment may be less interesting. A single star architecture or point-to-point (PTP) provides a direct connection between the central office (CO) and the remote node (RN). Each connection has an optical line termination at the CO and at the RN. With this kind of architecture, the bandwidth provided to each user can easily be upgraded but its deployment costs are higher than other solutions like a point-to-multi point (PTMP) architecture. The cost-efficiency of a PTMP architecture becomes more profound when the length and/or the amount of RN's increases.

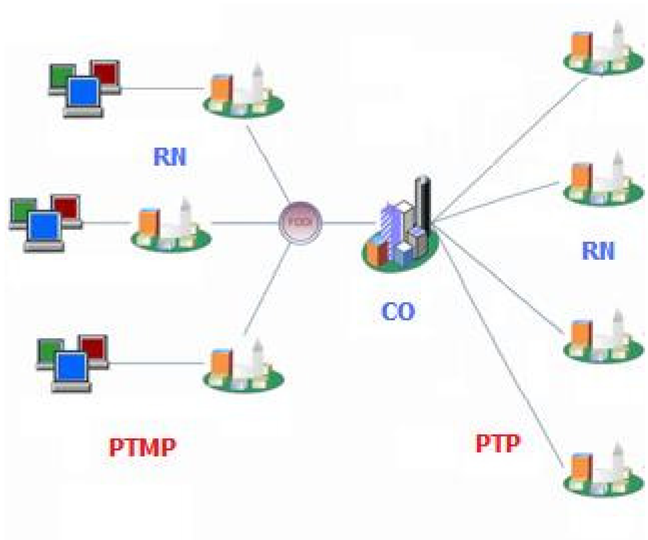

Fig. 1-2: PTP versus PTMP fiber optic access architectures

For PTMP there is additional intelligence in the active node, such as optical amplification or wavelength routing abilities, where the signals are split and distributed to the RNs. This increases the complexity thus the system costs because the active node requires powering and possibly housing of the components. PON has a passive optical distribution node where the signals are broadcasted to the RNs via power or wavelength splitting. Consequently, PON is a more robust and cost-effective option than the active double star because no active elements are in the field and all remaining active components as well as the intelligence are located at the CO.

Multiple access techniques

A multiple access mechanism has to be employed on the PON because the (feeder) fiber from the central office to the aggregation node is shared and, therefore, if the access is not controlled collisions occur at that node between information transmitted by different users in the upstream direction.

The three more important techniques to provide access to the shared fiber link are based on assigning a time slot to each user (TDMA), a wavelength (WDMA) or an optical code (OCDMA). Currently, TDMA is widely implemented in broadband access networks and employing WDMA, either to multiplex TDMA streams or to provide multiple access, is considered as a powerful and future-proof upgrade. OCDMA has many attractive features that make it a promising technology for the (future) access networks.

On TDMA system a central clock is present in the system to which all have to synchronize. When implementing TDMA on PON, synchronization difficulties arise and ranging techniques have to be employed in order to properly schedule the transmitted data. Additionally, the system bandwidth increases significantly if a high throughput for each channel is required. TDMA may also be applied on top of a WDM scheme to provide a very high transmission capacity.

A WDMA system divides the frequency spectrum into discrete slots whereby each slot is assigned to a user. The resolution of such frequency slots may range from coarse to dense depending on the amount of simultaneously active nodes allowed on the network. Commonly, in order to accommodate a large amount of active wavelengths, high quality optical sources are installed because of narrow wavelength spacing.

In an OCDMA system, a unique and (pseudo-)orthogonal optical code (OC) signs each data bit transmitted by a user which allows the optical carrier to be asynchronously shared with other users on the network. The OC's are designed in such a way that, on the one hand, if the encoded data matches with the proper key at the receiver the auto-correlation is maximal and, on the other hand, if there is no match the cross-correlation approaches zero.

1.1 Goals and motivation

In this project, the performance of PON-OCDMA architecture will be studied. This study will focus on a specific design of these networks where the communication between the Central Office (CO) and the user is made over a single fiber. On this scheme, the bidirectional transmissions are taken place at two different wavelengths for the upstream and the downstream data using colorless and sourceless Optical Network Units (ONU).

The technique used for this architecture is an adaptation of the Code Division Multiple Access (CDMA) widely used on wireless communications. This Optical CDMA (OCDMA) is based on the transmission of optical codes formed by pulses. In this study we will deepen on the particular case of two-dimensional codes, constructed on time and wavelength dimensions.

The light source is located at the CO, for the downstream and upstream. The ONU has a Reflective Semiconductor Optical Amplifier (RSOA) that has the role of modulating this input signal from the CO by reflective modulations, so the information will be sent back to the CO with the upstream data.

One of the problems of this kind of bidirectional transmissions are the optical impairments produced by the fiber. One of these intrinsic properties of the material forming the fiber produces the Rayleigh Backscattering (RBS) effect. This effect produces interferences and in-band crosstalk, causing distortion on signals propagating in opposite directions. It eventually causes penalties on the transmission. This is one of the most important issues to be solved on this kind of schemes.

These optical impairments produced by RBS are studied on this thesis. Techniques to reduce the transmission penalties produced by this effect are proposed and its performance evaluated.

Chapter 2

State of the Art

In this chapter, the state of the art of the topics to be studied will be presented. OCDMA technology will be described and explained. It is also explained in this chapter how RBS is produced and what impairments can it induce to optical signals traveling through a fiber. Finally, there will be a brief description of how SPM can be induced and how an optical pulse is distorted when it is self-phase modulated.

2.1 Optical Code Division Multiple Access

Recent improvements on technologies like Wave Division Multiplexing (WDM) or Time Division Multiplexing (TDM) have boosted the development of optical networks for Metropolitan Area Networks (MAN) and Wide Area Network (WAN) environments. However these technologies have known limitations on protocols and hardware that add unnecessary complexity and costs. The limits on the number of users or access latencies of these technologies can be resolved using OCDMA.

The optical networks based on OCDMA are a clear example of the extrapolation to the optical domain of a technology widely used on actual wireless networks. OCDMA is capable of providing a gigabit- or even multigigabit-per-second for each user both in the up- and downlinks, and OCDMA over WDM PON could be one of the most promising system architectures that can break through the last/first mile bottleneck. It effectively provides an extra dimension on top of each wavelength, meaning that each wavelength is shared by many users and thereby increasing the total available capacity.

There are clear advantages that make OCDMA a suitable access technology for passive optical networks with large number of users that randomly use the connection. Some of these advantages are:

- There is no need of high quality lasers
- There is no centralized network control because of the simplicity of the protocol
- Self-routing by code sequence and characterized by a high security in the network
- Effective utilization of bandwidth and high tolerance to noise
- Low-cost devices
- Random and simultaneous access protocol. No need for the strict timing synchronization

Depending on how the codes are represented in the optical domain, some advantages may not apply. The multiplexing procedure by which each user will encode its data is distinguished by a specific optical code rather than a wavelength or time-slot. An encoding operation optically transforms each data bit before transmission. At the receiver, the reverse decoding operation is required to recover the original data. OCDMA uses this procedure to establish the access among multiple network users because the codes are (pseudo-)orthogonal.

OCDMA offers flexibility with coding, large cardinality, and the code conversion. OCDMA coding creates a soft limit in terms of a number of users, allowing the network to operate at different levels of BER performance. It has been shown that this is an important advantage of OCDMA systems; the network can easily be adapted to various networking requirements or load conditions, which might not be feasible in more rigid WDM based networks. Dynamic networks can therefore benefit from the OCDMA routing. A large offered cardinality is also an advantage of the OCDMA: powerful 2-D coding can be used to create a large pool of codes while using few wavelengths. This increased granularity eliminates many routing impairments.

In this study we will consider the use of two dimensional codes. They are constituted by a sequence of short pulses, arranged in time at different wavelengths. On-Off Keying modulation (OOK) is performed, that is, if a logical "1" or "0" arrives the code will be transmitted or not. At the receiver side, with a mechanism of delay lines, the opposite process will be performed, reconstructing the pulses in time. It is clear that a bit slot is divided into smaller slots which are referred to as the chips of an optical code.

The different pulses of the code will add up in intensity at the receiver side. If a correct code arrives, the receiver will have a high intensity input while a low intensity input will be received for incorrect codes. This forces the need of thresholds to define where is the limit between correct and incorrect codes. This kind of encoding is cost efficient, because all operations can be done in the optical domain, using multiple lasers and delay lines, reducing access time and increasing bandwidth limits.

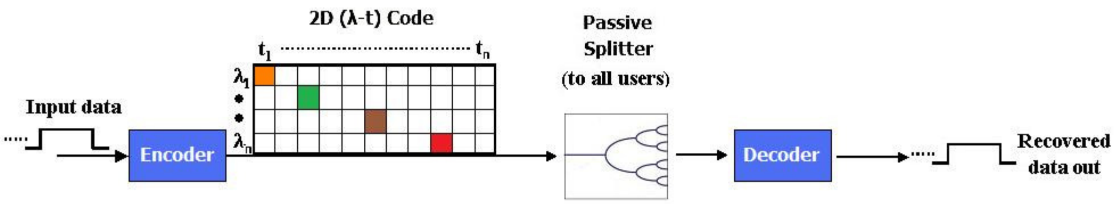

Fig. 2-1: OCDMA-PON architecture from the encoding point of view

OCDMA systems may be classified according to their coding principle (incoherent or coherent) and their coding domain (time, wavelength, or time and wavelength). The properties of these codes determine the characteristics and capabilities of the network. The more users the networks has, more complex the codes will be and more resources will use, otherwise the performance of the network will deteriorate. For several reasons, an active user may cause a crosstalk to all the other active users. This is referred to as Multiple User Interference (MUI). The MUI is not the focus of this study. With one set of codes access to the network can be given to 40 users, having the bit error rate below one erroneous bit per million [6].

2.2 Rayleigh Backscattering

The Rayleigh scattering is the effect responsible of reflections and refractions of light when passing through the glass inside the fiber. The intrinsic properties of the material with which the fiber is made and the non-ideal manufacturing process making the glass imperfect. The fiber is characterized by microscopic variations in the material density, compositional fluctuations, and from structural inhomogeneities or defects [3].

The fiber manufacturing is a complex process and many different chemicals are involved that need to be mixed as uniformly as possible. This structure contains regions in which the molecular density is either higher or lower than the average density of the glass. These effects change the refractive-index of the glass along the fiber, causing deviations on the lights path, losses and even interferences given that the light can be reflected and travel into the opposite direction.

The refractive index is a way of measuring the speed of light in a material. Light travels fastest in a vacuum, such as in outer space. The actual speed of light in a vacuum is about 300,000 kilometers (186 thousand miles) per second. Index of refraction is calculated by dividing the speed of light in a vacuum by the speed of light in some other medium. The index of refraction of a vacuum is therefore 1, by definition. The typical value for the cladding of an optical fiber is 1.46. The core value is typically 1.48. The larger the index of refraction, the slower light travels in that medium. Therefore, nonlinear refractive indexes cause the light to travel at different speeds, clearly degrading the signal.

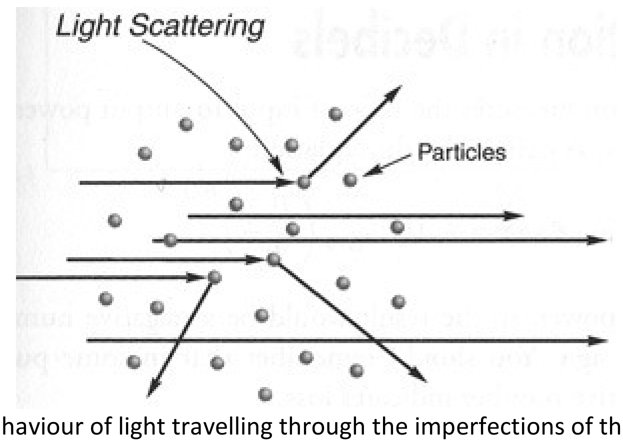

Fig. 2-2: Behaviour of light travelling through the imperfections of the fiber glass

This effect degrades the quality of the signals travelling through the glass produces an appreciable attenuation of the light. These losses are called Rayleigh scattering loses and have to be considered when designing optical networks where information is transmitted in both directions using a single fiber.

Structural inhomogeneities and defects created can also cause scattering of light out of the fiber. These defects may be in the form of trapped gas bubbles, unreacted starting materials, and crystallized regions inside the glass. In general, the preform manufacturing methods have evolved and these extrinsic effects are minimized to the point where they are negligible compared to the Rayleigh scattering losses.

Scattering directly depends on the size of the particles relative to the wavelength of light. The closer the wavelength is to the particle size, the more scattering. This is why the amount of scattering increases rapidly as the wavelength decreases. This produces that the system performance will directly depend on the laser line-width [8].

In this study we will deepen into the particular case of Rayleigh backscattering losses. The light passing through the imperfections of the fiber is reflected in many directions, in the case of backward reflections we will have an optical signal at the same wavelength of the original towards the emitter.

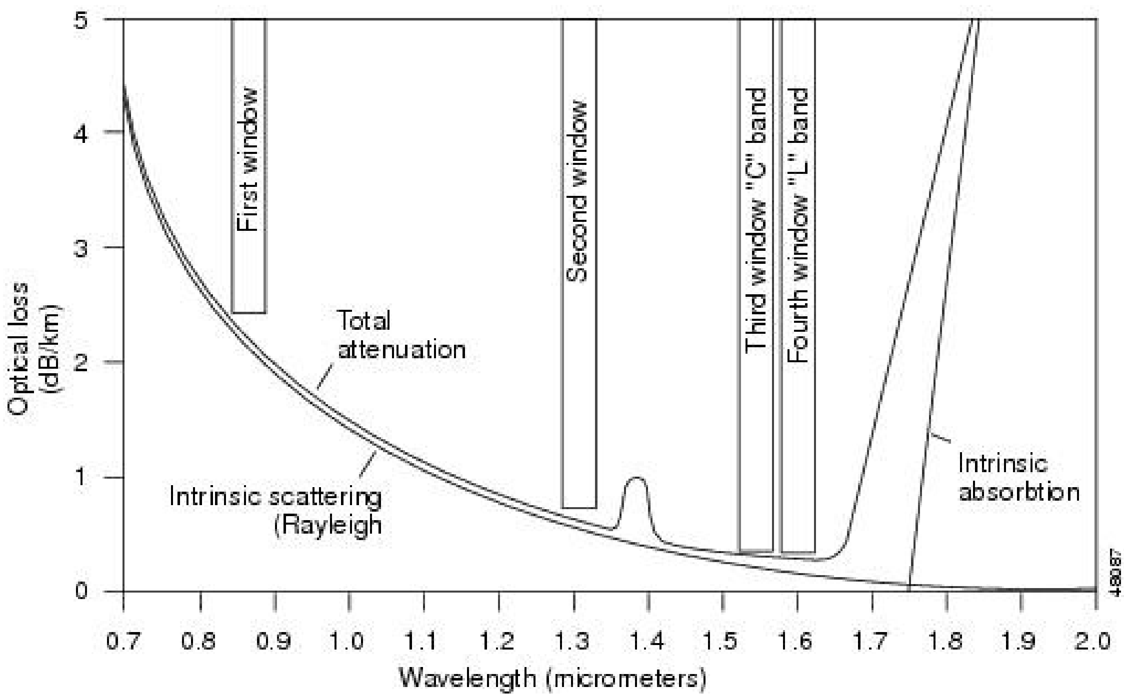

Fig. 2-3: Rayleigh scattering losses versus wavelength. Source: CISCO

This is an important issue when we talk about bidirectional transmissions [5]. If we are sending information in both directions at the same wavelength, the Rayleigh backscattering effect will not only insert losses but also get in-band interferences of the signal coming from the opposite direction. The degradation of the signal depends on the power ratio between the co-propagating signals, so called Attenuation to Crosstalk Ratio (ACR). In systems with narrow linewidth optical sources, crosstalk penalties due to interferometric conversion of laser phase noise to intensity noise of the backscattered light can far exceed the crosstalk penalties observed in bidirectional systems using incoherent sources. Thus, Rayleigh backscattering is a limiting factor for bidirectional transmission [9].

Rayleigh backscattering noise power grows with the fiber length to saturation at a specific value of the launched signal power multiplied by the Rayleigh backscattering coefficient. This means that the signal will also be deteriorated for long fibers because the receiving signal power of the counter-propagating signals will go down due to fiber attenuation, while Rayleigh backscattering noise power will remain constant [7].

2.3 Self Phase Modulation

Self Phase Modulation (SPM) is an effect caused by the intensity dependence of the refractive index in nonlinear optical devices. This effect causes spectral broadening of optical pulses. SPM can be observed on solids and glasses by using high intensity and short pulses [11].

The physic fundamentals of self phase modulation on optical fibers are explained by the Kerr effect [4], also called the quadratic electro-optic effect discovered in 1875 by John Kerr, a Scottish physicist [12]. This is the special case in which a slowly varying external electric field is applied by, for instance, a voltage on electrodes across the fiber. Under this influence, the glass becomes birefringent, with the different indices of refraction for light polarized parallel to or perpendicular to the applied field. This means that the optical ray will be decomposed into two rays caused by the different refractive indexes [11]. This difference of the refractive index, Δn, is given by

$$\Delta n = \lambda K E^2$$

where λ is the optical wavelength, K is the Kerr constant, and E^2 is the pump intensity. Therefore, when the light travels through crystal or glasses, the refractive index will be modified proportionally with the intensity of the pulse.

In the case of light generated by semiconductor lasers or amplified by semiconductor optical amplifiers (SOAs), a high intensity signal reduces carrier densities, which in turn leads to a modification of the refractive index and thus a phase change per unit length during propagation [4]. The self phase modulation in SOA's is an effect produced as a result of index nonlinearities induced by gain saturation. This is an important issue when talking about short and powerful pulses arriving to a semiconductor optical amplifier. The amplifier can be saturated by the pulse edge and the gain available for the trailing edge will be reduced. This will induce gain saturation modifying the linearity of the refractive index and pulse distortion.

The chirp of an optical pulse is usually understood as the time dependence of its instantaneous frequency. Specifically, an up-chirp (down-chirp) means that the instantaneous frequency rises (decreases) with time. An chirped Gaussian pulse can be described as [18]:

$$A(0,t) = A_0 \exp\left[-\frac{1+iC}{2} \left(\frac{t}{T_0} \right)^2 \right]$$

where A_0 is the peak amplitude, T_0 the half width (which is related to the FWHM) and C governs the frequency chirp imposed to the pulse.

When an un-chirped pulse arrives to the amplifier the intensity is highest at the peak of the pulse and therefore, that part of the pulse experiences the highest refractive index and as a result, propagates slower than the leading and trailing parts of the pulse. This causes the carrier wave to stretch out on the leading part of the pulse and to pile up on the trailing part of the pulse. The resulting spectrum will be then modulated and broadened.

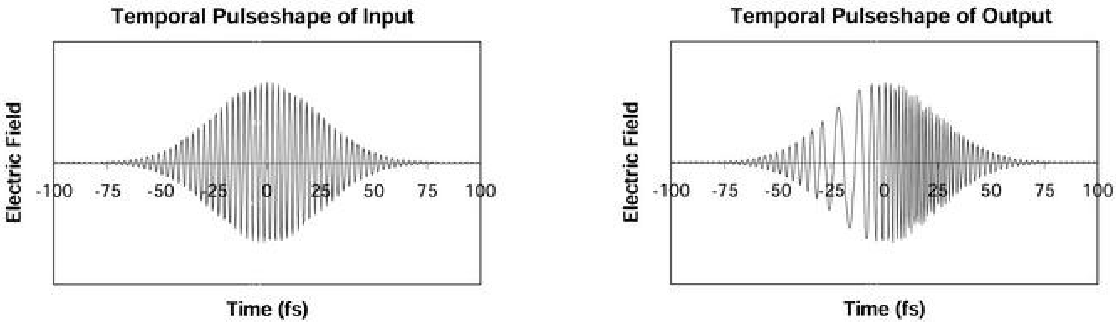

Fig. 2-4: Time domain representation of Self Phase Modulation effect on an optical pulse

This way the initially un-chirped optical pulse acquires a chirp, a temporary varying instantaneous frequency, causing a broadening and shifting of the original pulse spectrum.

When an electromagnetic wave interacts with the bound electrons of a dielectric, the medium response, in general, depends on the optical frequency *w*. This property, referred to as chromatic dispersion, manifests through the frequency dependence of the refractive index n(w). Fiber dispersion plays a critical role in propagation of short optical pulses because different spectral components associated with the pulse travel at different speeds given by *c/n(w)*. Even when the nonlinear effects are not important, dispersion-induced pulse broadening can be detrimental for optical communication systems.

Physically speaking, the envelope of an optical pulse moves at the group velocity while the parameter β_2 represents dispersion of the group velocity and is responsible for pulse broadening. This relation can be described as [13]:

$$\beta_2 = \frac{1}{c}\left(2\frac{dn}{dw} + w\frac{d^2n}{dw^2}\right)$$

If the effects of SPM and chromatic dispersion are combined, the result is amplitude distortion when the pulse is in the anomalous dispersion region. The leading edge of the chirp induced by the SPM will be shifted to the lower frequencies (red-shift) and the trailing edge to the higher frequencies (blue-shift). In the presence of chromatic dispersion, the red-shifted and blue-shifted parts of the pulse travel at a different speed, causing amplitude distortions. The chirp caused by the self-phase modulation cannot be eliminated as this would require a material with a negative Kerr effect. The impact can be reduced by choosing a positive chromatic dispersion coefficient, so the chirp will be cancelled partially.

The importance of this effect lies on the spectrum broadening. As seen, this effect mainly produces chirping on optical pulses, modifying the pulse shape and possibly distorting the signal. Even so, carefully inducing SPM can be useful to reduce RBS penalties, as it will be explained later in this study.

Chapter 3

System setup

3.1 Architecture description

In this chapter a basic OCDMA architecture will be described, its components analyzed and its performance evaluated. The objective is to know the structure, the possibilities and performance of this kind of new generation Passive Optical Network architectures. The particularity of this kind of schemes is the transmission of pulses between the ONU and the Optical Line Termination (OLT) at the CO instead of continuous signals using OOK modulations. These pulses are transmitted such that together they will form a unique code identifying each user of the network. These codes can be constructed using 1 (time) or 2 (time, wavelength) dimensions and can have different lengths. The length and the dimensions used to form the code will define the characteristics and performance of the system.

In order to implement the multipoint-to-multipoint communications, the core networks usually employ the ring and mesh network topologies and the local area networks commonly exploit the star, ring and bus network topologies. The access network is a type of service distribution networks, which may utilize the point-to multipoint tree architecture to form a passive optical network (PON), as shown in Figure 3-1. This structure facilitates low cost and high bandwidth utilization of fiber-to-home (FTTH)/premises (FTTP), fiber-to-building/business (FTTB) and fiber-to-cabinet (FTTCab). The upstream and downstream links can employ different optical fibers to achieve space division or different wavelengths to realize wavelength division.

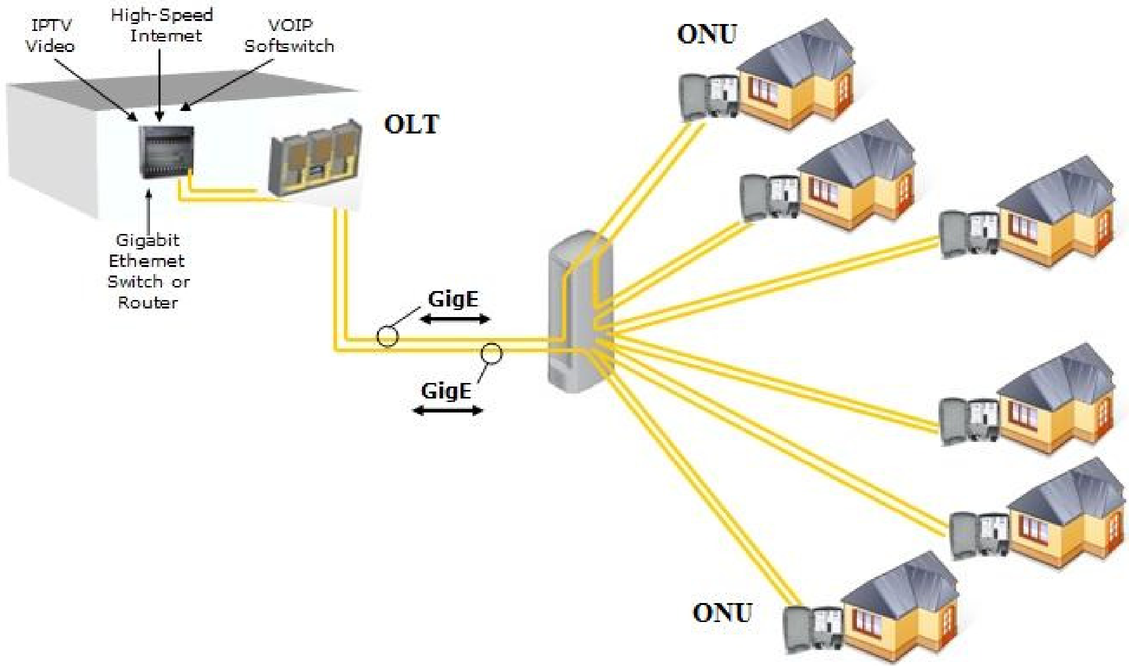

Fig. 3-1: FTTH PON architecture

The considered scheme of this study is composed of a colorless reflective ONU with no optical source that can work at any wavelength of the same window, situated at the user-end. On the other side of the network there is an OLT that generates the light remotely, being this component the only active of the system. The CO has the task of sending the (modulated) information downstream and the (unmodulated) optical source signals to the users at the different wavelengths. This optical source will be in form of a train of pulses that will be used by the ONU's to encode their information and send it back to the CO, forming the upstream data. In other kind of bi-directional PON's the light source is a constant signal, being used at the user side to modulate the upstream data.

The ONU has two major tasks. Firstly, it terminates the optical path and converts the downstream data to the electrical domain and, secondly, it transmits the upstream data after converting it from the electrical domain to the optical domain. The transmission process of upstreaming data is carried by a reflective modulator. This device uses the optical pulses received from the CO to send the digital signal using optical codes and OOK modulation. This module has no optical source and can work at any wavelength considering that it works like a mirror with amplification.

The advantage of this network approach is that wavelength referencing and control is provided by CO and thus the more complex devices (high performance lasers and processing units) are less in number and as a result the costs are reduced dramatically, the devices at the end-user are the simplest possible. Also passive optical components alleviate maintenance requirements in the access network. The node in between the CO and ONU of Fig. 3-1 is a passive coupler.

All this transmissions can be done using two fibers, one for the upstream data (and the pulses sent from the CO) and the other for the downstream data. In this study a single fiber transmission will be considered. These bidirectional transmissions have counter-effects like in-band crosstalk caused by reflections inside the fiber and Rayleigh Backscattering.

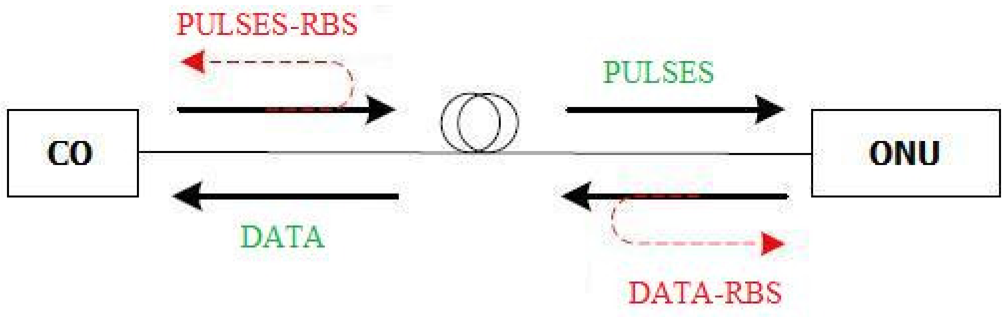

Fig. 3-2: Simple scheme of the Rayleigh Backscattering contributions

As studied in [8], RBS is an important issue on bidirectional transmissions. Figure 3-2 shows the two contributions to the Rayleigh Backscattering effects in our scheme, interfering with the upstream signal sent to the CO. The first contribution is generated by the carrier being delivered to the ONU and the second contribution by the modulated upstream signal at the output of the ONU. The backscattered light re-enters the ONU where it is re-modulated and reflected towards the Rx. The relatively low power backscattered light is also amplified by the reflective modulator, which usually provides net gain.

3.2 Optical CDMA architecture principles and components

The system to be described is designed to connect 4 users simultaneously at a distance of 25.4 km from the CO. The system transmission speed is set to 1.25 Gbps due to restrictions on the bandwidth of the RSOA. Figure 3-3 shows the setup to be described on this chapter. The distance consists of 20 km of Standard Single Mode Fiber (SSMF) with 5.4 km of Dispersion Compensating Fiber (DCF) to compensate for the dispersion.

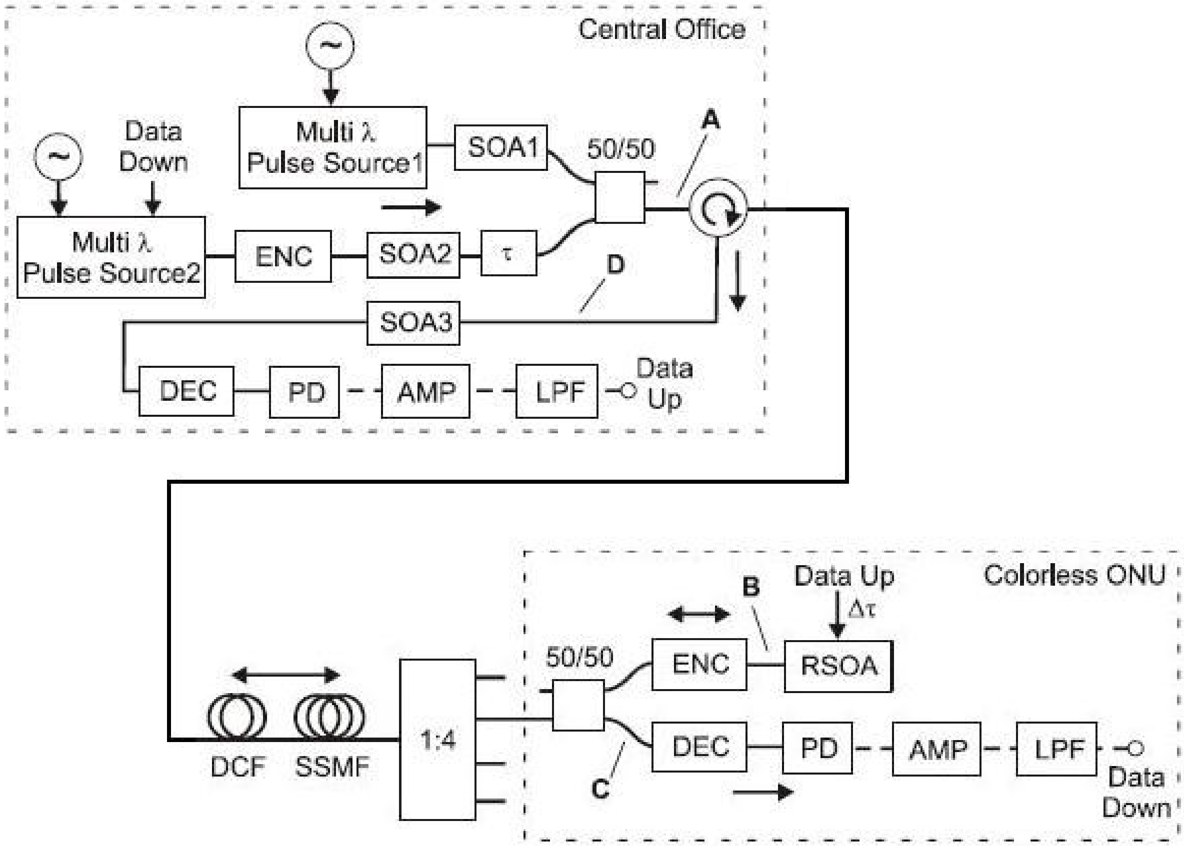

Fig. 3-3: Basic bloc diagram of an OCDMA architecture

The scheme shown in figure 3-3 describes a basic OCDMA setup. The CO side is divided in three parts: the optical pulse source (to be used by the ONU), a second pulse source that will be encoded and modulated (for the downstream data), and the receiver with the decoder (upstream data). After the CO the fiber link is placed and splitters will connect several users to the same CO. The ONU is a simpler device, composed of an RSOA and a encoder that will send the upstream information, and a receiver with the decoder that will receive the downstream data.

3.2.1 Pulse amplification

The optical pulses used in this architecture are generated at the CO. These pulses are designed to travel through 25.4 km of fiber and be reflected and amplified at the user side by an RSOA. Since pulses behave differently from continuous wave transmissions, the nonlinear effects of pulse amplification have to be considered.

Amplification of pulses using semi-conductor amplifiers may introduce nonlinear effects and distort optical pulses when being amplified. Dispersive effects are not important for SOA's because of small material dispersion and a short amplifier length (<1 mm in most cases). These effects occur when the pulse width is short and optical power high, causing saturation to the amplifier and modifying the pulse shape. Seen the importance of pulse width and power [6], the pulse can be analyzed by using its partial energy

$$E_o(\tau) = \int_{-\infty}^{\tau} P_{in}(\tau) d\tau$$

where $E_0(\infty)$ equals the input pulse energy. Seen the time-dependence of the input pulse, the amplifier gain can be defined as [18]

$$G(\tau) = \frac{G_0}{G_0 - (G_0 - 1)\exp\left[-E_0(\tau)/E_{sat}\right]}$$

where G_0 is the unsaturated amplifier gain. This equation shows that the amplifier gain is different for different parts of the pulse. The leading edge experiences the full gain G_0 as the amplifier is not yet saturated. The trailing edge experiences the least gain since the whole pulse has saturated the amplifier gain. The intermediate values of the gain depend on the pulse shape. Nonlinear amplification of the pulse will produce chirping, and therefore the pulse spectrum will be broadened. This is caused by gain saturation, leading to a time-dependent phase shift across the pulse. Since the pulse modulates its own phase through gain saturation, this phenomenon is referred to as saturation-induced self-phase modulation [20].

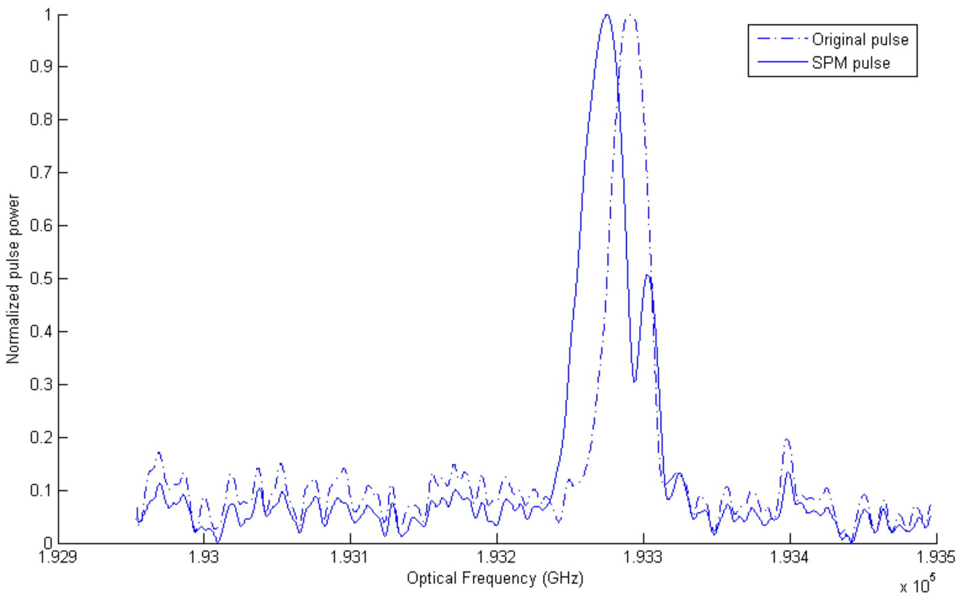

Fig. 3-4: spectrum showing SPM effect on optical pulse

The frequency chirp is larger for more energetic pulses simply because gain saturation sets in earlier for such pulses. Self-phase modulation and the associated frequency chirp can affect lightwave systems considerably. The spectrum of the amplified pulse becomes considerably broad and contains several peaks of different amplitudes [20]. The dominant peak is shifted toward the red side and is broader than the input spectrum. It is also accompanied by one or more satellite peaks.

The temporal and spectral changes depend on amplifier gain and are quite significant for G_0 = 30 dB. The experiments performed by using pico-second pulses from mode-locked semiconductor lasers confirm this behaviour [20]. In particular, the spectrum of amplified pulses is found to be shifted toward the red side by 50–100 GHz, depending on the amplifier gain. Spectral distortion in combination with the frequency chirp would affect the transmission characteristics when amplified pulses are propagated through optical amplifiers [32].

3.2.2 Optical Codes

The optical codes used by OCDMA systems can be divided into two branches: coherent and incoherent codes. Coherent codes are formed via phase coding, modulating the optical signal using phase modulations. Incoherent codes that use standard techniques of intensity modulations with direct detection.

The most common approaches to incoherent OCDMA are based on spectral-amplitude coding [11], spatial coding [12], temporal spreading [13], and 2-D wavelength-hopping time-spreading (WHTS) coding [14]–[16]. Coding in multiple dimensions, such as spectral amplitude and WHTS, adds more flexibility while increasing the capacity and performance. Incoherent OCDMA systems are preferred because it presents robustness to environmental conditions, nonlinearity, and coherent effects and utilizes commercial off-the-shelf components. Coherent codes have worse performance when talking about signals propagating through multiple hops [29].

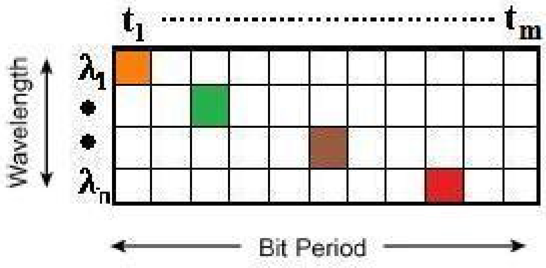

Fig. 3-5: 2-Dimensional Time-Wavelength Optical Code Matrix, also denominated by Wavelength Hopping Time Spreading (WHTS)

In OCDMA systems, the pulses are encoded in both the time domain and the wavelength domain simultaneously: the codes can be represented as matrices with time and wavelength on the two axes. The wavelength domain is divided into n channels of bandwidth ν and the time domain into m time chips of duration τ. A code consists of K short pulses of different wavelengths, where K is called the weight of the code, within the m available time chips.

The biggest merits of 2-D codes are the significant increase of the cardinality, which makes the numbers of users and simultaneous subscribers in a network increase enormously, and the reduction of the code length, which results in the data rate of single user to boost largely [17].

Most recent implementations of 2-D OCDMA utilize multi-wavelength sources to avoid the need for sources that can rapidly wavelength hop. The pulses can be generated from an array of mode-locked lasers, which is limited in scalability due to the higher complexity in controlling a large number of lasers or from a broadband source. The encoder essentially creates a combination of two patterns: a wavelength-hopping pattern and a time-spreading pattern. Some implementations perform the two patterns independently like array waveguide gratings (AWG's) or thin-film filters (TFF's) [11], or simultaneously as fiber Bragg gratings (FBG's) [12], holographic Bragg reflectors (HBR's) [13], or chirped Moire gratings (CMG's) [14].

The position and length of the delay lines will determine the codes that will be created. The position of the wavelengths within the bit interval can be changed in order to create a different code from the same code family. We define a code family ψ as the total number of valid codes, which is also called the cardinality, that can be obtained with the same n wavelengths and m chips. A valid code has to satisfy specific values of cross and autocorrelation. The crosscorrelation of a code refers to the interference caused to other users which is an additive effect in the network. In that sense, as more codes are active, the more mutual interference is experienced. Orthogonal codes have a crosscorrelation of 0; however, many code-sets have relaxed requirements and are designed to be pseudo-orthogonal. Physical imperfections also have their impact on the orthogonality of the code-set.

While an encoder spreads the wavelengths in time over the bit period, on the decoder side there is a system of delay lines that are ordered in the way that the code will be reconstructed. The pulses, from the different wavelengths are realigned in time and summed up to create a peak of height *K*. Then a threshold will determine weather or not the code is right, whence the data was sent to that user.

3.2.3 Encoder/Decoder

As discussed previously, there are different kinds of encoders/decoders in OCDMA systems. In this section two kinds of encoders/decoders will be described, using TFF's and BFG's.

Optical Encoders and Decoders using TFF's

A broadband light source or a multi-wavelength light source outputs short pulse trains with the repetition rate equal to the bit rate, which are modulated by the input data in an optical modulator. For the on-off keying modulation, the transmitter only outputs an optical pulse when a transmitted data bit is "1". Then, the narrow optical pulse corresponding to the data bit "1" is fed into a 2-D incoherent WHTS optical encoder to perform encoding.

The fixed 2-D incoherent WHTS optical encoder consists of a 1:W wavelength-division demultiplexer, W fixed fiber-optic delay lines and a W:1 wavelength-division multiplexer, with W the number of wavelengths. The short optical pulse corresponding to data bit "1" is therefore firstly separated into W optical pulses. These pulses will have a defined spectral width and frequency distance, which depends on the quality of the filters and the transmission characteristics of the network that we will be working on. These W optical pulses are finally combined and output by the wavelength division multiplexer. With this procedure, the 2-D WHTS optical encoding of data is achieved.

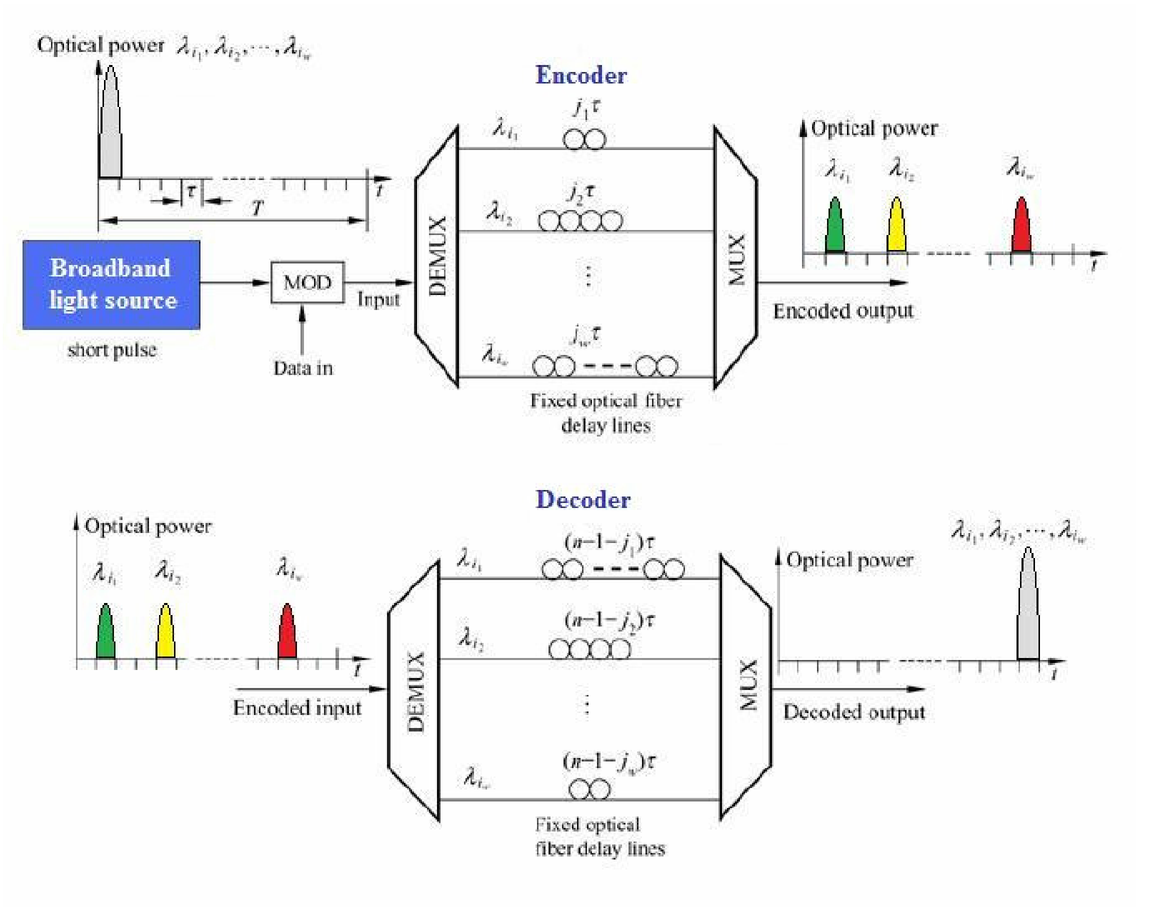

Fig. 3-6: Two-dimensional WHTS encoder/decoder (modified from [17])

The architecture of a 2-D WHTS decoder is similar to that of the 2-D WHTS encoder. The only difference is that the delay lines have an inverse configuration as the encoder. This is done to shift the output autocorrelation peak to the last slot (chip) position in a corresponding data bit period after the encoded signal is decoded. When the input code of the decoder corresponds to the right code, the decoder will output the autocorrelation function. The data bit is restored after optical-to-electrical conversion and then it passes through the threshold circuit. If an input code of the optical decoder doesn't correspond to the right code, the output of the decoder will be the cross-correlation function. In this case, after certain processing of electronic circuits, there will be no data output in the receiving end, this means that the receiver sees a "0" level.

Optical Encoders and Decoders using FBG's

A two-dimensional incoherent WHTS optical encoder and decoder can be composed by fiber Bragg gratings (FBG's) to reflect the optical signals with different wavelengths, which adopt a series [18] or a parallel structure [19].

A fixed optical encoder and decoder using a series structure consist of an optical circulator with three ports, a circulator, W FBG's and W fiber-optic delay lines. A short optical pulse coming from a broadband light source is firstly modulated by data in a modulator and then the modulated narrow optical pulse is fed into port 1 of the optical circulator. The optical signals output from port 2 of the circulator are reflected back by FBG's with different wavelengths. Meanwhile, two adjacent FBG's are connected with the delay lines with different lengths in order to implement the desired delays in terms of the requirement of a two-dimensional codeword. The returning optical pulse signals with different wavelengths and different delays exit the encoder at port 3.

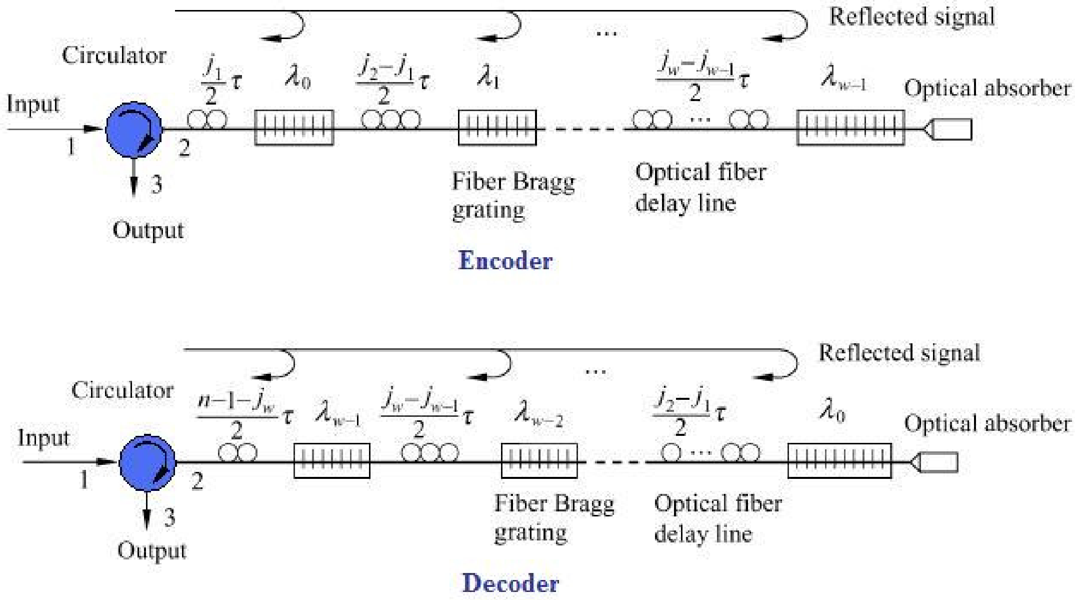

Fig. 3-7: Series structure of an Encoder/Decoder using FBG's (modified from [17])

The structure and operational principle of the optical decoder is similar to its corresponding encoder. The necessary variations are to put these FBG's in reverse order and to change the delays of fiber-optic delay lines between two adjacent FBG's in order to make their delay values be complementary values of those in its corresponding encoder. The structure of a tunable optical encoder/ decoder using serial FBG's is the same as that of its fixed encoder/decoder except that the fixed delay lines are changed into tunable delay lines. However, this would result in large optical power loss [17]. Hence, such a structure is only suitable for the implementation of fixed encoder/decoder.

A tunable optical encoder and decoder using parallel FBG's, shown in Figure 8, consists of a circulator with three ports, an arrayed waveguide grating (AWG) wavelength-division demultiplexer, *W* FBG's and *W* fiber-optic delay lines. After the short optical pulse from a broadband light source is modulated by data, it is fed into port 1 of a circulator. The optical signal output from port 2 is decomposed into W parallel output by the AWG. They pass through the fiber-optic delay lines with different lengths and are reflected by FBG's with different wavelengths, and return into the AWG again. The resulting optical pulse trains multiplexed by the AWG enter the optical circulator from its port 2 and then output from port 3 of the circulator. For the decoder, the same functional structure is preceded for the decoding.

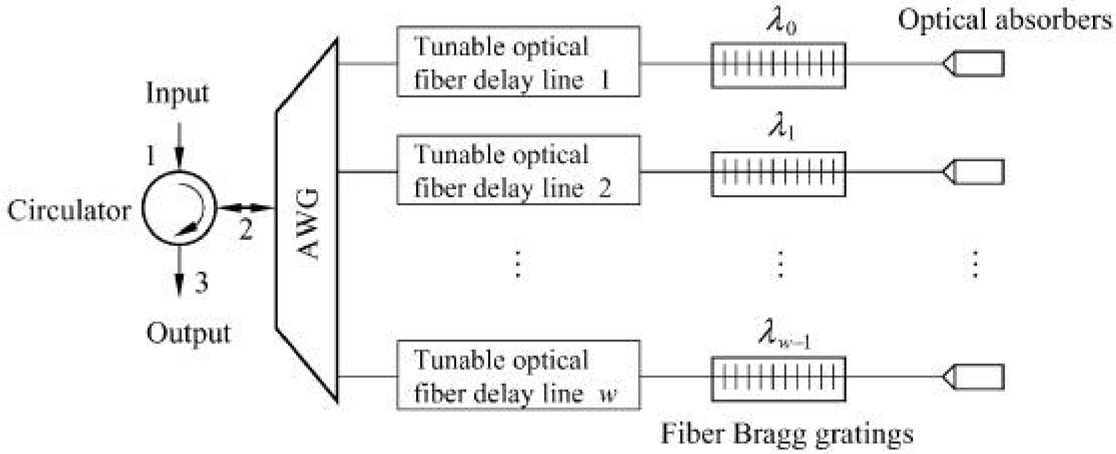

Fig. 3-8: Parallel structure of an Encoder/Decoder using FBG's (modified from [17])

3.2.4 RSOA

The goal of using Reflective Semiconductor Optical Amplifiers in this kind of setups is clearly in the way of cost reduction at the user side, given that the ONU will be just housing the RSOA and the encoder. Therefore the most complex equipment of the system will be at the CO, where unmodulated pulses are broadcasted at a repetition rate equal to the bit rate at which they are encoded before going to the RSOA.

Semiconductor Optical Amplifier

Optical communication with semiconductor amplifiers has been successfully demonstrated in the past, achieving appropriate transmission results. The first works date of the middle '90s [7]-[9]. Semiconductor amplifiers are similar to conventional semiconductor lasers except that they have no strong feedback at the facets. This is accomplished by blocking any residual internal cavity reflections using an antireflection (AR) coating and the technique of angle cleaving the chip facets (angle of about seven degrees). The RSOA is a modified version of a Semiconductor Optical Amplifier (SOA), with the difference that it just has one optical port. The other port will be replaced by a high reflection coated facet, close to 100% reflectivity. The internal cavity has the same physical fundamentals as the SOA, the input signal is amplified in both directions, one way going towards the mirror and then backwards towards the optical port [10]. The signal driving the bias current of the amplifier will be the responsible of managing the On-Off Keying (OOK) modulation. Thus, when no current goes into the amplifier, the input signal will not be amplified and merely experience material losses.

Fig. 3-9: SOA and RSOA transmission diagram

An SOA consists of a central active region (typically 300-500µm) of a semiconductor material between two semiconductor layers of different compositions. When the device is driven by an electrical current, the electrons are excited in the active region. The photons travelling through the active region cause the electrons to lose part of their extra energy in the form of more photons with the wavelength as the initial ones (stimulated emission) generating thus an amplification of the incoming signal.

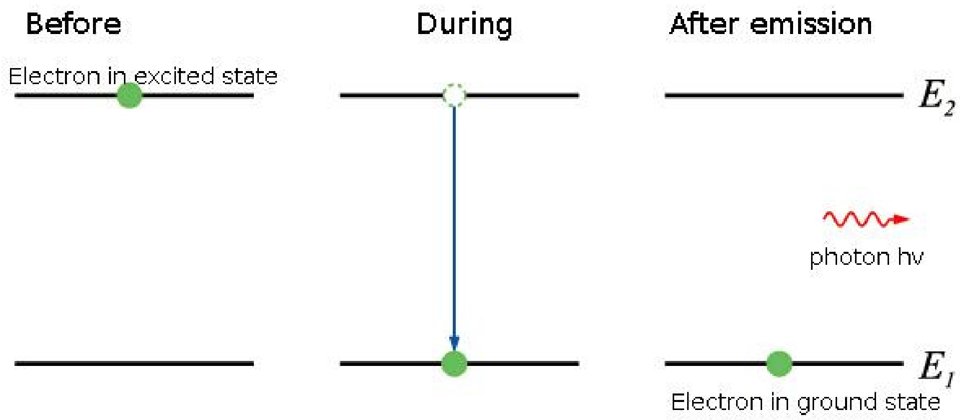

Fig. 3-10: Photon-Electron recombination process

Some semiconductor material structures can transform electrical current into light and vice versa. For this process to be possible, some requirements have to be fulfilled. The semiconductor material has to be designed in a diode structure to allow electrons and holes to concentrate at the pn-junction, where they can recombine.

Recombination mainly takes place in the intrinsic layer, which explains why it is also called the active region. When the electron-hole pairs recombine, the recombination process results in the formation of a photon with energy equal to the energy difference between the original electron and hole. The energy of a photon is related to its frequency ν or wavelength λ, according to the following relation (*h* is Planck's constant, *c* is the speed of light).

$$E_{ph} = h\nu = \frac{hc}{\lambda}$$

For the purpose of signal amplification, stimulated emission is the most important process in the gain medium of a SOA. When the optical signal to be amplified travels through the cavity of the SOA, the stimulated emission of photons will amplify the optical pulse.

Carrier-density

For the description of the behaviour of a SOA with respect to optical signals are described by the carrier-density equations. The carrier density equation is the sum of all process that changes the carrier-density, which is the density of electrons and holes of a semiconductor. The density of electrons in a semiconductor is related to the density of available states and the probability that each of these states is occupied. Thus, the carrier-density is increased by the pump current and decreased by several recombination mechanisms, and can be described as [18]:

$$\frac{dN}{dt} = \frac{\eta_i I}{qV_{act}} - R_{recomb}$$

where R_{recomb} represents all recombination mechanisms and the first term represents the influence of the pump current I reduced by the injection current efficiency η_i. q is the electron charge and V_{act} is the volume of the active region.

Amplifier gain

The optical gain, in general, depends not only on the frequency (or wavelength) of the incident signal, but also on the local beam intensity at any point inside the amplifier. Details of the frequency and intensity dependence of the optical gain depend on the amplifier medium. The gain can be described as [4]:

$$g(w) = \frac{g_0}{1 + (w - w_0)^2 T_2^2 + \frac{P}{P_s}}$$

where g_0 is the peak value of the gain, w is the optical frequency of the incident signal, w_0 is the atomic transition frequency, T_2 is the dipole relaxation time and P the optical power of the signal being amplified.

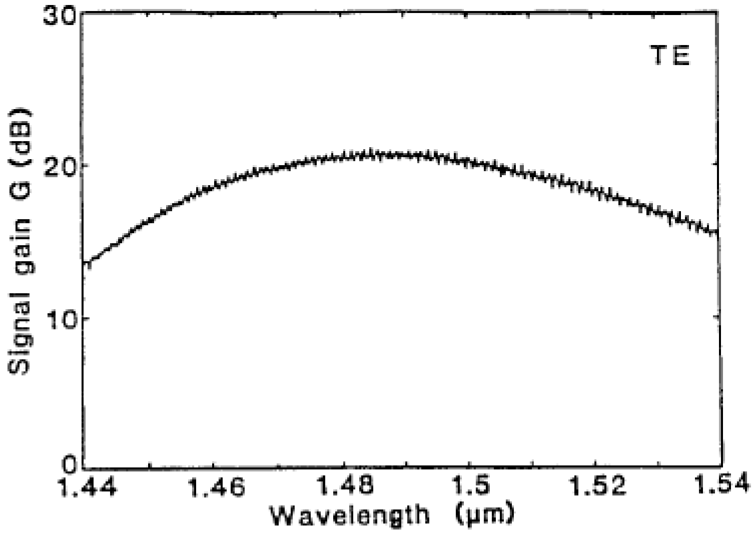

Fig. 3-11: Gain versus Wavelength of a Semiconductor Optical Amplifier [18]

The gain is maximum when the incident frequency *w* coincides with the atomic transition frequency w_0. The gain reduction for $w=w_0$ is governed by a Lorentzian profile that is a characteristic of homogeneously broadened two-level systems [4]. Amplifiers with a relatively large bandwidth are preferred for optical communication systems because the gain is then nearly constant over the entire bandwidth of even a multichannel signal.

Gain saturation P_s, depends on gain-medium parameters such as the fluorescence time and the transition cross section. Since g is reduced when P becomes comparable to P_s, the amplification factor G decreases with an increase in the signal power. This means that there is a limit on the input optical power that the amplifier can amplify. This limit is determined by the SOA´s carrier pumping capacity. When the input optical power reaches this limit the amplifier gain will decrease.

ASE noise

Another factor to take into account is amplification noise or Amplifications Spontaneous Emission noise (ASE noise). All amplifiers degrade the signal-to-noise ratio (SNR) of the amplified signal caused by spontaneous emission that adds noise to the signal during its amplification.

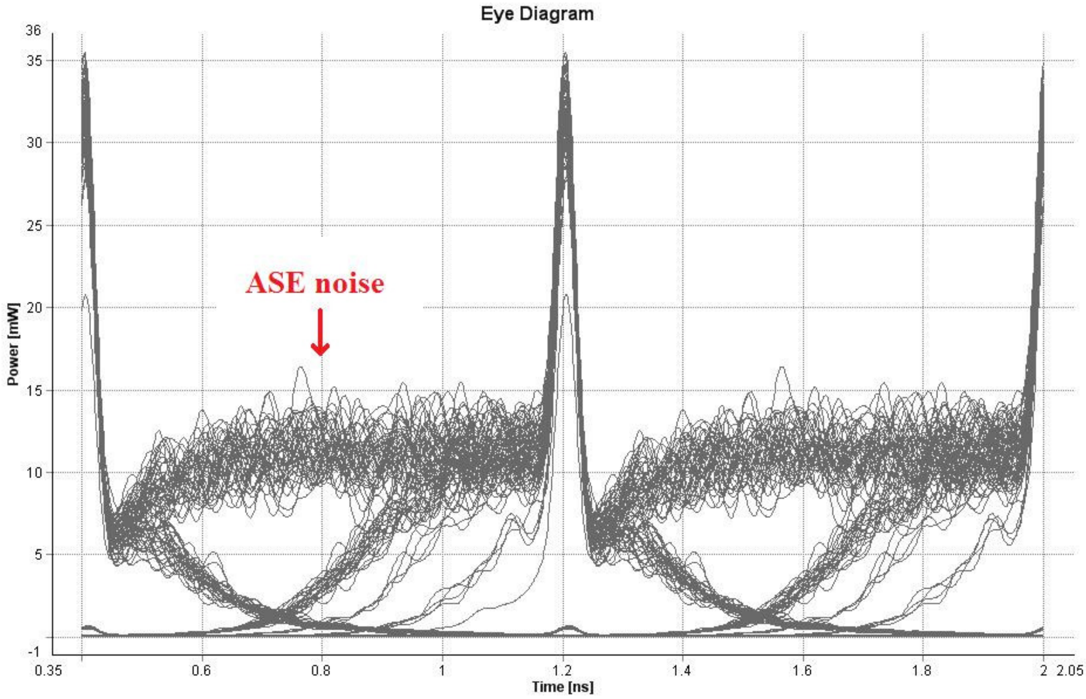

Fig. 3-12: Eye diagram showing ASE noise influence when optical pulse is amplified by a SOA

This effect is caused by spontaneous emission of light because of electrons and holes being recombined at random instants, and then amplified by the SOA. Therefore, when no optical input into the amplifier, spontaneous recombination will be more important and ASE noise will have more influence on the system [21]. In figure 11, the eye diagram clearly shows this effect, where ASE noise is high when no optical pulses have to be amplified, and therefore the spontaneous emission is more important. To evaluate the SNR of the amplified signal, the spontaneous emission should be added to the contribution of the receiver noise. Since it typically is a wideband optical phenomena, ASE noise can be filtered by using a bandpass filter.

3.3 Studied architecture

In this thesis, a simpler version of an Optical CDMA architecture will be studied in order to simplify the influences of the transmitted signal and focus on pulse propagation and RBS reduction. Therefore, information will not be encoded and just a train of optical pulses will be transmitted to the user. It is expected that by studying a single pulse transmission, the RBS effects at the larger OCDMA system can be understood.

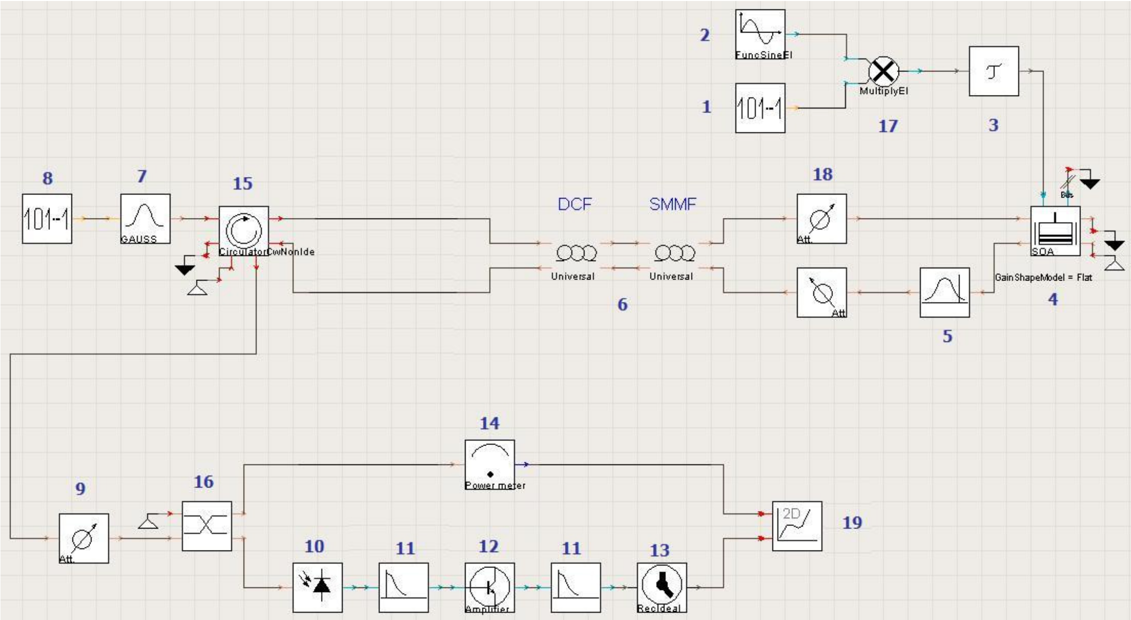

Fig. 3-13: Scheme used for VPI simulations (simplified)

Figure 13 shows the schematic used in the following chapters for performance simulations. There are some OCDMA characteristic components used in this schematic are:

1. Data generator, this device has the role of creating a random sequence of data that will be transmitted simulating the user's upstream transmission.
2. RF signal, explained in following chapters it implements a RBS reduction technique based on bias dithering.
3. Delay line, which purpose is to synchronize user's data with the optical pulses sent from the ONU side. It has a fixed value and its optimization is explained on following chapters.
4. Reflective Semiconductor Optical Amplifier, used for the reflective On-Off Keying modulation and amplification of the received pulses.
5. Filter, optimized to filter any noise out of the pulse bandwidth, specially ASE noise produced by the RSOA.
6. Fiber link, composed by a Single Mode Fiber (SMF) and a Dispersion Compensating Fiber.
7. Pulse transmitter used to send a train of Gaussian pulses.
8. Pulse generator, it sends alternate logical ceros and ones to the laser at a rate of 1,25 Gbps.
9. Receiver attenuator, will define the power margin with which the system is error free (BER bellow 10^{-9}).
10. Photo-detector, converts the optical signal coming from the fiber to the electrical domain, to enable signal treatment.
11. Filter, placed after the photo-detector and after the amplifier, is designed to filter any disturbance out of the data bandwidth.
12. Receiver amplifier, in general placed after the photo-detector to amplify the low power electrical signal coming from it.

13. Clock recovery module, used in VPI to synchronize and enable measurements of system performance.
14. Power meter, to evaluate error rates at different power levels.
15. Circulator, used at the CO side to separate signals from downstream and upstream transmissions.
16. Optical splitter.
17. Electrical multiplier, used in VPI to emulate the behaviour of a full-wave rectifier.
18. Attenuator, it emulates attenuations produced by the different connectors of the system.
19. BER and Q-factor meters that will calculate the system performance at the receiver side.

3.4 System settings

The most important parameters that define the characteristics of the simulated system, used in the simulation tool VPI, will be enumerated here.

System

Name	Value	Units
Bit Rate	1,25	Bits/s
Time Window	32 – 128	1/BitRate (=number of bits)
Centre Frequency	193,225	Thz
Sample Bandwidth	512*BitRate	GHz
Light Speed	299 792,46	Km/s
Pulse Wavelength	1550,92	nm
Chip Duration	19,4	ps
Rx Filter Bandwidth	12	GHz

RSOA

Name	Value	Units
Active Region Type	MQW	-
Device Section Length	0,468	mm
Active Region Width	1,2	µm
Current Injection Efficiency	1	-
Nominal Wavelength	1.5525	µm
Initial Carrier Density	10^{24}	$1/m^3$

Carrier Density Transparency	$2*10^{24}$	$1/m^3$
Gain Model	Linear	-
Gain Shape Model	Flat	-
Gain coefficient	$6.7*10^{-20}$	m^2
Build-up Time	3	ns

Pulses

Name	Value	Units
Pulse Type	Gaussian	-
Gaussian Order	1	-
Pulse Rate	$1,25*10^9$	Pulses/s
Peak Power	1	mW
Emission Frequency	193,299	THz
FWHM	19	ps

Fiber

SMF

Name	Value	Units
Fiber Type	SMF	-
Length	20	Km
Refractive Index	1.47	-
Attenuation	$0,25*10^{-3}$	dB/Km
Dispersion	$17*10^{-6}$	s/m^2
Core area	80	pm
Rayleigh Coefficient	-83	dB | 1/m

DCF

Name	Value	Units
Fiber Type	DCF	-
Length	5,397	Km
Refractive Index	1.47	-
Attenuation	$0,313*10^{-3}$	dB/Km
Dispersion	$-63*10^{-6}$	s/m^2
Core area	19	pm
Rayleigh Coefficient	-83	dB | 1/m

Chapter 4

System parameters

The system to be studied is based on OCDMA architectures and therefore is characterized by the transmission of optical pulses. These pulses will have different behaviours when passing through the components and elements of the system. A detailed description of all these aspects of the pulse transmission will be performed in this chapter. The pulses to be transmitted from the CO will be first analyzed. Eye diagrams and spectrums will be explained after passing through the fiber. It will be shown how the RSOA behaves under different bias conditions and how the signal to be amplified is affected in terms of noise and distortions showing how filtering at the output of the RSOA may improve the quality of the signal. The importance of optimizing data delay will be emphasized. Finally, the quality of the signal arriving to the receiver will be analyzed.

4.1 Pulses

The CO, as discussed in previous chapters, has the role of sending an unmodulated and continuous train of Gaussian pulses towards the user, in order to enable the reflections of these pulses and modulation by the user for upstream data transmission. A reduced scheme will be studied where no codes are used and only one user will perform data transmission at a single wavelength. Pulses will be sent from the CO at a rate equal to the user data bit rate, and therefore each pulse will transport one bit when reflected at the ONU side.

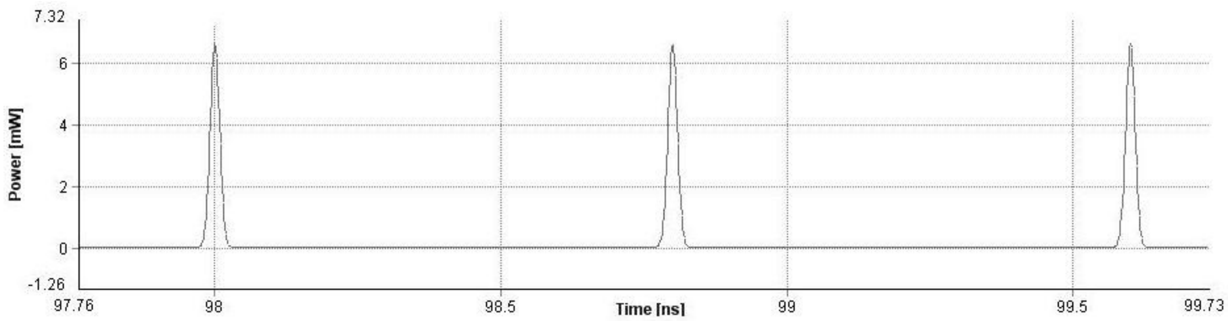

Fig. 4-1: Pulse train transmitted by the CO.

The pulses shown in figure 4-1 are a time domain representation of three pulses at the output of the pulse laser at the CO. They are first-order Gaussian pulses, separated by 0.8 nano seconds, a duration (or Full Width at Half Maximum FWHM) of 19 pico seconds, and a peak power of 1 mW. These pulses are transmitted at a frequency of 193.1 THz, using a 1550.92 nm wavelength, and have a bandwidth of 50 GHz. In this system no chirping will be induced to the pulses sent from the CO.

4.2 Fiber

The fiber used in this system is composed of a Single Mode Fiber (SMF) preceded by a Dispersion Compensating Fiber (DCF) used to suppress dispersion impairments induced by the SMF.

Dispersion is a phenomenon in which the phase velocity of a wave depends on its frequency. Dispersion is sometimes called chromatic dispersion to emphasize its wavelength-dependent nature. A single optical signal will travel at different speeds, depending on the geometry of the fiber and the lights spectrum width. The signal distortion will depend on the length of the fiber mainly because the varying delay in arrival time between different components of the signal produces distortion in time.

To decrease this degradation a dispersion compensating fiber is placed before the main fiber. Its role is to pre-compensate the distortion that the SMF fiber will introduce in the downstream direction. In the other direction, the DCF will compensate for the dispersion. For this, it is necessary to calculate the total distortion that the fiber will introduce so that the DCF has the right length and the arriving signal is undistorted. In this study a 20 Km SMF is chosen, having a dispersion factor of $17*10^{-6}$. The DCF is therefore chosen to be 5,397 Km of length having a distortion of $-63*10^{-6}$ which equals the D*L of the SMF.

As shown in figures 4-2 and 4-3, the DCF modifies the optical pulse and broadens the spectrum. The pulse becomes wider and delayed in time in order to compensate the dispersion that the SMF will introduce. After the SMF, the pulse goes returns to its original shape but attenuated.

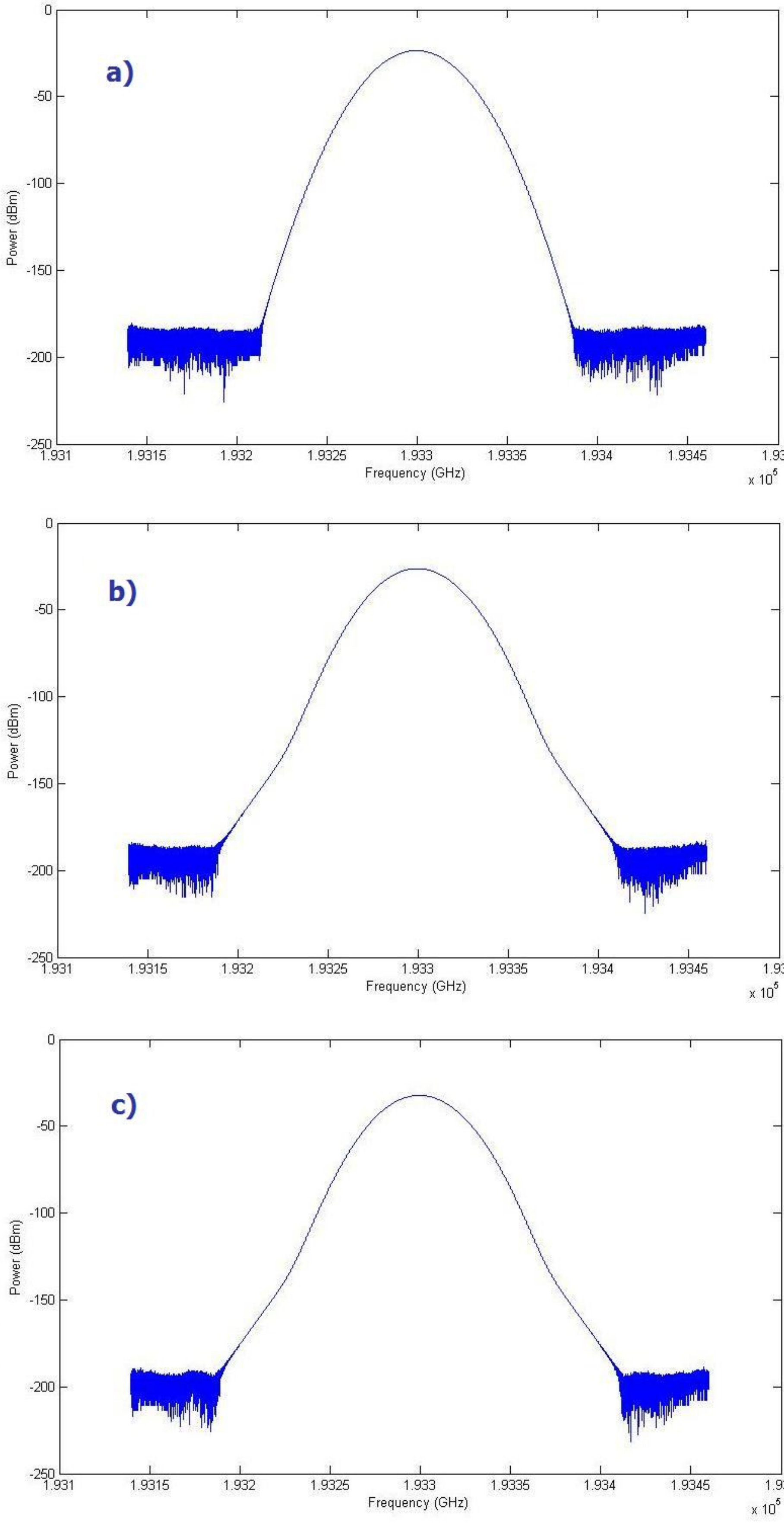

Fig. 4-2: Optical spectrums of pulses when a) going into the DCF, b) between DCF and SMF, and c) after the SMF, when a pulse is sent on the downstream direction.

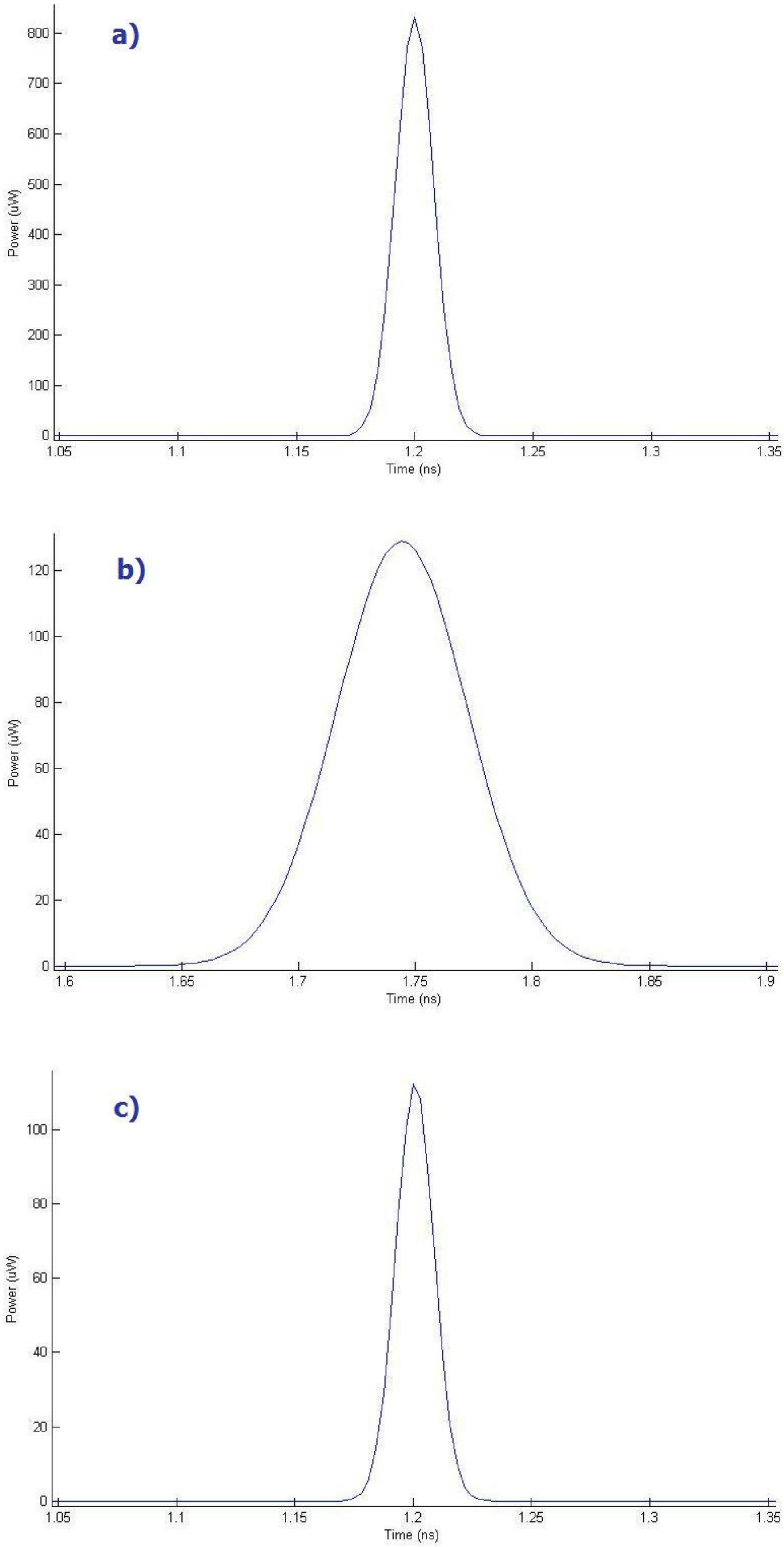

Fig. 4-3: Eye diagrams of pulses when a) going into the DCF, b) between DCF and SMF, and c) after the SMF, when a pulse is sent on the downstream direction.

4.3 RSOA

Amplifier gain

The RSOA is the main component of the system. It is characterized by many nonlinearities and impairments that introduce distortions to the signal when being amplified. It has to be optimized to behave as expected. As described in previous chapters, the amplifier gain depends on the input electrical current, or bias, that will induce optical gain to the input pulses or not. In the described system, this bias current is driven by a data generator, therefore acting as an OOK modulator and also simulating the behaviour of a reflective modulator.

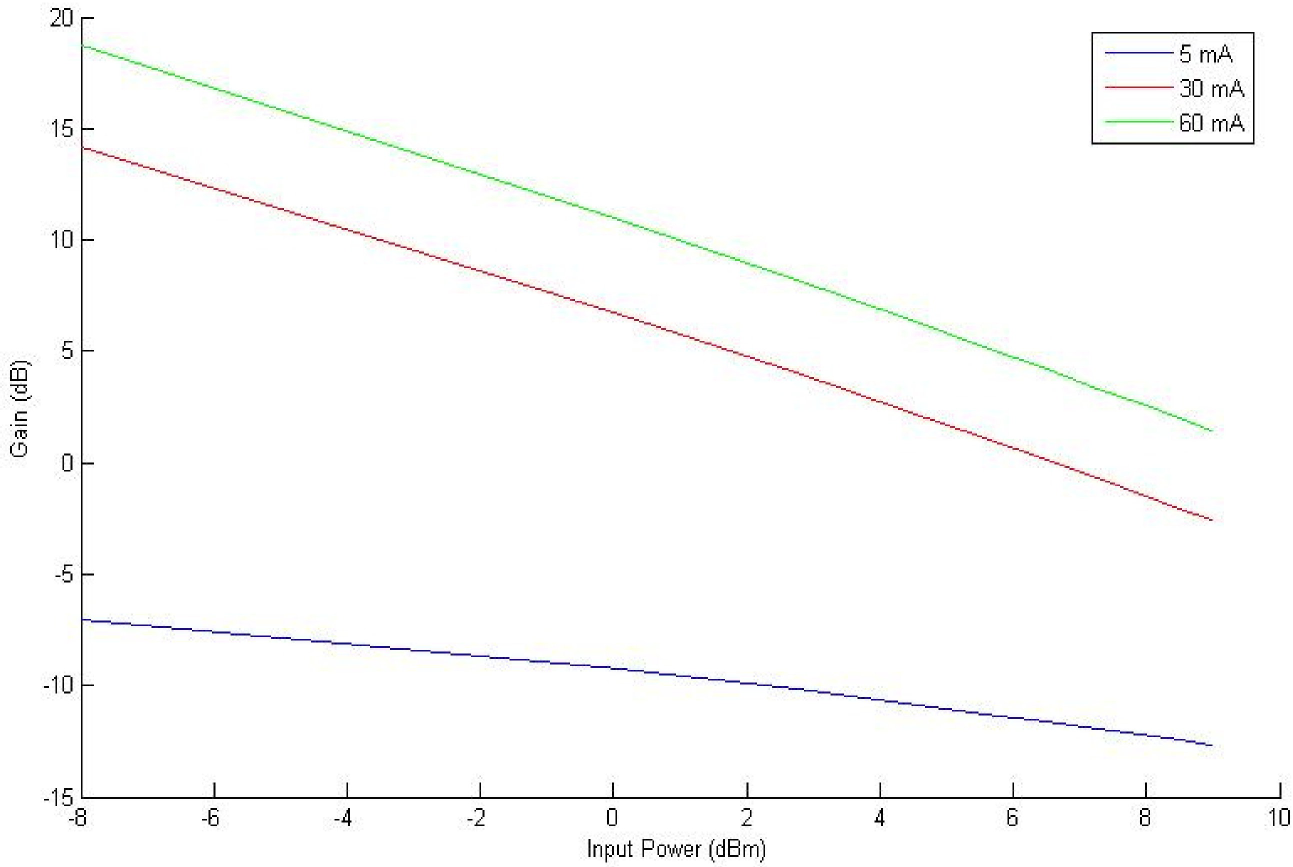

Fig. 4-4: RSOA Gain Vs Input power at different bias current levels, using a continuous wave input power.

Figure 4-4 shows the gain behaviour of the RSOA when sweeping the input power at different bias levels. The first thing to remark is the difference between the 5 mA curve and the 30 mA curve, and that the first one is under 0 dB of gain. This is due to the transparency current minimum that is not reached in the first case. When an optical incoming signal goes into an RSOA having a bias current lower than 10 mA, which is the transparency current of our amplifier, not only there will not be any gain but also the signal will be attenuated. For the correct recombination of electrons and holes, and thus the optical amplification, there has to be a minimum amount of electrical current that feeds the cavity and compensates its internal energy loses.

The decreasing shape of the curve is caused by saturation of the amplifier. Any optical amplifier has an optical input power limit at which linear amplification can be achieved. This limit is shown in figure 4-4, where it can be seen that the gain of the amplifier decreases with the optical input power. The power that an amplifier can output is directly determined by the bias current injected into it. No more electrons, than the electrons pumped by the bias current, can be recombined and transformed into optical power.

Gain saturation may also introduce distortion on optical signals to be amplified caused by self phase modulation if the signal is in form of high power pulses. As described in more detail in previous chapters, amplification of pulses may introduce gain saturation. The lower the bias of the amplifier, the easier the optical pulses will induce gain saturation. Pulses will be distorted and chirped, as described by the effect of self phase modulation. An example of pulse distortion when using an RSOA being pumped by a low bias current is shown in figure 4-5, where the attenuation and distortion of the optical pulses is clearly seen. In the upper figure the ideal incoming pulses are presented and the output pulses of the bottom figure that are too distorted and low power for correct transmission.

Finally, in the remaining of this report, the maximum bias current to be launched into the RSOA is 100 mA. This is a reasonable value considering the state-of-the-art in pattern generators which drive the RSOA.

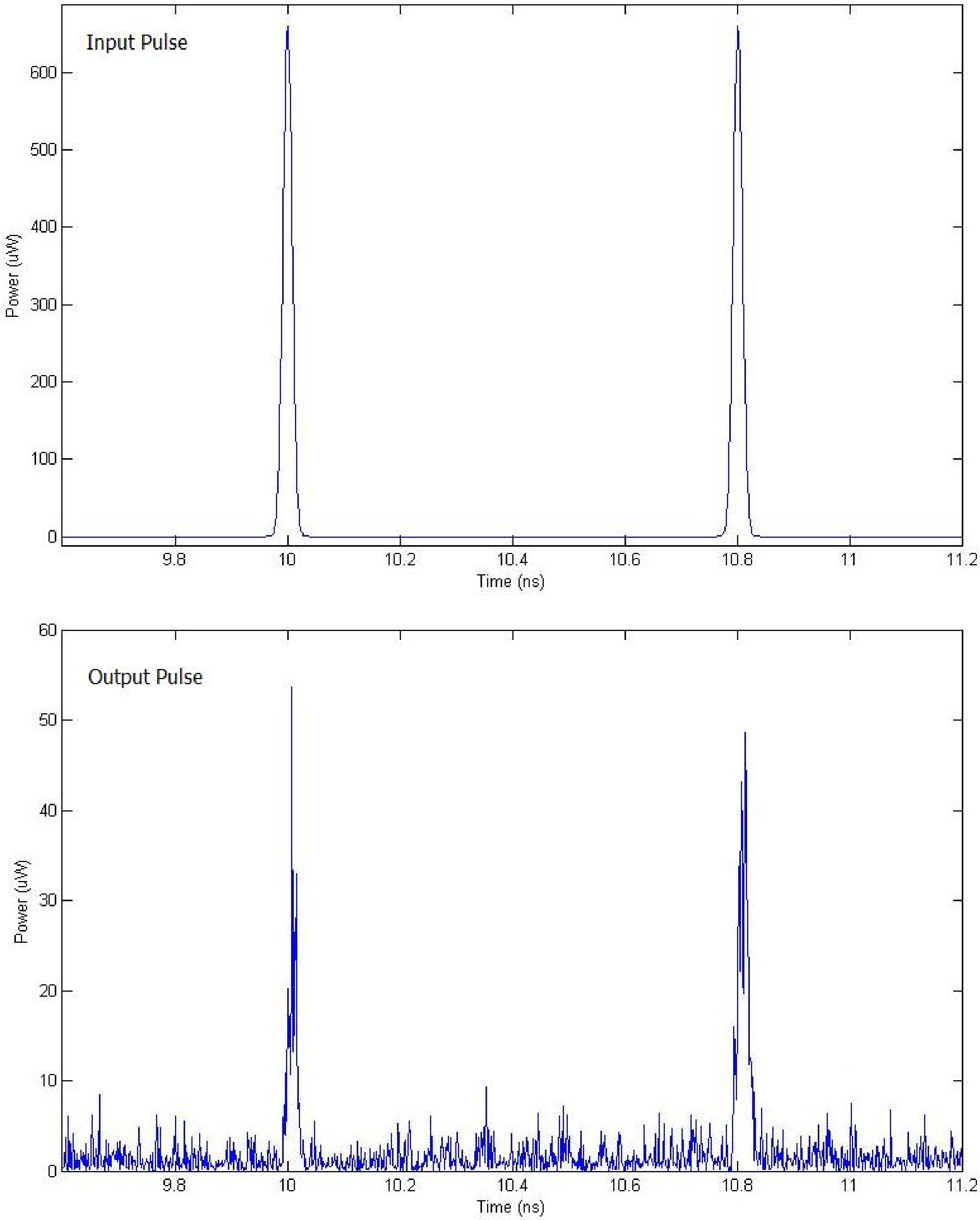

Fig. 4-5: Pulse distortion caused by low bias RSOA amplification

ASE noise

Another impairment produced when using semiconductor optical amplifiers is ASE noise. This noise can be clearly seen on eye diagrams and time domain plots.

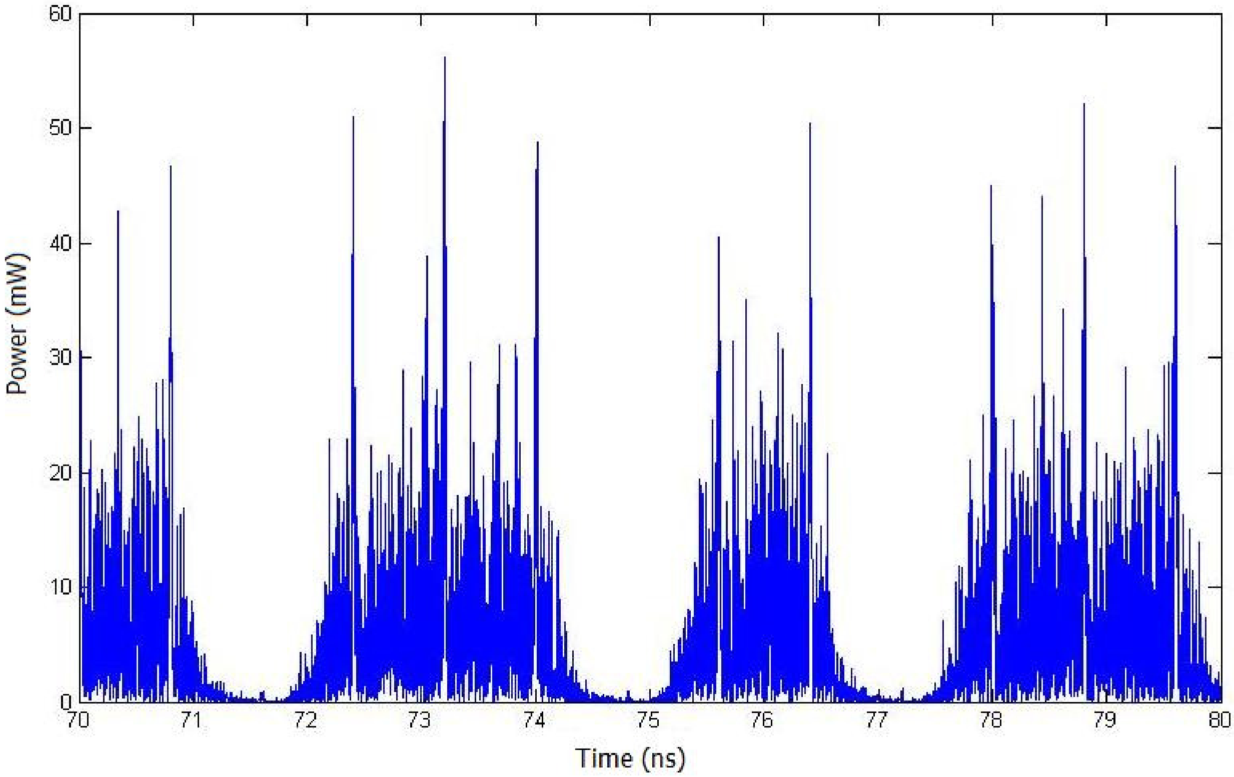

Fig. 4-6: Pulses coming out from an RSOA. It shows the influence of the ASE noise on the quality of the signal

Spontaneous emission is common in all optical amplifiers. Its effect is shown in figure 4-6 where noise can be seen around the pulses. In the case of the studied architecture there is ASE noise only when optical pulses are transmitted. This is because the OOK modulations, when a logical "0" has to be transmitted the bias current is zero and therefore no amplification is done and neither ASE noise is at the output. In figure 4-6, the zones where there is no noise and either pulses, correspond to the instants where logical zeros are transmitted.

Bandpass filters can be used to filter out any kind of noise out of the pulse bandwidth. This filter will be very effective in the reduction of ASE noise. In order to reduce any additional power produced by this noise when travelling through the fiber, the pulse filter will be placed right after the RSOA. This filter is a 4th order band pass Butterworth filter, centered at 193.1 THz and a width of 50 GHz. The effect on ASE noise is clearly shown by the next figure.

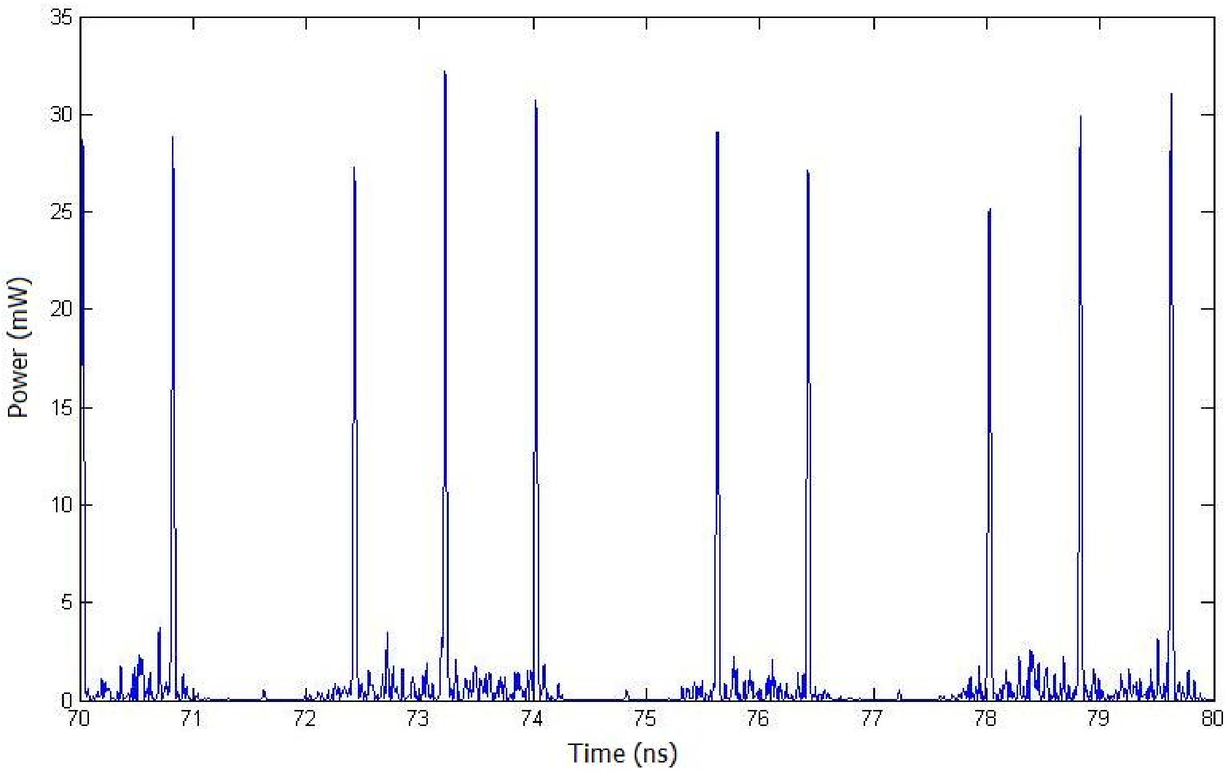

Fig. 4-7: Pulses coming out from an RSOA and filtered at the output of the amplifier.

Signal quality is improved significantly when using the pulse filter. Comparing both time domain plots, from figure 4-6 and 4-7, the need of a pulse filter after the RSOA is proved. ASE noise is almost eliminated and therefore the signal to be transmitted through the fiber will have fewer disturbances and potential distortions caused by this noise when passing through the fiber will be eliminated.

Even though the signal is clearly improved, the pulse will remain unchanged as can be seen in the eye diagrams of figures 4-8 and 4-9. The effect of ASE noise reduction is also seen, but the pulse shape is not changed. The eye in both cases is almost equal, as it was expected because the purpose of the filter is just to eliminate everything out of the pulse bandwidth, so the pulse will remain intact.

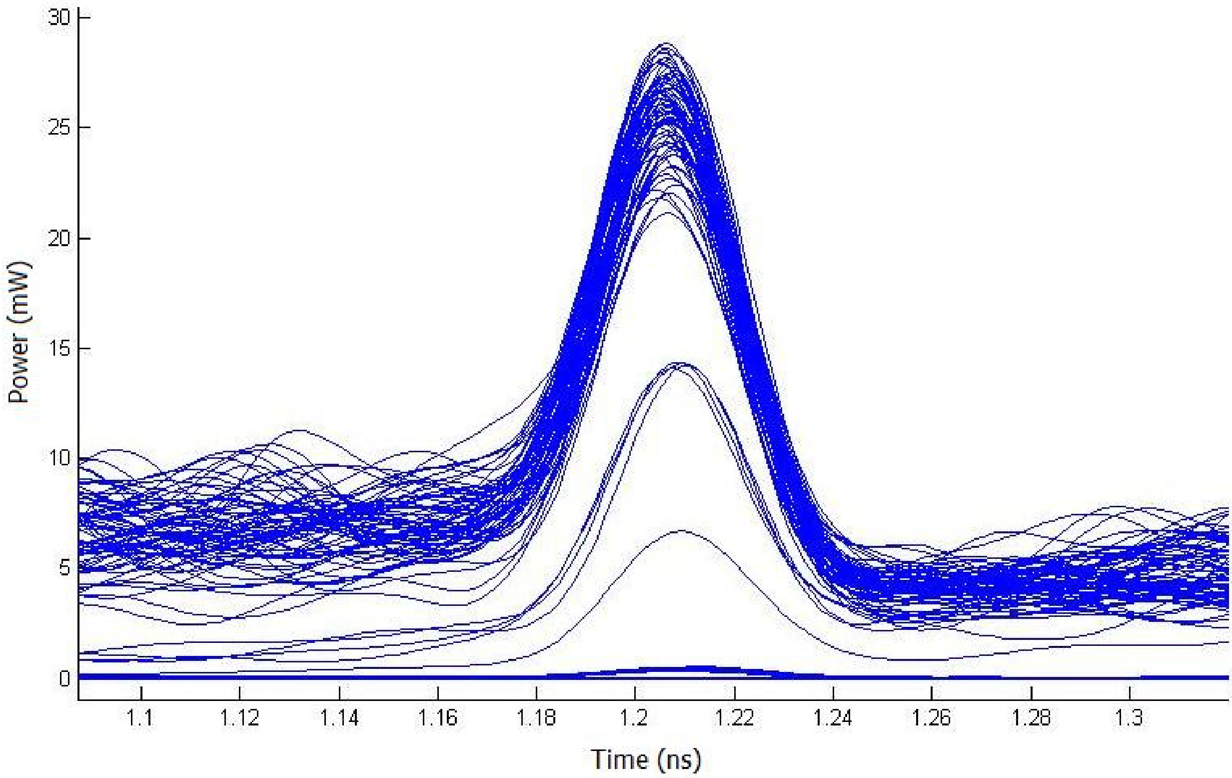

Fig. 4-8: Eye diagram of the RSOA output signal

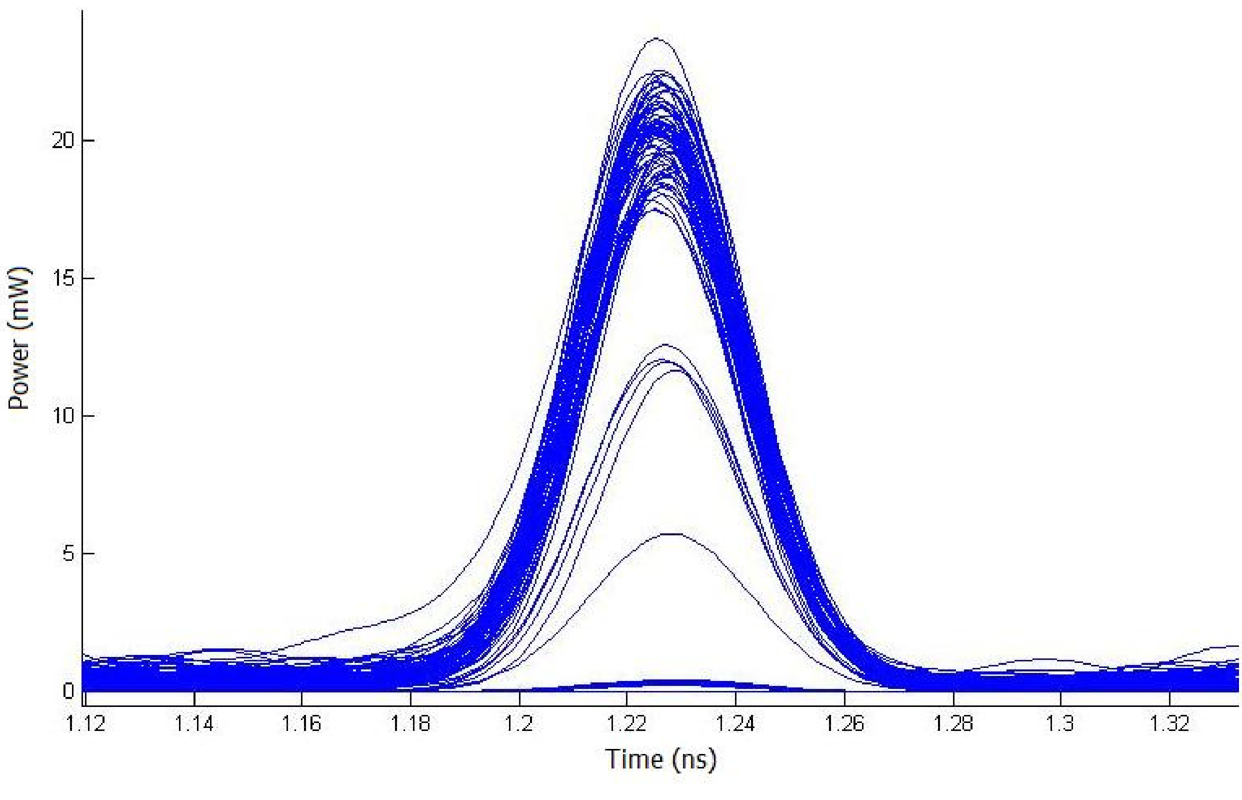

Fig. 4-9: Eye diagram of the filtered RSOA output signal

The optical spectrum will also have a sensible modification. Before the filter the spectrum has side lobes that correspond to the pulse surrounded by a constant and high level of optical power belonging to the ASE noise. In the frequency domain, it can also be seen that this noise produced by the amplifier has a constant power contribution.

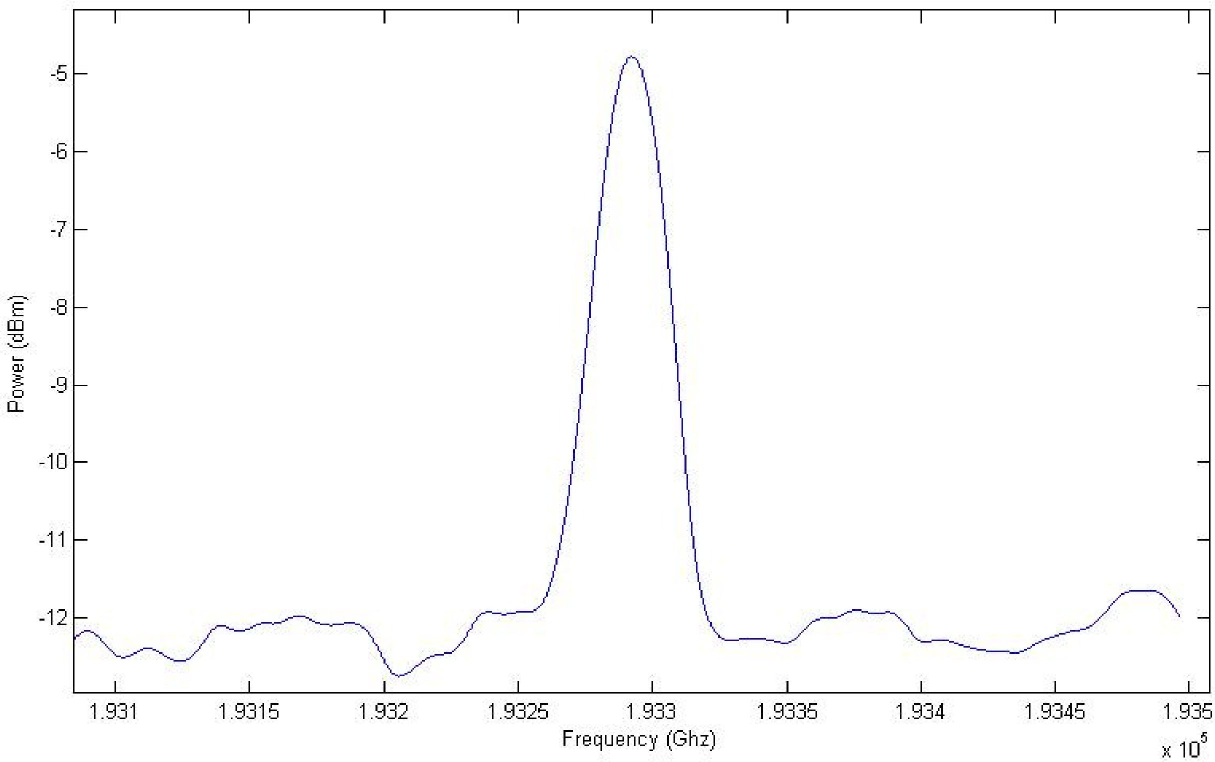

Fig. 4-10: Optical spectrum at the output of the RSOA

When applying the filter, the constant power corresponding to the ASE noise is eliminated. Instead, the shape of the spectrum corresponding to the pulse is longer and goes down to a zero power level.

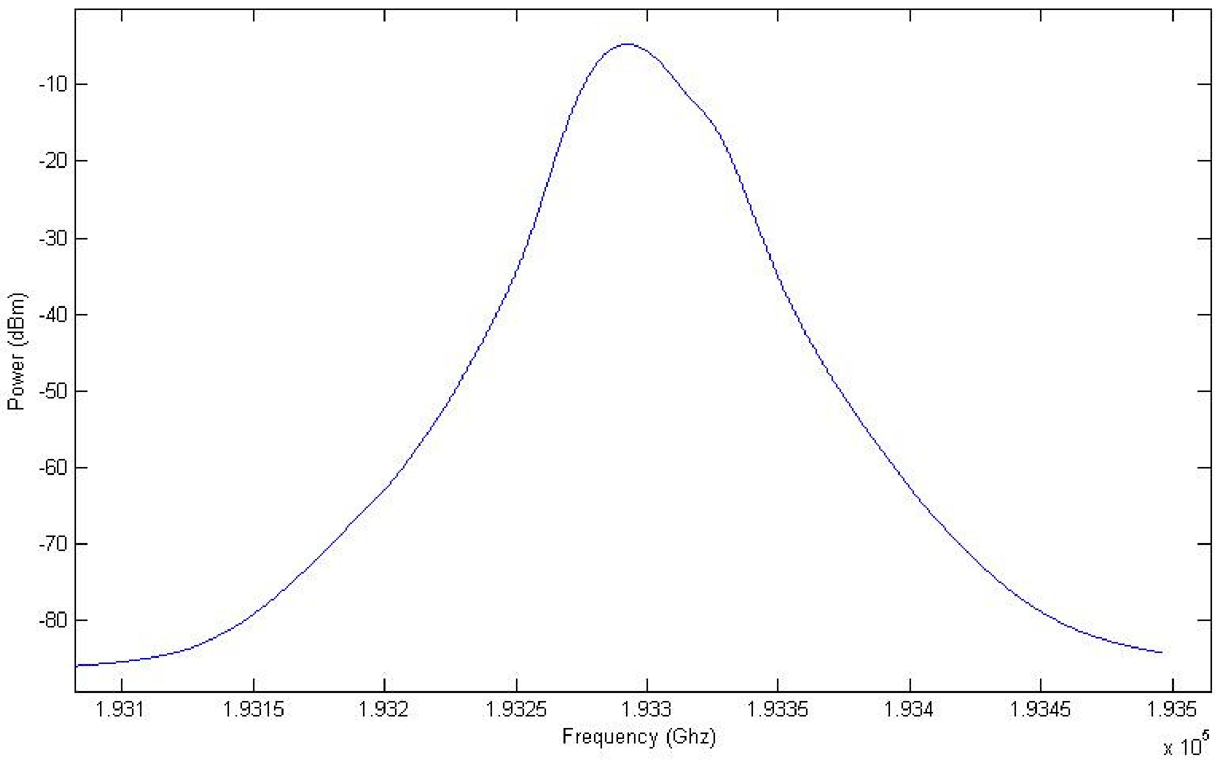

Fig. 4-11: Spectrum of the filtered signal after the RSOA

4.4 Data delay

Data delay is an important parameter to be set for performance optimization. As the basis of the system is pulse transmission, data and pulses have to be synchronized. Pulses can arrive at any time to the RSOA because of different system delays. It is optimum to have the RSOA fully charged by electrons when the optical pulse has to be amplified, and as the data signal is the carrier of the bias current, it is determinant to synchronize data with pulses.

It will be assumed that the system does not loose synchronism and therefore the delay will be a constant parameter. This parameter will depend on separation between pulses, and therefore in the range of 0 to 0.8 nanoseconds.

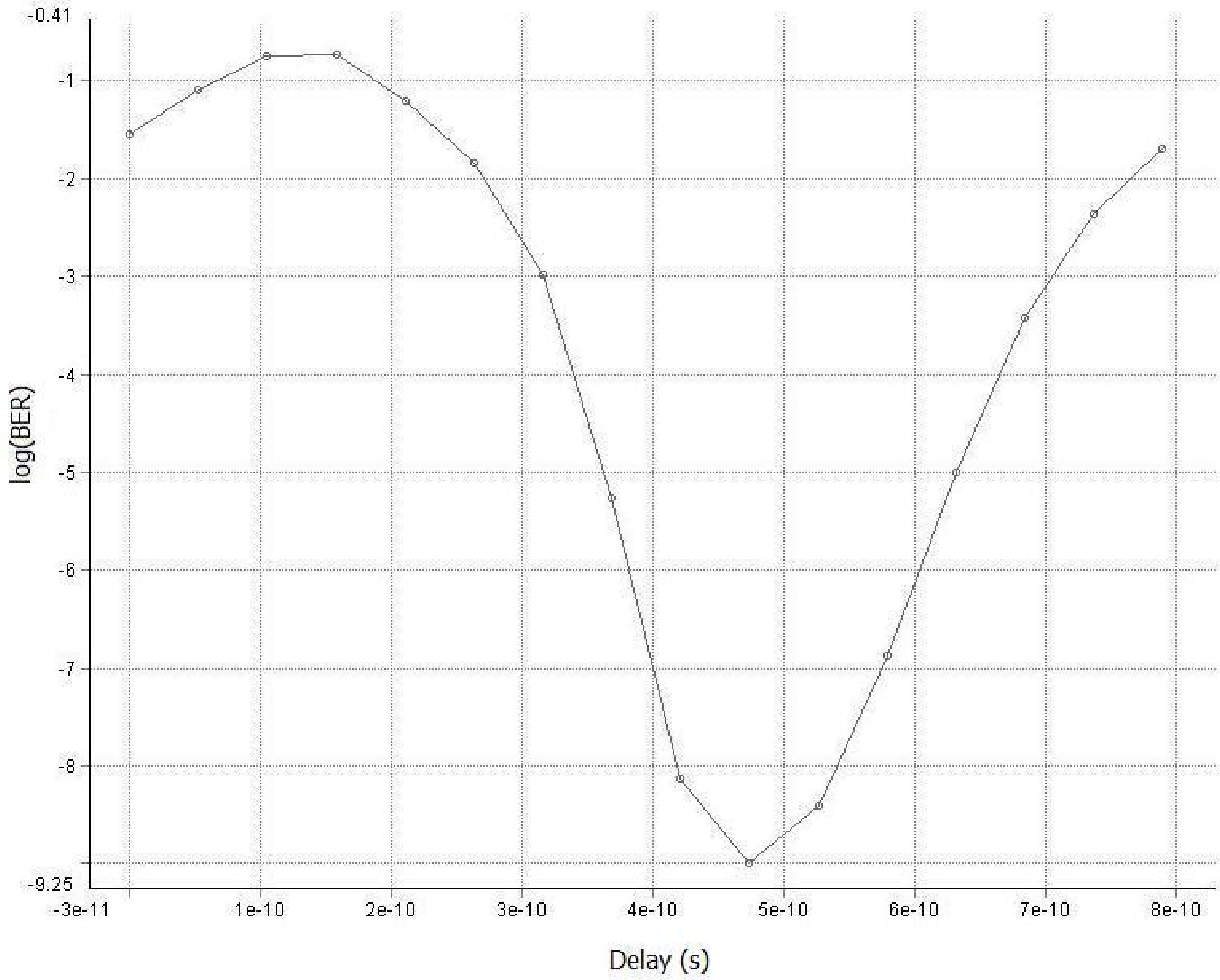

Fig. 4-12: System performance versus data delay

The importance of the data delay is explained by the level of charge that the cavity of the amplifier has. It is optimum to have the amplifier full of electrons ready to recombine and start light emission right when the pulse inputs the device, as shown in figure 4-14. If the arrival of the pulse concurs with the data, the pulse will saturate the amplifier and gain may be negative. Even attenuation or distortion of the pulse may occur when the delay is not optimized. Figure 4-12 shows the importance, in terms of system performance, of the data delay. No optimization of this parameter may introduce a full error transmission, disabling data transmission. This oscillation of the system performance when modifying the delay can go from almost error free rate to a maximum error rate. In case of no delay, the data and pulses are synchronized to the internal clock of the simulation environment. The objective is to have the pulses corresponding to the 0-level as attenuated as possible and the pulses corresponding to the 1-level as powerful as possible, so that the difference in power between them is the maximum.

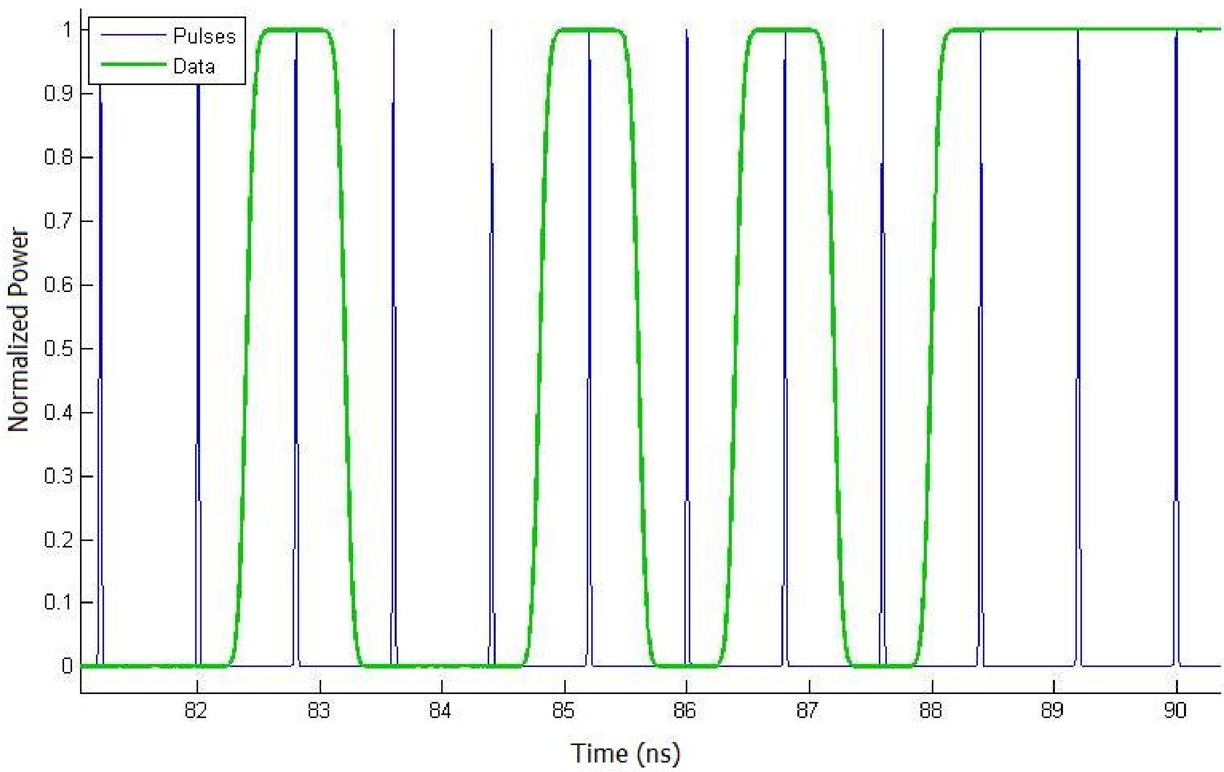

Fig. 4-13: Representation of pulses and data arriving to the RSOA without data delay

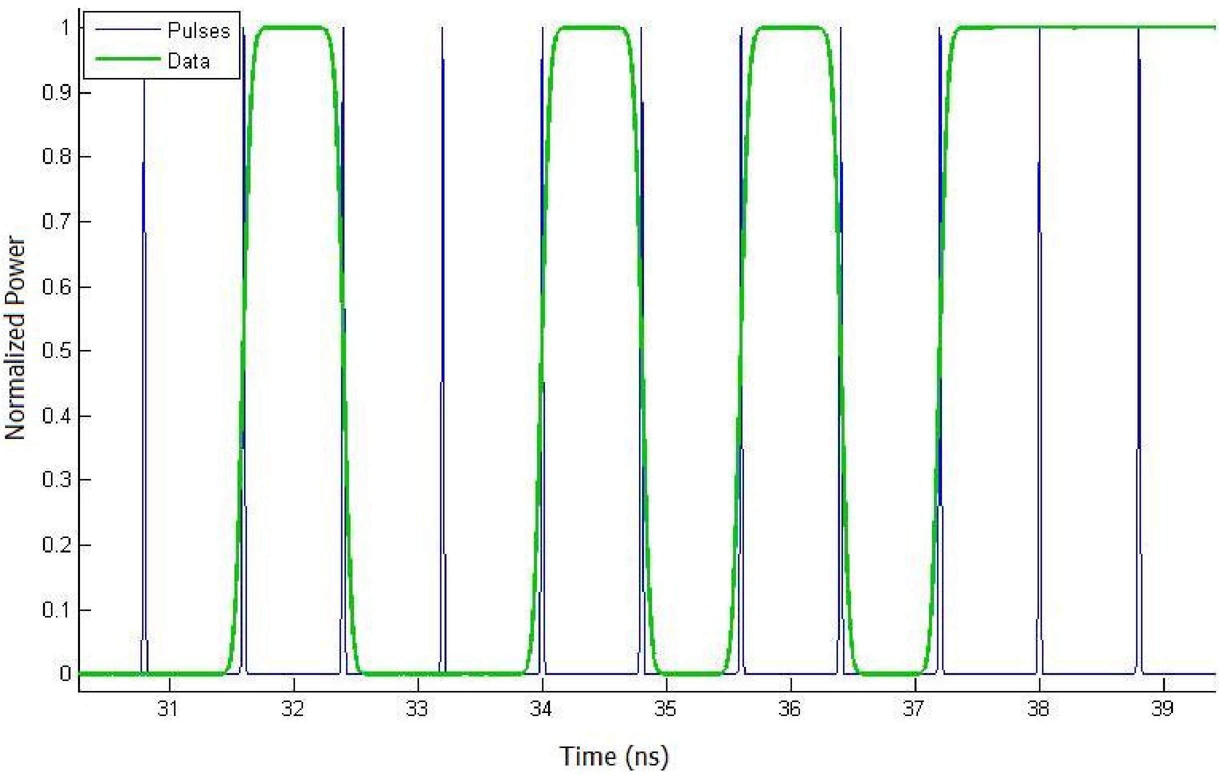

Fig. 4-14: Representation of pulses and data arriving to the RSOA with an optimum data delay

4.5 Receiver

After travelling through the fiber and be reflected and amplified by the RSOA the pulses arrive to the receiver and are converted into the electrical domain. In this process a photo-detector, filters and operational amplifiers are involved in order to have an optimal electrical signal and calculate system performance.

Photo-detectors generally have associated operational amplifiers because the voltage that outputs is too low and noise can distort the signal when going through the decoding circuits. Before this amplifier a filter is introduced to eliminate everything out of the data bandwidth, in our case 12 GHz. The minimal required filter bandwidth can be calculated by considering the Time-Bandwidth Product (TBP) for chirp-free (transform-limited) 1^{st}-order Gaussian pulses. The TBP is a multiplication of the pulse duration and the bandwidth at Full-Width at Half-Maximum (FWHM). In this case, the TBP is greater or equal than 0.44 so the bandwidth is equal to 23.15 GHz. The Nyquist theorem then stipulates that the minimum receiver bandwidth should be equal to 0.5*23.15 = 11.6 GHz. This filter is especially important when applying spectral broadening techniques for RBS reduction. These techniques will introduce power out of the pulse bandwidth and it is preferred to be eliminated at the receiver side using low pass filters.

It can be seen in figure 4-15 that the shape of the pulses remains almost unchanged. The photo-detector is optimized for this particular pulses and the optical to electrical transition is achieved linearly. The figure also shows that the pulses voltage is in the order of micro-volts, which would be low for data treatment after being decoded.

The amplifier introduces a sensible gain to the pulses, passing from micro-volts to hundreds of micro-volts. In the other hand, thermal noise is added reducing the quality of the signal. There is also a pulse broadening because the pulse exceeds the filter bandwidth and cuts high frequencies.

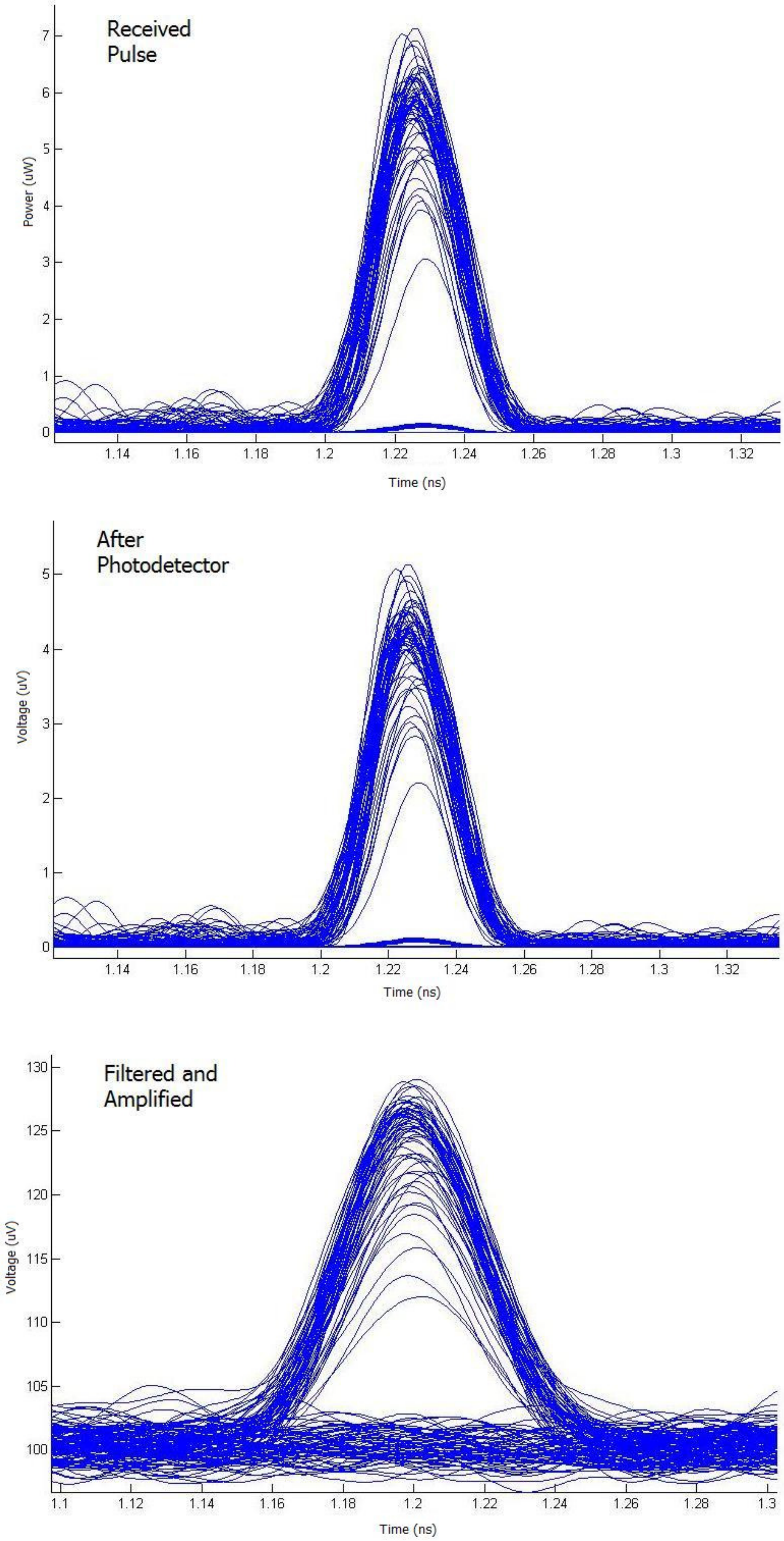

Fig. 4-15: Eye diagram of pulses travelling through the components of the receiver

For all simulations and system analysis, a receiver attenuation has been first established in order to reference all changes in performance to a 10^{-9} bit error rate.

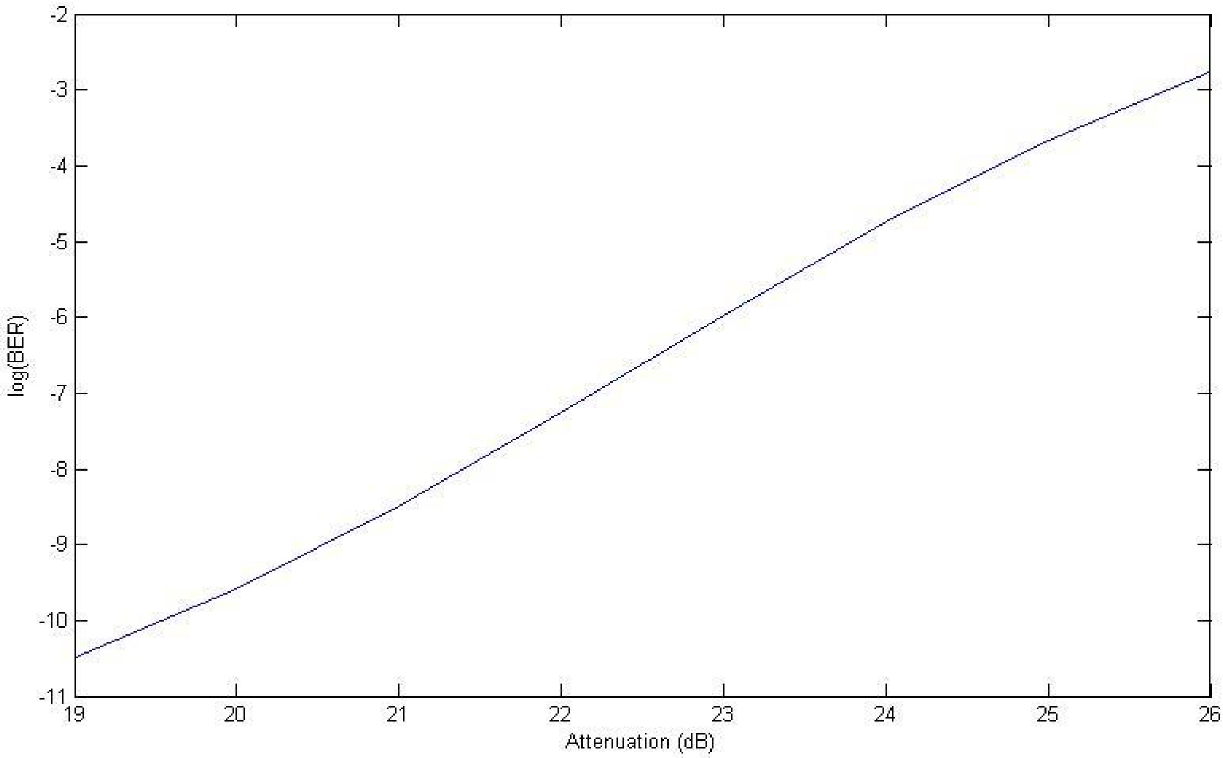

Fig. 4-16: Bit Error Rate versus Receiver attenuation

The system performance has a linear behaviour when increasing the receiver attenuation. On a real system, this attenuation would be the power margin at which the system is guaranteed to work under error-free conditions. Thus, in the following system simulations, the receiver attenuation will be set to 21 dB.

Chapter 5

RBS reduction

This chapter will introduce how the system behaves when applying two techniques of spectral broadening: SPM and bias dithering. The application of these two techniques will be studied for RBS penalties reduction. In this chapter the techniques will be presented and analyzed, some network elements are tuned without taking fiber into account to optimize their individual performance, like the receiver and the RSOA. Then, fiber is taken into account. The overall performance, with fiber RBS impairments activated, will be evaluated in the following chapter for further conclusions on the capabilities of these techniques.

5.1 Reducing RBS penalties

As explained previously, Rayleigh Backscattering effects may cause considerable penalties produced by in-band crosstalk on bidirectional transmissions. Applying broadening techniques to the system may improve the overall performance. The goal is not to remove the Rayleigh Backscattering effects, it is to prevent that the backscattered signal induce in-band crosstalk. The goal of spreading the spectrum is to spread the optical power over a larger bandwidth. This means that the coherence length of the light is reduced. The relation of the coherence length and spectral width is described by [34]:

$$L_c = \frac{c}{n \Pi \Delta\lambda}$$

where *c* is the vacuum light speed, *n* is the refractive index and $\Delta\lambda$ is the spectral linewidth.

The optical spectrum of the signal can be broadened deploying the amplitude-to-phase coupling in the RSOA. Due to the change in the carrier density caused by a variable current applied to the device, the refractive index of the active material also changes. This causes spectral broadening and consequently, the Rayleigh Backscattered in-band crosstalk can be suppressed.

The desired amplitude-to-phase coupling is achieved when an extra modulation signal with an appropriate amplitude and frequency (dithering signal) is applied to the RSOA together with the bit stream. In the electrical spectrum, if the frequency of the dithering is high enough, it is out of the data bandwidth. Then, applying a low-pass filter at the receiver the dithering frequency is rejected.

5.2 Bias Dithering

For optical spectrum broadening of the pulses coming out of the RSOA, a bias dithering technique will be studied. The bias current that drives the RSOA, and thus the optical power gain to the pulses, is modulated by the data to be transmitted in the upstream direction. For bias dithering, a sinusoidal signal will be added to the transmitted data before driving the RSOA. Therefore the bias current will be re-modulated in order to achieve spectral broadening.

5.2.1 Rectifier

When using Optical OOK modulation, it is important to transmit logical zeros as close to null pulse power as possible. The objective is to have a big difference of received power between pulses corresponding to logical ones and pulses from logical zeros. When and RSOA is used, this can be achieved modulating the bias current of the amplifier and setting the cero level to zero. With this kind of setting, no optical signal will be amplified when the bias current is zero, and even signals coming into the amplifier will be attenuated.

The objective of this study is to apply spectral broadening techniques to reduce RBS. One of these techniques is bias dithering. It is based on the application of a RF signal to the data in the electrical domain. The effect can be seen as a modulation of data at a frequency double the bit rate, as shown in [1]. That value was limited by the modulation bandwidth of the RSOA (approx. 3 GHz) modeled in VPI.

As data is used to pump the amplifier, the modulation of data will dither the bias current going into the RSOA. This technique will reduce the quality of the overall signal, as pulses will now have amplification when logical zeros are transmitted, but it still may be worth because of RBS penalties reduction. The effect of adding the dithering signal to the data current is shown later in this section.

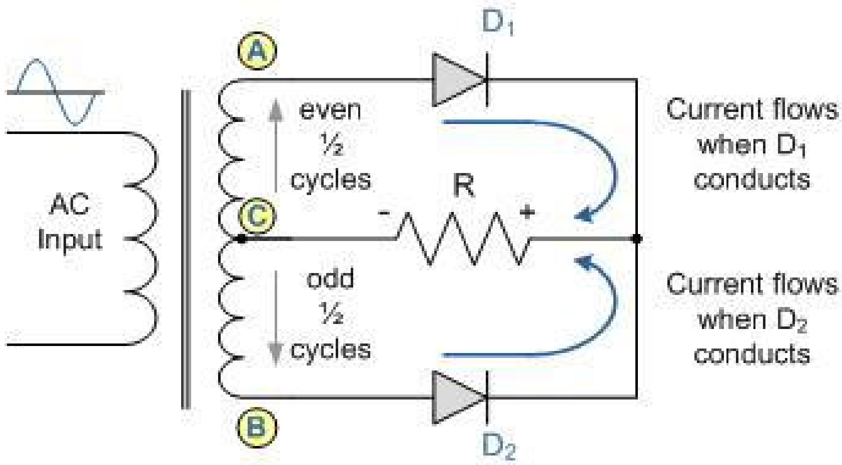

Fig. 5-1: Scheme of a Full-Wave rectifier circuit

Adding an RF signal to the bias current means that at cero levels current will introduce negative currents into the amplifier risking the stability and security of the amplifier. To prevent negative bias current from going into the amplifier, a rectifier will be used before the RSOA. Due to simulation software limitations, the element to be used in this study will approach the behaviour of a full-wave rectifier when the input signal is half the frequency of the signal original signal. Even though a half-wave rectifier could have better performance in terms of bit error rate, because it would introduce less amplification to the logical cero pulses, a full-wave approach will be studied due to simulation software restrictions.

This element changes the sign of negative voltages when arriving to the device. If a sinusoidal signal swinging around 0 volts, of amplitude V is applied to a rectifier, the resulted signal will approach another sinusoidal signal of amplitude V/2 swinging around V/2 volts.

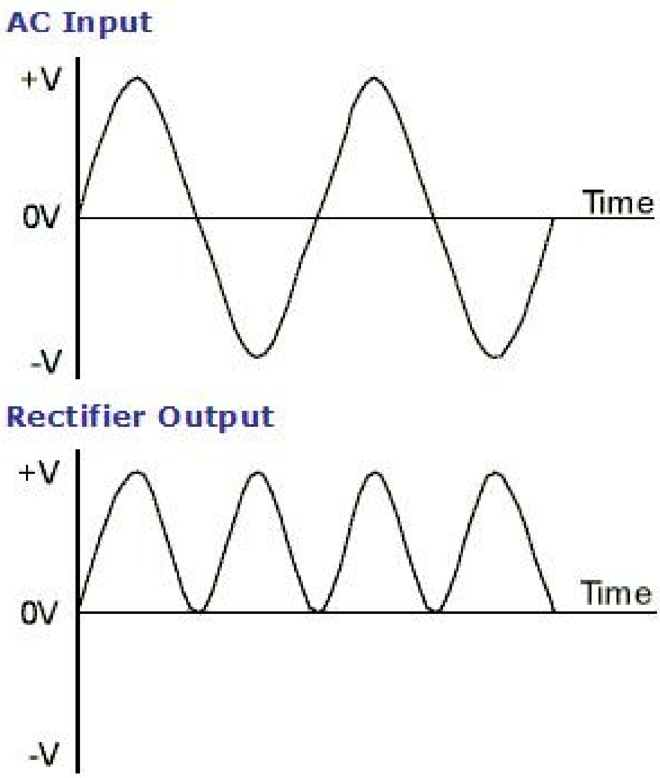

Fig. 5-2: Time domain representation of the behaviour of a Full-Wave rectifier

In the case of this study, the RSOA bias driving signal will have the shape of a sine wave of 45 mA amplitude swinging around 55mA for the logical one level. The zero level will be rectified, and thus, the peak-peak amplitude will be 45mA above 0 A.

The objective of having the signal over 10mA for the “1”-level, is to exceed the transparency current level of the amplifier. If the current is under this level, the amplifier will not be working correctly as will be shown later when analyzing the behaviour of the amplifier. For this reason the signal minimums corresponding to the logical ones need to be above 10 mA.

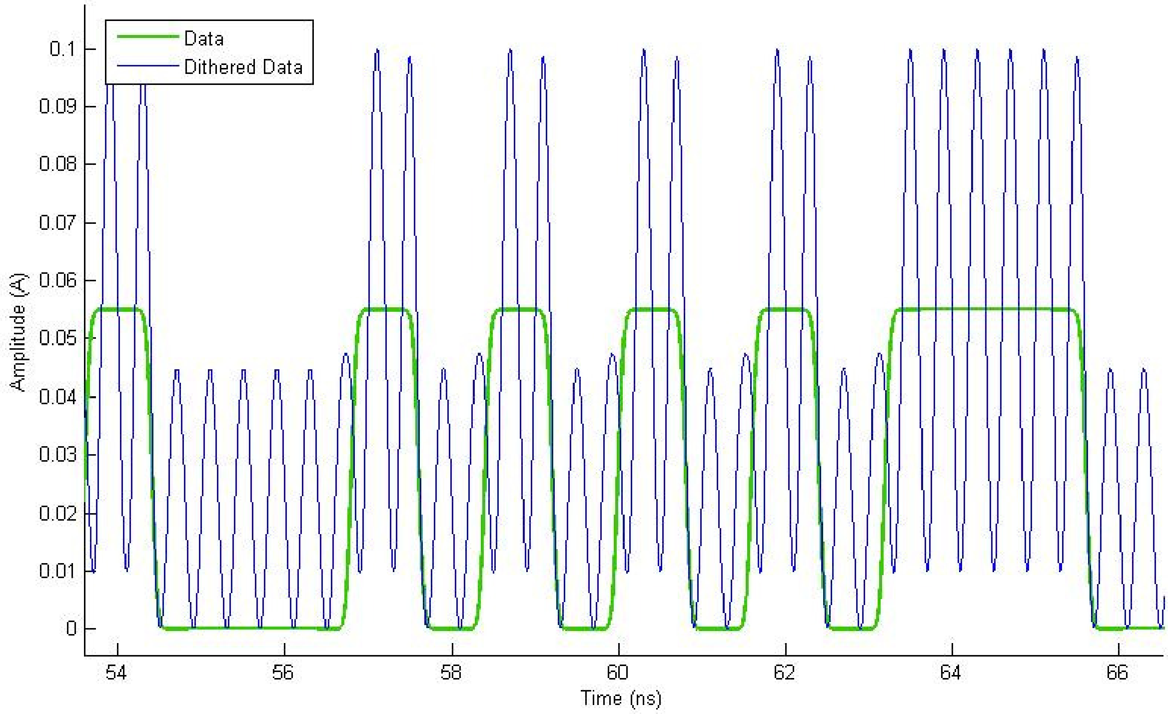

Fig. 5-3: RSOA bias driving signal after being data-modulated and dithered

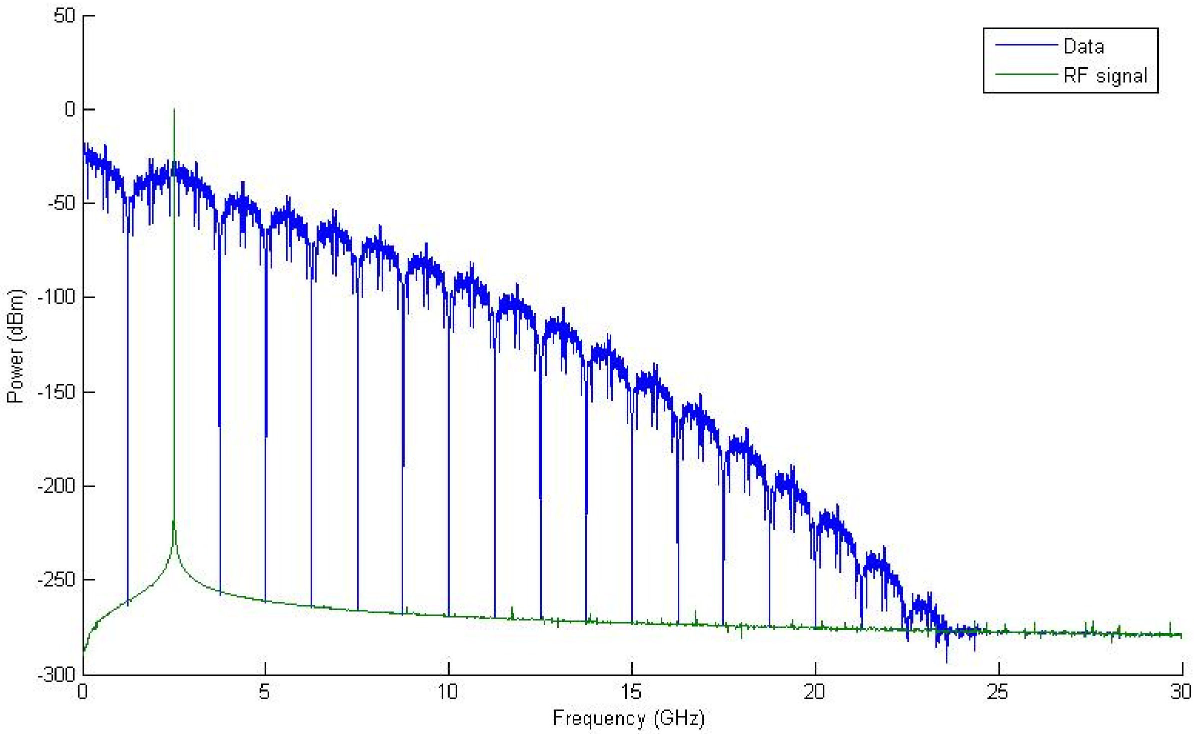

Fig. 5-4: Spectrum of both data and RF signal applied to the bias current

The contribution of the dithering to the spectrum of the signal arriving to the RSOA is a delta positioned at 2.5 GHz. It has a peak power of 1mW, over passing the power of the data signal. Figure 5-3 shows the final time-domain signal that will be driving the bias of the RSOA. It is important to notice that the signal never goes under 10mA when there is a logical one in order to surpass the transparency current of the amplifier. If this was limit was not respected the signal will be attenuated rather than amplified as it will be shown in RSOA gain performance. The upper limit of 100mA determines a linear behaviour. This limit, as studied in [34], if surpassed there will be a distortion of pulses.

It can be concluded that the application of a dithering signal to the data stream modifies noticeably the driving signal of the amplifier and therefore the system performance will have a different behaviour.

5.2.2 Amplitude and Phase

A big difference on system performance is expected when applying different RF signals to the bias current. The amplitude and the phase of this RF signal are closely related and will determine improvements or deteriorations on the quality of the pulses arriving to the receiver.

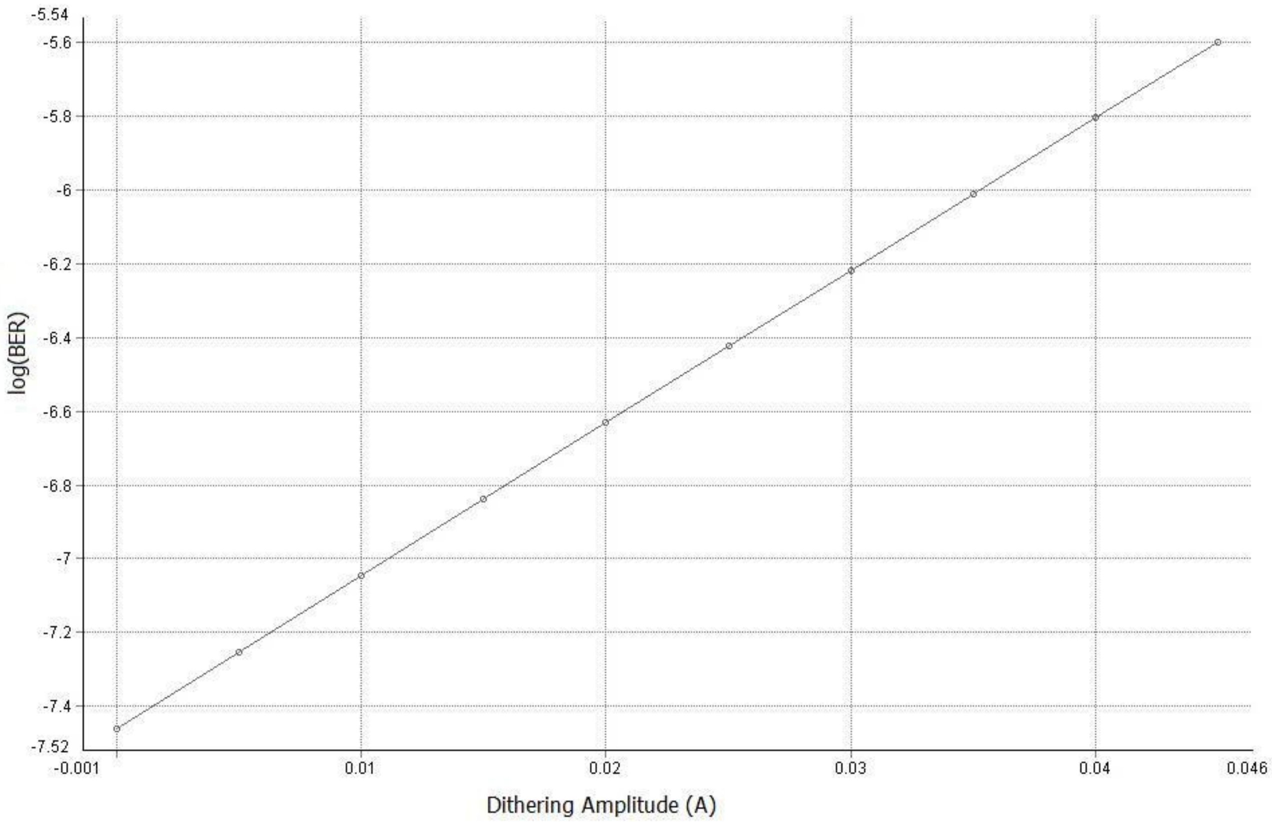

Fig. 5-5: System Bit error rate versus Dithering amplitude

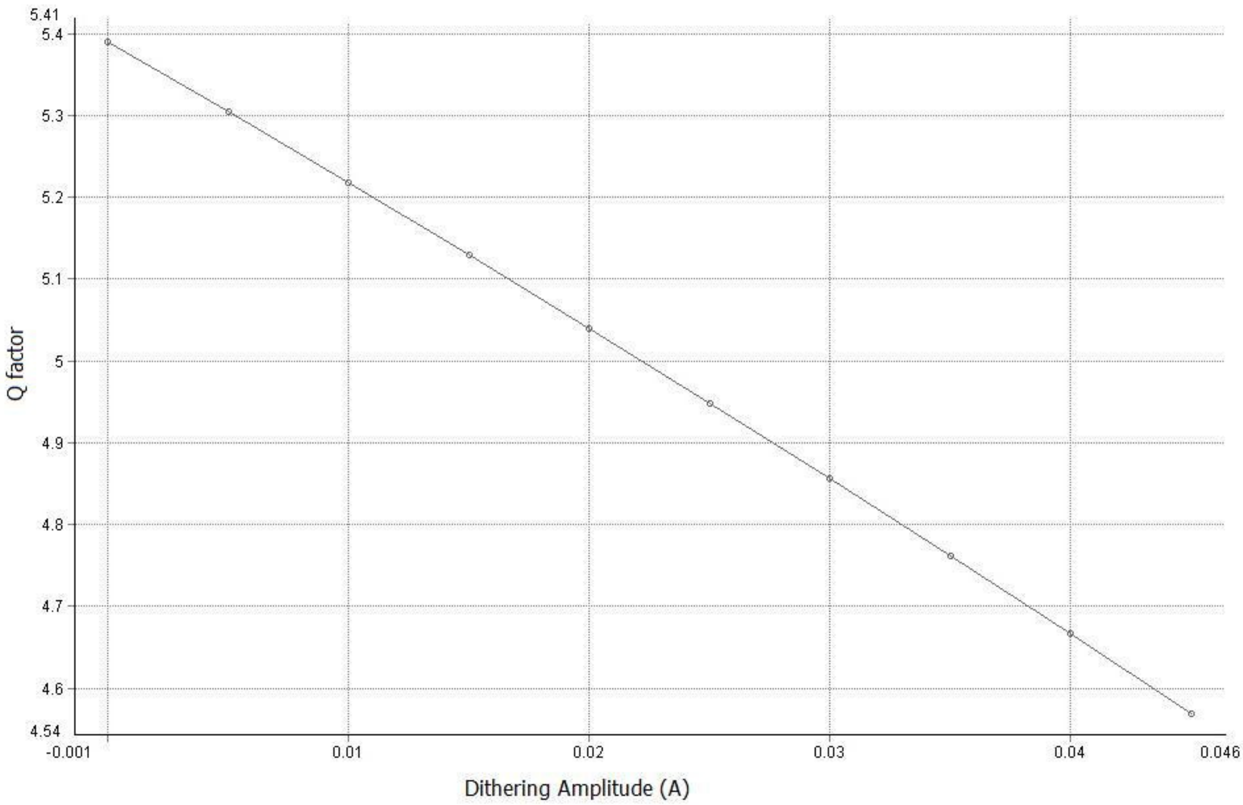

Fig. 5-6: Q factor versus Dithering amplitude

Figure 5-5 and 5-6 show the performance of the system when applying the RF signal at different amplitudes. The Q factor or quality factor is a measure of the "quality" of a system, and like BER it is used for performance comparisons. The relation between the Q factor and BER is

$$BER = \frac{1}{\sqrt{2\Pi Q}} \exp\left(-\frac{Q^2}{2} \right)$$

The phase of the signal is set to zero. It is the worst case, where the gain of the amplifier decreases with the amplitude. This is explained by the arrival of the optical pulses to the amplifier. The pulses arrive at a moment where the amplitude of the bias is lowest and therefore the gain is the minimum. The amplitude is lowest coinciding with the minimum of the RF wave as it is shown later in figure 5-9.

To improve amplification of pulses, the phase has to be set in order to have both RF signal and pulses synchronized. This phase value can be obtained using a similar sweep, but focusing on the phase. Figures 5-7 and 5-8 prove the dependence of the system performance with the phase.

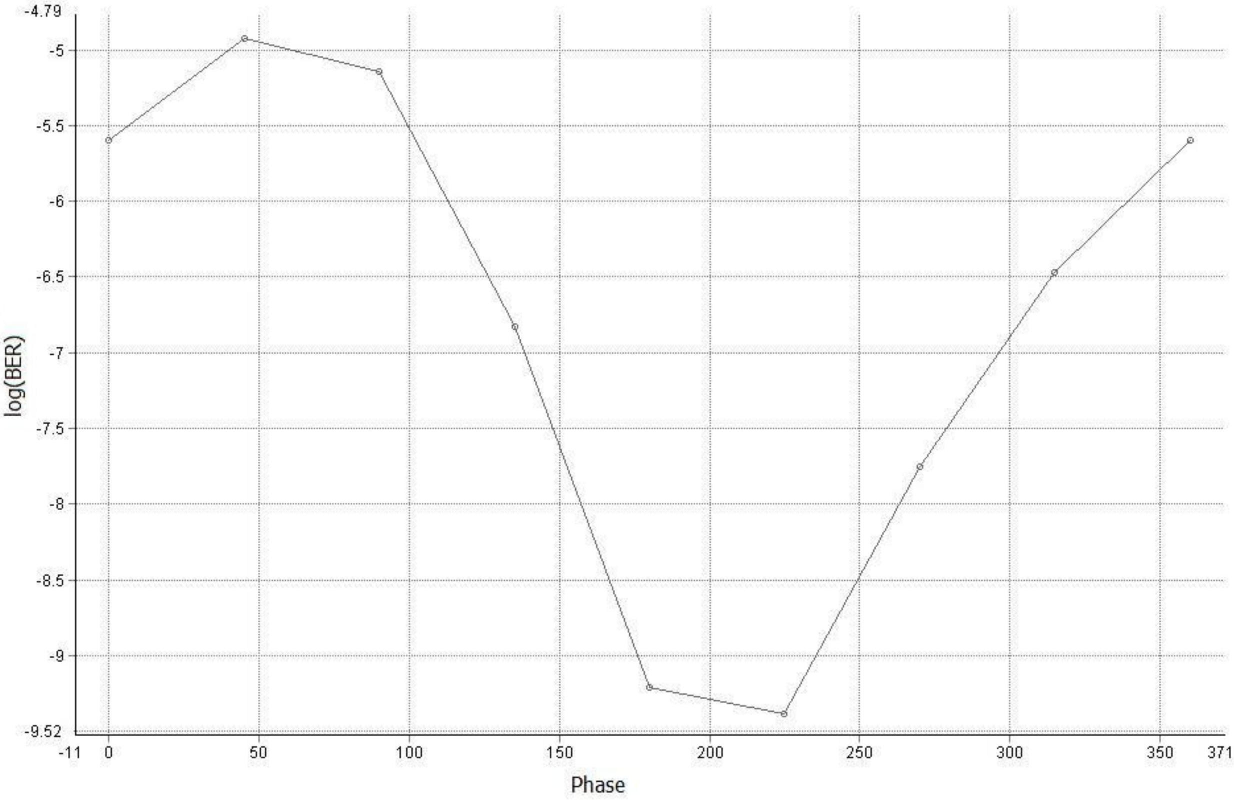

Fig. 5-7: Bit error rate versus Dithering phase (Amplitude: 45mA)

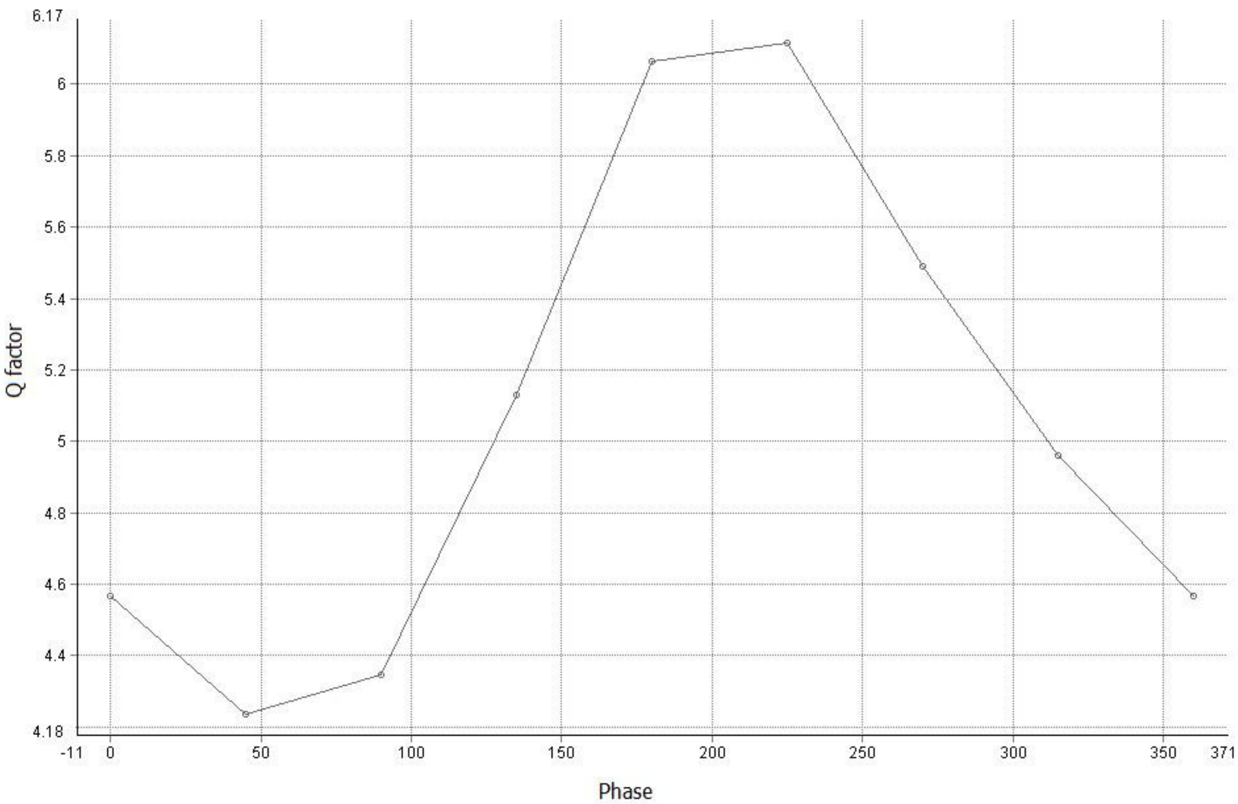

Fig. 5-8: Q factor versus Dithering phase (Amplitude: 45mA)

The difference in performance at different phase values is close to five orders of magnitude of bit error rate. The RF amplitude for these sweeps is set to 45 mA, meaning that if the amplitude of the logical one is 55 mA, the minimum is near 10 mA. If the amplifier is fed by 10 mA there will not be any amplification, because it is the transparency current at which the amplifier will start to emit photons when an optical signal enters the cavity.

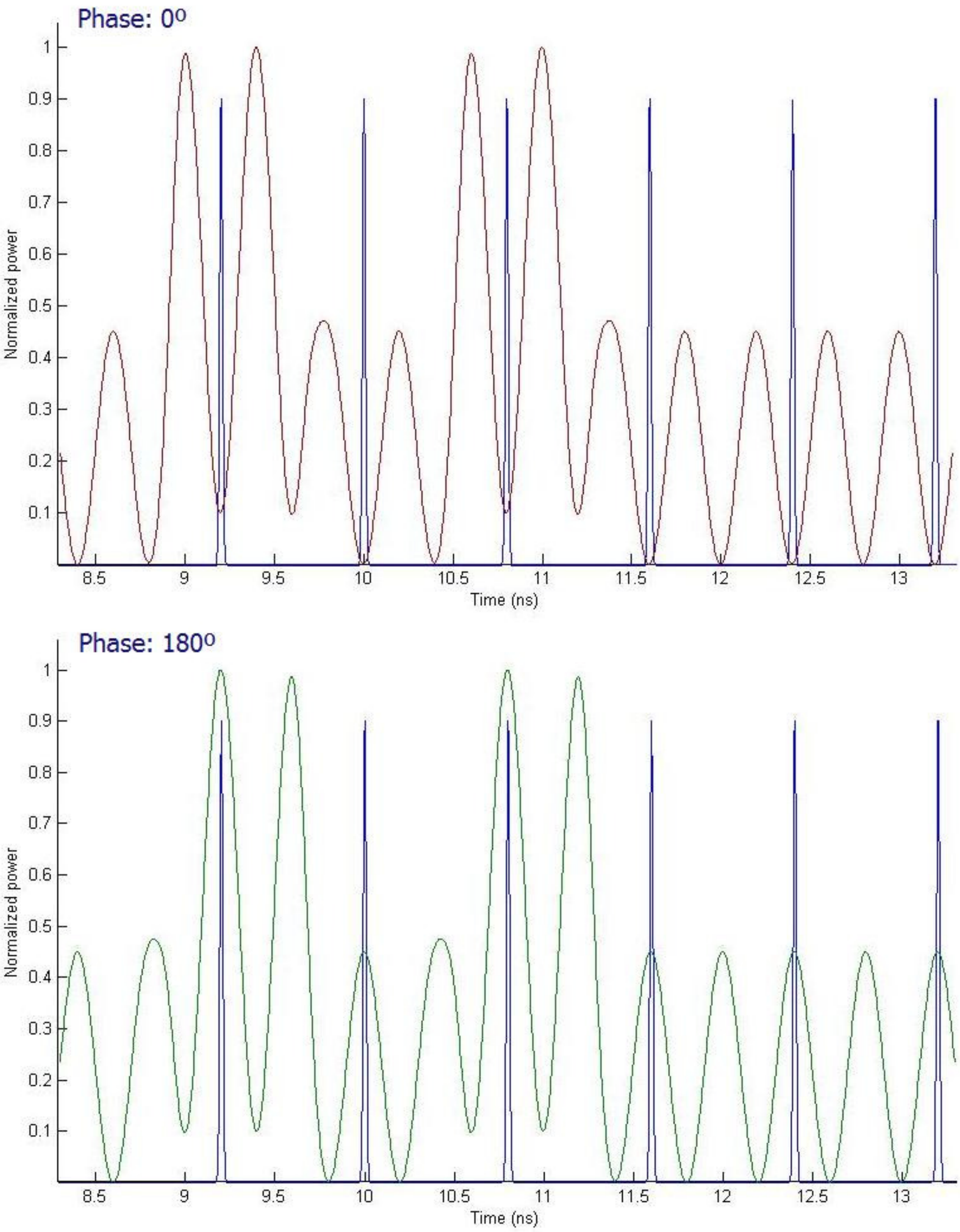

Fig. 5-9: Incoming pulses to the RSOA and modulated bias current at two different phases (0 and 180)

When the phase is set to 0 degrees, the pulse is synchronized with the minimum of the bias signal and therefore the RSOA will not have electrons to convert into photons and thus optical amplification. The pulses will be reflected back with some distortion (because is in the transparency current limit) and no optical gain, finally arriving to the receiver with double attenuation, from both trips through the fiber, decreasing sensibly the system performance.

On the other hand, when pulses are synchronized with the RF maximums, both “zero” and “one” logical pulses will get maximum amplification by the RSOA. The “zeros” will arrive when the amplifier is fed by 22.5 mA and the “ones” by 100mA. It would be optimum to have a full attenuation for “zero” but the phase is constant and it is preferred to have full amplification of “one” pulses even though the whole of the eye diagram will be reduced.

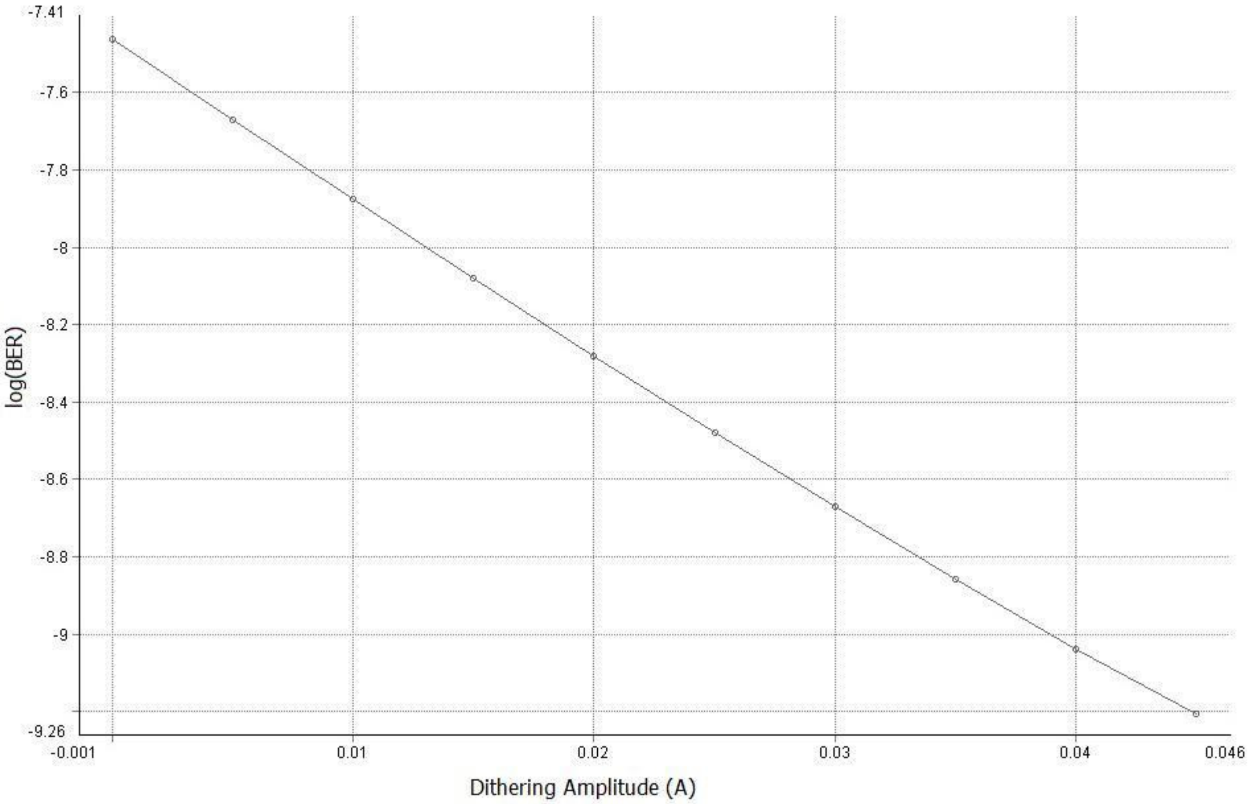

Fig. 5-10: Bit error rate versus dithering amplitude at a phase of 180 degrees

It can be concluded that when phase is optimized the amplification of pulses is maximum, so the bigger the RF amplitude the bigger the gain of the amplifier. The limit on this amplitude will only be the linearity of the amplifier. The RSOA used in this study is capable of amplification of pulses with no distortion if the bias current is under 100mA. Above that limit the gain will increased, but distortions caused by the non-linearity of that region will appear.

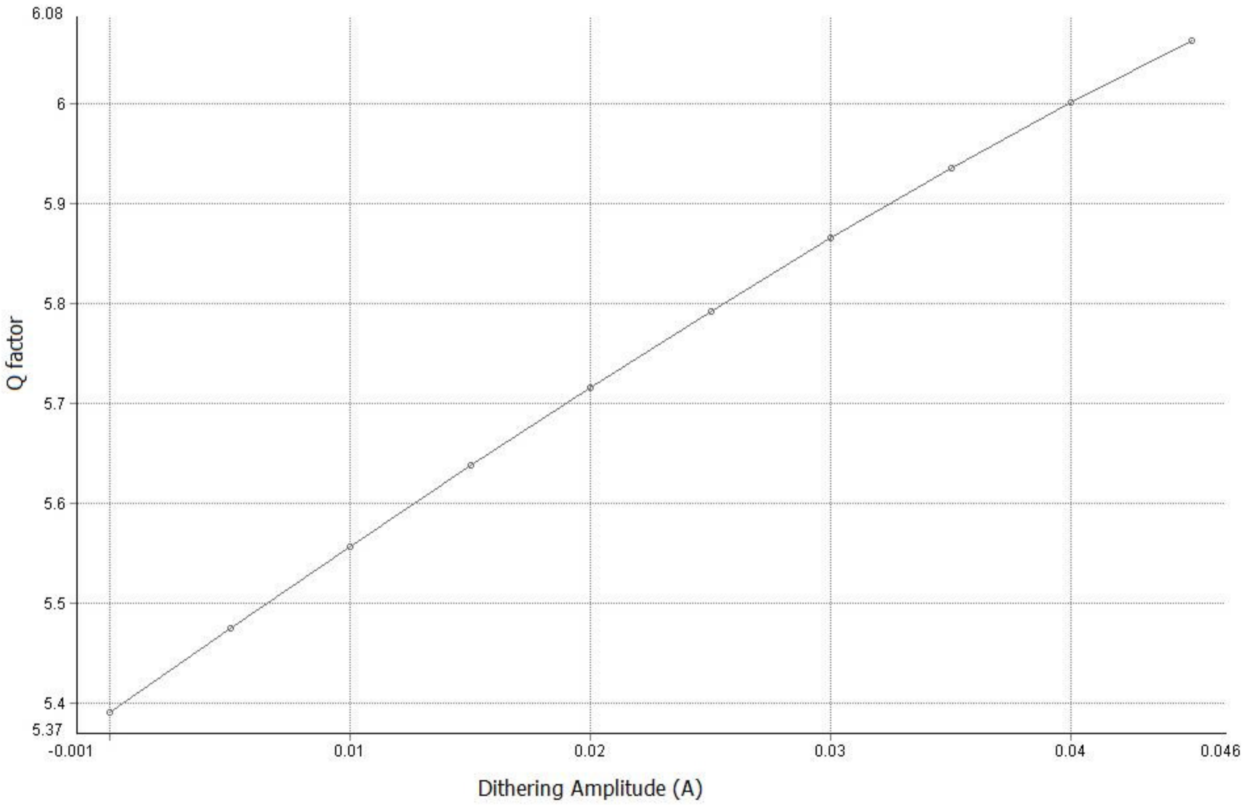

Fig. 5-11: Q factor versus Dithering amplitude at a phase of 180 degrees

Finally, it is shown in figures 5-10 and 5-11 that the system performance increases with the RF amplitude.

5.3 Self Phase Modulation

Self Phase Modulation (SPM) is an effect caused by the intensity dependence of the refractive index in nonlinear optical devices, like an RSOA. This effect causes spectral broadening of optical pulses, producing chirping, modifying the pulse shape and possibly distorting it. Even so, carefully inducing SPM can be useful to reduce RBS penalties.

One of the ways of inducing SPM is saturating the RSOA sending pulses surpassing the power limit at which the amplifier works linearly. Increasing the power will improve the signal to noise ratio along the fiber link, but when arriving to the amplifier, the distortion caused by SPM may be too harmful under high saturation. To get to the point where there is SPM but the performance is not deteriorated is necessary to analyze the system at different pulse power values.

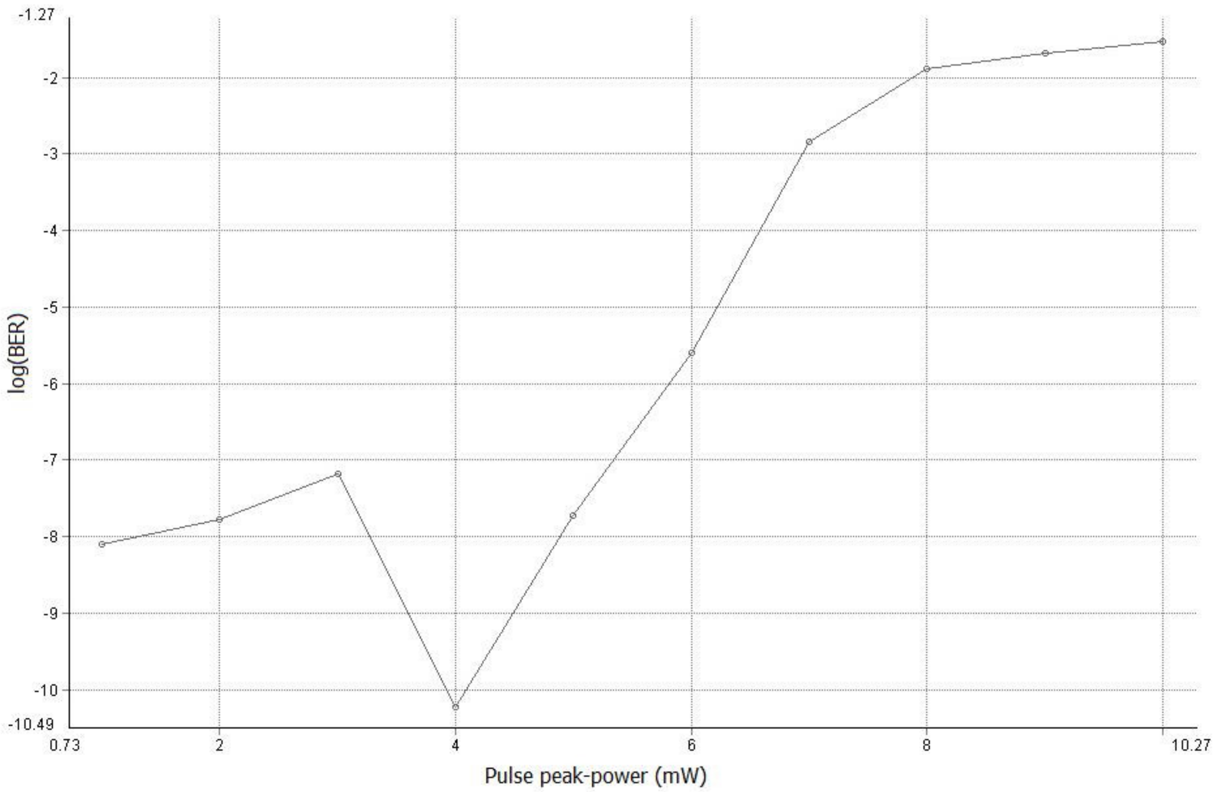

Fig. 5-12: Pulse power transmission versus system performance

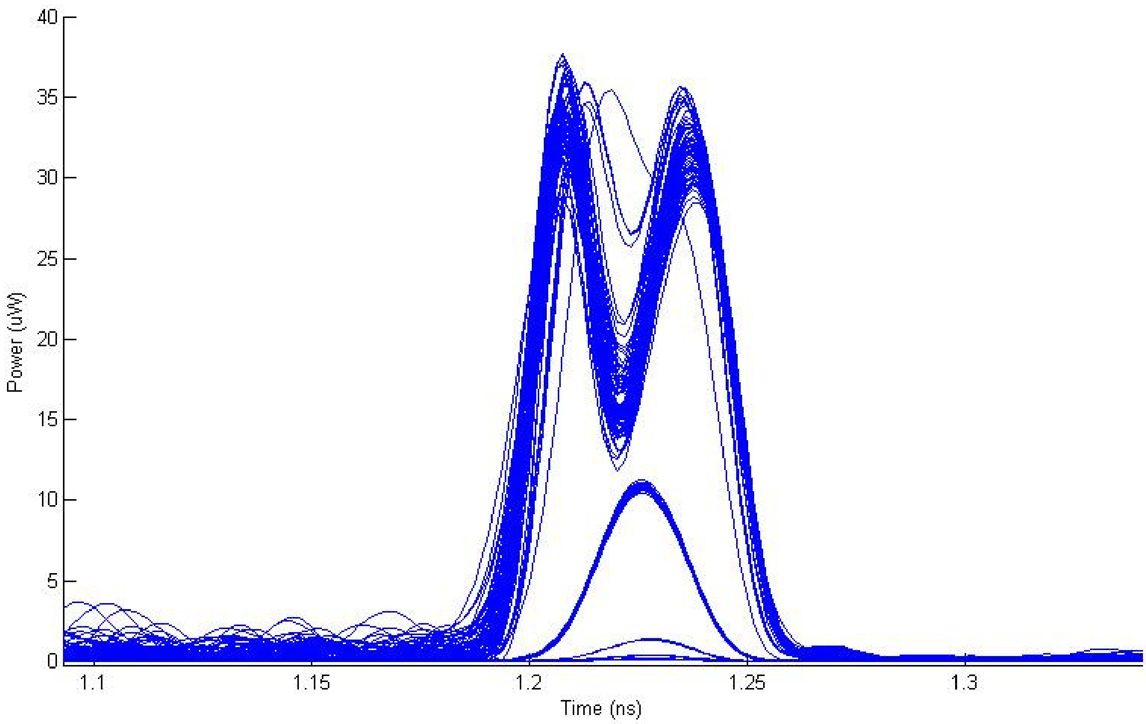

Fig. 5-13: Eye diagram of a pulse distorted by a saturated RSOA

When transmitting pulses above 4 mW, the performance starts to deteriorate fast. The pulses arriving to the RSOA, get distorted and even split if they surpass certain power limits, as it can be seen on the eye diagram of figure 5-13.

Seeing figure 5-12 shows why the performance is deteriorated and can arrive to full error values. Detection of this kind of pulses makes impossible to distinguish if pulses correspond to logical zeros or ones using power thresholds of general decoders.

The spectrum shows that this distortion corresponds to a shift on the frequency of the pulse to lower values and the emergence of new frequencies at higher values. When an un-chirped pulse arrives to the amplifier the intensity is highest at the peak of the pulse and therefore, that part of the pulse experiences the highest refractive index and as a result, propagates slower than the leading and trailing parts of the pulse, delaying it and lowering its frequency. This causes pulse to stretch out on the leading part of the pulse and to pile up on the trailing part of the pulse.

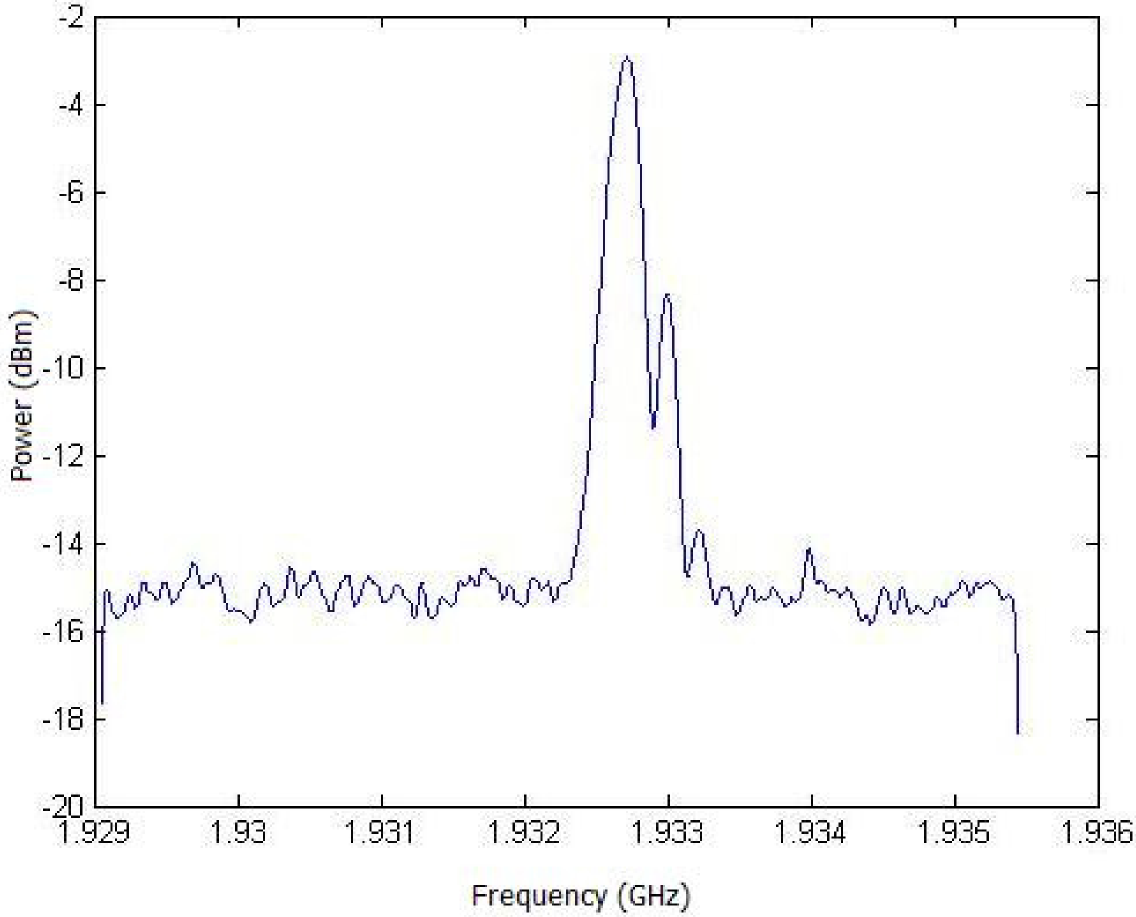

Fig. 5-14: SPM effect on the spectrum of an optical pulse, as studied in [32].

While increasing the power of the pulse, and thus increasing the saturation of the amplifier, new slopes will start to appear at the higher frequency side of the pulse spectrum. These new slopes correspond to the new smaller pulses created from the original pulse.

Pulse Power	1 mW	10 mW	20 mW	30 mW	40 mW	50 mW
Pulse width (Ghz)	22,6172	56,6309	65,127	65,7969	67,9395	69,1797

Table 5-1: Comparison of pulses at different power levels and their spectral width after being amplified by the RSOA

When measuring the Full Width at Half Maximum (FWHM) of the SPM pulses in the frequency domain as shown in table 5-1, it is noticed that the spectrum rapidly increases for lower values of the pulse peak power. In the other hand, when talking about bigger pulse power the spectrum broadens at a lower rate. This is explained by the new slopes created on the high frequency side of the original pulse (which cause of the broadening) that are relatively lower in power to the main pulse. They all start to appear below the threshold of half peak power.

A pulse peak-power of 4mW is best for SPM inducing at the RSOA. It does not introduce enough distortion to reduce system performance and it produces spectral broadening, as it is the goal.

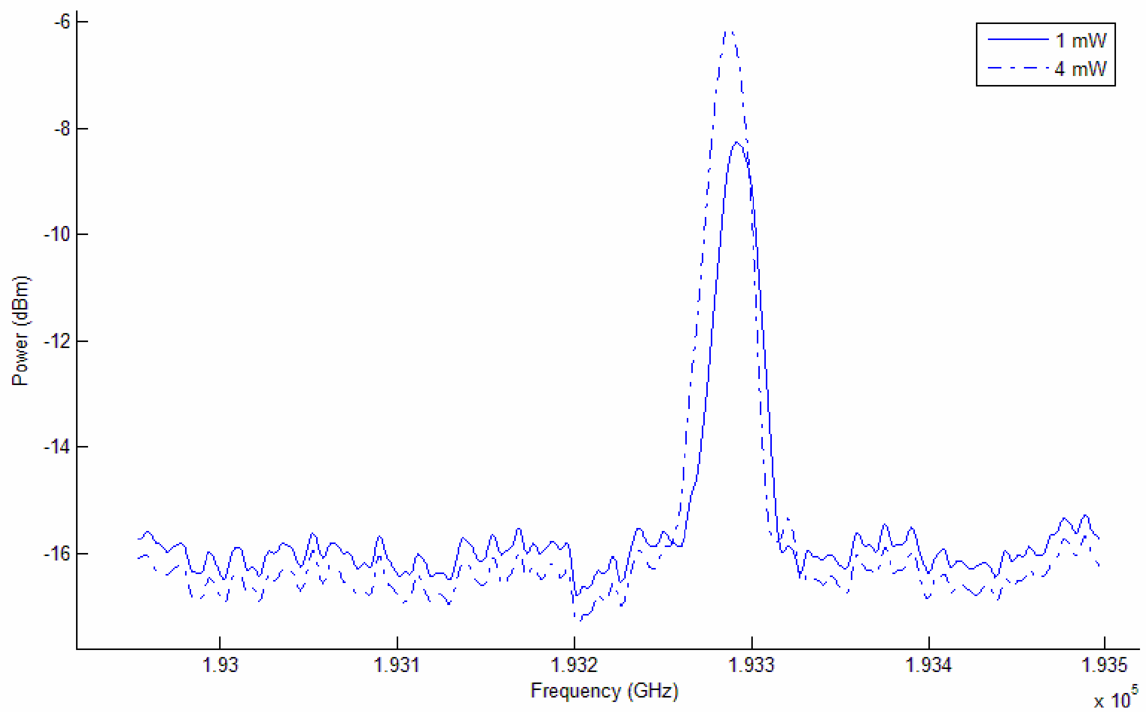

Fig. 5-15: Spectrum comparison at the output of the RSOA when transmitting a 1 mW peak power pulse and a 4mW.

At the output of the RSOA, if a 1 mW (no SPM) peak power pulse is transmitted, a 29.68 GHz width pulse will be obtained. In the other hand, if a 4 mW pulse is transmitted, the width of the pulse at the output of the amplifier will be of 31.29 GHz. Even thought spectrum is only broadened by 5.5%, the pulse is more powerful, and thus it will be transmitted with more quality, including the possibility of RBS reduction that may improve even more the transmission.

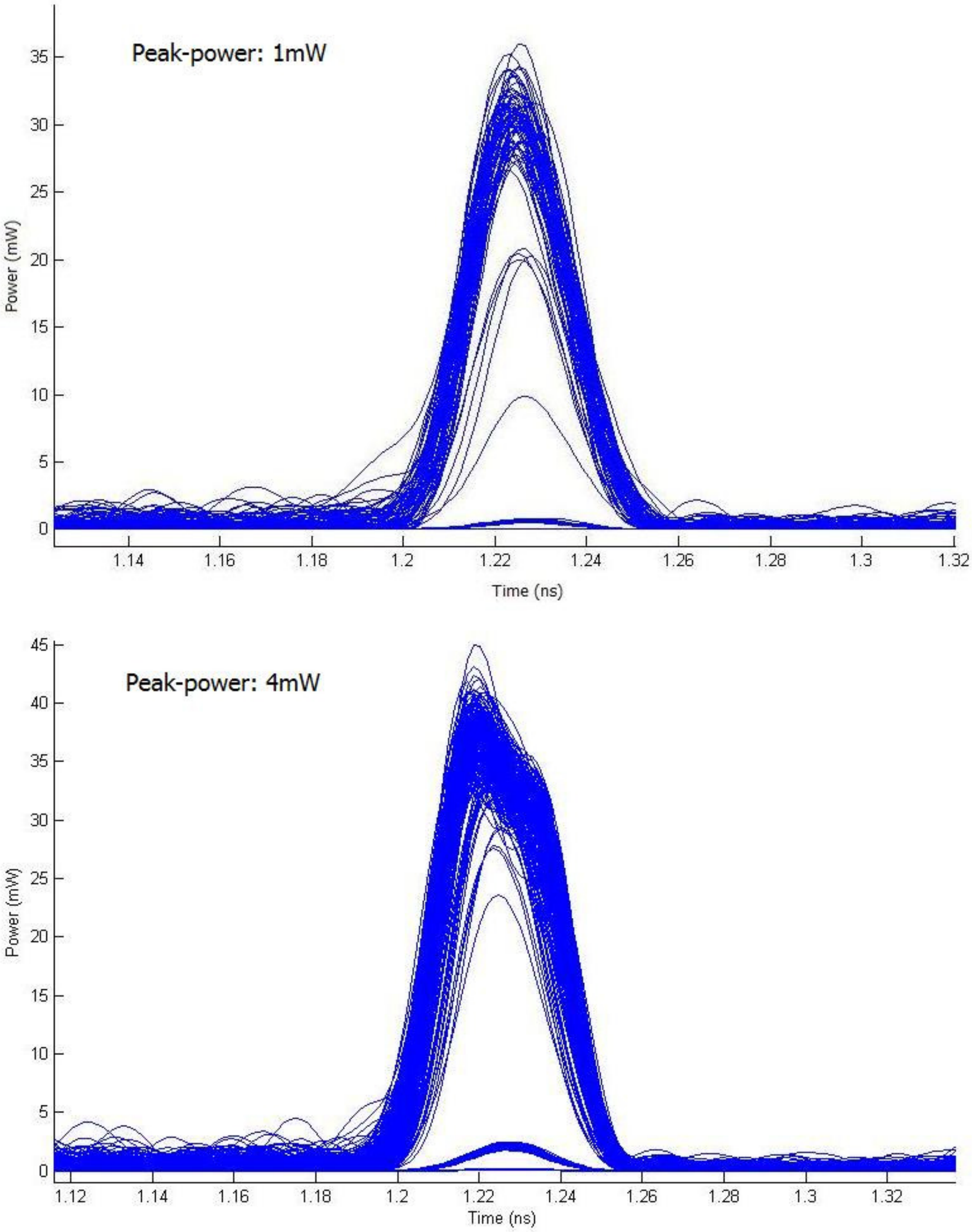

Fig. 5-16: Eye diagrams of the output of the RSOA of two different input pulses

5.4 RSOA output

The optimum pulse coming out of the RSOA will be a powerful pulse similar in shape with the incoming pulse but with broader spectrum. After applying the bias dithering and SPM techniques the pulses coming from the RSOA have been modified. As it can be seen on figure 5-17, a noticeable pulse modification is achieved in comparison with the original pulse.

When dithering the bias current that drives the RSOA, a more powerful pulse is obtained. The RSOA is charged with more electrons when the pulse comes preparing it for amplification. As a result the pulses are more homogeneously amplified. On the other hand, an impairment produced by the rectifier is that lower pulses appear corresponding the logical zeros. As discussed previously it is not possible to turn off the bias current if a logical zero comes into the amplifier when dithering. The optimum is to have these pulses the closest to zero so that the eye is the most open possible.

For the SPM technique, it is clearly shown that the pulse is distorted in comparison with the original pulse. This is caused by the so mentioned self phase modulation effect. In the other hand the pulse is powerfully transmitted and, when properly tuned, the distortion does not affect the aperture of the pulse, making it eve wider than the original.

On the frequency domain SPM introduces an improvement in the form of a broader spectrum, shown in figure 5-18. This broadening is caused by the emergence of a side lobe on the high frequency side of the pulse. It has a low influence to the overall power but it should still improve the RBS performance. The power is spread over a wider frequency range and at the receiver side the RBS input may be reduced by filtering the pulse.

The spectrum at the output of the dithered RSOA is also broadened. This broadening is much lower than the SPM case and appears in lower power levels. This spectral broadening should improve RBS performance in order to compensate a smaller eye of the pulse if we want to conclude that bias dithering is a feasible technique for this kind of architecture.

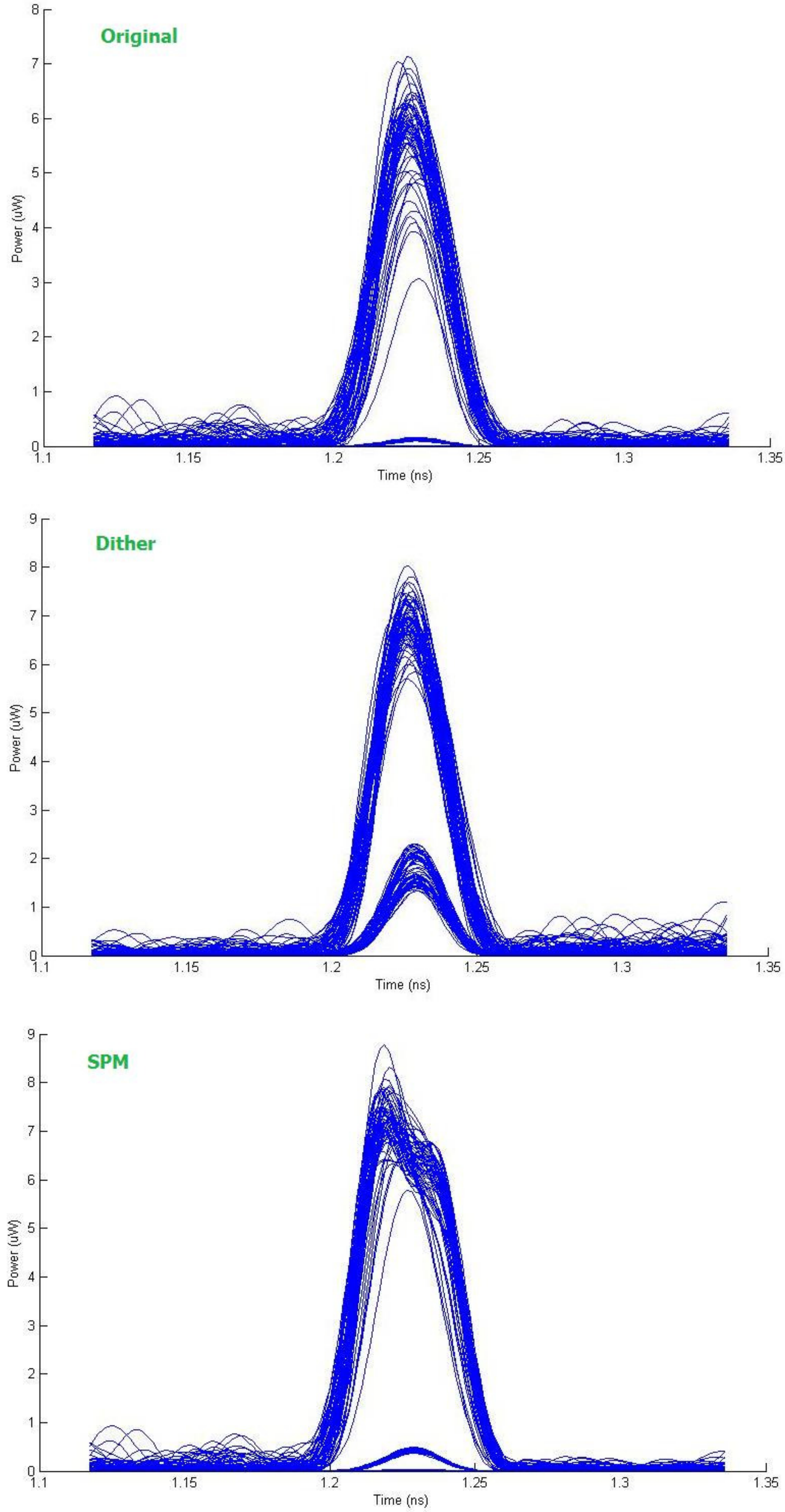

Fig.5-17: Comparison of eye diagrams at the output of the RSOA when applying bias dithering and SPM

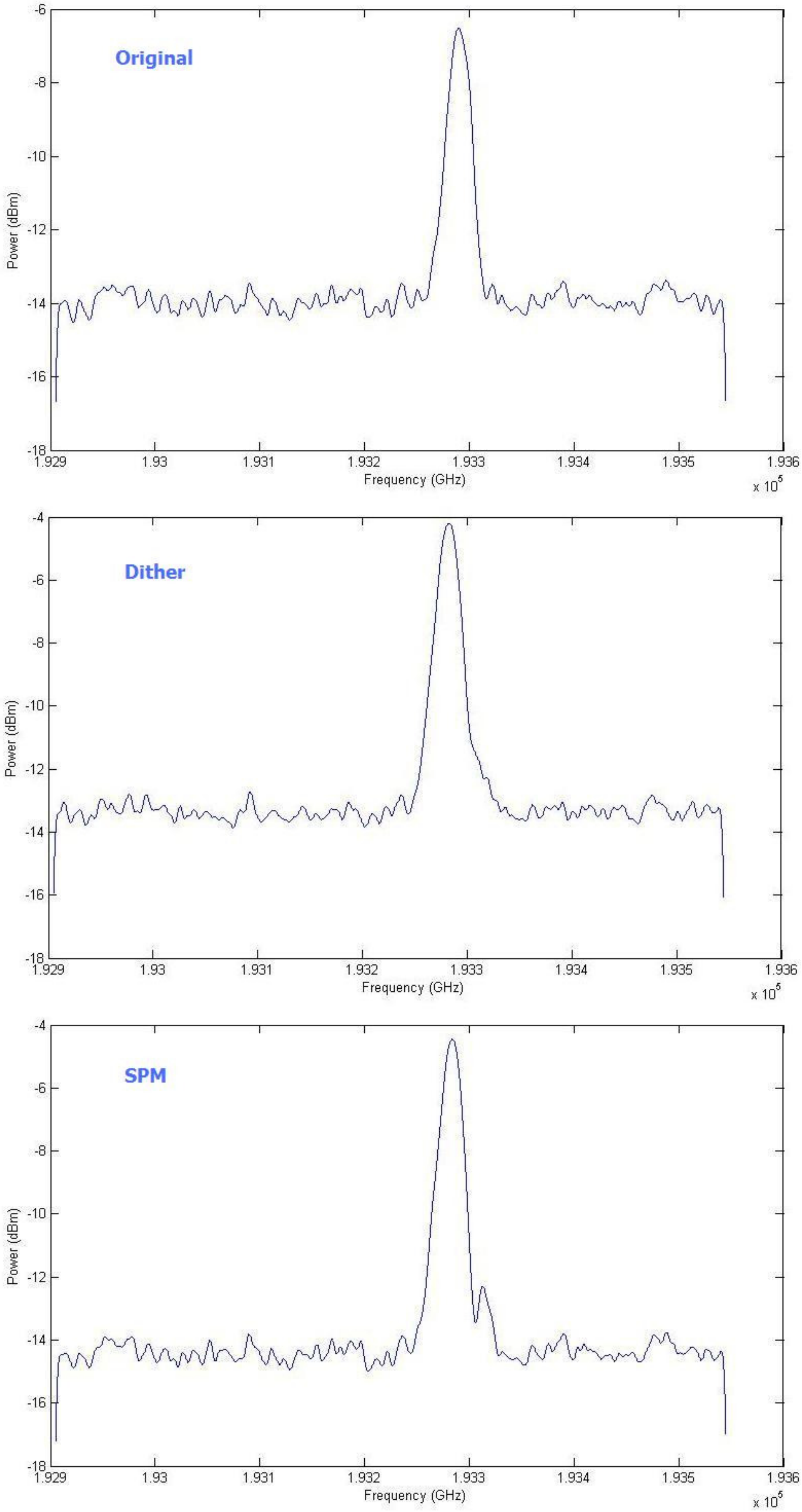

Fig.5-18: Comparison of spectrums at the output of the RSOA when applying bias dithering and SPM

Chapter 6

System Performance

The objective of this study was to apply two different spectral broadening techniques in order to reduce RBS impairments in bidirectional OCDMA transmission systems. The functionality of these techniques has been shown in previous chapters. In this chapter, the receiver behaviour when applying the techniques will also be analyzed. Finally the behaviour of the system will be presented in terms of bit error rate for each of the techniques.

In this chapter, a comparison of RBS performance will be done. It is known that RBS impairments directly depend on the optical power that travels through the fiber. There actually may be a power threshold that determines at which power level RBS starts influencing the system performance. For the BER performance simulations shown in this chapter, a comparison at different power levels will be done so that this RBS power threshold influence can be also shown.

6.1 Original setup

A characteristic of RBS impairments is its power dependence. The more power is transmitted through the fiber, the more power is reflected by the fiber nonlinearities and imperfections. This causes attenuation of the transmitted signal and induces crosstalk to the signal travelling in the opposite direction.

On the original setup the RSOA is driven by a data modulated bias current set to 55 mA. The power output by the RSOA is low enough to not induce any RBS effect as it can be seen on the BER curves of figure 6-1. The difference of performance between curves when no RBS effects are turned on and all RBS impairments is almost none.

The pulse power threshold where RBS effects are introduced into the signal is about 3dB higher than the pulses pumped by 55mA of bias current from the RSOA. Setting the bias current to 70mA, this threshold is over passed. The penalty introduced by RBS is less than 0.5 dB. It is a low impairment but also low power transmission.

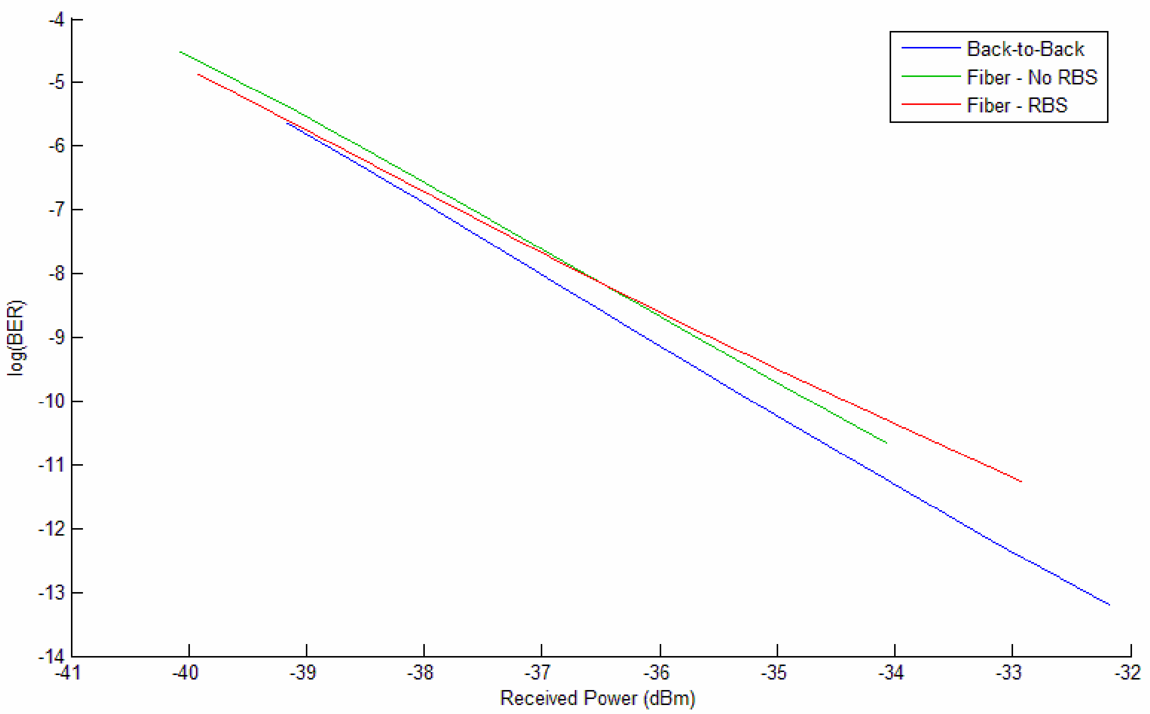

Fig.6-1: Original setup system performance when data amplitude is 55mA

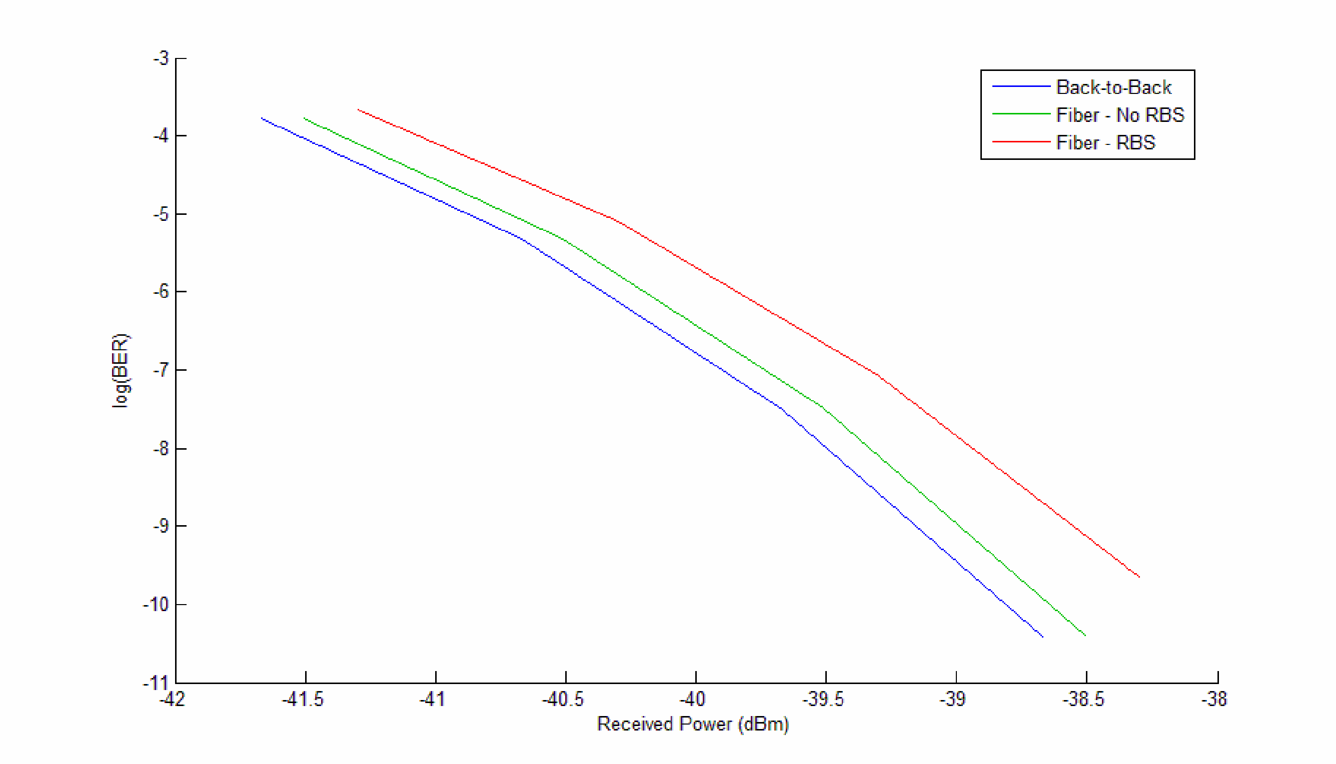

Fig.6-2: Original setup system performance when data amplitude is 70mA

6.2 Bias Dithering

The main effect produced by RSOA bias dithering, at the optimum settings, is an improvement on the amplifier gain. Therefore, the use of this technique will increment the output power of the amplifier, if comparing it with a no dithered RSOA. It will be expected to have a RBS influence on the system performance at lower data amplitude values compared with the original no dithered system.

When analyzing figures 6-3 and 6-4, the difference on the RBS impairments is noticeable. When using a system with a data amplitude of 70mA a 2 dB penalty can be seen, while using a 55mA system a 1.5 dB penalty is shown.

Its worth mentioning that the bias dithering technique introduces a power gain in comparison with the original system. Even though the RBS penalty is bigger, the distance that a pulse can travel through the fiber is longer, possibly making it feasible for specific networks.

On figure 6-3, it is noticeable that the original setup performance decreases slower with low received powers, compared to the dithering performance. This can be explained again with the power threshold of RBS impairments. The original setup transmits with less power; therefore RBS interferences are fewer than those from the dithering setup where pulses are more powerful. The higher the optical power the steeper the performance lines are.

On the other hand, when over passing this power threshold (using 70mA for bias current), the dithering setup has a worse performance compared to the original setting as shown in figure 6-4. With the dithering setup the pulses are more powerful and RBS induces a 2 dB penalty on these pulses. Even so with this dithering setup pulses have lower quality, a longer transmission may be achieved.

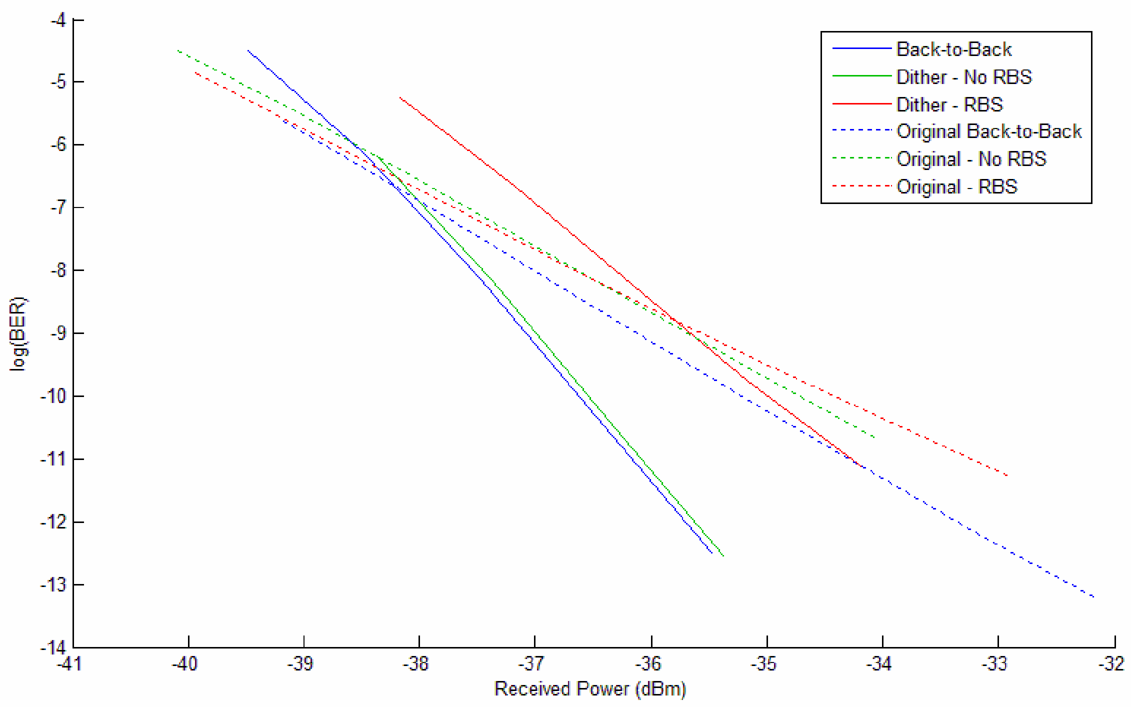

Fig.6-3: Dithering setup system performance when data amplitude is 55mA

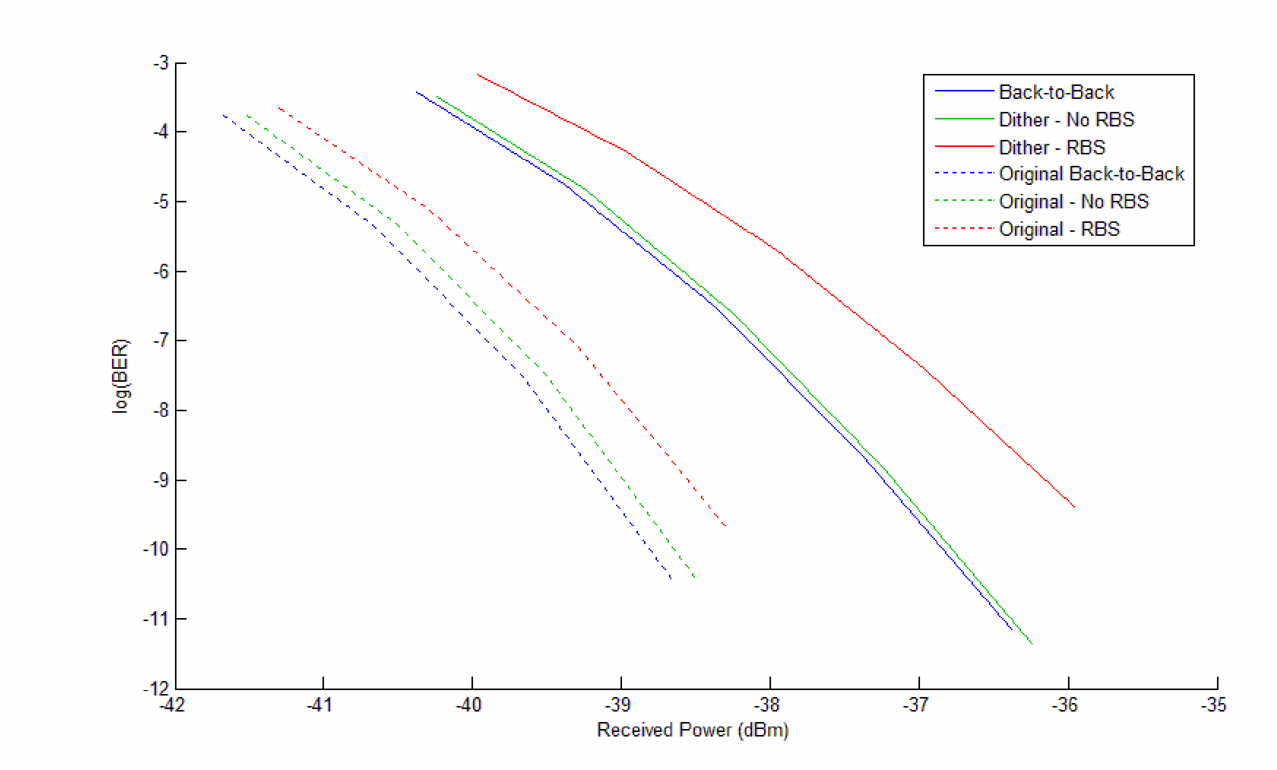

Fig.6-4: Dithering setup system performance when data amplitude is 70mA

6.3 SPM

Induced SPM is characterized of having more powerful pulses, implying longer transmission distances but higher RBS penalties. In the other hand, pulse spectrums is broader than original pulses, so it may be expected that the RBS influence will be lower than the other techniques.

For the SPM to effect to occur, the RSOA must be saturated. As explained in the previous chapter, for a bias current of 55mA, and a fiber attenuation of around 8dB, a pulse peak-power of 4mW is optimum. When increasing the gain of the amplifier with a 70mA bias current a bigger pulse power will be needed in order to saturate the RSOA. In this case, a 6mW pulse peak-power send by the CO is optimum, in terms of BER, for the system.

Figures 6-5 and 6-6 show that the actual RBS penalty, is again higher for 70mA data amplitude. The difference is that the RBS penalty for both cases is much lower than the penalties of bias dithering and even the original setup. Being this difference less than 0.5 dB for both 55mA and 70mA for the RSOA bias current.

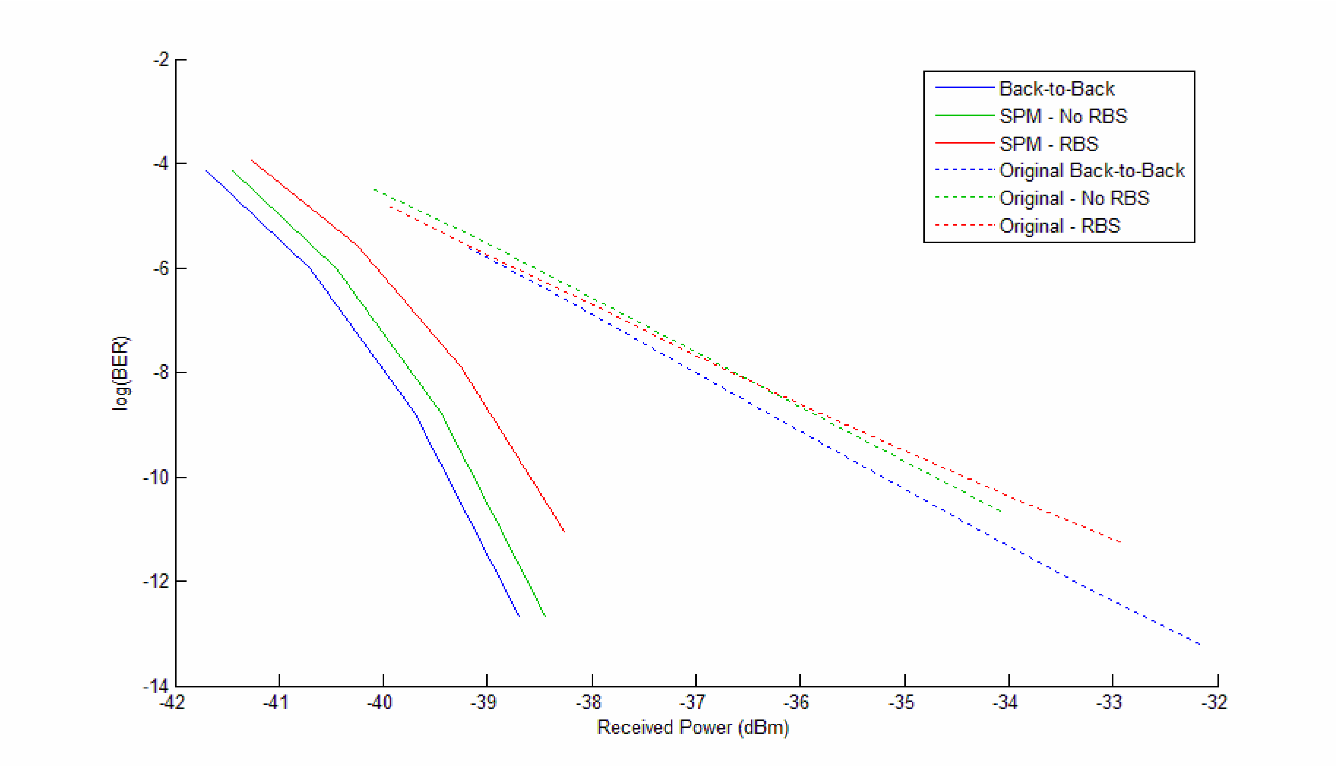

Fig.6-5: SPM setup system performance when data amplitude is 55mA

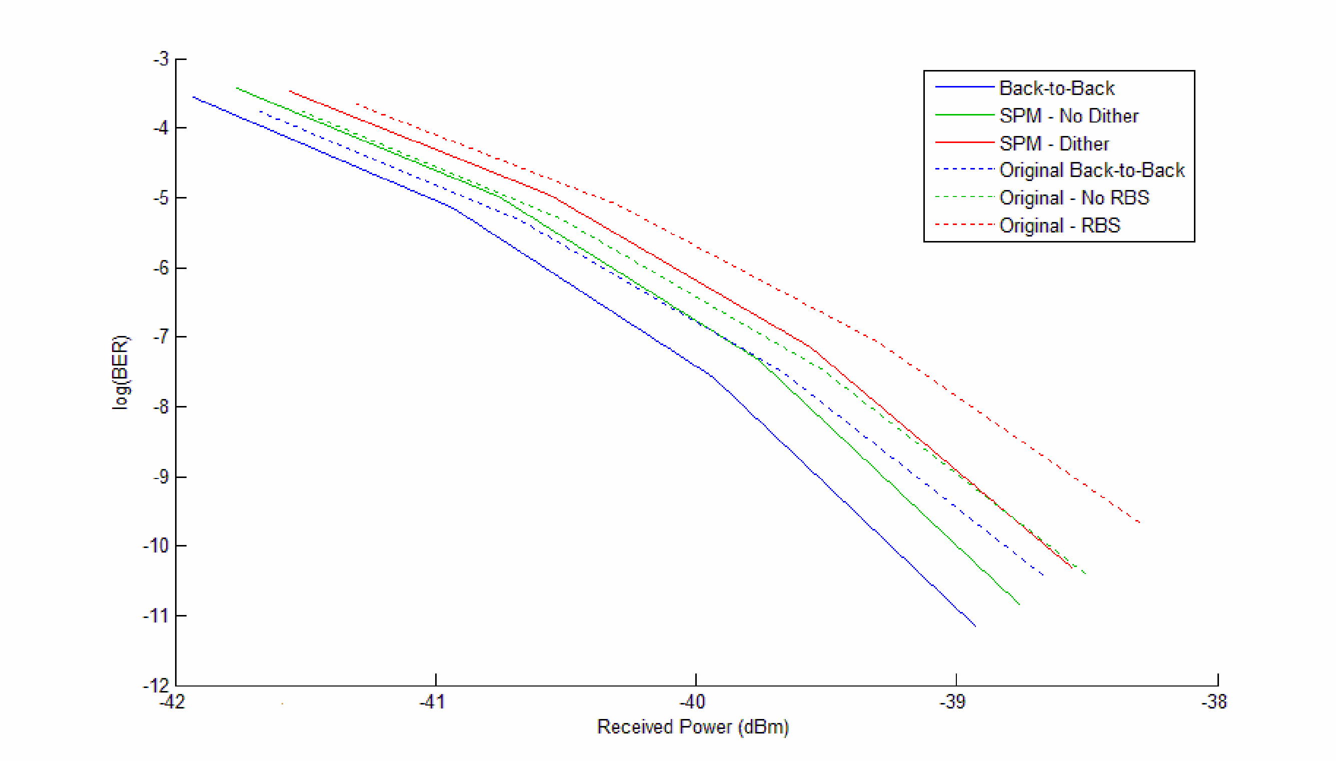

Fig.6-6: SPM setup system performance when data amplitude is 70mA

When comparing the original setup with the SPM with figures 6-5 and 6-6, it is proved that the system performance has a big improvement when using a low amplification, and some improvement when amplifying at higher powers. The first case can be explained by a higher power transmissions rather than RBS improvement, seen that on the original case the RBS impairments can be negligible. On the second case, the improvement on system performance is due to a RBS impairments reduction. It is a 0.5 dB improvement, but not forgetting that the pulse is more powerful and longer distances are achievable.

It is difficult to compare both techniques and the original system because of the different system settings used on each setup. Pulses are transmitted at different power levels and shapes making a direct comparison very difficult. For this reason, a RBS penalties comparison has been done for later analysis and conclusions.

SPM may offer a better potential, because dithering amplifies the zero-pulses, and as it is seen from figures 6-1 to 6-6 it can be seen that SPM introduces a smaller penalty. So, SPM can be considered as a non-intrusive technique that gives higher pulses to enable a longer transmission distance. But there’s a trade-off, higher pulses also increase RBS but also reduce RBS via SPM. This trade-off can be interesting for further study.

Chapter 7

Conclusions and further work

Conclusions

After presenting the system, describing the different components composing the system, explaining the techniques and analyzing the system performance a final conclusion can be made. Comparing both techniques with the original system setup, it is clearly seen that the RBS penalty is lower when the optical power is low. On the other hand, higher pulse powers guarantee longer transmission distances.

OCDMA networks are characterized by tree topologies, where many splitters and long fiber links compose the architecture. When talking about a reduced number of users, it may be useful to reduce the amount of power sent into the fiber in order to avoid RBS impairments. When this number increases, the splitting factor and the distance covered also increase forcing the OLT to transmit powerful pulses, making RBS impairments inevitable. When working with large amount of users, a solution to these impairments must be chosen.

Bias dithering does not clearly improve RBS penalties but its effects increase the amplification capacity of the RSOA. It is also complex to make it work in an optimum way because of the elements that are involved. If we maintain the system BER under 10^{-9}, an improvement of 1 dB at the received power is achieved when modulating the bias current at 70mA. The penalties produced to the overall system performance when introducing the bias dithering should also be taken into account.

For the case of induced SPM, there is a clear difference in terms of transmitted power. The laser at the CO sends a train of 6 power-peak pulses, arriving with a 8 dB attenuation to an RSOA fed by 70mA of bias current. RSOA outputs pulses with a broader spectrum, which explains the good behaviour under RBS conditions. RBS penalty through a chirped pulse (produced by SPM) is in the same penalty orders as the original system but with a 2 dB decrease on the power needed to guarantee a BER under 10^{-9}.

It can finally be concluded that inducing SPM at the RSOA, the system performance improves. Pulses are transmitted with more power, which means further travel distances or higher splitting ratios are possible, and pulse spectrum is broader reducing the influence of RBS impairments. All this is achieved by only tuning the power sent by the laser at the CO, to the point where it saturates the RSOA enough to broaden the spectrum but without introducing a big pulse distortion.

Further work

The application of these techniques to scheme closer to a real OCDMA setup may be a challenge but it is the first thing to do. It would be interesting to see the performance on a setup of more than one user, where splitters and longer fibers are involved. The encoding and higher attenuation may be a challenge when applying bias dithering and SPM for RBS reduction.

A further study of SPM effect may be helpful in order to understand its behaviour so the elements of the system can be optimized. The introduction of different filters with determined work bands, on different parts of the scheme may improve the pulse quality. Also inducing SPM or finding the way of chirping the pulses from the begging of the trip, at the laser side or through the fiber can also be studied, so RBS will be reduced on the downstream direction.

The performance of introducing bias dithering may improve if a real half wave rectifier is used, so the amplification of logical zero pulses reduces. This way the pulse eye will be bigger, enabling a better transmission. Also, a further optimization of the dithering frequency may be a viable option.

The RSOA is a complex device, and the overall system performance could be improved adapting the dithering to the limits of the amplifier. Spectral broadening should be achieved by choosing the right RF parameters or pulse shapes.

Appendix

A. References

[1] Sandvine. Global broadband phenomena, Executive report. 2008.

[2] FierceIPTV - The IPTV weekly monitor "So many streamers, so little bandwidth" http://www.fierceiptv.com, 2007.

[3] http://www.itu.int/

[4] http://www.radioptica.com/

[5] Kenichi Kitayama, Xu Wang, Naoya Wada "OCDMA Over WDM PON, Solution Path to Gigabit-Symmetric FTTH" Journal of Lightwave Technology, Vol. 24, No. 4, April 2006

[6] Kaiser, Gerd "Optical Fiber Communications" McGraw-Hill

[7] http://www.rp-photonics.com/

[8] M. Oskar van Deventer "Power Penalties Due to Reflection and Rayleigh Backscattering in a Single Frequency Bidirectional Coherent Transmission System" IEEE Photonics Technology Letters, Vol. 5, No. 7, p. 851 – 854, July 1993

[9] Taher M. Bazan, David Harle, and Ivan Andonovic "Performance Analysis of 2-D Time-Wavelength OCDMA Systems with Coherent Light Sources: Code Design Considerations" Journal of Lightwave Technology, Vol. 24, No. 10, pp. 3583-3589, October 2006

[10] Wang Yan-Hong, Ni Guo-Qiang, Guo Pan, Gao Kun, "Theoretical Analysis on Coherent Noise by Rayleigh Backscattering in Bidirectional Transmission System with Single Mode Fiber," ifita, vol. 1, pp.209-212, 2009 International Forum on Information Technology and Applications, 2009

[11] W.S. Jang, H.C. Kwon and S.K. Han, "Suppression of Rayleigh backscattering in a bidirectional WDM optical link using clipped direct modulation", IEEE Proc.-Optoelectron, Vol.151, No.4, 2004, pp:219-222

[12] R. K. Staubli, et al, "Crosstalk Penalties Due to Coherent Rayleigh Noise in Bidirectional Optical Communication Systems", JLT, vol. 9, no. 3, pp. 375-380 (1991)

[13] Nonlinear Fiber Optics, Third Edition (Optics and Photonics) by Govind P. Agrawal

[14] Weinberger, P. (2008). "John Kerr and his Effects Found in 1877 and 1878". Philosophical Magazine Letters 88 (12), pp. 897–907

[15] http://www.lce.hut.fi/

[16] V. Baby, et al., “Experimental demonstration and scalability analysis of a four-node 102-Gchip/s fast frequency-hopping time-spreading OCDMA network,” IEEE Photon. Technol. Lett., vol. 17(1), pp. 253–255, 2005.

[17] A. E. Siegman, Lasers, University Science Books, Mill Valley, CA, 1986.

[18] Fiber Optic Communication Systems. 3rd. ed. (Govind P. Agrawal, 2002)

[19] M. Feuer, J. Wiesenfeld, J. Perino, C. Burrus, G. Raybon, S. Shunk, N. Dutta, “Single-port laser-amplifier modulators for local access”, IEEE Photon. Technol. Lett., vol.8, no.9, pp.1175-1177, September 1996

[20] N. Buldawoo, S. Mottet, F. Le Gall, D. Sigonge, D. Meichenin, S. Chelles, “A Semiconductor Laser Amplifier-Reflector for the future FTTH Applications”, Proc. ECOC’97, p196-199, Edinburgh (UK), September 1997

[21] N. Buldawoo, S. Mottet, H. Dupont, D. Sigogne, D. Mechenin, “Transmission Experiment using a laser amplifier-reflector for DWDM access network,” ECOC 1998, Vol. 1, pp. 273 -274, 1998

[22] Cristina Arellano Pinilla, “Investigation of reflective optical network units for bidirectional passive optical access networks”. Ph.D. thesis, June 2007.

[23] D. Zaccarin and M. Kavegard, “An optical CDMA system based on spectral amplitude encoding of an LED,” IEEE Photon. Technol. Lett., vol. 4, no. 4, pp. 479–482, 1993.

[24] A. Hassan, J. Hershey, and N. Riza, “Spatial optical CDMA,” IEEE J. Sel. Areas Commun., vol. 13, no. 3, pp. 609–613, Apr. 1995.

[25] P. Prucnal, M. Santoro, and T. Fan, “Spread spectrum fiber-optic local area network using optical processing,” Electron. Lett., vol. 4, no. 5, pp. 547– 554, May 1986.

[26] L. Tancevski and I. Andonovic, “Wavelength hopping/time spreading code division multiple access systems,” Electron. Lett., vol. 30, no. 9, pp. 721–723, 1994.

[27] G. Yang and W. Kwong, “Two-dimensional spatial signature patterns,” IEEE Trans. Commun., vol. 44, no. 2, pp. 184–191, Feb. 1996.

[28] R. Yim, L. Chen, and J. Bajcsy, “Design and performance of 2-D codes for wavelength-time optical CDMA,” IEEE Photon. Technol. Lett., vol. 14, no. 5, pp. 714–716, May 2002.

[29] David J. Richardson, Hongxi Yin "Optical Code Division Multiple Access Communication Networks". Springer Berlin Heidelberg

[30] Jinsoo Kim, Chung-Keun Lee, Seung-Woo Seo, and Byoungho Lee, "Frequency-Hopping Optical Orthogonal Codes with Arbitrary Time-Blank Patterns," Appl. Opt. 41, 4070-4077 (2002)

[31] Kyoungsik Yu, Jongyoon Shin, and Namkyoo Park: Wavelength-Time Spreading Optical CDMA System Using Wavelength Multiplexers and Mirrored Fiber Delay Lines. IEEE Photonics Technology Letters, Vol.12, No.9, 2000, pp 1278-1280

[32] G. P. Agrawal and N. A. Olsson,"Self-Phase Modulation and Spectral Broadening of Optical Pulses in Semiconductor Laser Amplifiers" IEEE J. Quantum Electron. Vol. 25, No 11,November 1989.

[33] Xinliang Zhang, Dexiu Huang, Junqiang Sun and Deming Liu. "Single to 16-channel wavelength conversion at 10 Gb/s based on cross-gain modulation of ASE spectrum in SOA" Optical and Quantum Electronics 36: 627–634, 2004.

[34] Patryk Jan Urban "Dynamically Reconfigurable Optical Access Network". Ph.D. thesis, November 2009.

B. Presupuesto

1) Ejecución Material

- Compra de ordenador personal .... 2.000 €
- Licencia anual del software de simulación VPI..... .... 1.000 €
- Material de oficina .... 150 €
- Total de ejecución material.. 3.150 €

2) Gastos generales

- 16 % sobre Ejecución Material... 504 €

3) Beneficio Industrial

- 6 % sobre Ejecución Material... 189 €

4) Honorarios Proyecto

- 600 horas a 15 € / hora.. 9.000 €

5) Material fungible

- Gastos de impresión .... 60 €
- Encuadernación .... 200 €

6) Subtotal del presupuesto

- Subtotal Presupuesto.. 13.103 €

7) I.V.A. aplicable

- 16% Subtotal Presupuesto.. 2.096,48 €

8) Total presupuesto

- Total Presupuesto .... 15.199,48€

Madrid, Septiembre de 2010

El Ingeniero Jefe de Proyecto

Fdo.: Borja Badiola Ramos
Ingeniero Superior de Telecomunicación

C. Pliego de Condiciones

Este documento contiene las condiciones legales que guiarán la realización, en este proyecto, sistemas de transmisión sobre Optical CDMA. En lo que sigue, se supondrá que el proyecto ha sido encargado por una empresa cliente a una empresa consultora con la finalidad de realizar dicho sistema. Dicha empresa ha debido desarrollar una línea de investigación con objeto de elaborar el proyecto. Esta línea de investigación, junto con el posterior desarrollo de los programas está amparada por las condiciones particulares del siguiente pliego.

Supuesto que la utilización industrial de los métodos recogidos en el presente proyecto ha sido decidida por parte de la empresa cliente o de otras, la obra a realizar se regulará por las siguientes:

Condiciones generales

1. La modalidad de contratación será el concurso. La adjudicación se hará, por tanto, a la proposición más favorable sin atender exclusivamente al valor económico, dependiendo de las mayores garantías ofrecidas. La empresa que somete el proyecto a concurso se reserva el derecho a declararlo desierto.

2. El montaje y mecanización completa de los equipos que intervengan será realizado totalmente por la empresa licitadora.

3. En la oferta, se hará constar el precio total por el que se compromete a realizar la obra y el tanto por ciento de baja que supone este precio en relación con un importe límite si este se hubiera fijado.

4. La obra se realizará bajo la dirección técnica de un Ingeniero Superior de Telecomunicación, auxiliado por el número de Ingenieros Técnicos y Programadores que se estime preciso para el desarrollo de la misma.

5. Aparte del Ingeniero Director, el contratista tendrá derecho a contratar al resto del personal, pudiendo ceder esta prerrogativa a favor del Ingeniero Director, quien no estará obligado a aceptarla.

6. El contratista tiene derecho a sacar copias a su costa de los planos, pliego de condiciones y presupuestos. El Ingeniero autor del proyecto autorizará con su firma las copias solicitadas por el contratista después de confrontarlas.

7. Se abonará al contratista la obra que realmente ejecute con sujeción al proyecto que sirvió de base para la contratación, a las modificaciones autorizadas por la superioridad o a las órdenes que con arreglo a sus facultades le hayan comunicado por

escrito al Ingeniero Director de obras siempre que dicha obra se haya ajustado a los preceptos de los pliegos de condiciones, con arreglo a los cuales, se harán las modificaciones y la valoración de las diversas unidades sin que el importe total pueda exceder de los presupuestos aprobados. Por consiguiente, el número de unidades que se consignan en el proyecto o en el presupuesto, no podrá servirle de fundamento para entablar reclamaciones de ninguna clase, salvo en los casos de rescisión.

8. Tanto en las certificaciones de obras como en la liquidación final, se abonarán los trabajos realizados por el contratista a los precios de ejecución material que figuran en el presupuesto para cada unidad de la obra.

9. Si excepcionalmente se hubiera ejecutado algún trabajo que no se ajustase a las condiciones de la contrata pero que sin embargo es admisible a juicio del Ingeniero Director de obras, se dará conocimiento a la Dirección, proponiendo a la vez la rebaja de precios que el Ingeniero estime justa y si la Dirección resolviera aceptar la obra, quedará el contratista obligado a conformarse con la rebaja acordada.

10. Cuando se juzgue necesario emplear materiales o ejecutar obras que no figuren en el presupuesto de la contrata, se evaluará su importe a los precios asignados a otras obras o materiales análogos si los hubiere y cuando no, se discutirán entre el Ingeniero Director y el contratista, sometiéndolos a la aprobación de la Dirección. Los nuevos precios convenidos por uno u otro procedimiento, se sujetarán siempre al establecido en el punto anterior.

11. Cuando el contratista, con autorización del Ingeniero Director de obras, emplee materiales de calidad más elevada o de mayores dimensiones de lo estipulado en el proyecto, o sustituya una clase de fabricación por otra que tenga asignado mayor precio o ejecute con mayores dimensiones cualquier otra parte de las obras, o en general, introduzca en ellas cualquier modificación que sea beneficiosa a juicio del Ingeniero Director de obras, no tendrá derecho sin embargo, sino a lo que le correspondería si hubiera realizado la obra con estricta sujeción a lo proyectado y contratado.

12. Las cantidades calculadas para obras accesorias, aunque figuren por partida alzada en el presupuesto final (general), no serán abonadas sino a los precios de la contrata, según las condiciones de la misma y los proyectos particulares que para ellas se formen, o en su defecto, por lo que resulte de su medición final.

13. El contratista queda obligado a abonar al Ingeniero autor del proyecto y director de obras así como a los Ingenieros Técnicos, el importe de sus respectivos honorarios facultativos por formación del proyecto, dirección técnica y administración en su caso, con arreglo a las tarifas y honorarios vigentes.

14. Concluida la ejecución de la obra, será reconocida por el Ingeniero Director que a tal efecto designe la empresa.

15. La garantía definitiva será del 4% del presupuesto y la provisional del 2%.

16. La forma de pago será por certificaciones mensuales de la obra ejecutada, de acuerdo con los precios del presupuesto, deducida la baja si la hubiera.

17. La fecha de comienzo de las obras será a partir de los 15 días naturales del replanteo oficial de las mismas y la definitiva, al año de haber ejecutado la provisional, procediéndose si no existe reclamación alguna, a la reclamación de la fianza.

18. Si el contratista al efectuar el replanteo, observase algún error en el proyecto, deberá comunicarlo en el plazo de quince días al Ingeniero Director de obras, pues transcurrido ese plazo será responsable de la exactitud del proyecto.

19. El contratista está obligado a designar una persona responsable que se entenderá con el Ingeniero Director de obras, o con el delegado que éste designe, para todo relacionado con ella. Al ser el Ingeniero Director de obras el que interpreta el proyecto, el contratista deberá consultarle cualquier duda que surja en su realización.

20. Durante la realización de la obra, se girarán visitas de inspección por personal facultativo de la empresa cliente, para hacer las comprobaciones que se crean oportunas. Es obligación del contratista, la conservación de la obra ya ejecutada hasta la recepción de la misma, por lo que el deterioro parcial o total de ella, aunque sea por agentes atmosféricos u otras causas, deberá ser reparado o reconstruido por su cuenta.

21. El contratista, deberá realizar la obra en el plazo mencionado a partir de la fecha del contrato, incurriendo en multa, por retraso de la ejecución siempre que éste no sea debido a causas de fuerza mayor. A la terminación de la obra, se hará una recepción provisional previo reconocimiento y examen por la dirección técnica, el depositario de efectos, el interventor y el jefe de servicio o un representante, estampando su conformidad el contratista.

22. Hecha la recepción provisional, se certificará al contratista el resto de la obra, reservándose la administración el importe de los gastos de conservación de la misma hasta su recepción definitiva y la fianza durante el tiempo señalado como plazo de garantía. La recepción definitiva se hará en las mismas condiciones que la provisional, extendiéndose el acta correspondiente. El Director Técnico propondrá a la Junta Económica la devolución de la fianza al contratista de acuerdo con las condiciones económicas legales establecidas.

23. Las tarifas para la determinación de honorarios, reguladas por orden de la Presidencia del Gobierno el 19 de Octubre de 1961, se aplicarán sobre el denominado en la actualidad "Presupuesto de Ejecución de Contrata" y anteriormente llamado "Presupuesto de Ejecución Material" que hoy designa otro concepto.

Condiciones particulares

La empresa consultora, que ha desarrollado el presente proyecto, lo entregará a la empresa cliente bajo las condiciones generales ya formuladas, debiendo añadirse las siguientes condiciones particulares:

1. La propiedad intelectual de los procesos descritos y analizados en el presente trabajo, pertenece por entero a la empresa consultora representada por el Ingeniero Director del Proyecto.

2. La empresa consultora se reserva el derecho a la utilización total o parcial de los resultados de la investigación realizada para desarrollar el siguiente proyecto, bien para su publicación o bien para su uso en trabajos o proyectos posteriores, para la misma empresa cliente o para otra.

3. Cualquier tipo de reproducción aparte de las reseñadas en las condiciones generales, bien sea para uso particular de la empresa cliente, o para cualquier otra aplicación, contará con autorización expresa y por escrito del Ingeniero Director del Proyecto, que actuará en representación de la empresa consultora.

4. En la autorización se ha de hacer constar la aplicación a que se destinan sus reproducciones así como su cantidad.

5. En todas las reproducciones se indicará su procedencia, explicitando el nombre del proyecto, nombre del Ingeniero Director y de la empresa consultora.

6. Si el proyecto pasa la etapa de desarrollo, cualquier modificación que se realice sobre él, deberá ser notificada al Ingeniero Director del Proyecto y a criterio de éste, la empresa consultora decidirá aceptar o no la modificación propuesta.

7. Si la modificación se acepta, la empresa consultora se hará responsable al mismo nivel que el proyecto inicial del que resulta el añadirla.

8. Si la modificación no es aceptada, por el contrario, la empresa consultora declinará toda responsabilidad que se derive de la aplicación o influencia de la misma.

9. Si la empresa cliente decide desarrollar industrialmente uno o varios productos en los que resulte parcial o totalmente aplicable el estudio de este proyecto, deberá comunicarlo a la empresa consultora.

10. La empresa consultora no se responsabiliza de los efectos laterales que se puedan producir en el momento en que se utilice la herramienta objeto del presente proyecto para la realización de otras aplicaciones.

11. La empresa consultora tendrá prioridad respecto a otras en la elaboración de los proyectos auxiliares que fuese necesario desarrollar para dicha aplicación industrial,

siempre que no haga explícita renuncia a este hecho. En este caso, deberá autorizar expresamente los proyectos presentados por otros.

12. El Ingeniero Director del presente proyecto, será el responsable de la dirección de la aplicación industrial siempre que la empresa consultora lo estime oportuno. En caso contrario, la persona designada deberá contar con la autorización del mismo, quien delegará en él las responsabilidades que ostente.