# Optimization of a 10G recirculating loop test bed

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# Abstract

An optical fiber recirculating loop is a device used to experiment and study long haul transmissions for optical fiber communication applications. It simulates long distance communications by making the signal circulate through a loop containing one or multiple spans of optical fiber a certain number of times, saving the expensive cost of the equipment needed to reach thousands of kilometers.

This bachelor thesis aims to optimize the 10G optical recirculating loop test bed placed in the Network Laboratory of ETS University. This loop contains approximately 160 km of optical fiber, two dispersion compensator modules (DCM) and four EDFA amplifiers. The signal under test is a 10G (OC-192) NRZ in a DWDM 50 GHz channel span.

Test bed is characterized and various configurations are studied to optimize its performance. Different software is developed in order to control the loop and obtain results of the quality of transmission of the signal after it. Finally, different experiments are performed and results are provided to demonstrate the operation.

# Résumé

Une boucle de recirculation optique est un dispositif utilisé pour étudier des transmissions à longue distance pour les applications de communication par fibre optique. Ce dispositif simule les communications à longue distance en faisant circuler le signal à travers une boucle contenant un ou plusieurs spans de fibre optique pendant un certain nombre de fois. Cela permet d'économiser le coût de déploiement de l'équipement nécessaire pour les transmissions à plusieurs milliers de kilomètres.

Cette thèse vise à optimiser la boucle de recirculation optique à 10 G placée dans le laboratoire de Technologies de Réseaux de l'École de Technologie Supérieure. Cette boucle est constituée d´environ 160 km de fibre optique, de deux modules compensateurs de dispersion (DCM) et de quatre amplificateurs EDFA. Le signal étudié est un OC-192 codé NRZ et multiplexé en DWDM avec un espacement canal de 50 GHz.

Le banc de test est caractérisé et diverses configurations sont étudiées pour optimiser sa performance. Différents logiciels sont développés pour contrôler la boucle et obtenir des résultats de la qualité de transmission du signal. Enfin, différentes expériences sont effectuées et des résultats sont fournis pour démontrer l'opération.

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## Glossary

| | |
|---|---|
| ASE | Amplified Spontaneous Emission |
| ATM | Asynchronous Transfer Mode |
| B2B | Back to back |
| BER | Bit Error Rate |
| DCM | Dispersion Compensator Module |
| DWDM | Dense Wavelength Division Multiplexing |
| EDFA | Erbium-Doped Fiber Amplifier |
| IL | Insertion Loss |
| IP | Internet Protocol |
| ITU | International Telecommunication Union |
| NRZ | Non-return to zero |
| OOK | On/Off Keying |
| OSA | Optical Spectrum Analyser |
| OSC | Oscilloscope |
| PRBS | Pseudo Random Binary Sequence |
| RODAM | Reconfigurable Optical Add-Drop Multiplexer |
| SMF | Single Mode Fiber |
| WB | Wavelength Blocker |
| WDM | Wavelength Division Multiplexing |

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# 1. Introduction

## 1.1. Objective

Nowadays, optical networks are connecting the major part of the world and they are constantly growing in all their aspects. Long haul optical communications have a crucial role in theses networks and constitute a fundamental field of research and study.
Since 90s, optical recirculating loops have become an essential device for practical studies in this field. Recirculating loops are able to simulate long distances with less equipment than in a conventional system and in consequence with less cost.

The 10G recirculating loop has been set up at the Network Technology Laboratory several years ago and different studies have been performed using the test bed [1] [2]. When making experiments with the recirculating loop, the controller, test instruments and transmission equipment have to be configured manually. Also, the equipment used in this loop is shared with a 100G recirculating loop under construction and changes are performed in the loop every time it is used for diverse experiments.
For this reasons, this project pretends set up, characterize and optimize the 10G recirculating loop test bed using the current physical configuration.  Optimization is done performing different experiments to achieve the best set up and developing different software tools that allow automatic equipment configuration and measurements.

The main purpose of the optimization is to make the 10G recirculating loop test bed a complete tool where students and researchers can perform long haul optical measurements with the current equipment or test the behaviour of new devices in the recirculating loop. In addition, results generated on this project are going to be used as reference for the new measurements.
To accomplish this purpose, an operational manual describing the configuration of the recirculating loop is written. It explains the structure of the recirculating loop, the components, instruments configuration, connections between equipment and procedures to use the test bed. Also, another similar guide is written in order to introduce the developed software tools for future users.

A complete set of measurements is performed in the recirculating loop using the studied and optimized setup. This includes BER measurements as a function of the distance, eye diagrams of the received signal and OSNR measurements. Furthermore, measurements of BER as a function of received power are done. All the results obtained in the measurements are validated comparing them with the theoretical expectations or with other similar experiments available in literature.

These results and measurements generated during the project will provide information for the Ph.D. visiting researcher from Télecom ParisTech about the laboratory devices and simulation models.

## 1.2. Context

### SONET OC-192

Synchronous Optical Networking (SONET) is a standardized protocol for data transmission over optical fiber. It was defined by Telcordia and the American National Standards Institute (ANSI) and its generally used in north America. Its equivalent in the rest of the world is Synchronous Digital Hierarchy (SDH).

Both standards were originally designed to transport circuit mode communications, mainly voice. But they quickly evolved changing its internal structure to transport IP packets, Ethernet frames and ATM cells.

SONET and SDH are based on a synchronous frame structure for multiplexed traffic. That structure has a basic frame format and speed. SONET defines a base rate of 51.84 Mbps and a set of multiples of the base rate known as Optical Carrier levels.

OC-192 is the optical carrier standard at 9,95328 Gbps and it is still widely used in optical networks.

## 1.3. Methodology

The methodology used in this project consists at first of reviewing literature about recirculating loops and 10G long haul communications.

Second, the procedures of the optical communication laboratory as safety rules, connectors, power management and equipment configuration have been taught by the laboratory technicians Nelson Landry and Martin Leclerc and reading the equipment manuals.

Third part has consisted in understanding, characterizing and improving the configuration of the 10G recirculating loop by doing some measurements about spectrum, BER, received power, OSNR and changing the equipment set up. Literature has been used to understand how measurement were needed to be done.

Fourth part, which has been done in parallel with the third one, consisted in developing the software tools and Labview has been used for this purpose.

Finally, a complete set of measurements have been performed using the recirculating loop with the software and configuration developed. These measurements have been validated using theoretical references from books and similar experiments available in papers and thesis.

## 1.4. Thesis outline

The structure of this document is organized as follows. In chapter 2, the principle of operation of optical recirculating loops is explained. After that, there is a description of the pulse signals that operate the loop and at the end the main parameters that indicate the transmission quality are presented.
Chapter 3 explains the 10G recirculating loop placed at the Network Technology Laboratory, dividing it in four main parts: loop, controller, input and output.
In chapter 4, the set up of the test bed is presented by explaining some measurements as well as the results and decisions after them.
Chapter 5 is devoted to explain the software generated to do automatic measurements in the loop.
In chapter 6, the measures and results obtained with the 10G recirculating loop are presented and discussed.
Finally, in Chapter 7, the conclusions of the thesis are summarized and the future work is presented.

# 2. Recirculating loop principle of operation

Optical fiber recirculating loop basic structure contains a transmitter, a receiver, a 3dB coupler, two switches, an isolator, one or more spans of fiber and optical amplifiers [3].

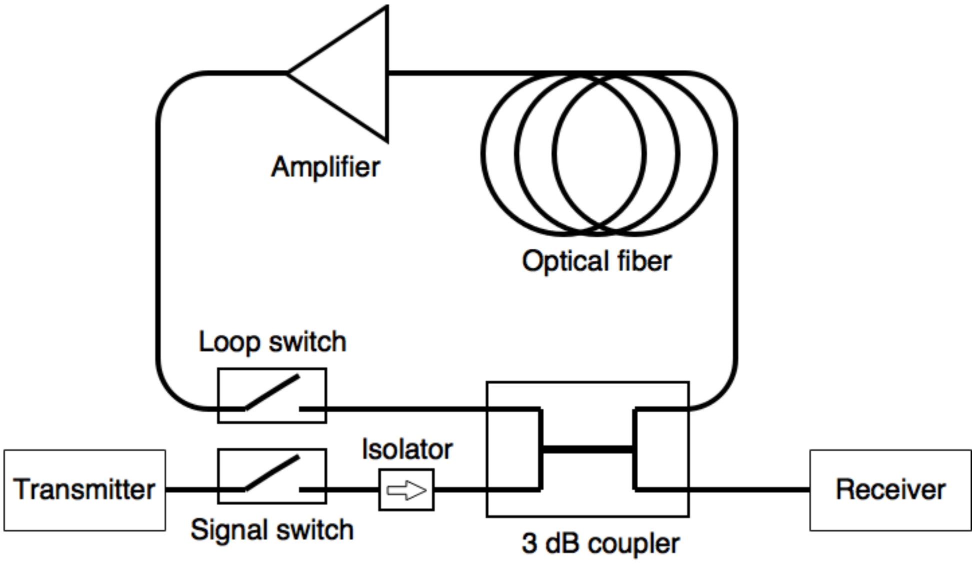



Figure 2.1: Recirculating loop schematic

To understand the operation of a recirculating loop is necessary to know the behaviour of switches, coupler and isolator [4].

Switches have two states: on (closed) when the light propagates through them and off (open), when no light can propagate. These switches are acusto-optic modulators which provide a high speed and high extinction ratio.
For the correct operation of the recirculating loop switches have to work in opposite states: when signal switch is open, loop switch is closed and vice-versa.

An optical 3 dB coupler is a 4 port device (2 inputs and 2 outputs). Light enters in a particular port on one side and exits from each of two ports on the other side, splitting the input signal in half at each output.
Isolator allows the transmission of the light only in one direction, preventing the signal to return to the transmitter and switch.

The operation of the recirculating loop is based in two states:

> **Load state:** optical signal is feed into the loop through the signal switch and the coupler. Signal switch is On and loop switch is Off.
>
> **Loop state:** optical signal loaded into the loop circulates within the loop the required number of times. Signal switch is Off and loop switch is On.

Transmission experiments using recirculating loop start with the load state. The optical signal generated by the transmitter passes through signal switch and isolator. In the coupler, half of the signal goes to the receiver and other half enters in the loop. When the loop is filled completely, switches can change to loop state. Then, signal circulates through the loop the required number of times, splitting half of the signal to the receiver every lap. Finally, when the signal has completed the required number of turns switches change to load state and start the process again. The signal that goes to the receiver is only analyzed during the last lap when it has completed the required distance.
Amplifier or amplifiers in the loop are used to compensate the signal loss produced by the fiber span and also by the coupler.

Acousto-optic switches are activated by an electrical tension. Thus, the control of the loop consists in correctly operate a pulse generator to turn on or off the switches depending on the loop fiber length, the required distance and the time the loop has to be filled.

## 2.1. Pulse Configuration

The most important parameter for the recirculating loop operation is called loop time and it is the time delay for the ligthwave to travel through one single loop. It can be theoretically calculated by the equation:

$$\text{Loop time } (\tau) = \frac{\mathrm{nL}}{\mathrm{c}} \tag{2.1}$$

Where $\mathrm{n}$ is the refractive index of the fiber (approximately 1,5), $\mathrm{L}$ is the length of the fiber and $\mathrm{c}$ is the speed of the light.
Loading state or loading time has to be large enough to fill completely the loop:

$$\text{Load state} \geq \text{ Loop time} \tag{2.2}$$

Load state can be also calculated by multiplying loop time by a loading factor that has to be bigger than one:

$$\text{Load state} = \text{Loading factor} \times \text{Loop time} \tag{2.3}$$

Finally, the period of the electrical pulse is:

$$\begin{gathered}\text{Period} = \text{Load state} + \text{Loop state} \\ \text{Period} = \text{Load state} + \mathrm{N_{laps}} \times \text{Loop time}\end{gathered} \tag{2.4}$$

Taking into account these equations, the recirculating loop is controlled with a pulse generator. It must have, at least, three channels to generate three different pulses to control the signal switch, the loop switch and the trigger.

Trigger pulse is used by the receiver to measure the optical signal after N circulations. Because of the coupler, the receiver is always receiving signal but it has only to be measured after the required number of laps.
CH1 (controlling the signal switch) has to be high during the load state and low during the loop state.
CH2 (controlling the loop switch) has to be low during the load state and high during the loop state (opposite of CH1).
CH3 (controlling the trigger) Has to be raised during the last lap. A delay in the raise and advance in the fall can be used to avoid the effect of the switch fall and rise time that can generate errors.

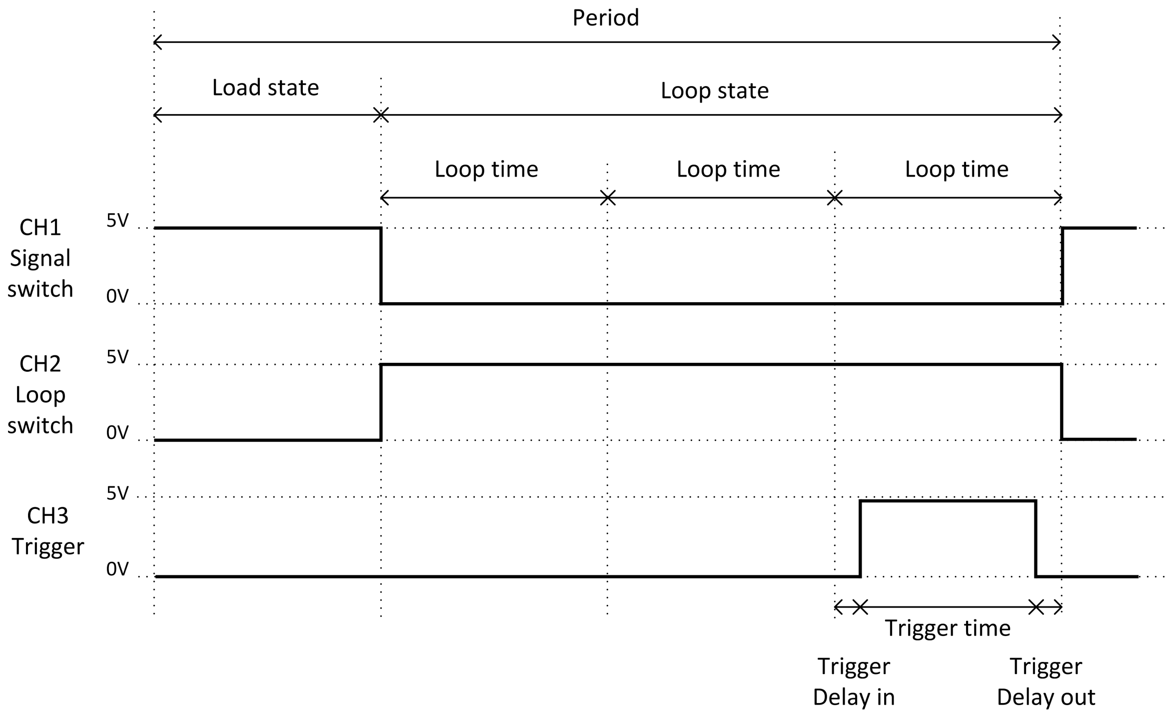


Figure 2.2: Pulse configuration schematic

## 2.2. Quality of transmission indicators

Different parameters can be used in order to study the quality of the signal at the receiver. In this section bit error rate, Q factor, optical signal to noise ratio and eye diagram are going to be introduced.

### 2.2.1. Bit Error Rate

Bit error ratio (BER) is calculated comparing the transmitted sequence of bits with the received bits and counting the number of errors.

$$BER = \frac{N_{errors}}{N_{bits}} \tag{2.5}$$

BER measurement is a binomial process: each received bit and compared against the expected data, hence there are two possibilities: either the bit was received in error or not. Assuming that the errors observed during a BER measurement are independent of each other and the conditions do not change over time, BER measurement can be modeled using Poisson distribution [5].

Since it is a statistical process, the measured BER only approaches the actual BER as the number of bits tested approaches infinity. As it is impossible to measure an infinite number of bits a confidence level is established in order to measure it. The confidence level is the percentage of tests that the system's true BER is less than the specified BER [6].

$$CL = 1 - e^{-N_{bits} \cdot BER} \tag{2.6}$$

From this equation we can extract the number of bits necessary to achieve a certain confidence level, and it can be easily related with the measurement time (MT, in seconds) introducing the data rate in the equation:

$$MT = \frac{-\ln(1 - CL)}{f \cdot BER} \tag{2.7}$$

In the recirculating loop, bit error rate is only measured during a certain time on the last lap. For this reason, the required measure time to reach a confidence level will depend on the number of laps or turns the signal makes in the loop. To make it simple, it can be considered that the measure is done during the entire last lap (trigger delay and advance=0) and that the loop is loaded during one loop time (loading state = loop time). Then the necessary measurement time to reach a certain confidence level is:

$$\text{Recirculating loop MT} = \frac{-\ln(1 - CL)}{f \cdot BER} \times (N_{laps} + 1) \tag{2.8}$$

In our case, the transmitter uses OC-192 standard, which corresponds to a data rate $f = 9{,}95328\,\text{GHz}$. As an example, if the required confidence level is $CL = 95\%$ the measurement times should be, at least, the following ones for 2, 4 and 9 laps:

*Table 2.1: BER measurement times for a 95% confidence level*

| BER | 2 laps | 4 laps | 9 laps |
|---|---|---|---|
| $10^{-14}$ | 25,1 h | 41,9 h | 83,9h |
| $10^{-13}$ | 2,6 h | 4,2h | 8,4h |
| $10^{-12}$ | 16 min | 26 min | 51 min |
| $10^{-11}$ | 1,6min | 2,6 min | 5,1 min |

### 2.2.2. Q factor

The Q factor is the signal-to-noise ratio at the decision circuit in voltage or current units, and is typically expressed by [7]:

$$Q = \frac{\mu_1 - \mu_0}{\sigma_1 + \sigma_0} \qquad (2.9)$$

Where $\mu_{1,\ 0}$ is the mean value of the marks/spaces voltages or currents, and $\sigma_{1,\ 0}$ is the standard deviation. It is related to the signal-to noise ratio required to achieve an specific bit error rate [8].

### 2.2.3. OSNR

Optical signal to noise ratio (OSNR) is defined by ITU in [7] as:

$$\text{OSNR} = 10\log\left(\frac{P_i}{N_i}\right) + 10\log\left(\frac{B_m}{B_r}\right) \qquad (2.10)$$

Where $P_i$ is the optical signal power in watts at the i-th channel. $N_i$ is the amplified spontaneous emission (ASE) noise power in watts measured in noise equivalent bandwidth, $B_m$, at the i-th channel and $B_r$ is the reference optical bandwidth which is typically 0,1 nm.

### 2.2.4. Eye diagram

Eye diagrams are an accurate representation of the received electrical signal and a very successful way of quickly and intuitively assessing the quality of a digital signal.

They are generated by an oscilloscope driven by a master clock by overlaying many different sweeps of received data. It contains 1's, 0's and corresponding transitions between them that form an image that looks like the opening of an eye.

Different measures can be made in an eye diagram as bit period, amplitude, one level and zero level, rise time, fall time, eye height, eye width and jitter. But the main quality indicator is the eye opening measured by the eye height and eye width. If it has a big aperture the BER will be lower than with a smaller one.

# 3. 10G Recirculating Loop Characterization

The 10G Recirculating Loop Test Bed is based on the structure explained before. It is equipped to simulate a 50GHz spacing DWDM transmission. The studied channel is the 1555,75nm of the ITU grid. The transmitter uses an NRZ OOK modulation to transmit a fixed OC-192 SONET tram.
This recirculating loop test bed can be divided in four parts: loop, controller, input and output.

## 3.1. Loop

The loop basically composed by the controller, different spools of single mode fiber (SMF 28), 4 EDFA amplifiers (Nortel MOR+), 2 dispersion compensator modules (DCM 60 and DCM 100) and one wavelength blocker (JDSU Wavelength Blocker 50GHz). The total length of the loop is about 160km.

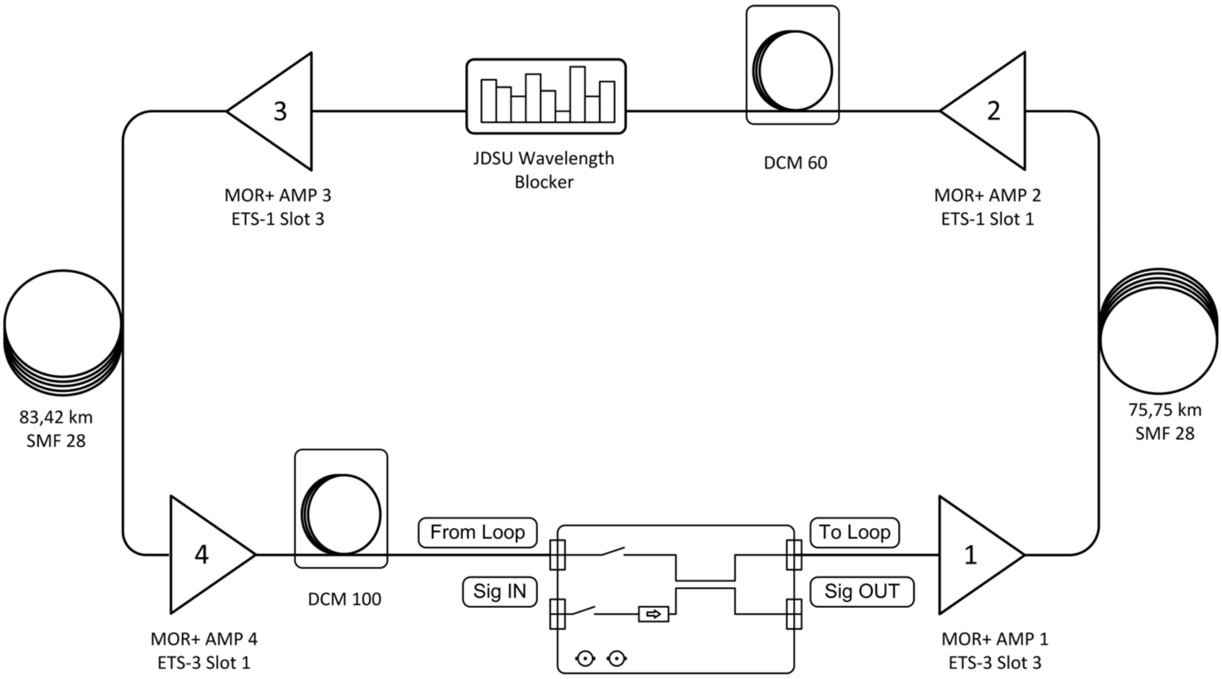


Figure 3.1: Loop schematic

Nortel MOR+ amplifiers are configured in total output power. As explained in [9], first amplifier is configured as Post amplifier, second and forth are configured as Mid-Stage Access Pre amplifiers (MSA Pre) and third is configured as Mid-Stage Access Post amplifier (MSA Post). For more information, see *Table 9.1* in the annex.

The dispersion compensator modules are designed to compensate, respectively, 60km and 100km of Corning SMF 28 optical fiber. As studied in [10] this DCM do not compensate the totally the dispersion in the loop. Length, insertion loss and chromatic dispersion of the fibers can be seen in the following table.

| *Table 3.1: Optical fiber characteristics* | | | |
|---|---|---|---|
| **Fiber type** | **Length (km)** | **Insertion Loss (dB)** | **Chromatic dispersion (ps/nm) at 1555,75nm** |
| SMF 28 (1) | 75,75 | 16 | 1287,75 |
| DCM 60 | ≈ 11,256 | 6,22 | -984,61 |
| SMF 28 (2) | 83,42 | 17,21 | 1418,14 |
| DCM100 | ≈ 17,836 | 8,3 | -1558,06 |

Source: Nelson Landry, F. Ouambo Baudelaire

DCM fiber is not taken into account to compute the total loop length, which is:

$$\text{Total loop length} = 75{,}75 + 83{,}42 \ = \ 159{,}17 \text{ km} \quad (3.1)$$

Residual dispersion (RD) at 1555,75 nm in the recirculating loop is:

$$\text{RD} = 1287{,}75 - 984{,}61 + 1418{,}14 - 1558{,}06 \ = \ 163{,}22 \text{ ps/nm} \quad (3.2)$$

JDSU Wavelength Blocker can attenuate or block dynamically any channel in the 50 GHz grid. Can attenuate a maximum of 20 dB with a precision of 0,1 dB and has a typical insertion loss of 4,5 dB (see *Table 9.2* for more characteristics).

Loop time has been experimentally characterized using the following procedure.
First, a theoretical approximation of the loop time has been calculated using equation 2.1.
Second, using this result, a load state smaller than loop time has been set on the pulse generator (Load state < Loop time). Due to this configuration, recirculating loop was not completely filled with signal.
Third, the period has been set to approximately 5 laps. As the loop was not completely loaded there was always a part of it without signal which we called discontinuity.
Finally, the output of the recirculating loop has been monitored using a ligthwave detector connected to an oscilloscope. The time between two discontinuities corresponds to the loop time and it has been measured on the oscilloscope. The result obtained has been:

$$\text{Loop time} = 0{,}9236 \text{ ms} \quad (3.3)$$

## 3.2. Controller

The main element in this recirculating loop is the controller. It is a Petawave Networks Optical Recirculating Loop and contains two acusto-optic switches, an isolator, a 3dB coupler and a Berkeley Nucleonics Corporation Pulse Generator Model 500.
As can be seen in the schematic, this pulse generator has got 4 channels: 2 of them to control the switches and the other 2 to trigger the BER detector and the OSA.

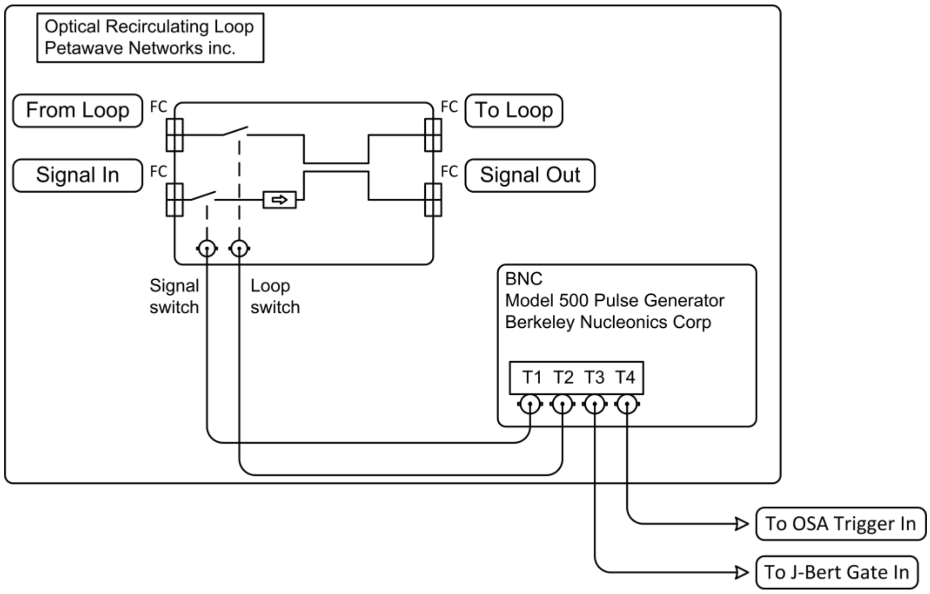



Figure 3.2: Petawave controller schematic

The main characteristics of the recirculating loop controller have been put together in the following table.

| *Table 3.2: Petawave Networks Optical Recirculating loop characteristics* | | |
|---|---|---|
| Spectral Range | 1528nm to 1568nm | |
| Insertion Loss | From Loop – To Loop | 5,47 dB |
| | From Loop – Signal Out | 6,27 dB |
| | Signal In – To Loop | 6,65 dB |
| | Signal In – Signal Out | 6,63 dB |
| Acusto-optic Switches | Switching time | < 2μs |
| | Stabilization time | < 3μs |
| | Extinction ratio | > 50 dB |
| Pulse Generator | Resolution | 0,2μs |
| | Jitter between channels | >1ns |

Sources: Petawave recirculating loop manual/ Nelson Landry

## 3.3. Input

Input signal is generated by the combination of a MPB Comb Source and the Nortel OC-192 transmitter.
Nortel OC-192 transmitter uses an OOK NRZ modulation with a negative chirp to transmit a SONET tram containing the header and a PRBS of $10^{20,19}$ bits approximately. Transmitter optical power has been set at 0,75 dBm to match with the Comb Source. Its characteristics are the following ones.

| *Table 3.3: Nortel 10G WT Transmitter* | |
|---|---|
| Wavelength | 1555,75 nm |
| Optical power | -10 dBm to 1,5 dBm (used 0.75 dBm ) |
| Spectral width | 0,115 nm |
| Modulation | NRZ-OOK |
| Chirp | Positive, Negative (used Negative) |
| Transmission rate | OC-192 (9953.28 Mbit/s) |
| Laser | DFB laser |

Source: Nortel 10G WT specifications

Its spectrum, measured using an OSA with a resolution of 0,01nm and no average, is the following one:

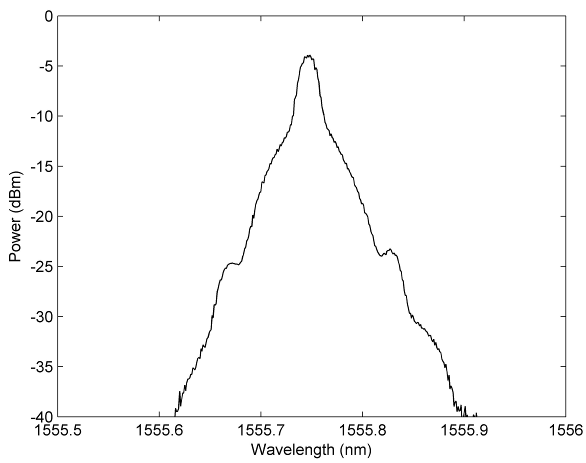



Figure 3.3: Nortel 10G WT spectrum

DWDM MPB Communications Comb Source 9022 generates 90 ITU channels spaced 50GHz in from 1529,5nm to 1565,5nm. This source is capable of similar power loading over the C Band as typical high performance WDM DFB Lasers (see *Table 9.3* for more characteristics).

Comb source signal is introduced to a WDM coupler to select the band between 1553,5 nm and 1560,5 nm. Then, with an MPB Add-Drop multiplexer the channels 1555,52 nm and 1555,75 nm are dropped and the modulated signal from the Nortel 10G Transmitter is added.

Add-drop output is connected to Signal In connector of the recirculating loop controller.

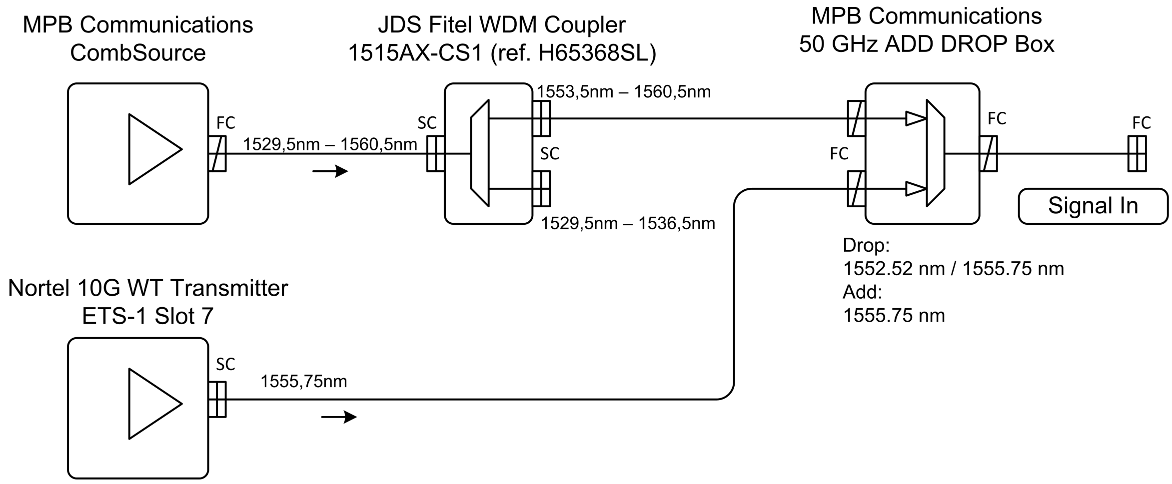


Figure 3.4: Input schematic

In the following figure it can be seen the spectrum of the signal at the input (Signal In). It can be appreciated that channel 1552,52 nm is dropped and channel 1555,75 nm is added with the same power as the other channels. OSA has been configured with a resolution of 0,01nm and and no average.

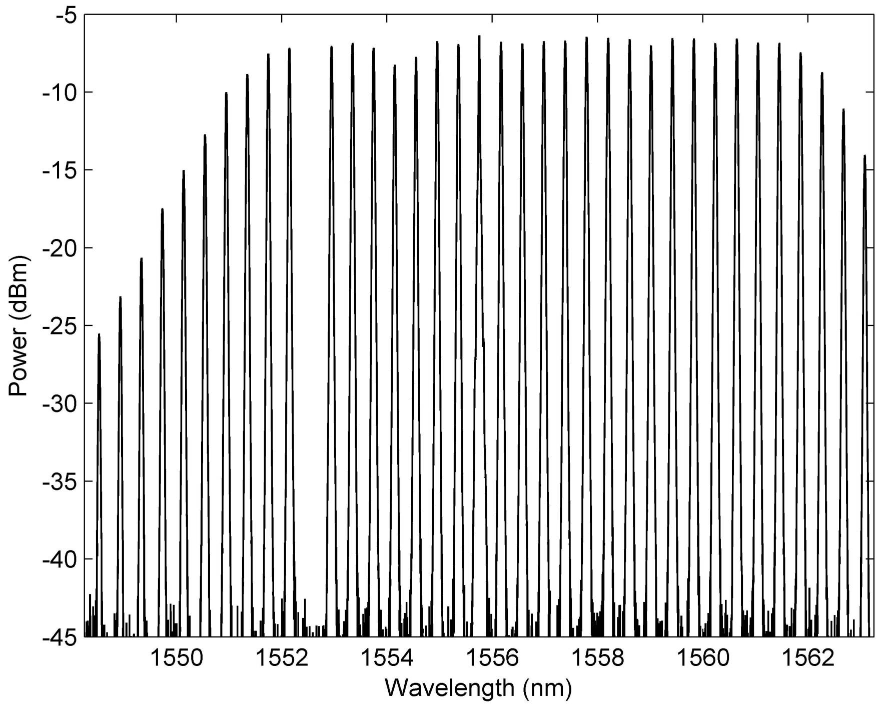


Figure 3.5: Input spectrum

## 3.4. Measurements Setups and procedures

### 3.4.1. Output measurements

Four different configurations have been used at the output depending on the studied parameters at the output. In all configurations, there is first an MPB two stage EDFA amplifier configured with output power control mode at 14 dBm (see *Table 9.4* for more characteristics). Except OSNR setup, others contain a JDSU tunable filter set at 1555.75nm (specifications in *Table 9.5*).

**Output Spectrum**

First configuration contains a JDSU tunable filter, an Agilent 81577A variable attenuator mounted in an Agilent 8164A ligthwave measurement (characteristics in *Table 9.6* ) system and Ando AQ6317B optical spectrum analyzer.

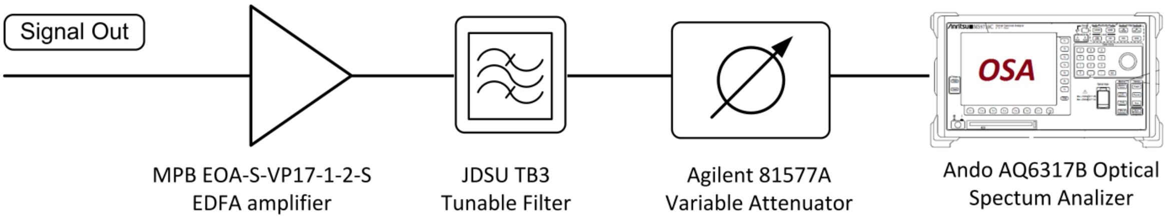



Figure 3.6: Loop output for spectrum measurements

**Bit Error Rate (BER)**

Second configuration is used to perform the bit error rate analysis. It contains the same elements than the first one (amplifier, filter and attenuator) changing the spectrum analyzer for an Agilent 10Gb/s receiver (see *Table 9.7* for more information) and Agilent J-BERT N4903A bit error ratio tester.

J-BERT N4903A is used to perform the BER analysis. The transmitted fixed SONET tram containing a PRBS of $10^{20,19}$ bits approximately is introduced to the analyzer and it compares the received bits with the pattern obtaining bit error rate and other useful parameters to measure the quality of the link. When it is used at the output of the recirculating loop its analysis is performed in Burst mode synchronized with the trigger from the pulse generator and also the sampling point can not be auto aligned.

JDSU tunable filter has been set up at 1555.75nm and each BER accumulation has been done with sampling point located at 0V, 40ps.

Variable attenuator has been used decrease the power at the receiver to generate BER vs. received power curves. During the rest of the measurements the attenuator has been set at 0 dB.

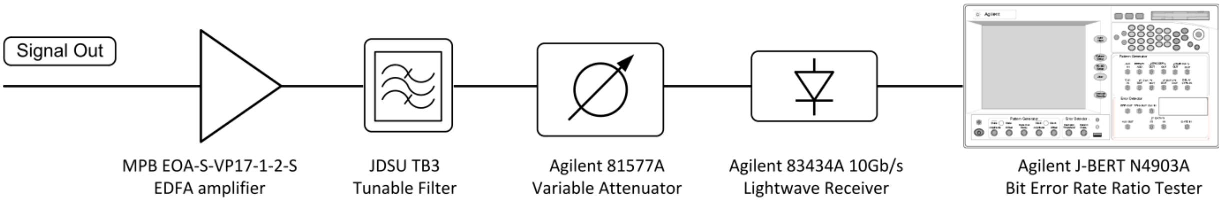


Figure 3.7: Loop output for BER measurements

**Eye Diagram**
Third configuration is used to generate eye diagrams. It contains the same elements than the third one but also an Agilent 6100A Oscilloscope with an HP 83484A module. J-BERT is only used to divide the receiver clock by 8 to trigger the oscilloscope.

To do the measurements the auto scale mode is used, it sets the Scale at 100mV/division and the time at 16,2ps/ds. Once the scale is setup, the delay on the time scale is used to correctly position the eye in the screen.

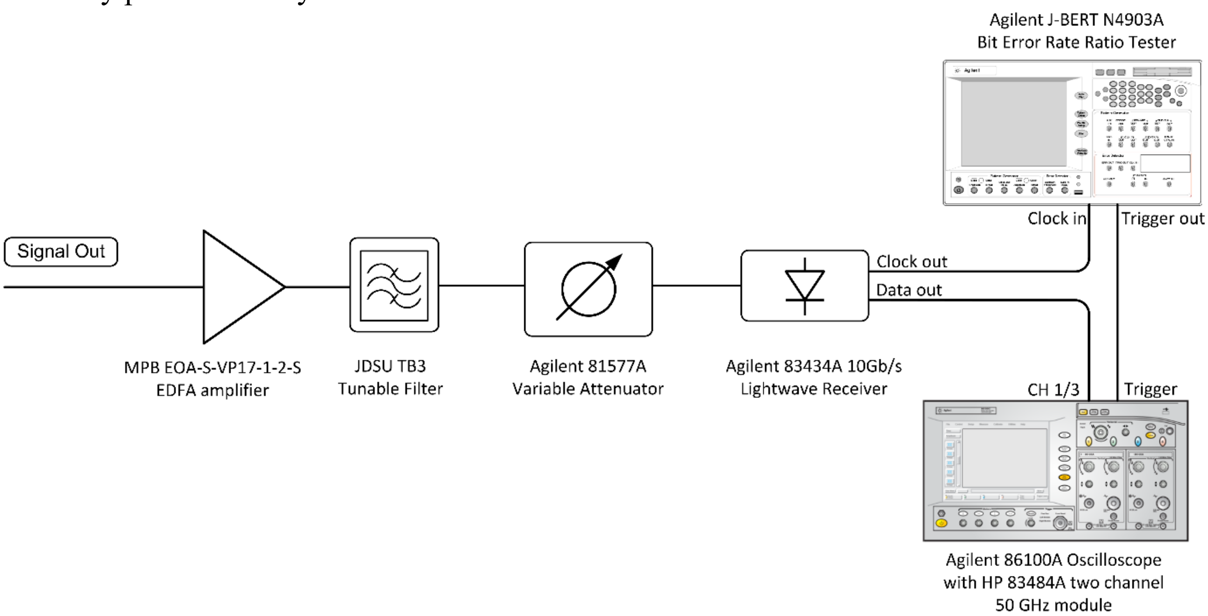


Figure 3.8: Loop output for eye diagram measurements

**Optical signal to noise ratio (OSNR)**
OSNR measurements have to be performed in-band (before the filter and the attenuator) because after the optical filter the noise floor that is seen on the optical spectrum analyzer (OSA) is not the real one.

The following figure is a plot of the signal spectrum after 795,85 km (5 circulations on the loop) before and after the filter. The measurement has been done using the OSA with an average of 4 and a resolution of 0,01 nm, insertion loss produced by the filter has ben added to the signal to compare them.

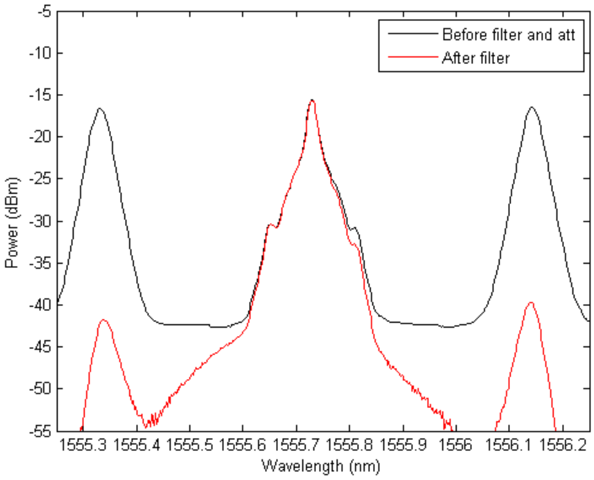


Figure 3.9: Spectrum after 795,85 km (5 laps)

Although there are different methods to analyze OSNR of a WDM signal, as discussed in [11] [12] on a 10G system without ROADM, OSNR can be measured using the interpolation method explained by ITU in [7].

To make OSNR measurements the following configuration, containing the MPB EDFA amplifier and Ando AQ6317B optical spectrum, analyzer has been used.

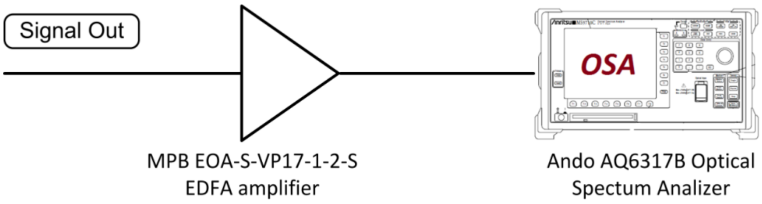


Figure 3.10: Loop output for OSNR measurements

This OSA has an auto analysis mode designed to measure WDM signals up to 50GHz spacing. Using this mode, it is able to measure SNR in a variable optical noise bandwidth. To do that it calculates the SNR using the interpolation method, by computing the power on the corresponding channel and the average power between the noise at the left and the right of the channel.
It has been set to its maximum resolution 0.01 nm and the noise bandwidth has been set at 0.1 nm which corresponds to the definition of OSNR (equation 2.10).

### 3.4.2. B2B measurements

Back to back measurements have been performed connecting the input signal setup shown in *Figure 3.4* with the wavelength blocker and the output setups explained to measure the different parameters.

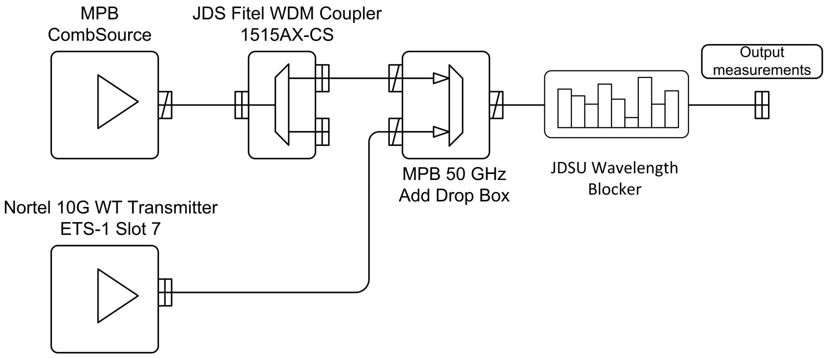



Figure 3.11: B2B measurement schematic

### 3.4.3. Input measurements

Input spectrum and power measurements have been performed with the OSA after the first amplifier using the setup shown below. Wavelength blocker is used to select the number of channels.

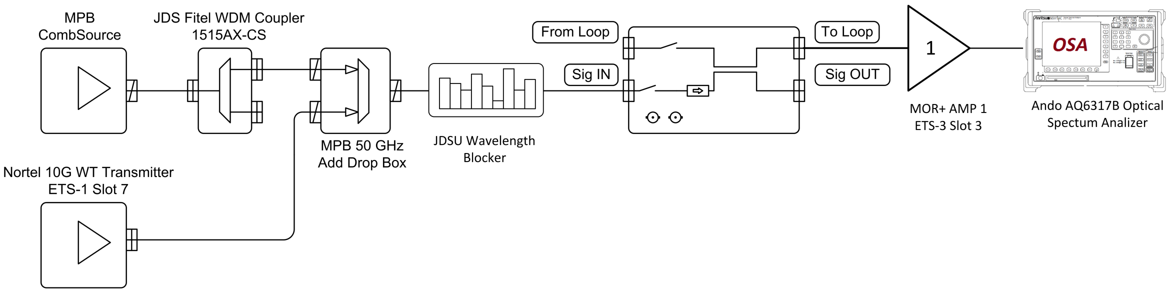



Figure 3.12: Input measurements schematic

# 4. Loop setup

## 4.1. Channels and amplifiers setup

The input signal combination of the Nortel WT and comb source simulates a DWDM 50GHz grid transmission. As the number of channels generated by the Comb Source is too big for the correct operation of the Nortel MOR+ amplifiers in the loop, the spectrum has been reduced to 13 channels using wavelength blocker. This allows having 6 dummy channels at each side of the studied channel as shown in the following spectrum capture. With the WB inside the loop there is also the advantage of blocking the noise on both sides of the DWDM signal reducing the noise and spontaneous amplified emission (ASE) generated by the amplifiers each turn.

Following figure compares the spectrum after 5 laps (795,85 km) using all channels and using 13 channels. The measurement has been done using the OSA with a resolution of 0,01nm and no average.

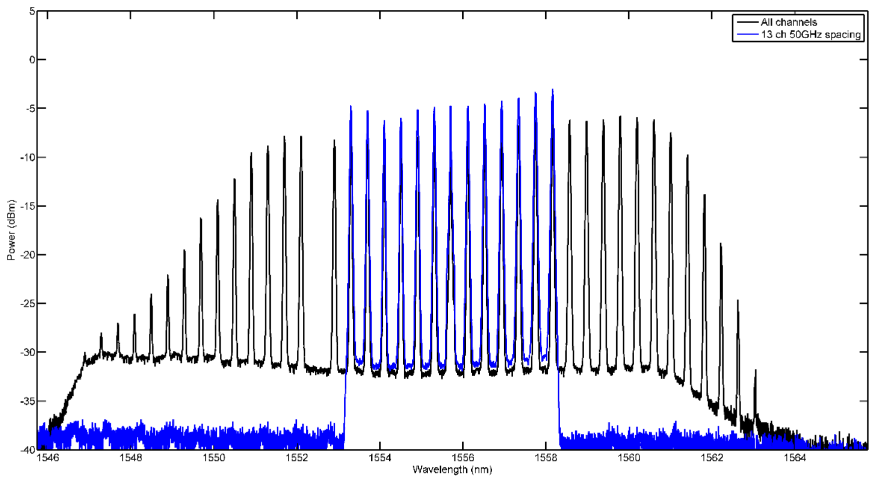



Figure 4.1: Spectrum all channels and 13 channels

As discussed before, Nortel MOR+ amplifiers are controlled by the total output power. We have tested experimentally the output power target that fits better using 13 channels. The recirculating loop has been set at 5 laps and BER has been monitorized setting the amplifiers output power target from 10 dBm to 16 dBm. Results conclude that an output power target of 14 dBm leads to a lower BER and that has been the configuration chosen for all the measurements.

Furthermore, it has to be taken into account that the WB is placed before the third EDFA amplifier. Hence, during the first lap, the first and second amplifiers are not working on its optimal configuration.

## 4.2. Loading state and trigger configuration

In this section loading state and trigger delay in / advance out have been tested to improve the performance of the recirculating loop test bed. To do that experiments the loop has been configured at 955,02 km (6 laps) using the attenuator before the receiver. BER measurements have been performed during 10 minutes for each configuration which is enough for the measured BER levels as explained in *Table 2.1*.

Due to the EDFA amplifiers characteristics sometimes could be better to feed the loop during a time bigger than the loop time to avoid non linarites in the behaviour of the amplifier as discussed in [4]. It has been tested different loading time from 1 to 3 and the bit error rate has not improved significantly while using a loading time factor bigger than 1. For this reason, it has been decided to use a loading factor of 1 or what is the same, load state=loop time during the experiments.

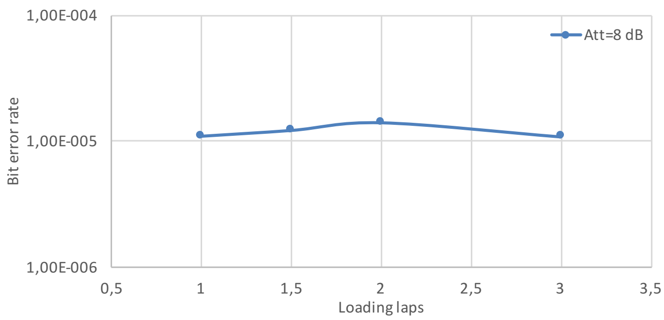



Figure 4.2: Loading time factor comparison

As explained before, acusto-optic switches need a time to change its state. That time has to be taken into account when generating the trigger to analyze the signal at the output of the recirculating loop. The recirculating loop has been set to 6 laps with an attenuation of 6 dB and 8 dB and it has been tested a trigger delay in and advance out from 0 µs to 50 µs while monitoring the BER. As it can be seen on the graphic below a trigger advance and delay of 2 µs is enough. For this reason, it has been decided to use 5 µs.

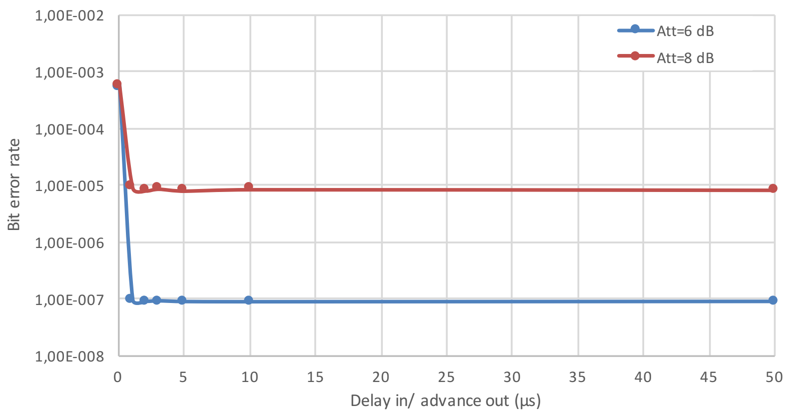



Figure 4.3: Trigger delay / advance comparison

## 4.3. Sampling point setup

Sampling point location can increase or decrease the bit error depending on the received signal in terms of power and noise. Its location is defined on J-BERT by the 0/1 threshold (in voltage) and the data delay (in time). For the 10G signal the 0/1 threshold goes from 0,25V to -0,25V and the data delay goes from 0 ps to 100 ps.

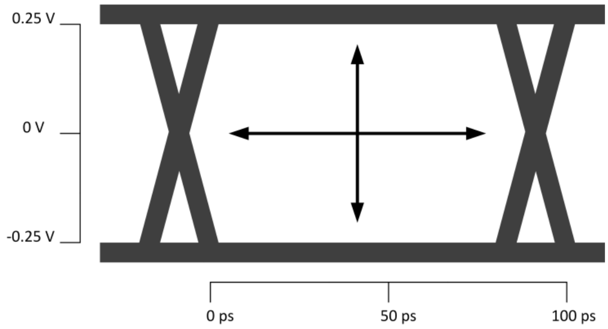



Figure 4.4: J-Bert sampling point location schematic for a 10G signal

In the following experiment it has been used an algorithm created by Mohamed-ali Atoui explained in [1] to obtain the best sampling point setup. This algorithm determines the eye diagram aperture by obtaining vertical and horizontal limits for a defined BER threshold. Then, it calculates the sampling point as the midpoint of the aperture limits.

The experiment has consisted on changing the distance (number of laps) and the power of the received signal by attenuating it (from 0 to 16 dB by steps of 4 dB) and use the algorithm to obtain the best sampling point in each case.

As it can be seen in the graphic with the results, the variation in the 0/1 threshold is remarkable, it goes from -5 to -85 mV. On the other hand, the data delay is mostly centered on 40 ps.

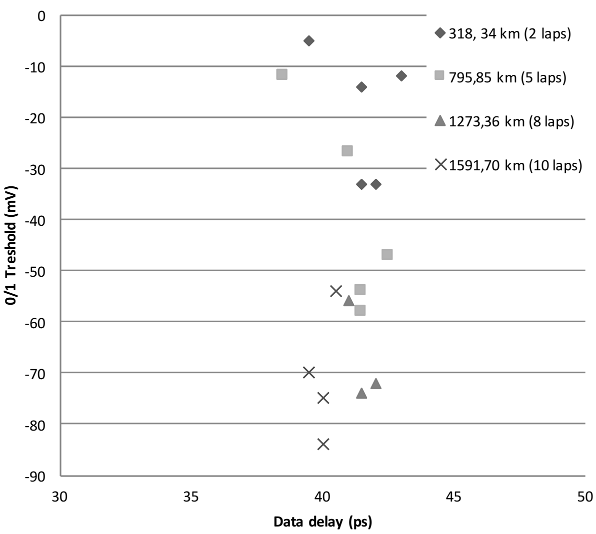



Figure 4.5: Best sampling point location

As the measures and experiments have to be done in a fixed sampling point it has been decided to use 40ps, 0V as it is the most convenient without attenuation on the received signal.

# 5. Software tools

An important part in the optimization of the 10G recirculating loop test bed has been developing different software to make test bed faster and easier for the future users. Labview has been the programing software used in order to develop this tools due to its features communicating with the instruments in the test bed and because there was other software created before by Nelson Landry and other former members of the laboratory that has been used to program this tools.
Software developed has been Ando OSA acquisition tool, Petawave controller to configure the pulse generator, BER accumulation software and Power level measurement software.

## 5.1. Petawave controller

Petawave controller tool is used to configure the pulse generator used to control both, 10G and 100G recirculating loops. It calculates and sends the time parameters to the pulse generator, using the values introduced by the user, making loop set up faster and easier.

Users have to set number of laps, loop time, loading time factor and trigger delay and advance.
Loop time is predefined at 923,6 μs for the current configuration of the 10G loop. Loading time is obtained by multiplying the loading time factor by the loop time as explained in equation (2.3). And trigger delay and advance are used to avoid the error produced by the switching time as discussed before.
Channel polarity is configured to use CH1 for signal switch (positive) and CH2 for loop switch (negative). CH3 and CH4 polarity can be selected. By default, CH3 is positive (TTL high) for OSA trigger and CH4 is negative (TTL low) for J-Bert trigger.

Furthermore, another version of the program named Petawave and attenuator controller has been created in order to control the recirculating loop and the attenuator to obtain different power levels at the receiver.

The following figure corresponds to a capture of the software interface.

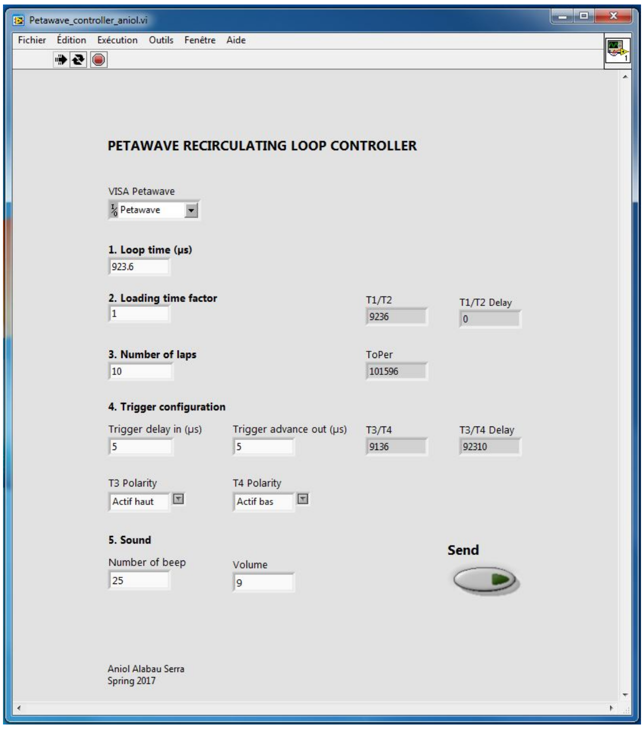



Figure 5.1: Petawave recirculating loop controller

## 5.2. BER accumulation tool

BER accumulation program is designed to obtain BER results automatically changing the number of laps and/or the attenuation of the signal. It allows performing bit error rate analysis with different distances and power levels. It can be used to make long BER accumulations during the night or on weekends.

The program has an easy configuration. First, users have to decide the time each BER accumulation is going to take. Second, set the number of laps and attenuation selecting a start, stop and step for both of them. Finally, they have to select a directory and a name for the results.
It creates a results text file containing the following information in columns: number of laps, distance, attenuation and bit error rate.
When it is executed, it first configures the Petawave controller, then the attenuator, and finally the J-BERT and starts the BER accumulation. It waits until the accumulation is done saves the result and changes the attenuation, if necessary, and/or the number of laps and starts the process again.

The following figure corresponds to a capture of the interface of the program.

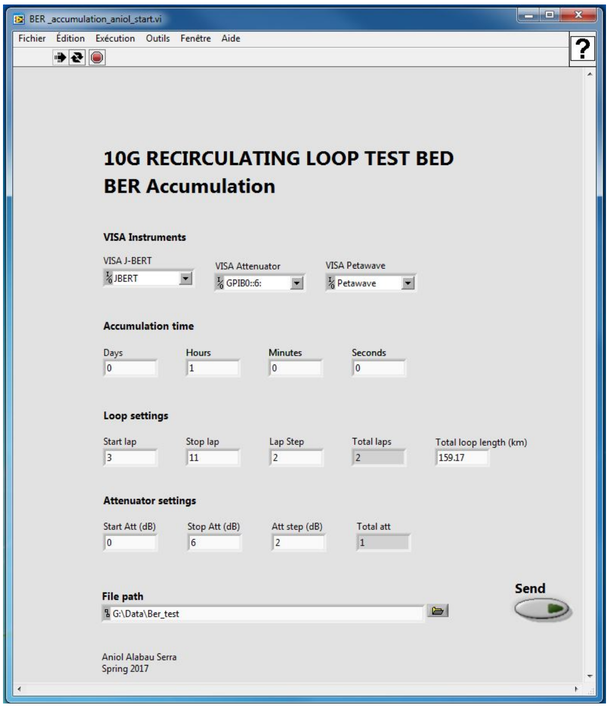


Figure 5.2: BER accumulation software

## 5.3. Received power measurement tool

Received power level measurement program is used to make automatic optical power level measurements changing the number of laps and/or the attenuation of the signal.

It has the same structure than the BER accumulation program. User has to decide the number of laps and attenuation selecting a start, stop and step for both of them. Then the program starts automatically, configuring first with the Petawave controller, then the attenuator, and finally the Ando OSA. It does a single sweep and obtains the peak power level.
Ando spectrum analyzer has to be configured manually before using the program to be sure that it is going to be able to detect the power level of the signal.

# 6. Measurement results and analysis

## 6.1. BER as a function of distance

Bit error rate as a function of distance is an effective way to show the degradation of the transmission quality as the distance travelled by the signal increases. BER accumulations have been done during 1:30h for each distance ranging from 4 to 12 laps in the recirculating loop. Attenuator has been set at 0 dB during the measurements.

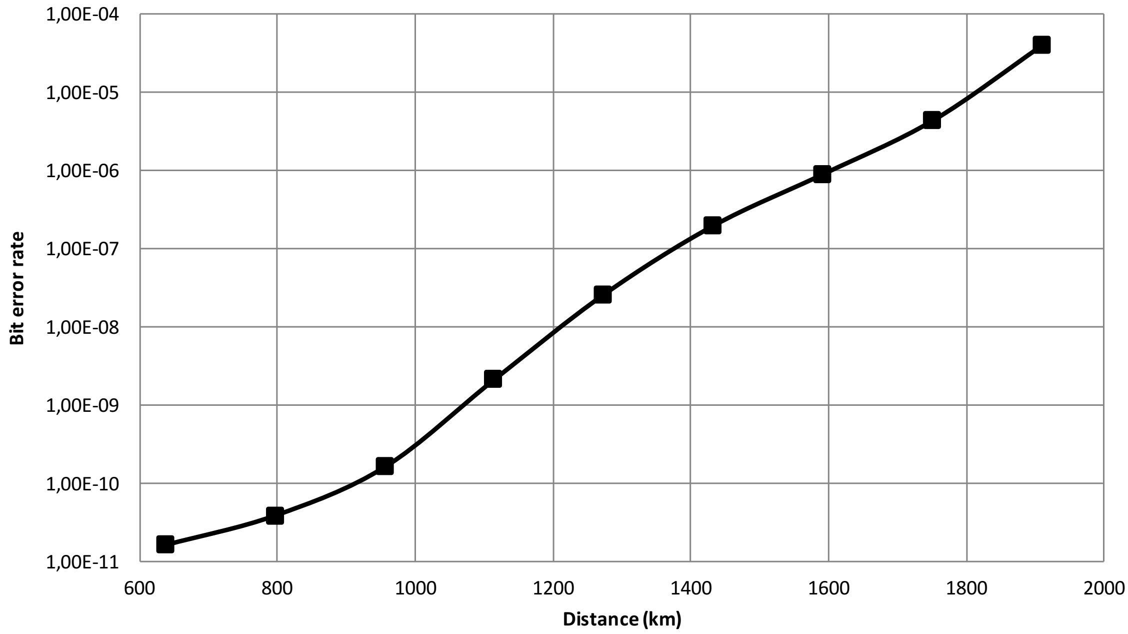



Figure 6.1: BER vs. distance curve

It can be seen on the graph a BER degradation as the distance traveled by the signal is increased. When the number of turns in the recirculating loop is incremented, the OSNR of the signal decreases due to ASE noise accumulation as it is amplified more times. This decrease in the OSNR leads to an increase of the BER.

If the results are compared with a conventional system, it has to be taken into account that in the recirculating loop there are insertion losses produced by the Petawave controller and the wavelength blocker each turn. Hence, the first and third EDFA amplifiers gain is higher than in a conventional system to compensate this IL. This generates a higher ASE which leads to a higher BER.

## 6.2. OSNR measurements

In the following section OSNR measurements are discussed and compared to the theoretical expectations.
First, we have done spectrum and OSNR measurements running different experiments for multiple number of laps using the setup shown in *Figure 3.10*. OSA has been configured with a resolution of 0,01nm and an average of 2. Spectrum results are shown below.

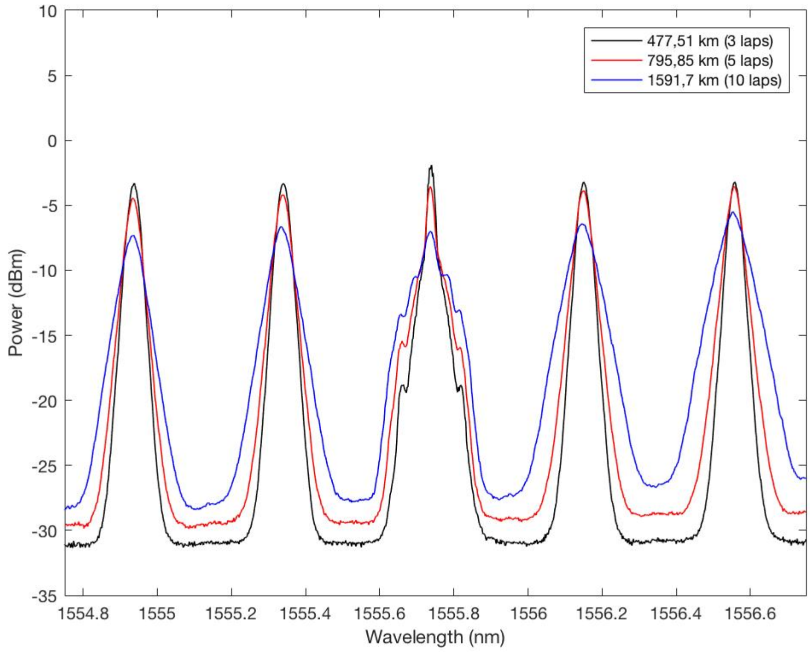



Figure 6.2: Spectrum of the signal after different distances

These measurements show how the noise floor increases when the signal travels more distance due to the ASE noise generated by the EDFA amplifiers. Furthermore, it can be seen how the power level per channel decreases while the width increases when the number of laps is higher due to the dispersion. This produces a decrease in OSNR.

Second, the following equation is used to calculate theoretical OSNR for a WDM system with a single amplifier of gain G [12].

$$OSNR = \frac{P_{in}}{P_{ASE}} = \frac{P_{in}}{2n_{sp}(G-1)hv\nabla f} \quad (6.1)$$

Where $P_{in}$ is the input power, $h$ is Plank's constant ($6{,}626\times10^{-34}$), $v$ is the Optical frequencyv 193 THz , $\nabla f$ is the bandwith where the noise is measured and $n_{sp}$ is the population inversion parameter related to the noise factor.

For an WDM point to point link with N amplifier stage system, with each amplifier compensating for the loss of the previous span it can be obtained the relationship for final stage OSNR.

$$OSNR_{Final} = \frac{P_{in}}{NF\Gamma h\nu\nabla f N} \qquad (6.2)$$

Where $NF$ is the noise factor of each amplifier (assuming that all amplifiers have the same noise factor) and Γ is the span loss (assuming all the spans have the same loss).

Taking logarithm to the common base (10) and assuming that $\nabla f = 0.1nm\ or\ 12.5GHz$ the following equation is obtained.

$$OSNR\ (dB) = 58 + Pin(dBm) - \Gamma(dB) - NF(dB) - 10\log(N) \qquad (6.3)$$

Input power, measured as the peak power at the output of the first amplifier with a WDM of 13 channels (Figure *3.12*) is $Pin = -2\ dBm$. Noise factor has been considered $NF = 5dB$ as a standard value for EDFA amplifiers.
IL is different between the amplifiers on the loop. In the following table an average IL value is calculated from all spans between amplifiers. Connections between two connectors are considered to have an IL=1dB.

*Table 6.1: Average IL calculation*

| **Span** | **Instrument/Fiber** | **IL (dB)** | **Total (dB)** |
|---|---|---|---|
| Amp. 1 to Amp. 2 | 75.75 km SMF28 | 16 | 21 |
| | 5 Connections | 5 | |
| Amp. 2 to Amp. 3 | DCM 60 | 6,22 | 18,22 |
| | WB | 6 | |
| | 6 Connections | 6 | |
| Amp. 3 to Amp. 4 | 83,42km SMF 28 | 17,21 | 22,21 |
| | 5 Connections | 5 | |
| Amp. 4 to Amp. 1 | DCM 100 | 8,3 | 19,77 |
| | Controller | 5,47 | |
| | 6 Connections | 6 | |
| | Average IL | | 20,3 |

There are 4 EDFA amplifiers in the loop and another one is placed before the receiver. As the input power has been calculated after the first amplifier $N = (4\times N_{laps})$. If the discussed values are introduced in the equation the result obtained is:

$$OSNR\ (dB) = 58 + 0 - 5 - 20{,}3 - 10\log(4\times N_{laps}) \qquad (6.4)$$

OSNR is calculated for $N_{laps}$ ranging from 4 to 12. Figure *6.3* shows both measured and theoretical OSNR.

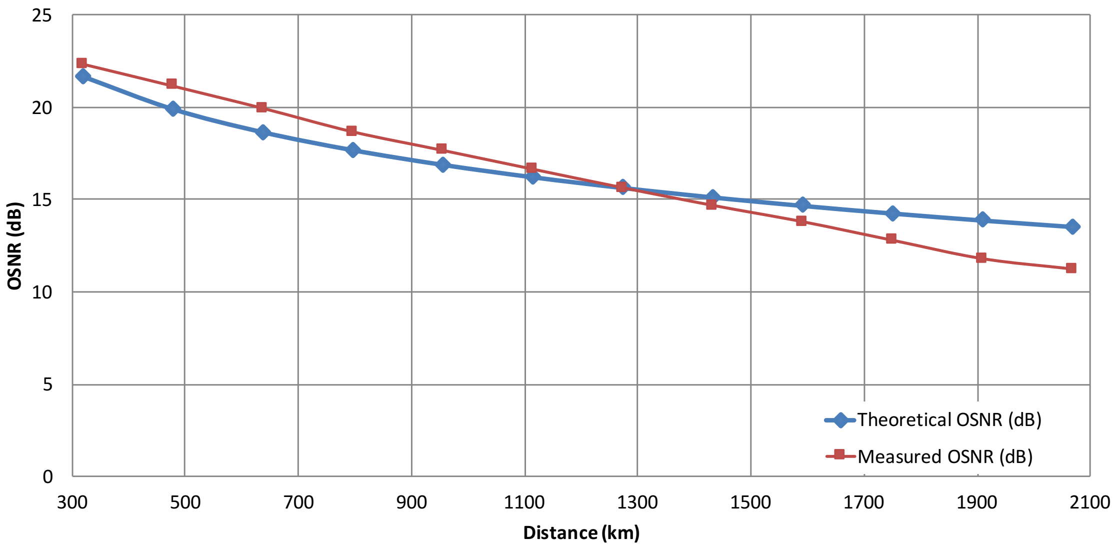



Figure 6.3: Theoretical and measured OSNR as a function of distance comparison

Finally, as it can be seen on the graphic, measured OSNR is a slightly higher (0,5 dB to 1,2 dB) until 1200 km but it decreases faster than the calculated using the theoretical approximation for a WDM link. For longer distances the measured OSNR is up to 2 dB lower than the theoretical one. Furthermore, OSNR measured on the test bed is close from theoretical expectation.

The figure of OSNR as a function of distance can also be compared with results obtained in [15] taking into account the type of fiber used.

## 6.3. BER as a function of OSNR

The following figure shows the measured BER as a function of OSNR.

BER accumulations have been done during 1:30h for each measurement ranging from 4 to 12 laps in the recirculating loop using the setup is shown in *Figure 3.7*. Attenuator has been set at 0 dB during the measurements. OSNR measurements have been performed using the setup shown in *Figure 3.10*.

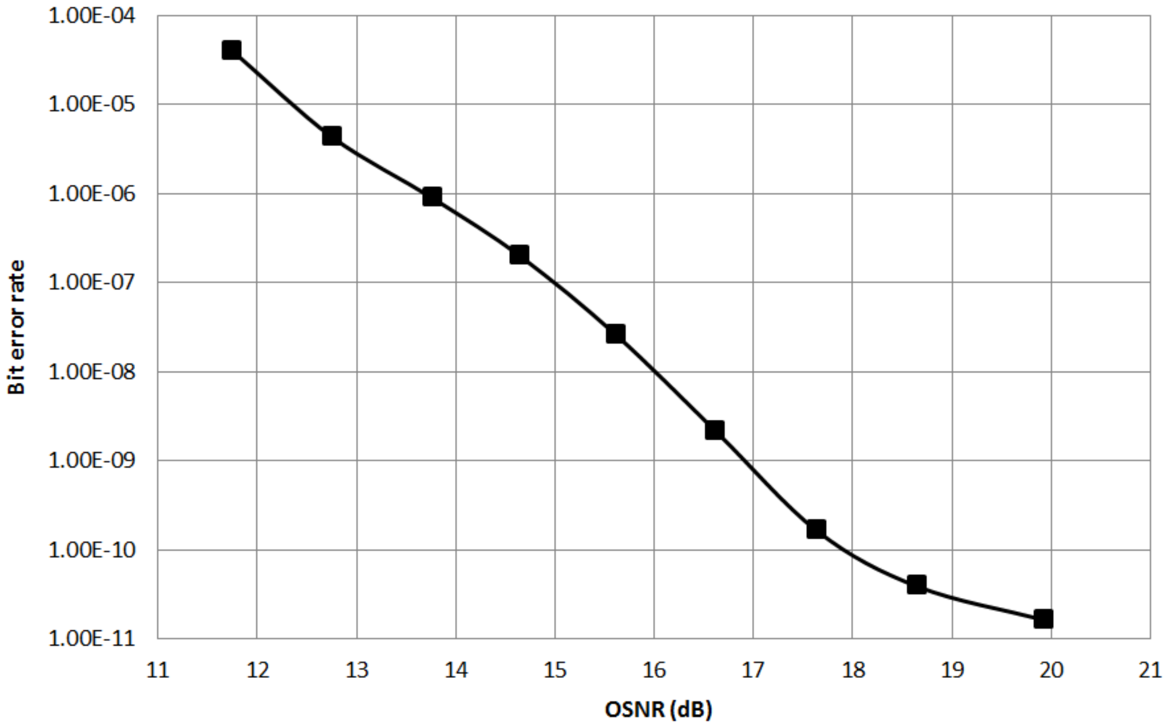



Figure 6.4: BER vs. OSNR

It can be seen on the figure above how BER increases as OSNR decreases. At low OSNR the accumulated ASE noise limits the transmission performance. In addition, it can be noticed that at higher OSNR levels BER decreases more slowly. This measurement can be compared with the experiments realized in [14].

To discuss this BER vs. OSNR results, we are going to obtain theoretical BER results from the OSNR measurements. To do that, we calculate Q factor using the following equation [17]:

$$Q = \frac{2\sqrt{2}OSNR}{1 + \sqrt{1 + 4OSNR}} \tag{6.5}$$

Once Q is calculated, BER can be obtained using equation that follows:

$$BER = \frac{1}{2} erfc(\frac{Q}{\sqrt{2}}) \tag{6.6}$$

To match the theoretical results with the measured values, it has to be taken into account that OSNR measurements have been performed in-band, before the filter and attenuator (as shown in *Figure 3.10*) and BER measurements have been performed at the receiver (see *Figure 3.7*). This means that OSNR at the receiver is affected by the attenuator and the filter. Attenuator only reduces the signal power due to its insertion loss because it is set at 0 dB. However, the filter lowers the signal power and also reduces the noise as it can be seen on *Figure 3.9*. That could lead to a complete study but it is not the purpose of this section. Since the attenuator has an IL of 1 dB and the filter has an IL of 5 dB but also reduces the noise by approximately 2 dB it has been considered that:

$$OSNR_{receiver} \approx OSNR_{in-band} - 4dB \tag{6.7}$$

Once made this approximation, BER has been calculated using equations 6.4 and 6.5. Results comparing the measurements with the theoretical calculations have been represented on the figure that follows.

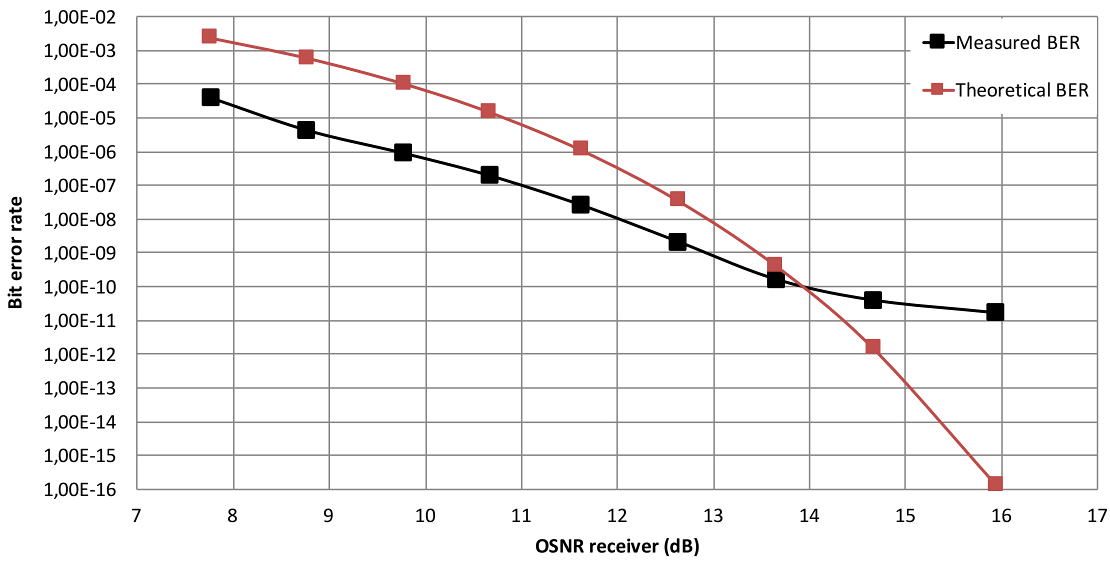


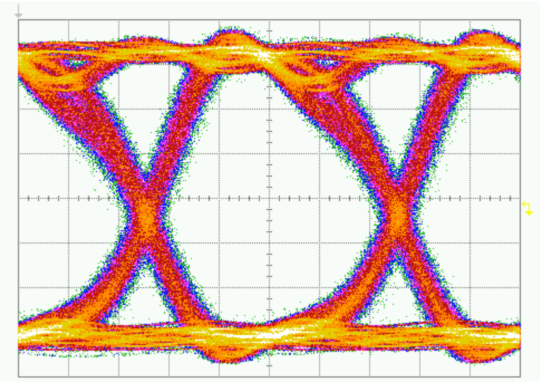

Figure 6.5: Comparison of theoretical and measured BER vs. OSNR

On the one hand, it can be seen on the figure how the theoretical BER is higher in low OSNR values. On the other hand, theoretical BER decreases faster than the actual BER measured on the recirculating loop which trends to stabilize even the OSNR increases.

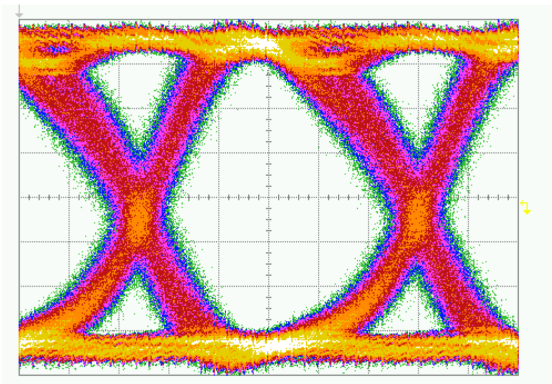
## 6.4. Eye diagrams

Eye diagrams have been measured using the setup shown in *Figure 3.8*. Measurements have been done with back to back setup and using the recirculating loop from 3 to 11 laps using a step of 2. Vertical scale is 100mv/div and horizontal scale is 16.2 ps/div.

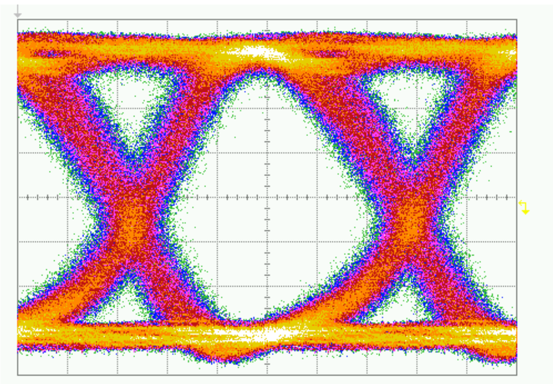
B2B



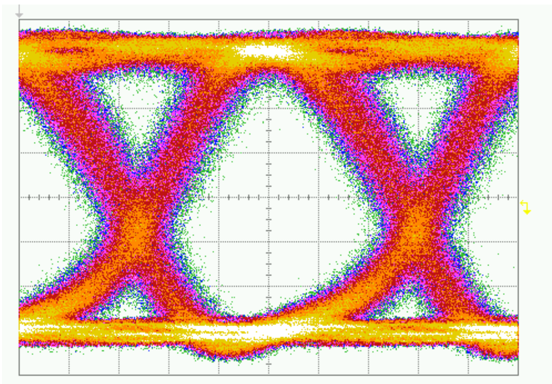
477,51 km (3 laps)



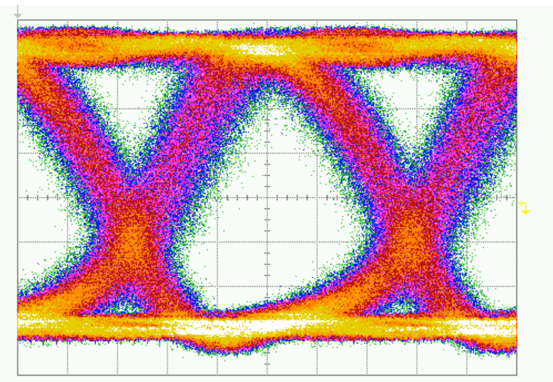
795,85 km (5 laps)



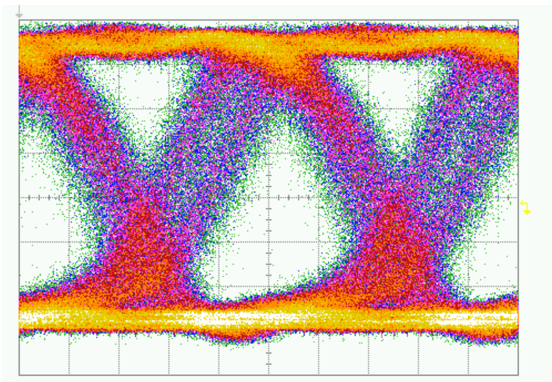
1114,19 km (7 laps)



1432,53 km (9 laps)



1750,87 km (11 laps)



It can be seen that the eye opening is reduced as the distance or number of laps the signal made in the loop is increased. It can also be noticed the increment of the ASE noise and the increase of the jitter when the distance is larger.

Q factor measurements have been performed using the oscilloscope measure mode Signal to Noise which, despite the name, is defined exactly like Q factor as explained in equation (2.9).

Results obtained using this measurement, even different setups and eye thresholds have been tried, are not correct and will need to be further studied. To demonstrate that, we have compared the Q factor measured on the oscilloscope with the Q factor obtained from equation (6.5) using the OSNR measurements realized and making the assumption summarized in equation (6.7).

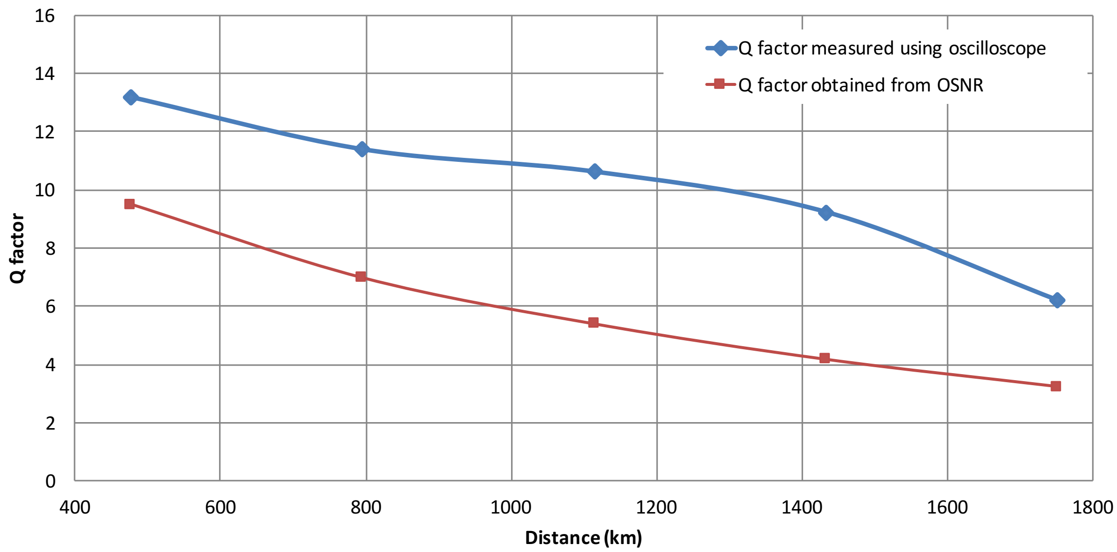



Figure 6.6: Q factor comparison

It can be seen on the figure above that Q factor measured with the oscilloscope is between 3 and 5 points higher than the Q factor obtained using the OSNR measurements.

In addition, an example can be used to show that Q factor measurements realized on the oscilloscope are not correct. Using 3 laps in the recirculating loop (477,56 km) we measured a Q factor of $Q = 13{,}2$, if we use equation (6.3) to obtain the corresponding bit error rate we obtain that it corresponds to $BER = 4{,}3 \times 10^{-40}$ which is not possible.

## 6.5. BER as a function of received power

On the following section BER as a function of the received optical power level is going to be discussed.

BER accumulations have been performed with the setup shown in *Figure 3.7* using the variable attenuator to reduce the optical power at the receiver by step sizes of 1 dB. For each power level 1 hour BER accumulation has been performed.
Measures have been done for different distances on the recirculating loop ranging from 3 to 11 laps using a step size of 2 laps. Also, a reference measurement back to back (B2B) has been realized using the setup shown in Figure *3.11*. The complete measurement has taken approximately 4 full days.
As the output EDFA amplifier is fixed at 14dBm output power control mode the received power only depends on the attenuation set during the experiments. Power has been measured at 0 dB attenuation and calculated as a function of the attenuation.

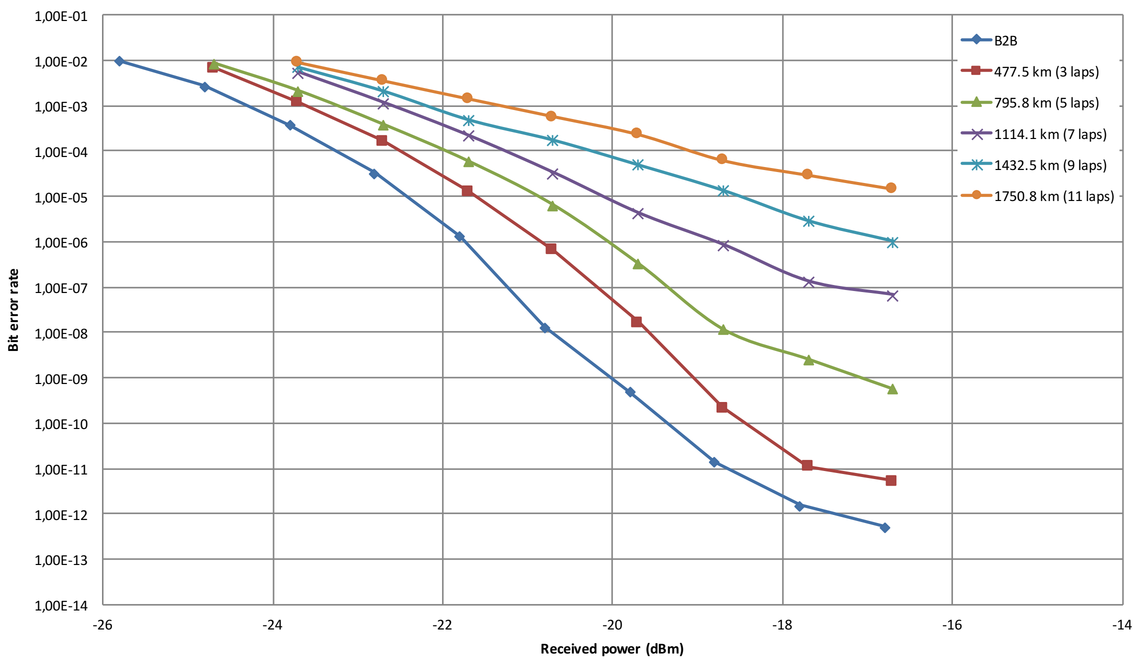



Figure 6.7: BER vs. Received Optical Power

It can be observed on the figure above how BER increases as the received power decreases. This is because at low received power, the system is limited by linearities resulting to signal attenuation hence high BER.
It also can be noticed that with longer distances the power need to achieve a certain BER is higher than with lower distances. Furthermore, with longer distances the variation on the BER as the received power increase is lower because the signal has a lower OSNR that leads to a bigger BER. This figure can be compared with the results discussed in [18] and [19].

## 6.6. BER as a function of received power using sampling point algorithm

In this section, it has been used an algorithm to achieve the best sampling point to improve BER when the received power level changes.
Measures of BER and power have been realized using the procedure explained in the previous section except that before each BER measurement algorithm created in [1] has been applied to set up the sampling point location to minimize BER.

Results presented in the figure below compare the results of BER as a function of received optical power using the sampling point algorithm with the results obtained using a fixed sampling point (40 ps, 0 V).

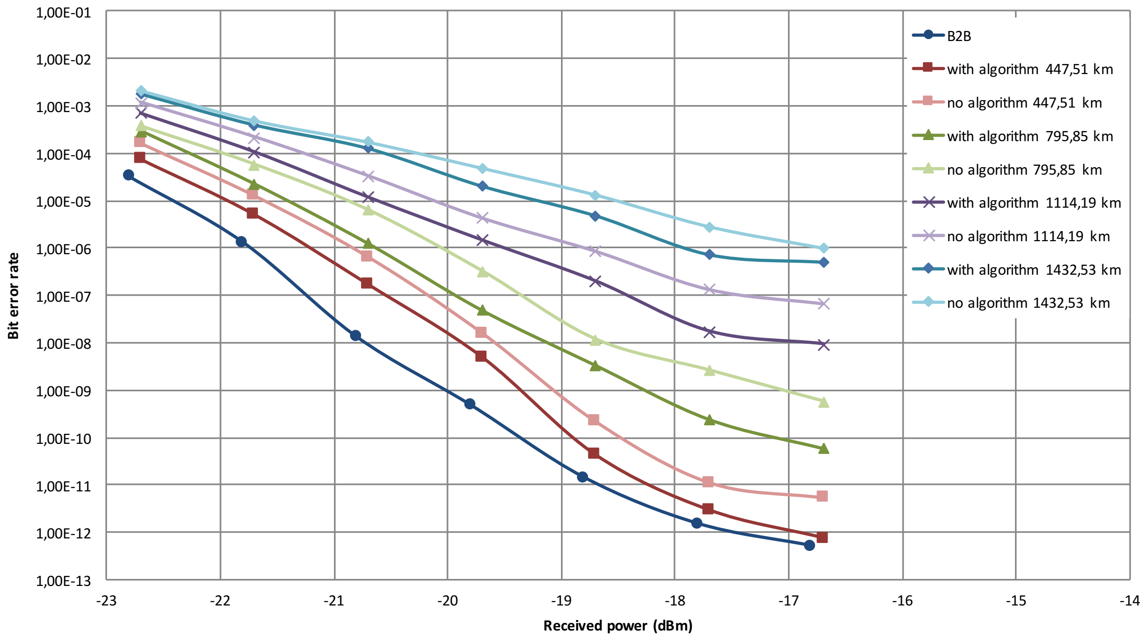



Figure 6.8: BER vs. received power using sample point algorithm

As expected, the adaptation of the sampling point location to the conditions of the received signal in terms of power and noise improves the BER. It can be seen on the figure how the received power necessary to achieve a certain BER level is higher using a fixed sampling point than when using the adaptative algorithm. The BER difference with the same received power is between half and one magnitude order.

# 7. Conclusions

Long haul optical communications development is going to continue during the next few years. The optimization of the 10G recirculating loop test bed improves this tool and allows new studies in this field.

During this thesis, the test bed had been optimized and properly characterized with experiments and tests on the equipment. A new configuration had been provided in order to control the recirculating loop and trigger the instruments used to check the quality of the transmission at the output. Amplification parameters had been optimized according to 13 DWDM channels.

The operational manual written during this project provides help to new users in order to be more familiar with the test bed. It allows understanding the equipment setup, the configuration of the loop and the procedures used to make measurements and experiments. The collection of software tools developed as well as the manual created to introduce this programs provide an upgrade to this equipment allowing automatic measurements and configuration. Petawave controller tool is also used on the 100G recirculating loop.

BER measurements as a function of the distance as well as eye diagrams also showed the degradation of the signal when the distance is increased although Q measurements realized need to be further studied. OSNR measurements at the output of the loop had matched with the theoretical expectations and demonstrated a good behaviour of the setup. Furthermore, measurements of BER as a function of received power had provided figures that match with other results on the literature.

All these results proved that the configuration of the loop had been done correctly, fulfilling the main purpose of optimizing this test bed and provide a variety of references for further studies.

## 7.1. Future work

After this project, 10G recirculating loop test bed is ready to be used for new experiments on long haul communications.

Measurements of BER as a function of input power have been started during this project but not presented in this thesis due to the deadline, they showed the degradation of the BER as the input power is decreased but they need to be further studied and analyzed.
Another interesting part that has not been done in this project will be to study the polarization effects in the recirculating loop.

The physical configuration of the test bed has not been modified during this project, but a suggestion in order to improve the results would be to place the wavelength blocker at the beginning of the loop, after the controller and before the first amplifier. With this configuration the channels will be blocked before and the EDFA amplifiers could work in an optimal configuration according to the number of channels from the first turn.

The software tools that have been developed for the measurements done in this project are available in the laboratory. They could be modified, improved and adapted to new purposes and experiments on the recirculating loop.

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# 9. Appendices

## 9.1. Equipment characteristics tables

| Table 9.1: Nortel MOR+ Amplifier Settings | | |
|---|---|---|
| Parameter | Setting | Used setting |
| Amplifier configuration | Off, Pre, Post, MSA Pre, MSA Post | Amp 1: Post<br>Amp 2: MSA Pre<br>Amp 3: MSA Post<br>Amp 4: MSA Pre |
| Power Control | Peak, Total | Total |
| Power target | -20 dBm to 16.8 dBm | 14 dBm |
| Input shut-off mode | None, Soft, Hard | Soft |
| Optical reflectometer | Enabled/disabled | Enabled |
| Input LOS threshold | -30 dBm to 0 dBm | -26 dBm |
| Input shut-off threshold | -36 dBm to -6 dBm | -26 dBm |
| Optical return loss threshold | 10 dB to 40 dB | 24 dB |

Source: Nortel Optical Long Haul 1600 MOR Plus Provisioning Procedures

| Table 9.2: JDSU Wavelength Blocker characteristics | | |
|---|---|---|
| Spectral Range | | 1526,4 to 1567,1 nm |
| Wavelength Spacing | | 50 GHz |
| Insertion Loss | Typical | 4,5 dB |
| | Maximum | 6 dB |
| Tunable Attenuation range | | 0 to 20 dB |
| Attenuation step size | | 0,1 dB |
| Attenuation accuracy | | 0,3 dB |

Source: JDSU dynamically reconfigurable wavelength blocker for C band specifications

| Table 9.3: MPB Communications Comb Source 9022 characteristics | |
|---|---|
| Spectral Range | 1529-1565nm |
| Wavelength Spacing | 50 GHz |
| Number of channels | 90 |
| Extinction Ratio at 0,02 nm resolution | ≥ 45 dB |

Source: MPB Communications Comb Source 9022 specifications

| *Table 9.4: MPB EOA-S-VP17-1-2-S two stage EDFA amplifier characteristics* | | | |
|---|---|---|---|
| Parameter | Condition | Min | Max |
| Modes | APC (power control)<br>AGC (gain control)<br>ACC (current control) | - | - |
| Wavelength | 1529-1563 nm | - | - |
| Power | All channels | -6 dBm | 4 dBm |
| | 2 to 32 channels 23 dB gain | -6 dBm | 19 dBm |
| | 1 to 32 channels 13dB gain | -11 dBm | 4 dBm |
| Gain | | 13 dB | 23 dB |
| Merit figure | 23 dB gain | 5,5 dB | |
| | 13 dB gain | 12,5 dB | |

Source: MPB EOA-S-VP17-1-2-S specifications

| *Table 9.5: JDSU TB3 Tunable Filter characteristics* | |
|---|---|
| Optical shape | Gaussian |
| -3 dB bandwidth | 0.28nm ±15% |
| 3/20 dB ratio | 0.31 nm ±0.05 |
| Insertion Loss (1520 nm - 1610 nm) | <5.8 dB |

Sources: JDSU TB3 datasheet/ Nelson Landry

| *Table 9.6: Agilent 81577A Variable Attenuator characteristics* | |
|---|---|
| Attenuation range | 0 to 60 dB |
| Accuracy | 0,1 dB (at 1550 nm) |
| Insertion Loss (1520 nm - 1610 nm) | Typ. 0.7 dB (without connectors) |

Source: Agilent 81577A datasheet

| *Table 9.7: Agilent 83434A Lightwave Receiver characteristics* | |
|---|---|
| Detector | PIN |
| Optical input power recommended | -16 dBm to 0 dBm |
| Maximum safe input level | 7 dBm |
| Loss of optical input alarm | -25 dBm |
| Data output amplitude | 0.5 V to 1.5 V |

Source: Agilent 81577A products overview