Analysis of physical effects on multi-flow flex-grid optical networks

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by

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Telecommunications Systems **ENGINEERING**

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Abstract

In the present project, the effect of physical impairments induced by the transmission trough a flexgrid optical network, has been studied by means of numerical simulations. In particular, the frequency filtering effect of the network elements, like multiplexers, has been evaluated. The filters' characteristics have been chosen to match state of the art equipment in terms of bandwidth and frequency stability.

Two different modulation formats have been considered, namely, intensity modulation with direct detection and quadrature amplitude modulation (QAM). The first one has been the standard for many years and the last one is and advanced scheme for the years to come.

The simulation tool utilized has been a commercial software, VPI TransmissionMaker by Virtual Photonics Inc. (VPI). This is a very powerful software widely used by the research community in this field.

The results obtained allow us to define the minimum frequency bandwidth of the optical elements and the minimum channel spacing to guarantee a certain quality.

Resum

En el present projecte s'ha estudiat, mitjançant simulacions numèriques, l'efecte dels impediments físics induïts per la transmissió a través d'una xarxa flexgrid òptica. En particular, l'efecte de la freqüència dels elements de la xarxa de filtrat, com multiplexors, han sigut evaluats. Les característiques dels filtres han sigut tríades per a que coincideixin amb l'estat tècnic dels equips en termes d'ample de banda i estabilitat de freqüència.

S'han considerat dos formats diferents de modulació, modulació d'intensitat amb detecció directa i modulació d'amplitut en quadratura (QAM). La primera ha sigut la estàndard durant alguns anys i l'altre, és un esquema avançat pels propers anys.

L'eina de simulació utilitzada ha sigut un software comercial, VPI TransmissionMaker de Virtual Photonics Inc. (VPI). És un software molt poderós extremadament utilizat per la comunitat d'investigadors en aquest camp.

Els resultats obtinguts ens han permès definir l'ample de banda de freqüència mínima dels elements òptics i el mínim espai de canal per a garantitzar una certa qualitat.

Resumen

En el presente proyecto se ha estudiado, mediante simulaciones numéricas, el efecto de los impedimentos físicos inducidos por la transmisión a través de una red flexgrid óptica. En particular, el efecto de la frecuencia de los elementos de la red de filtrado, como multiplexores, han sido evaluados. Las características de los filtros han sido escogidos para que coincidan con el estado técnico de los equipos en términos de ancho de banda y estabilidad de frecuencia.

Se han considerado dos formatos diferentes de modulación, modulación de intensidad con detección directa y modulación de amplitud en cuadratura (QAM). La primera ha sido la estándard durante algunos años y la otra, es un esquema avanzado para los próximos años.

La herramienta de simulación utilizada ha sido un software comercial, VPI TransmissionMaker de Virtual Photonics Inc. (VPI). Es un software muy poderoso y extremadamente utilizado por la comunidad de investigadores en este campo.

Los resultados obtenidos nos han permitido definir el ancho de banda de frecuencia mínima de los elementos ópticos y el mínimo espacio de canal para poder garantizar una cierta calidad.

Acknowledgements

First of all, I would like to thank my two advisors, Jaume Comellas and Joan M. Gené who have helped me from the beginning, have guided me in every step, have encouraged me in difficult times and have made this project possible. With both of them, this project has been realized with happiness and enthusiasm. Each has devoted much of his time to me.

Thanks to Joan for all those hours in the laboratory making me understand how VPIphotonics works, giving me advice, for guiding me every step of the project, and for his interest every week to see how the project progressed.

I want to thank Jaume for stimulating my interest in the world of optical communications, for giving me the opportunity to do this project with him, for all those hours debating how to progress in this work, all these explanations he gave me over and over again until I have understood everything, for his confidence in me and especially for the interest he has shown me on this project.

Thanks to my parents and my sister, who in one way or another have helped me and accompanied during these months making it easier to carry out this project. Thank you for your unconditional love, patience, and for supporting me in every decision of my life.

Specially I want to say thank you to my dearest Arantxa for staying always by my side, giving me support, calling me every day, for her interest in this project and also on me in every step of my life.

I thank with all my heart to all of you.

Finally, I would like to dedicate this project to the most important person in my life, my mother, who since my first year in Engineering has supported me, entrusted in me and has never doubted this day would come. Thank You.

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1 Introduction

1.1. Project background

This project has born as an idea of one of my tutors, Jaume Comellas. I was her student at Optical Communications and I really enjoyed this subject. Since there, I have been interested on Optical Networks, and I decided to do two more subjects related to this theme. Firstly, was PAE in which I had to design a real passive optical network in a village with other classmates. As I expected, I found it very exciting and attractive. Secondly, I did an elective subject called Fibsys (Optical Fiber Systems), where I finally decided to do my final project in the Optical Communications environment.

The main project initial ideas are provided by my tutor. I commented to him that I wanted to do a project related with Optical Communications. So, he proposed me to do some simulations with VPIphotonics software in order to simulate an elastic optical network and analyze some parameters of the network.

1.2. Project overview and goals

The project has carried out at Universitat Politècnica de Catalunya, Campus Nord, in the department of Signal and Communications Theory, particularly in Optical Communications Laboratory.

This project has consisted on doing theoretical analysis and simulations using VPIphotonics. The main purpose of these simulations has consisted on seeing the effects of different parameters on the flex-grid network performance, assuming that multi-flow optical channels are sent.

The main goal has been to obtain quantitative results about the parameters allowing a satisfactory performance of the whole system.

1.3. Requirements and specifications

Project requirements:

- Deep knowledge about the devices involved in a flex-grid optical network and the main parameters defining the performance of these devices.
- Using VPI for simulations about the performance of the different network elements.
- Extract conclusions about the best parameters to be used in different scenarios.

Project specifications:

- Theoretically analyzing the problem.
- Using VPIPhotonics to assess the outputs of the theoretical analysis.
- Generate generic rules that help in the design of flex-grid multi-flow optical networks.

1.4. Workplan

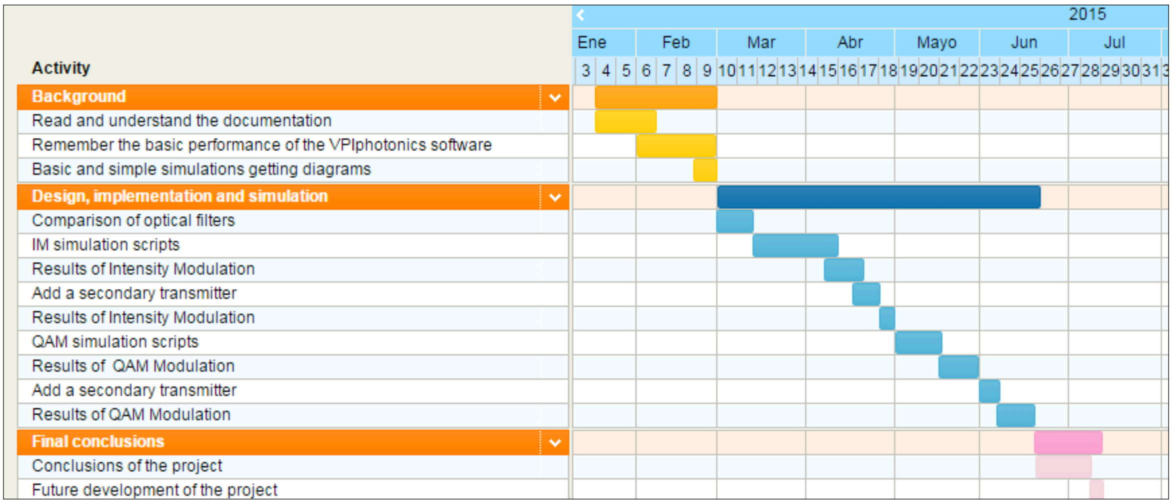

Figure 1. Project final workplan

2 State of the art of the technology used or applied in this thesis:

In the last decade, communications networks field has grown exponentially in data traffic due to the popularity of the Internet to the point that in terms of volume, data traffic has already exceeded traffic voice today. In the Telecommunication networks context, this entails a predictable change in the technological paradigm that will support future optical networks, evolving from the current, based on circuit switching or optical channels to new, more next to the existing currently in the electrical domain , which will be based on switching IP packets (Internet Protocol) directly in the optical domain . Besides its own packet switches, the new platform based on a single data structure and integration of voice must be able to provide routing and management services without the information into electrical format on each router.

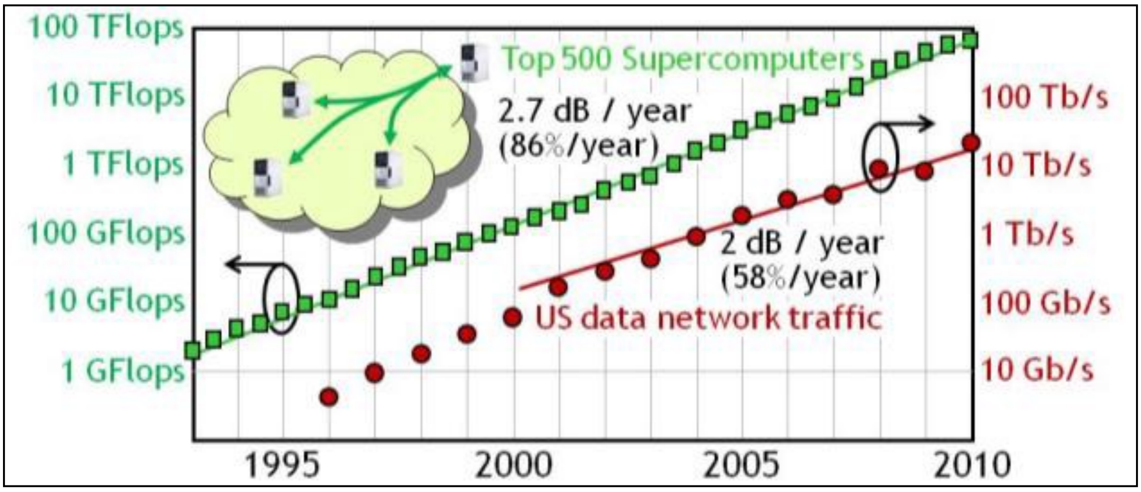

Figure 2. Exponential data network traffic growth

Exponential network traffic growth is driven by high-bandwidth digital applications (Video-on-demand, telepresence, wireless backhaul, cloud computing and services).

This is leading to a lot of new development opportunities in the current communication networks, because the final user demands better applications and faster solutions, therefore, there is an immediate need for development of new high-capacity networks.

2.1. Optical networking

Optical fiber transmission technologies have evolved in the last decade too, because of the growing demand for broadband services, high speed and high bandwidth.

Optical networking is a means of communication that uses signals encoded onto light to transmit information among various nodes of a telecommunications network. They operate from the limited range of a local-area network (LAN) or over a wide-area network (WAN), which can cross metropolitan and regional areas all the way to national, international and transoceanic distances. It is a form of optical communication that relies on optical amplifiers, lasers or LEDs and wave division multiplexing (WDM) to transmit large quantities of data, generally across fiber-optic cables. Because it is capable of achieving extremely high bandwidth, it is an enabling technology for today's Internet and the communication networks that transmit the vast majority of all human and machine-to-machine information.

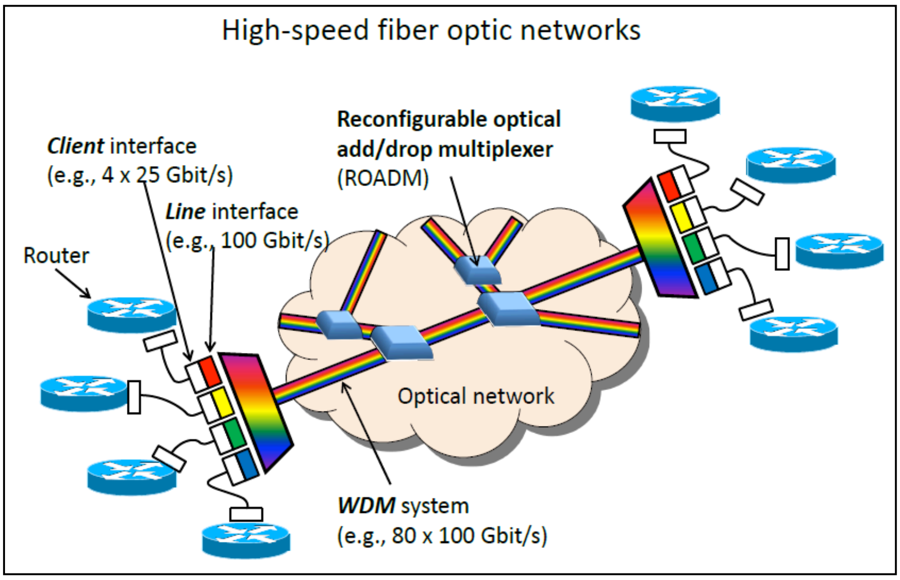

Figure 3. Components of a high-speed fiber optic networks

2.2. Routing and wavelength assignment

WDM in optical fiber networks is rapidly gaining acceptance to handle increasing bandwidth demands of networks users. It allows to set-up simultaneous communications between different user pairs via optical WDM channels, referred as lightpaths, which may share the same fiber links.

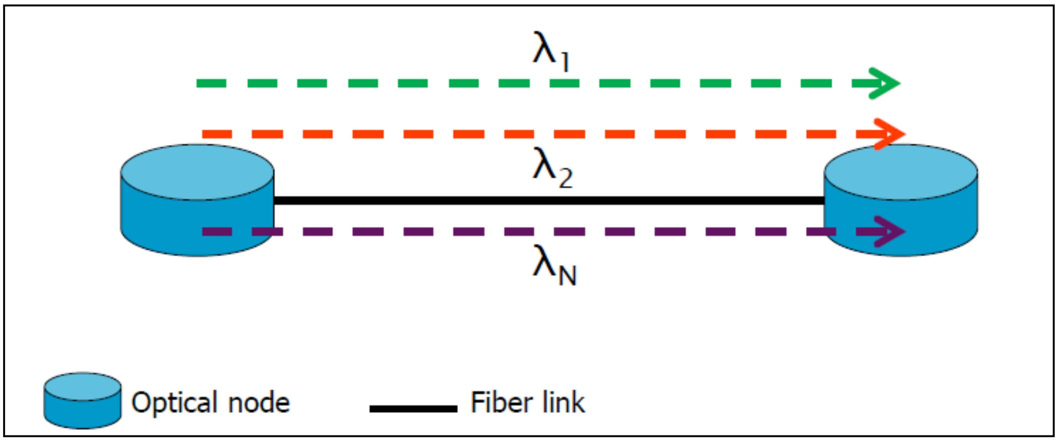

Figure 4. WDM channel composed by optical nodes and fiber links (lightpaths)

However, WDM poses several challenges that have to be addressed when setting up connections in a optical network. One of the most important of these challenges is the **Routing and Wavelength Assignment** problem (RWA).

So, RWA can be defined as, given a set of connections between node pairs in a optical network, set up a lightpath for each connection by assigning a route (sequence of physical links) and a wavelength to be employed for every connection.

But RWA has also several restrictions:

- **Wavelength clashing constraint:** two lightpaths cannot employ the same wavelength in the same physical link.
- **Wavelength continuity constraint:** in a transparent optical network, a lightpath must employ the same wavelength in all the links along its route.

2.3. Flex-grid optical networks

Flexgrid optical networks are attracting huge interest due to their higher spectrum efficiency and flexibility in comparison with traditional wavelength switched optical networks based on the wavelength division multiplexing technology. To properly analyze, design, plan, and operate flexible and elastic networks, efficient methods are required for the routing and spectrum allocation (RSA) problem.

RWA is a very important optimization problem for all-optical networks. It allows for the realization of several optimization goals:

- Maximize the number of successfully allocated connections on the network.
- Minimize the necessary number of wavelengths per fiber link in order to serve a set of connections.
- Balance the load of optical links, so a minimal number of connections are affected if a link failure happens.

Routing and wavelength assignment has three main variations depending on the nature of the connections and the knowledge about them:

- **Static RWA.** Given an optical network, find a lightpath (route and wavelength) for a set of permanent connections, for which their characteristics (source, destination, bandwidth) are fully known in advance.
- **Incremental RWA.** Given an optical network, find a lightpath (route and wavelength) for a set of permanent connections, that arrive sequentially at the network.
- **Dynamic RWA.** Given an optical network, find a lightpath (route and wavelength) for a every incoming connection at the network, according to the actual state of the network. Every connection is released after some time, changing the state of the network.

Once the RWA problem is solucionated, elastic (Flex-grid) optical networks adjust the optical spectrum for each demand, based on the bit rate and transmission distance. It consists on divide the optical spectrum flexibly assuming that transceivers can generate paths with variable bit rates. It allows an adaptive use of resources, a flexible use of spectrum and a flexible relationship between client technologies (IP) and the optical layer, regarding the issues such as spectrum assignment and continuity.

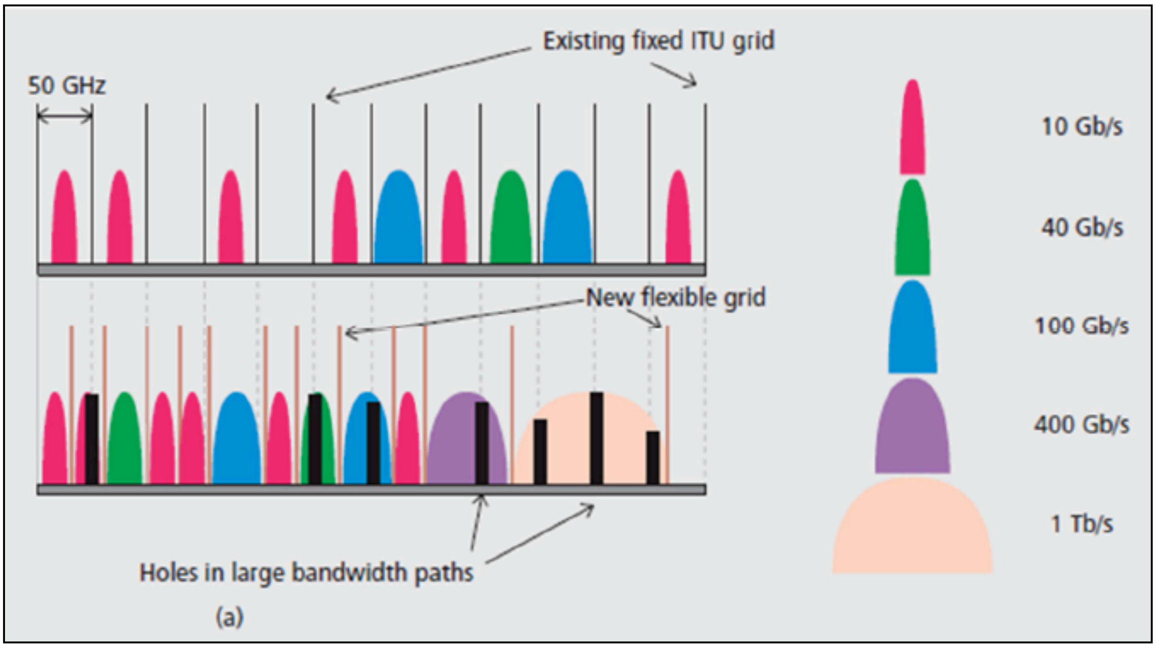

Figure 5. Fixed optical spectrum and elastic (Flex-grid) optical spectrum adjusted by demand

EON Advantages
• Expansion of the optical reach • Support for 400 Gb/s, 1 Tb/s, and other higher bit rate demands • Dynamic networking • BVTs (Bandwidth Variable Transceivers) which adjust their bandwidth to the IP layer demands

Table 1. Elastic Optical Networks advantages

3 Methodology / project development:

On this project, two different types of modulations of an optical network have been simulated using VPIphotonics software. In order to characterize the parameters of all network elements, two different schematics have been done, one simulating an Intensity modulation and the other one, simulating a QAM modulation.

3.1. Intensity Modulation

Some interesting simulations have been done with the Intensity modulation. Basically, it consists in three different modules: transmitter, channel and the receiver.

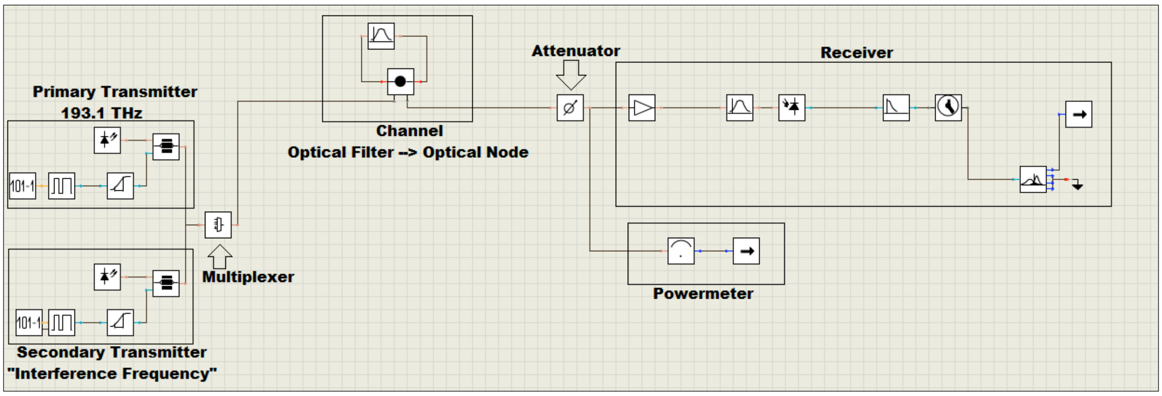

Figure 6. Complete scheme of the intensity modulation

3.1.1. Transmitter

The first simulations were made ignorin the effect of the interfering transmitter. Anyway, both transmitters are identical:

- **Laser.** Produces a continous wave Optical signal with a power of 10 mW and centered at a 193.1 THz emission frequency.
- **Data.** Generates many types of pseudo random data sequences.
- **Coder.** Generates a sampled, NRZ (Non Return to Zero) coded signal defined by a train of bits at its input.

- **Rise Time Adjust.** A Gaussian filtre that transforms, for example, rectangular electrical input pulses into smoother output pulses with a user-defined rise-time. Its effect is to band-limit the modulated Optical signal, which is required to avoid numerical artefacts when resampling to higher sample rates.
- **Modulator.** Simulates a Mach-Zehnder modulator.

In these simulations where the secondary transmitter is adding, the only change has been set different a pseudo random data in order that both transmitters have no the same sequences.

3.1.2. Optical channel

The optical channel has been interpreted as an optical filter. In order to see the effects of this filter, the transmitted data goes through the filter ten times or loops simulating ten optical nodes of a typical optical network.

- **Optical Filter.** A model of a filter with a Gaussian transfer function with order 1. Its center frequency is changing depending on the type of simulation. It has been very interesting to find an optical filter which meets the specifications of a marketed optical filter found. For checking the specifications, a new schematic have been created. It just consists on an optical impulse function that is transmitted and goes through the optical filter studied. In order to see how it works, a display lets see how is the transfer function of the filter.

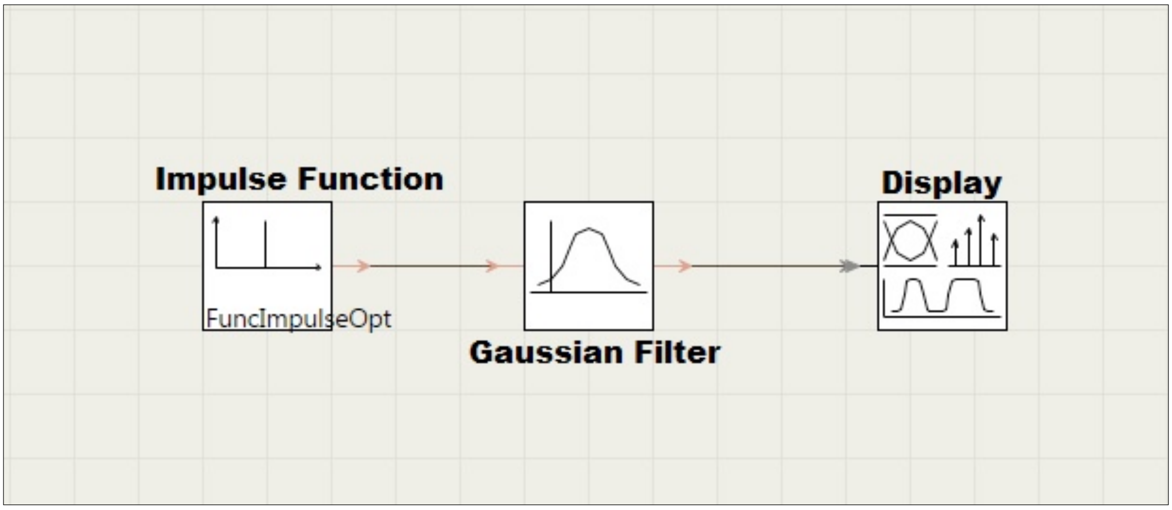

Figure 7. Scheme to analyze the transfer function of the optical filter

The bandwidth of the optical filter was fixed to 12.5 GHz. In this case at 6.25 GHz, it attenuates 3 dB:

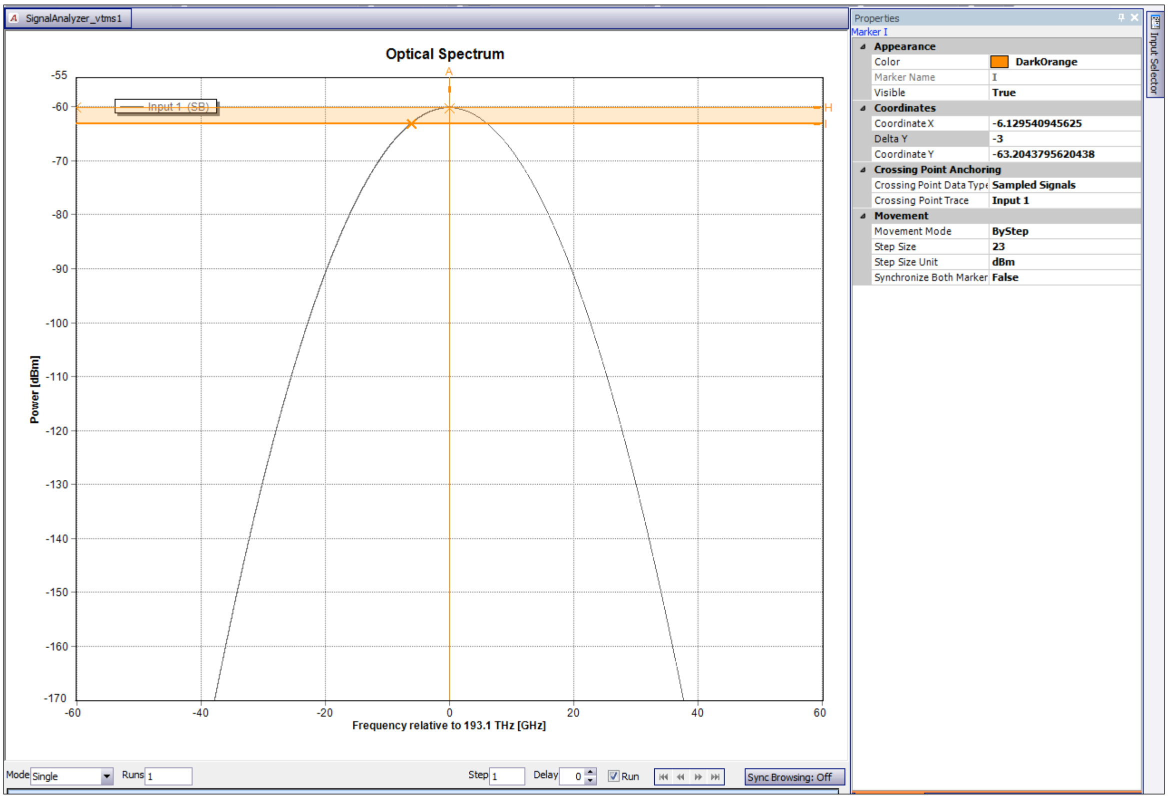

Figure 8. Transfer function of the optical filter evaluated when it attenuates 3 dB

For seeing the angle of the slope, two points separated 1.25 GHz (0,01 nm) are selected in the marked area in the next picture, and it corresponds to4 dB approximately.

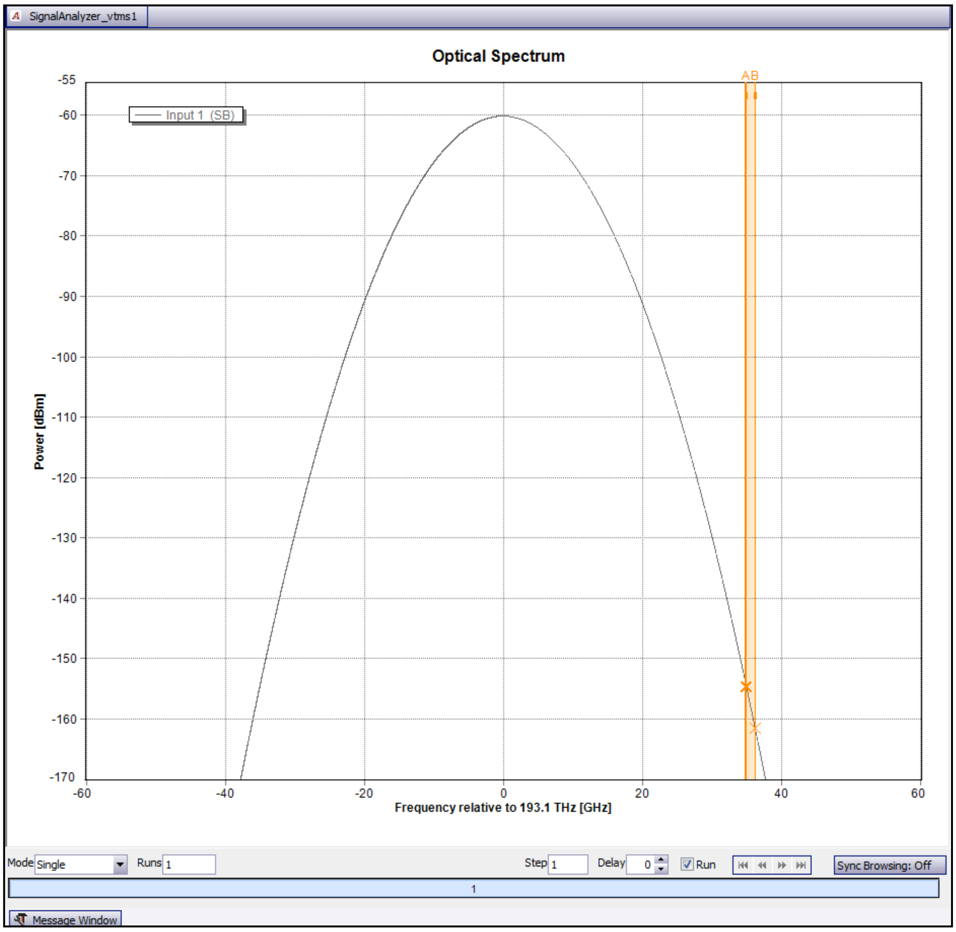

Figure 9. Transfer function of the optical filter evaluated in two points separated 1.25 GHz (0,01 nm)

With this filter the specifications of the marketed filter found are keeped (400dB/nm).

3.1.3. Attenuator and Amplifier

The amplifier is considered in the Receiver module but it is very useful to characterize it with the attenuator in order to help us find the receiver sensitivity.

- **Attenuator.** Attenuates the optical signal. In each loop, a fixed value of the attenuator is set in order to get a properly value of the BER (10^{-3}).

- **Amplifier.** A model with fixed gain shape for the system. Its main function is to contribute the noise factor to the system.

With these two modules the optical power can be fixed in order to get the specific desired BER at the receiver varying the SNR received.

3.1.4. Receiver

The receiver is basically composed by:

- **Amplifier.** A model with fixed gain shape for the system. Its main function is to contribute the noise factor to the system.
- **Powermeter.** Calculates the power of an optical signal.
- **Optical Filter.** Eliminates out of band optical noise.
- **Photodiode.** It corresponds to a PIN photodiode model.
- **Electrical Filter.** It is low pass electrical filter with a Bessel transfer function. It eliminates out of band electrical noise.

3.2. QAM Modulation

In this case, the transmitter and the receiver used have been the ones provided by the simulator because they fulfilled our requirements. Apart from this, the scheme is exactly the same as in the Intensity Modulation, the optical node and the structure of the receiver are the same as the other modulation, so the only changes are in the transmitter and the receiver.

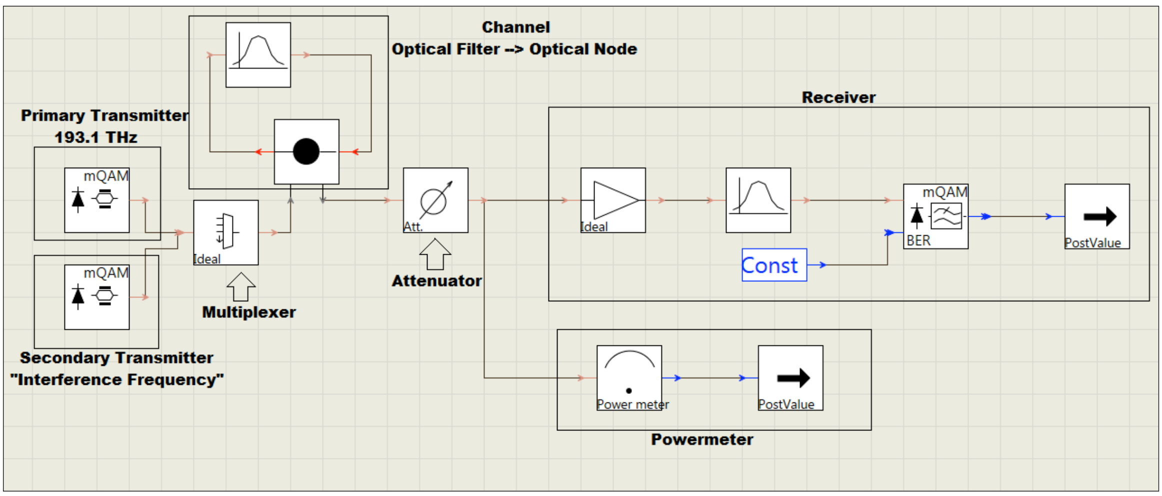

Figure 10. Complete scheme of the QAM modulation

3.2.1. Transmitter

As in the Intensity modulation, The first simulations were made ignoring the effect of the interfering transmitter. With these simulations, the scheme of the transmitter and the receiver were done by default in VPIphotonics. The QAM symbols are generated and then, the in-phase and in-quadrature electrical signals are used to modulate the optical carrier by using a Standard IQ modulator.

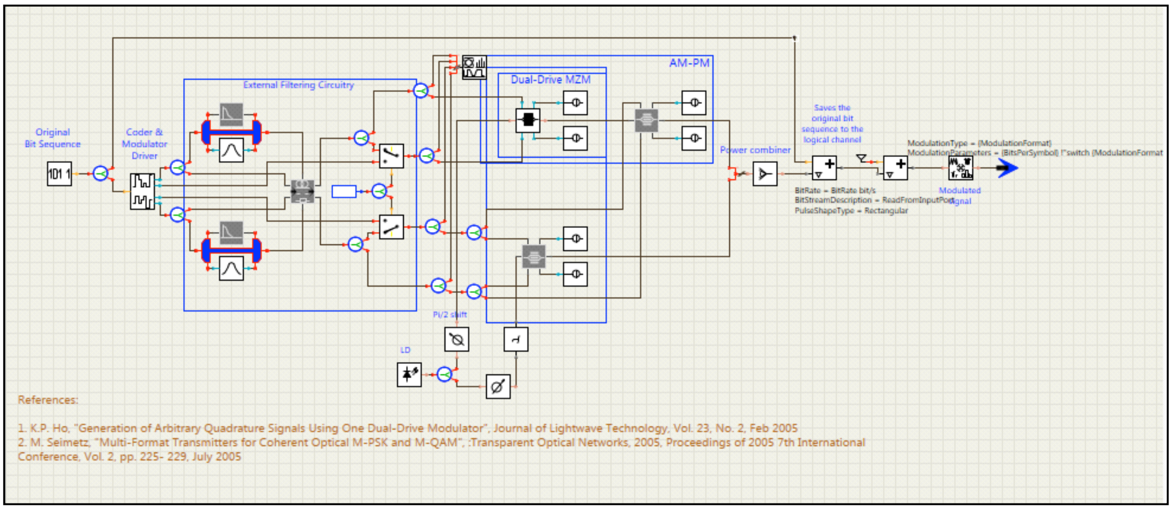

Figure 11. Transmitter's scheme of a QAM modulator given by default

3.2.2. Receiver

As the transmitter, VPIphotonics has a made scheme of a standard coherent QAM receiver which allows us to recover the in-phase and in-quadrature information using a 90° hybrid and two balanced detectors. The receiver includes polarization diversity however in our case, only the upper branch is the used for the simulations done with this modulation.

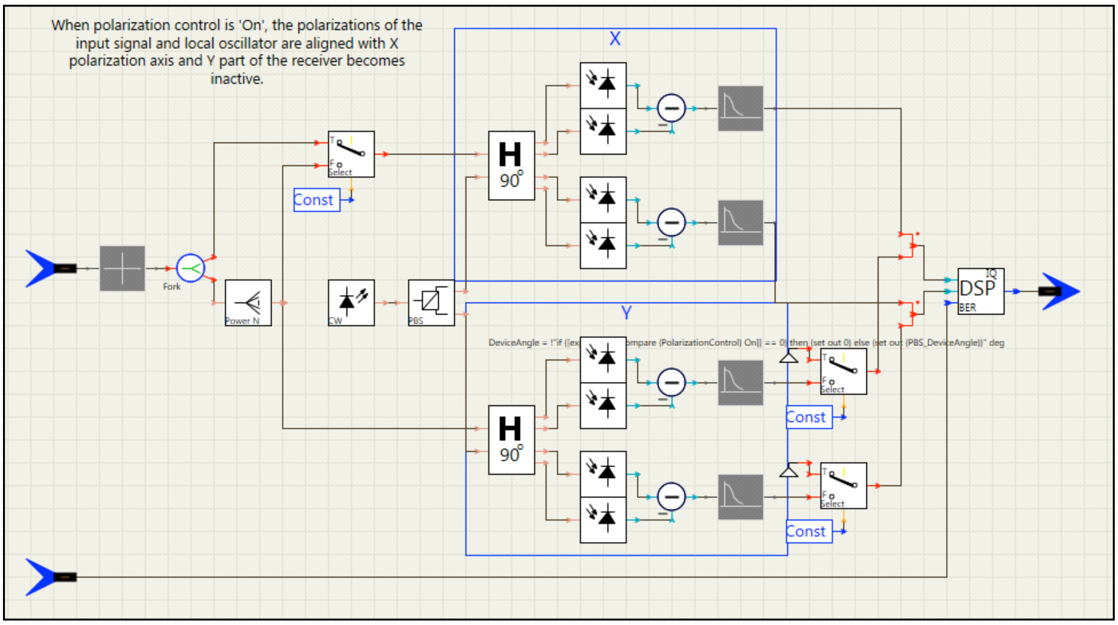

Figure 12. Receiver's scheme of a QAM modulator given by default

4 Results

4.1. Simulations and results of the Intensity modulation

The first interesting simulation was to see how works the intensity modulation with just one transmitter. In this way, the bandwidth's optical filter behaviour can be observed when the signal crosses the filter for only one loop and taking into account the optical power received in the receiver, which corresponds with a BER of 10^{-3}. The bit rate was set to 10 Gb/s.

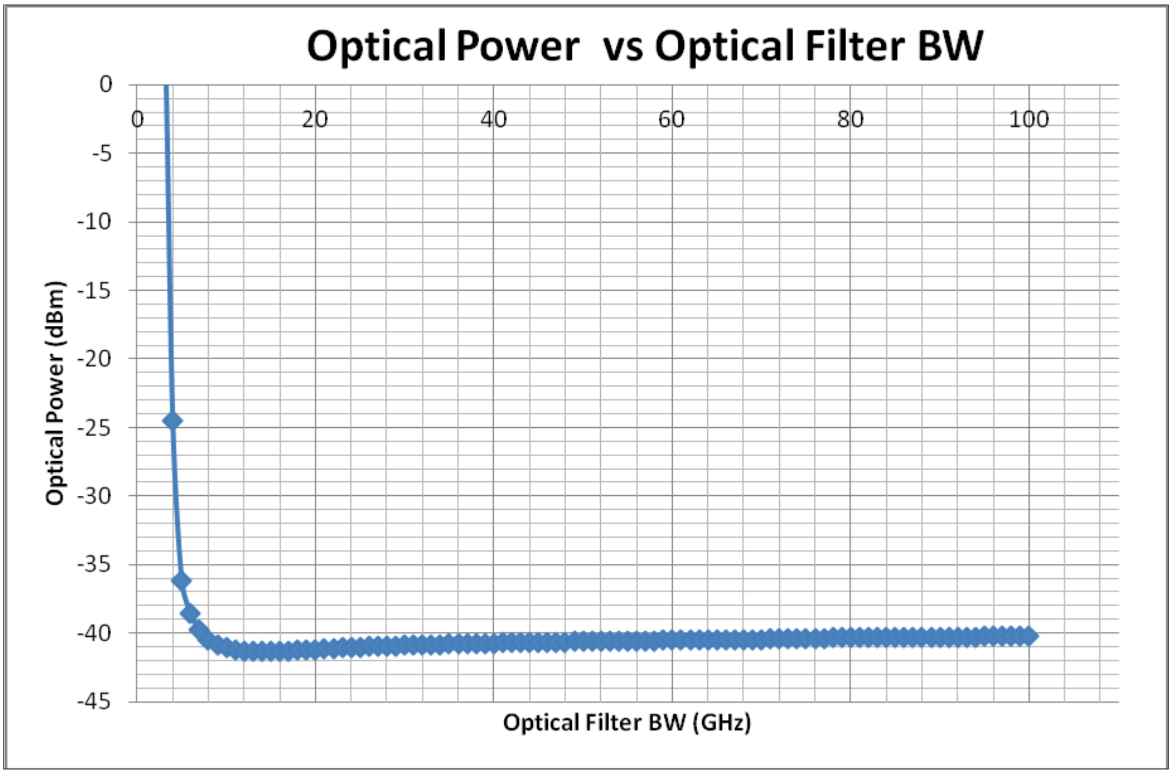

Figure 13. Optical Power vs Optical Filter BW with just one loop and without offset

Once this first simulation is done, it can be appreciated that there are a lot of frequencies which have approximately the same behaviour. For this reason, conclusions were taken with these values which are between the interesting range that is, from 5 GHz to 30 GHz, where the optical power has an important change.

A penalty of about 1 dB is introduced when the bandwidth is around 7 GHz. When the bandwidth is above 10 GHz, the slope is almost flat.

The next simulation is exactly the same study as before. This is one transmitter, one loop but now watching how the optical power received changes for different bandwidths varying the central frequency of the optical filter that is the offset frequency of the filter but always keeping the goal of getting a BER of 10^{-3}.

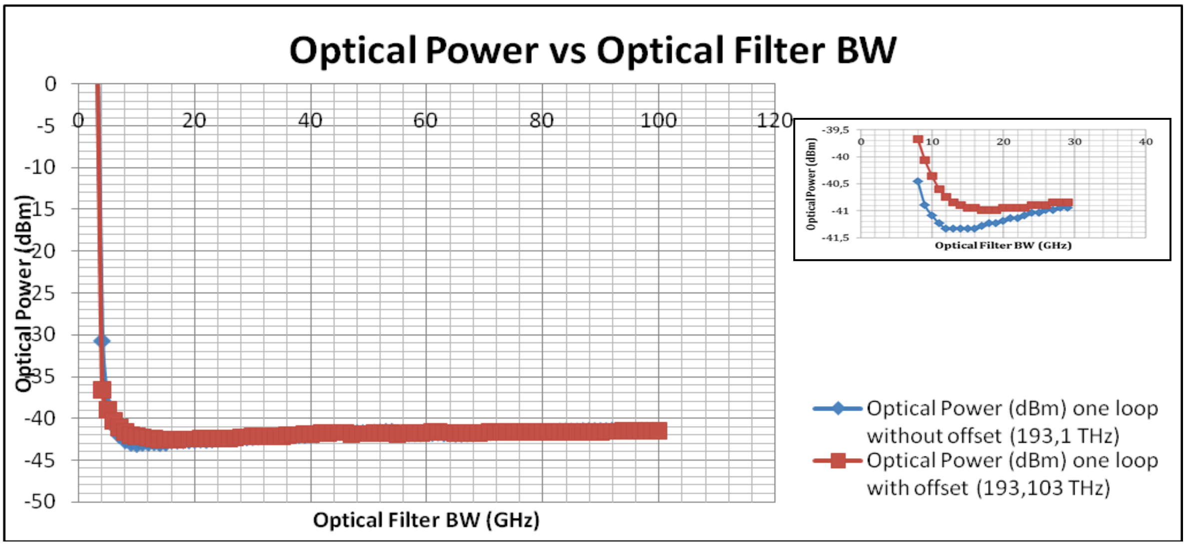

Figure 14. Optical Power vs Optical Filter BW with just one loop with and without offset

The maximum offset frequency of the optical filter considered is 193.103 THz, 3 GHz above the central frequency without offset (193.1 THz). This is because, 193.103 THz corresponds with the maximum offset value of a marketed optical filter found and in this way, it can be evaluated as a real study.

The results of this simulation are quite interesting. The values, around the important range commented before, seem that have no an important difference. But zooming this range, it can distinguish that results are a little better in the case without offset, the optical power received for obtaining the interesting BER is better. Anyway, the difference is not absolutely clear. This is because the value of the offset is not as higher as is necessary for notice this effect. The required bandwidth for a 1 dB penalty is very similar (within 1 GHz).

The next step was to see the same till now but increasing the number of loops, from one to ten, which normally is the number of optical nodes in a real optical network. So, the goal is again observe the optical power received for the specific value of the BER varying the bandwidth of the optical filter, increasing the number of loops and moving the central frequency of the optical filter (offset frequency).

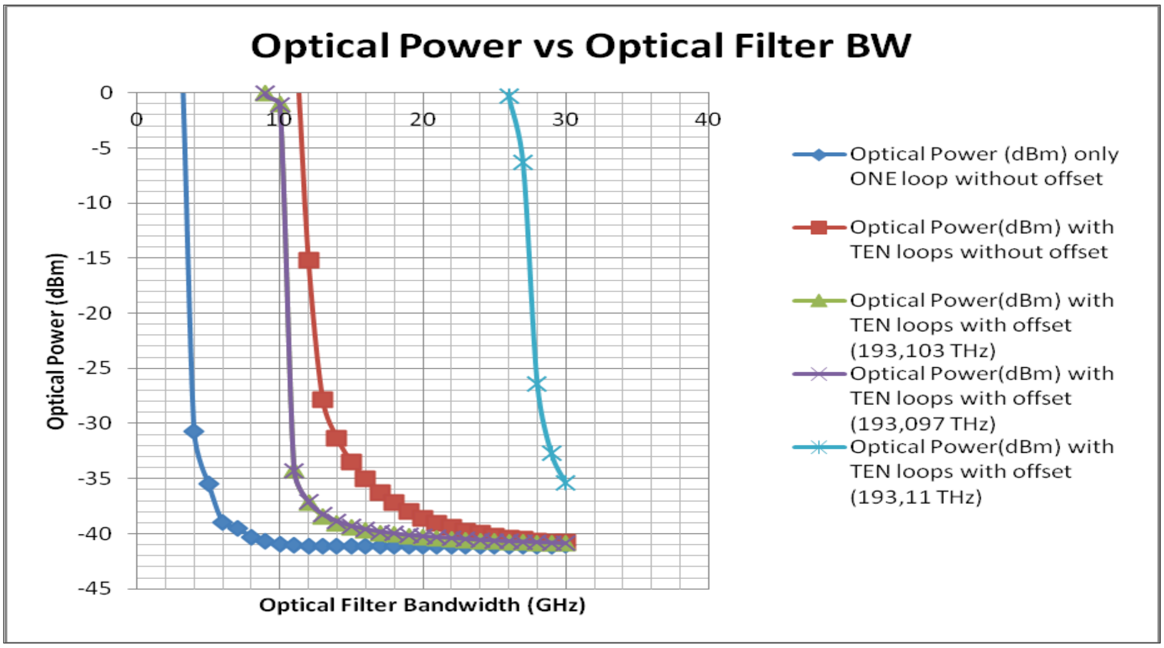

Figure 15. Optical Power vs Optical Filter BW varying the offset frequency and the number of loops

Unlike the previous simulation, it can be observed that there is a relevant difference between the case of cross the optical filter one loop and cross the optical filter ten loops. This is because the effect of go through the optical filter ten loops is exactly the same of go through an optical filter with a smaller bandwidth once. On the other hand, again, the results of cross the filter with or without offset are quite similar even with ten loops. As it has been commented, this is because the offset frequency selected is not big enough to see this effect.

The mentioned effect can be appreciated when the offset is 10 GHz above the central frequency, 193,11 THz. It is a high and significant value of frequency where the effect can starts to be observed.

In order to check the effect of the offset frequency of the optical filter in another way, another simulation has been made too. It has consisted on divide the number of loops in two identical optical filters. With this situation, 5 loops are represented by the first one, and the other five by the other optical filter.

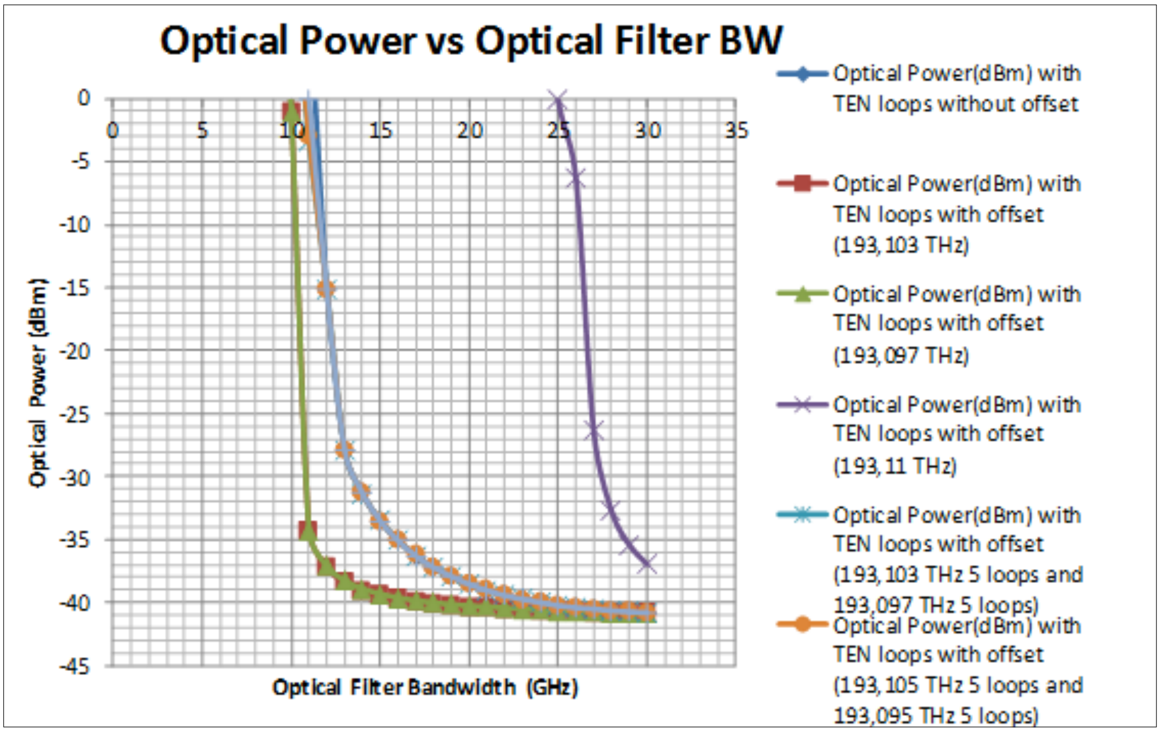

Figure 16. Optical Power vs Optical Filter BW varying the offset frequency and the number of loops

The most interesting thing in this last simulation is the fact that the obtained results in the cases of ten loops with offset, 3 GHz and 5 GHz beyond or under the central optical frequency of the filter, are exactly indentical with the results of ten loops without offset.

It can be shown that when a signal crosses an optical filter without offset at the central frequency ten loops, the output is exactly the same as cross two filters with five loops each one and with the same offset frequency beyond and under the central frequency without offset. One schematic has been made with the purpose of check this explanation:

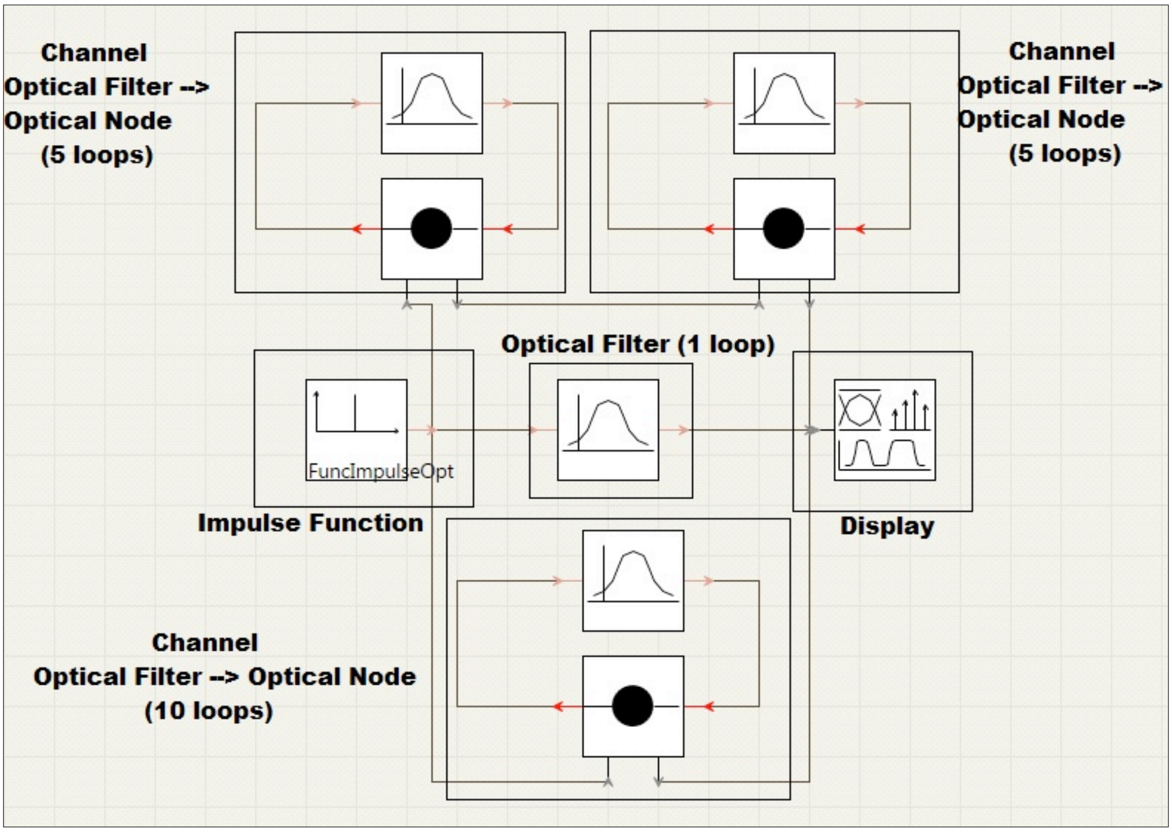

Figure 17. Designed scheme for analyze the transfer function of the optical filter in different situations

With this scheme, it has been possible to draw three important and relevant situations:

a) The response of crossing the optical filter with the centered frequency once.
b) The response of going through the optical filter with the centered frequency ten loops.
c) The response of crossing two optical filters with the same offset frequency but the first one with a number of GHz beyond the centered frequency and five loops, and the other one with the same number of GHz under the centered frequency and five loops too.

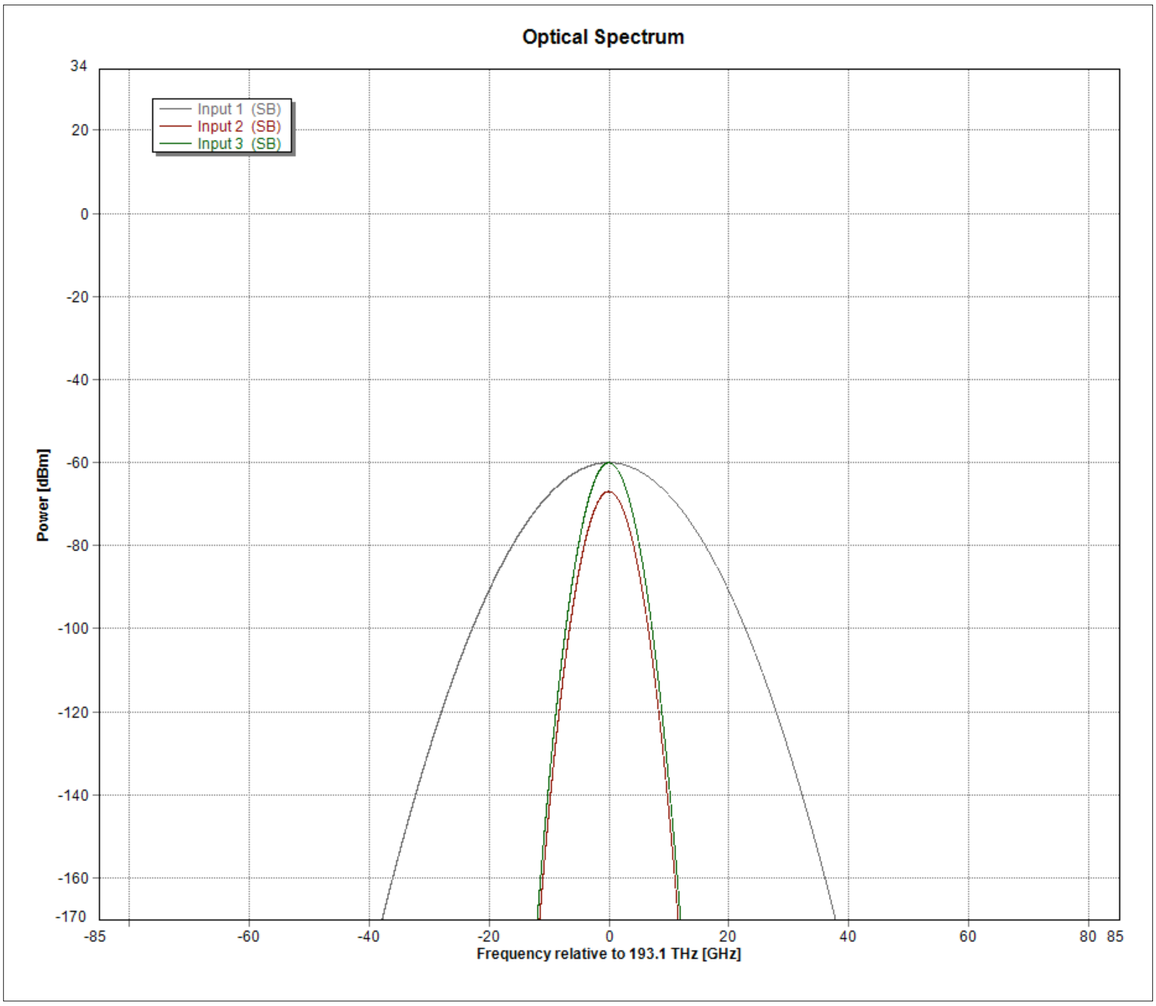

Figure 18. Transfer function of the optical filter for cases a), b) and c)

The blue line corresponds to the case a) that is exactly the frequencial response of the optical filter. The green line belongs to case b), where can be analyzed that the bandwidth of the optical filter has decreased due to the number of loops. The red line is the case where there are two identical filters, case c). Is in this case, it can be checked that the only thing that changes from case b) to case c) is the amplitude of the filter because the bandwidth remains equally.

After these simulations, it was interesting to put another transmitter acting as interference. The main goal was to know which is the minimum central frequency of the interference transmitter for not vary the good performance of the whole system as in the previous studies. In this study, loops are fixed to one and the bandwidth of the optical filter is fixed for each case.

The number of loops is fixed to one because, in this situation, the filter not damage almost the signal transmitted and in order to evaluate the effect of putting an interference transmitter and study his behaviour, this is the right situation.

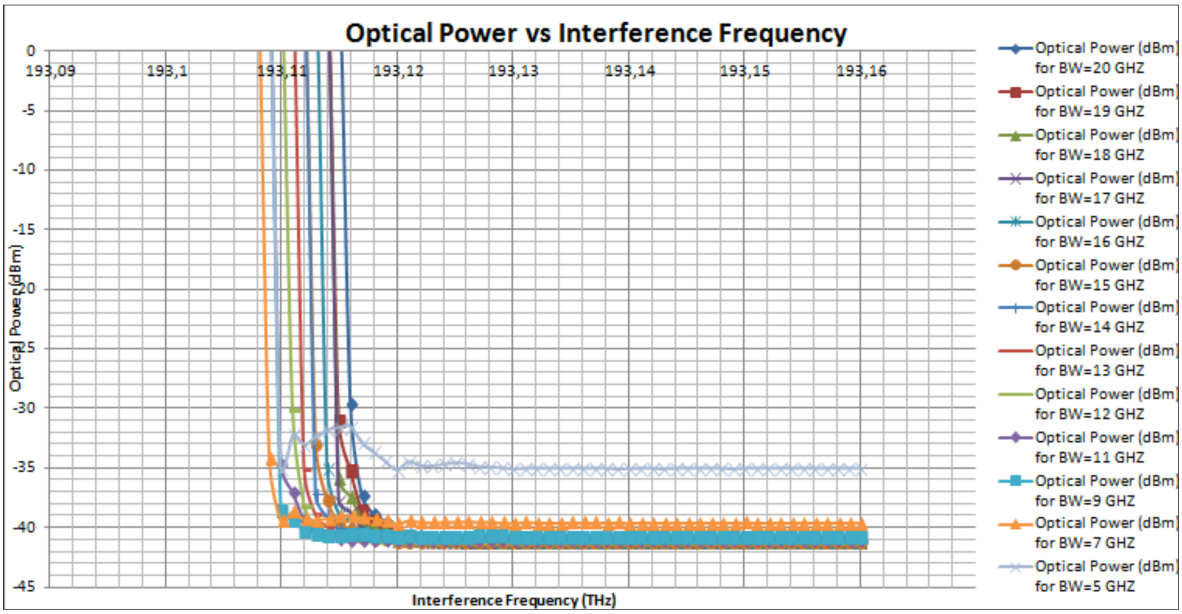

Figure 19. Optical Power vs Interference Frequency varying the BW of the filter with just one loop and no offset

The study of this simulation has been done for different bandwidths of the optical filter that is at 193,1 THz. The main goal was to get which is the optimum frequency of the secondary transmitter (interference) without forget the main aim in all the simulations, which is to get a specific BER of 10^{-3} at the receiver. It can be checked, that when the bandwidth of the optical filter is narrower, the frequency of the secondary transmitter may be closer to the frequency of the primary transmitter. This is because the interference carrier has more space to reach interfere the carrier of the primary transmitter without damage the signal. Anyway, the effect is observed when the bandwidth is around 5 GHz, but in this case, apart from the damage of the secondary transmitter, also the fact that the bandwidth is so smaller harms the signal. The best tradeoff would be a bandwidth of 7-9 GHz with which we keep the integrity of the signal and at the same time minimize the effect of the interference.

4.2. Simulations and results of the QAM modulation

With this modulation, the studies are really similar as in the Intensity modulation. It has tried to do more or less the same studies as before in order to know how is the behaviour of this modulation and in this way, compare the results of two different type of modulations. We chose a QAM modulation with 2 bits per symbol (i.e. a QPSK). The bit rate in this case was 20 Gb/s.

The first study has consisted on evaluate the optical power received at the receiver in order to get a SER of 10^{-3}, for different bandwidths of the optical filter varying the number of loops and also, the offset frequency of this filter.

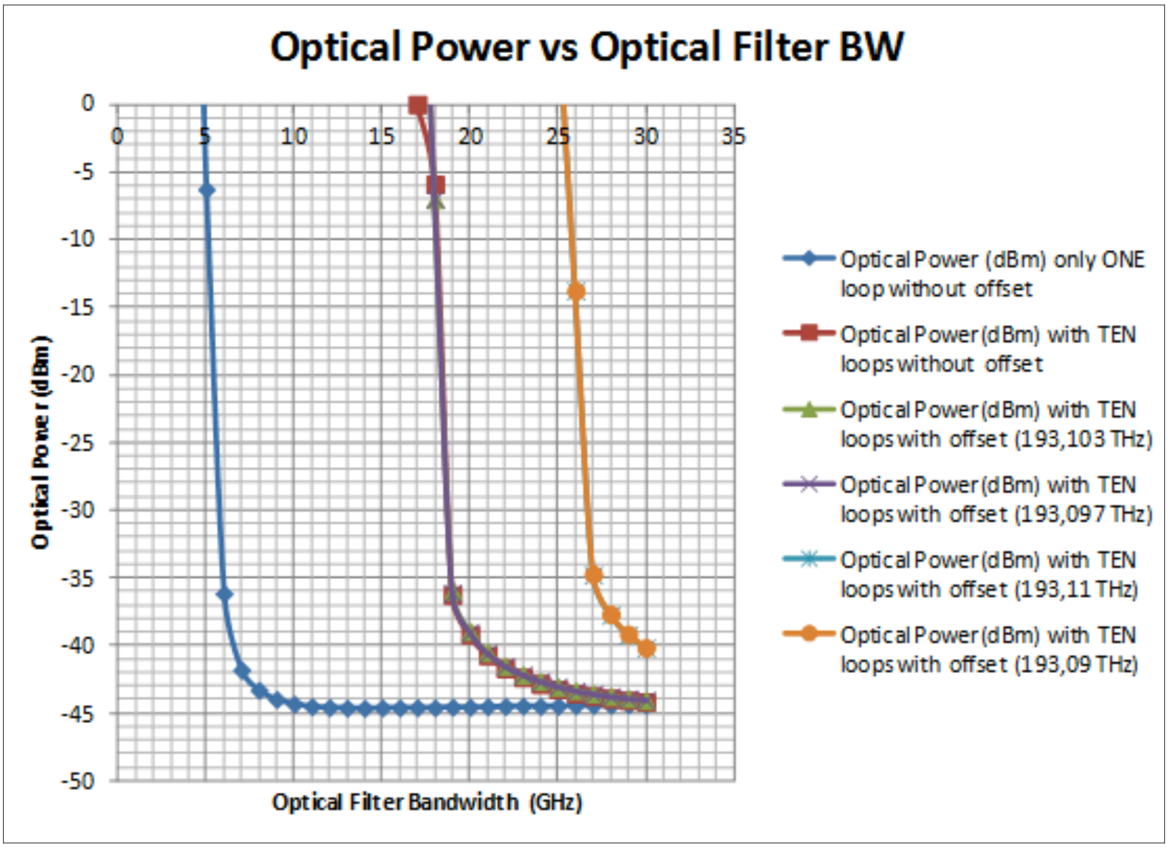

Figure 20. Optical Power vs Optical Filter BW varying the offset frequency and the number of loops

Looking at these results, it is clearly that there is an important difference between the case of doing the simulation with just one loop and with ten loops. This has been an expected fact because obviously, the bandwidth limitation has to have more impact on the second case, where the number of loops causes the narrowing of the optical filter. For 1 dB penalty, the minimum bandwidth would be 9 GHz and 25 GHz for the 1 loop and 10 loop cases, respectively.

On the other hand, the impression of the offset frequency just only has sense when the offset frequency of the optical filter is around 10 GHz behind or under the central frequency. In the other cases studied, 193, 103 THz and 193, 097 THz, frequencies are really close of the central frequency and for this reason, at first sight, it seems there are no difference.

The second interesting simulation is, as in the intensity modulation, the case of adding a secondary transmitter, which acts as an interference.

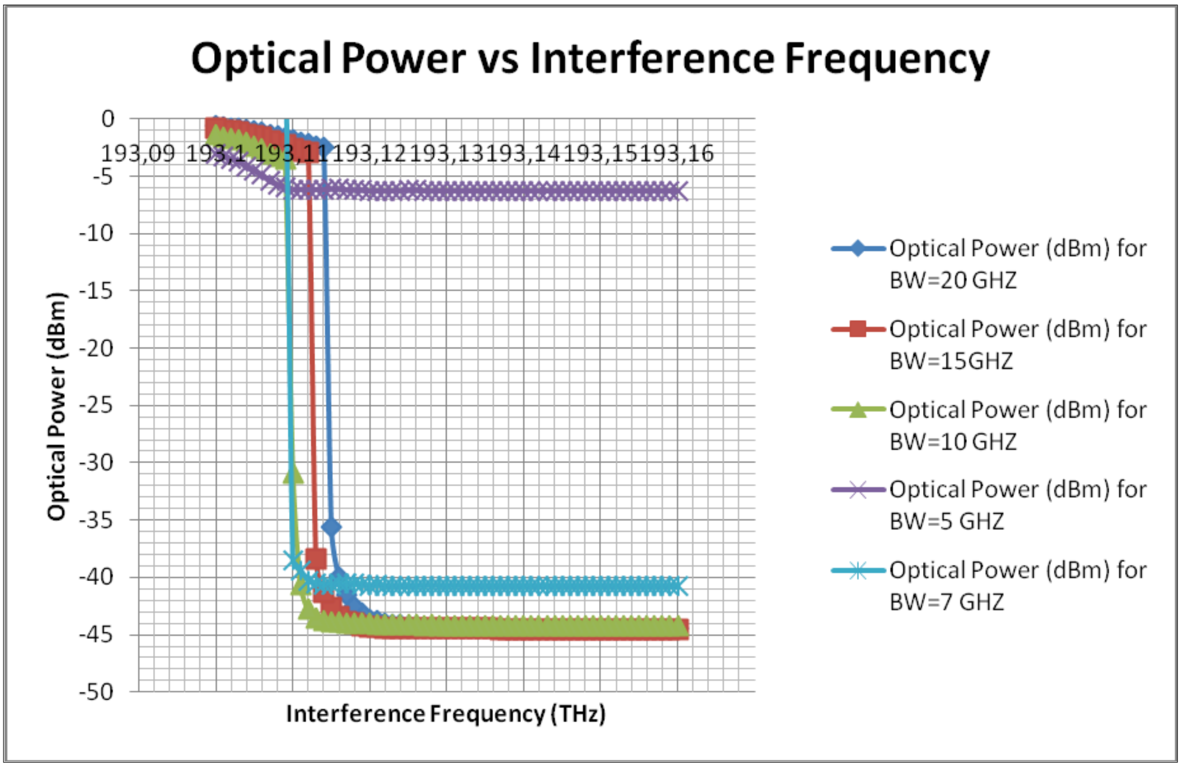

Figure 21. Optical Power vs Interference Frequency varying the BW of the filter with just one loop and no offset

Once again, in this type of simulation there are two different effects made. The first one, is the fact of move the interference frequency closer to the transmitter, if the bandwidth of the optical filter is not considered really wide, the interference carrier maybe will get to be really near of the frequency of the primary transmitter. So, but there is another effect, it consists, again, on that the signal is damaged by the own filter before the interference carrier appears. As it has been explained in the intensity modulation, this is because if the bandwidth of the optical filter is not high enough, the signal can be damaged by the optical filter. The best tradeoff would be a bandwidth of 10 GHz with which we keep the integrity of the signal and at the same time minimize the effect of the interference. The impact is slightly higher when compared to the intensity modulation.

5 Conclusions and future development:

After doing all the simulations some conclusions can be drawn:

- It is clear that increasing the number of loops severely damages the signal. The equivalent bandwidth after 10 loops is reduced to a 30% of the reference filter.
- A frequency offset of the filter of ±3 GHz, a value which represents a typical instability of commercial products, shows almost no impact. This is because, and offset frequency of 3 GHz is relatively small compared to the bit rate. When increasing the number of loops the effect is not relevant. For the offset effect to be relevant it should be much closer to the symbol rate (10 GHz).
- The case with half of the loops with a positive offset and half of the loop with negative offset showed an equivalent frequency response to the case with all the loops with the filter centered. The only effect was an extra attenuation. This guarantees that the worst case has been taken as a reference.
- Simulations adding a secondary transmitter show the highest interference with just one loop, with just one loop. Obviously, when the bandwidth of the optical filter increases, the interference increases as well and viceversa. If the bandwidth is to tight it damages the signal before the interference carrier do.
- The effects on the 20 Gb/s QAM are very close to those of the 10 Gb/s intensity modulation because the symbol rate is the same. For equal bit rates it is expected to see less impact on QAM signals.

	Number of loops	Optical Filter Central Frequency	Offset Frequency	Interference Frequency	Minimum BW's Optical Filter allowed
Intensity Modulation	1	193,1 THz	No	No	10 GHz
	10	193,1 THz	No	No	20 GHz
	1	193,103 THz	Yes (3 GHz above)	No	15 GHz
	10	193,103 THz	Yes (3 GHz above)	No	15 GHz
	10	193,097 THz	Yes (3 GHz under)	No	15 GHz
	10	193,11 THz	Yes (10 GHz under)	No	30 GHz
	5 and 5 (cascade)	193,103 THz and 193, 097 THz	Yes (3 GHz above and under)	No	20 GHz
	5 and 5 (cascade)	193,105 THz and 193, 095 THz	Yes (5 GHz above and under)	No	20 GHz
	Number of loops	Optical Filter Central Frequency	Offset Frequency	BW's Optical Filter	Minimum Interference Frequency allowed
	1	193,1 THz	No	20 GHz	193,122 THz --> 22 GHz
	1	193,1 THz	No	18 GHz	193,121 THz --> 21 GHz
	1	193,1 THz	No	16 GHz	193,118 THz --> 18 GHz
	1	193,1 THz	No	14 GHz	193,116 THz --> 16 GHz
	1	193,1 THz	No	12 GHz	193,114 THz --> 14 GHz
	1	193,1 THz	No	11 GHz	193,112 THz --> 12 GHz
	1	193,1 THz	No	9 GHz	193,111 THz --> 11 GHz
	1	193,1 THz	No	7 GHz	193,111 THz --> 11 GHz
	1	193,1 THz	No	5 GHz	193,11 THz --> 10 GHz

Table 2. Conclusions of the intensity modulation

	Number of loops	Optical Filter Central Frequency	Offset Frequency	Interference Frequency	Minimum BW's Optical Filter allowed
QAM Modulation	1	193,1 THz	No	No	10 GHz
	10	193,1 THz	No	No	25 GHz
	10	193,103 THz	Yes (3 GHz above)	No	25 GHz
	10	193,097 THz	Yes (3 GHz under)	No	25 GHz
	10	193,11 THz	Yes (10 GHz above)	No	30 GHz
	10	193,09 THz	Yes (10 GHz under)	No	30 GHz
	Number of loops	Optical Filter Central Frequency	Offset Frequency	BW's Optical Filter	Minimum Interference Frequency allowed
	1	193,1 THz	No	20 GHz	193,122 THz --> 22 GHz
	1	193,1 THz	No	15 GHz	193,118 THz --> 18 GHz
	1	193,1 THz	No	10 GHz	193,115 THz --> 15 GHz
	1	193,1 THz	No	7 GHz	193,114 THz --> 14 GHz
	1	193,1 THz	No	5 GHz	193,113 THz --> 13 GHz

Table 3. Conclusions of the QAM modulation

In the future, the implementation of the present project, could be improved evaluating each modulation but changing some modules of the schemes or with the same modules, different parameters of them.

For example, it would be very interesting to repeat the same simulations but changing the type of the optical filter of the channel. It has been used a Gaussian filter with order 1 because it was similar to a marketed optical filter found. Maybe it would be a good idea to increase the order of the filter or even change completely the filter.

Moreover, apart from repeat the same simulations, it would be interesting to add a third transmitter at the other side of the signal in order to see how to distribute the spectrum for having no interference, obtaining the desired BER at the receiver and getting the correct performance of the whole system. In this case, also it would be very interesting to test this situation but in different environments: the three transmitters with the same type of modulation, two with one type and the other one with other...

Certainly, this project offers the possibility of being extended in any field because of the quick growth of the optical network. New designs, new devices, new trends that can be implemented with this project and somehow, approach and understand its operation.

Bibliography:

- Masahiko Jinno, Bartlomiej Kozicki, Hidehiko Takara, Atsushi Watanabe, Yoshiaki Sone, Takafumi Tanaka, and Akira Hirano, NTT Corporation, "Distance-Adaptive Spectrum Resource Allocation in Spectrum-Sliced Elastic Optical Path Network" IEEE Communications Magazine, August 2010

- Santec Optical Instruments, "Programmable Optical Filters WSS-1000" WSS-1000-C-E / Ver.1.3 CODE-201408-HK-MT-CPY

- VPIphotonics Design Automation, "Developer Guide" VPItransmissionMaker™/VPIcomponentMaker™

- Gustavo Puerto Leguizamón, Beatriz Ortega, José Capmany, Karen Cardona Urrego, Carlos Suárez Fajardo. "Data networking evolution: Toward an all-optical communications platform" Instituto de Telecomunicaciones y Aplicaciones Multimedia, Universidad Politécnica Valencia, 2007. [Online] Available: http://www.scielo.org.co/pdf/rfiua/n45/n45a13 [Accessed: 2 March 2015].

- Wikipedia, the free encyclopedia. "Optical networking" [Online] Available: https://en.wikipedia.org/wiki/Optical_networking [Accessed: 2 March 2015]