UNIVERSITÀ DEGLI STUDI DI ROMA
"TOR VERGATA"

FACOLTA' DI INGEGNERIA

DOTTORATO DI RICERCA IN INGEGNERIA DELLE TELECOMUNICAZIONI E MICROELETTRONICA

XXII CICLO

All Optical 2R Regeneration Systems for Broadband Agile Dense Wavelength Division Multiplexing Transparent Optical Networks

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A.A. 2009/2010

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Special Thanks

First of all, I would like to dedicate this work to my parents;
like for every things in my life, for this thesis they have demonstrated their love, giving me the power to overcome this fight. I want to give my special thanks to my sister Federica and my brother Fabrizio for having lift me up when I was in a particular and very hard moment of my life.....
I would like to give thanks to my supervisors Ing. Giorgio Maria Tosi Beleffi and Prof. Silvello Betti for having gave me this important and great opportunity.
A special thank goes also to Ing. Franco Curti for his help, experience, professionalism and suggestions.
Last but not least, I want to give my thanks to Silvia, Stefano, Davide and Valeria for the great and cheerful days spent all together in the labs.
....

To all Thanks!

Abstract

A recent increase of multimedia service demand from end-users has been noticed, thus several solutions have been implemented to guarantee the high rate and relative QoS (Quality of Service) needed for these kind of services. All optical networks have been deployed in many countries (Japan, Korea, China, at all) in order to supply broadband services to the home.

Consequently, devices able to operate in optical domain are requested in order to avoid the so called “bottle-neck” coming from the O/E/O data conversion format. Thus, new kind of systems (optical processing and passive optical networks, at all) able to operate in photonic domain are requested because only this kind of solution is the better way to offer high performances in term of services, rate and low cost per bit.

The work performed during this PhD program has been focused on the evolution of regeneration devices able to perform Re-amp and Re-shaping also know as 2R. Studies and experiments have been carried out at the ISCOM labs exploiting the possibility to a multi-channel 2R all optical regeneration device which is able to work with different client signals at the same time. The system has been implemented in a dense WDM (Wavelength Division Multiplexing) scenario. Moreover, working completely in optical domain, the format conversion (O/E/O) is avoided. The regeneration system is based on phase modulation present in the fiber and used to obtain, under particular conditions, the generation of new signal replica.

These new replica, being placed at new different wavelengths can be used both to reach a wavelength conversion and to obtain an all optical regeneration effect. Each replica, in fact, is characterized by a Bessel like transfer function able to clean the noise accumulated along the signal transmission.

The idea of this work is based on a multi-wavelength approach, thus only one device can be used to provide all optical 2R regeneration to several client signals at 10 Gbps at the same time.

The ability of the systems, implemented at the ISCOM labs, to reshape the signals, has been experimentally confirmed in terms of eyes diagrams and BER (Bit Error Rate) measurements.

Contents

Introduction

The today available optical systems and in particular the optical cables, are the most important key factors of the communication revolution which gradually leads the human society to the knowing society, especially in the last period in which several applications for the communication services are provided to the clients. Only the optical technologies are able to transport, switch and process the high data traffic required to guarantee the different applications inside the communication structure, where Internet services, for example, are just the beginning point.

The optical fibres permits innumerable advantages with respect to the traditional transmissive media, like electrical cables, and in the last years the number of applications based on optical fibres increased more and more. In fact, that some today applications, would be impracticable without the use of optical devices and the optical technology.

In the last 20’ years, the optical fibres became the principal transmissive media for the point-to-point (PTP) and for the long distance networks. From 1988, for example, the undersea cables networks, requiring very high performances, have been replaced with the ones based on optical fibres cables thanks to the ripening and the trusty degree they have achieved. Also Free Space Optics (FSO) optical technology is employed in order to guarantee a whole network between ships or between ship and base stations placed not so near respect the ships.

Furthermore, the optical fibres can be advantageously employed in that particular applications where an high performance link must be guarantee, for example, between the central and the radio-mobile system antennas or from the central office up to the client premises.

Until some years ago, the signals which had to be sent on optical fibres, needed, inevitably, a conversion from optical to electrical format in order to elaborate end maintain the high performances data signal in electrical domain.

Moreover, because of the chromatic dispersion and attenuation effects, an optical signal which propagates through the optical fibre needs amplification and regeneration at regular steps to guarantee an high data quality.

This operations were made after the conversion of the signal: from optical to electronic and, after the signal elaborations, from electronic to optical (conversion O/E/O).

Nowadays, the actual trend tends to optimize this kind of techniques and to realize these operations at an all optical level removing the useless format conversions which involve the slowing down of the data transmissions on networks which support bit rate ever higher.

In order to increase the performances of the optical communications and to lower the per bit costs, Wavelength Division Multiplexing (WDM) and Dense WDM (DWDM) techniques have been adopted. These techniques permit to inject into the same fibres more than one signal, achieving the high band that the optical fibre is able to provide.

The purpose of this thesis has been, therefore, to realize an all optical regenerator able to increase and regenerate several transmitted signals together, exploiting a particular non linear effect as Four Wave Mixing (FWM), achieving an optical fibre DS sample.

This project has been carried out in ISCOM labs, technical and research arm of the Ministry of Economic Development.

Present work places the advantages brought by the optical fibres employment in new generation telecommunications networks.

In chapter one, the Wavelength Division Multiplexing (WDM) theme with an introduction about the optical networks used in the today scenario widely used in optical communications, has been described.

In chapter two and three, the main regeneration techniques adopted using the non linearity media and using particular attention about the 2R all optical regeneration achieving the FWM effect, have been described. Also theory, remote regeneration concept, experimental set-up with the main results and the principle of the all optical regeneration have been depicted.

Chapter 1

Introduction: The growth of optical networks

The today optical networks are the communication infrastructures able to guarantee an high transport capacity, based on optical devices which provides to routing, management and regeneration (restoration) operations of several optical client signals [1].
In order to satisfy the high bandwidth asked from several end-users, the necessity to have a fast deployed optical networks is become a real thing. This kind of networks are totally (or nearly) composed by optical technologies which permits to increase the transport capacity, decrease the cost per bit and make available new kind of services like high bandwidth Internet, multimedia interactive applications and digital advanced services.
Starting from 60' years, the optical cables are become a media used often together traditional electrical cables and radio communications. From 80' years there was a real revolution in communication world due to the large use of optical cables, in fact in the middle of 90' years in the United States of America was installed more then 500.000 km of optical cables, a total of deployed cables 20 millions km long [Source: Federal Communications Commission-FCC]. This kind of expansion permit an economical reduction in term of costs and, at the same time, a remarkable increase of network quality. As result, an innumerable progress for optical network and for its technology was noted. Thus, the old network which provided

only phone services turn into a complex network that are able to transport some Tbit/s at the same time.

During this period, the digital network has been developed, increasing its features, where asynchronous network, synchronous network and optical network are just some examples. In synchronous networks each network element is equipped with an internal clock which permit the signals synchronization.

In order to obtain an unambiguous standard which characterize the optical technologies, “synchronous optical network” (SONET) has been developed. In this way are defined all optical standards, like transmission rate, access hierarchy, code schemes and the operations to maintain and manage the optical network. Moreover, the optical network features are exploited in order to realize the hardware devices and the network architecture are also implemented inside the devices.

The most important aspect which has permitted the SONET to survive is the scalability of this kind of technology. In effect, when the bit rate is considerable, come up some problems and physical limitation offered by the optical cables but also by the devices used in the network, like laser sources, EDFA (Erbium Doped Fiber Amplifier) or SOA (Semiconductor Optical Amplifier) amplifiers.

To the other side, the tremendous demand of data traffic asked from the end users drive the technology to realize the end-to-end connections (see figure 1.1). The all optical networks assume now a role of leader for communication network develop, offering the capacity and flexibility for present and future requirements.

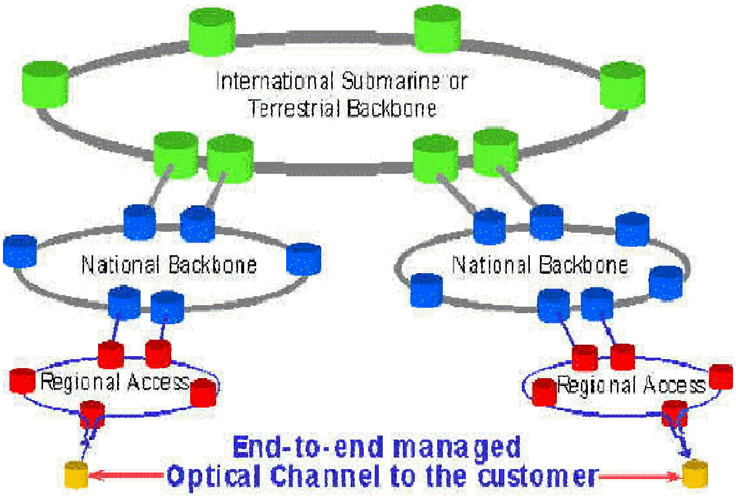


Figure 1.1 - Example of End-To-End connection.

The optical networks, with respect the SONET, are based on WDM (Wavelength Division Multiplexing) which permit to increase the capacity of the optical cables already existing. Analyzing the optical networks with layers approach, is requested an introduction of optical layer. In order to define the functions of the networks, these are divided in some layers both physical and logical. The first layer (services layer) permit the data introduction in the communication network. The second one, SONET, is responsible to actuate the signals regeneration, management, network and performances monitoring and result transparent with respect the first level. Thus, there is the optical layer which will provide to carried out the same operations of the SONET layer but in all optical way, moreover, will provide to adapt the different rate of the data transmitted.

It is possible to identify two categories of optical networks: "Broadband&select" network and "Wavelength routing" network (see figure 1.2).

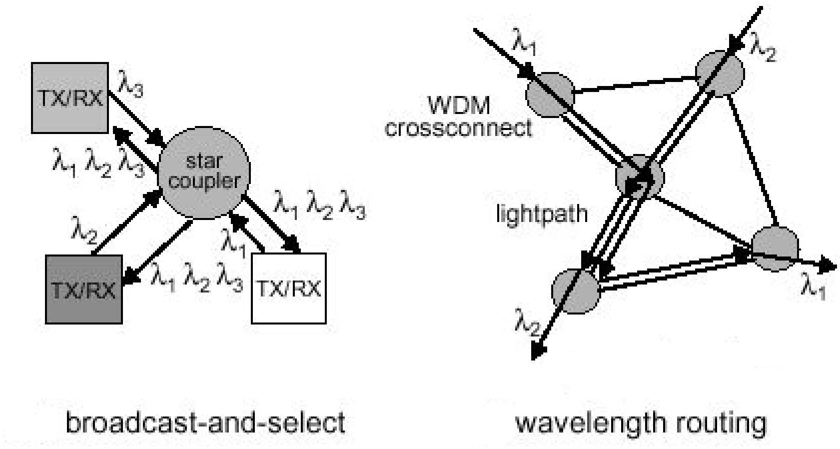


Figure 1.2 – Optical network topology.

The develop of optical network come from the improvement of optical technology which permit the increase of the performances like the transport capacity.

From 1994 year, two particular technologies have been used to increase the diffusions of the optical devices: Broadband WDM and optical amplifiers EDFA. WDM technology, in fact, permit to send the data generated by several clients over the same optical fiber, thus the network capacity result increased, even if the past performances of the optical cables do not permitted rate more then 5 Gbit/s.

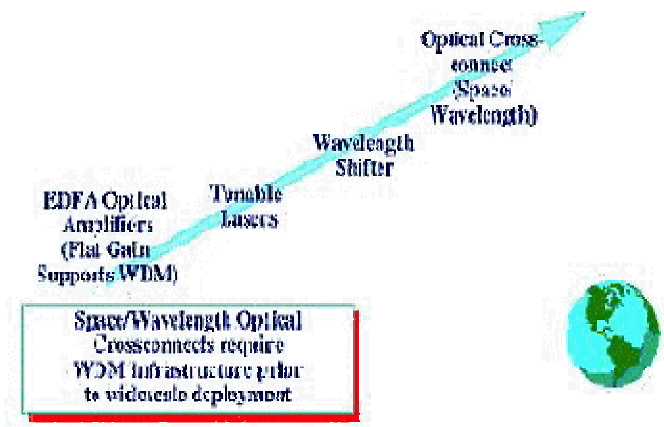


Figure 1.3 – Evolution of optical technologies.

The real innovation consist in optical amplifiers EDFA which permitted to push the optical network towards the future networks.

With this kind of devices, composed essentially by a short sample of optical fiber doped with Erbium (or other kind of rare hearts), it was possible to amplifier the signals directly in optical domain without any electrical conversion format, which result slow and more expensive in term of time needed to realize the conversion format in order to manage the electrical signal. The today optical amplifiers offer an high degree of amplification and permit to manage several signals at the same time, making the WDM a mature technology to be employ in the modern optical networks. The improvements of optical technologies of laser devices and optical filters, make possible the assembling of more complex devices in order to obtain an efficient multiplation as the DWDM technology (Dense WDM) which permit a sensible increase of capacity data transmitted offered from by single optical fiber.

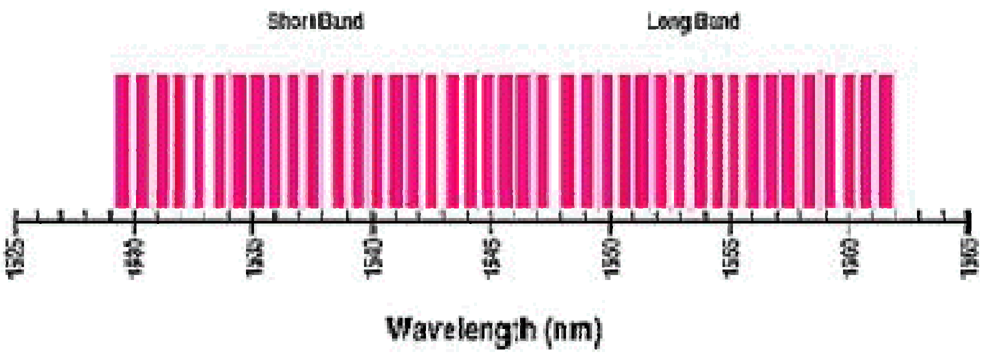


Figure 1.4 – DWDM channels spacing.

The technology described previously is supported with narrow band laser sources which permit to obtain light signals having a very narrow emission band, an high degree of coherence end show a very stable properties.

Thus, these kind of laser sources allowed to optimize the channel spacing in optical fiber.

1.1 Multiplation in optical network

The multiplation is a technique that permit to share the available transmission medium with several users [2].

In traditional phone networks which uses an electronic technologies, commonly TDM (Time Division Multiplation) technology of multiplation is used. This kind of multiplation is present also in optical network but shows several problems in term of electronic implementation. Besides, the high channels capacity used in optical network involve that is hard to divide the time slot of right duration for each client. For this reason, other kind of multiplation is used for optical networks.

1.1.1 Multiplation Techniques

There are different multiplation employed in optical network depicted following.

Space Division Multiplexing (SDM) is a way to divide the space offered by a physical transmission channel (e.g. an optical cable), thus several channels are propagated in different spatial position. Applying this structure in optical case, the multiplation is achieved exploiting different optical fibers deployed in the network. Sometime, not all fibers are used for guarantee the link but a small number of these are used in order to realize a protection and a sort of path redundancy. This kind of multiplation is not expensive and its realization is easy.

The disadvantage consist in deploy the optical cable and this is involve several costs for the optical network vendors.

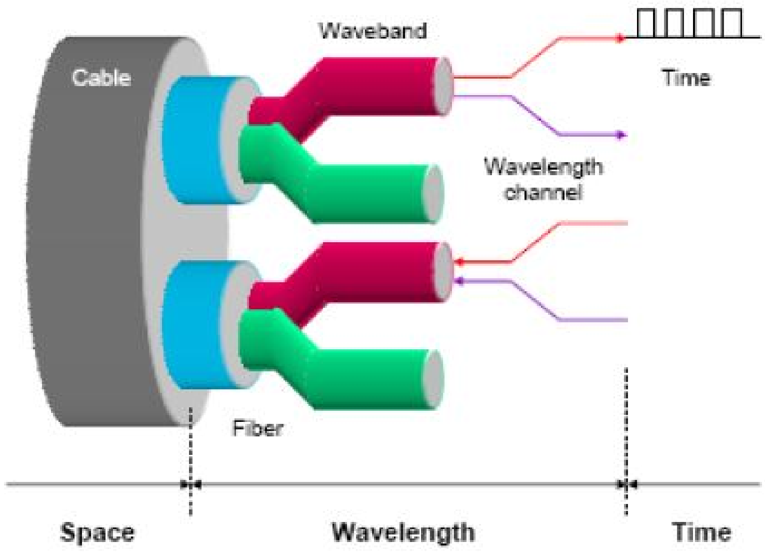


Figure 1.5 – Multiplation techniques used in different layers on an optical network.

Wavelength Division Multiplexing (WDM) is the hinge multiplation of the optical communications. This kind of concept is based on the idea to transmit several signals into the same optical fiber; each signal is modulated with a particular wavelength.

In optical fiber each wavelength is driven in independent way and, if there aren't non-linear phenomenon, the different signals are not affected from cross-talking phenomenon. Thus in output from the optical fiber it is possible to separate exactly the incoming signals. The goal of the WDM is that it is possible to transport different modulations format in only one optical fiber. The following picture shows the scheme of an point-to-point optical communication system in which is used WDM technique. Every signals is modulated with different rate and different format and than the multiplexer is able to insert all modulated signals into a single optical fiber.

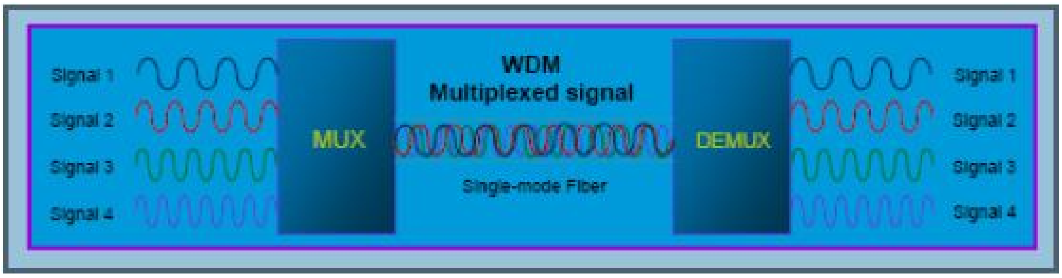


Figure 1.6 – Principle of WDM multiplation.

A demultiplexer will be able to demultiplate the different received signals in order to give back the right signal to right receiver.

The technology which uses the wavelength division multiplexing has been modified several times in the years.

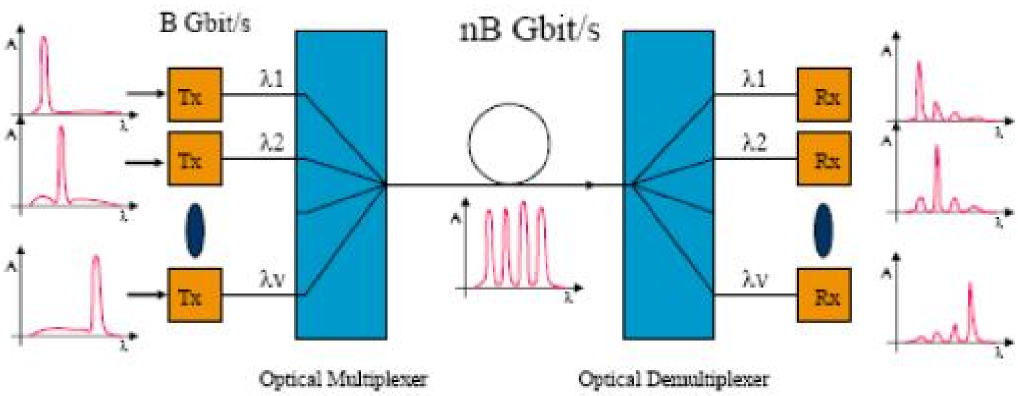


Figure 1.7 – Point-to-Point transmission system with WDM technique.

In particular, the spacing between the channels has been reduced in order to transport more channels in the same bandwidth.

Dense WDM (DWDM) is today used in the long distance backbone networks and has the spacing between the channels varying from 3.2 nm up to 0.4 nm (from 400 GHz up to 50 GHz). Obviously, a system which uses a very small spacing between the channels will employ devices more complex and more expensive in order to have very accurate and cooled lasers and thin filters. Another kind of multiplation consist in Coarse WDM (CWDM) which uses a larger spacing between the channels and this involve the use of not cooled lasers. Then following picture shows the difference between DWDM and CWDM systems.

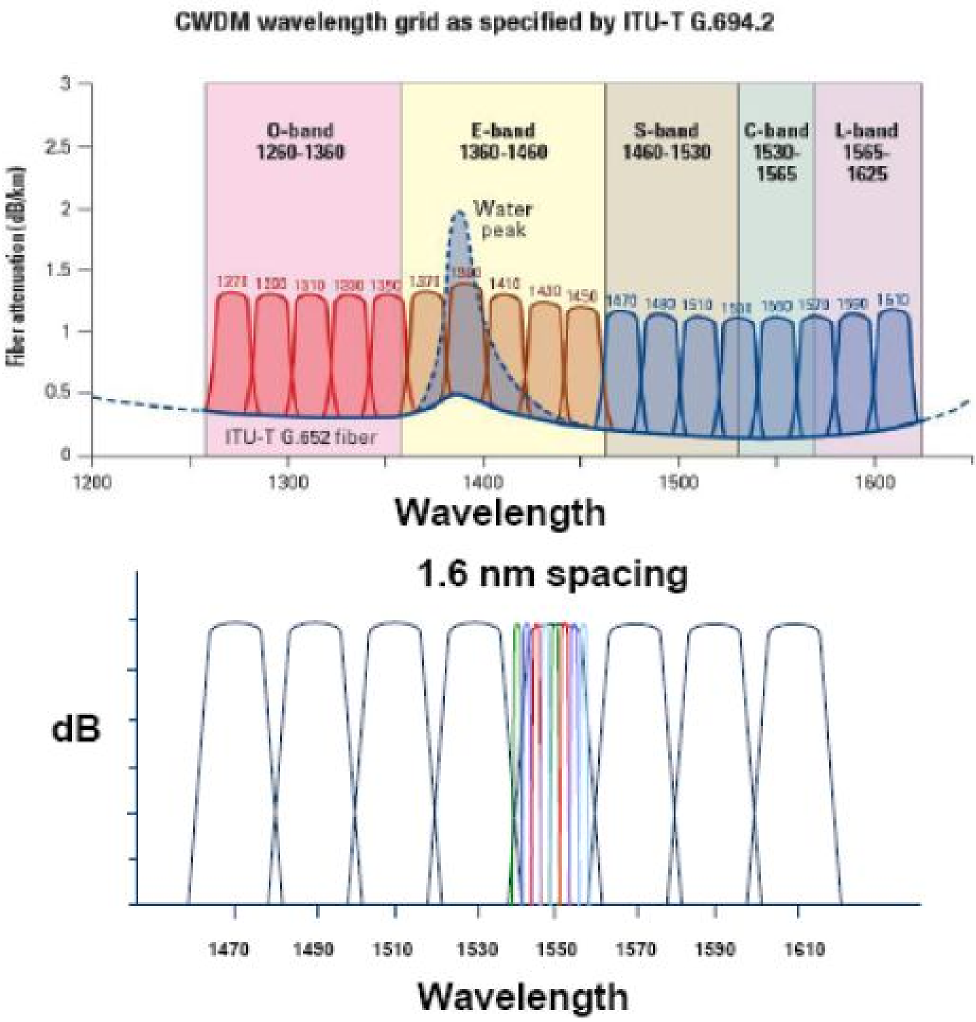


Figure 1.8 – Comparison between DWDM and CWDM in term of number of channels.

DWDM technique represent a revolution in optical communication word. The picture 1.9 shows the difference between a traditional transmission system compared with a transmission system which uses DWDM multiplation. In order to transport a total capacity of 20 Gbit/s over 360 km, the traditional system required 8 optical fibers, 64 regenerator systems (8 for each fiber) placed every 40 km. The other system, uses only one optical fiber with 4 regenerators placed every 120 km.

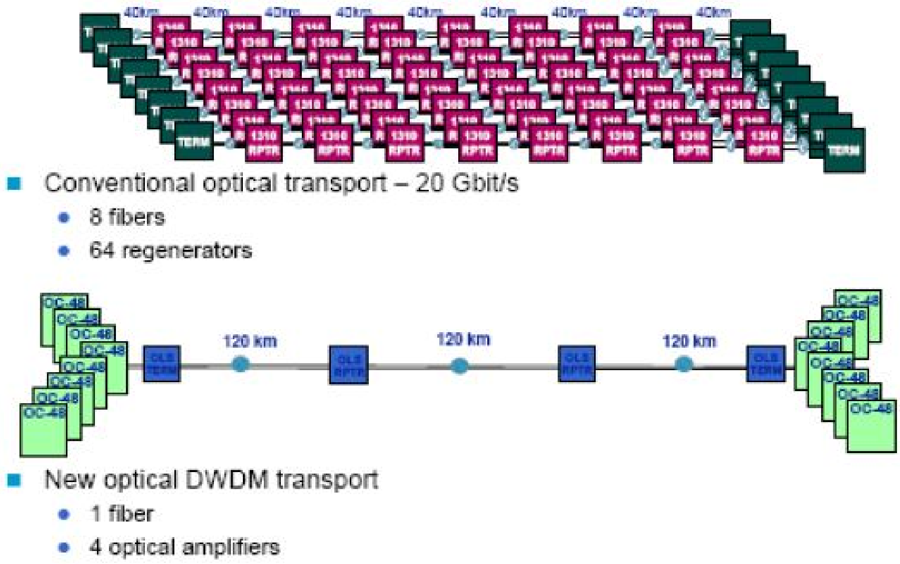
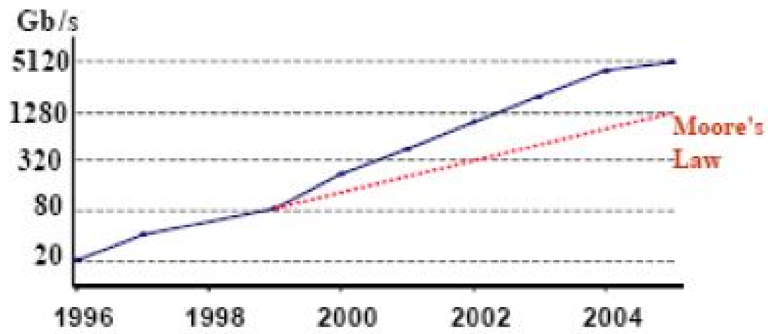


Figure 1.9 – Comparison between optical system which uses traditional multiplation and DWDM multiplation.

Time Division Multiplexing (TDM) technique is not often utilized in optical system but could be convenient use this multiplation in order to further subdivide the single channel managed with DWDM technique already.

1.1.2 Network Capacity

The capacity of an optical network assume an important role in order to send the major number of channels in the same optical fiber. Figure 1.10 depict the trend of capacity referred to an optical fiber with the years.



$$\text{Capacity} = \frac{\text{Bandwidth}}{(\text{Bandwidth}/\lambda)} * (\text{Bits}/\lambda)$$

Figure 1.10 – Trend of capacity referred to one optical fiber.

As an example, an optical cable composed by 100 optical fibers is considerate to calculate the total capacity; each fiber transport 64 channels WDM at 10 Gbit/s, thus the total capacity of the cable is equal to 64 Tbit/s. This result show the potential of optical systems.

The figure reported below suggest the relationship between the transmission band and the total capacity. Different transmission systems are depicted, in particular the submarine optical systems uses few band and capacity because the data traffic is narrow with respect a terrestrial system.

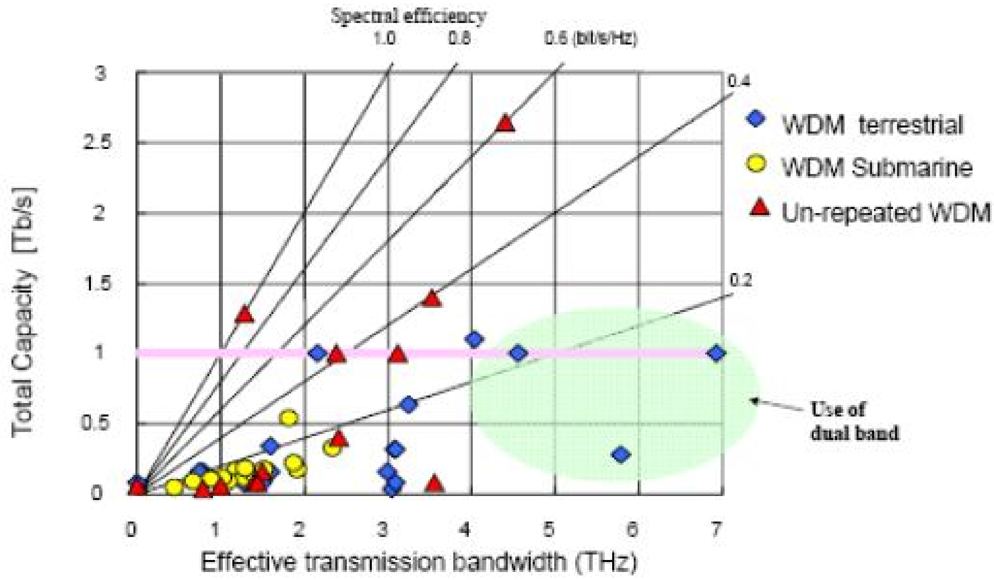


Figure 1.11 – Transmitted band with respect total capacity for DWDM Systems.

1.1.3 Development of new multiplation technologies

New multiplation technologies are under study in order to improve the today multiplation techniques allowing to obtain the better results.

The first multiplation technology is *Polarization Division Multiplexing (PMD).* With this kind of approach, the polarization of the signal is used to realize the multiplation which is based on the state of polarization that result orthogonal each other. Thus the two orthogonal state of polarization are independent and in this way it is possible to transport two different information without any cross talk effect.

Another kind of multiplation consist in *Optical Time Division Multiplexing (OTDM)* which could be exploit to avoid the electro/optical conversion but this kind of technique result too expensive.

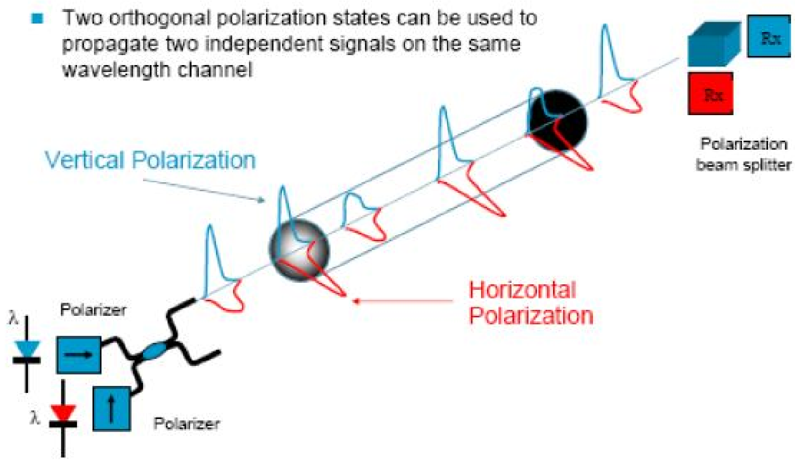


Figure 1.12 – Polarization division multiplexing.

Thus *Optical Code Division Multiplexing (OCDM)* has been studied in order to achieve different codes for each client assuming that, if the codes are not orthogonal the total signal result near to zero value. Unfortunately, also this kind of multiplation result very expensive.

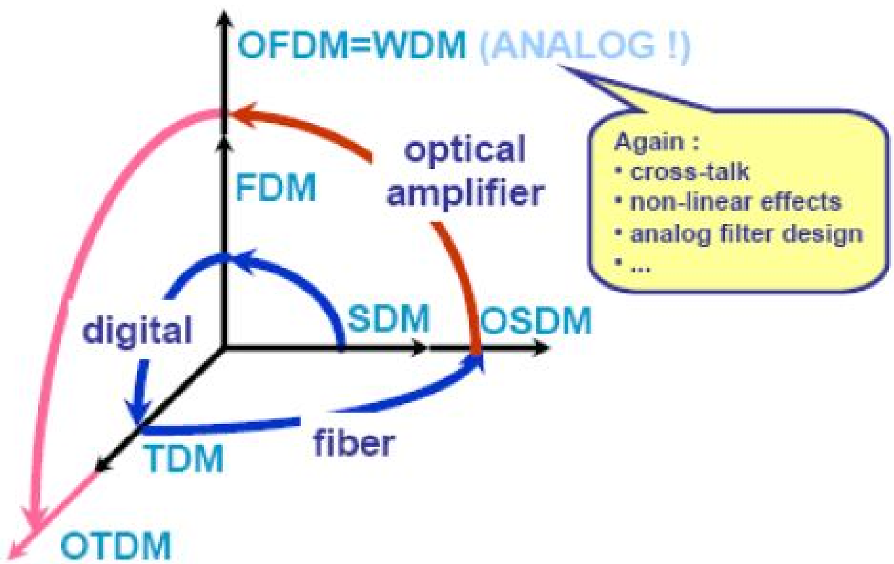


Figure 1.13 – Optical point-to-point system evolution.

1.2 Transport Network

Transport network is composed by several nodes; where the treatment (e.g. the permutation, the extraction and the reintroduction of the signal, the multiplation, and so on.) of the client signal is carried out. In general, the transport network can be divided in three principal parts: access, metropolitan and backbone network [3].

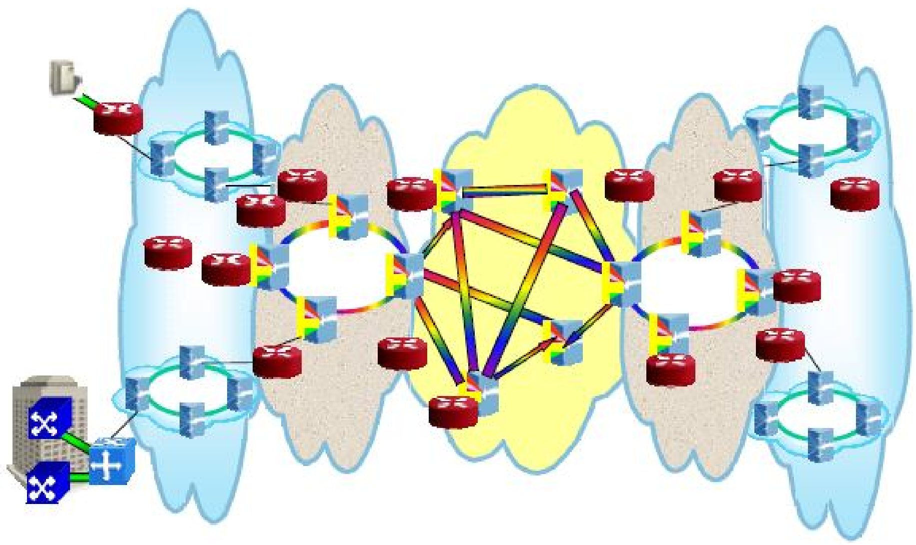


Figure 1.14 - The network configuration.

Transmissive resources of a transport network are suitable to transport all type of client signal (voice, music, images, data and video).

With the introduction of networks liberalization and telecommunication services, transport network operators, now, work in competition with the other ones. Therefore its realization and its management have to reach price, quality and flexibility aim and last, but not least, availability too. Currently operators offer transmissive capacity with different availability (and cost) purposes, divided in classes. Obviously, the network structure (configuration and redundance), the characteristics and the devices technology are employed to the main purposes.

The optical technology is the key element for the transport network realization except for the access network where the use of the traditional twisted pair (copper cable) and other metallic conductor based approaches are still used. Today it is possible foresee the use of the optical technology in the metropolitan network and in the backbone one towards an all optical network, the AON.

1.3 Optical data transmission

Nowadays, to transmit high data rates required from the several end-users, optical technologies are used, because offer high optical frequencies and very broad bandwidths [4]. The wavelength range from 1.3 μm to 1.6 μm, corresponds to a bandwidth as large as 43 THz, unreachable to the other cables technologies. This is the reason why it is easy to understand that the optical fibres allow the use of a very broader bandwidth than the one used for any other electrical cable. In most cases, data transmissions are based on optical media, since the optical fibres allow to guide light over very long distances, presenting low losses. There are also other applications, however, which involve free space data transmission (Free Space Optic), most of all, used in satellite communications, but also to transmit data among buildings where few hundreds meters long distance systems can be quickly installed with low costs. Even an optical transmission system can presents some faults caused by some factors which limit the optical fibres performances. Usually, the bit error rate is strongly dependent on the transmitted signal power, and the received signal must be above a fixed power level established. If the received signal is different respect these rules, a possible error can be easily detected and corrected. The error correction scheme is based on the assignment of more redundancy levels at the transmitted signal, so as to make easier the task of error detection. Additional detrimental influences such as fibre losses or dispersion or non linear effects, which compromise very high distances link, can be moderated increasing the data transmission power.

Nowadays, the application field in which mostly optical fibres are exploited is in long distance networks, but they are also used in few kilometres networks, as phone traffic, Internet traffic and cable TV. In the future, optical fibres will be used in very short distance networks, and, step by step, they will enter in the houses, as it has already occurred in Japan, where many internet connections exploit at all the optical technology.

Recently, the development of the optical fibre technology, has been so fast that there is even the intention of use inter-optical connections inside the super computer to connect several devices.

Current local area networks (LAN) work using electrical cables at data rates of 100 Mbit/s, in spite of 10 Gbit/s, which can be achieved with optical connections.

1.3.1 Single channel system

The devices that transmits the client signal on the optical fibre can be divided in two main classes: the single channel systems and the multichannel systems [5].

The single channel systems, are called also TDM (Time Division Multiplexing) since the transmitted signals are multiplied in the time domain; they transmit only one optical channel on the pairs of optical fibres and this procedure is necessary since the client signals are bidirectional.

The single channel optical systems are composed, as a rule, by a transmitting device, which executes the electro-optical signal conversion, a receiving device, which executes the optical-electric signal conversion, and by a number of optical amplifiers. The number of the amplifiers is variable and it is determined by the network length.

The optical TDM systems employed, are used only on the peripheral networks. The ITU rules indicate a length of 160 Km for the 2,5 Gbit/s systems capacity and a length of 120 Km for 10 Gbit/s systems capacity.

The optical technology permits to realize TDM systems without intermediate amplification for special application, for example, the undersea networks.

1.3.2 Multi-channels systems (WDM)

Multi-channels systems, indicated by the acronym of WDM (Wavelength Division Multiplexing), transmit more channels using different wavelength into optical fibre. In these systems, the transmission ends, which outputs have a different wavelength, are followed by an optical multiplexer which multiply all the transmission channels on the same optical fibre. An optical demultiplexer, with complementary function with respect to the optical multiplexer shown in the picture above, divides all the channels according to the wavelengths [5].

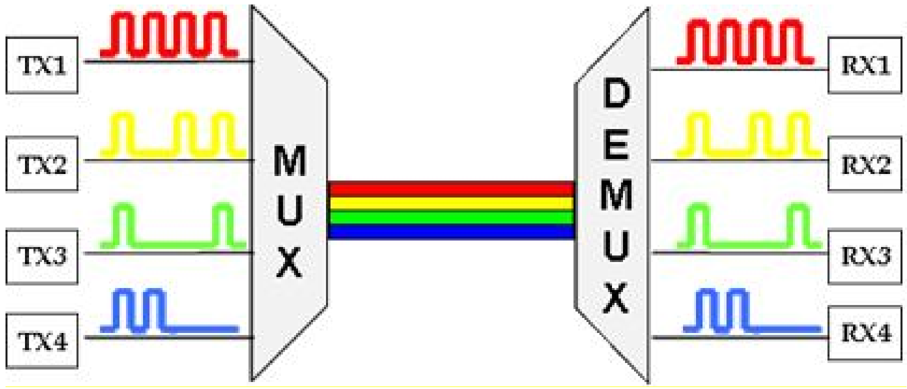


Figure 1.15 - WDM scheme.

The typical lengths of the amplification sections are of around 80 Km. The regeneration carried out in the receiving devices avoid the degradation effects introduced by fibres, devices and network length.

The spacing channel, in terms of wavelength or in terms of frequency, is different. WDM systems are divided in two main classed:

The DWDM systems (Dense WDM) with channel spacing of 100 GHz in frequency (0,8 nm in wavelengths) and CWDM (Coarse WDM) systems with spacing channel of 20 nm in wavelengths (1600 GHz in frequency).

1.3.3 DWDM systems

Even if DWDM systems has small frequency spacing among channels, are characterized by an high capacity in terms of transmitted channels on the same optical fibre. Typical applications of these systems are backbone networks.

The most spread systems permit the transmission of 40 Channels at 10 Gbit/s spacing of 100 GHz in C band (1530-1565 nm), along 600 Km distance without intermediate regeneration. More advanced solutions are available with 80 and 160 channels at 10 Gbit/s, with spacing lower then

100 GHz, which can cover, without electrical regeneration, a very long distance. In particular situations, for example undersea networks, DWDM systems have covered distances of 8000 Km without intermediate electrical regeneration; this result is possible for the particularity environment and for the short section of amplification (50 Km).

DWDM systems can transmit on a single optical fibre data with bit-rate of 1 Tbit/s. Often, a telecommunication cable contains ten optical fibres, so the transmission capacity on optical cables can arrive at 10 Tbit/s.

Now, if the optical cable would casually cut, the consequence for the clients, would be disastrous. For these reasons, is necessary to design networks with high redundancy [3].

1.3.4 CWDM systems

Although the higher spacing among channels, CWDM systems are characterized by a limited number of channels. Such systems are also characterized by a big wavelength range from 1260 nm up to 1610 nm (O+ E + S + C + L band).

The maximum bit rate for the systems is about 2,5 Gbit/s. The maximum lengths are around 80 Km without amplification. For these reasons, CWDM systems are applied in metropolitan networks. CWDM at 16 – 18 channels needs, besides, the availability of the particular optical fibre, which are characterized by a very low loss attenuation.

The most common applications, actually, are limited to 8 channels in the 1460 nm – 1610 nm band. The advantage of CWDM systems is that its cost is lower than DWDM systems, since the high spacing channels allows the use of low-cost devices.

1.3.5 OTN - Optical Transport Network

Using the acronym OTN (Optical Transport Network) a step more to all optical network direction has been made.

OTN is composed by optical elements, connected by optical cables. The OTN architecture is composed by three main levels: optical channel, optical multiplation channel, transmission section. Each level has a basic function. For the client signal transmission, OTN is based on three blocks: The first is able to transport signal with bit rate at 2,5 Gbit/s; the second is right for signals from 2,5 Gbit/s up to 10 Gbit/s and the third for signals from 10 Gbit/s up to 40 Gbit/s. These blocks constitute the elements of an optical hierarchy (OTH) which permit the transport of more channels.

At the network entrance the transmitter assigns to the channel the right wavelength. This characteristic of the OTN guarantees the high transparency to the client signal in the selected optical channel.

The trame of each of the three kinds of channels is composed by a payload, which contain data, and by an overhead, where all the necessary information to manage the configuration, are contained. With such structure of the optical channels OTN (payload+overhead), all the optical channels are equipped with all the necessary resources for its own management. In this way, the client signal can be transmitted on the optical channels.

An OTN characteristic is the optical transparency, that is network capacity of transport optical signal for long distances through its node without O/E and E/O conversions. This transparency is not total for two reasons: because of the degradation of the optical transmission and because not all the functions are made in the optical domain (that is why are commonly referred as opaque). Today, indeed, are available the devices for the drop and for the optical channel insertion referred as OADM (Optical Add Drop Multiplexer).

The OTN network is composed by transparent optical islands with limited dimensions (100–200 Km), in which, in the near future, optical channels will be always maintained at an optical level, and where all optical regenerators will be adopted.

A considerable enrichment of an OTN is the ASON (Automatic Switched Optical Network), where optical channels routing is intelligent and faster. The ASON permits an elaboration time very small (from 10 ms up to 1 s) and the new routing when the damaged is present. This new network can offer also new services as Bandwidth on Demand and Optical Virtual Private Network.

1.3.6 AON – All Optical Network

The all optical network is the final step of the evolution of the transport network since it permits to remove the electrical regenerator placed in the optical network achieving a total transparency. The evolution of the OTN in the AON permits to create a broad optical island in which the client signal is converted from electrical to optical only in the beginning point and the same signal is converted from optical to electrical format only in the final point. This evolution will be possible when all the network optical elements will be available.

1.4 Wavelength Division Multiplexing WDM

The modern technique to transport high amounts of data on optical fibres is called Wavelength Division Multiplexing (WDM). This technique uses optical fibres to transport data and permits simultaneously transmission of more independent channels on the same medium.

An alternative way to consider WDM is to see it under the point of view of the transmission of several channels, giving to each one a different colour (different wavelength). In this way the transmitted spectrum can be seen as a “rainbow” [5].

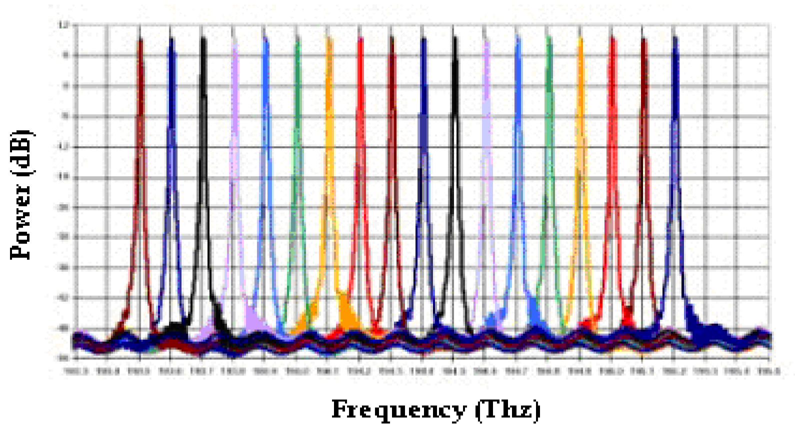


Figure 1.16 - WDM system spectrum.

Obviously, the wavelengths taken under consideration, are characterized by frequencies which can not be seen by human eye. Nevertheless, this peculiarity of the wavelength can be exploited to describe such technique in a funny way.

WDM permits to combine more optical channels with several wavelengths, transmitting them together and filtering at the receiving side. Usually, in optical fibres communications, different wavelength channels are transmitted to increase the channel capacity and to create a good data transmission link lowering the per bit costs [6].

Exploiting at the most the optical fibres potentialities with a single channel at high bit rate, very broad bandwidth might be obtained.

However, given the enormous available bandwidth about THz of the low loss transmission window of silica single-mode fibres, this would lead to a data rate which is so much more higher than what can be handled by transmitters and receivers.

Nevertheless the bandwidth given by the optical fibres is very broad, dispersions might have a damaging effect in high distances transmission.

WDM is able to solve these problems since maintains the transmission rate of each channel at a low level (e.g. 10 Gbit/s or 40 Gbit/s) and can combine several channels together, giving a total transmission broad bandwidth.

Dense wavelength division multiplexing (DWDM) is characterized by a channel spacing equal to 100 GHz and can be made by using several transmission channels (about 40 or 80 channels), while on the contrary, Course wavelength division multiplexing (CWDM) is usually referred as that systems that works with low channels numbers far away from each other (one, for example, propagating at 1.4µm and the other one at 1.5µm).

Moreover, when more channels are transmitted together and suffer some losses, they can be amplified by a single device, since modern erbium amplifiers have a very high amplification bandwidth. Obviously, wavelength division multiplexing, is affected by some problems which can be caused by the interactions of the data channels as the crosstalk and channel interference, or by variation of gain with different wavelength, or again, by non linear effects [7]. Combining together more techniques, essential progress has been made to attenuate these detrimental effects. Furthermore, many fundamental parameters at the basement of the transmission systems must be chosen and varied in a right way to make WDM a complete system for all the performances, and so the services, required by end-clients. These parameters, such as channel spacing, transmitters power levels, fibre and amplifier types, modulation formats, if suitably chosen, permit to satisfy the demand of the client in term of bandwidth and performances.

Since the bandwidth required is increasing and sometimes it can not be foreseen, even in optical fibres link, which use few channels, it is correct to place devices which are able to manage many channels. In fact, often it has been avoided to place additional cables if the bandwidth, required by the clients, increased. In such way, the old systems, no more able to offer all that was required to them, that is high bit rate, have not been substituted but amplified, obtaining the transmission capacity required.

In many cases, TDM can be an alternative to WDM. The TDM technique is based on the concept that different channels are distinguished by arrival time rather than by wavelength.

The modern technology offers several kinds of WDMs. A basic form of WDM can be built using a wavelength around 1300 nm and another one around 1500 nm or utilizing a wavelength couple with values of 850 nm and 1300 nm. This kind of system is realized with few components with low coast (CWDM). The following picture shows an example of a very simple WDM system using multimode fibres [5].

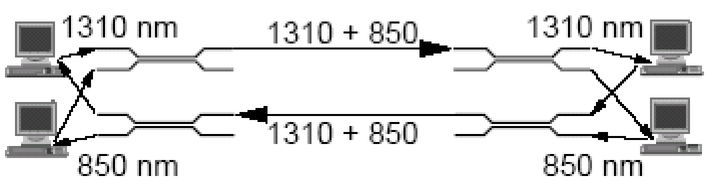


Figure 1.17 – Simply WDM system scheme.

In this kind of multiplation, some couplers, having multiplexer and demultiplexer function, are used to mix transmitted signals and to separate the received signals. So it is clear that this system use different bands rather than different wavelengths in the same band.
The scheme shown in the picture, uses separate fibres for each direction, while there are other schemes which use just one bi-directional fibre, used for both data transmission and receiving. Besides, some systems use bands different from the one shown in the picture above.
The most common systems operate at a very low transmission rate, so it is clear that these systems are not employed in the large communication networks. Nevertheless, such systems, which do not offer a very high transmission rate, find application in the transport of video signal for security control.
Another kind of multiplation is the Dense WDM which is an evolved versions of WDM multiplation. This kind of technique allows to transmit so much more channels on the same optical media than the multiplation WDM does.

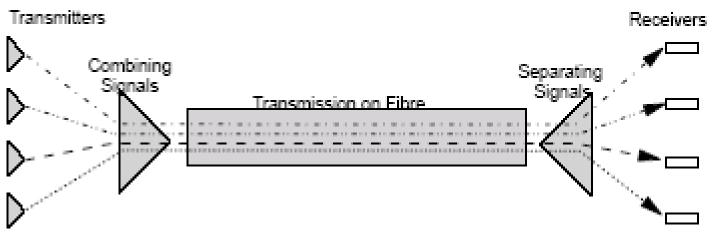


Figure 1.17 – Dense WDM (DWDM) scheme.

The scheme shown in the figure, illustrate the principle devices used to realize a simple DWDM multiplation. Each channel uses its own wavelength and more channels are multiplated in the same optical media, besides the wideness among the channels can be 1 nm. The width of the channels depends on many factors such as the stability and the tolerance of the laser sources used, the kind of modulation and the performances of the other optical devices employed in the general system.

In general, the WDM system, is constituted by some key parts which have the task of generate, transmit and receive the client signal. Very often, occurs that the transmitting source is a laser which must have a very narrow line-width to leave the signal in the allocated band.

The next step is to mix more channels together using different wavelength. There are more ways to combine these channels; the most simple is to use a coupler which couple, each time, the channels. The coupler presents a loss of about 3dB and such loss occurs at each stage in which the two channels have coupled.

It is clear that, if an high number of channels is used, the initials loss result too much high and this yields to use more amplificatory stages to compensate the losses.

Therefore, it can be easily understood that a coupler can be used to achieve the WDM scheme only if few channels have to be transmitted.

Gratings and planar waveguides have very lower losses which do not depend on the number of channels. This is the reason why they are very often used in systems transmitting much more channels. After having combined the signals in the right way, they have to be transmitted through only one optical medium.

During the transmission, among adjacent channels some effects can be generate such as the crosstalk and the Four Wave Mixing (FWM) which lower the performances of the whole system. By controlling the channel spacing and the transmitted power levels, the crosstalk effects provoked can be minimized; besides some techniques, which allow to establish exactly the channel spacing, can be adopted to completely remove the non linear effect FWM. Another fundamental aspect is the amplification that the transmitted signals have to undergo on long haul transmissions. The amplifier skill to amplify simultaneously more multiplated channels make possible to realize the WDM multiplation among long distances.

Nevertheless, when several amplifiers are used together, especially in long distances networks, their noise (Amplified Spontaneous Emission - ASE) are add up together causing great difficulties.

Once a time that the signal is arrived to the receiver, the various channels transmitted have to be separated, assigning to each client the respective data traffic. This is a very difficult operation and different techniques can be used to realize it. Reflective grating, splitters or waveguide grating routers can be used.

To receive the transmitted signals, common detectors are used and they are applied also in other circumstances since the signal has been already demultiplated. It is clear that each channel data rate is independent from the other channels; that means that a channel can have a rate of 2.5 Gbit/s, while another one can run at 622 Mbit/s and the last group of channels can run at 200 Mbit/s.

1.5 WDM systems - The limitative factors.

As it has been seen up to now, WDM multiplation allows to transmit more channels together in a very profitable way on the same optical fibre [8].
Nevertheless, some factors which limits the performances of this technique, especially in long distance network, does exist. Fibres non linearities, amplifier spontaneous emission (ASE) and chromatic dispersion can be taken as example; besides some of these can induce the distortion of the transmitted signals.
Since networks are usually very long, a series of cascading amplifiers will have to be used.
Obviously, when a channel wavelength is centred with the optical amplifier gain peak, the optical SNR of that channel will be increased respect to the other channels; this involve that a channel with a SNR very different from the other channels, make possible the non equalization of the channels with a consequent decrease of transmission performances.
Another factor in long distances transmissions which has not to be undervalues is FWM effect which strongly limits system performances. When several waves having different wavelength are transmitted, they interact giving rise to new pulses placed at different wavelengths. These new pulses are commonly called replica which can become very dangerous since they take away energy from the signals which have to be transmitted. Follow, is presented a picture which depict this kind of non linear effect when three channels are used.

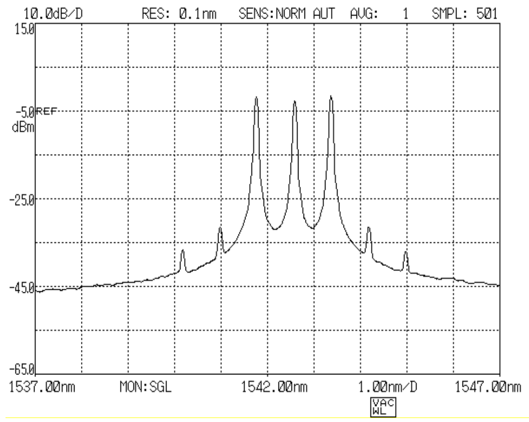


Figure 1.18 – Generation of FWM effect using three channels.

The picture shows FWM effect produced by the interaction of three signals co-propagating in an optical fibre. Generating these replica, the power level of the three signals is affected and time interactions between other co aligned channels (in a WDM scenario) are strongly enhanced. Therefore, it is necessary to limit or remove such effect to increase the WDM transmission system performances. Another example of FWM effect is shown in the following picture. Here only two signals are transmitted on the optical fibre. In particular conditions, these signals, can generate more replicas which degrade the data signals.

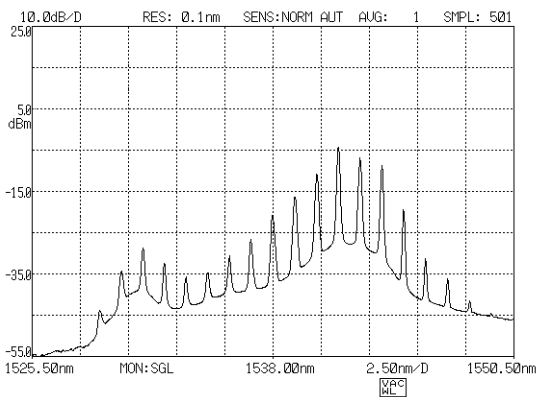


Figure 1.19 – Another case of FWM effect.

1.6 Protection techniques in WDM systems

A more important aspect of the wavelength division multiplexing is the protection and the technique used to make this kind of multiplation very safety [9].

In fact, the interruption of the optical connection which work at high bit rate (for example 10 Gbit/s or 40 Gbit/s), even only for a few seconds, provokes a high data loss. For this reason, the telecommunication management which use this technology, must guarantee at the final client a limited out-of-service time and fast network recovery. In the past, if a damages which occurred in the optical networks resulting worked out, a routing from damage connection to the operated link was done. Nowadays, this should be unthinkable because the optical network worked out should be considered insecure and vulnerable. Moreover, the damage management and the data re-direction is carried out by an operating central which make these choices in the distance. The management will not accept a transmission data system without protection but will consider a networks which routing automatically the connection when a damage is present.

The optical networks commonly used are systems based on a layer architecture. The function of WDM layer is the *provisioning* of the connectivity and of the band needed. This service realizes the point-to-point required connection achieving the point-to-point optical link. These circuits are called light-path and are composed by a number of channels WDM which transport the data from the source node to the destination node. Each light-path have a data flow with high bit rate which is inserted and extracted by the optoelectronic interface between the WDM layer and the upper one. The WDM layer is divided in more sub-layers to realize in a more simple way the function as the light-path control or the routing band the wavelength assignation, error detect (*fault recovery*) and signal management in the optical network. The sub-layers of the WDM layer are called optical channel sub-layer, optical multiplex sub-layer, physical media sub-layer and optical transmission sub-layer. The first layer provides for the routing and the wavelength assignation, for fault recovery and for the connections control. This layer check also the light-path.

Each link is managed by the optical multiplex sub-layer, thus local resources check is possible. The optical transmission sub-layer, in the end, manages all the control functions of the transmission devices as the amplifiers and the regenerator.

1.6.1 Protection technique in WDM layers

Optical channel sub-layer or optical multiplex sub-layer (OMS), are two layers where is possible to adopt the protection technique. In the first case, the light-path is protected, for this reason this case is called path protection. In case of damage, each introduced data is routed on another protected light-path; this is defined working, while the light-path used before the damage is called protection.

In the second case, the transmitted WDM channels are protected; this protection is a local function carried out by the OMS devices which constitute the single link.

The channels multiplexed are routed on another link, if the damage is present, without data loss. The substantial difference between the two technique is that the second is able to treat simultaneously all the damaged light-paths, while the first can operate on the single light-path.

The traditional WDM networks are based on an optical cable composed by couple of fibres and each of them permits the propagation in a single direction. The OMS protection modality utilize four optical fibres to each link; besides, the fibres couple normally are utilized for the data transmission. In this case is placed another fibre which is called *backup* and permits to route the data in case of damage. A second modality which use a single fibres does exist, and in case of damage one direction is used to transmit half WDM channel and the another half is used for protection task. To manage the protection resources, two solutions are possible and these solutions are very different. The most common technique is called *preplanning* in which, first of all, the protection resources are allocated. The tasks carried out by the network devices to obtain the data protection are very simple because the network has been already treat. These reasons allow a very fast *recovery* but the resources are destined to a stiff way.

The other solution is called *provisioning* which involves the over-size of the network even if the data required are lower then the real network dimension. This implies that in case of damage, the network can re-allocate the new connection in a dynamic way always obtaining new resources. Another advantage is the possibility to guarantee the total security even in case of many simultaneously damages as, for example, the environmental disaster.

This is, on the contrary, the dynamic way which result more complex to manage but this is the solution more suitable especially in this time in which the phenomenon of IP over WDM is very important.

Chapter 2

Introduction: 2R all optical regeneration – state of the art.

Different way to obtain all optical regeneration of signal are presented in this section. Several techniques are described in order to evaluate and characterize the differences that exist between the mentioned approach. There are two big categories: Single-channel regeneration, in which different ways to obtain the regeneration are implemented exploiting, for example, the non linearity offered by the optical medium. Moreover, this kind of approach is applied to one channel only, thus if several channels needs 2R all optical regeneration, the regenerator is applied to each channel.

For this reason, new kind of systems are under study in order to manage several clients using only one optical regenerator system for all end-users. These are the second category: Multi-channels regeneration. In this way it is possible maintain low the cost per bit and also to guarantee low power consumption using less devices whit respect to the single channel systems. Following are described some techniques used from single channel system but also the 2R all optical regeneration system used for multi-channels regenerations. Multi-channels regenerator permit to employ the reshape system in WDM or DWDM scenario because are able to manage several channels at the same time offering also a wavelength conversion.

2.1 Single channel regeneration

The single channel systems have been a first step towards the introduction of optical communications backbones. The fundamental problem was constituted by the continuous conversion of format which slowed down the transmission speed. By introducing all optical regenerators in the networks, this problem has been exceeded, guaranteeing very fast signals elaboration.

2.1.1 2R Optical regenerator based on interferometric structures

The interferometric structures, used in order to obtain some 2R regenerators, can be grouped in the two big categories of the interferometers: Sagnac and Mach-Zehnder.
Sagnac interferometer is composed by a bidirectional coupler to whose output doors are connected the ends of one optical fibre.

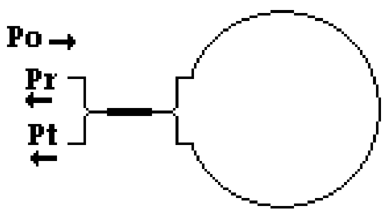


Figure 2.1 – Schematic structure of Sagnac interferometer.

Even if the fibre constitutes a loop, feedback mechanisms do not take place and, therefore, all the input light exits from the interferometer after a complete turn. The input signal with power Po is divided in two counter-propagating signals, which, after a complete turn in the fibre loop, interfere giving back in output the two signals Pr and Pt:

$$p_r = \frac{p_0}{2}(1 + \cos\Delta\varphi)$$

$$p_t = p_0 - p_r.$$

The difference of phase depends on the non linearity by the two counter propagating signals. Different Sagnac interferometer can be obtained: NOLM (Nonlinear Optical Loop Mirror), is an interferometer where a piece of fibre exploit the non linear effect; SLALOM (Semiconductor Laser Amplifier in a Loop Mirror), where the non linearity is generated by inserting in the interferometer loop a semiconductor amplifier working in a non linear conditions.

The Mach-Zehnder interferometer is composed by an input and an output couplers, connected by two passive waveguides constituted of Lithium Niobate. Also in this case the input signal can be split in two parts interfering at the output coupler in accordance with the different distortion suffered through the two passive waveguides.

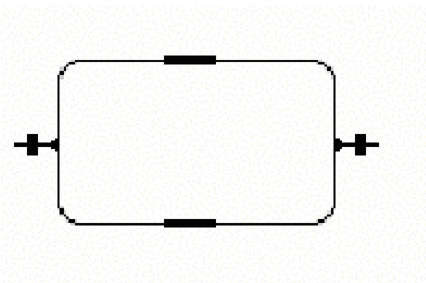


Figure 2.2 – Mach-Zehnder interferometer.

In both cases a right phase-difference of the two fields concentrates all the power on a single output branch of the interferometer and the device has a transfer function able to suppress the noise, regenerating the input signal.

2.1.2 2R Optical regenerator based on NOLM

A generic pulse signal, which arrives at the input coupler, is divided in two components travelling in the loop in a counter-propagating way and showing different peak powers depending on the couple relationship ρ [10].

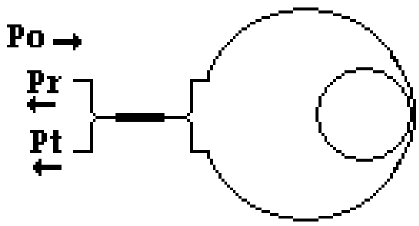


Figure 2.3 – NOLM Scheme.

After a complete loop, the components have different phases $\Delta\phi_{out}$, constituted by a linear term determined by the fibre length covered, and a non linear one, determined by SPM and XPM phenomena which is present during the propagation. Being the linear term the same for both components, their relative phase-displacement depends on the non linear term. In $\rho = 0.5$ case, also the non linear phase-displacement is null and the two components, interfering in the coupler, recombine themselves in phase, giving back a signal equal to the input one, that is $p_r = p_0$. The interferometer behaves like a perfect mirror. For $\rho \neq 0.5$ case, $\Delta\phi_{out}$ values do exist, for this $p_r = 0$ and $p_t = p_0$, that is all the input power is transferred by the interferometer on the other branch of coupler input-output. The interference generated at the end of the ring depends on the phase difference existing between the two components, which, in its turn, depends on their power difference, determined by the couple relationship ρ. Increasing the input power level, the output power increases but in a non linear behaviour. The non linear input-output characteristic shows a flat area. Working around these powers it is possible to reduce the signal amplitude noise, obtaining a regenerated signal. In fact, Sagnac interferometer is able to reflect the low power and transmit the high intensity radiation, reducing, in such a way, the noise level. The NOLM is a passive regeneration device, able to operate on different wavelengths signals and with a speed of answer around the femto second. Besides, the NOLM device require powers and fibre length such to induce non linear effects; these parameters depend on the kind of fibre used.

2.1.3 2R Optical regenerator based on SLALOM

In the same way, NOLM device has the input signal in the loop which is divided in two parts through an input coupler. A part travels the loop clockwise and reaches the SLA first, in which it is linearly amplified.

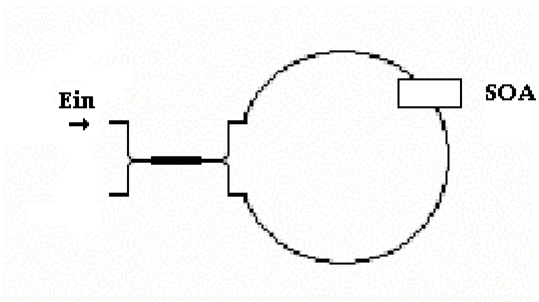


Figure 2.4 – SLALOM Scheme.

The part of signal that travels counter-clockwise, reaches the SLA in a T time, after the signal travelling clockwise, facing a different amplifier gain. This gain depends on the saturation imposed by the signal travelling clockwise and by the recovery times τ , in terms of bearers in conduction band, of the same amplifier. The two pulses interfere in the coupler producing an output signal depending on the phase difference and gain experimented in the loop by the two input signals. The pulse is re-shaped according the interferometer functioning principle. Respect to the NOLM, the SLALOM has two advantages: compactness and lower optical power demand. In the NOLM, in fact, powers of the order of W are necessary in order to activate the Kerr effects which generates the non linear phase-displacement. Moreover, the optical fibre, in which such effects verify, must be sufficiently long in order to allow the effect efficiency. In order to carry a semiconductor amplifier in a non linear zone, powers of the order of tens mW, are sufficient. Moreover, the effect is concentrated in the same amplifier and for this the unique optical fibre piece used is the one for the amplifier connection with the coupler. The processing speed is slower (some GHz against the THz of the NOLM).

2.1.4 2R Optical regenerator based on SOA-MZI

The regenerators based on interferometric structures, such as Mach-Zehnder type, are ultra-fast devices but, at the same time, they depend on the input pattern, for the SOA intrinsic characteristics [11]. They allow the contemporary conversion of wavelength and modulation format, passing from NRZ to PRZ (pseudo RZ). Two families of devices can be observed: one based on interferometric structure, with two identical SOAs on the branch of the interferometer; the other with a monomodal SOA on a branch and a multimodal SOA on the other branch.

In the case on the left side, in both the SOAs the low power clock signal and the data signal enter in the device.

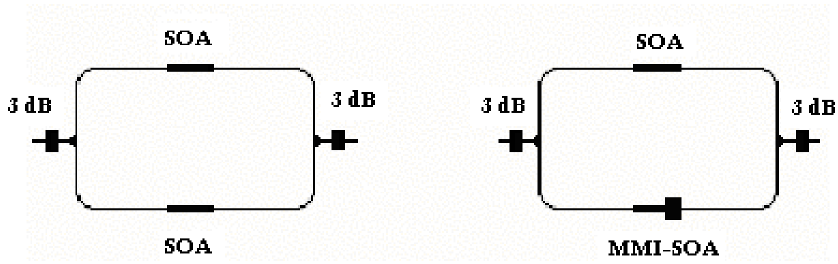


Figure 2.5 – Interferometric structure with equal and different SOA.

Until the two SOAs are crossed by the clock signal, and therefore they are not saturated, this last join itself again at the Mach-Zehnder output, reproducing the logical level zero [12]. When the data signal reaches one of the two SOAs, the interferometer overbalances and, at output coupler, the logical level “one” is created. When the signal reaches also the second SOA, the interferometer balances itself again and the logical level zero is produced. The signal reshaping mainly happens at the logical level one, thanks to the sinusoidal transfer function of the device, while the improvement of the extinction relationship is rather poor, around 4 dB. This device is based on the processes of Cross Gain modulation (XGM) and Cross Phase Modulation (XPM). In the XPM case, the loss balance of the device depends on the difference between the two SOAs. The multimodal SOA has active area more width and, consequently, the saturation power is considerably higher, while it is possible to obtain the same gain not saturated. That implies, in addition, that the logical level low is obtained. The consequence, is that the variation of the phase difference between the two branch is realized more quickly in the first case and that the transitions between the two logical levels can happen in short intervals, fallowing higher bit-rate. For equal bit-rate, better regenerating behaviours are obtained.

2.1.5 2R Optical regenerator based on Q-switched laser

An alternative to the interferometric structures, up to now analyzed, is constituted by the Q-switched laser. This laser is made by an integrated passive section between two DFBs: one along 200 µm and one along 350µm, which shows like a dispersive reflector. A shorter DFB section has a bias current such as the region behaves as a laser emitting a continuous that travels in section two and it is back-spread by the reflector (section three in the next figure).

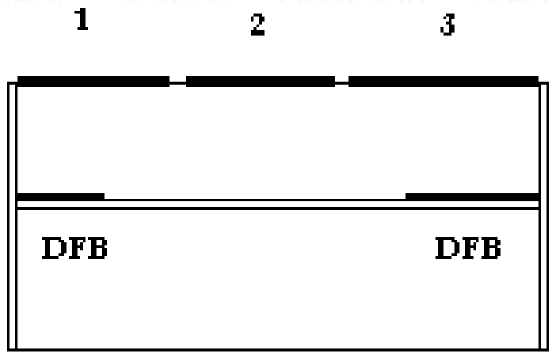


Figure 2.5 – Q-switch Laser.

The combination of sections two and three allows to control the back-spread light in amplitude and phase. The cavity laser made by the three regions emits or not on the basis of the existing interference between the light back-spread and that emitted by region one. By the fact that the quality (Q) of the resonator, constituted by the three sections, influences the activity of the laser, this is the reason why of the device name. The three sections are controlled in current: the current of section two is tied to the refractive index of such region and, therefore, it controls the signal phase passing in the same region; the current of the first section is tied to the wavelength of emission. Its variation influences also the phase relation existing between the optical beam emitted by the first DFB and the one back-spread by section three; therefore, its variation generates a power difference in output from the cavity. If an optical signal is sent into the cavity, the devices can be used as decision element. The optical signal injection in the region laser of the device, in fact, increases the refractive index of this section, generating a variation of its wavelength of emission and consequently generates a variation of the spectral correlation of the cavity. The signal which has to be re-shaped can be introduced through a circulator which collects at the output, the re-shaped signal, thanks to the non linear transfer function shown from the device.

2.1.6 Optical regeneration exploiting Quasi-Continuous Filtering technique.

This kind of optical regeneration is based on quasi-continuous filtering technique. It is composed by a sequence on N samples of non linear optical fibres divided by filtering optical devices where the central frequency changes gradually along the length of the regenerator [13].

Figure 2.6 –Regenerator scheme.

Referring to the picture 2.6, each optical filter which is moved a little in term of frequency with respect the previous filter, reduce the spectral band of each section.

As result of quasi-continuous filtering (QCF) technique, the pulse spectral band is strongly reduced. For low intensity signals, the spectral broadening is small and the noise is subsequently attenuated from the other following optical filters; for high intensity signals, the self phase modulation (SPM) induces a spectral broadening and this permit the signals to go through the low loss of the filters. In this way, the amplitude of the signals result reshaped; thus the noise present in the zero level and the amplitude fluctuation of the mark level are either reduced.

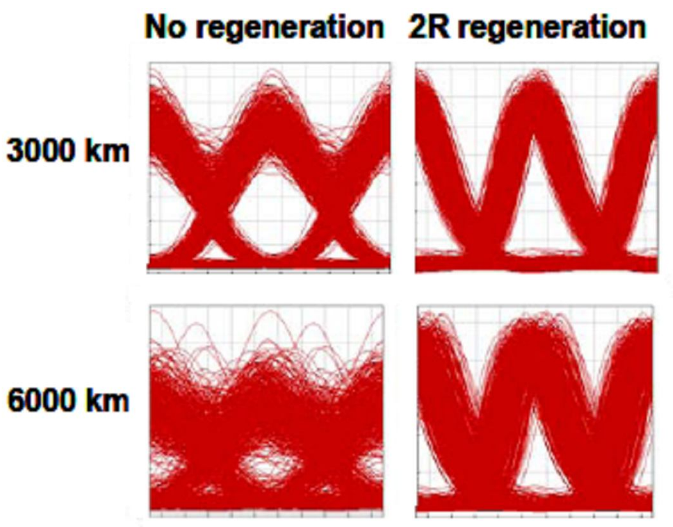


Figure 2.7 – Optical eyes after transmission with and without regeneration.

Referring to picture 2.6, each optical fiber is 200m long, has $\gamma= 13\ w^{-1}\ km^{-1}$ and $\alpha= 0.2$ dB/km. with these parameters, the system shows the ability to regenerate the noisy signals. In particular, the picture 2.7 shows a regenerated signal after 3000 km and 6000 km. A comparison with non regenerated signal is depicted too.

2.1.7 Mamyshev 2R regenerator.

Mamyshev 2R regenerator is an all optical system able to manage and regenerate optical signal used in optical communication in order to obtain an all optical data elaboration. In 1998, the researcher Pavel Mamyshev of Bell Labs, suggested the adoption of the non linear effect, in particular self phase modulation (SPM) used for single channel optical signal, obtaining the re-amplification and the re-shaping at the same time and all in optical domain [14].

The design of the regenerator mainly consist of a sample of high non-linear fiber with a band-pass filter (BPF). This is the main configuration which is repeated more time if the system required high performances of regeneration.

The modulated optical signal (for example NZ or NRZ format) run through a few km of non linear optical fiber and the signal is spectrally broadened due to self phase modulation, thus SPM broadens the signal spectrum with the pulse intensity. Then, the BPF which has a fixed spectral bandwidth, is able to filter the noisy signal giving back a reshaped signal. In this way the filtering behavior is inside the SPM effect; for low signal ("zero" level) which has low intensity do not broaden significantly and is out of the BPF, thus the output zero signal is compress towards the zero level.

When "one" level is present, the signal intensity is sufficiently strong in order to broaden the spectra of the signal by the SPM, thus sufficient portion of the signal run trough the filter giving back a regenerated signal corresponding to high part (one level) of the signal.

In picture 2.8, it is possible to see (above part) the regenerated signal starting from the noisy signal presented in below part of the figure. It is possible note also how the regenerated output is boosted to the same power level of the signal (referring to the one level), while the zero level of the signal is compressed too. In picture 2.9 is shown also the transfer function of the regenerator able to compress the noise present in the mark and zero levels.

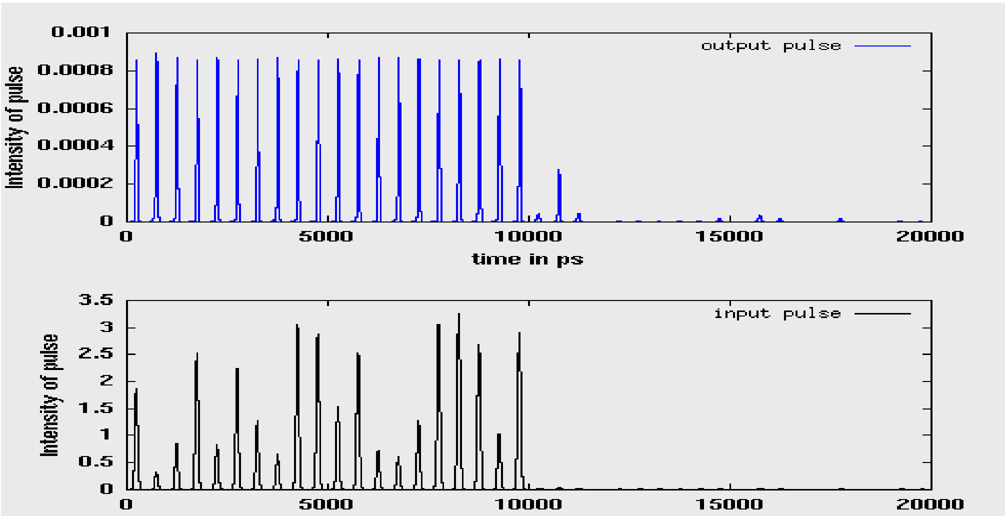


Figure 2.8 – Input signal and output regenerated signal from the regenerator.

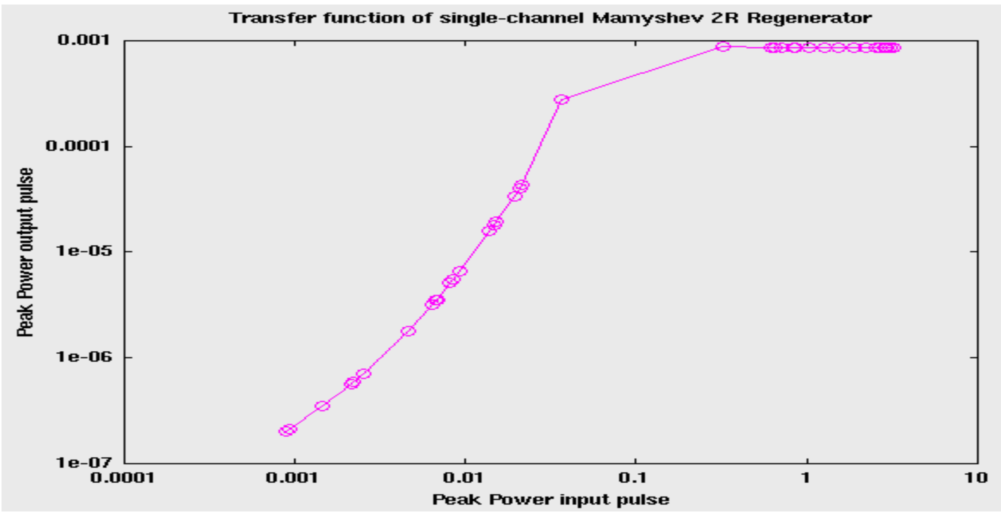


Figure 2.9 – Mamyshev 2R regenerator transfer function (Input / Output power).

The operations made by the regenerator like broadening, filtering and regeneration are shown in picture 2.10 in which it is possible to know the schematic step made from the Mamyshev regenerator.

Because the regenerated signal result shifted respect to the original signal frequency, applying another regeneration step which uses the BPF with frequency placed at the starting signal frequency allow to overcome this kind of problem. Moreover, the Mamyshev regenerator is also able to move the optical wavelength of the signal to different new wavelength.

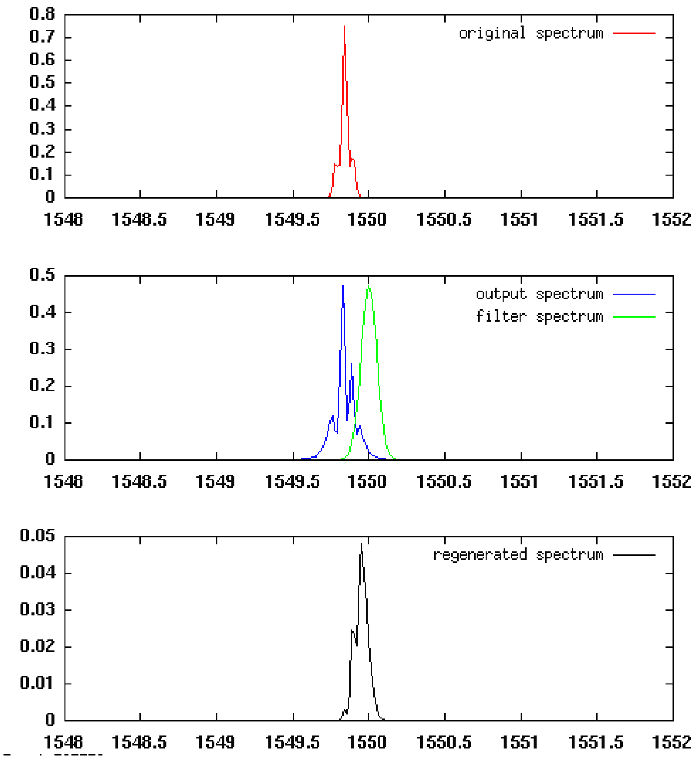


Figure 2.10 – Scheme of the 2R regenerator. Above is present the original pulse, in the middle is shown the broadened by SPM and filtering action, below is present the filtered spectrum.

The principle of Mamyshev 2R regenerator is based on the discrimination between the zero level and the mark level present in the signal which must be regenerated [15]. This is obtained through the power dependence of the spectral broadening induced by the SPM but also from the Mamyshew regenerator design, filter properties, optical non linear fiber physical parameters and from the properties of the incoming signal.

For an high degree of regeneration and optimal signal noise suppression, the transfer function must present a plateau zone; moreover this kind of transfer function provide a power dependant temporal delay and fluctuation in the regenerated signal duration. A reduction of this temporal delay can be erase using the transfer function but in a different working point. The delay time come from the different amount of signal frequency chirp induced by the high non linear effect offered by the optical cable. As shown in figure 2.11, the different arrival time is the result of the power dependent chirp rate value. Moreover, starting from the position of the centred filter, the power dependent delay is mapped in asymmetrical way in the output signal. Connecting two regenerators which have opposite frequencies, it is theoretically possible to erase the temporal delay introduced by the first regenerator. Anyway the performances of the second regenerator depend strongly from the signal that come from the first regenerator.

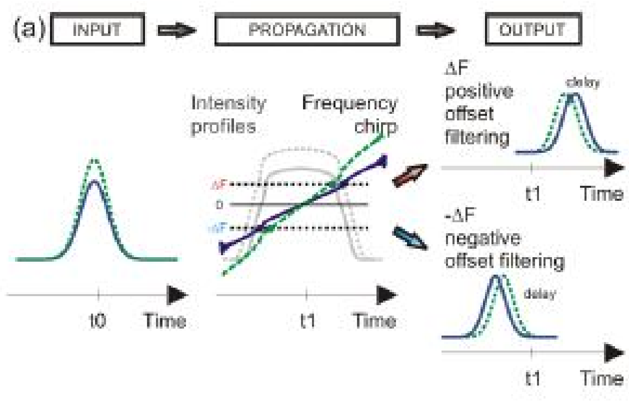


Figure 2.11 – General scheme.

2.1.8 Optical regeneration in silicon chip.

In optical system, it is important to avoid or limit the impairments like chromatic dispersion, noise amplifier, non linearity in optical fibre and polarization dispersion which causes low performances of telecommunication systems.

For this reason an optical regeneration is necessary in order to obtain a no-noise signal; especially when an high rate is used and in case of compact devices for high integrated system. An example of this kind of integration consist of the regeneration step inside the chip achieving the non linear effect like FWM [16].

Recent advances in silicon devices offer a potential increasing of integrations and high degree of electro-optics architecture. Using the high non linearity obtained inside the chip and controlling the dispersion in a correct way, it is possible to exploit the FWM effect in silicon nanowires in order to obtain the regeneration effect.

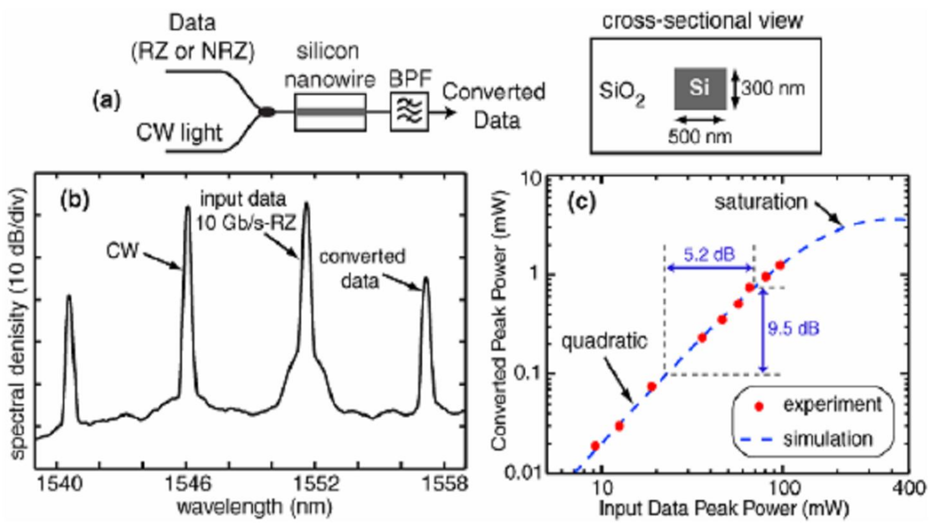


Figure 2.12 – Experimental set-up used to obtain the non linear effect inside the silicon chip and transfer function of replicas.

Using the method described in this section, it is possible to obtain the regeneration effect using FWM non linear effect (for example) in the silicon waveguide. This kind of effect permit to obtain also a wavelength conversion as shown in picture 2.12: a CW signal is sent within the silicon devices together the modulated signal which will be reshaped. As first result a wavelength conversion is obtained at a longer wavelength. The second most important result consist of the regeneration of the incoming signal as depicted in the following picture:

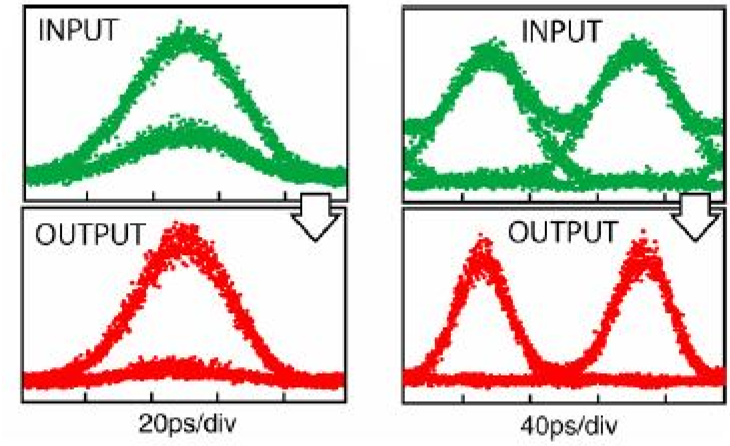


Figure 2.13 – Experimental result about the regeneration in silicon chip.

All optical regeneration using low power FWM non linear effect can be advantageous used inside the silicon chip devices providing wavelength conversion, optical reshaping, extinction ratio improvement and time jitter reduction.

2.1.9 Optical regeneration based on Super-Continuum effect.

This technique for this kind of regeneration is based on super continuum effect [17]. A small pulse (few pico-second) with adequate amplitude which run trough inside of optical cable with particular features in term of dispersion and non linearity, has a very hard spectral enlargement; this new pulse maintain the same characteristics of the starting pulse. A portion of the spectra can be select with particular filter; this signal will have the same modulation format of the starting signal.

The generation of signal replica permit to reduce the signal noise present on the zero level because the noise power present in this level is not able to trigger the SC phenomenon. Moreover, the output spectral power density result constant and this make the system able to compress the noise also on the mark level. The total effect of this regeneration system is to provide a reshaped signal both zero level and mark level of the output signal.

2.2 Multichannel regeneration

In order to take advantage of the enormous capacity of the optical fibres, multichannel systems has been introduced. WDM system has been the first introduced, able to transport information of more clients on a single optical fibre at the same time by means of several co-propagating channels. DWDM technique is another step ahead, which multiplies the channel capability of each fibre, introducing more wavelengths with low spacing, each of them able to transport data generated by more clients. With the advent of DWDM multiplation, moreover, channel capabilities ever higher have been reached. Always on a unique optical media. DWDM system allows, therefore, to face the always increasing necessities of band, due to the remarkable increment of the services demands. Also for the multichannel systems, the only way to exceed large transmission distances was to use opto-electronic regenerators introducing an opto-electronic conversion. This involved, once again, transmission delays caused by the continuous conversions of data format. In DWDM systems, in special way, there is the need to regenerate more channels simultaneously with just one device able to operate a completely optical regeneration.

In this case, the same techniques introduced for the single channel systems cannot be used since they do not act on the total of the system, but they operate only for the single channel. With the outbreak of DWDM technique, which has concurred to also increase the channel capability, maintaining a cost for bit relatively low, the need to construct an optical regenerator able to elaborate more channels simultaneously, has come out. What is required is that the presence of a variable number of channels, due to add and drop functions made along the channel path, in the time does not alter the compression capability of the noise on the channels present in the system. DWDM system, unlike of the single channel system, works using more transmission channels and would be unthinkable to employ an optical regenerator for every transmitted channel. The work of this thesis has been based on the realization and the characterization of a single optical device able to regenerate more channels simultaneously and in different ways in a DWDM scenario, working with an high bit rate.

The recent progress in the development of multi-wavelength all optical regeneration permit to introduce the 2R optical regeneration to future all optical systems in which several clients must be manage at the same time [18].

Avoiding the noise and the impairments accumulating during the propagation, all optical regeneration system remain the method used to guarantee the elaboration and regeneration of more clients using only one device. The simultaneous all optical regeneration of a multiple signal system consist in a great challenge in term of transparency and implementation. In this way, a quantum-dot semiconductor optical amplifier devices can be exploit in order to obtain the right results because it permit to obtain a gain inhomogeneous and this kind of approach reduce the inter-channel interaction between the adjacent channels in WDM system.

Chapter 3

Introduction: Principles of an all optical 2R regeneration system

In this section, the main features of non linear effects provided by an optical cable under some conditions, are the fundamental proprieties used to optically regenerate one or more signals. These features will be analyzed in this chapter.

In particular, this work has been based on the use of WDM multiplation, described in the first chapter, and the non linear effect known as Four Wave Mixing (FWM). A WDM all-optical regenerator has been realized; this kind of device is able to amplify and to regenerate one or more signals at the same time, without any format conversion of optical signal since works completely in photonic domain.

In the past, these operations were carried out with the aid of electronic devices while today they became obsolete due the slowly functions. Furthermore, the optical signal that had to be processed by such devices, had to be converted in electronic format, dealt by such devices and successively converted in optical format again. In this case, is referred as O/E/O conversion. Currently, the step through the electronic devices has been limited since they do not have an answer time able to assure an high calculation speed like the one offered by optical fibres. Moreover, using such devices, the problem of the "bottle-neck" comes out; the data, travelling at high speed from the far network, cannot be amplified with the same speed, obtaining in such way, an accumulation of data in the amplifiers proximity and making vain the benefits brought by the optical fibre. The project of this thesis was carried out in the ISCOM laboratories avoids the passage through electronic devices, realizing the necessary operations for data transmission on the network, in an all optical way. Various methods exist to amplify and to reshape the optical signal: through optical Semiconductor Optical Amplifier (SOA) or Erbium Doped Fibre Amplifiers (EDFA), for example, or using, for the reshaping side, non linear effects such as FWM or MFWM.

The amplification and the optical regeneration, leave the quality of the data unchanged and increase the transmission distance, the temporal transparency, the “scalability” and the flexibility of the optical networks. Moreover, the bit rate and the transmission power increment do not alter the projected regeneration system.

3.1 Four Wave Mixing (FWM) non linear effect: theory

Usually, the refractive index of silica, which the optical fibres are mainly constituted, does not depend on the waves intensity that propagates through the fibre itself [3]. However, for high field intensity, the refractive index can be much more sensitive to the variations of such intensity. Non linearity offered by some types of optical fibre, can induce a degradation of the transmitted signals through these fibres; the most important non linear phenomenon is Four Wave Mixing (FWM) which creates replicas of the transmitted signal, when it propagates with another optical signal through the fibre, falling at new different wavelengths respect to the original one. These new replicas can be placed in the same place previously occupied by other optical client signals flowing along the fibre inducing interferences effect or unwanted noise. This type of degradation happens when more optical channels, like in case of WDM system, are transmitted at the same time over the optical fiber.

By choosing in the right way the geometrical, dimensional and optical characteristics, the degradation induced by the non linear effects can be reduced.

The optical fibre G.652, for example, that is the most common fibre used in the 80% of cases, is the most diffused and introduces a relatively high chromatic dispersion in the range of wavelengths between 1530 nm and 1565 nm. The optical fibre G.655, instead, introduces a chromatic dispersion sufficiently elevated in the same band that concurs to limit the non linear effects but in such way not to make complex the actions of compensation. As it has been seen, therefore, the presence of non linear effects, can induce interferences between adjacent channels which propagate at the same time. Such interference is due to the interaction among more waves that travel together, generating new components at new wavelengths.

The main non-linear effect is the optical Kerr effect according to which the presence of strongly intensity signals induces a change of the fibre refractive index:

$$n = n_0 + \overline{n_2} I \qquad [1]$$

where I is the intensity of the field, n_0 is the linear refractive index and n_2 represents the non linear refractive index.

The beat, composed by the interaction between a signal characterized by an high intensity, called pump, and a client signal both transmitted on the optical fibre, generates a modulation of the optical refractive index medium.

The FWM consists in the generation of new components at new wavelengths called replicas or sidebands through the interaction of client signal and one pump signal (high intensity signal); such process is used to obtain a frequency translation, or wavelength conversion, and to obtain the signal regeneration [19].

The wavelength conversion, always obtained with the non linear phenomena, is particularly useful when more transmitted signals are forwarded in a network that uses those particular wavelengths or that it does not support such wavelengths [20] [21] [22].

If, at the input of a non linear optical fibre with particular performances, two waves with angular frequencies ω_1 and ω_2 respectively travel through the fibre, two first degree sidebands with angular frequencies are generated. The new frequency is equal to:

$$\omega_3 = 2\omega_1 - \omega_2 \qquad \text{and} \qquad \omega_4 = 2\omega_2 - \omega_1 . \qquad [2]$$

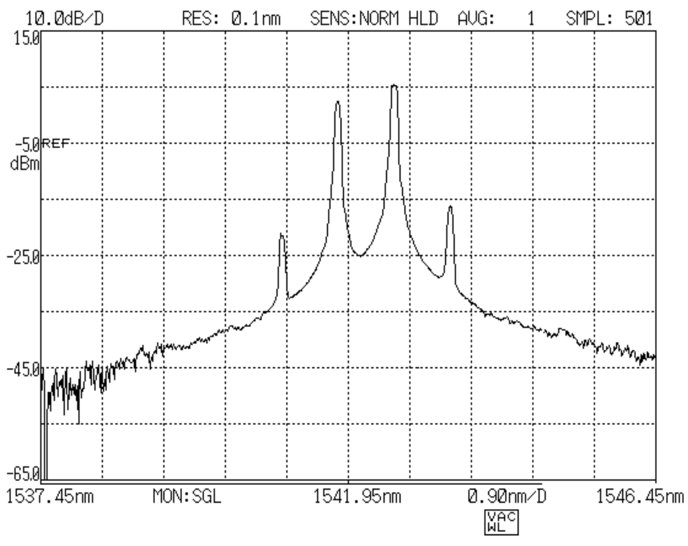


Figure 3.1 – Generation of new replicas due to the FWM non linear effect.

If non linear phenomenon is particularly efficient, as a result of a strong pump "depletion", furthers sidebands of higher degree can be generated [23]. The replicas of second degree introduce angular frequencies equal to the following formula:

$$\omega_5 = 2\omega_3 - \omega_1 \qquad \text{and} \qquad \omega_6 = 2\omega_4 - \omega_3 . \qquad [3]$$

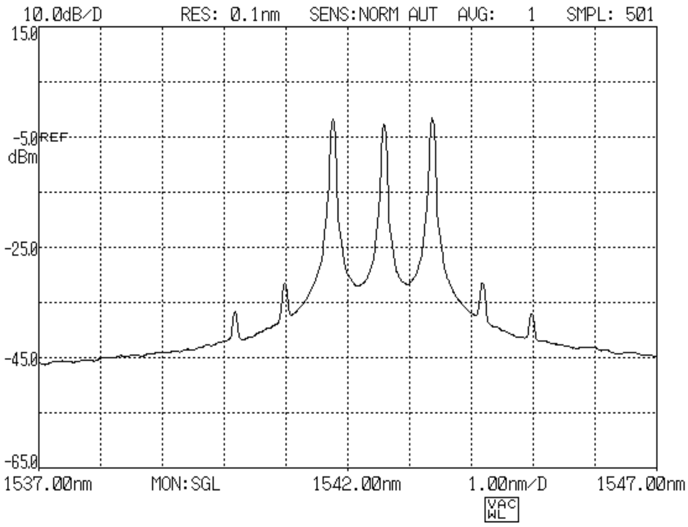


Figure 3.2 – Generation of advanced degree sidebands.

Therefore, the FWM phenomenon transfers energy from a strong pump to new replicas which will appear to the border of the strong intensity pump [24] [25]. All the sidebands generated will be found at symmetrical distance regarding to signal-pump detuning ω_p. To study the FWM phenomenon, let start from the Shrödinger non linear equation. Considering the total electric field $E(z,t)$ at the central frequency ω_0, average between ω_s (signal frequency) and ω_p (signal pump frequency), it results that:

$$i\frac{\partial E}{\partial z}+L(t)+\gamma|\mathrm{E}|^2 E+i\alpha E=0 \qquad [4]$$

with:

$$L(t)=i\beta^{(1)}\frac{\partial E}{\partial t}-\frac{\beta^{(2)}}{2}\frac{\partial^2 E}{\partial t^2}+\frac{i}{6}\beta^{(3)}\frac{\partial^3 E}{\partial t^3} \qquad [5]$$

where γ is the non linear coefficient, α is the loss coefficient and L(t) is an operator which derives from the Taylor series.

The previous formula describes the propagation of signals in an optical fibre considering the linear and non linear effects due to the Kerr effect. Considering the initials conditions to resolve our equations it results that:

$$E_0(t)=E_0(0,t)=A_p e^{-i\frac{\Omega}{2}t}+A_s e^{+i\frac{\Omega}{2}t} \qquad [6]$$

In this way, the input signal to the fibre with power of $P_s=A_s^2$ and frequency ω_s and signal pump with power of $P_p=A_p^2$ to a frequency of ω_p, are considered.

Moreover, the condition $\Omega=\omega_p-\omega_s<0$ must be satisfied, that is the spectral distance between the two considered waves. Such condition must be much minor than ω_0.

Our purpose is to make FWM effect much more efficient and it happens for high pump power at the fibre input.

At this point, by neglecting the losses ($\alpha=0$) we have that the formula [4] can be simplified as:

$$i\frac{\partial E}{\partial t}+\gamma|E|^2 E=0 \qquad [7]$$

The incoming field in the optical fibre can be expressed with the following formula:

$$E_0(t) = 2A_m \cos\left(\frac{\Omega}{2}t\right) + 2i\delta A \sin\left(\frac{\Omega}{2}t\right) \qquad [8]$$

where the values A_m and δA are:

$$A_m = \frac{1}{2}\left(A_s + A_p\right) \qquad \text{and} \qquad \delta A = A_m = \frac{1}{2}\left(A_s + A_p\right) \qquad [9]$$

These formulas concur to express the field as:

$$E(z,t) = E_0\,(t)\, e^{i\gamma z P_{tot}}\, e^{i2\gamma z\sqrt{P_s P_p}\cos(\Omega_s t)} \qquad [10]$$

where P_{tot} is the sum of the pump and signal powers. Therefore, $P_{tot} = P_s + P_p$ indicates the total power at the fibre input and that, in our simplified conditions (null losses), it results to be also the outgoing power from the fibre. At this point, considered that:

$$e^{ix\cos(\gamma)} = \sum_{n=-\infty}^{+\infty} J_n\,(x) e^{-in\left(\gamma\frac{\pi}{2}\right)} \qquad [11]$$

the spectral components of modulated signal can be found from the expression in Bessel series and from the subsequent Fourier transform [26]. In this way, it is found an infinite number of harmonicas at the $\omega_0 \pm n\frac{\Omega}{2}$ frequencies where the components amplitude is proportional to the Bessel functions of the first type. In the particular case in which $P_s \approx P_p$, the power of the different harmonic of FWM is given by:

$$P_n(z) = \left[J_{\frac{n-1}{2}}(\gamma z P_{tot}) \right]^2 + \left[J_{\frac{n+1}{2}}(\gamma z P_{tot}) \right]^2 \qquad [12]$$

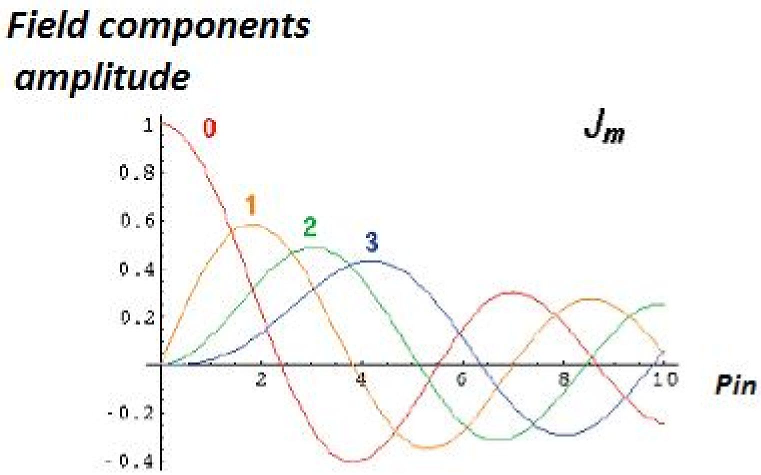


Figure 3.3 – Bessel function behavior.

The Bessel functions of higher order present a null derived in zero and a saturation around a given input power. This carriage is the intentional behaviour to be able to obtain an optical regeneration of signal. If the pump power and power signal do not have the same value, the equation that regulates the power of the harmonicas becomes:

$$P_n(z) = P_s \left[J_{\frac{n-1}{2}}\left(2\gamma z \sqrt{P_s P_p}\right) \right]^2 + P_s \left[J_{\frac{n+1}{2}}\left(2\gamma z \sqrt{P_s P_p}\right) \right]^2 \qquad [13]$$

The pump power behaviour begin to decay when the input signal increases and successively it oscillates around to medium value.

Furthermore the phenomenon called Brillouin scattering has been analyzed; it reveals itself inside the optical fibres generating a Stokes wave which degrades the transmitted signal energy. Such process is evident exceeding a particular value called Brillouin threshold. Using a continuous signal pump, the scattering Brillouin phenomenon can occur starting from few mW as power value.

The field present in input of optical fibre, generated by the signal pump, creates a wave that modulates the refractive index of the fibre on which it travels. A way to increase the threshold value is, therefore, to modulate in phase the optical signal transmitted.

Increasing the pump power to obtain an high FWM efficiency, which concurs to obtain a good optical regeneration, a fraction of power gradually is transmitted in the backward propagation direction; this is caused by the Brillouin scattering. To limit its effects, a phase modulation of the transmitted signal in fibre has been carried out.

3.2 All optical 2R regenerator system description.

The experimental set-up's realized in laboratories have been composed using non linear effect know as FWM and using, at the same time, WDM multiplation, with different configurations in term of channels travelling along the same optical medium.

Before analyzing in details the work carried out, it is useful to understand which results produces the interaction between the strongly intensity pump and the signal transmitted along the fibre. An optical 2R regenerator is a device able to re-amplify and re-generate an optical transmitted signal. It is possible to take advantage of the replicas transfer functions, able to compress the noise, induced by the interaction between pump and signal.

Considering a first experimental set-up [28], in Fig. 3.4, it can be observed how the FWM effect it is essentially due to the interaction between a pump and the signal which must be regenerate.

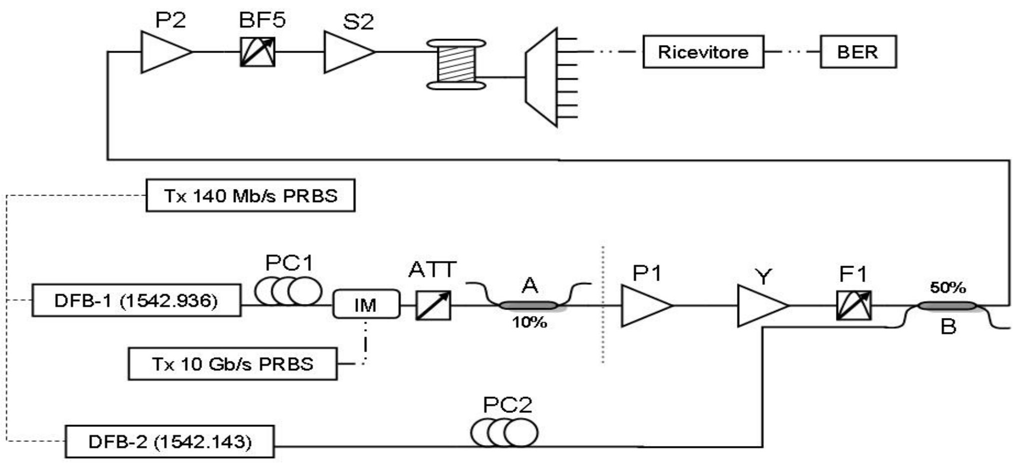


Figure 3.4 – Experimental Set-Up.

The operational feature of this set-up is based on a non linear phenomenon caused by the beat between the pump indicated with p and a transmitted signal indicated with s; the $E_1 = s + p$ will have a beat at a frequency equal to the frequency difference of the two component signals. This beat will modulate the intensity of the E_1 field and, due to the optical Kerr effect, also the refractive index of the fibre. This modulation will modulate E_1 in phase generating spectral replicas able to regenerate the signal and to operate wavelength conversion. The transfer functions of the replicas, follow the Bessel functions behaviour, and can be exploited to obtain the signal regeneration. The non linear phenomenon will be obtained sending signals (s and p) at the input of the DS fibre and, therefore, the generated replicas will follow the same modulation of the signal s which has been transmitted [17].

The central frequency of the field (E_1) has been chosen close to the zero dispersion of the fibre (about 1539 nm) to maximize, for this particular type of optical fibre, the non linear phenomenon of Multi Wave Mixing and therefore, to cause the generation of a high number of replicas.

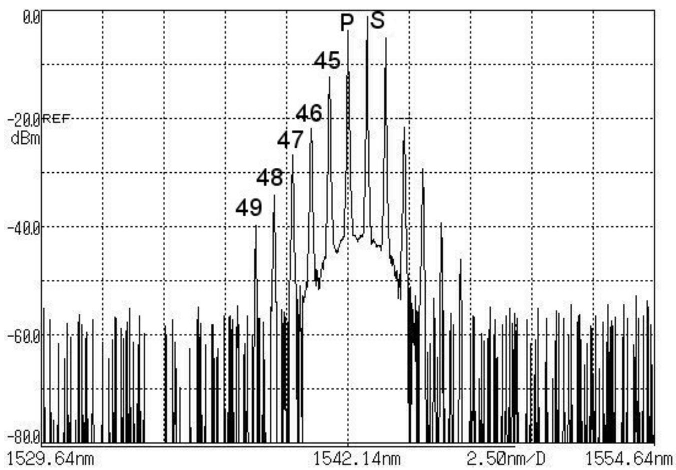


Figure 3.5 – Replicas generated by FWM non linear effect.

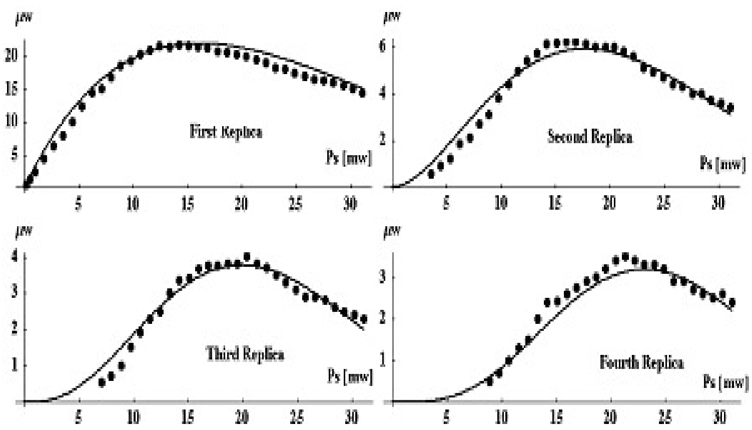


Figure 3.6 – Replicas transfer function.

Fig. 3.6 shows that to each replica corresponds a particular transfer function able to compress the noise present on the signal [29].

In particular, the transfer function of the first order replica grows linearly and, therefore, it is not able to compress the noise on the low values (zero level) of the signal but it is useful to compress the noise present on the marks. On the contrary, the characteristics of a higher order replicas, are able to reduce the noise which is introduced on the zero value and on the high level of the signal (Fig. 3.6 last figure right side).

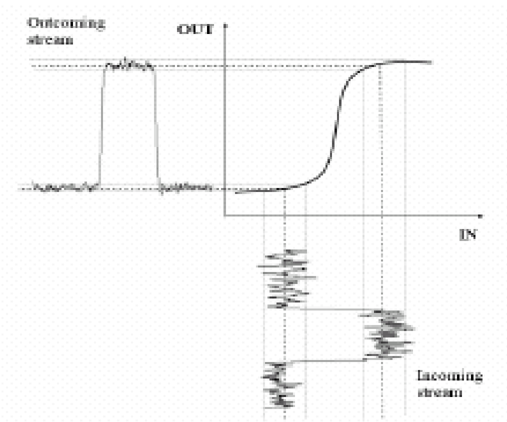


Figure 3.4 – Ideal transfer function – Regeneration action.

3.3 *Wavelength conversion adopting all optical 2R regenerator system.*

Exploiting FWM non linear effect also a wavelength conversion can be reached. The presence of several replicas in output of the 2R regenerated system, permit to filter the side-band having the desiderated wavelength in order to obtain a new signal, placed in a different spectral position, but having the same starting modulation format.

This is useful if a generic client signal with particular wavelength want to accede in a network which does not permit the use of that particular optical wavelength. Thus, changing the value of wavelength signal but leaving the modulation format unchanged, the client can accede to the new network which does not allow the use of the starting wavelength.

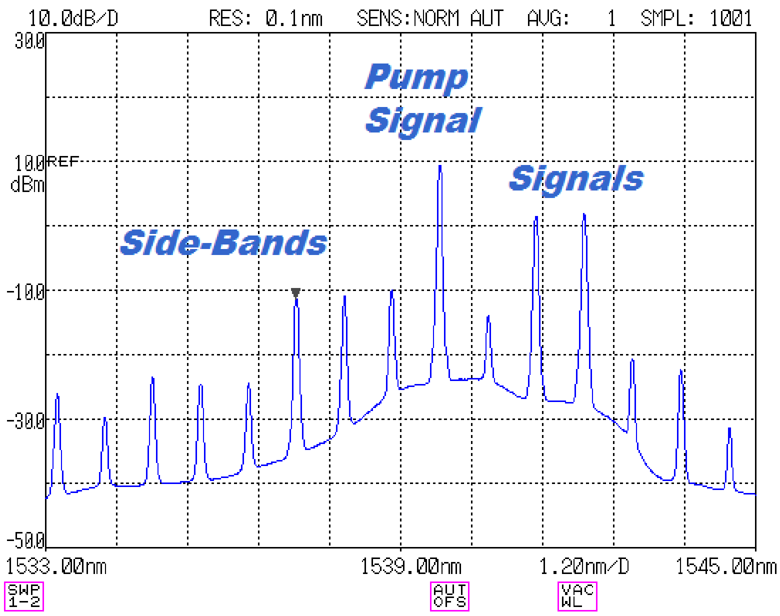


Figure 3.5 – Example of wavelength conversion.

3.4 Remote 2R regeneration.

A further step in term of signal regeneration consist in remote reshaping concept. This new line of research, permit to use all passive components located in a Remote Node (RN) including the erbium doped fiber pumped with Raman pumps (pumped in remotely way) placed in Central Office (CO).

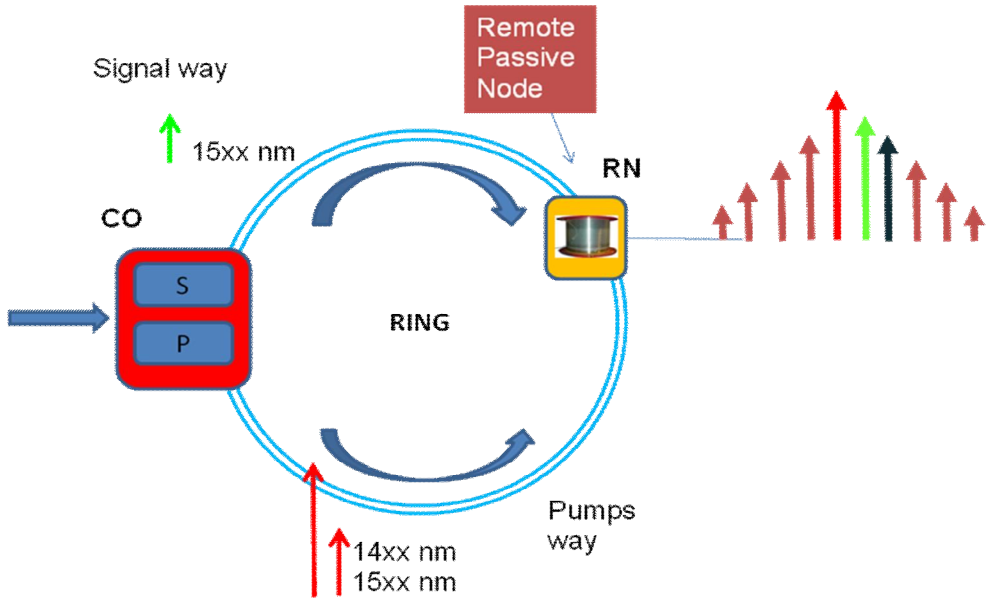


Figure 3.6 – Remote regeneration concept.

The figure above, depict a CO which include modulated signal and pump section, an optical ring in which the pump is running in one way, the signals are running in the opposite way (counter propagation configuration) and a remote node with all passive components which add and drop the wavelength for the several end users.

At this point the 2R regeneration resides inside the remote node in which is present the non linear optical fiber useful to generate the FWM effect in order to reach the signal regeneration. The signal which must be reshaped and pumped to generate the FWM effect are sent from the central office in remotely way. Thus in output from the remote node will be present a comb function which will be employed to select a right order of replica able to regenerate the client signal.

3.5 Wavelength conversion and optical regeneration via PCF photonic crystal fibre.

Using a Photonic Crystal Fibre PCF it is possible to obtain both wavelength conversion and optical regeneration. A PCF are characterized by a configuration of air-micro tubes which composes all optical sample. These new structures shows unusually characteristic of propagation, for example the propagation of an optical signal along the whole spectral region from 400 nm up to 2000 nm. Besides, the micro tubes can be filled with gas or another material in order to obtain several effects. In this way, some optical parameters like chromatic dispersion or polarization dispersion, very useful for optical high bit rate systems, are controlled. Another particular effect provided form PCF is that, optimizing one parameter, other parameters do not changed, the contrary happens for standard optical cables.

This particular optical photonic crystal fibre don not reach very long distance (up to 100m), thus it is not applied in telecommunication field, but rather then in photonic field and in optical integrated systems obtaining compact and small size devices.

Exploiting the proper of PCF it is possible to reach the optical wavelength conversion using a very small sample of optical fiber (for example sample 50m long) but also the optical regeneration, obtaining some replicas useful for the optical signals management. Small size of optical media (like PCF) permit to realize devices with good performances in term of conversion efficiency and permit to realize devices with compact dimensions.

In next figures are represented some samples of PCF able to provide wavelength conversion using only short optical fiber.

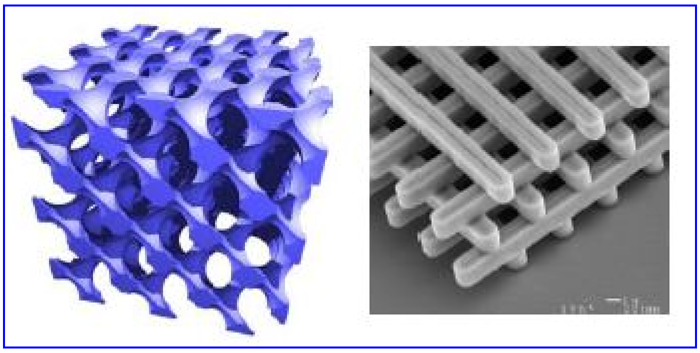


Figure 3.7 – Internal structure of Photonic Crystal Fiber.

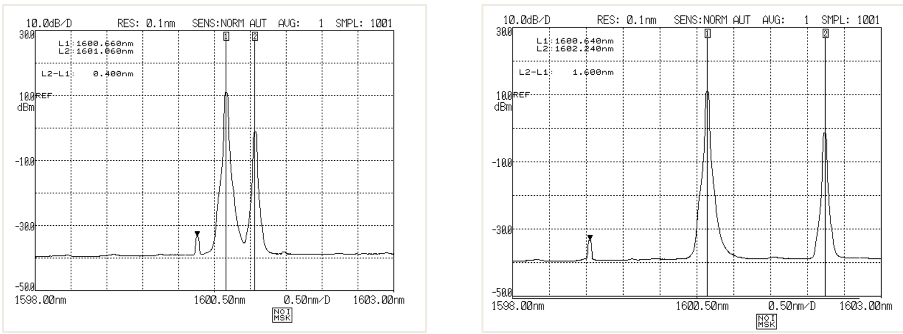


Figure 3.8 – Generation of replica using very short optical cable 50 m long.

Chapter 4

Introduction: Measurements and Experimental Set-Up. Obtained results

In this section, several set-up's, realized in ISCOM lab, will be analyzed. These set-up's are based on different configurations of 2R regeneration system in order to obtain different results about the signals management and reshaping. Particular attention has been dedicated for multi-wavelength DWDM systems able to regenerate more client channels at the same time projecting the systems towards a real DWDM scenario.

Moreover, several experiments have been done achieving also an optical experimental cable placed between Rome and Pomezia (50 and 100 Km) in order to test the behaviour of the systems when the signals are propagated in a real deployed optical cable.

Back to back and propagation tests have been carried out in order to underline the difference, in term of system performances, between both configurations.

4.1 Single channel Set-Up

The principle of 2R regenerator system is depicted in following picture; a signal which present noise and low power, is amplified by an optical amplifier (EDFA or SOA) and this composes the 1R step. 2R step consist to reshape the signal, the noise present on the mark level and zero level must be removed. The last step, 3R, consist in signal Re-Timing but this part is not reported in this work.

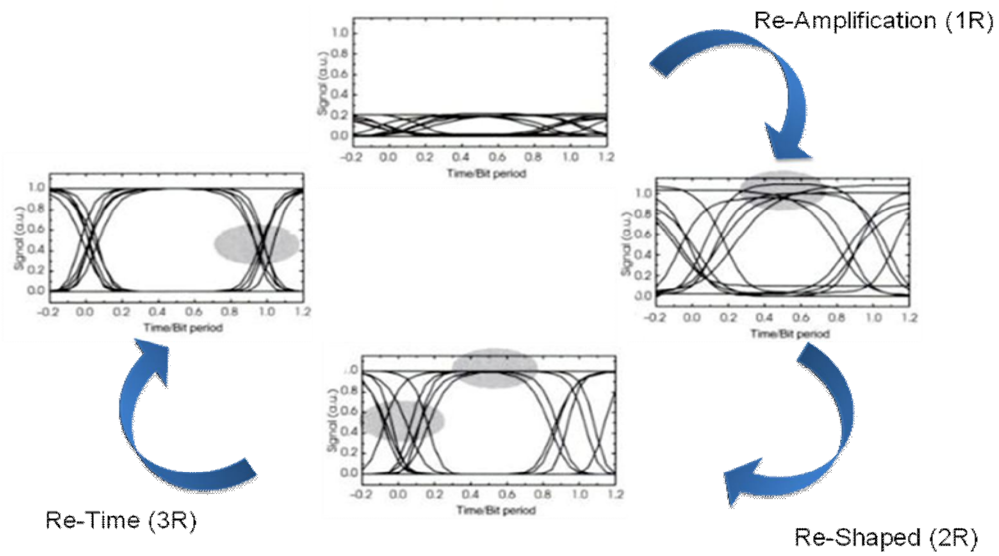


Figure 4.1 – Steps of all optical 2R regeneration system.

Only one channel is used for this test together with the signal pump. Part of pump power, beating with client signal, is transferred at new pulses called replicas which are able to regenerate the client signal. As shown in fig. 4.2 it is possible to note that if a signal coupled with pump signal is sent inside a particular non linear optical fiber, exploiting the FWM effect, in output will be present the same signals (client and pump signal) with the replicas placed at particular new wavelengths [30].

The obtained replicas presents a transfer function similar to the Bessel function which permit to compress the noise present at low and high level of the client signal selecting the right order of the generated replicas.

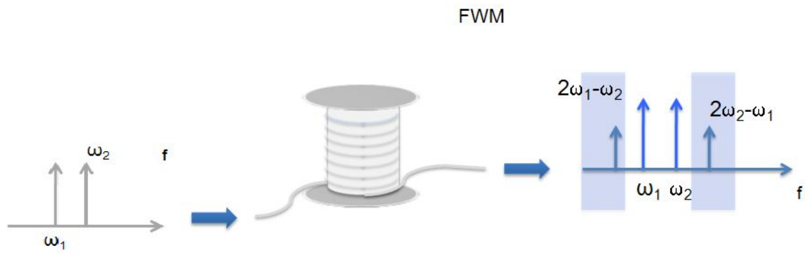


Figure 4.2 – FWM effect and generated replicas.

Moving the working point of the system it is possible obtain the reshaped signal as is shown in fig. 4.3. Different transfer function using different pump power are presented in figure and it is possible to see that if the working point is placed on top level of the transfer function, the starting noisy signal results regenerated and present low noise at the mark level. On the contrary, if the working point is placed at different point of the transfer function, the same signal present much noise.

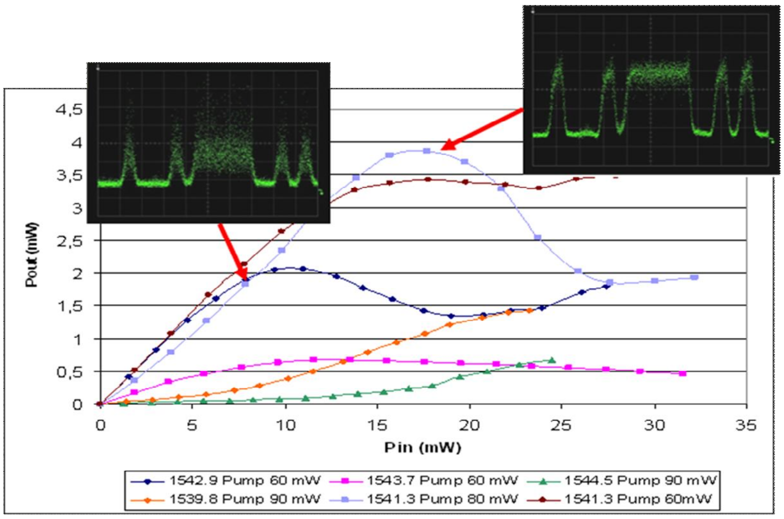


Figure 4.3 – System working point – Transfer function.

4.2 Multi-channel regeneration system

A first step for multichannel system consist to add more channels (in this case two channels) operating at the same time. In this way using only one pump signal for both client signals it is possible obtain the all optical regeneration using only one system. Thus the following set-up was carried out in the labs. This system (see fig. 4.4) is composed by two DFB laser sources placed respectively at 1542.14 nm and 1542.93 nm with power equal to +5dBm for each channel, two polarization controls (PC) and after a 50% coupler, was placed an external Mach-Zehnder modulator in order to apply a modulation format at 10 Gbit/s PRBS sequence to both client signals. After an amplifier and a demultiplexer was placed two delay line τ_1 and τ_2 to decorrelate the signals and then were amplified by an EDFA to reach the right power value to induce the FWM inside the non linear optical fiber. For the pump way was used an ECL laser source placed at 1539,82 nm and power approximately equal to +10dBm, an external phase modulator in order to limit the Brillouin effect and EDFA amplifiers to obtain the adequate pump power value inside the optical fiber to generate the non linear effect.

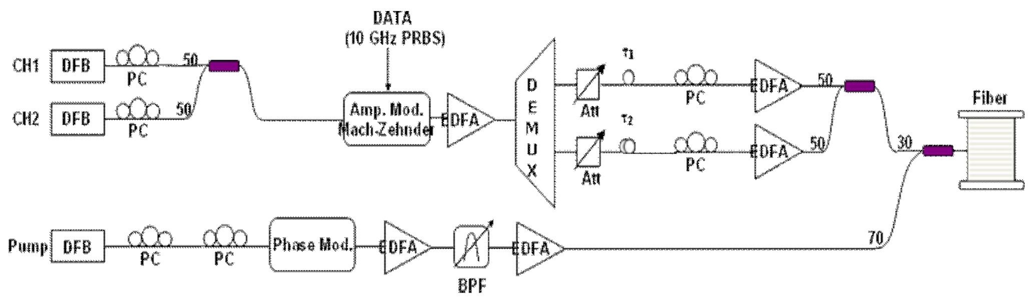


Figure 4.4 – Experimental Set-Up.

The results are presented in fig. 4.5 and it is possible to note that when both client signals are switch on at the same time, the obtained replicas result distorted (see fig 4.5 right) because the other orders of the generated replicas are overlapped and placed at the same wavelength of the replicas generated from the client signals.

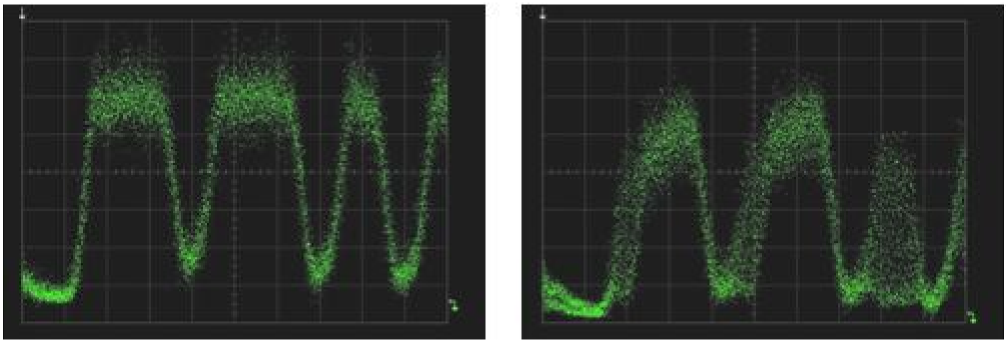


Figure 4.5 – Replicas interference between two channels.

Thus, this solution was avoided and another system configuration was employed in lab in order to obtain a solution without any interference.

4.2.1 Different state of polarization system (SoP)

In order to avoid the problem presented previously, a different set-up configuration has been employed. In fig. 4.6 is presented a new system which exploit a polarization beam splitters (PBS) in order to guarantee the different state of polarization of the two client signals [31]. In this way, adding this device, the components of the signals are maintained orthogonal respectively. Thus the pump signal can be divided between the two orthogonal signals optimising the one channel or the other one at the same time in term of replicas generation.

The employed parameters are the same with respect previous set-up but now is adopted the PBS which assure the orthogonal state of polarization of the signals. This fact permit to control the pump degree that must be employed to obtain a respectable result in term of noise compression and signals regenerations.

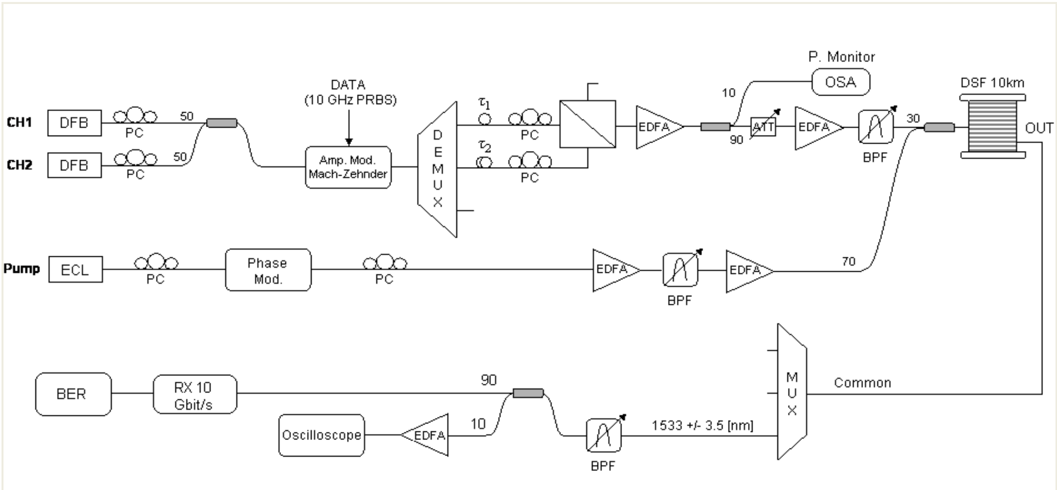


Figure 4.6 – Experimental Set-Up.

As result, in output from the system is present the pump and the two client signals. Their interaction produce new components placed at different wavelengths like a comb function. In particular, moving the pump power control in order to optimize the first replica generated from channel one, is emphasized the regeneration of the first channel also in case the presence of channel two switched on. In this way, with this new configuration, is not present the interference between the replicas because now the two signal components are orthogonal respectively. The same thing happens when the pump power is optimized for the generation of the replica from channel two when channel one is switched on. Also in this case the result show (see figure 4.7) that is present the replica generated from channel two in presence of channel one switched on. The third case depicted in fig 4.7 show the case when both channels are switched on and the pump power is optimizing for the generation replicas from the two channels; at this point the system is able to regenerate the noisy signals (ch1 and ch2) at the same time without any interference between the channels.

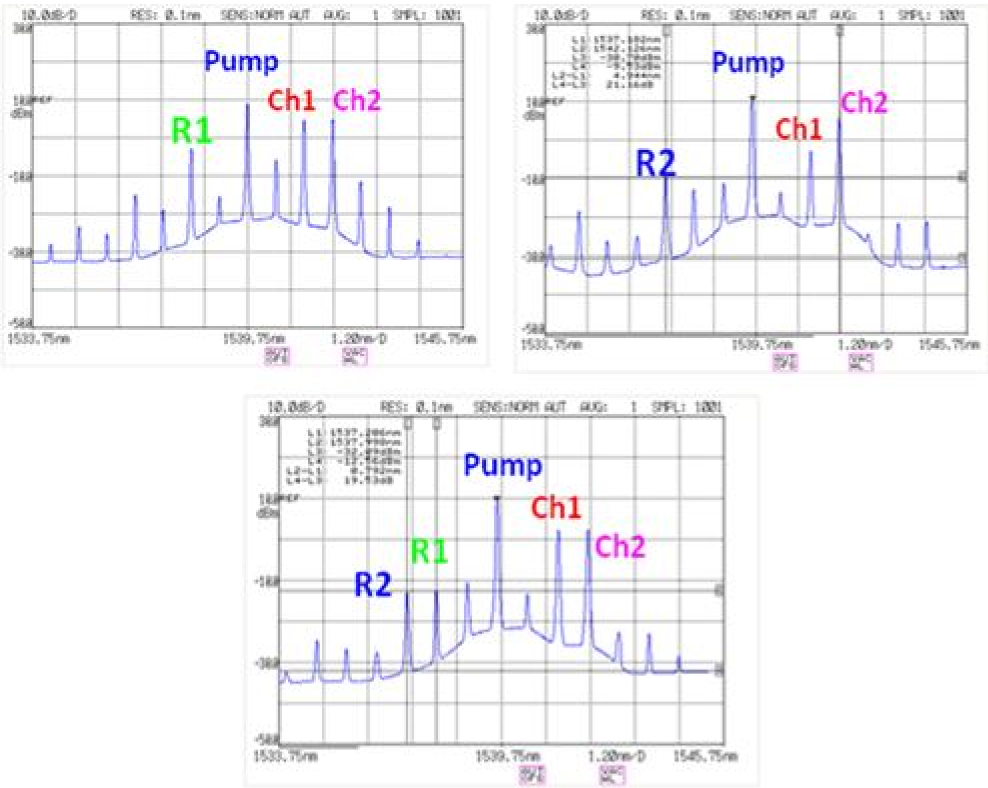


Figure 4.7 – Replicas generation results.

Following picture (fig 4.8) show the modulated signals results; is present the noisy signal applied in input of the system, then is shown the output regenerated signal when the second channel in switch-off. Thus, also the second channel was switched-on (in this case this channel is intended how interference channel) but the result is not affected from the channels interaction. The same thing has been performed for the second channel using the first one as interference channel.

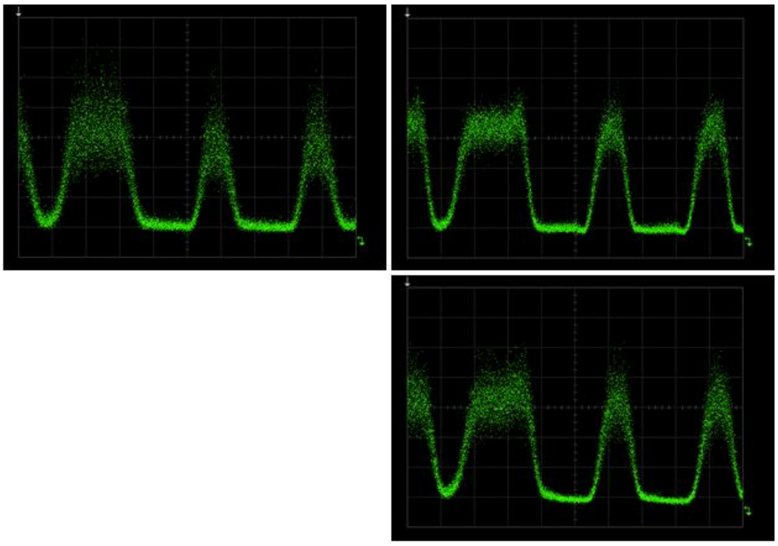


Figure 4.8 – Experimental results: Noisy channel 1 signal, regenerated signal on the right (above) and regenerated signal in presence of the interference channel (Channel 2).

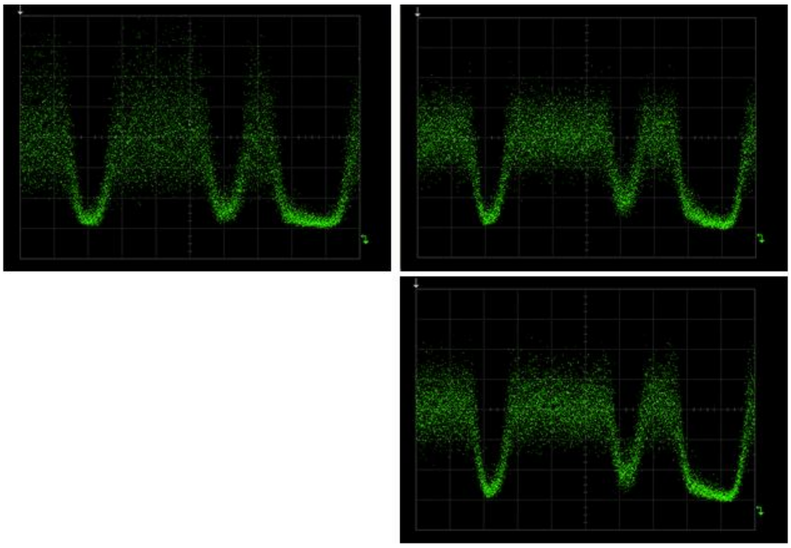
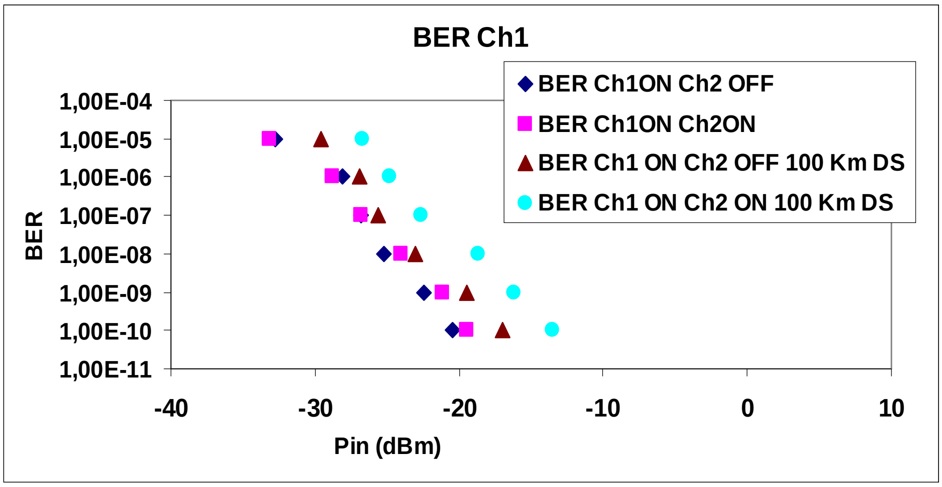


Figure 4.9 – Experimental results: Noisy channel 2 signal, regenerated signal on the right (above) and regenerated signal in presence of the interference channel (Channel 1).

For the second channel, the regeneration system performance is not efficient like the result offered by the channel one because the second channel is farer, in term of wavelength, from the pump action. Following are reported the BER (Bit Error Rate) measurements which confirm that the system is able to reach the error free condition also in case the interference channel presence. Is reported also the propagation condition over 100 km of optical cable deployed between Rome and Pomezia; the experiments have been realized with 100 km long DS optical fiber, 100 km long NZD optical fiber and 100 km long SMR optical fiber (NZD and SMR not reported in figure).



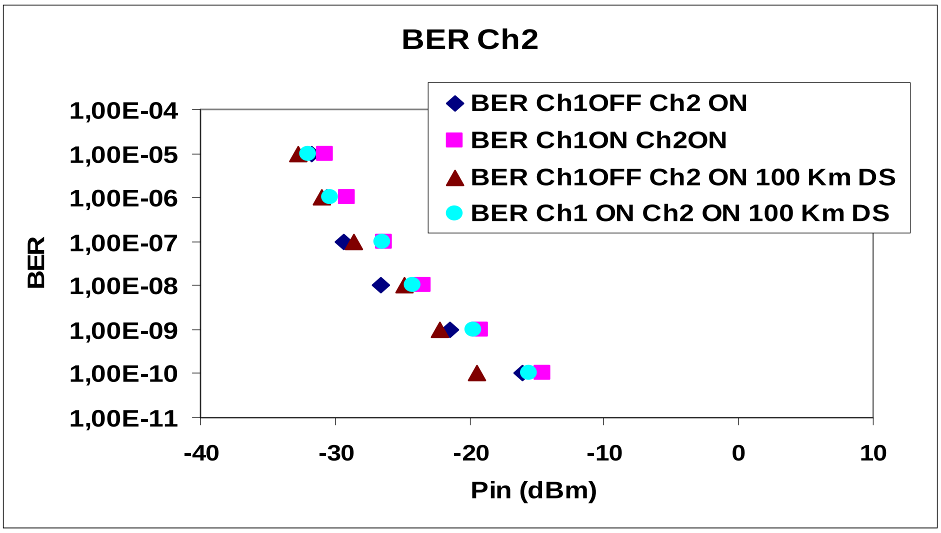


Figure 4.10 – BER measurements.

Another kind of measurement and system configuration is depicted follow. The set-up has been modified removing the second channel. In this way only first channel is applied at the regeneration system [32]. Has been used the PBS device in order to guarantee the different state of polarization of the first client signal placed at 1542.14 nm using a power of +5dBm. Thus, after the external Mac-Zehnder modulator using the same modulation mentioned previously, the polarization beam splitter offer two output composed from the two polarization components of the first channel orthogonally respectively. In this case, the first component go through in optical fiber from input to output, and the second one go through form the output to input at the same time, offering a counter propagation configuration. The pump way has been divided in two equal 50% parts (approximately +8dBm for each path) in order to better distribute the pump power at the two components moving the attenuators present in the two paths of the pump way. The set-up is reported here:

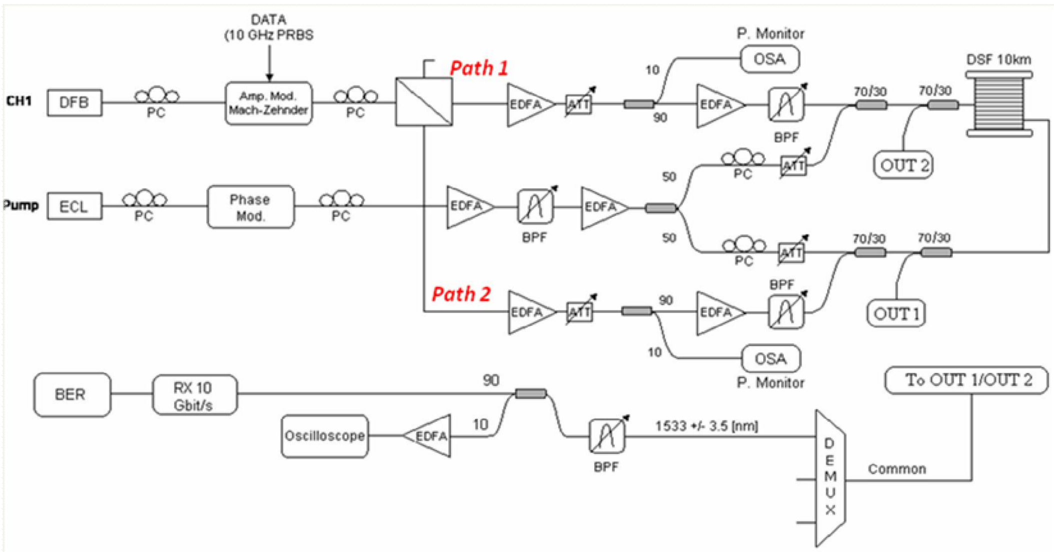


Figure 4.11 – Experimental Set-Up.

At this point, using only one channel it is possible to have two different paths composed from the orthogonal state of polarization of the client signal. The experimental results show that when first path is switch on and the second path is maintained off the system is able to regenerate the noise present at the mark level of the signal. Switching on also the second path, the results do not change, this confirm the capability of the system to work without any interference. It is possible to reach the same effect exploiting the second path when the first path is used as interference channel.

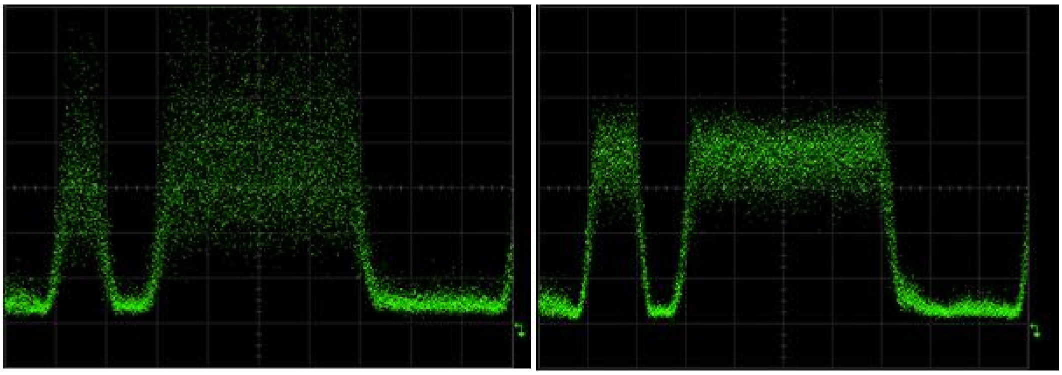


Figure 4.12 – Experimental results – noisy and regenerated signal referred to path1.

As is shown in fig 4.12, on the left side is reported the noise of the signal from the path 1, on the right side there is the regenerated signal and the same result it is possible to obtain when the second path is switched on. Thus, the second path as interference do not disturb the performances of the regenerate system. Moving the degree of the pump value it is possible to improve the regeneration effect in term of BER results reported following. The same results have been obtained for the second path, using the first path as interference channel, but in this configuration it is possible to note that the system performances is a little worse respect the previous result because the path two go through from the output of the non linear optical fiber to its input; this means that the optical fiber show different parameters. Also in this case, the system is able to guarantee the optical regeneration signal confirmed from the BER measurements.

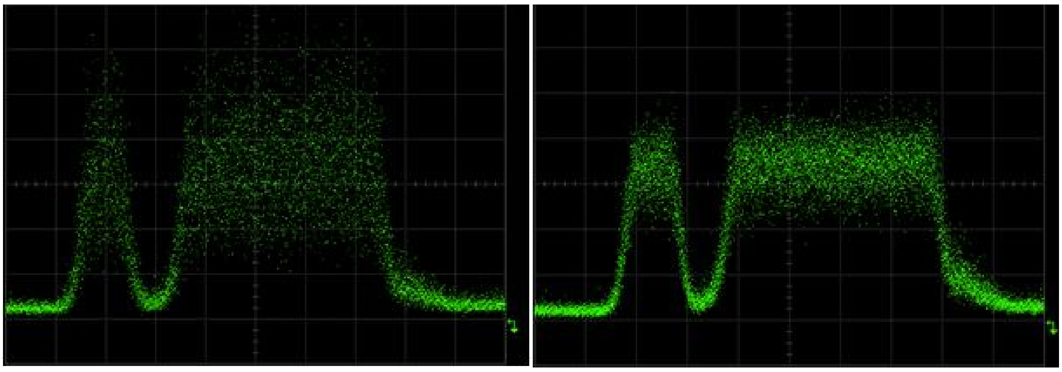


Figure 4.13 – Experimental results – noisy and regenerated signal referred to path2.

Also in this configuration, referring to fig 4.13, on the left side is reported the signal from the path 2 with noise on the mark level, on the right side is present the regenerated signal and if path 1 is switched on, the result is the same; thus also in this counter propagation condition the output signal results reshaped when an interfering channel is present.

Following are reported the BER measurements considering both back to back and propagation condition using, in this case, the experimental optical cable deployed from Rome to Pomezia:

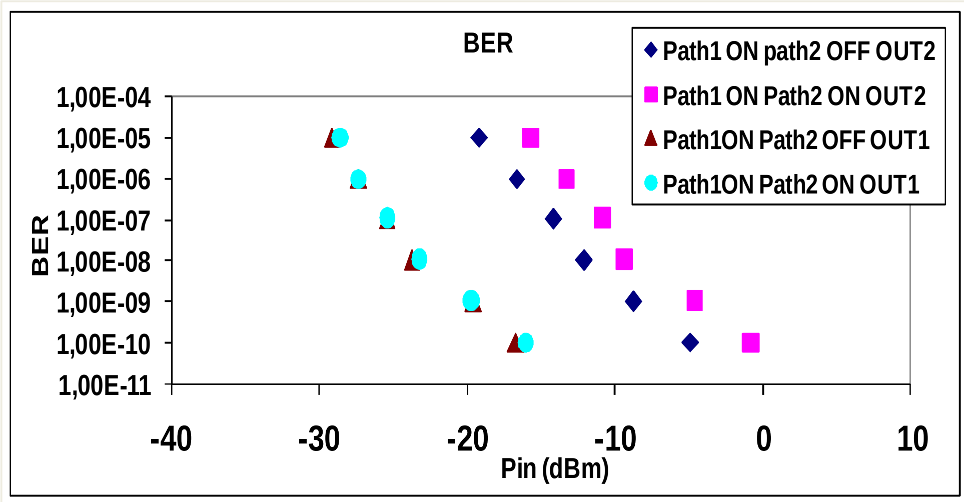


Figure 4.14 – BER measurements related to different configuration.

Paying attention on the fig 4.14, it is possible note that the results related to out1 are the same also in presence of the path interference while a little difference is present for the results related to out2. This is due to a counter propagation condition and from the different optical and geometrical parameters offered from the non linear optical fiber used to obtain FWM non linear effect. Anyway, moving the pump power optimizing the replica generations, the error free condition is reached for both optical paths output.

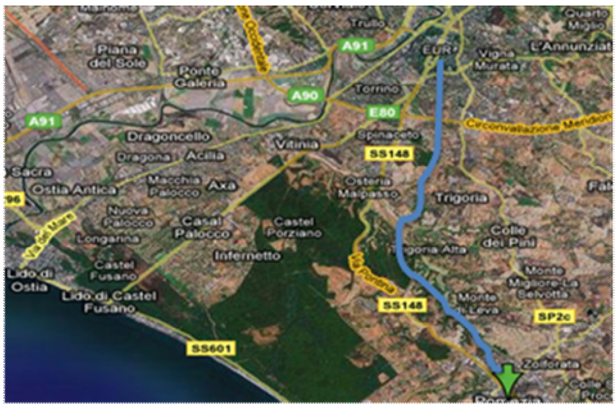


Figure 4.15 – Rome Pomezia optical fiber link.

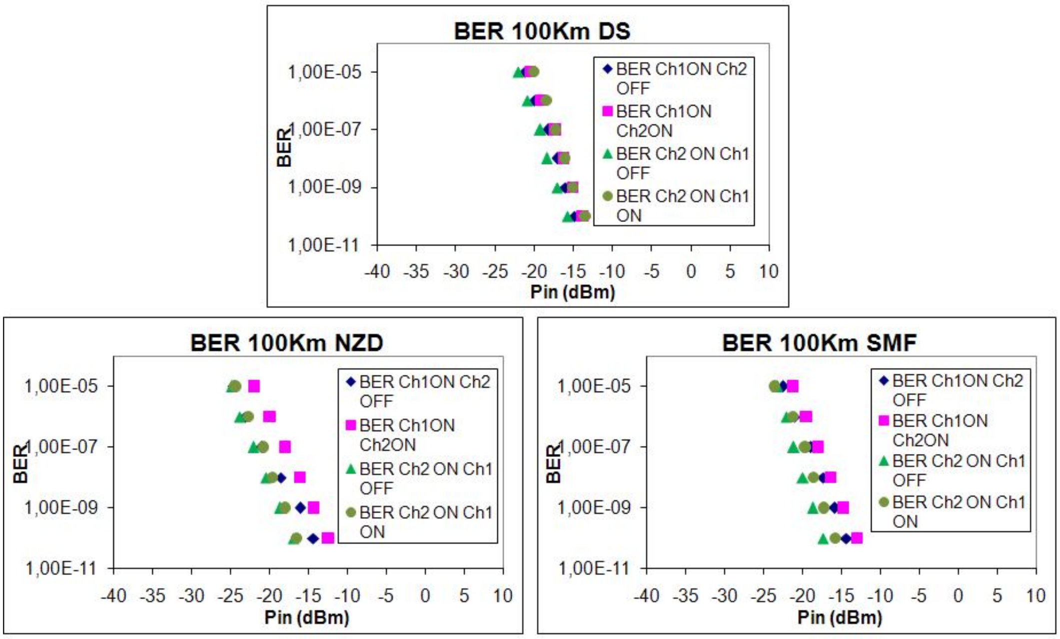


Figure 4.16 – BER measurements related to the propagation case using 100 km DS, NZD and SMF experimental optical cable.

A further step was to add another modulated channel placed at 1542.93 nm with a power set to +5.2dBm in input of the PBS obtaining a system with two channels split in two orthogonal components for each channel having orthogonal states of polarization.

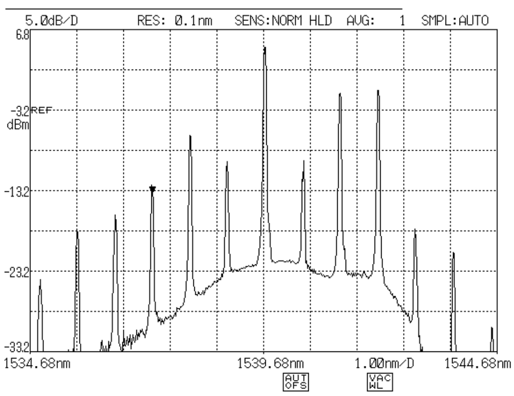


Figure 4.17 – Optical spectrum captured from OSA device related to the two channels with orthogonal state of polarization.

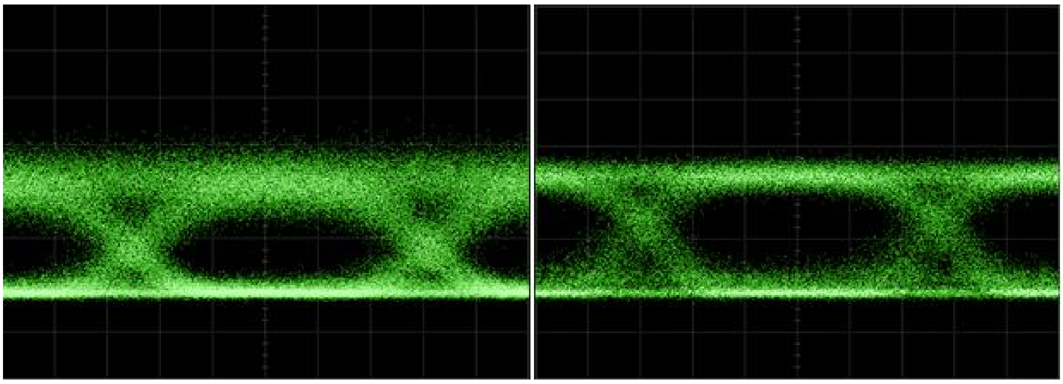


Figure 4.18 – Eye diagram of noise signal and regenerated signal. Measurement related to first channel when the second channel is switch on.

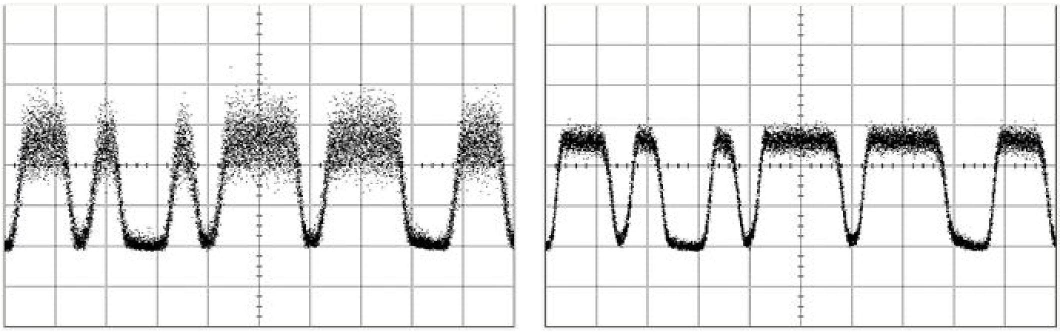


Figure 4.19 – Modulates signal referred to noisy and regenerated signal. Measurement related to first channel when the second channel is switch on. The noise compression is evident on mark level.

Figure 4.18 and 4.19 shows the obtained results; eye diagram and modulated signal related to channel one with noise and with regeneration effect when all orthogonal components are switch on.

4.2.2 Remote all optical 2R Regeneration

The remote all optical regeneration concept is used when the end-users are placed so far from the Central Office (CO) which is able to manage all kind of modulated signals. The principle is that several clients are connected to one or more Remote Node (RN). RN is placed several kilometres far from the CO; the managements and the regeneration parameters are working inside the CO. Thus, in order to provide the regeneration action to the clients, an high values of pumps is needed in order to cover the high distance. For this reason, an high performance Raman pump is located inside the CO. As it can be possible note form the set-up depicted in fig. 4.20, in CO is present the modulated client signal placed at 1542.54 nm with power equal to +8dBm and the local pump with power of +12 dBm at 1542.09 nm. After the CO two fiber coils 10 km and 7 km long respectively, are placed in order to simulate the optical ring that connect the CO with the RN's present in the system (one in our experiment).

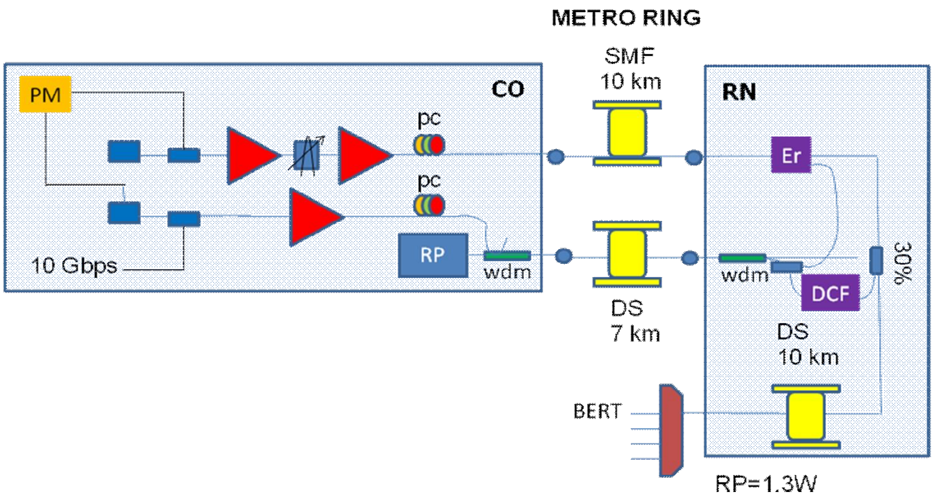


Figure 4.20 – Experimental set-up related to remote regeneration concept.

From the RN side, it is present a sample of optical Erbium doped fiber 2.5 m long. This optical fiber is remotely connected with Raman pump (Starting form the CO with a power equal to +20dBm at 1466 nm). Optical Erbium doped fiber is requested because provide a local signal amplification without any active device; this means that the remote node does not requires local power to provide the optical regeneration making the RN a passive component in the whole system. In RN it is present also the non linear optical fiber useful to generate the FWM non linear effect to provide the regeneration action. At this point the Raman pump is equal to 1.3 W and selecting the different obtained replicas (first order placed at 1541.54 nm with a power of -8dBm and second order placed at 1540.7 nm with a power of -22dBm) it was possible to obtain the eyes diagram here reported:

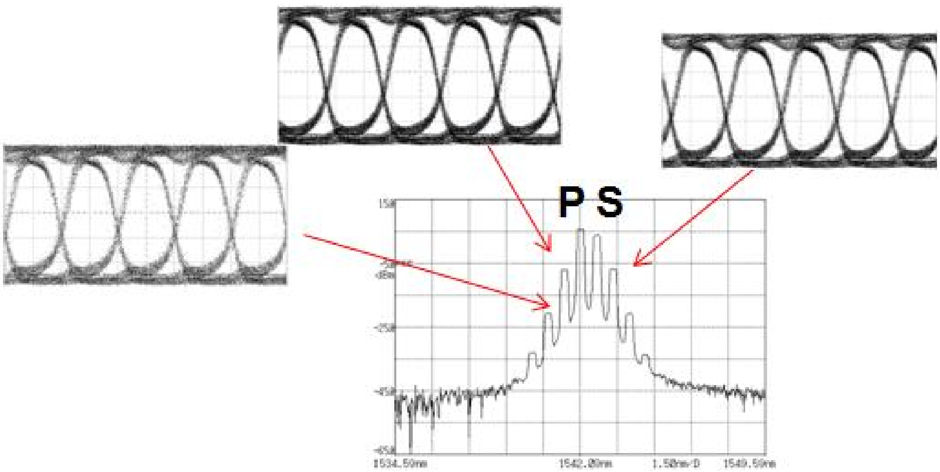


Figure 4.21 – Experimental results - Optical spectrum and eyes diagram related to first and second replica order.

These results shows the capability of the system to regenerate in remote way a modulated signal obtaining different order of replicas and the opened eyes diagram confirm that the performances offered by the system guarantee the remote all optical regeneration.

4.3 PMD Measurement (Polarization Mode Dispersion) in PCFs

This section is devoted to expose the measurements achieved in NIT lab's in Poland related to Photonic Crystal Fiber in order to evaluate the behavior of this kind of optical fiber when itself are under pressure, high temperature and twisting effect. Also the polarization mode dispersion concur to degrade the transmitted signals, thus an accurate analysis of all these phenomenon has been done.

In optical fiber, especially when the core lacks perfect symmetry or internal strains are present, optical birefringence is usually present. This phenomenon can appear or be modified also if the fiber is twisted, bent, squeezed or subjected to temperature changes. Thus, the two orthogonal polarization components of the electro-magnetic field propagating in the optical fiber can separate in time, producing effect known as Polarization Mode Dispersion (PMD), resulting in distortion of the propagating signal. This effect must be avoided especially if the rate of the optical link is high (>10Gb/s) because the inter-symbolic interference becomes significant. For these reasons, it is very interesting to study the PMD behavior when the structure of the optical fiber changes (for example during twist experiments) or the temperature changes (thermal test).

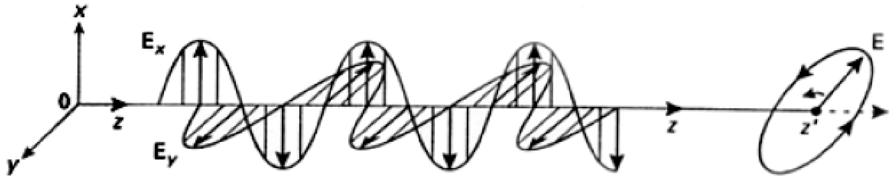


Figure 4.22 – Example of electrical field components (orthogonal and linear polarization) with the elliptical polarization.

For PMD measurements on the PCF samples, it was used a setup composed by a tunable laser source HP 8186F and polarization mode dispersion analyzer Adaptif Photonics A2000 controlled via PC with a Polarization Navigator 3.15 software. PMD analyzer device was connected to tunable laser source via GPIB interface. For each measurement, A2000 compares the SOP of the incoming signal at its input with the SOP of the signal received after the optical sample under test, using the Jones Matrix Eigen analysis (JME) method. In addition to polarization parameters, signal power and device loss are also measured. Setting the test parameters is done with software, including the starting and stop wavelengths, the wavelength step and laser power. For connections to test instruments, PCF samples were fusion spliced to short lengths of standard single-mode fiber terminated with FC/PC connectors. The measurement setup is reported:

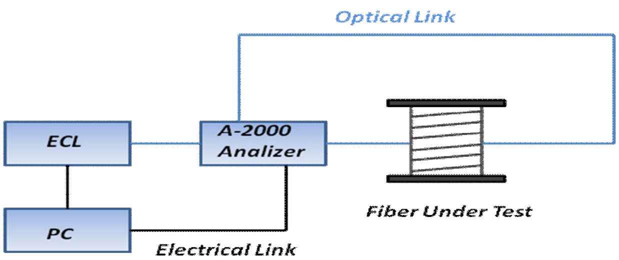


Figure 4.23 – Experimental set-up.

As previously mentioned, the personal computer used for measurements is able to control both the ECL source and the A2000 analyzer. A screenshot of the program is reported following.

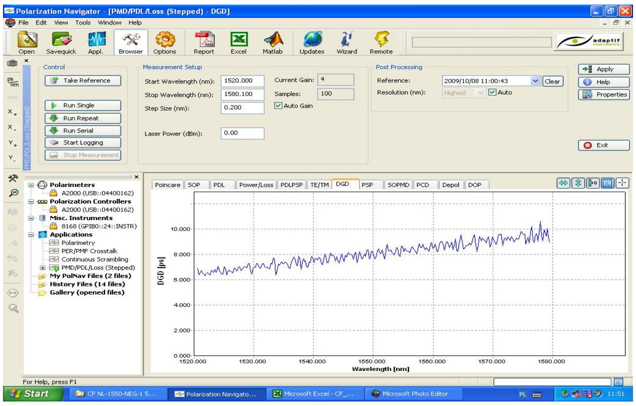


Figure 4.24 – Screenshot of polarization Navigator software working with Adaptif A2000 analyzer.

It was first tested the PMD of two PCFs: Crystal Fiber NL-1550-NEG-1, 50m long and UMCS 070119P2, 1.34m long; the latter has a PANDA-like structure. The first fiber has a triangular core (2.1µm avg. diameter) and 128µm cladding diameter, while the latter has two large holes (3.5µm) parallel to an un-doped core; the diameters of small holes and cladding are 1.3µm and 126µm.

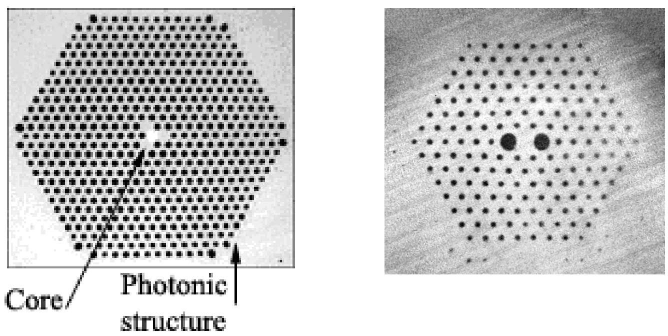


Figure 4.25 – Structures of fibers under test: Crystal Fiber NL-1500-NEG-1 (left) and UMCS 070119P2 (right).

Was measured both samples in two wavelength bands:

- λ =1520-1580 nm the first test, and
- λ =1460-1590 nm for the second test (wideband measurement limited by HP8168F source).

Laser power has been set to 0dBm (1mW) for all measurements. Samples did not exhibit significant polarization mode mixing and their PMD coefficients could be calculated assuming linear length dependence. The following table contains summary of results at room temperature:

Fiber Type	Range (nm)	Step (nm)	PMD (ps)	PMD coefficient (ps/km)	PDL (dB)	Average loss (dB)
UMCS	1520-1580	0.15	3.738	2789.6	0.63	5.56
UMCS	1460-1590	0.15	3.640	2716.4	0.55	5.47
NL 1550	1520-1580	0.15	8.045	160.9	0.66	5.50
NL 1550	1460-1590	0.15	6.791	135.8	0.59	5.95

Table 1 – PMD measurements of PCF NL 1550 NEG-1 and UMCS 070119P2 fibers.

Figures 4.26 and 4.27 show spectral distributions of DGD for both PCF samples. In both cases DGD rises linearly with wavelength, but much stronger in the NL-1550-NEG-1 fiber.

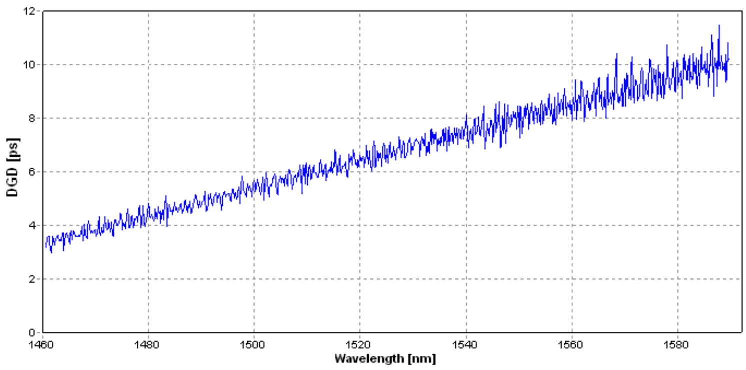


Figure 4.26 – DGD spectrum of Crystal Fiber NL-1500-NEG-1 (L=50 m).

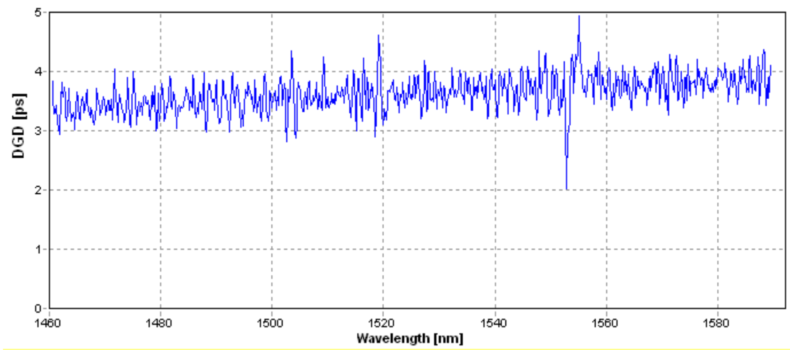


Figure 4.27 – DGD spectrum of UMCS 070119P2 (L= 1.34 m).

It was used the same approach also for testing a longer sample of the same fiber (UMCS 070119P2), being 8.62m long; the wavelength step was reduced to 0.025nm in order to accommodate higher DGD values without loss of tracking polarization states. For this reason, this measurement took much longer time with respect to the previous measurements - about 5 hours. The duration of measurement with setup used at NIT is calculated as follows:

$$T = [(\lambda_2 - \lambda_1) / \Delta\lambda] * 3s$$

where λ_2 is the stop wavelength, λ_1 is the starting wavelength and $\Delta\lambda$ the spectral scanning step. A summary of results is given in table below.

Fiber Type	Range (nm)	Step (nm)	PMD (ps)	PMD coefficient (ps/km)	PDL (dB)	Average loss (dB)
UMCS 070119P2	1460-1590	0.025	24.013	2785.7	2.35	8.71

Table 2 – PMD measurements of UMCS 070119P2 fiber 8.62m long.

4.3.1 *Characterization of temperature dependence of PMD (Thermal Test)*

It was evaluated also the PMD varying the climatic conditions. The PMD of optical fibers can change with temperature, due mostly to mismatched thermal expansion of fiber parts producing temperature-dependent strain or thermal expansion / contraction of fiber coating resulting in fiber being squeezed or bent. If temperature changes, the behavior of fiber changes too and different parameters can determine the behavior of the optical sample. The two components of the EM field that run through the optical fiber, can be affected by temperature-dependent mechanical strains in the core; the net effect is specific for each optical fiber. Also the signal state of polarization changes with temperature.
For all these reasons, was interesting to test PMD variations with temperature. PCF sample was placed inside a climatic chamber, and measurements of polarization parameters and fiber loss were performed at several temperatures. Test setup is shown below:

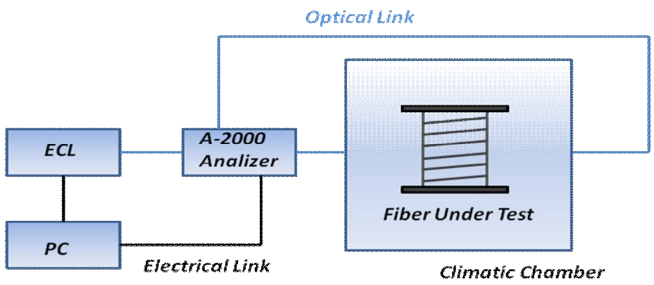


Figure 4.28 – Set-up for the thermal test.

The following table summarizes measurements of PCF NL 1550 NEG-1 sample during thermal test. The temperature was changed from -20°C up to +60°C in 20°C increments. For optical measurements, the wavelength range was 1520÷1590 nm, the step 0.2nm and laser power 0dBm. It was performed re-calibration of the A2000 PMD analyzer, with fiber under test replaced by patchcord.

Results of measurements No.4 and No.5 (table 3) were not satisfactory, since the sample state has not stabilized yet. Another problem was the interference caused by vibrations produced by chamber fan and cooling system, producing SoP variations due to fiber bending. Therefore, most measurements were made with chamber temporarily switched off. We have performed repeated measurements at each temperature until monitored optical parameters have stabilized.

Measurement No.	T [°C]	Climatic chamber state	PMD (ps)	PDL (dB)	Average loss(dB)
1	+20.8	OFF	8.064	0.43	5.15
2	+19.5	ON	8.055	0.41	5.16
3	+19.7	ON	8.066	0.42	5.15
4	-18.5	ON	7.586	0.42	5.22
5	-19.5	ON	7.775	0.44	5.21
6	-20.8	ON	7.839	0.43	5.23
7	-19.8	ON	7.865	0.41	5.21
8	-1.3	ON	8.041	0.44	5.20
9	0.0	ON	8.040	0.41	5.22
10	+19.6	ON	8.036	0.41	5.16
11	+19.7	OFF	8.033	0.41	5.17
12	+21.2	OFF	8.032	0.40	5.16
13	+39.6	ON	7.688	0.40	5.12
14	+39.6	OFF	7.742	0.42	5.12
15	+39.8	ON	7.770	0.42	5.12
16	+39.7	ON	7.800	0.43	5.12
17	+39.7	ON	7.812	0.41	5.11
18	+60.0	ON	7.759	0.41	5.09
19	+61.0	ON	7.795	0.41	5.09
20	+60.2	ON	7.834	0.41	5.08
21	+60.2	ON	7.851	0.42	5.07
22	+60.3	OFF	7.882	0.40	5.10
23	+21.0	OFF	7.758	0.39	5.15
24	+22.3	OFF	7.898	0.41	5.14
25	+22.6	OFF	7.908	0.41	5.14

26	+20.9	OFF	8.059	0.38	5.19

Table 3 – PMD measurements of PCF NL 1550 NEG-1 (thermal test).

Ongoing movement of fiber sample due to contraction (at decreasing temperature) or expansion (at rising temperature) of fiber polymeric coating and plastic spool can induce some artefacts in test results. In particular, it was observed several times that spectral distribution of differential group delay (DGD) deviates from the linear shape specific to undisturbed fiber.

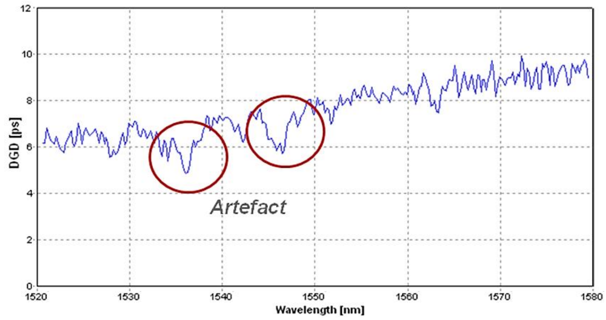


Figure 4.29 – Artefact present in result No.4.

Using average values from all unperturbed measurements at each temperature, it was obtained the graphs of PMD vs. temperature shown in Fig. 4.30.

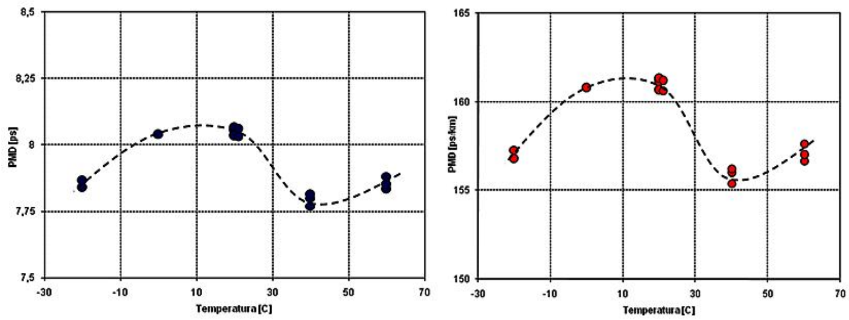


Figure 4.30 – DGD (left side) and PMD coefficient vs. temperature (right side) of NL-1550-NEG-1 fiber.

In measurement No. 25, the acquired DGD distribution had some irregularity between 1538nm and 1546nm. This means that the fiber has most likely a multimodal behavior. In measurement No.26 it was found the same condition, thus it was stop the temperature test for this fiber.

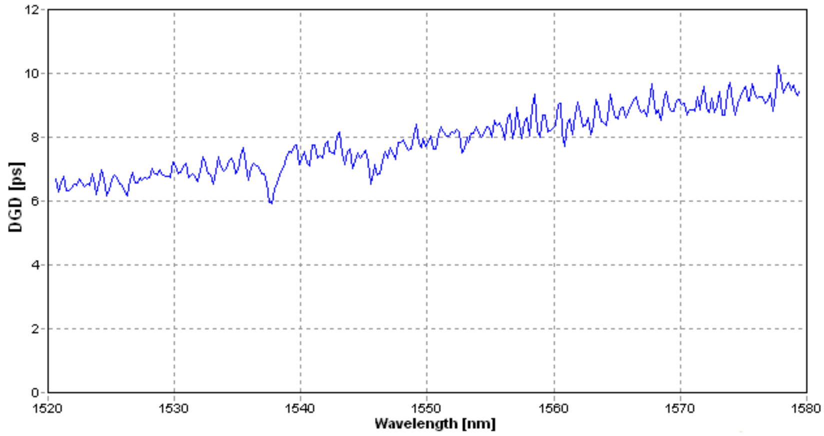


Figure 4.31 – DGD plot with irregularities obtained from measurement No.25.

The same experiment has been carried out also using an IPHT 252b5 fiber 16.08m long. This is a nonlinear PCF having a core doped with 36% mol. Germania and hexagonal photonic structure. Core diameter is 2µm and cladding diameter is about 80µm. Fiber core structure is shown below:

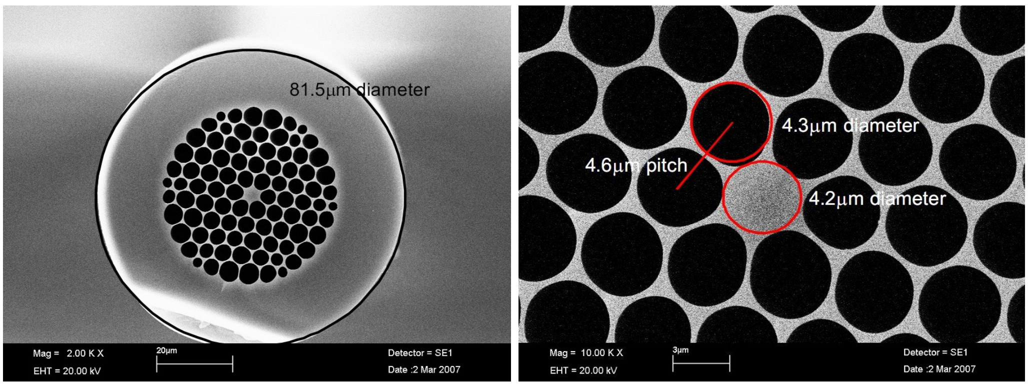


Figure 4.32 – Cross-section of IPHT 252b5 fiber (SEM photos by GAP- Optique / Univ. of Geneva).

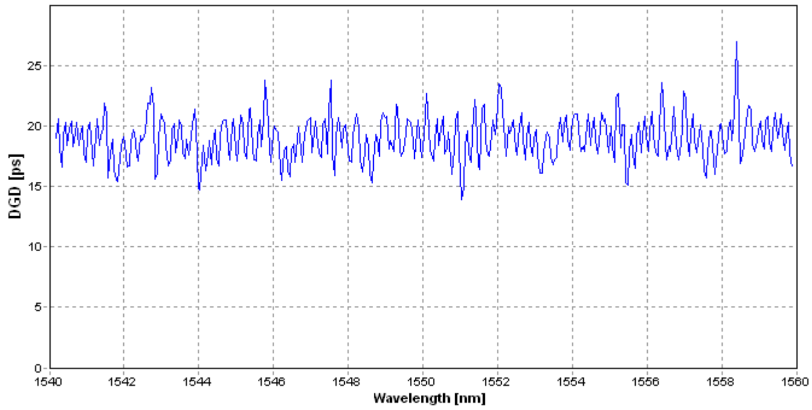
For this experiment, the wavelength range was set to 1540÷1560 nm with a step of 0.05nm, being tailored to high PMD of this sample. Laser power was again 0dBm. Before the start of measurements, it was performed again the calibration of PMD analyzer in order to ensure the best accuracy. The following table reports the related results:

Measurement No.	T [°C]	Climatic chamber	PMD (ps)	PDL (dB)	Average loss(dB)
1	+21.6	OFF	18.945	0.23	4.56
2	+20.0	ON	18.889	0.24	4.57
3	-18.5	OFF	18.756	0.23	4.60
4	-20.7	ON	18.791	0.23	4.59
5	-19.3	OFF	18.800	0.23	4.60
6	-20.1	OFF	18.818	0.23	4.60
7	-0.3	OFF	18.890	0.24	4.57
8	+0.8	OFF	18.797	0.24	4.57
9	+2.5	OFF	18.805	0.23	4.57
10	+22.1	OFF	18.947	0.23	4.56
11	+39.7	ON	19.012	0.23	4.52
12	+39.8	ON	18.895	0.23	4.52
13	+40.3	ON	18.958	0.24	4.52
14	+40.3	ON	18.968	0.24	4.52
15	+59.8	ON	19.047	0.24	4.48
16	+59.5	ON	18.942	0.24	4.49
17	+60.8	OFF	19.252	0.23	4.49
18	+58.3	OFF	19.129	0.24	4.49
19	+56.5	OFF	19.111	0.24	4.49
20	+22.0	OFF	18.961	0.23	4.55
21	+22.0	OFF	18.952	0.23	4.55

Table 4 – Summary of PMD measurements of IPHT 252b5 sample during thermal test.

Referring to measurement No.4, it is possible to note periodic artefacts in the DGD plot. This is mainly due to the periodic switching on and off of the climatic chamber cooler, which produced strong vibrations and unwanted movement of optical fiber placed inside the chamber and connecting pigtails; the measurement was repeated with chamber switched off.

Bottom there is a graph of wrong measurement which presents some periodic artefacts. This measurement is compared with a correct measurement without any artefact.



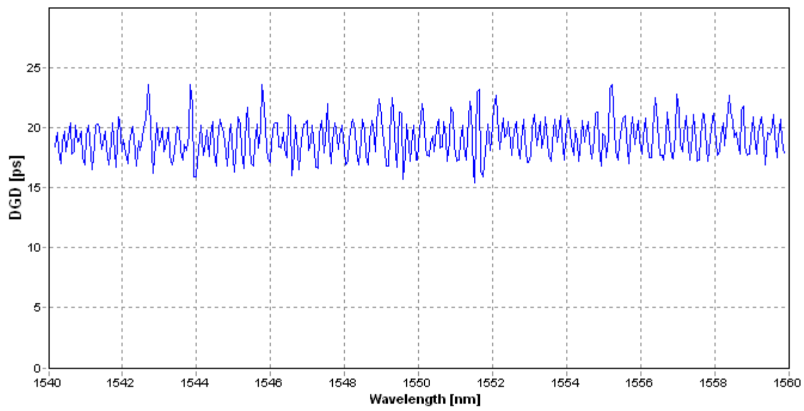


Figure 4.33 – Distorted PMD measurement result with periodic artefact (above) compared with a correct measurement without interference (lower graph).

Another problem, has been found for N.15 because the measurement presents some fluctuations probably due to non uniform temperature inside the climatic chamber. The same problem is also present in measurement No.16. These measurements were repeated.

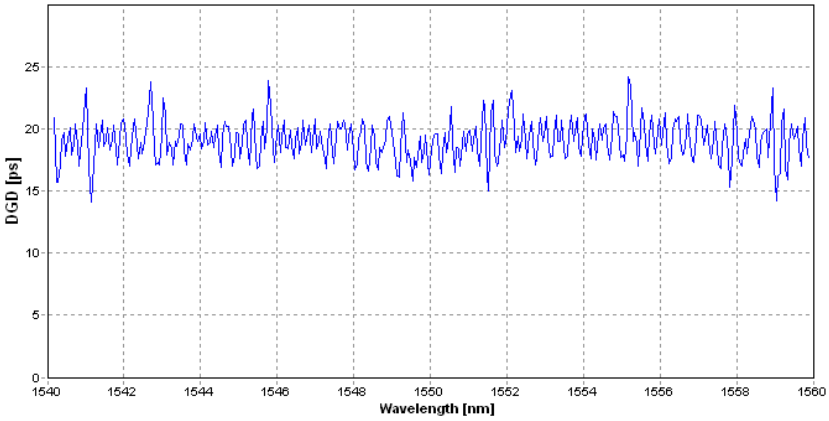


Figure 4.34 – Fluctuations observed during measurement No.15.

It is reported the results of the PMD coefficient respect to the temperature, presenting two graphs in which are presents also the average measurements. The PMD behavior of this kind of fiber is quite stable respect to the previous samples measurements.

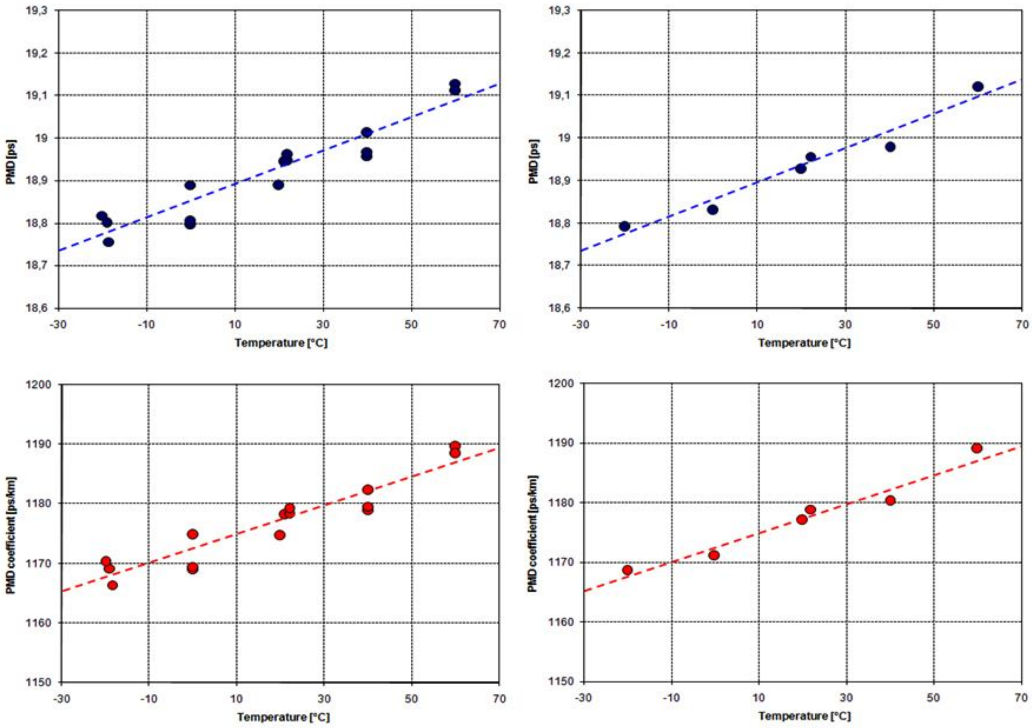


Figure 4.35 – Graph of PMD coefficient vs. temperature (blue). Averaged results presented on the right. The PMD coefficients vs. temperature shown in red.

4.3.2 Twist measurements of optical fibers (Mechanical Test)

The test involved measurements of PMD in fiber subjected to twist; the set-up used enabled to guarantee different amount of torsion, increased in multiple steps. The equipment for PMD measurements evaluation was the same as used for all previous experiments. Have been adopted two clamps in order to fix both ends of the optical fiber under test. For this test has been used two fiber samples: IPHT 252b5 0.5m long and UMCS 070119P2 with PANDA-like structure 1.34m long. The experiment consist of twisting one end of the optical fiber in several steps in order to evaluate the changes of the fiber structure in term of PMD coefficients. To avoid twisting of interconnecting fibers, the twisted end of the sample is always disconnected before twisting or untwisting and re-connected again for measurements. The PMD of samples, in fact, change both with temperature and torsion stress. This experiment intend to simulate increasing torsion stress applied to the fiber sample under test.
The following drawing shows the set-up used in NIT lab.

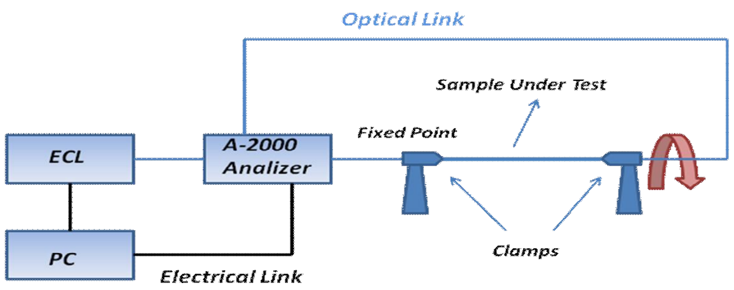


Figure 4.36 – Set-up used for fiber twist test.

For PMD characterization, we have used the following settings; wavelength range: 1460÷1590 nm, scanning step: 0.5nm, laser power:

0dBm. The first fiber under test was the IPHT 252b5 having a length of 0.5m. The results are presented in the following table:

Measurement No.	No. of fiber revolutions	Fiber twist (rev/m)	PMD (ps)	PDL (dB)	Average loss (dB)
1	0	0	0.544	0.36	2.52
2	0	0	0.544	0.34	2.52
3	10	20	0.516	0.35	2.51
4	20	40	0.452	0.33	2.52
5	30	60	0.390	0.36	2.51
6	40	80	0.336	0.34	2.51
7	50	100	0.291	0.34	2.51
8	60	120	0.259	0.36	2.50
9	70	140	0.236	0.34	2.54
10	80	160	0.212	0.33	2.48
11	0	0	0.516	0.36	2.50
12	0 (after1h)	0	0.521	0.37	2.50
13	0 (after 15h)	0	0.529	0.38	2.53
14	0 (after 15h)	0	0.528	0.35	2.51
15	0 (after 44h)	0	0.538	0.35	2.69

Table 5 – Results of PMD measurements of IPHT 252b5 sample during twist test.

With these results, has been obtained a graph of PMD coefficient versus the number of optical sample twists. Interestingly, PMD measurements No.11-15 gave lower values in comparison to initial state (measurements No.1-2). Fiber PMD measured after untwisting was 5% lower than the initial value, approximately as during application of 20 rev./m twist. A slow recovery of fiber PMD to initial conditions was observed during the next 2 days, but was not complete after 44 hours. The different value of loss obtained in measurement No.15 is due to temporary re-connections being made in order to test another fiber before returning to this sample. The twist dependence of fiber PMD is presented:

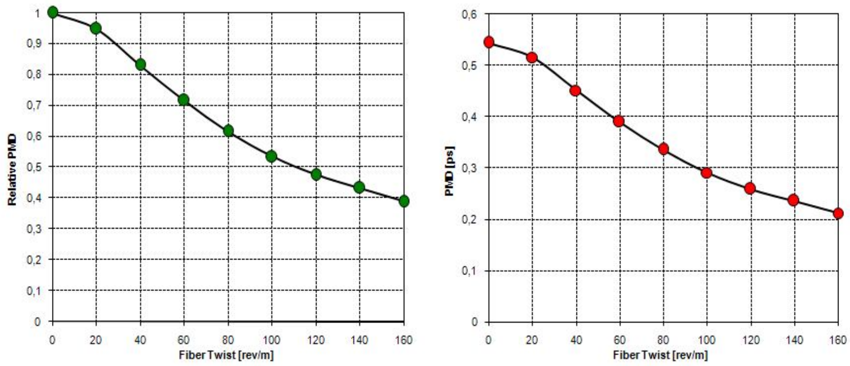


Figure 4.37 – PMD vs. fiber twist characteristic – IPHT 252b5.

The same experiment has been carried out also on the sample of UMCS 070119P2 fiber 1.34m long. Has been used the same equipment, but set the A2000 analyzer differently: wavelength range was 1520÷1580 nm, step was 0.2nm and source power was 0dBm. The following table and graph of PMD vs. fiber twist calculated in term of revolutions per meter [rev/m] present results obtained during this experiment.

Measurement No.	No. of fiber revolutions	Fiber twist (rev/m)	PMD (ps)	PDL (dB)	Average loss (dB)
1	0	0	3.738	0.62	5.39
2	0	0	3.727	0.62	5.40
3	0	0	3.724	0.62	5.40
4	8	5.97	3.475	0.62	5.35
5	16	11.94	3.475	0.61	5.35
6	24	17.91	3.739	0.61	5.28
7	32	23.88	3.747	0.62	5.24
8	40	29.85	3.754	0.60	5.22
9	48	35.82	3.744	0.59	5.29
10	56	41.79	3.755	0.59	5.20

11	0	0	3.737	0.61	5.21

Table 6 – Results of PMD measurements of UMCS 070119P2 sample during twist test.

The results obtained during the initial and final measurements No.1 and No.11 on twist-free sample are almost identical, meaning the fiber has immediately returned to original condition after untwisting. In this case, fiber PMD essentially does not change when the fiber is twisted.

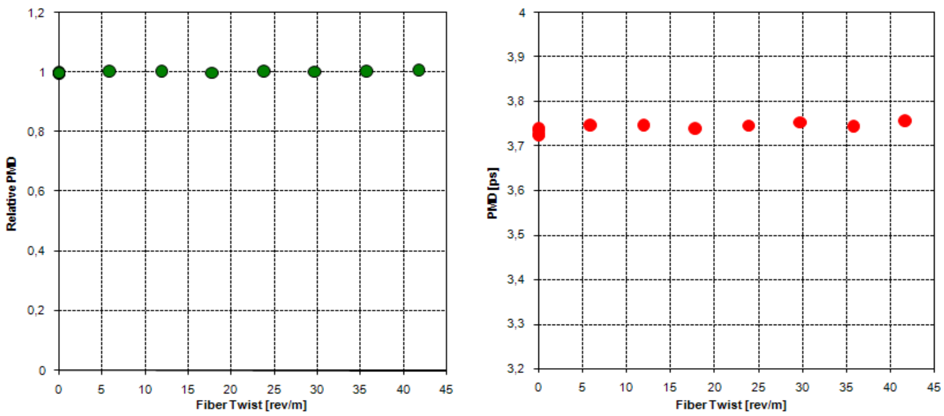


Figure 4.38 – PMD vs. fiber twist (rev / m) characteristic – UMCS 070119P2.

4.4 OTDR measurements of optical fibers

Has been also realized brief measurements of the NL 1550 NEG-1 (50m long) PCF fiber with an optical time domain reflectometer (OTDR). Has been used the following setup, with a Tektronix TFP2 instrument:

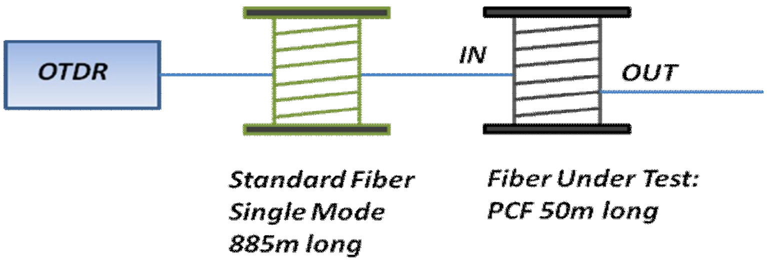


Figure 4.39 – Set-Up for OTDR measurements.

The sample present before the PCF fiber under test was placed to compensate the OTDR death zone and to increase the distance of the measurement. We have performed several measurements regarding the sample under test using a Tektronix OTDR with two different sources: 1310nm pulse and 1550nm pulses for both optical fiber sides. Using both pulses sources we have obtained the results reported in the following table:

Fiber Type	Wavelength (nm)	Fiber Direction	PCF attenuation α [dB/km]
NL 1550 NEG-1	1310	I / O	14.0
NL 1550 NEG-1	1550	I / O	8.5
NL 1550 NEG-1	1310	O / I	13.025
NL 1550 NEG-1	1550	O / I	8.5

Table 7 – Attenuation of NL 1550 NEG-1 fiber measured with OTDR.

Fiber attenuation is in agreement with manufacturer data (9 dB/km @ 1550 nm, no data for 1310 nm). Below is an example of OTDR trace shown by a Tektronix FM-TAP software, where it is possible to see the length of a standard single mode fiber (885m) and the PCF under test (50m). It is possible to see attenuation, fiber length and other optical parameters.

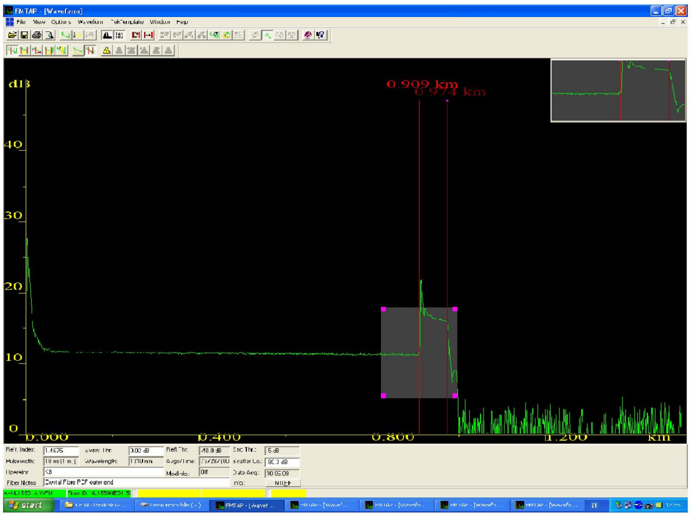


Figure 4.40 – Example of OTDR trace, showing lengths of SMF and PCF (highlighted).

4.5 Spectral loss measurements

Has been also performed spectral loss measurements, using a broadband supercontinuum source (Koheras SuperK Compact), a variable optical attenuator set to 10dB and having a total 13dB insertion loss (Anritsu MN95D), a 20m long standard single mode fiber patchcord serving as launching fiber and an optical spectrum analyzer (OSA) Ando AQ-6315B. This arrangement is shown on Fig. 4.41.

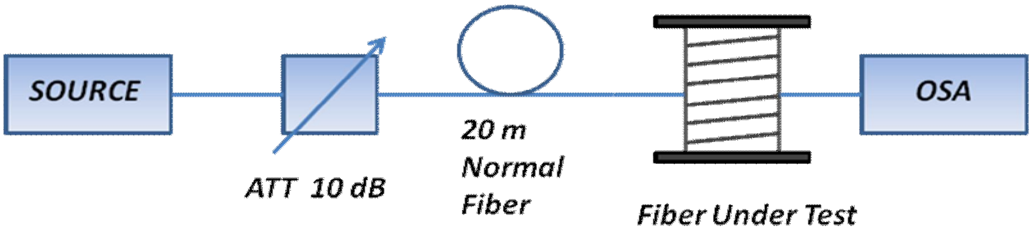


Figure 4.41 – Set-Up for spectral loss test.

The first step was to set the OSA with spectral range of 1200-1700 nm; measurements at shorter wavelengths were preclude by a possible multimode propagation both in the launching fiber and the sample under test. Then, we have connected the output of the launching fiber directly to the OSA in order to obtain the reference spectrum (trace A) which will be compared with other results, when fiber samples are introduced. At this point, connecting to OSA the different samples of optical fibers, we have obtained the curve (trace B) for each sample. Making the difference between trace A and trace B we have obtained the net loss result, displayed and recorded as trace C.

The optical fibers we have used for this test were:

NL 1550 NEG-1 (A)

Photonic Crystal Fiber PCF, 50m long, sample which has a triangular core (2.1µm avg. value) and cladding size equal to 128µm.

UMCS 070119p2 (B)

PCF with “PANDA-like” structure, 8.62m long; has the two large holes core size of 3.5µm; the small hole is 1.3µm and a cladding size equal to 126µm.

IPHT 282b4 (C)

104m long PCF optical fiber. Has an Hexagonal structure with a Germania doped core.

IPHT 252b5 (D)

16.08m long optical fiber, 36% Germania doped, with an hexagonal structure. Core size is 2µm and cladding size is about 80µm.

For each sample we have obtained the spectral loss characteristics shown here:

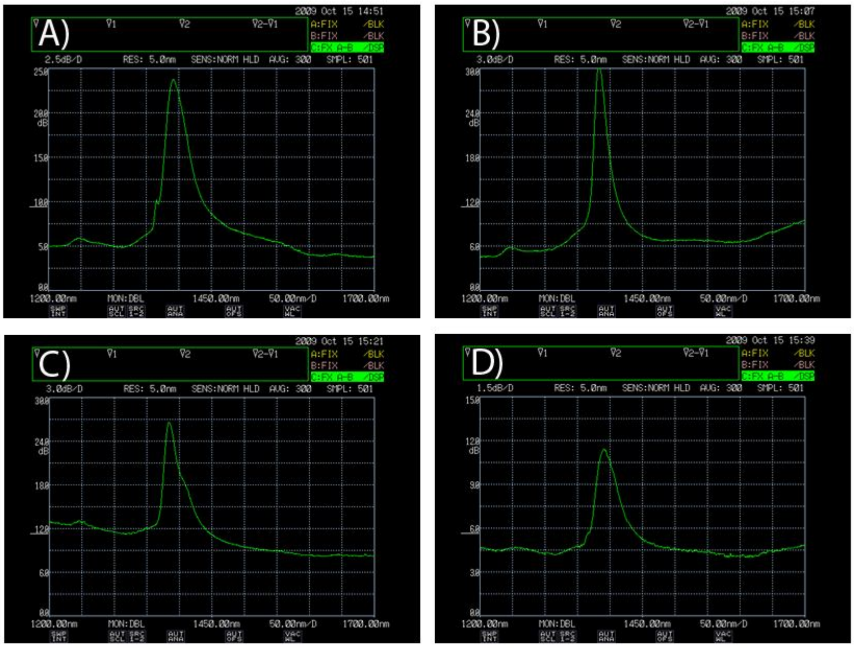


Figure 4.42 – Spectral loss plots of fibers samples (A-D).

The results are different for each fiber (Fig. 4.42); it is possible note that if we want use one of these samples for DWDM applications, the last sample (IPHT 252b5) is the best one because of relatively flat loss characteristics between 1450nm and 1650nm.

4.6 Splicing of optical fibers and power meter measurements

Was performed a splice of some optical samples. In particular, has been measured the length of intermediate fiber present between PCF fiber NL 1550 NEG-1 (50m long) and its pigtails with a standard single mode fibers fitted at both ends (Fig. 4.43). After this operation, was spliced the two sides of the PCF fiber using a splicer equipped with a CMOS camera connected to a PC. The splicer allowed to set different values of arc current in order to obtain different power levels and temperatures, thus splicing fibers of different types and sizes is possible.

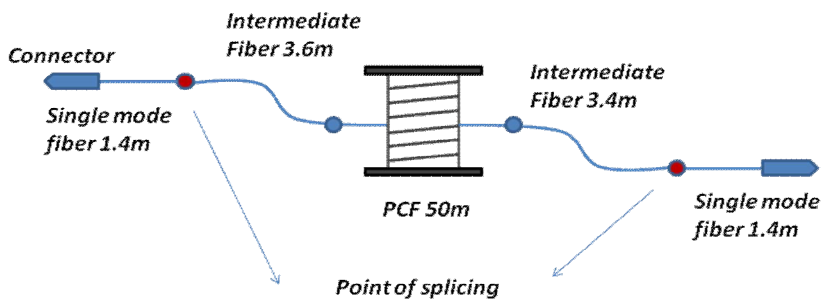


Figure 4.43 – Composition of PCF sample.

Connecting this sample to a laser source emitting at 1558nm with 3.40dBm output power and a power meter (HP 8153A) we have measured the insertion loss of the pigtailed PCF sample including the intermediate fibers and splices. The pictures below show the fiber splicing; with a low current arc it is possible to clean the optical fiber end of impurities, higher current value is used to fuse the fibers and make the splice.

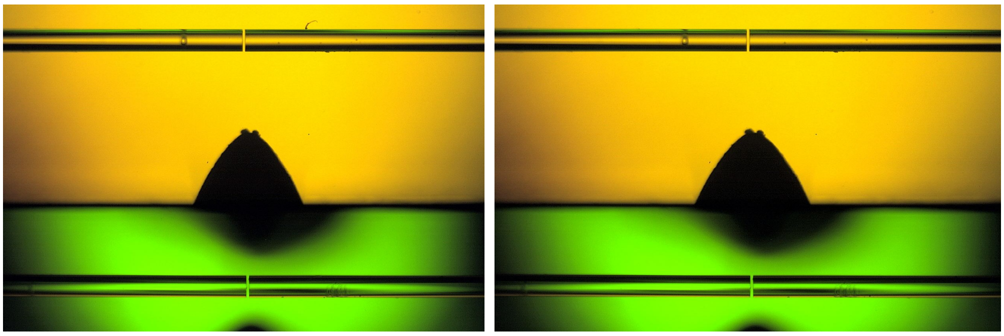


Figure 4.44 – Optical fibers before splicing. Two views, splicer electrode visible in the center of the figure.

On the left side there is a picture of an optical fiber just after cleaving. Using a brief low current discharge, it is possible to obtain a clean surface, which is shown in the right side. The area illuminated in yellow is observed from the X axis, while the green part presents the Y axis view of the fibers. After the optical sample cleaning, the splice was made.

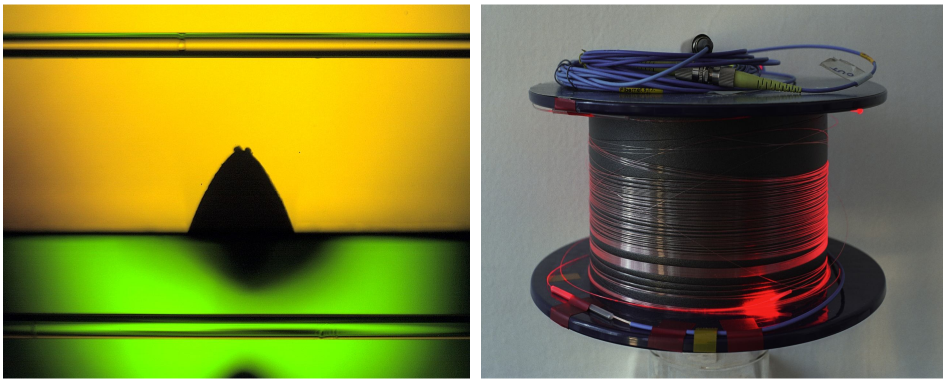


Figure 4.45 – NL 1500 NEG-1 fiber after the splicing.

On the left side is presented the fiber image after the finishing of splicing procedure and on the right there is the same optical sample connected to a visible laser source (655nm laser) in order to see in which point of the junctions the light is lost or leaked. As can be seen, a considerable proportion of light is lost at splices between the PCF and the intermediate fibers. This is due to mismatch between mode field diameters of spliced fibers. In the length of PCF itself, only an evenly distributed scattering of light was observed. No localized defects with outstanding light scattering were detected.

Conclusions

In this work has been presented a 2R (Re-amp and Re-shaped) all optical system able to regenerate several client signals at 10 Gbps at the same time in a real DWDM (Dense Wavelength Division Multiplexing) scenario. Starting from a single channel regeneration approach the system has been improved obtaining a multi-channel 2R all optical fiber based regeneration device operating directly in optical domain. The fiber used is a standard 10 km long DS (Dispersion Shifted) optical fiber. In this way, the problem generated from the continuous electro-optical data conversions is avoided. Different configurations have been experimented in order to find the better solution in term of noise compression and signal amplification, 1R (Re-amp) and 2R (Re-amp and Re-shaping) steps. Moreover, the ability of the system to handle more channels has been demonstrated using 4 channels with BER (Bit Error Rate) results in back to back and condition and also in propagation conditions, using a deployed cable between Rome and Pomezia.

Besides, a study and characterization of photonic crystal fibers samples has been done in order to test the possibility to integrate the previously mentioned regeneration device. These few meters of optical fibers can be used, due to high non linearity, to obtain a more compact regeneration based device.

Appendix 1

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Appendix 2

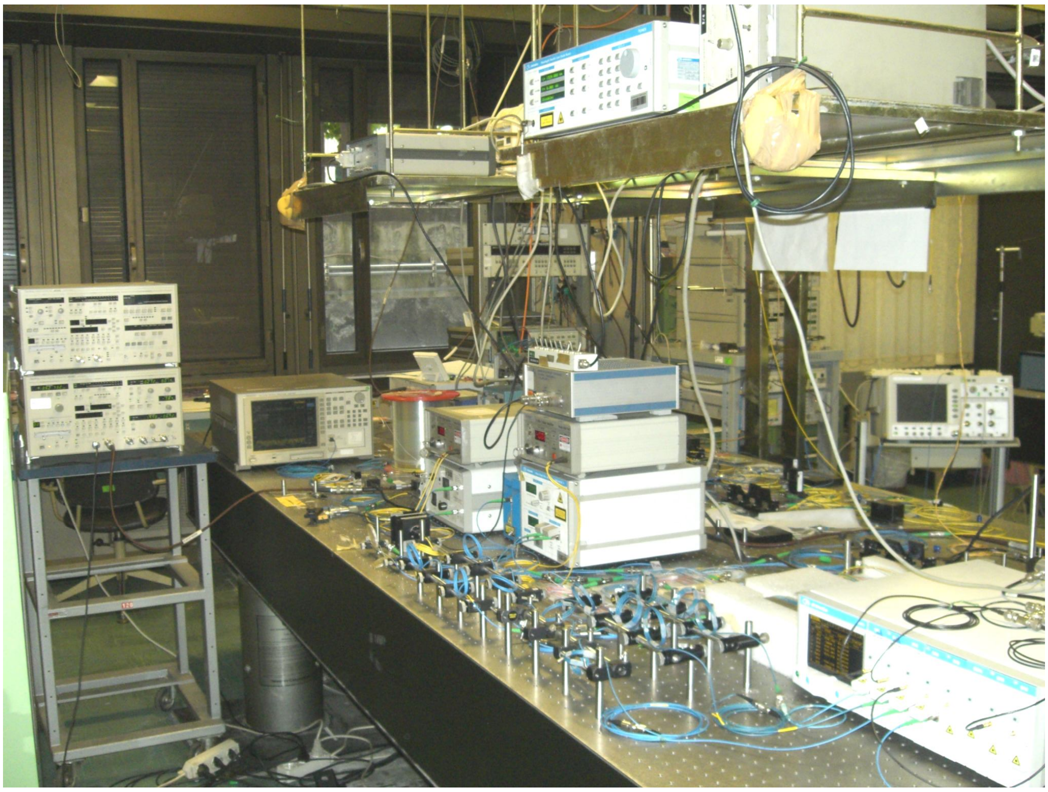

Figure A.1 – Photograph of 2R all optical regenerator set-up realized in ISCOM labs.

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