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EXPERIMENTAL CROSSTALK CHARACTERIZATION IN A 7-CORE MULTICORE FIBER

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Alla mia famiglia che mi è sempre stata accanto in questo lungo ed impegnativo percorso di laurea

Ringraziamenti

Ringrazio tutti quanti specie la mia mamma che mi ha fatto così funky

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Sommario

Lo studio di tecniche di multiplazione quali SDM (Space-Division Multiplexing) nell'ambito delle comunicazioni in fibra ottica si sta diffondendo sempre di più a causa della sempre crescente richiesta di capacità dovuta all'aumento del traffico internet. Lo scopo di questa tesi è la caratterizzazione del cosiddetto intercore crosstalk (ICXT) su sistemi ottici basati su SDM che utilizzano fibre ottiche multicore (MCF) come tecnica di multiplazione spaziale. A partire da un modello matematico che restituisce le caratteristiche dell'ICXT in base ai parametri della fibra e al segnale trasmesso in essa, si è caratterizzata la variazione dell'ICXT nel tempo in una MCF a 7 core lunga 2,9 km prodotta dal Photonic Network Systems Lab al National Institute of Information and Communications Technology (NICT) in Giappone. Negli esperimenti abbiamo trasmesso, solo nel core centrale, segnali che differiscono per ampiezza di riga del laser utilizzato e per modulazione e bandwidth del segnale stesso; tutti alla stessa potenza e lunghezza d'onda nominale. In particolare per quanto riguarda i segnali modulati, abbiamo usato la modulazione discrete multitone (DMT): questa modulazione ci permette di caratterizzare il comportamento dell'ICXT quando i segnali trasmessi nella MCF non presentano uno spettro piatto. Inoltre è interessante perchè è una modulazione adattativa: utile nelle MCFs dove l'ICXT colpisce in modo ineguale i diversi canali del mezzo trasmissivo. Si è inoltre caratterizzato l'impatto dei battimenti di due segnali; nel caso di segnali provenienti da sorgenti laser differenti propaganti in diversi core della fibra (entrambi alla stessa lunghezza d'onda nominale).

Abstract

The study of SDM (Space-Division Multiplexing) techniques are spreading in optical communications due to the growing of the demand of capacity caused by the increasing of the internet traffic. The purpose of this thesis is to characterize the so-called intercore crosstalk (ICXT) in the SDM optical systems that use multicore fibers (MCF) as spatial multiplexing technique. Starting from a mathematical model that gives as output the ICXT characteristics; it uses the fiber parameters and the kind of signal transmitted, it is characterized the behaviour in time of the ICXT present in a 7-core MCF. The fiber is long 2.9 km and was made by the Photonic Network Systems Lab at National Institute of Information and Communications Technology (NICT) in Japan. In the experiment we transmitted, only in the central core, laser sources with different linewidth and signals with different modulation and bandwidth; but at the same power and nominal wavelength. More in detail, for the modulated signals, we used discrete multitone modulation (DMT): this modulation allows to characterize the ICXT behaviour in presence of signals without a flat spectrum. Moreover it is interesting because is an adaptive modulation: useful in the MCFs where the ICXT affects unequally the channels of transmission medium. It is moreover characterized the impact of the beating of two signals; in the case of signals coming from different laser sources propagating in different cores of the fiber (both at the same nominal wavelength).

Chapter 1

Introduction

To meet the ever-increasing demand for data services, highly spectral efficient modulation formats in combination with polarization-division multiplexing are already standard in several optical networks. For future networks, space-division multiplexing (SDM) using multicore fibers (MCFs), is widely considered as the next level to aggregate and to increase data throughput. However, MCFs are limited by inter-core crosstalk (ICXT) arising from non-negligible coupling between cores. For continuous wave (CW) light or signals with a strong carrier, ICXT exhibits a stochastic behaviour in time and modulation frequency, that potentially is a limit with intensity-modulated (IM) signals. An additional approach to reduce the ICXT impact is to adopt adaptive discrete multitone (DMT) signal format. With this format, adaptive bit and power loading can assign higher capacity to subcarriers less degraded by ICXT. The aim of this thesis is characterize the ICXT in a 2.9 km 7-core MCF. The ICXT is generated by different kinds of signals that differ from laser linewidth, modulation and bandwidth. In particular, we did the characterization of the ICXT generated by a DMT signal in case of single side-band (DMT SSB) and dual side-band (DMT DSB) spectrum.
We characterize also the ICXT behaviour when it is generated by two sources, focusing on the effects in the ICXT behaviour of the beating of two DMT SSB modulated signals.
The thesis work is organized in 5 chapters as follows.

Chapter 2 gives an overview on Space Division Multiplexing (SDM) in optical domain, focusing on MCF. An overview of the theoretical model used to obtain the behaviour of the ICXT is given. Finally, multiplexing and demultiplexing devices used for interface single fibers with the cores of the

MCF are described.

Chapter 3 gives a detailed description of the MCF used for the experiments.

In chapter 4 the two setups used for the experimental measures are illustrated.

Chapter 5 is devoted to report the results of the experiments. After a preliminary characterization of the fiber under test, the results obtained using the different kinds of signal as single source of the ICXT and the results of the measure done with two sources generating the ICXT are presented.

In chapter 6 the obtained experimental results are discussed with the conclusions.

Chapter 2

Multicore optical fibers

2.1 Space Division Multiplexing

The capacity of a channel cannot exceed the limit imposed by Shannon-Hartley theorem[1]

$$C_{MAX} = W \log_2 \left(1 + \frac{S}{N}\right) \tag{2.1}$$

where W is the spectral bandwidth of the channel and $\left(\frac{S}{N}\right)$ is the *signal to noise ratio (SNR)*. There are two ways to face the problem of increasing the channel capacity:

- increasing the SNR: increase the spectral efficiency, by exploiting for example digital coherent detection
- increasing the spectral bandwidth: increase the number of signals that can be sent into the fiber by implementing for example Wavelength-Division Multiplexing (WDM) technique.

The present WDM coherent optical communications have already exploited the degrees of freedom (amplitude, frequency, phase, and polarization) of a lightwave in a SMF (Single Mode Fiber)[2]. The more and more increasing Internet protocol traffic will cause the installed SMFs to saturate their capacity in a few years. The capacity limit is not related to specific modulation formats, but it is given by the filling of C and L amplification bands of an EDFA (Erbium-Doped Fiber Amplifier), bounding the maximum transmission rate of a SMF to 100 THz/s. Starting from the same concept of a MIMO (Multiple Input Multiple Output) channel in wireless communications, the further step to increase the performances is the deployment of the dimension space. Space Division Multiplexing (SDM) is a multiplexing technique, as shown in Figure 2.1, in which a transmission medium is *physically* subdivided in several communication channels using insulation, distance, or different waveguides[2].

There are two different techniques for doing the space division multiplexing:

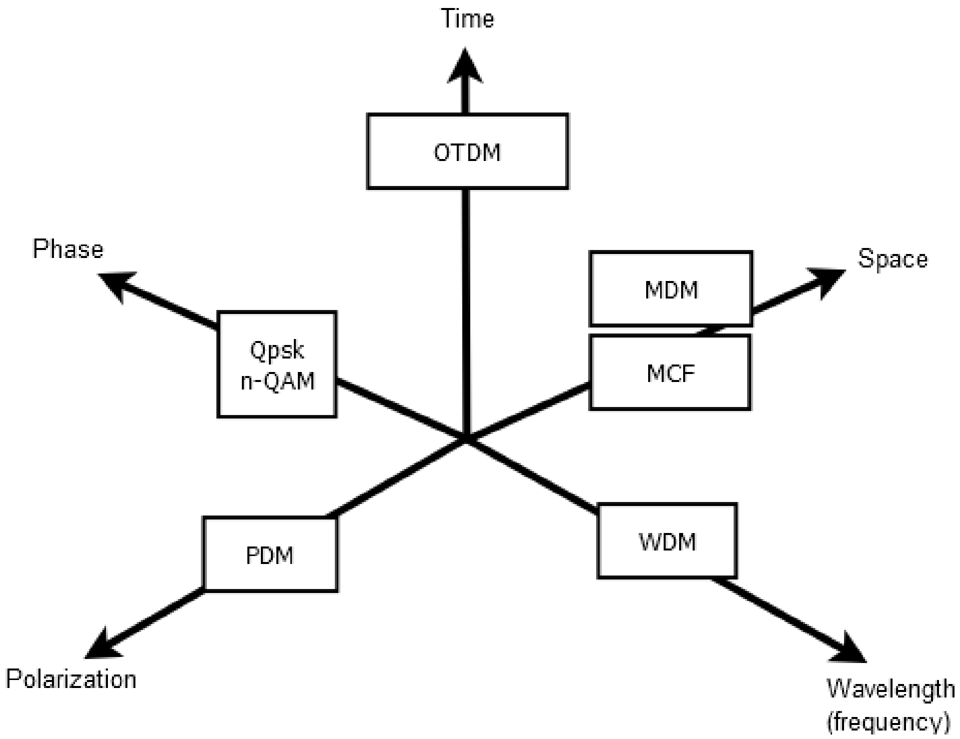
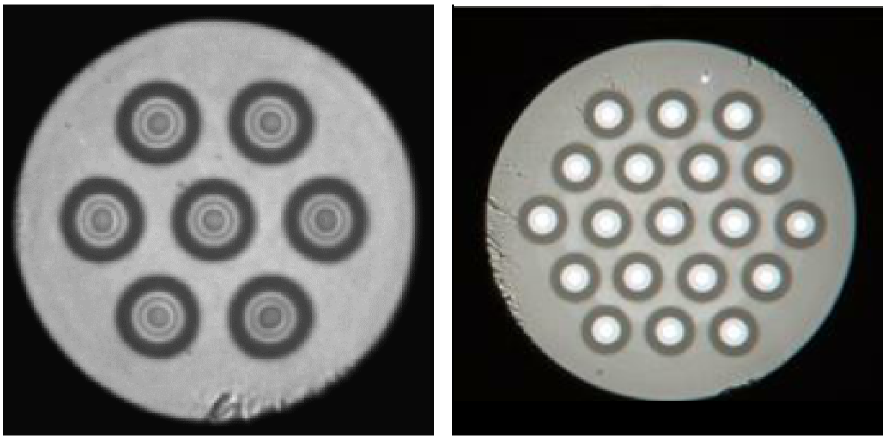


Figure 2.1: a graphical representation of the different dimensions in which it is possible to implement channel multiplexing. OTDM: orthogonal time division multiplexing, WDM: wavelength division multiplexing, PDM: polarization division multiplexing, QAM: quadrature amplitude modulation

- Mode-Division Multiplexing (MDM), by adopting few-mode fibers (FMFs) or multimode fibers (MMF). They use different modes that are self-consistent electric field distributions in waveguides during the propagation[3], acheiving spatial division multiplexing.
- Core multiplexing, by using the multicore fibers (MCFs). These kinds of fibers allow to overcome the capacity of a classical single core fiber and reach multipetabit trasmission capacity[4][5][6][7].

2.2 Multicore optical fiber

The MCF is a particular kind of optical fiber constituted of several cores. It consists of a matrix of cores in a hexagonal or circular structure, designed



(a) MCF with 7 cores (b) MCF with 19 cores[6]

Figure 2.2: examples of multicore optical fibers

to maximize the core density given a cladding diameter, maintaining the inter-core crosstalk as low as possible. Each core can carry either only the fundamental mode or also higher-order modes, depending on the employed method of SDM. The feasible number of core is limited, since the cladding diameter of the MCF is no more than 250 μm; in order to be compliant with the dimension of the standard SMF. Figure 2.2 shows two examples of optical fibers, differing in the number of cores. There are different kinds of multicore optical fibers, differing for number of carried modes and for the physical structure of the core itself[2].
In terms of carried modes the MCF can be defined as:

- single mode multicore fiber (SMMCF);
- few-mode multicore fiber (FMMCF);
- multi-mode multicore fiber (MMMCF).

If the cores can carry more than the single mode, the two last SDM techniques can be employed to further increase the fiber capacity.
On the physical structure point of view two typologies can be identified:

- homogeneous: the cores have all the same diameter, the central core suffers more crosstalk than the others, because it is surrounded by the maximum number of cores placed at the same distance from the central one in a concentric pattern.
- heterogeneous: the cores have different dimensions. The power transferred among cores significantly decreases when the cores have different

dimensions. As a consequence they suffer the inter-core crosstalk less than the fibers with homogeneous distribution of cores.

Usually it is preferable to use homogeneous optical fibers because, as reported in [4], in them the wavelength dependence of the crosstalk could be addressed applying optical coding across the sub-channels; this ensures similar BER across all the channels, furthermore they support spatial super channels for shared transmitted hardware[4].
The SMMCFs are the easiest and most natural migration path for the adoption of high capacity SDM technology[2]. They have a better spectral efficiency than MMF[4]. Moreover, they can cover more distance than MMMCF and they have a relatively low crosstalk with respect to the modal crosstalk in the FM-MCF[2]. The SMMCF can also be fabricated with smaller core diameter than FM-MCF[4], making splicing and handling easier. Moreover, it is possible to put more cores into the fiber or leave more space between them.

2.3 Intercore crosstalk

The intercore crosstalk (**ICXT**) is generated when a non negligible mode[3] propagates from a source core to neighbor cores. In the fibers, when a laser beam hits the end face of a fiber, most of its power may then propagate in the fiber core. Some fraction of the power, however, will propagate in the cladding; these modes are called cladding modes[8]. This power, in the MCFs, enters in the cores close to the core in which the laser beam propagates. This issue is unavoidable because a core too confining will have a small mode area degrading communications. For the signals transmitted in the core under test, these contributions are sources of noise, which lead to a performance degradations[9][10]. It is experimentally demonstrated that the ICXT is the main source of penalty in the multi-core fibers performances[5][10]. The ICXT is shown[10] to have a stochastic behavior in time and frequency and the fluctuations in amplitude can reach significant levels, in the order of tens of dB. It can rapidly change: its variations can occur 10 times faster[11] in presence of signals propagating along several cores (that is the more realistic scenario for this kind of transmission system[10]) with respect to the case of having one single signal propagating along one core of the fiber, since the signals in all the active cores contribute to the total crosstalk. In the example, as reported in [10] a MCF with 7 cores was used and a PDM-QAM signal was transmitted, with a bandwidth of 24.5 GHz, in the 6 outer cores. The extreme values are on average bounded to 4.5 dB

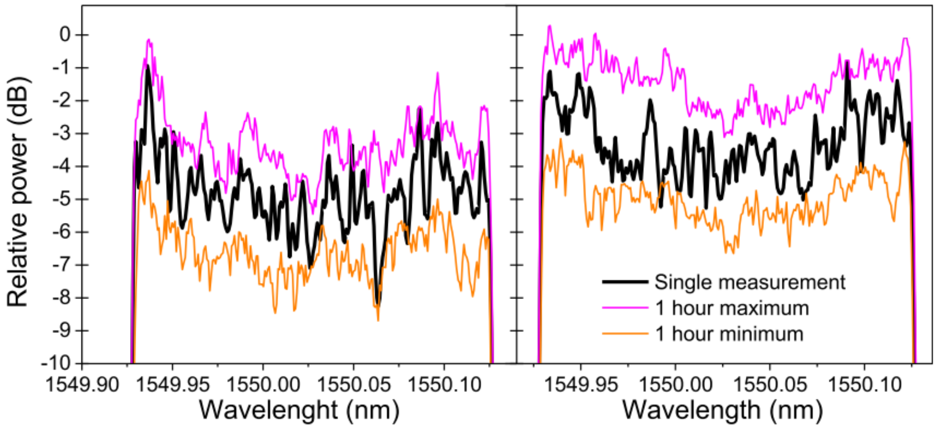


Figure 2.3: the power of the crosstalk for different wavelength: at the left 1 core case, at the right 6 core active case[10]

across the signal bandwidth when several cores contributes to the crosstalk against the over 7 dB in the case only one single core contributes to the crosstalk; although the potential for crosstalk from multiple cores is evident by the max and min measurements, shown in Figure 2.3, that are more separates than in the the case with 1 core XT. All these features of the ICXT are a critical aspect that can lead to a potential outage of the transmission system. The crosstalk variation depends from many factors:

- environmental disturbances and the bend of the fiber[12]: it was found[4] a dependence with the employed wavelength and modulation: the crosstalk variations can be obtained as a function of spectral occupancy of the signal,
- the skew and the dispersion proprieties: it is observed [13] a dependency of the crosstalk with the group velocity dispersion (GVD) that starts to have noticeable impact on the mean and variance of the crosstalk with frequency below the inverse of the *skew* $\omega_n = 2\pi/(d_{mn}L)$ where d_{mn} is the walkoff i.e. the difference between the group delays of the signals propagating in the cores and L is the length of the fiber,
- number of cores that contributes at the overall crosstalk.

This stochastic behaviour leads to use an adaptive modulation that reduces the impact of the crosstalk and consequently improves the performance of the system. We can use, instead of a fixed modulation, a modulation such as *the adaptive bit-loading-direct-detection (DD) orthogonal frequency division multiplexing (OFDM)* or discrete multi-tone (DMT): these type of modulations allows to dynamically allocates the bits for each subcarrier of the OFDM signal[5] assigning higher modulation formats to subcarriers with a higher Signal-to-Noise Ratio (SNR). As reported here[6] and here[10] the *adaptive modulation* can reduce the effects of the crosstalk using less spectral efficiency modulation formats when the crosstalk is higher, since they are more resistant to noisy channels. When the level of crosstalk is lower, higher-order modulation formats can be employed. Using an adaptive modulation allows to gain more than 13% of capacity[6] with respect to adopting a fixed modulation.

2.4 Model for the characterization of the crosstalk

In this paragraph we consider the average crosstalk power estimated over intervals of 200 ms; this average is called short term average crosstalk (STAXT).

In literature an analytical model[7][9][13] was presented to estimate the ICXT of the homogeneous MCF. In this model it is assumed that the total crosstalk can be approximated as the sum of contributions from all *phase-matching points (PMPs)* weighted by a random phase shift as well as the corresponding propagation delay. This allows to approximate the random changes in discrete points. PMPs[14][15] are points of the fiber in which the crosstalk power has the main contribute, they are uniformly distributed over all the fiber length.
The crosstalk can be characterized in the frequency domain by computing the crosstalk transfer function (XTTF) as the sum of the contributes of N PMPs[9], given for a single quadrature of a single polarization as:

$$H_{XT}(L,\omega) = -jK_{nm}\sum_{k=1}^{N} e^{-j\phi_k} e^{-js_{nm}z_k\omega}, \tag{2.2}$$

where ω is the angular frequency, ϕ_k is the phase shift between two phase-matching points, s_{nm} is the difference between the group delays of core n and core m, (also called skew), z_k is the z coordinate of the k-th matching point, K_{nm} is the discrete coupling coefficient; for homogeneous MCF its absolute value is:

$$|K_{nm}| = \sqrt{\frac{\kappa}{\beta}\frac{R}{D_{nm}}\frac{2\pi}{\gamma}}, \tag{2.3}$$

where κ is the mode coupling coefficient, β is the propagation constant, D_{nm} is the distance between cores n and m and γ is the twist rate. Knowing the transfer function, the crosstalk in core n due to core m can be computed as

$$A_n(L,\omega) = H_{XT}(L,\omega)A_m(0,\omega). \tag{2.4}$$

The statistical distribution of the short-term average of a narrow-linewidth $A_n(L,\omega)$ can be described by a Gaussian distribution for a sufficiently large number of PMPs[9]. Furthermore, the sum of the contributions from the two quadratures and two polarizations within a core may be assumed to follow a chi-squared distribution with four degrees of freedom. These statistical proprieties are valid for CW and a signal modulated in all the possible modulation formats. Now we are interested in the variance of the crosstalk power, since the fluctuation of the crosstalk is the main issue when it was designed this kind of transmission system.
The variance is 0 if the crosstalk is generated by using ASE as source signal in the core m. To evaluate it in other cases we need a signal in the core m as a source of crosstalk. For simplicity we use a carrier-free signal with rectangular spectrum; in these conditions we can define $A_m(0,\omega)$ as:

$$A_m(0,\omega) = \begin{cases} 1 & \text{for } |\omega| \leq \pi f_{mod}, \\ 0 & \text{for } |\omega| \geq \pi f_{mod}, \end{cases} \tag{2.5}$$

where f_{mod} is the highest modulation frequency.
The variance of the STAXT in core n can be written as:

$$VAR_{XT} = Var\left(\int_{-\infty}^{+\infty} |A_n(L,\omega)|^2 \, d\omega\right) = Var\left(\int_{-\pi f_{mod}}^{+\pi f_{mod}} |H_{XT}(L,\omega)|^2 \, d\omega\right). \tag{2.6}$$

To simplify the model we assume that the signal and thus the crosstalk are composed of M discrete spectral lines at frequency ω_l separated by $\Delta\omega$. We can thus approximate Eq 2.6 as:

$$VAR_{XT} = Var\left(-jK_{nm}\Delta\omega \sum_{l=1}^{M} \left|\sum_{k=1}^{N} e^{-j\phi_k} e^{-js_{nm}z_k\omega_l}\right|^2\right). \tag{2.7}$$

$$VAR_{XT} = (-jK_{nm}\Delta\omega)^2 \, Var\left(\sum_{l=1}^{M} \Omega_l\right). \tag{2.8}$$

Ω_l is a random variable associated to frequency ω_l. In general ω_l cannot be assumed independent. However, we can rewrite the variance as sum over all Ω_l in terms of variance and covariance between all Ω_l, omitting the factor $(-jK_{nm}\Delta\omega)^2$, so the Eq 2.8 becomes:

$$VAR_{XT} \propto \sum_{l=1}^{M} Var(\Omega_l) + \sum_{l\neq p}^{M} \sum_{p\neq l}^{M} Cov(\Omega_l, \Omega_p) \tag{2.9}$$

It is possible simplify Eq 2.9 for two extreme cases of skew and/or modulation bandwidth.

1. If either the skew between cores n and m is small or the signal is modulated at low symbol rate, Ω_l can be semplified as:

$$\Omega_l = \left| \sum_{k=1}^{N} e^{-j\phi_k} e^{-js_{nm}z_k\omega_l} \right|^2 \approx \left| \sum_{k=1}^{N} e^{-j\phi_k} \right|^2 \tag{2.10}$$

   from Eq 2.10, it can be seen that all Ω_l are equal, as they only depend on random phases ϕ_k that are the same for all frequencies l. This case corresponds to having all the frequency components of the crosstalk fully correlated.

2. When the skew between cores n and m is high and/or signals are modulated at high symbol rates, the random variable ϕ_k may be neglected.

$$\Omega_l = \left| \sum_{k=1}^{N} e^{-j\phi_k} e^{-js_{nm}z_k\omega_l} \right|^2 \approx \left| \sum_{k=1}^{N} e^{-js_{nm}z_k\omega_l} \right|^2. \tag{2.11}$$

   Hence we can rewrite Eq 2.9 as:

$$\sum_{l\neq p}^{M} \sum_{p\neq l}^{M} Cov\left(\left| \sum_{k=1}^{N} e^{-js_{nm}z_k\omega_l} \right|^2, \left| \sum_{k=1}^{N} e^{-js_{nm}z_k\omega_p} \right|^2 \right). \tag{2.12}$$

   The random variables z_k are equal for all Ω_l: this means that the arguments are strongly correlated. However, the exponent function erases these covariances, as the arguments $js_{nm}z_k$ are multiplied by a different ω_l. This corresponds to uncorrelated spectral lines.

Finally we can summarize the results of the model for the variance[9] in Figure 2.4, which shows that the variance of the crosstalk power tends to 0.5 if the crosstalk was generated by a CW and a signal modulated in all the possible modulation formats. When the *skew per symbol rate* starts to increase the crosstalk variance starts to decrease until reaching zero for carrier-free modulation such as the Quadrature Phase Shift Keying (QPSK) and 0.12 for modulation with strong carrier such as the On-Off Keying (OOK). This happens due to the de-correlation of the neighboring frequencies: when the skew-symbol-rate product reaches 1 this product starts to increase. When it becomes larger than the random phase variations, it starts to delete the covariance among the frequency components of the signal. Since the strong carrier modulations have not a flat spectrum, the signal carrier has a strong contribution; there is never a total decorrelation and as a consequence the

variance of the crosstalk reaches a bound upper than zero. For this reason links that use modulation with strong carrier requires an additional performance margin.
This behaviour that links the variance with the skew per symbol rate has also an important impact in the behaviour with respect to the length of the fiber, since the skew is defined as $d_{mn}L$ with L length of the fiber. For long-haul transmission systems with carrier-free modulation formats there is a constant average contribute of the crosstalk, instead, for short-haul transmission systems the crosstalk has random fluctuations and these systems require an additional performance margin.

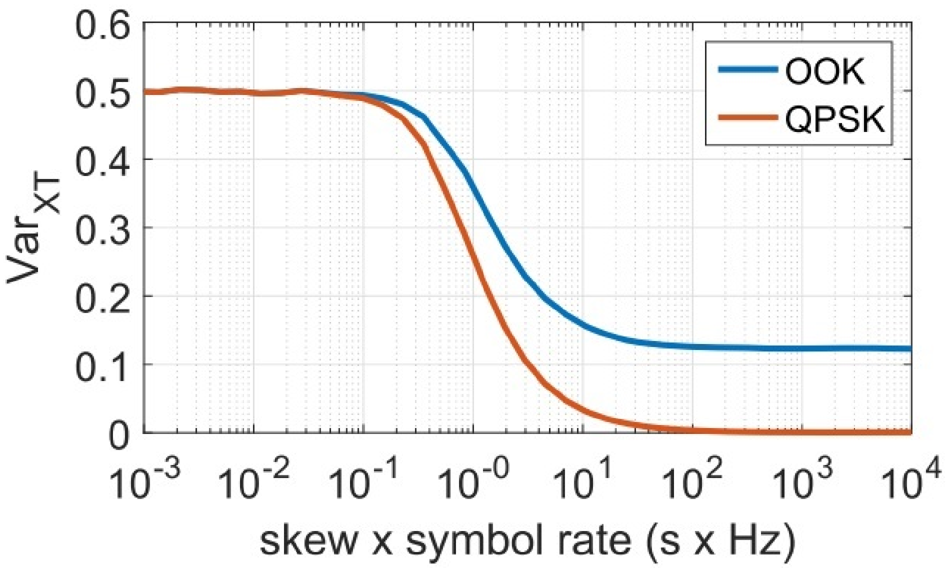


Figure 2.4: simulated variance of STAXT for OOK and QPSK modulated signal a various value of skew-symbol-rate[9]

2.5 Multiplexer and demultiplexer for MCF

The MCF must be connected to a bundle of SMFs. These fibers have usually a standard cladding diameter of 125 μm whereas the cladding diameter of MCFs may range from 125 to 250 μm with a core pitch, the distance between the cores, between 30 and 50 μm[16]. It is not possible to simply splicing the single core fibers with the cores of the MCF. A device performing MUX/DEMUX operations is needed to efficiently couple each core of the MCF to a single SMF. There are two methods to realize this operation

- direct coupling method;
- indirect coupling method.

In the *direct coupling method* there is a waveguide-optics interface that directly connects the MCF with the SMFs. An example is the waveguide integrated device[17] in this device each core of the MCF can be addressed to single fibers separately by inscribing ultra-fast waveguides. In this example a MCF with 4 cores was employed, thus the waveguide integrated device has 4 inputs, as show Figure 2.5.
Each waveguide is directly connected to a core of the MCF, so the position of the waveguides is designed to perfectly match the lattice of the cores. Moreover these devices are addressed for single mode MCF. Both these characteristics make this setup a solution of little flexibility.
More in general devices that use direct coupling method offer the advantage, to be compact. On the other hand they require a sophisticated splicing technology, which may be an additional source of loss and crosstalk.
In the device taken in example, reported in [17], the performance of each waveguide was investigated separately, using ASE as source for the measures. The insertion losses (ILs) in the 1.55 μm spectral region for each of the four waveguides were measured to be 5.4 dB, 3.3 dB, 3.1 dB and 5.0 dB for waveguides 1, 2, 3 and 4 respectively. The error in the IL measurements is estimated as $\approx$ 0.2 dB due to alignment accuracy; due to the nature of the measurement, however, the true IL cannot be higher than measured one. The IL due to coupling losses is of 1.0 dB, $\pm$ 0.4 dB the remaining part is due to propagation, crosstalk and bend losses.

Indirect coupling method does not require a splice between MCF and SMFs;

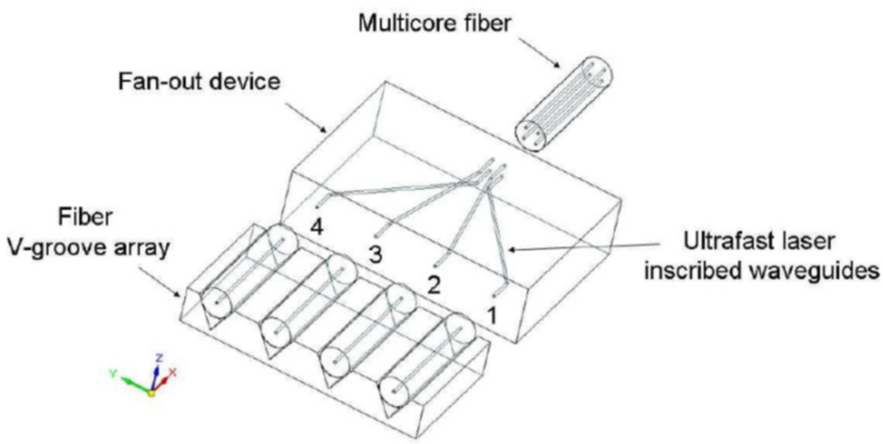


Figure 2.5: an example of waveguide for a MCF with 4 cores

devices that use this method are more flexible than devices that use direct coupling method. An example of them is the free-space bulk optics MUX that, since it is easier to implement, is a more widely diffused device. It works as described in[18]. The MCF facet is placed in the front focal plane of a single lens which translates the laterally displaced diverging beams emerging from the MCF cores into a bundle of collimated beams each one propagating at a slightly different angle and crossing the optical axis at the lens back focal point f_{MCF}. The propagation over a few centimetres is sufficient to spatially separate the beams and focus them onto the facet of each SMF as shown in Figure 2.6. To facilitate the coupling on the SMF side, the beams carrying the light of the inner and outer cores are deflected by two layers of circularly arranged prisms. In this way, the SMFs need not to be in a conical arrangement, but they can be placed in two separate planes denoted as top and middle layer as shown in Figure 2.7. The flexibility of this device and in general of the coupling devices that use this method lies in the fact that it could be used also with MCFs with different core pitches and cladding diameters without building a new device. It is sufficient to adjust the lens position; this allows to have a more generic device with respect to coupling devices that use direct coupling method. From the point of view of the performance, as reported in[16] and in[18] the average insertion loss, when a MCF with 19 cores and a MUX/DEMUX of 19 channels are used, was measured to be 1.3 dB with a variation of ± 0.2 dB across all 19 channels. This value includes also losses due to connectors at the interface between the optical source and SMF on the MUX side (<0.5 dB) and to two uncoated MCF facets (0.3 dB). Other contributions can be attributed to the combined loss of AR-coated optical surfaces inside both coupling devices, which was estimated to be in the range of $0.2 - 0.3\,dB$, and the loss due to mode field mismatch at both fiber facets which was estimated by numerical calculations to be 0.4 dB in total. The maximum aggregate crosstalk of the 19 channels was measured at the center and in the inner cores and amounted to -50 dB.

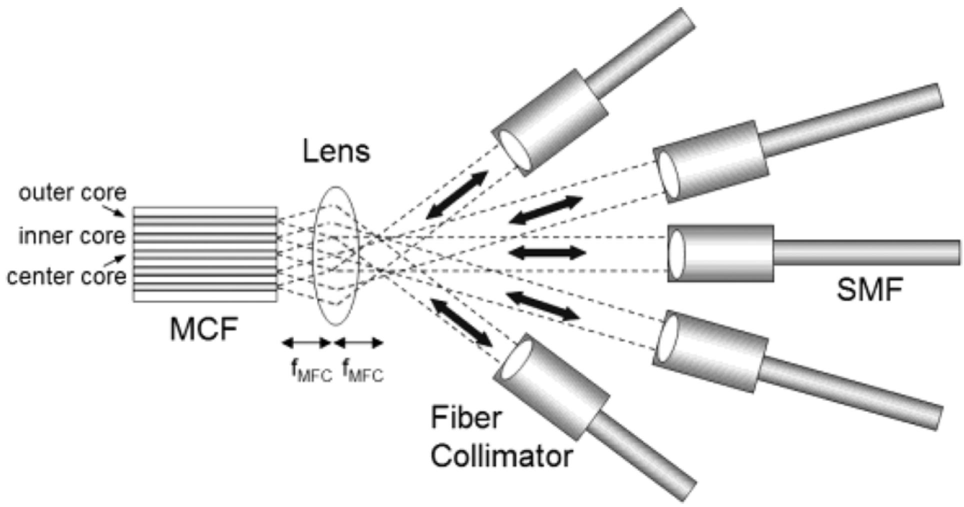


Figure 2.6: the coupling with free-space bulk optics[18]

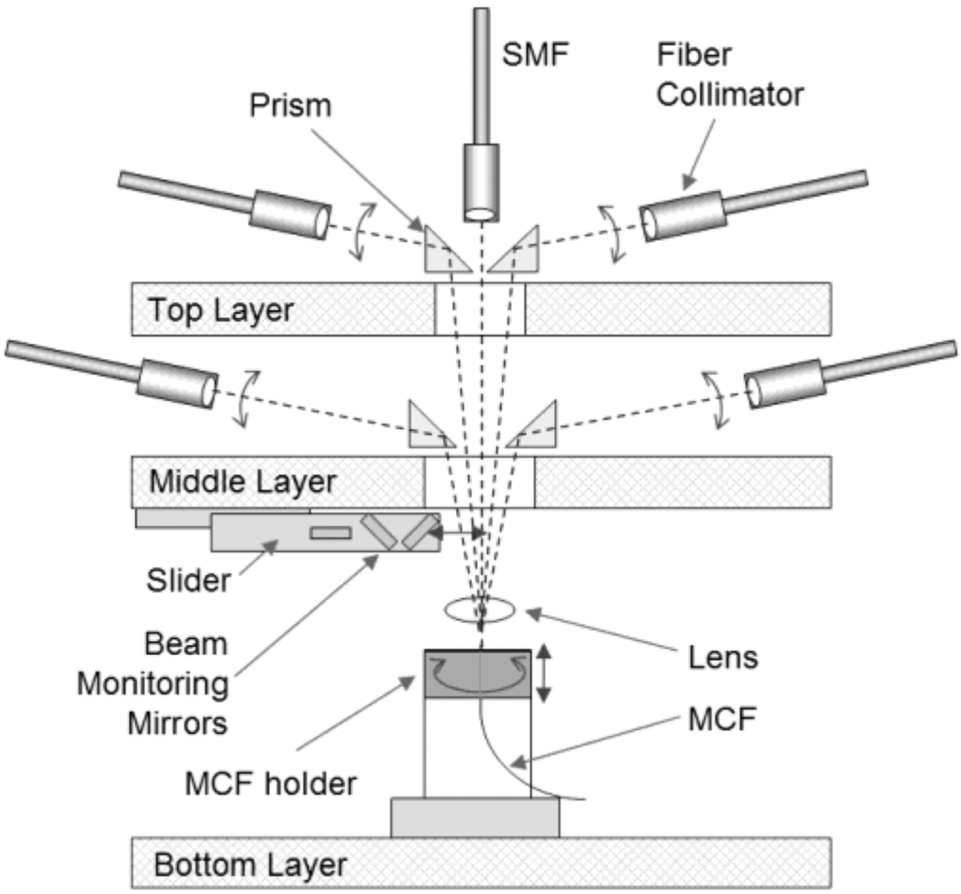


Figure 2.7: cross-sectional view of the 19-channel coupling device[18]

Chapter 3

The characterized 7-core MCF

For the characterization of the ICXT in the MCFs we use a 7-core MCF made by the Photonic Network Systems Lab at National Institute of Information and Communications Technology (NICT) in Japan. The fiber is long 2.9 km, each fiber core has a step-index profile with a cladding refractive index of 1.4445, a cladding diameter of 160 μm, a core pitch of 44.3 μm and a core-cladding index difference of 0.42%. The seven cores are arranged in a circular structure; there are 6 outer cores around one central core. Two 3D waveguide couplers, made by optical network group Lab of UCL London, act as SDM multiplexer and demultiplexer. They are direct coupling method devices described in 2.5. The average loss is 4 dB per core.

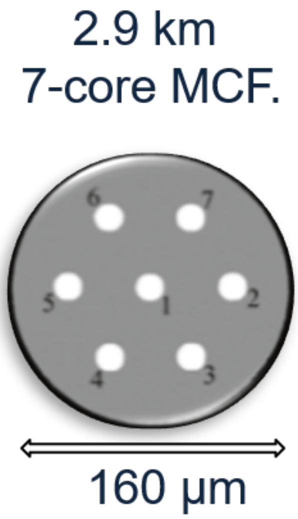


Figure 3.1: section of the MCF under test

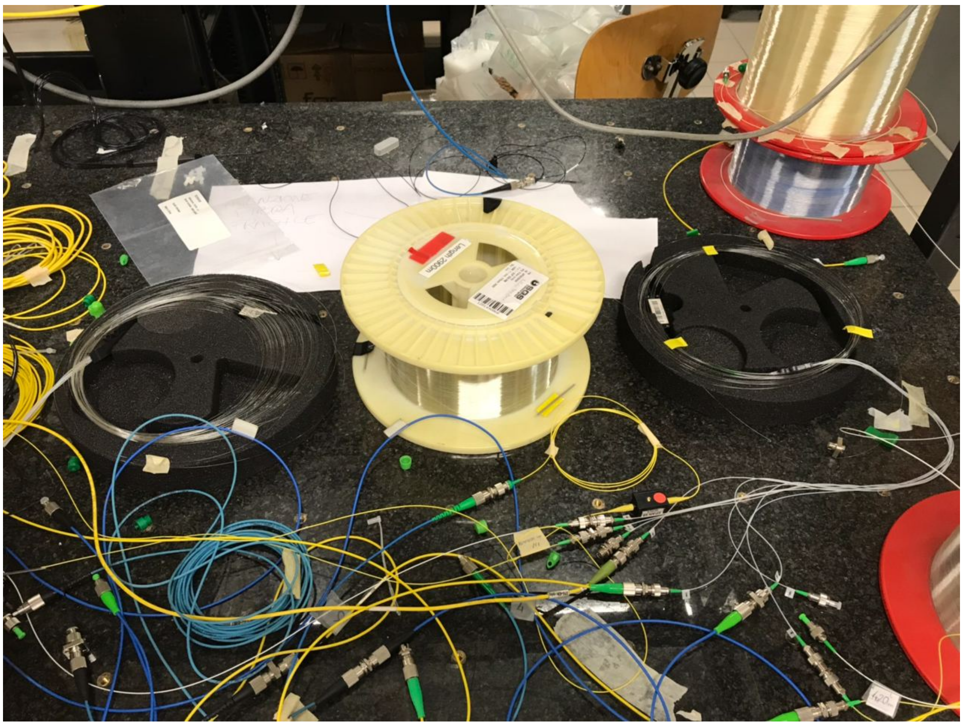


Figure 3.2: The MCF under test

Chapter 4

Experimental setup

4.1 Experimental setup for ICXT measures with single source

The ICXT measures were performed in the Policom laboratory, the Optical Communications Lab at Politecnico di Milano.
The experimental setup is shown in Figure 4.1. We used a 500 kHz linewidth distributed feedback laser (DFB) to generate the optical signal; the modulated signals were externally modulated by a Mach-Zehnder modulator (MZM). After the modulator, the signal was amplified by an Erbium-Doped Fiber Amplifier (EDFA) and it entered in a polarization controller. After that, it passed in a Polarizing beam splitter (PBS) that splitted the input in two outputs, one received by a power meter the other one, was filtered in order to cut the ASE noise. The output of the filter was further amplified by an EDFA with a gain of 30 dBm, followed by a splitter with 8 outputs. One of these outputs was connected to a variable optical attenuator (VOA) in order to obtain the desired power for the signal that generated the ICXT. The output of the VOA entered in the *fanin* of the MCF fiber i.e. the multiplex device described in paragraph 2.5. At the output of the MCF, 6 of the 7 outputs of the *fanout* (i.e. the demultiplex device) were connected to a switch. The switch was connected to a power meter and both these devices were controlled by a PC. The remaining output was further amplified by an EDFA, than it was filtered and further amplified. Finally, it was splitted in two arms, one connected to a polarimeter to monitor the polarization evolution and another one detected by a photo-diode by direct detection.

4.2 Experimental setup for ICXT measures with two sources

Figure 4.2 shows the experimental setup of the ICXT measure in case of the 7-core MCF, described in chapter 3, with two signals that contributed to the overall ICXT. These two signals are coming from different laser sources. We used a 500 kHz linewidth DFB to produce the signal transmitted in the central core. Similarly, we used a 300 kHz tuneable external cavity laser (ECL) to produce the signal transmitted in the outer core. In order to emulate independent signals, a SMF span was used for temporal decorrelation, with the length chosen to exceed to coherence length of the tuneable laser. The ECL wavelength was tuned to within few hundreds of MHz from the DFB one. The ICXT was purposely increased to emulate the behaviour of longer links by launching high power (+10 dBm average power) in one of the outer cores and -10 dBm in the central one. The nominal wavelengths of the DFB and tuneable source were 1550 nm, while both signals were externally modulated by a MZM. The other components were the same described in the previous paragraph, with the exception of the ASE source that in this experiment was not present.

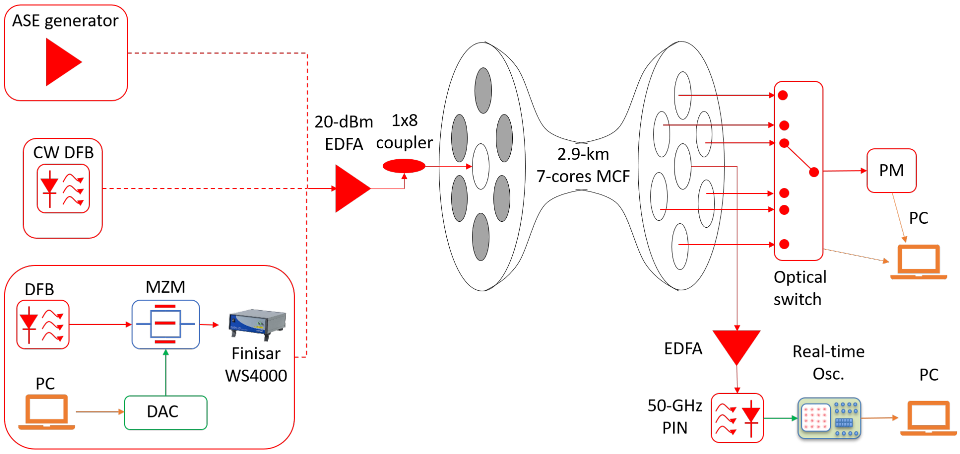


Figure 4.1: setup of experiments with one signal that generates ICXT

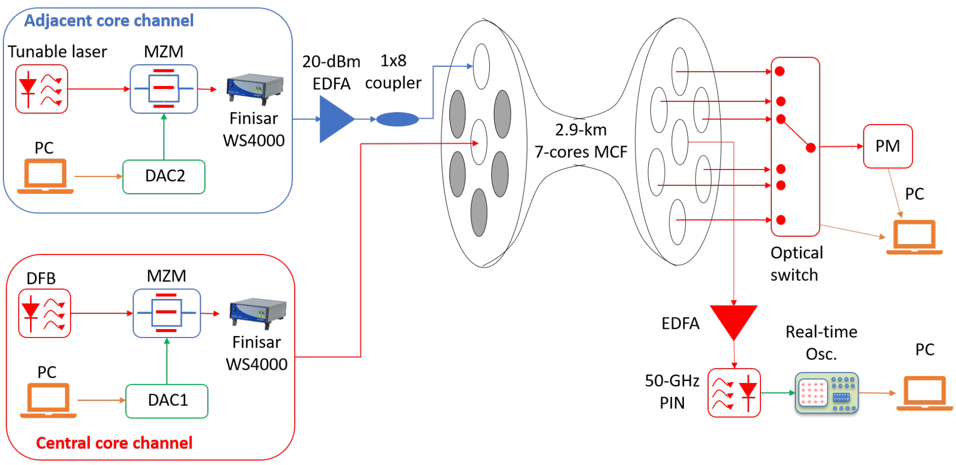


Figure 4.2: setup of experiment with two signals that contribute to the ICXT

Chapter 5

Experimental crosstalk characterization

5.1 Preliminary characterization of the 7-core fiber

We did a preliminary characterization of the fiber under test, described in chapter 3, using ASE as source. The aim of this characterization is to evaluate the ICXT induced in case of broad linewidth of the employed laser. The ASE had a power of -9.5 dBm and it was transmitted only in one core for each measure of the characterization. In the table 5.1 the measured ICXT is reported, in the rows there are the inputs, the core which carries the source while in the columns there are the outputs. In the diagonal there is the measured attenuation for each core. The values are already normalized to the power entering in the MCF and take care also of losses due to: connectors, the switch, the input/output SMFs and the optical measurement tools.

5.2 The experimental measures

From the previous characterization of the fiber, the central core is the core called number four. In the next paragraphs we report the measured ICXT done with different source conditions: they differ for bandwidth, linewidth and modulation used. We used either ASE or CW or DMT signals with SSB or DSB modulation. We chose to use the DMT modulation format because it is an adaptive modulation format: the basic idea is to split the available bandwidth into a large number of OFDM subcarriers. DMT can allocate data so that the throughput of every single subcarrier is maximized; in the MCF this means allocate more data in the subcarriers less affected by

ICXT. If some subcarriers are too penalized by ICXT, they can be turned off. The signal that generated the ICXT was transmitted only in the central core, except to the last two paragraphs. The DMT modulated signal had an electrical bandwidth of 20 GHz, a power of -10 dBm and a wavelength of 1550 nm in all the experiments. The measures were done reading the power in the 6 outer cores for 16 hours (5 hours in the last experiment reported in this chapter), reading it in each core every 30 seconds. In these 30 seconds the power was measured in each core for one second, the last 24 seconds were idle time between measures. Since no signal was transmitted in the outer cores, in them we had only ICXT. In all the following figures, in the data represented in the graphics, the continuous lines are instantaneous data while dashed lines are the smoothing average that represents the trend of the power during time (we are cleaned from spike).

5.3 ICXT measure with ASE source

We measure the ICXT using as source the ASE coming from an amplifier with an output power of -9.5 dBm. The results obtained are shown in Figure 5.1. They are coherent with the theoretical model in paragraph 2.4 and confirm that the ICXT has a constant contribution in case of ASE as source. In the table 5.2 we report the statistics of the measure. All the values are in dB; these data highlight the few variation of the ICXT in these conditions. In Figure 5.2 we show the power distributions of core called 1 and core called 5 that since the variance is ≈ 0 they are both shrink around the mean value (-50.5 dB). The power distributions of the others cores are not reported because there are few differences between cores so the histograms are very similar between them.

	Output						
	core 1	core 2	core 3	core 4	core 5	core 6	core 7
core 1	-4	-50.1	-51.25	-49.3	-53.7	-60.4	-65.3
core 2	-50.3	-3.9	-59.4	-51.05	-50.2	-56.3	-59.2
core 3	-50.8	-57.3	-3.7	-49.05	-54.9	-51.9	-56.8
core 4	-49.2	-50.8	-49.85	-2.8	-50.2	-51.7	-51.4
core 5	-55	-51.3	53.85	-50.9	-3	-57.7	-49.9
core 6	-48.7	-50.6	-50.55	-47.4	-54.1	-3.9	-49
core 7	-62	-54.6	-58.65	-49.4	-49.9	-49.4	-4.1

Table 5.1: ICXT characterization of the 7-core fiber

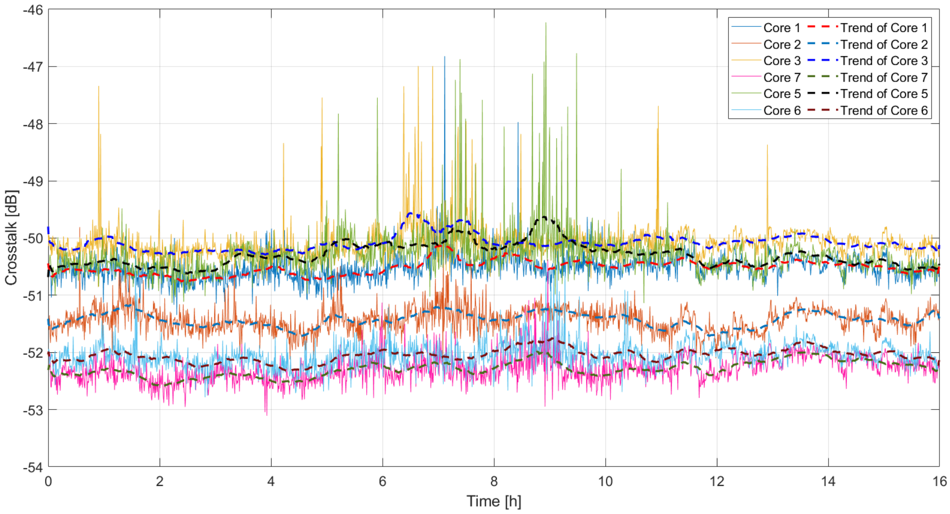
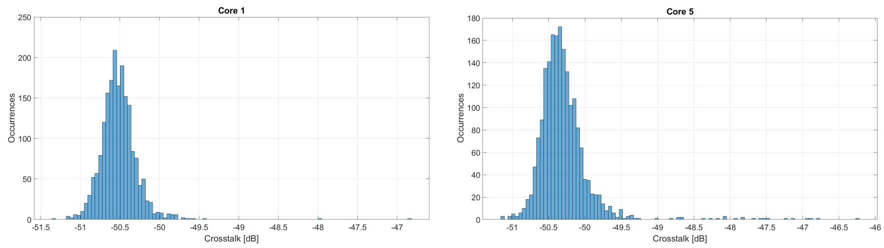


Figure 5.1: ICXT power with ASE source



(a) power distribution of core 1

(b) power distribution of core 5

Figure 5.2: power distributions of core called 1 and core called 5 with ASE as source of the ICXT

statistic	core 1	core 2	core 3	core 5	core 6	core 7
mean	-50.518	-51.427	-50.084	-50.294	-52.045	-52.288
variance	0.054	0.048	0.098	0.149	0.051	0.052
peak to peak	4.525	2.389	3.865	4.908	2.569	2.734
maximum	-46.821	-49.809	-46.992	-46.23	-50.215	-50.374

Table 5.2: statistics of the ICXT with ASE source

5.4 ICXT measure with CW signal source

We measure the ICXT using, as signal source, a continuous wave directly coming from a DFB laser. The DFB laser is characterized by a narrow linewidth compared to the ASE source, previously tested. The power of the source signal entering in the fiber was -10 dBm with a wavelength of 1550 nm. The results obtained are shown in Figure 5.3. They show, as expected, a variation of the crosstalk very fast and also very large in amplitude i.e. the peak to peak reaches 15 dB. This behavior of the ICXT is better understandable in the table 5.3 which shows the statistics of the measure. Moreover the table shows that there are not substantially differences between cores. The graphic shown in Figure 5.4 is the sum of the ICXT contributions of each outer core. The results show that a constant trend is present in the long period. However, in short period there are some fluctuations: the behavior is comparable to the ICXT observed in the cores, shown in Figure 5.3.

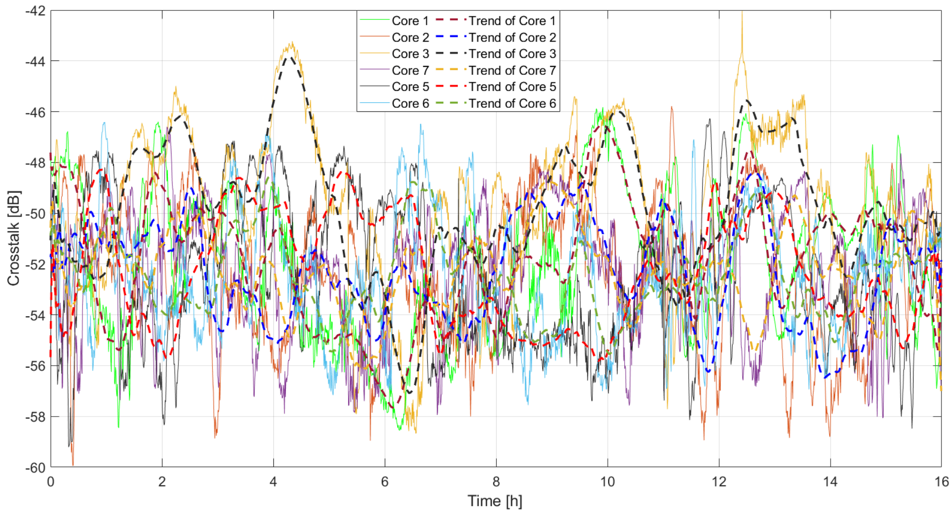


Figure 5.3: ICXT power with CW as source

5.5 ICXT measure with DMT DSB signal source

In this measure a signal modulated with DMT modulation in case of dual side-band spectrum (DMT DSB) was used. The obtained results are summarized in Figure 5.5. They show a behavior similar to the one obtained with CW as signal source, also the statistics reported in table 5.4 and the sum of the ICXT contributions shown in Figure 5.6 are similar. This experiment condition allows to analyze the ICXT behaviour in case of a signal mod-

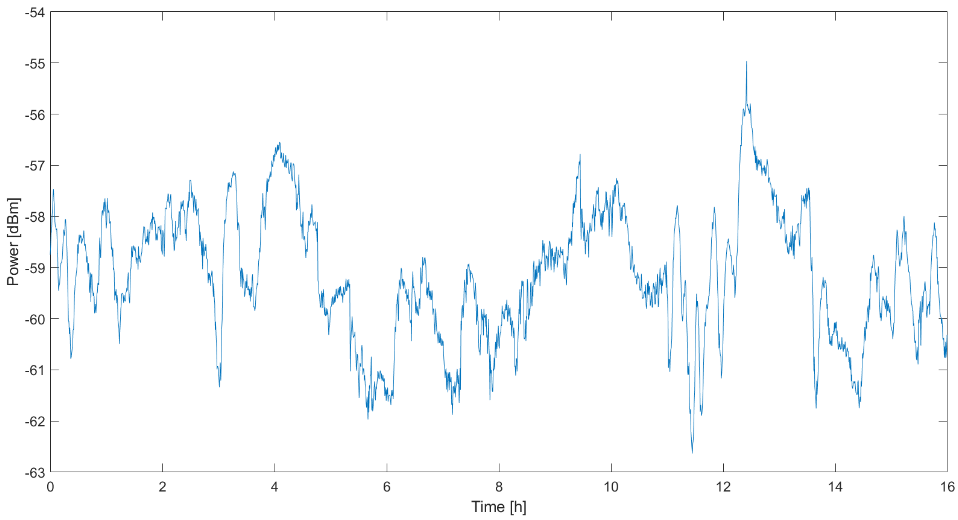


Figure 5.4: sum of the power contributions of each outer core with CW as source signal of ICXT

statistic	core 1	core 2	core 3	core 5	core 6	core 7
smoothing mean	-51.860	-52.302	-49.770	-52.311	-52.426	-52.276
mean	-51.859	-52.297	-49.772	-52.316	-52.431	-52.268
smoothing variance	5.819	4.011	6.863	4.778	2.601	2.497
variance	8.325	7.253	9.733	7.864	5.370	5.547
smoothing peak to peak	11.128	8.088	13.269	7.551	6.974	8.227
peak to peak	12.734	14.16	16.642	12.938	11.143	11.472

Table 5.3: statistics of the ICXT with CW as source

ulated with a very interesting format such as DMT. DSB spectrum covers around 40 GHz around the carrier.

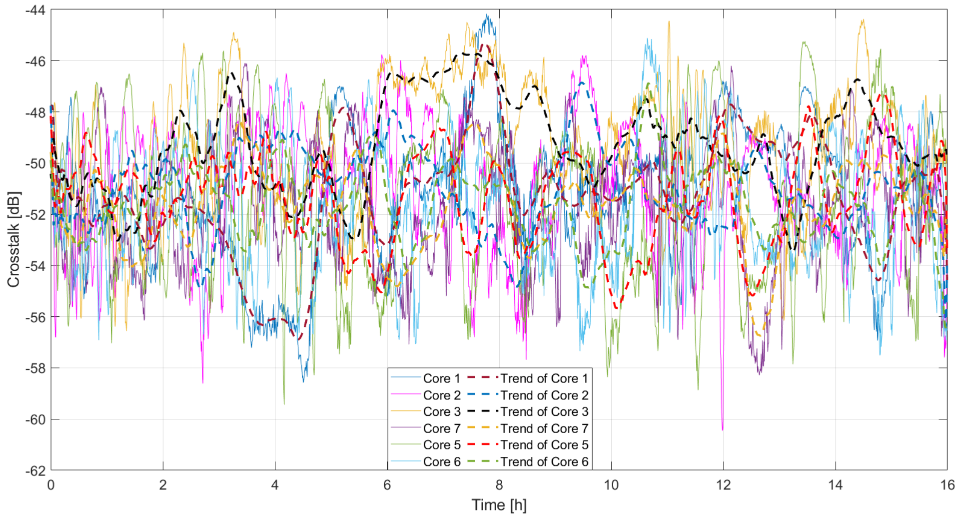


Figure 5.5: ICXT power with source a DMT DSB modulated signal

5.6 ICXT measure with DMT SSB as signal source

We measured ICXT made by a signal modulated with DMT modulation in case of single side-band spectrum (DMT SSB). In this case, filtering just a single side-band the bandwidth of the DMT signal is around 20 GHz. The obtained results, shown in Figure 5.7, are very similar to the results achieved using DMT DSB as signal source, also the statistics reported in table 5.5 and the sum of powers contributions of the ICXT in Figure 5.8 are very similar.

5.7 ICXT measure with a DMT SSB signal source transmitted in one outer core

We measured the ICXT generated by transmitting a DMT SSB modulated signal in the core called 1 that is an outer core. The results obtained are summarized in Figure 5.9 while the statistics of the measure are reported in table 5.6. Experimentation is done in case of DMT SSB signal. It is possible to notice an average power difference of 10 dB between the couple of cores composed by core called 6, core called 7 and the others cores, being

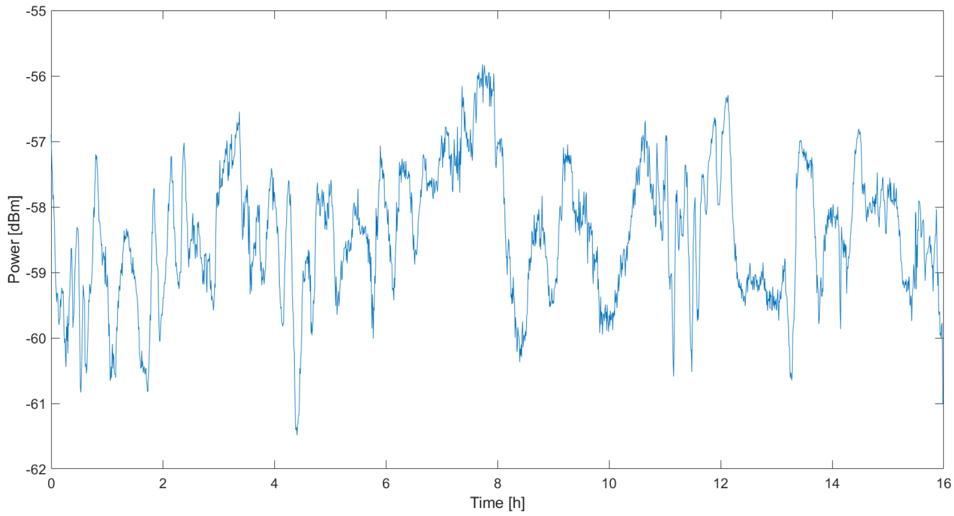


Figure 5.6: sum of the power contributions of the outer cores with source a DMT DSB modulated signal

statistic	core 1	core 2	core 3	core 5	core 6	core 7
smoothing						
mean	-51.239	-50.951	-49.296	-51.389	-51.612	-51.630
mean	-51.237	-50.948	-49.299	-51.393	-51.606	-51.635
smoothing						
variance	4.963	2.540	3.467	3.315	2.114	2.527
variance	6.681	5.624	5.895	9.326	5.957	5.715
smoothing						
peak to peak	11.611	9.580	7.813	8.399	9.682	8.401
peak to peak	14.407	14.695	12.189	12.186	12.386	14.193

Table 5.4: statistics of the ICXT with DMT DSB modulated signal as source

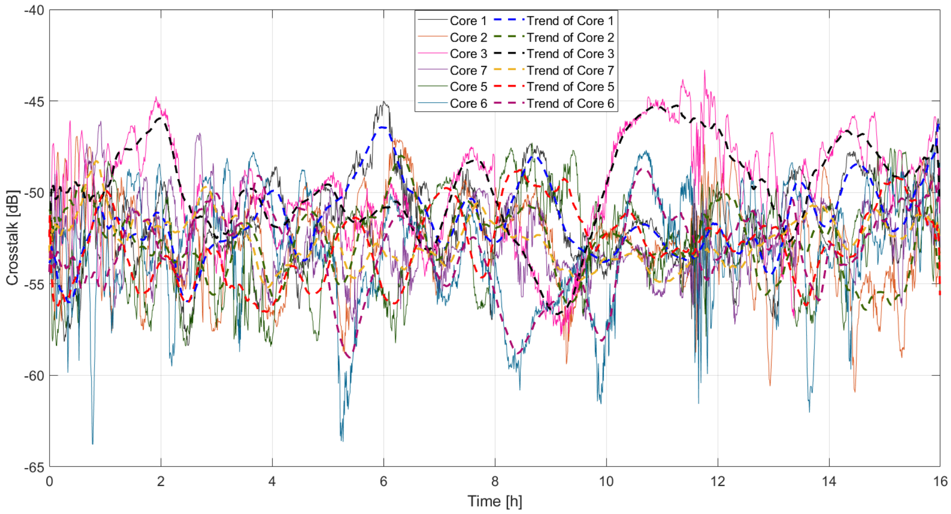


Figure 5.7: ICXT power with source a DMT SSB modulated signal

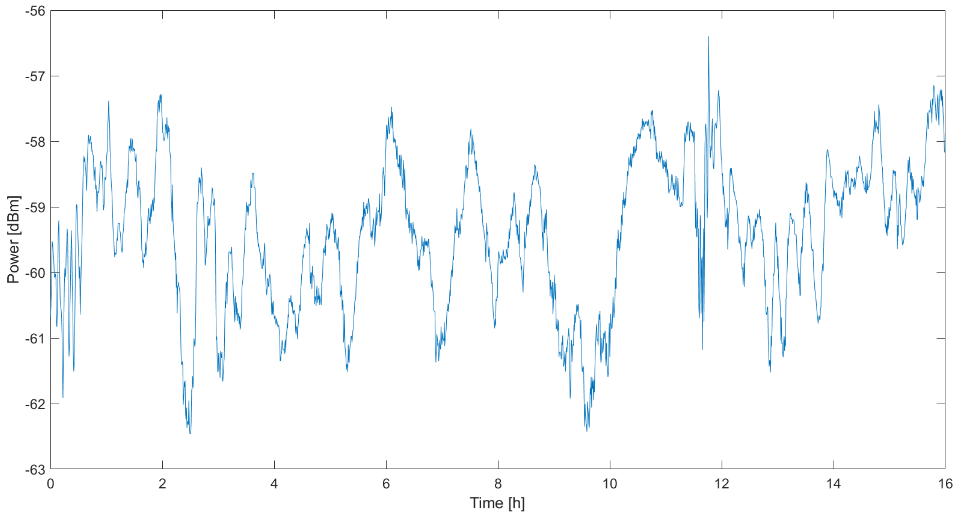


Figure 5.8: sum of the power contributions of each outer core with source a DMT SSB modulated signal

the core called 1 an outer core. From the data, it is possible to conclude that the core called 7 is the opposite core with respect to core called 1. The differences between core called 5 and core called 6, which should have a similar behavior, are probably, due to the fact that either the fiber used for the measure was rolled up or the cores are not perfectly symmetric.

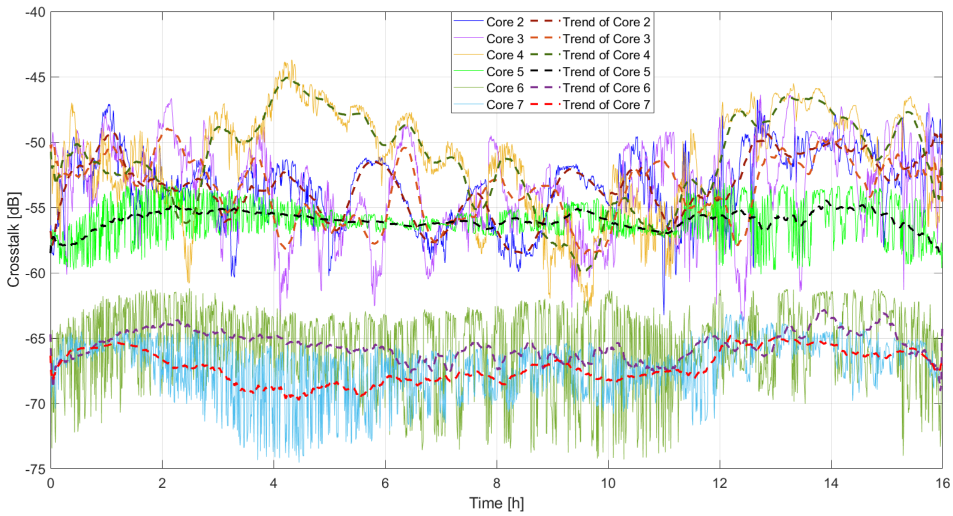


Figure 5.9: ICXT power with source a DMT SSB modulated signal transmitted in an outer core

5.8 ICXT measure with two DMT SSB signals sources transmitted in core called 1 and in core called 4

For this measure of the ICXT we used the experimental setup described in paragraph 4.2. The results obtained are shown in Figure 5.11. The graphic has less resolution in showing the crosstalk variations than in previous cases, this happens due to the fact that it was read also power in the core called 1 in which there was also a signal, not only ICXT. The data show that core called 1 is the main source of ICXT, since core called 6 and core called 7 are the most distant cores from core called 1, they see less the impact of the propagating signal in core called 1. For this reason core called 6 and core called 7 have a smaller ICXT than the other cores. The ICXT fluctuations in core called 2 and core called 3 are due to beating between the two signals propagating in the core called 1 and in the core called 4.
The statistics of the measure in table 5.7 show a very stability of the signal

statistic	core 1	core 2	core 3	core 5	core 6	core 7
smoothing						
mean	-51.585	-52.739	-49.783	-52.830	-53.170	-52.627
mean	-51.599	-52.729	-49.778	-52.834	-53.172	-52.623
smoothing						
variance	3.869	3.134	6.516	4.0347	5.416	1.782
variance	5.949	6.383	8.390	6.791	10.014	3.931
smoothing						
peak to peak	9.714	8.412	11.407	7.779	10.455	6.901
peak to peak	13.373	14.009	14.548	11.149	16.386	11.64

Table 5.5: statistics of the ICXT with source a DMT SSB modulated signal

statistic	core 1	core 2	core 3	core 5	core 6	core 7
smoothing						
mean	-53.359	-53.603	-51.299	-55.980	-65.586	-67.212
mean	-53.350	-53.609	-51.298	-55.978	-65.582	-67.208
smoothing						
variance	4.932	5.592	12.256	0.468	1.183	1.562
variance	7.521	11.924	15.222	1.927	8.839	4.367
smoothing						
peak to peak	9.213	9.569	14.864	4.089	6.281	4.909
peak to peak	16.466	17.37	19.258	6.983	13.097	11.434

Table 5.6: statistics of the ICXT with source a DMT SSB modulated signal transmitted in an outer core

power propagating in the core called 1. In this case, the mean value of the core called 1 in the table is not ICXT; it is the difference between the power of the signal propagating in it and the power of the signal propagating in the core called 4.
The ICXT is higher than in previous cases: this happens due to the presence of two signals instead of one and due to the fact that the reference power, for which the ICXT is calculated, is -10 dBm. The variance and the peak to peak, reported in table 5.7, are similar to the previous cases. The sum of powers read in the outer cores is reported in Figure 5.11 showing little variations during the 5 hours of measurement. However, the power read in the core called 1 is much more higher than the power read in the others cores. The presence of a signal in core called 1 has the effect that the power read in it *dominates* over the power read in the others cores; therefore, the sum of powers read in the outer cores, in this case, it is mainly the power read in the core called 1.

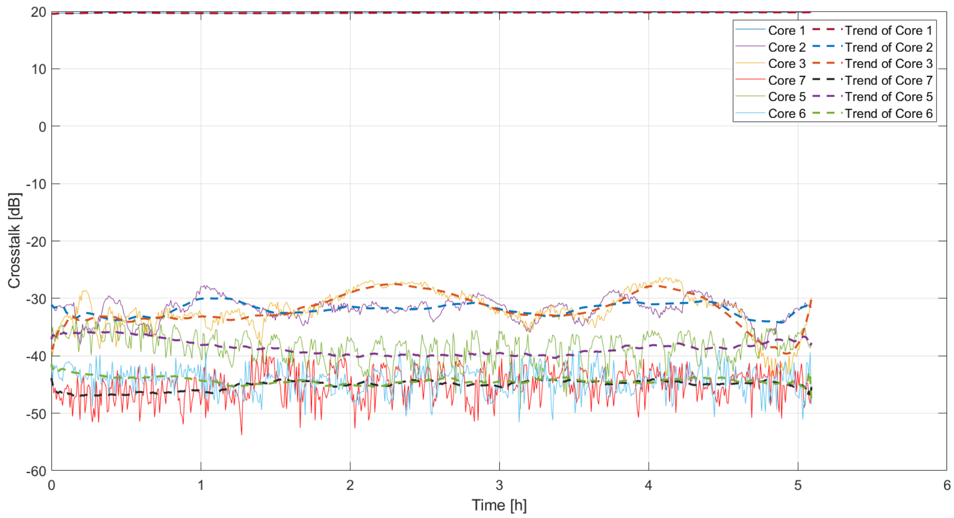


Figure 5.10: power measured in the 6 outer cores of the MCF with two DMT SSB modulated signals as sources of ICXT

5.9 Position of the cores

In the experimental measure reported in paragraph 5.7 it is possible to notice an average power difference of 10 dB between core called 1, the core in which the signal was transmitted and core called 7, the core with the lower ICXT measured power. The higher ICXT measured power in core called 2 and core called 3 with respect to the other cores suggests that they are the two

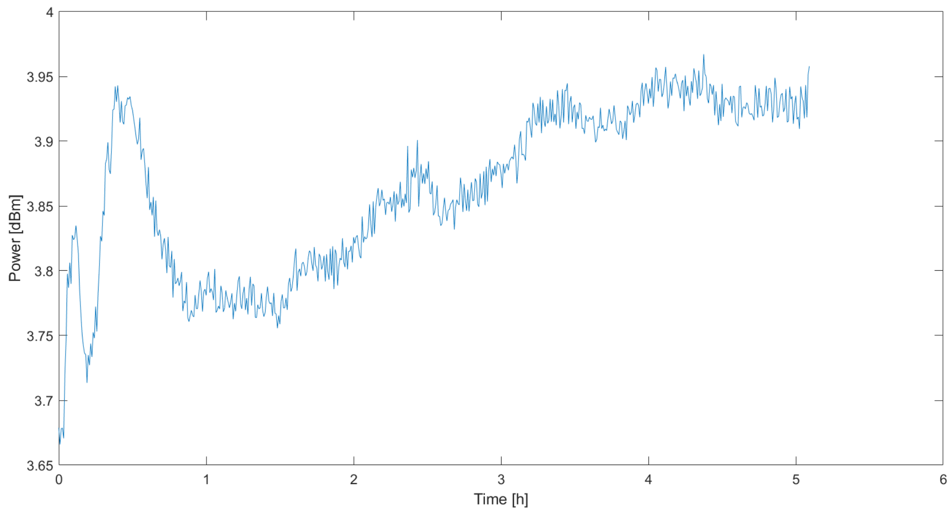


Figure 5.11: sum of the power contributions of each outer core of the MCF with two DMT SSB modulated signals as sources of ICXT

statistic	core 1	core 2	core 3	core 5	core 6	core 7
smoothing mean	19.763	-31.903	-31.999	-38.545	-44.319	-45.125
mean	19.763	-31.950	-32.026	-38.539	-44.325	-45.126
smoothing variance	0.003	1.101	7.780	1.723	0.397	0.687
variance	0.004	4.002	12.132	6.536	4.996	7.354
smoothing peak to peak	0.283	4.219	12.120	4.524	7.011	3.206
peak to peak	0.3012	11.175	17.309	15.981	12.668	15.493

Table 5.7: statistics of the ICXT with two DMT SSB modulated signals as sources

closest cores to core called 1. The other experimental measures confirm that core called 4 is the central core. Finally, it is possible to do a hypothesis about the position of the cores into the MCF shown in Figure 5.12.

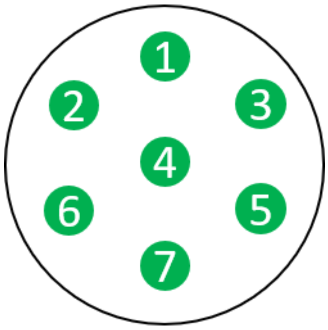


Figure 5.12: hypothesis about the position of the cores into the MCF

Chapter 6

Conclusions

We investigated time-dependent performance impairments due to ICXT in a 7-core MCF, produced by NICT, in presence of different kinds of sources transmitted in the central core. We confirm that with ASE source we have a constant contribution of the ICXT impairments. Instead with CW and DMT SSB and DSB signals, we have a strong variation of the ICXT, even in the order of tens of dB during long period (16 hours of measure). We did also an experiment in which we transmitted two DMT SSB signals in two cores of the MCF, respectively, one transmitted in an outer core and the other one transmitted in the central one. The two sources feeding the different cores are at the same nominal wavelengths. We obtained a ICXT with an average value higher than in the cases in which there was only a single source, however, the variance and the extreme values not changed significantly. We can conclude, from our experiments, that the modulation used and the bandwidth of the signal have a negligible impact in the ICXT behaviour. We observed that its fluctuations do not increase if there are more than one source that contributes to the overall ICXT. We can expect that with all the cores excited there will be a ICXT with an higher mean value, however, a variance smaller than in the case in which only one core is excited. The future develop of this work could be confirm the hypothesis about the behaviour of the ICXT with several sources, doing an experiment in which all the 6 outer cores are exited.

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