### Master thesis in

# Machine Learning Enabled Nonlinear Phase Noise Mitigation for a Coherent Optical System

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A thesis submitted in partial fulfillment of the requirements for the degree Master in Photonics



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# Dedicated to

the endless source of knowledge that we all strive to be part of. Life has given me the chance to pursue my dreams, light has given me a way to understand my life.

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#### Abstract

In recent years, the process of absorbing two photons using a non-classical light sources has been studied thoroughly. In particular, it has been experimentally demonstrated that the absorption cross section of two entangled photons is much greater than the absorption cross section of two uncorrelated photons. In this dissertation a source of entangled photons produced through spontaneous parametric down conversion or SPDC was constructed and characterized. It was found that for a pump laser of 411.32 nm and a BBO crystal of 1 mm the produced photons followed the same optical path as the laser, it was also found that the joint spectrum is symmetric at the degenerate wavelength of  $822 \pm 0.5 \ nm$ . This work conclude by showing a first approximation to execute a measurement of the Hong-Ou-Mandel effect. The objective of the measurements of joint spectrum and the Hong-Ou-Mandel effect are to understand the correlation properties of the photon source, with this information a virtual state spectroscopy technique can be implemented on the experiment constructed.



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CHAPTER

ONE

### INTRODUCTION

Throughout human history technological innovation has redefined our experience in the world, changing the way we interact with each other and the perception of the distances that separate us. Communication is basic need for anyone; however, our expectations on what communicating means has transformed through time. Most recently, from the beginning of the new millennium we require fast, long reach and high capacity telecommunication systems, like the telephone network or the This are not simple requirements, consider that just under 250 years ago the United States Postal Services was established to bring a way of sending and receiving information through a robust network throughout North America, which was a great innovation at the time, but it does not come close to fulfill the requirements that seem natural to us today. Our current communication needs are in some ways more similar to the mailing system than to a phone network in the beginning of the 19th century. We expect to send and receive packets of any size, to a location as convenient as possible, with reliable service and with little hassle to the user. A phone network from the beginning of the 19th century was nothing close to this, usually with single phone for large areas. It was connected by operators that required information from the user and had poor coverage with low reliability.

Today we take for granted the technology developed to satisfy our need to communicate over a reliable and robust network. It is common practice for most of us to connect with family members or friends that may be anywhere around the world or request information from any server in the world. Just two decades ago it wasn't possible to depend so reliably on the communications networks due to low capacity, lack of redundancies and inefficient routing schemes that added latency to the network [1]. As powerful as our current networks might be, it is the human way to find higher and more complex requirements for the way we communicate. When the first consumer deployment of 3G in 2001 was implemented most consumer analytic professionals questioned the idea of offering such a large capacity to consumers [1]. At the time there was no service that used the full capacity of the bandwidth offered. Now we know that you just have to give the tools to the public and use scenarios will show up as did Meme sharing or video streaming.

Current networks can handle heavy loads but in the future the need of low latency communication ( for self-driving cars or remote surgeries), the Internet of

Things (IoT), high quality video streaming and others will require creative solutions to the current limits of communication systems. New technology will be deployed in the network, improving its capacity, but there is also a need to extract as much use from older networks to maintain there current coverage and reduce costs. Coherent Optical telecommunications gives a path forward that improves the network as whole, improving the current operating network and pushing the limits for the future transparent network [2,3].

## 1.1 General Objective & Motivation

In coherent optical communication the effects of dispersion and attenuation can now be compensated for. However, the noise that arises from the interaction between the optical power and the fibers optical Kerr effect limit the transmission length of the system [4]. The noise sources that arise from this interaction are known as nonlinear interference noise. The aim of this thesis is to study the effects of nonlinear noise in a coherent optical communication system and suggest a nonparameter digital signal processing detection scheme enabled by machine learning. Two communication links are built, a long-haul and a dense wavelength division multiplexed system, to detect nonlinear interference noise. Each communication link architecture is used to test if the suggested digital singal processing scheme improves the transmission distance of the signal compered to a traditional scheme.

Bringing together machine learning and optical communications has been on surge for the past decade and has been implemented in performance monitoring [5,6], modulation format identification [7] and amplitude/phase noise characterization [8]. This techniques improve the performance of the system and extends the operational capacity. Increasing the transmission length of the optical system allows a further reach simplifying the deployment of the network, and reducing the need of re-transmitter. Given that the most expensive part of deployment is digging and laying optical fiber it is necessary to reduce the deployment complexity and cost. Getting more use from older network segments helps improve coverage as well, resources can be allocated to reach more people instead of having to lay again the same network segments. The current bottle neck in a fiber link is the presence of nonlinear noise [9], machine learning could be a way to mitigate nonlinear noise without needing any information on the physical state of the fiber system [10]. This is a relatively novel idea that has been implemented in References [8, 10] and others. Our approach implements algorithms that have been improved over time and now enable more efficient and robust predictions.

## 1.2 Optical Telecommunications

Transporting information requires a protocol that standardizes a measurement of a physical event. Through time there have been many information links used to communicate at a distance from a smoke signal or a telegraph up to the telephone. All these have revolutionized our way of communicating and the reach at which we can expect to get an immediate response. Optical communication is the field interested in studying the implementation of communication systems using light as an information carrier. The beginning of Optical communication by this definition could be traced back to the Greeks in 1084 B.C where its said that a 500-km-long line of fire beacons was built to convey urgent messages, like the fall of Troy [1]. In the framework we understand optical communication now, a first proposal of a Fiber-Optic Communication was done by Jun-ichi Nishizawa in 1963 at Tohoku University [11]. This type of lightwave system uses optical fiber to contain a light pulse guiding it to a receiver, where it is detected and decoded into a digital signal containing information like voice message or video.

Today fiber-optic communication is the most prominent technology in long-haul communication, enabling the vision of a global society thanks to its effective reduction of immediate communication length. Fiber optics has also had a large implementation in the metro networks in the paste decade, due to improvements in fibers made out of polymers, reducing the cost of deployment [12]. When we place a call or use the internet, we expect a fast, reliable and robust coverage. These requirements set high constraints into the technology development. Not all communication needs can be satisfied with the same technology.

Currently, a combination of electrical and optical systems are used depending on the requirements given, each scheme has benefits an drawbacks. For long haul communications it is necessary to have a system that can be implemented over hundreds of kilometers, with high capacity and low latency, making fiber optics an ideal technology. Today's optical communications systems can fulfill these requirements but it has taken a lot of effort to develop and perfect a reliable communication link [13].

### 1.2.1 Brief History of Optical Communication

A more contemporaneous start to optical communications would be the invention of the optical semaphore telegraph in the 1790s by C. Chappe [14]. However, it took one more century for a new development in the field, in 1880s A. Bell created the Photophone an optical telephone system that never saw much use [1,14]. The 1960 marked a true revolution in optical communication thanks to the invention of the laser and glass fiber [15]. C. K. Koa, G. Hockman and J. Nishizawa where among the first to notice the potential of this new technologies [11,16], they realized that the attenuation in a fiber could be reduced to a usable value of 20 dB/km by decreasing the impurities in the glass fiber. At this time the attenuation was approximately 1000 dB/km in a usual fiber. Corning Glass Works was able to manufacture the worlds first low-loss single mode fiber operating at 633 nm with an attenuation of 20 dB/km in the 1970 making it commercially available by 1975 [1,14]. The technological developments achieved through the history of Optical Communications can been divided into four generations. Distinguishing from each generation the operating wavelength, data rate and transmission distance.

In the starts of 1975 the commercially available communication system was a multimode fiber with a 800 nm GaAs semiconductor laser. The systems main limitations was the high fiber loss, intermode and intramode dispersion [17]. Giving it a performance of 45 Mbit/s for a transmission distance of 10 km without repeaters. A set of improvements would be carried out in the next five years that tripled the data rate; thus, naming this first implementation a *first generation* link. [13]

Improvements done in 1980 allowed further reach and higher bit rate operation. By changing the operating wavelength and breakthroughs in glass fiber manufacturing substantial improvements to the technology where archived [13, 18]. Marking the start of the second generation link, which had a new InGaAsP semiconductor laser operating at 1330 nm with a low loss -at the time- 1dB/km single mode fiber. Second generation optical communication systems could reach a data rate of 1.7 Gb/s with a transmission distance of 50 km without repeaters [2, 18]. A significant improvement over the first generation; however, the fiber losses where still high and no dispersion management had been implemented yet.

At the beginning of the 1990 a solution was found to mitigate the fiber losses and have the minimum dispersion coefficient around the operating wavelength. The development of dispersion shifted fibers [13] enabled deploying longer fibers without presenting dispersive effects. The new communication system operated with a low loss single mode fiber 0.2 dB/km at 1550 nm. The two main breakthroughs in this third generation system was the shift to an operating wavelength with minimum attenuation and the improvement in the core-cladding fiber design such that the chromatic dispersion is minimum at the 1550 nm wavelength region. This system achieved a data rate of 2.5 Gbit/s at a transmission distance of 100 km without repeaters [2,18]. Multiplexing and transparent amplification where the last two key technologies needed for a robust communication system.

The last three decades have brought a fleet of improvements, three different types of information multiplexing, the invention of transparent amplification and higher order modulation formats, enabling 109 Tbit/s performance with further reach without repeaters. Wave division multiplexing (WDM), polarization division multiplexing (PDM) and time division multiplexing (TDM) [2, 18, 19] have helped extract as much capacity as possible from different communication systems. The erbium dope fiber amplifier (EDFA) gave way to longer transmission range without repeaters and DFB lasers with stable phase coherence enabled the implementation of higher order modulation formats. Fourth generation optical communication system are defined by use of this technologies. Currently, fourth generation systems are still operational and Telecom operators are interested in extending the life span of this systems as a cost effective update.

### 1.2.2 Current Outlook in Optical Communications

The lightwave systems currently deployed are referred to as Intensity Modulation with Direct Detection (IM/DD). An alternative to IM/DD is to transmit information by modulating the frequency, amplitude or phase of the optical carrier. Detection of the transmitted signal is done by a scheme known as *coherent detection* that allows the extraction of all the signals information. Phase coherence with the optical carrier plays an important role in Higher-Order Modulation (HOM) format links, also known as *coherent lightwave systems*. These systems fall into the field known as *Coherent Optical Communications*, that has been studied extensively since the 1980. Its deployment was slow at the time due to limitations on amplification and cost effective improvements in IM/DD systems [3, 20].

Coherent optical receivers follow a heterodyne detection scheme where a *local* oscillator (LO) is required to detect the incoming signal. When the LO and the

transmitted signal are mixed, a beat frequency equal to the difference between the two frequencies is created. By adjusting the local oscillator frequency, the beat frequency retrieved could be the signal that was modulated on top of the optical carrier. These detection arrangement makes the receivers require more power and physical components. At the time IM/DD receivers where cheaper to run and manufacture making them more widely deployed. In current networks IM/DD system are reaching their limit [13], this has brought new interest to coherent systems, thanks to the possibility of improving already deployed links and giving space to create new solutions for future demands. Currently, the main objective of coherent optical communications is exploiting Photonics to engineer the next generation transparent network. However, a main limitation is phase noise distorting the signal while it propagates through the fiber making noise compensation a vital part for a high quality link [21].

### 1.3 Modulation Formats

A HOM format is a scheme to standardize information for a correct representation of a signal and extract a bit stream from a physical measurement. In optical communication the amplitude and phase of a DFB continuous wave laser is modulated to encode information in them, this information can be later decoded at the receiver side by heterodyne detection. A single detection of a combination of phase and amplitude components is denominate a symbol. A set of M unique symbol can be mapped to unique bit sequences of m bit long. A graphical representation of the modulation of optical carrier is shown in Figure 1.3.1 which depicts the basic transformations that can be done to the carrier. In digital communication amplitude and phase are referred to as the *in-phase* and *quadrature* components or IQ components. It is usual to represent the transmission signal in phase diagram as shown in Figure 1.3.2 where you can represent each symbol by its IQ components also known as a constellation point when represented in a phase diagram. When the carrier signal is amplitude modulation (AM) or phase modulated (PM) the transformation under gone in the phase diagram is just a translation or rotation, as shown in the top left of Figure 1.3.2.

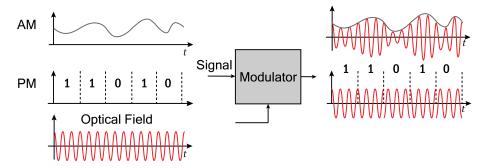


Figure 1.3.1: Amplitude modulation and phase modulation can be implemented to transmit information over a optical field. In this figure a visual representation on how information can be imprinted to a carrier signal is shown.

With this two basic transformations, an array of modulation formats are possible.

A modulation format is in general a scheme to determine a set of equidistant points of unique IQ component that each represents a unique bit sequence, also called a constellation. The most simple case is the *binary phase shift keying* (BPSK) that consists of two unique constellation points, determining how to classify a detected symbol is simple if it falls to the left of the y-axis the symbol is a 1 or if it falls to the right the symbol is a 0. Thus a simple decision region dividing in half the phase diagram would suffice to accurately classify the detected symbols.

An extension to phase modulated BPSK can be achieved with a clear signal, higher resolution on the receiver and increasing the amount of constellation points. Modulation formats like quadrature phase shift keying (QPSK) or eight constellation point phase shift keying (8PSK) are extension on BPSK as can be seen from the constellation diagram (observe Figure 1.3.2). To transmit more bits per symbol, it is useful to have a compact constellation diagram. Thus, using both AM and PM is a logical next step to modulate the carrier signal.

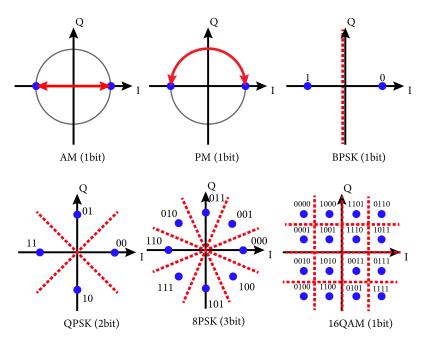


Figure 1.3.2: A phase diagram can be used to represent the changes in the state of detected signal. A HOM implement more complex constellations architectures to transport more information per symbol.

A widely implemented modulation format in modern telecommunications is  $Quadrature\ Amplitude\ Modulation\ (QAM)$ , a technique in which two carriers shifted in phase by 90 degrees are modulated and combined. Due to this phase difference the carriers are in quadrature, giving the modulation format its name [22]. This technique allows a communication system to reach higher data rates within the same bandwidth and higher spectral capacity [23]. The number of bits m needed to decode each symbol is related to the number of symbols M or constellation points that represent all bit unique combinations as  $M=2^m$  [24]. A representation of a 16QAM square constellation is shown in the bottom right of Figure 1.3.2, the corresponding constellation point and decode 4 bit message are displayed for each symbol. The quality of the link relies on having little noise, such that the transmitted symbol

can be detected with its original phase and intensity. Making noise mitigation a necessary component for robust systems.

# 1.4 Optical Noise

Photonics gives a framework to describe and engineer a communications link that can have high capacity, low latency and long-distance coverage. A wide range of creative solutions are required to counter impairments that arise from the light-matter interaction between the light pulse and the fiber cable. When noise is present in a channel, it deteriorates the quality of the signal. The quality of the signal can be quantified by the Optical Signal to Noise Ratio (OSNR). Information is imparted onto a light pulse by modulating its physical properties within a predetermined scale or protocol like a HOM. The main purpose of a communication link is to transmit symbols that can be decoded into bits, the amount of errors encountered in a bit stream is known as bit error rate (BER). It is worth mentioning that the symbol error rate (SER) does not have to be the same as BER, depending on the modulation format and the forward error correction (FEC) there can be significant difference reducing the actual amount of mistakes made [22].

When light propagates through a medium it can suffer a change in speed depending on its wavelength, this effect is known as chromatic dispersion (CD) or group velocity dispersion (GVD). A pulse of light contains multiple wavelengths rather then a single frequency. Thus, when the pulse acquires CD it stretches in time, affecting the timing of the link corrupting the information carried. Dispersion is not the only noise source in a fiber link, the inline optical amplifiers that counter the fiber attenuation produces amplified spontaneous emission (ASE) noise which is added to the signal as additive white gaussian noise (AWGN), reducing the OSNR. Amplifiers contribute to other types of noise indirectly, like the noise produced by intense light propagating through a medium [20].

The architecture of the detector can also add noise to the received signal depending on the resolution of a heterodyne detection with a large offset between the incoming signal and the LO, known as the *carrier frequency ofset* (CFO). Linear sources of noise arise primarily from the response of the dielectric -the silica optical fiber- to low intensity light propagating through it.

In the regime of low intensity light a transparent medium is represented by its refractive index. The electrical susceptibility of the medium is connected to its optical response, the linear or first order response is connected to the refractive index. The higher order or nonlinear response of the susceptibility has a small contribution to the total interaction at low intensity. The higher order susceptibility only has a significant contribution in the presence of an intense electromagnetic field like an intense laser or tightly confined light, as presented in the waveguide geometry of a fiber. Some part of these noise sources can be mitigated using digital signal processing (DSP), clever exploitation of physical phenomena on pre/post-compensation extending the throughput of the link [25].

A critical limiting factor is *nonlinear interference Noise* (NLIN) produced by the interaction between the signal and the ASE noise via the higher order response of the electrical susceptibility. Compensating for nonlinear effects is possible, using pre-compensation or DSP [4]. However, the main adversity to these techniques is the requirement on knowing the physical sate of the link, which is possible in a point-to-point link but it is not practical for a deploying a dynamic optical network.

Nonlinear noise set the limit for the maximum amount of information transmitted over a set distance of an optical communication link [26]. Restriction in optical power help reduce nonlinear noise, but high power is also necessary in HOM to obtain the necessary OSNR, limiting how low the power should be set. Noise mitigation becomes then interesting to retrieve an accurate representation of the link that permits computing decision regions for the transmitted symbols based on the links configuration. However, having a complete physical representation of the link is an impairment in real deployment, since there must be some tolerance in the real specifications and its cumbersome to keep count of system length, type of fiber etc. Nonparameter noise mitigation is a novel solution to mitigate nonlinear noise in a system where the physical attributes are unknown, the detection scheme would produce the most reliable decision regions based on the noisy signal [27].

### 1.4.1 Optical Noise in a QAM Channel

In a QAM channel NLIN is imparted as a phase shift to each symbol. Since the HOM classifies each symbol based on its phase (Figure 1.3.2) a phase shift could change the classification of the symbol. The reduction of the OSNR due to the noise produced by the linear susceptibility is visualized in Figure 1.4.1, where the different sources of noise previously mentioned are shown for the case of a square 16QAM constellation. Mitigation techniques can improve the quality of the signal in the case of CFO, but improving the OSNR is not possible due to the non-stochastic nature of linear noise.

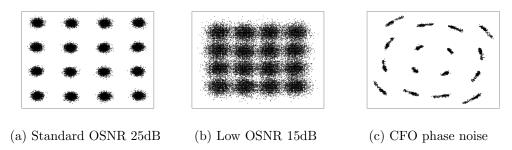


Figure 1.4.1: Square 16QAM constellation comparison between different types of linear noise.

In the presence of an intense light source, as is needed in QAM, nonlinear noise distorts the signal and hampers the transmission distance. Nonlinear effects also alter the constellation of a QAM link, an example of this distortions is shown in Figure 1.4.2. Nonlinear noise has the advantage of being stochastic source of noise, such that a probability distribution could be extracted from the noise [28]. From Figure 1.4.2 it is noticeable that the decision region for each symbol has to be more complex than in the case of Figure 1.4.1.

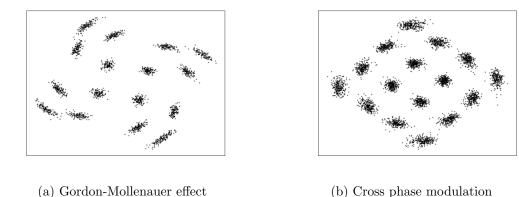


Figure 1.4.2: 16QAM constellation comparison between different types of Nonlinear Noise

Complicated decision regions have been implemented through DSP and nonlinear back propagation [9] showing improvements on a known system. An other approach is being done through *machine learning* which show unique advantages [10, 28] by making accurate predictions with out the need of back propagation or heavy numerical analysis. A more detailed description of the DSP and machine learning will be presented later on in this report.

# 1.5 Machine Learning

Learning has been a fundamental ability for humans throughout time, observing our surrounding, using tools and developing technological advancements are only possible due to the ability to remember previous experiences to make prediction of the future. Since 1957 with the development of more powerful computers and more sophisticated software, the notion that a machine could learn from data in comparable way as humans learn from experience has captivated many [29]. As currently defined Artificial Intelligence (AI) uses a computer to perform cognitive tasks; such as, perception, learning, reasoning or other similar abilities. A branch of AI is machine learning (ML), based on the idea that patterns and trends in a given data set can be learned through some algorithm. From the learned structures a decision or prediction can be made for some other data set in the system of interest [30].

Machine learning is offering a different perspective to problems that traditionally have been solved with complicated numerical models. The term nonparameter detection schemes comes from the idea that ML can suggest decision regions without needing any information on the current state of the link. Thus, ML can be a tool to work around imperfections in a fiber or as our main interest mitigate nonlinear noise sources. In Figure 1.5.1 two different algorithms are implemented to learn the best decision regions for a noisy constellation. Notice how this two ML algorithms perform differently for the same dataset due to their individual learning approach. Our interest is using this algorithms to extend the distance of transmission by improving their prediction capability with noisy signals.

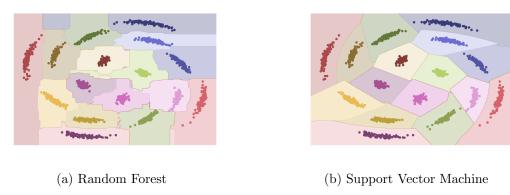


Figure 1.5.1: Machine learning determined decision regions for 16QAM constellation with NLIN acquired from 26 segments of 80 kilometer fiber.

# 1.6 Thesis organization

This thesis is divided into six chapters that cover the physical description of the system, the digital processing algorithms used and the simulation of the system. In the next chapter the physical layer will be discussed, describing the signal detection, modulation and the light-matter interaction undergone by the propagating signal in the fiber cable. In Chapter ?? the ML algorithms and a analytically derived algorithm are introduced. After this the simulation of the two communication links and the retrieved data will be presented in Chapter ??. To conclude this report the results will be discussed in Chapter ??, with final remarks and conclusion in Chapter ??.

CHAPTER

**TWO** 

### PHYSICAL LAYER

In this chapter the physical description and basic concepts implemented through this report will be discussed. The following are the basic assumptions and technology used to design, simulate and analysis the results of this thesis. In each section a different element of the communication link will be discussed, ultimately from this understanding it is perused to investigate nonlinear noise and its fundamental role in the transmission link.

## 2.1 Emission, Detection & Modulation

The components of a coherent optical communication system will be given a short description in this section. The basic components for an optical communication system are the *laser*, *modulator* and *detector*. For a coherent system the modulation format is an important design parameter, as was mentioned in the introduction, noise effects affect in different ways a given modulation format. Each component plays a fundamental role in a optical system; the correct selection of this elements can improve the throughput and transmission distance of a link. First let us consider the emission source that enabled coherent communication due to its high phase coherence, the *distributed feedback laser* (DFB) laser.

## 2.1.1 Light emitting source

In the beginning coherent optical communications did not get as much attention as IM/DD systems because in the 1990 all available light sources presented large phase noise and frequency drift [31], which is not useful for a coherent system. With the invention of the DFB laser new interest sprung in coherent systems. The main advantage of a DFB laser is the ability to emit a single longitudinal mode, which implies high frequency and phase stability.

A DFB laser is either a semiconductor laser or fiber laser where its whole resonator consists of a periodic structure, that acts as a distributed reflector. This reflector can be designed to reflect the desired wavelength range, which is amplified in the gain medium and emitted by the laser [32,33]. The emitted optical spectrum for a general DFB laser is shown in Figure 2.1.1c, where we can see that a single

mode is prevalent over all other noise present. The linewidth of a DFB laser is usually bellow 10 MHz [31] and for this implementation a narrow linewidth laser was simulated with a 1MHz linewidth. Wavelength tunability is also possible for a range of 1000 GHz or a wavelength range of 8 nm, allowing the implementation of WDM systems [31,33]. A critical advantage for coherent systems is the use of HOM, which increase the systems capacity for the same bandwidth. Thus, modulating a DFB laser and detecting its physical properties like intensity, amplitude and phase are necessary to achieve higher system capacity.

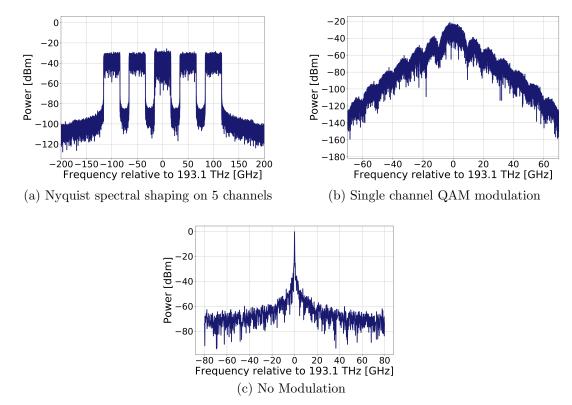


Figure 2.1.1: Optical frequency spectrum for different systems. A DFB laser frequency spectrum is shown in (c) and a set frequency spectrum after modulation are also shown in (a) and (b).

To determine the operating power of a fiber system two noise sources constrain the system. The first noise source arises from the optical fibers refractive index dependence on the transmitted signal power [20]. With a high power signal distortions can be induced if power fluctuations interact with the electrical susceptibility of the fiber. The second noise sources is common amplification effect when a low power signal is amplified AWGN noise is added [34], decreasing the OSNR and transmission length. Optical modulators require a strong carrier signal to operate at high OSNR. This requirements limits the minimum operating power. To determine the optimal operating range a detailed analysis will be discussed throughout this thesis.

#### 2.1.2 Modulator & Detector

Some of the advantages of optical communication systems rely on the modulation of the carrier signal and on the high sensitivity detection. To transmit more information over the same bandwidth a clever representation of the signal has to be standardized, as is done by HOM. However, it is necessary to modulate the carrier signal physical properties with precision to control reliably the information transmitted. Detection in coherent optical communication requires a scheme that can extract simultaneously multiple physical measurements from a single pulse. These two requirements can be solved with clever implementation and design of well understood optical phenomena.

In coherent communication the amplitude and phase of the carrier signal are modulated to transmit information. For an optical system phase modulation (PM) can be achieved by passing through a non-centrosymmetric crystal that presents the Pockels effect [20,35]. This type of crystal have refractive index dependent on the applied voltage allowing PM [35]. If a set of this crystals are used in a Mach-Zehnder configuration amplitude modulation (AM) can be achieved. This type of modulators are known as Mach-Zehnder-type push-pull modulators or Mach-Zehnder modulator (MZM) [35]. To obtain a simultaneous amplitude and phase (In-phase and quadrature components) modulation two MZM in parallel with a  $\pi/2$  phase shift can be combined as shown in Figure 2.1.1a, modulating independently the IO components [35]. Any kind of multilevel modulation format can be done with this scheme [36], currently integrated Dual-drive MZM LiNbO<sub>3</sub> IQ modulators are available on the market. This is the same modulator architecture that was used for the simulation.

Modulation of the CW optical carrier not only alters the IQ components but it also modifies the optical spectrum of the laser. When the optical carrier undergoes QAM, the optical spectrum of the transmitted signal is altered as seen in Figure 2.1.1b. In Figure 2.1.1 the modulator is controlled by the digital to analog converters (DAC) and the driving signal is computed by digital signal processing (DSP) [35]. Filtering can be done by the DSP in the digital domain to modify the optical frequency spectrum of the signal and frequency spectrum close to a square pulse [20, 35], as seen in Figure 2.1.1a. The type of filtering implemented is a low-pass filter with a transfer function response as a raised cosine function, aslo know as raised-cosine filter. This type of filtering is known as Nyquist filtering and helps reduce the inter-symbol interference and maximize the available bandwidth [37], both of this effects can be observed in Figure 2.1.1a. Reducing inter-symbol interference alludes to the clear spacing between channels, and maximizing the bandwidth can also be achieved given that each channel is constrained in a small bandwidth allowing more channels to be add in the side bands.

Coherent detection of the quadrature and in-phase components of the optical signal can be done simultaneously using a phase-diversity homodyne receiver. The fundamental idea behind coherent detection is to compute the inner product of the local oscillator (LO) phasor and the received signal phasor to determine one of the signals quadratures [35]. A homodyne receiver has LO operating at the same frequency as the carrier signal [20]. However, to detect both IQ components simultaneously two LO signals are needed with a  $\pi/2$  offset. This LO architecture, as shown in Figure 2.1.1b, is called phase-diversity detection. Polarization diversity detection can be done with another LO that has orthogonal polarization, most commonly a random polarization state laser is used that is then divided using a

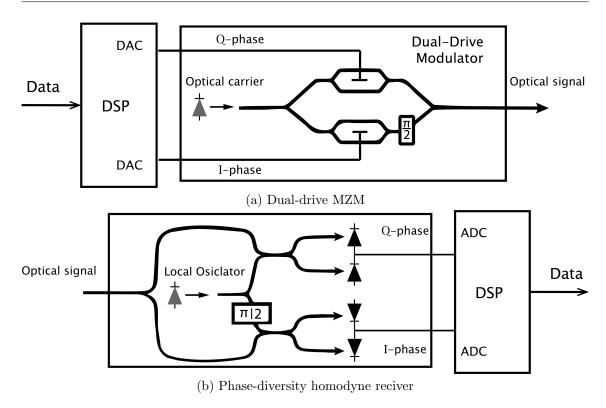


Figure 2.1.1: Detection and modulation scheme for a coherent optical communication system.

polarization beam splitter [35]. As for the modulator, an analog to digital conversion (ADC) converts the signal to a digital sequence that can be processed by the DSP. Many different DSP schemes exist today to process an optical signal and retrieve the carriers phase [38], determine the timing (clock recovery) [39], LO offset mitigation [35,38] and other processing can be done to improve the signal quality.

#### 2.1.3 Modulation Format

In the previous section, a short description of a dual-drive MZM was given. In this section, the multi-level modulation (or higher order modulation HOM) of the optical carrier will be discussed, which improves the link's spectral efficiency. In the digital domain the transmission of bits is mapped to a set of IQ components that determine the driving voltage of the modulator, producing the encoded optical signal that can be decoded on the receiver side. For the digital transmission, m bits are collected and mapped to a complex symbol chosen from an alphabet

$$s(k) = i_k + jq_k \in \{s_0, s_1, ..., s_{M-1}\}, M = 2^m$$
 (2.1.1)

where k represents the symbols interval with length  $T_S = mT_B$  and  $1/T_B$  is the bit rate [40]. One of the symbols in the alphabet is assigned depending on the bit combination, that is defined in a *constellation diagram*, where i and q are the IQ component of each constellation point. When m bit alphabet is designed, a M point constellation is defined, the architecture of this constellation can follow a determined standard like PSK, QPSK or QAM (as discussed in Section 1.3. In this project a

4 bit alphabet with a square 16QAM constellation was implemented as is shown in Figure 2.1.1. A detailed explanation on how to determine the complex function that modulates the carrier signal and what electrical driving signal should sent the the MZM can be found in Reference [40]. With this basic principals, our interest is shifted to the interaction between the transmitted optical signal and the optical fiber that guides the signal to the receiver. This interaction deteriorates the quality of the channel by corrupting the phase information imprinted by the modulators.

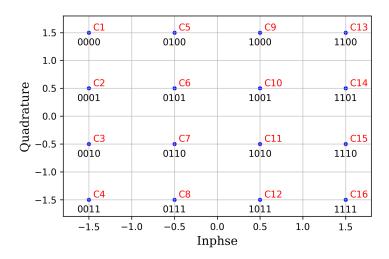


Figure 2.1.1: Four bit per symbol signal represented in a phase diagram of a square 16QAM constellation.

# 2.2 Electromagnetic Theory of Light

The current theory of light comes from the idea of photons as the smallest unit of radiation composed of electromagnetic energy. As described by quantum mechanics a photon can be represented either by a wave or a particle. For the propagation and nonlinear interaction it is convenient to work in the wave picture, while at the detector you detect individual particles. A photon can be represented by an electromagnetic field that arises from a set of coupled vector fields that are functions of time and position: the electric field  $\mathbf{E}(\mathbf{r},t)$  and the Magnetic field  $\mathbf{H}(\mathbf{r},t)$ . The phenomenological description of the interaction between this fields are known as the Maxwell's equations which describe all electromagnetic phenomena [20].

## 2.2.1 Maxwell Equations in a Medium

In this thesis, the interaction between a modulated optical signal and silica glass fiber is studied to get a better understanding of nonlinear noise that corrupts an optical communication system. For a fundamental understanding, it is necessary to take into account the physical interaction of the medium with the electromagnetic field. A mediums response in the presence of a electromagnetic field is described by two vector fields: the electric flux density  $\mathbf{D}(\mathbf{r},t)$  and the magnetic flux density

 $\mathbf{B}(\mathbf{r},t)$ . For an optical communication system we can assume an optical fiber that is a nonconducting medium and has no free charges or currents, simplifying the interaction. These four fields are related by the Maxwell's equations in a source-free medium [20, 32]:

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

$$\nabla \times \mathbf{H} = \frac{\partial \mathbf{D}}{\partial t}$$
(2.2.1a)

$$\nabla \times \mathbf{H} = \frac{\partial \mathbf{D}}{\partial t} \tag{2.2.1b}$$

$$\nabla \cdot \mathbf{D} = 0 \tag{2.2.1c}$$

$$\nabla \cdot \mathbf{B} = 0 \tag{2.2.1d}$$

The electric flux density **D** relation to electric vector field **E** is dependent on the properties of the medium, that are characterized by the polarization density P. For a dielectric medium the polarization density is the sum of the electric dipole moments induced by the electric field [32]. In an analog manner, the magnetic flux density B relationship with the magnetic field H is dependent on the magnetization density M that describes the properties of the material. The connection between the vector fields and the flux densities are given by

$$\mathbf{D} = \epsilon_0 \mathbf{E} + \mathbf{P} \tag{2.2.2a}$$

$$\mathbf{B} = \mu_0 \mathbf{H} + \mathbf{M} \tag{2.2.2b}$$

where  $\epsilon_0$  and  $\mu_0$  are the vacuum permittivity and permeability respectably. Due to the nonmagnetic nature of silica glass, an optical fiber has  $\mathbf{M} = 0$ . When operating far from the mediums resonance, a phenomenological relation between P and E can be used. This is the case for a optical fiber since we are interested in working in the low-loss wavelength region far from resonance.

In this project, nonlinear effects are the main objective, but it is necessary to have a description of linear dispersion effects as well. For a dispersive medium with a electric susceptibility  $\chi$  the relation between **P** an **E** is given as [20]:

$$\mathbf{P}(\mathbf{r},t) = \epsilon_0 \int_{-\infty}^{\infty} \chi(\mathbf{r},t-t') \mathbf{E}(\mathbf{r},t') dt'$$
 (2.2.3)

this response is dynamic, given that the electric field induces the bound electrons to start oscillating, and collectively create the polarization density. Given the oscillatory response of the bound electrons, different harmonics can be reached. The electric susceptibility describes the strength of different harmonic components in respect to the incoming field.

In the simplest case of a linear, nondispersive, homogeneous and isotropic dielectric medium the the vectors **P** and **E** are parallel and proportional for every position and time, such that  $\mathbf{P} = \epsilon_0 \chi \mathbf{E}$  [20, 32]. Using the definition of the electric flux density **D** the *electric permittivity* of the medium can be computed as  $\epsilon = \epsilon_0(1+\chi)$ , which for a nonmagnetic material is connected to the refractive index as  $n = \sqrt{\epsilon/\epsilon_0} = \sqrt{1+\chi}$ . From now on all materials discussed are homogeneous and *isotropic* making the relation between  $\mathbf{P}$  and  $\mathbf{E}$  independent of position  $\mathbf{r}$  and independent from the direction of  $\mathbf{E}$ . Drawing some insight from the linear interaction response, a nonlinear dielectric media can be understood as an extension of this case. By considering a small change to the polarization density due to higher order oscillatory dependencies of the electric field and the medium.

### 2.2.2 Nonlinear Dielectric Media

Linear dielectric media gives a framework that can be extended to take into account higher order components of the electric susceptibility interaction with nonlinear orders of the electric field. Let us consider the electric field vector  $\mathbf{E}(t)$ , only time dependent, as a single harmonic electric field of angular frequency  $\omega$  and complex amplitude  $\mathcal{E}(\omega)$  written as [32]

$$\mathbf{E}(t) = \mathbf{Re} \left\{ \mathcal{E}(\omega) e^{i\omega t} \right\} = \frac{1}{2} \left[ \mathcal{E}(\omega) e^{i\omega t} + \mathcal{E}^*(\omega) e^{-i\omega t} \right]. \tag{2.2.1}$$

This electric field propagates through a medium as dictated by Maxwell's equations, thus the polarization density describes the mediums response.

Inter atomic or crystalline field forces are much grater than the externally applied optical field, such that nonlinearity is usually weak. Thus, the relation between  $\mathbf{E}$  and  $\mathbf{P}$  is approximately linear for small  $\mathbf{E}$ , shifting slightly from linearity as  $\mathbf{E}$  increases. For a homogeneous isotropic dielectric media the polarization density can be expanded as a Taylor series around  $\mathbf{E}(t) = 0$ , as done in Equation 2.2.2a [32].

### Nonlinear Polarization Density frequency response

The polarization density for a nonlinear dielectric medium is expressed as the sum of the linear component  $(\epsilon_0 \chi \mathbf{E})$  and the nonlinear component  $(\mathbf{P}_{NL})$ , which characteristics the mediums response to an incident electric field.

$$\mathbf{P}(t) = \epsilon_0 \left( \chi \mathbf{E}(t) + 2\chi^{(2)} \mathbf{E}^2(t) + 4\chi^{(3)} \mathbf{E}^3(t) + \cdots \right)$$
(2.2.2a)  
$$\mathbf{P} = \epsilon_0 \left( \chi \mathbf{E}(t) + \mathbf{P}_{NL}(t) \right), \quad \mathbf{P}_{NL}(t) = \left( 2\chi^{(2)} \mathbf{E}^2(t) + 4\chi^{(3)} \mathbf{E}^3(t) + \cdots \right)$$
(2.2.2b)

It is enough to take into account the first three terms of the series, linear relation, second order and third order effects to describe the mediums response. The rest of the higher order effects have a very small contribution and can be ignored.

It becomes necessary to distinguish between media that have second order or third order effects. A centrosymmetric media presents a dominant nonlinear optical processes described by the terms in the polarization density that are a cubic function of the electric field [41]. Noncentrosymetric media polarization density exhibits dependencies on both the squared and cube of the electric field. Throughout this project our main concern is studying fiber optics made out of centrosymmetric media like fused silica SiO<sub>2</sub>, such that nonlinear effects arise from third order nonlinear dependencies of the polarization density.

### 2.2.3 Third Order nonlinear Kerr effect

Given this projects interest in centrosymmetric media it is necessary to describe the nonlinear response of the polarization density to a ideal monochromatic electric field like the one given in Equation 2.2.1. Lets consider only the effects of the third order response of the dielectric media  $\mathbf{P}_{NL}(t) = 4\chi^{(3)}\mathbf{E}^3(t)$ . Substituting Equation 2.2.1 into the nonlinear polarization density gives Equation 2.2.1, which describes the frequency response that arises.

### Nonlinear Polarization Density

The nonlinear polarization density  $\mathbf{P}_{NL}$  response to a monochromatic field can be decomposed into the individual frequency effects  $\mathcal{P}_{NL}(\omega_i)$  that emerge from a third-order nonlinear medium [32].

$$\mathbf{P}_{NL}(t) = \mathbf{Re} \left\{ \mathcal{P}_{NL}(\omega) e^{iwt} \right\} + \mathbf{Re} \left\{ \mathcal{P}_{NL}(3\omega) e^{i3wt} \right\}$$
 (2.2.1a)

$$\mathcal{P}_{NL}(\omega) = 3\epsilon_0 \chi^{(3)} |\mathcal{E}(\omega)|^2 \mathcal{E}(\omega)$$
 (2.2.1b)

$$\mathcal{P}_{NL}(3\omega) = \epsilon_0 \chi^{(3)} \mathcal{E}^3(\omega) \tag{2.2.1c}$$

Two different frequencies components  $\omega$  and  $3\omega$  emerge from the nonlinear response of the polarization density. The presences of a  $3\omega$  response indicates that third-harmonic generated (THG) light can be produced in the nonlinear interaction. However, in most cases the energy conversion efficiency is low for THG, which makes it hard to extract a strong  $3\omega$  signal from the third order polarization density [32]. Optical communications are interested in self induced sources of noise like the frequency response  $\mathcal{P}_{NL}(\omega)$ . Single frequency channel in a fiber link interacts with the fiber and self induced a distortion to the overall signal.

As has been mentioned before it is assumed that the polarization density response varies only slightly from the linear response  $\epsilon_0 \chi \mathbf{E}$  with increasing  $\mathbf{E}$ . It can be assumed that for a centrosymmetric material an incremental change  $\Delta \chi$  would be connected to the nonlinear polarization density [20, 32]. With this insight a similar assumption to the linear case can be made for  $\mathcal{P}_{NL}$ , relating it to the change in the susceptibility  $\Delta \chi$  at a frequency  $\omega$  by

$$\mathcal{P}_{NL}(\omega) = \epsilon_0 \Delta \chi \mathcal{E}(\omega). \tag{2.2.2}$$

Expressing the incremental susceptibility as a change in the refractive index would be useful given the ease of measuring the refractive index in general. Since  $n^2 = 1 + \chi$ , computing the deferential change would give  $2n\Delta n = \Delta \chi$ . It is also necessary to define the optical intensity of the electric field given by  $I = |\mathcal{E}(w)|^2/2\eta$  where  $\eta$  is the impedance of the dielectric medium. With this and Equation 2.2.2 the incremental refractive index can be written as a function of the optical intensity.

$$\frac{\mathcal{P}_{NL}(\omega)}{\epsilon_0 \mathcal{E}(\omega)} = 2n\Delta n \to \Delta n = \frac{3\chi^{(3)}|\mathcal{E}(\omega)|^2}{\epsilon_0 2n}$$
 (2.2.3a)

$$\Delta n = \frac{3\eta}{\epsilon_0 n} \chi^{(3)} I \equiv \bar{n}_2 I \tag{2.2.3b}$$

Given the proportionality between the refractive index  $\Delta n$  and the intensity I, the overall refractive index has a linear dependency of the optical intensity. This effect is known as the *Optical Kerr Effect* [42].

#### Optical Kerr effect

All material have a linear dependency on with the optical intensity for high enough power, this is known as the Optical Kerr Effect. The effect arises from the anharmonic response of electrons to optical fields, resulting in a nonlinear susceptibility. The nonlinear coefficient  $\bar{n}_2$  is also defined as the optical Kerr coefficient, but is also commonly known as the nonlinear-index coefficient. [20, 43]

$$\bar{n}_2 = \frac{3\eta_0}{n^2\epsilon_0}\chi^{(3)}$$
 Optical Kerr Coefficient (2.2.4a)

$$n(I) = n + \bar{n}_2 I$$
 Optical Kerr Effect (2.2.4b)

The optical Kerr effect makes a medium sensitive to power fluctuations, it is expected that some sort of distortion will be manifested in the signal due to its effect. In optical communication the Kerr effect induces nonlinear sources of noise that limit the system. To get a better understanding on the nonlinear effects it is necessary to study the properties of a optical fiber.

# 2.3 Fiber

In this section the phenomenological description for the optical fiber used to construct the communication links are discussed. To investigate nonlinear noise it is necessary to have a physical description of the interaction between the optical signal and the transporting fiber. First a few comments are done on the usual fiber refractive index profile and the definition of some fundamental properties, like the propagation constant of the medium. To describe the nonlinear interaction an extension will be to the linear polarization density to include higher order terms. A general overview of the physics will be done, since a more detailed presentation is out of the interest of this thesis.

## 2.3.1 Fiber Properties

### Refractive index fiber profile

An optical fiber in a ray optics frame work is just a clever exploitation of the law of refraction and the critical angle. In Figure 2.3.1 a step index fiber profile is visualized, that has a refractive index  $n_1$  in the core and  $n_2$  in the cladding. The light gathering capacity of an optical fiber is known as the *numerical aperture* (NA) that can be approximated for a step index fiber by

$$NA = n_1 (2\Delta)^{\frac{1}{2}}, \quad \Delta = \frac{n_1 - n_2}{n_1}$$
 (2.3.1)

where  $\Delta$  is the fractional index. Increasing the fractional index would improve the amount of light gather by the fiber, but it would also induce a large multipath or modal dispersion. Figure 2.3.1shows a set of propagating rays, each traveling a path of different length, as a result this rays disperse in time broadening the pulse. Current optical communication fibers are design to have a  $\Delta < 0.01$  allowing for better modal dispersion performance [20].

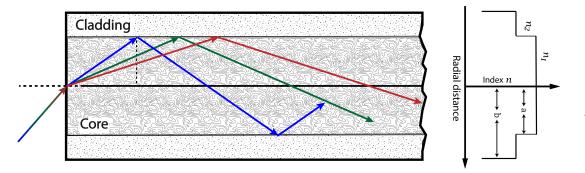


Figure 2.3.1: A step index fiber with its corresponding refractive index profile is shown. Modal dispersion is visualized with a set of propagating rays that enter the fiber at the same time and would exit dispersed in time.

In Figure 2.3.1 the *refractive index profile* of the step index fiber is also shown. The cores design plays an important role defining the fibers response to an optical signal. In Section 2.3.3 the refractive index profiles of more interesting fibers will be discussed.

### Power loss & Amplification

A critical parameter for an optical system is the attenuation of the fiber, it provides a measurement of the power loss during transmission. For communication system having a strong output signal is important to reliably detect the transmitted signal. An optical fiber of length L with an input launch power  $P_0$  produce a transmitted power  $P_T$  written as

$$P_T = P_0 e^{-\alpha L}, (2.3.2)$$

where  $\alpha$  the attenuation constant is a measure of all the losses in the fiber [44]. The attenuation constant has units of dB/km and is wavelength dependent, as reported in Reference [45] a fiber with  $\Delta = 1.9 \cdot 10^{-3}$  exhibits a fiber-loss of 0.2 dB/km in the wavelength region near 1550 nm. In today's optical communication system the usual operating frequency  $\omega$  is 193.1 THz because of its low fiber-loss and ease of amplification using erbium doped fibers.

Amplification is crucial to counteract the losses in the fiber, extending the reach of the communication system. An ideal amplifier would produce a output power  $P_{out} = GP_{in}$  without distortion given a input power  $P_{in}$ . In general a amplifier can be described by the amplification factor  $G(\omega)$  and the amplification profile  $g(\omega)$  given by  $G = e^{gL}$ . However, real amplifiers produce noise in the signal, quantified by the noise figure that will be described in Chapter??.

### Chromatic dispersion

When electromagnetic waves interacts with a mediums bound electrons different effects arise through the polarization density, some of which have been covered is Section 2.2.2. The interaction between the atomic structure and the electromagnetic field is also dependent on the fields frequency  $\omega$ , this property is known as *chromatic dispersion*. The frequency dependence is manifested through the refractive index  $n(\omega)$ . Far from the material resonance the refractive index can be approximated by the *Sellmeier equation* [20, 44]

$$n^{2}(\omega) = 1 + \sum_{j=1}^{m} \frac{B_{j}\omega_{j}^{2}}{\omega_{j}^{2} - \omega^{2}}$$
 (2.3.3)

where  $\omega_j$  is the resonance frequency and  $B_j$  is the strength of the jth resonance. In a optical fiber these parameters are found experimentally by fitting the material dispersion curve. Fiber dispersion plays a critical role when building a optical communication system. Transmitted light pulses are composed frequencies, in a dispersive medium each frequency would travel at its unique speed  $c/n(\omega)$  making the pulse spread in time.

When nonlinear effects are present in the fiber as well, the combination of dispersion and nonlinearity can result in a more complex behavior, this will be discussed in Section 2.3.2. The fiber dispersive effects are dependent on the mediums propagation  $constant \beta$  defined as

$$\beta(\omega) = n(\omega) \frac{\omega}{c}.$$
 (2.3.4)

A approximate response for the complete spectral range can be obtained by doing a Taylor expansion around the pulse center frequency  $\omega_0$ 

$$\beta(\omega) = \beta_0 + \beta_1(\omega - \omega_0) + \frac{1}{2}\beta_2(\omega - \omega_0)^2 + \cdots$$
 (2.3.5)

where the frequency derivatives of the propagation constant are given by

$$\beta_m = \left(\frac{d^m \beta}{d\omega^m}\right)_{\omega = \omega_0} \quad m = 0, 1, 2..., \tag{2.3.6}$$

and are related to different fundamental properties of the fiber. Due to the pulses spectral composition it propagates with a group velocity defined as  $\nu_g = (d\beta/d\omega)^{-1}$  [46]. It can be expressed in function of the refractive index as

$$\frac{1}{\nu_q} = \beta_1 = \frac{d}{d\omega} n(\omega) \frac{\omega}{c} = \frac{1}{c} \left( n + \omega \frac{dn}{d\omega} \right) = \frac{n_g}{c}$$
 (2.3.7)

where the group refractive index is  $n_g = (n + \omega \frac{dn}{d\omega})$ . Given the mediums frequency dependence different frequency components undergo different delays. This effect is known as group velocity dispersion (GVD) [44], the fibers dispersive effect is described by the dispersion parameter D either in terms of wave length  $D_{\lambda}$  or frequency  $D_{\omega}$  differing by a factor of  $d\omega/d\lambda = -2\pi c/\lambda^2$ .

$$D_{\lambda} = \frac{d\beta_1}{d\lambda} = -\frac{2\pi c}{\lambda^2} \beta_2 \tag{2.3.8}$$

The units for  $D_{\lambda}$  are [s/m-Hz] and for  $D_{\omega}$  has [ps/nm-km] presenting variation en value given a wavelength. Thus, a pulse spectrum would under go slightly different values of D which would broaden the pulse. This broadening is a higher-order dispersive effects governed by the dispersion slope  $S = dD/d\lambda$  that can be written in terms of propagation constant  $\beta_2$  and  $\beta_3$  as

$$S = \frac{2\pi c}{\lambda^2} \beta_3 + \frac{4\pi c}{\lambda^3} \beta_2. \tag{2.3.9}$$

A optical fiber can be design in such a way the total dispersion of the fiber can present desirable properties for an communication system. with a clever design the fibers dispersive response can be flattened to a have a constant value for a spectral range. An other fiber can also be designed to have shifted dispersion minimum present at frequency with lowest attenuation.

Dispersion in an optical communication link can alter the signals timing, due to the pulse broadening in time different pulses would start to overlap, distorting the signal. Optical compensation can be done using fibers with opposite dispersion parameters to cancel each others effect out. It is more useful to use a highly dispersive fiber to compensate in a short length a large amount of accumulated dispersion. A more detailed description of dispersion compensation is done in Section 2.3.3.

### 2.3.2 Higher Order Optical Noise

A silica fiber presents a linearly dependent refractive index due to the optical Kerr effect. As is discussed by S. Dris et al. in Reference [47] "Nonlinear interference noise (NLIN) due to the Kerr effect presents the most significant bottleneck towards increasing throughput in a flexible WDM optical networks". The objective of this project is to suggest a detection scheme that mitigates NLIN. Through this section a description of the different noise sources of inters will be presented.

First it is necessary to define quantities that represent the signals resilience. The signals quality is quantified by  $optical\ signal\ to\ noise\ Ratio\ (OSNR)$  that is dependent on the signals power P and noises average power N given by

$$OSNR = 10 \log_{10} \left( \frac{P}{N} \right) \tag{2.3.1}$$

in dB units [20]. In a coherent system it is necessary to have a high OSNR in the receive, usually above 20 dB, for a accurate detection. When noise is present, either linear or nonlinear, the OSNR drops distorting the signal. As discussed in the introduction the NLIN distortion is present as a phase noise rotation preserving some information.

In a communication system the quality of the transmission relies on the amount of correctly classified symbols. With a low number of misclassified symbols correction can be implemented in a higher layer of the communication system to recover or correct bit stream transmitted with FEC [4]. The SER describes the amount of mistakes made in the total transmitted signal as

$$SER = \frac{\text{no. of incorrect received symbols}}{\text{no. of transmitted symbols}}.$$
 (2.3.2)

Nonlinear noise in a optical communication system induces a phase shift to the detected signal. If not taken into account, it becomes a fundamental limiting factor to the transmission distance [9]. Having a physical description of the different nonlinear effects is then useful to alter the expected detection regions to improve the SER.

Three different nonlinear effects will be discussed that fall into two categories, intra-channel NLIN or self-channel interference and inter-channel NLIN or cross/multi-channel interference. The intra-channel effects in interest are self phase modulation and the Gordon-Mullenauere effect. For inter-channel effects the cross phase modulation will be considered in a WDM system.

### **Self Phase Modulation**

In a fiber absent of dispersion  $\beta_2 = 0$  the transmitted pulse undergoes a phase shift due to the intensity dependent refractive index, this modulation is known as self phase modulation (SPM). The refractive index intensity dependence induces a power dependence on the propagation constant [20], that can be written as [48]

$$\beta' = \beta + k\bar{n}_2 \frac{P}{A_{eff}} = \beta + \gamma P, \quad \gamma = \frac{2\pi\bar{n}_2}{\lambda A_{eff}}$$
 (2.3.3)

where  $A_{eff}$  is the effective area of the guided mode and  $k=2\pi/\lambda$  is the electric fields wavenumber. In it self the change to the propagation constant suggest an effect analogues to GVD, where the pulse is chirped and broaden [44]. As is deduced in Reference [48] the total nonlinear phase shift can be computed as the difference between  $\beta'$  and  $\beta$  over the interaction length as

$$\phi_{\text{SPM}} = \int_0^L \gamma(\beta' - \beta) dz = \int_0^L \gamma P(z) dz$$
 (2.3.4a)

$$\phi_{\text{SPM}} < \gamma L_{eff} P_{in}. \tag{2.3.4b}$$

The effective interaction length is defined as  $L_{eff} = (1 - e^{-\alpha L})/\alpha$  and the power in the fiber  $P(z) = P_{in}e^{\alpha L}$  [48]. Equation 2.3.4 gives us the amount of phase change over the fiber length L along the propagation axis z. The assumptions made to compute the nonlinear phase shift describes the maximum phase shift possible in a system where a CW driving laser is used with a IM/DD format non-return to zero (NRZ) [20,34,48].

It is an important to note that when dispersion effects are present the dependencies become more complex and require more sophisticated numerical solutions, making it cumbersome to have a complete model of the system [34,49]. In multiple references [20,44,48] the limit for  $P_{in}$  is introduced as a general rule to follow before SPM starts to corrupt the signal. The upper bound is given as  $P_{in} < 0.1\alpha/\gamma N_A$ , where  $N_A$  is the number of amplifiers [48]. For a average fiber system with 10 amplifiers the upper limit is 1.5-3 mW. Making it a critical impermanent for optical system. SPM is a NLIN and as concluded in Refrence [47] the effect are modulation format independent.

#### Cross Phase Modulation

In a WDM system the presence of multiple channels in a single fiber span would alter the interaction of the fiber with the transmitted optical signal. If we have a M-channel WDM system with a fixed channel spacing the cross-phase modulation for channel i can be described as

$$\phi_{\text{XPM}}^{i} = \gamma L_{eff} \left( P_{in}^{i} + 2 \sum_{j \neq i}^{M} P_{j} \right)$$
 (2.3.5)

where we can see that SPM effects are also taken into account for each channel. The XPM effects are important due to the dependence of the channels phase with the bit patterns of all the others [34]. As in the case of SPM a phase shift can be compute to represents the maximum shift acquired in a system

$$\phi_{\text{XPM}}^i < \frac{\gamma}{\alpha} (2M - 1) P_{ch} \tag{2.3.6}$$

where  $P_{ch}$  is the power per channel. Given the linear relation between the phase shift and the number of channels, there is a limitation to the number of channels or power per channel that can be transmitted.

In a system where GVD effects are present pattern-dependent phase shifts are converted to power fluctuations, reducing OSNR at the receiver [34]. A rough estimate for the power restriction is computed in Referene [48] for maximum phase shift  $\phi_{XPM} < 1$  the upper bound is  $P_{ch} < \alpha/\gamma N_A (2M-1)$  before XPM effects arise. In general the power restriction per channel is limited to bellow 1 mW depending on the system, increasing the amount of constraints in the system. Through this section no mention of the effect of amplification has been mentioned, the interaction between the spontaneous noise produced by amplification and the Kerr effect plays an important role in long-haul transmission links.

#### Gordon-Mollenauer effect

In a fiber communication link it is usual to use multiple segments of fiber with optical amplifiers (OA) to extend the systems reach. This type of architecture is known as lump amplification, commonly used in long-haul optical systems with over 10 amplifiers. Noise produced by OA interacts with the fiber through the Kerr effect producing phase fluctuations at the receiver and limiting the transmission distance [34]. This nonlinear source of noise is known as the *Gordon-Mollenauer effect* [49] or simply *Nonlinear Phase noise* (NLPN).

A transmission line that has N spans of optical fiber followed by its corresponding linear loss amplification is ultimately limited by the presence of *amplified spontaneous emission* (ASE) noise. Due to the refractive index dependence on optical power, fluctuation produced by ASE noise induces a phase shift in the received signal [49]. The nonlinear fluctuation can be approximated as [48]

$$\phi_{\rm GM} \approx N \gamma L_{eff} P_{in}.$$
 (2.3.7)

Notice that the ASE noise is still a linear source of noise add to the signal as AWGN. However, it also has a second effect by introducing small fluctuations in

the optical power, inducing a phase shift in the transmitted signal due to the Kerr effect. As is explained by P. Gordon and L. Mollenauer in Reference [49] noise produced by the amplifier can be decomposed into a noise field with two degrees of freedom that have the same shape as the pulse. "One in-phase with it, and the other in quadrature. The quadrature component produces a immediate phase shift, and the in-phase one alters the energy of the pulse. The energy change results in an additional nonlinear phase shift by the time the pulse reaches the receiver".

#### **Overall NLIN**

Three sources of nonlinear interference noise have been presented; self phase modulation, cross phase modulation and nonlinear phase noise. Each of this effects induces a phase rotation to the transmitted signal, corrupting the phase detected phase. Each of the NLIN sources has a complex interaction with the dispersive effect, making it necessary to carry out a numerical simulation for a precise model. However, it is not always possible to know the systems parameters before hand, given that in a real system deploying a fiber link requires tolerances.

A maximum phase shift can be expressed for each of the noise source, adding up to a total maximum nonlinear phase shift  $\phi_{nl}$ . A general approximation to quantify the expected phase shift for a signal can be computed as

$$\phi_{\rm nl} = \phi_{\rm SPM} + \phi_{\rm XPM} + \phi_{\rm GM}. \tag{2.3.8}$$

Each effect contributes to the total phase shift induced on the signal. Even though they all arise from the Kerr effect, some can be compensated more efficiently than others. Compensation in the end is what interest us, extracting as much transmission distance or capacity from the system before nonlinear noise corrupts the signal.

#### Bound Nonlinear Phase Shift

All sources of nonlinear noise; XPM, SPM and NLPN are found to have an upper bound for a fixed system configuration. Thus, a upper bound can be set on the total nonlinear phase noise that is detected at the receiver side.

$$\phi_{nl} < \frac{\gamma}{\alpha} \left( 2M + N \right) \tag{2.3.9}$$

Where  $\gamma$  is the nonlinear parameter definde in Equation 2.3.3 and  $\alpha$  is the absorption coefficient of fiber. A reference value can be drawn for a M-channel and N-span link, quantifying the nonlinear rotation undergone by the signal.

## 2.3.3 Optical Fiber & Compensation

As presented in the previous section, nonlinear effects are quantified by some fundamental parameters; the nonlinear refractive index, dispersion parameter and the dispersion slope. In Section 2.3.1 this properties were presented, discussing fundamentally where they come from. However, it is also necessary to discuses the different types of fiber that can be manufactured and how they can be used to compensate for fiber dispersion. In this section the physical description for dispersion

compensation is introduced. We conclude by discussing the different fiber used for the simulation and how they where implemented.

#### **Dispersion Compensation in Fibers**

All optical fibers manifest dispersive effects given the refractive index dependence on frequency. In Section 2.3.1 the dispersion coefficient was introduced, concluding that given the different frequency components of a optical pulse GVD would spread the pulse altering the systems timing [50]. Compensation becomes then necessary to retrieve the original signal. Fortunately, a clever design of the optical core can alter the dispersion parameter  $D_{\omega}$  and the dispersion slope S such that a zero dispersion system can be constructed. Consider a link composed of two fibers, a single mode fiber (SMF) with a  $D_1$  and a dispersion compensating fiber (DCF) with a  $D_2$ . The condition for perfect dispersion compensation is

$$D_1(\lambda_n)L_1 + D_2(\lambda_n)L_2 = 0 (2.3.1)$$

where  $\lambda_n$  is the operating wavelength of the nth channel and  $L_i$  is the corresponding length of each fiber. Its clear then that the dispersion compensation varies slightly for each channel. Thus, to have perfect compensation it is necessary to also consider the slope of the dispersion coefficient. It would be ideal if the dispersion slope for the DCF could be design to have a value of

$$S_2 = S_1 \frac{D_2}{D_1}. (2.3.2)$$

Unfortunately, manufacturing and fiber design have limits, such that it is not usual to have a perfectly compensated link. When designing a communication system the dispersion scheme is built around the operating wavelength  $\lambda=1550~nm$  (as has been mentioned before) this wavelength has a low absorption, present zero dispersion in some fibers and is the current standard in optical communication. Thus, to design a link the fiber is first selected depending on the system configuration. In practice it is desirable to have a DCF that has a dispersion coefficient and slope that best approximate the values given by Equations 2.3.1 and Equation 2.3.2.

A more accurate visualization of GVD is represented in Figure 2.3.1 where a propagating pulse is spreading in time, compensation is also shown using a short DCF that mitigates the dispersion accumulated in a long SMF. Ignoring losses between fiber splices notice that the effective core area for a DCF is smaller than SMF. Which in general makes compensating fibers have larger nonlinear refractive index  $\bar{n}_2$ , making NLIN more present in the system.

#### Manufactured Optical Fibers

The refractive index profile can be design to alter the optical properties of the fiber. In previous sections the connection between the refractive index and the dispersion coefficient, nonlinear coefficient and other parameters has been discussed. Now we are interested in making a few remarks about the optical fibers that were implemented during the simulation. Each fiber was used in the simulation but the specifications are taken from real fibers that exist on the market.

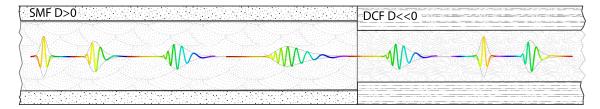


Figure 2.3.1: Visualization of chromatic dispersion compensation of pulse using a DCF.

First, lets consider a single channel system with a operating wavelength of  $1550 \ nm$ . If only one channel is present then it would be useful that the fiber would have zero dispersion for this wavelength. Multiple fibers exist in the market that present zero dispersion for this wavelength, they are known as dispersion shifted fiber (DCF) [51,52]. To design a optical fiber with a shifted dispersion the refractive index profile has to made in such away that the fibers modal dispersion and the waveguide dispersion balance each other out. The general refractive index profile is shown in Figure 2.3.2a, compared to a step index fiber (Figure 2.3.1) we can see four different refractive index must be used and a intricate design to achieve zero dispersion. However, not all system architectures can use DSF given that when multiple channels are present in the same fiber it is necessary to compensate the dispersion acquired by all channels.

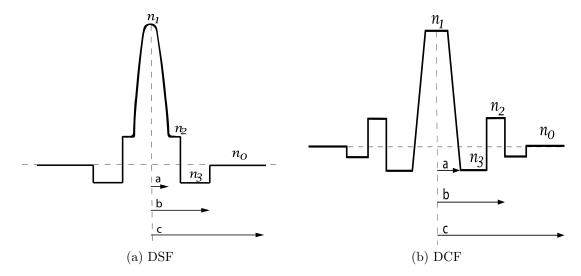


Figure 2.3.2: Refractive index for dispersion shifte or dispersion compensating fibers.

For WDM systems it is usual that all channels present dispersion in the transmission fiber. Instead of implementing a DSF a nonzero-dispersion shifted fiber (NZ-DSF) is deployed that presents a small dispersion value for the center wavelength 1550 nm. As was mention in Section 2.3.3 it is not enough to just consider the dispersion parameter, it is necessary to take into account the dispersion slope as well to compensate a multichannel system. To compensate a separate slope compensating-dispersion compensation fiber (SC-DCF) or SC-DCF module [53] is used to compensate the acquired dispersion for all channels in a short span of fiber. Figure 2.3.2b shows the refractive index profile for a general DCF, the fiber design

#### Table 2.3.1: Fiber Characteristics

Physical characteristics for the optical fibers used in the simulations. In the long-haul system the DSF is implemented and a combination of NZ-DSF and SC-DCF is used in the WDM system.

Fiber	$ \bar{n}_2  [10^{-20} \frac{cm^2}{W}]$	$\alpha \left[ \frac{dB}{km} \right]$	$A_{\rm eff} \ [\mu m^2]$	$D\left[\frac{ps}{nm-km}\right]$	$S\left[\frac{ps}{nm^2 - km}\right]$
DSF	2.4	0.21	70	< 0.13	0.11
NZ-DSF	2.25	0.2	65	4.2	0.085
SC-DCF	2.8	0.41	16.7	-47	-0.71

All values used for the fiber design in the simulation where taken from References [51-54]

is not trivial, but thanks to this clever design dispersion is not a limiting factor for transmission distance as it once was.

To simulate the long-haul optical system a DSF with ideal dispersion is considered. Due to our interest in measuring the NLPN after propagating in lump amplification this DSF is a good candidate for what would be deployed today. For the ten channel WDM system two fibers where implemented, a NZ-DSF for transmission and a SC-DCF to compensate for dispersion. This system present more nonlinear noise given the compensating fiber higher nonlinear coefficient, and both of them have a smaller effective area as well. In Table 2.3.1 the values for all fiber used in the simulation are shown, where all values are taken from manufactured fibers that can be bought today [54,55].

- [1] A. A. Huurdeman, The worldwide history of telecommunications. John Wiley & Sons, 2003.
- [2] M. Seimetz and R. Freund, "Next generation optical networks based on higher-order modulation formats, coherent receivers and electronic distortion equalization," *Elektrotechnik und Informationstechnik*, vol. 125, pp. 284–289, 08 2008.
- [3] M. Marciniak, "Future networks beyond next generation networking," in 2008 10th Anniversary International Conference on Transparent Optical Networks, vol. 1, pp. 25–28, June 2008.
- [4] S. Kumar, "Analysis of nonlinear phase noise in coherent fiber-optic systems based on phase shift keying," *Journal of Lightwave Technology*, vol. 27, pp. 4722–4733, Nov 2009.
- [5] T. S. R. Shen, K. Meng, A. P. T. Lau, and Z. Y. Dong, "Optical performance monitoring using artificial neural network trained with asynchronous amplitude histograms," *IEEE Photonics Technology Letters*, vol. 22, no. 22, pp. 1665–1667, 2010.
- [6] J. A. Jargon, X. Wu, and A. E. Willner, "Optical performance monitoring using artificial neural networks trained with eye-diagram parameters," *IEEE Photonics Technology Letters*, vol. 21, no. 1, pp. 54–56, 2008.
- [7] F. N. Khan, Y. Zhou, A. P. T. Lau, and C. Lu, "Modulation format identification in heterogeneous fiber-optic networks using artificial neural networks," *Optics express*, vol. 20, no. 11, pp. 12422–12431, 2012.
- [8] D. Zibar, L. H. H. de Carvalho, M. Piels, A. Doberstein, J. Diniz, B. Nebendahl, C. Franciscangelis, J. Estaran, H. Haisch, N. G. Gonzalez, et al., "Application of machine learning techniques for amplitude and phase noise characterization," *Journal of Lightwave Technology*, vol. 33, no. 7, pp. 1333–1343, 2015.
- [9] K.-P. Ho and J. Kahn, "Electronic compensation technique to mitigate nonlinear phase noise," *Lightwave Technology*, *Journal of*, vol. 22, pp. 779 783, 04 2004.

[10] M. Li, S. Yu, J. Yang, Z. Chen, Y. Han, and W. Gu, "Nonparameter nonlinear phase noise mitigation by using m-ary support vector machine for coherent optical systems," *IEEE Photonics Journal*, vol. 5, pp. 7800312–7800312, Dec 2013.

- [11] J.-i. Nishizawa and K. Suto, "Terahertz wave generation and light amplification using raman effect," *Bhat, KN and DasGupta, Amitava. Physics of semiconductor devices. New Delhi, India: Narosa Publishing House*, p. 27, 2004.
- [12] J. B. Gallegos, Doyle; Narimatsu and O. Ariana, *Innovative Business Models for Expanding Fiber-Optic Networks and Closing the Access Gaps*. World Bank Group, 2018.
- [13] K. Kikuchi, Coherent Optical Communications: Historical Perspectives and Future Directions, pp. 11–49. 06 2010.
- [14] M. Arumugam, "Optical fiber communication—an overview," *Pramana*, vol. 57, no. 5-6, pp. 849–869, 2001.
- [15] R. Ramaswami, K. Sivarajan, and G. Sasaki, *Optical networks: a practical perspective*. Morgan Kaufmann, 2009.
- [16] K. Kao and G. A. Hockham, "Dielectric-fibre surface waveguides for optical frequencies," in *Proceedings of the Institution of Electrical Engineers*, vol. 113, pp. 1151–1158, IET, 1966.
- [17] R. Ramaswami, "Optical fiber communication: from transmission to networking," *IEEE Communications Magazine*, vol. 40, pp. 138–147, May 2002.
- [18] P. Sharma, S. Pardeshi, R. K. Arora, and M. Singh, "A review of the development in the field of fiber optic communication systems," 2013.
- [19] K. Kikuchi, "Coherent optical communications—history, state-of-the-art technologies, and challenges for the future—," in OECC/ACOFT 2008-Joint Conference of the Opto-Electronics and Communications Conference and the Australian Conference on Optical Fibre Technology, pp. 1–4, IEEE, 2008.
- [20] G. P. Agrawal, Optical Fibers. John Wiley & Sons, Ltd, 2011.
- [21] C. Behrens, R. I. Killey, S. J. Savory, M. Chen, and P. Bayvel, "Nonlinear distortion in transmission of higher order modulation formats," *IEEE Photonics Technology Letters*, vol. 22, no. 15, pp. 1111–1113, 2010.
- [22] S. Benedetto and E. Biglieri, *Principles of digital transmission: with wireless applications*. Springer Science & Business Media, 1999.
- [23] W. T. Webb and L. Hanzo, Modern Quadrature Amplitude Modulation: Principles and applications for fixed and wireless channels: one. IEEE Press-John Wiley, 1994.
- [24] W. H. Paik, S. A. Lery, and J. M. Fox, "Mode selective quadrature amplitude modulation communication system," Nov. 8 1994. US Patent 5,363,408.

[25] G. Agrawal, Applications of Nonlinear Fiber Optics. Elsevier Science, 2010.

- [26] M. Born, E. Wolf, A. B. Bhatia, P. C. Clemmow, D. Gabor, A. R. Stokes, A. M. Taylor, P. A. Wayman, and W. L. Wilcock, Principles of Optics: Electromagnetic Theory of Propagation, Interference and Diffraction of Light. Cambridge University Press, 7 ed., 1999.
- [27] N. Ekanayake and H. M. V. R. Herath, "Effect of nonlinear phase noise on the performance of m-ary psk signals in optical fiber links," *J. Lightwave Technol.*, vol. 31, pp. 447–454, Feb 2013.
- [28] D. Zibar, O. Winther, N. Franceschi, R. Borkowski, A. Caballero, V. Arlunno, M. N. Schmidt, N. G. Gonzales, B. Mao, Y. Ye, K. J. Larsen, and I. T. Monroy, "Nonlinear impairment compensation using expectation maximization for dispersion managed and unmanaged pdm 16-qam transmission," *Opt. Express*, vol. 20, pp. B181–B196, Dec 2012.
- [29] A. Kaplan and M. Haenlein, "Siri, siri, in my hand: Who's the fairest in the land? on the interpretations, illustrations, and implications of artificial intelligence," *Business Horizons*, vol. 62, no. 1, pp. 15–25, 2019.
- [30] S. Marsland, Machine learning: an algorithmic perspective. Chapman and Hall/CRC, 2014.
- [31] K. Kikuchi, "Coherent optical communications: Historical perspectives and future directions," in *High Spectral Density Optical Communication Technologies*, pp. 11–49, Springer, 2010.
- [32] B. Saleh and M. Teich, *Fundamentals of Photonics*. Wiley Series in Pure and Applied Optics, Wiley, 2007.
- [33] Y. Kotaki and H. Ishikawa, "Wavelength tunable dfb and dbr lasers for coherent optical fibre communications," *IEE Proceedings J Optoelectronics*, vol. 138, no. 2, pp. 171–177, 1991.
- [34] G. Agrawal, Applications of nonlinear fiber optics. Elsevier, 2001.
- [35] K. Kikuchi, "Fundamentals of coherent optical fiber communications," *Journal of Lightwave Technology*, vol. 34, no. 1, pp. 157–179, 2015.
- [36] K.-P. Ho and H.-W. Cuei, "Generation of arbitrary quadrature signals using one dual-drive modulator," *Journal of lightwave technology*, vol. 23, no. 2, p. 764, 2005.
- [37] K. Zou, Y. Zhu, F. Zhang, and Z. Chen, "Spectrally efficient terabit optical transmission with nyquist 64-qam half-cycle subcarrier modulation and direct detection," *Optics letters*, vol. 41, no. 12, pp. 2767–2770, 2016.
- [38] M. Kuschnerov, F. N. Hauske, K. Piyawanno, B. Spinnler, M. S. Alfiad, A. Napoli, and B. Lankl, "Dsp for coherent single-carrier receivers," *Journal of lightwave technology*, vol. 27, no. 16, pp. 3614–3622, 2009.

[39] N. Stojanovic, F. N. Hauske, C. Xie, and M. Chen, "Clock recovery in coherent optical receivers," in *Photonic Networks*, 12. ITG Symposium, pp. 1–4, VDE, 2011.

- [40] M. Seimetz, "Multi-format transmitters for coherent optical m-psk and m-qam transmission," in *Proceedings of 2005 7th International Conference Transparent Optical Networks*, 2005., vol. 2, pp. 225–229, IEEE, 2005.
- [41] M. Levenson and N. Bloembergen, "Dispersion of the nonlinear optical susceptibility tensor in centrosymmetric media," *Physical Review B*, vol. 10, no. 10, p. 4447, 1974.
- [42] R. Stolen and A. Ashkin, "Optical kerr effect in glass waveguide," *Applied Physics Letters*, vol. 22, no. 6, pp. 294–296, 1973.
- [43] R. W. Boyd, Nonlinear optics. Elsevier, 2003.
- [44] G. P. Agrawal, "Nonlinear fiber optics," in *Nonlinear Science at the Dawn of the 21st Century*, Springer, 2000.
- [45] T. Miya, Y. Terunuma, T. Hosaka, and T. Miyashita, "Ultimate low-loss single-mode fibre at 1.55  $\mu$ m," *Electronics Letters*, vol. 15, no. 4, pp. 106–108, 1979.
- [46] M. Born and E. Wolf, Principles of optics: electromagnetic theory of propagation, interference and diffraction of light. Elsevier, 2013.
- [47] S. Dris, H. Louchet, and A. Richter, "Analysis of nonlinear interference noise in flexible optical networks," in 2017 Opto-Electronics and Communications Conference (OECC) and Photonics Global Conference (PGC), pp. 1–3, IEEE, 2017.
- [48] N. Le Binh, Advanced digital optical communications. CRC Press, 2015.
- [49] J. P. Gordon and L. F. Mollenauer, "Phase noise in photonic communications systems using linear amplifiers," *Optics letters*, vol. 15, no. 23, pp. 1351–1353, 1990.
- [50] G. Goldfarb and G. Li, "Chromatic dispersion compensation using digital iir filtering with coherent detection," *IEEE Photonics Technology Letters*, vol. 19, no. 13, pp. 969–971, 2007.
- [51] T. Kato, E. Sasaoka, and S. Ishikawa, "Dispersion-shifted fiber," June 6 2000. US Patent 6,072,929.
- [52] K. Kim, R. Stolen, W. Reed, and K. Quoi, "Measurement of the nonlinear index of silica-core and dispersion-shifted fibers," *Optics letters*, vol. 19, no. 4, pp. 257–259, 1994.
- [53] K. Aikawa, S. Shimizu, T. Suzuki, R. Suzuki, M. Nakayama, and K. Himeno, "Dispersion compensating fiber and dispersion compensating fiber module," Aug. 30 2005. US Patent 6,937,805.

[54] Y. Namihira, K. Miyagi, K. Kaneshima, M. Tadakuma, C. Vinegoni, G. Pietra, and K. Kawanami, "A comparison of six techniques for nonlinear coefficient measurements of various single mode optical fibers.," NIST SPECIAL PUBLICATION SP, pp. 15–18, 2002.

[55] M. Onishi, T. Okuno, T. Kashiwada, S. Ishikawa, N. Akaska, and M. Nishimura, "Highly nonlinear dispersion shifted fiber and its application to broadband wavelength converter," in *Integrated Optics and Optical Fibre Communications*, 11th International Conference on, and 23rd European Conference on Optical Communications (Conf. Publ. No.: 448), vol. 2, pp. 115–118, IET, 1997.