Chapter 1

Optical Fiber Communications

Optical fibre communication systems revolutionized the telecommunications industry by enabling true long-haul and high capacity transmissions that facilitated the development of the Internet, and clearly shaped the way we live, work, do business, and interact.

Optical communication systems use lightwave signals (in the THz frequencies) typically generated from semiconductor lasers to carry data and employ optical fibres, which present low attenuation, huge bandwidth and low electromagnetic interference, for transmission. These systems have been successfully implemented in the network since the 1980s, remarkably evolving in capacity growth and cost reduction to keep satisfying the demand for bandwidth.

This chapter gives an introduction to the current status of optical fibre communications networks and systems. It presents a historical overview of the main technological breakthroughs that consolidated their relevance and pushed their expansion. The late challenges that the next generation of optical networks faces due to the ever-increasing traffic demand, are then outlined. Finally, novel spectrally efficient techniques to enable greater network capacities are detailed and the motivation behind optical frequency comb sources is discussed.

1.1 Optical Network Topology

The current optical network is a complicated system consisting of interconnected sub-networks that ensure robust exchange of information throughout the world. The illustration of the general network topology is illustrated in Figure 1.1. The optical network is usually divided into core (long-haul), metropolitan (metro) and access networks according to their geographical extension, functionality and requirements [1].

Optical fibre communications have certainly dominated the core and metro network segments for a relatively long time, and more recently has started its expansion to the access network segment as well. An incessant growth in traffic is revolutionizing optical communications and forcing a transformation throughout the optical network towards reconfigurability, higher performance and reduced power consumption.

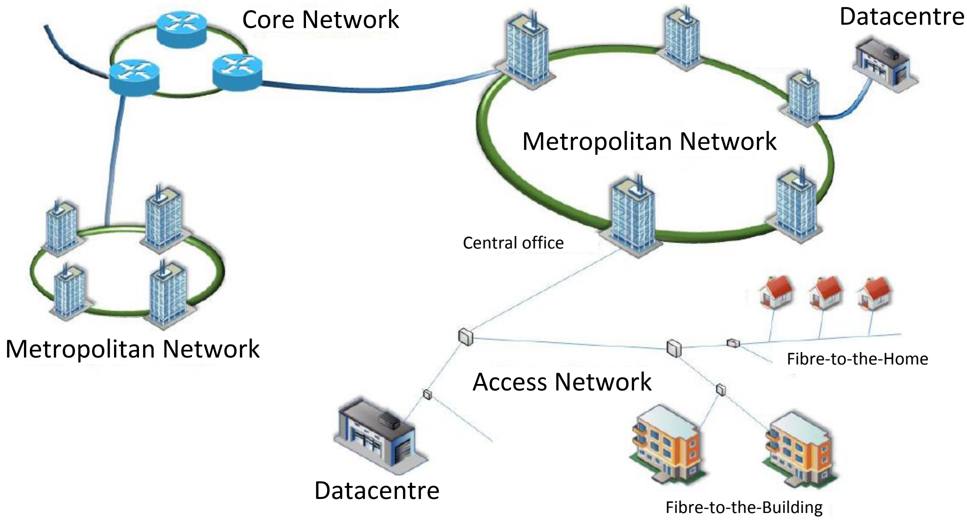

Figure 1.1: Optical Network Topology including core, metropolitan, access and datacentre networks. After: [2]

1.1.1 Core Networks

The core network is the backbone of global communications systems. It connects continents and countries, covering distances of hundreds and thousands of kilometres through terrestrial or submarine fibres. These networks concentrate millions of users and transport large amounts of aggregated data, thus, their long-haul links and systems require reliable technologies that allow ultra-high capacity and robust long distance communications even at a high cost.

1.1.2 Metro Networks

Metro networks interconnect core networks and access networks which connect to the end user. They typically span from tens up to a few hundred of kilometres. As data traffic increases, metro networks must also be upgraded to support the demand for bandwidth from users in the access network. Hence, currently deployed metro networks are evolving towards spectrally efficient 100 Gb/s data rates enabled by coherent reception and will soon require innovative technologies while keeping implementation costs down.

1.1.3 Access Networks

The access network connects the end users to the rest of the network, typically covering distances from a few hundred meters up to a few kilometres. The bit rates involved in access networks are not very high, but they present important technical challenges due to the non-uniform distribution of users. Service providers are currently commercializing the Fibre-To-The-X (FTTX) where *X* refers to the last point where fibre is deployed (cabinet, home, building, etc). Since the access part of the network is costly to deploy, Passive Optical Network (PON) with a cost-efficient tree-like point to multipoint distribution is the dominant approach.

1.1.4 Datacentres

Emerging cloud applications such as mobile devices interconnectivity, with data backup and synchronization, remote desktop, cloud computing, etc. require more traffic being delivered between datacentres.

Lately, significant research efforts are being made in the development of intra-datacentre networks [3]. Datacentres host a number of servers and short fibre links of up to a couple of kilometres are needed. These intra-datacentre systems require high throughput, reduced size of modules, low cost, power consumption and latency. On the other hand, communication links between datacentres, also known as inter-datacentre communications, are performed mainly within metro networks and in some cases, through long haul transport links.

1.2 Evolution of Optical Fibre Communication Systems

During the latter half of the twentieth century, major technological breakthroughs resulted in the development of optical fibre communication systems. The invention of the laser in 1960 [4] followed by the first proposed optical fibre in 1966 [5], primarily drove the research towards low-loss materials for feasible optical fibre transmission. In 1970, Corning Glass Works (now Corning Inc.) achieved and started to manufacture the first optical fibres with an acceptable low-loss of 17 dB/km [6] that, combined with advances in semiconductor laser technology [7], made optical communications practically possible.

Over the next 30 years, there would be extraordinary developments in the manufacturing of optical fibres and lasers that would dramatically boost the transmission capacity and consolidate optical communications as a superior emerging technology over electrical transmission.

1.2.1 Early history

The evolution of optical fibre communications can be divided into several distinct generations that are directly related to these technological innovations and to the resultant increase in the bit rate, B, and transmission distance, L, as illustrated by Figure 1.2.

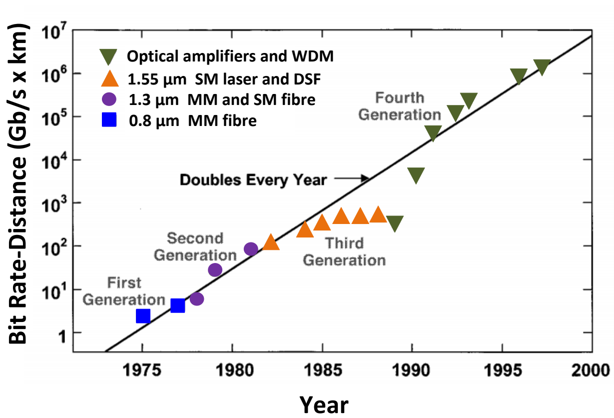

Figure 1.2: Evolution of $B \cdot L$ product over the period 1975 to 2000 through several generations of optical communication links. Each generation with the correspondent technological breakthrough is represented by a symbol. MM: Multi-Mode fibre, SM: Single-Mode fibre, DSF:dispersion-shifted fibre, WDM: Wavelength Division Multiplexing. After: [8]

The first generation of optical systems operated in the 0.8 µm wavelength region and utilized multimode optical fibres. Such systems became commercially available in 1980 [9] and transmitted 45 Mb/s with repeater spacings of up to 10 km, compared to 1 km spacing of the contemporaneous coaxial systems. During the second generation the focus was to increase the $B \cdot L$ product by shifting the operating wavelength towards 1.3 µm where the attenuation in fibres is below 1 dB/km. The first systems were developed in multimode fibres and limited by dispersion. Rapidly, single mode fibres that exhibit minimal dispersion at 1.3 µm were implemented and by 1981, a transmission of 2 Gb/s over 44 km of single mode fibre was demonstrated [10]. Consequently, single mode fibre (at 1.3 µm and later at 1.55 µm wavelength) became the standard fibre for long distance systems where large $B \cdot L$ is required. In 1987, commercial systems at 1.3 µm became available and the first optical transatlantic fibre, TAT-8, was deployed [11]. The third generation intended to use wavelengths around 1.55 µm where the fibre losses are lower, namely 0.2 dB/km. Nevertheless, optical fibres also present a larger dispersion at this wavelength range. Two alternative approaches were developed to overcome the dispersion impediment: the use of single longitudinal mode lasers and Dispersion-Shifted Fibres (DSF), specially designed to have minimum dispersion near 1.55 µm. Transmissions of up to 4 Gb/s over 100 km were first demonstrated in 1985 [12] and commercially deployed in 1990. As illustrated by Figure 1.2, these three generations resulted in a gradual increase of the bit rate and transmission distances.

The major revolution, however, took place during the fourth generation where the capacity of optical communication systems saw explosive growth [13] that resulted in a $B \cdot L$ doubling every year, as depicted in Figure 1.2. This was driven by the emergence of optical amplifiers and a technique defined as Wavelength Division Multiplexing (WDM), explained in detail in the next section due to their importance. These technological developments were mainly driven by the commercial deployment of the Internet and the resultant intensified demand for long-distance transmission capacity. Consequently, optical communications gained enormous attention as a prosperous business and substantially fostered the *Information Age*.

1.2.2 Information Age and Wavelength Division Multiplexing

The introduction of optical amplifiers, specifically the Erbium Doped Fibre Amplifier (EDFA), in the early 1990s resulted in extended all-optical transmission distances [14], [15]. EDFAs compensate for the signal attenuation due to fibre propagation, increasing the spacing between repeaters or, in some systems, their elimination. However, the advent of personal computers and the Internet evolution from a text to a multimedia platform drove a rapid traffic growth that also required higher bit rates.

WDM was the key technology that facilitated the development of high bandwidth communications by scaling the capacity transmission in frequency. WDM uses multiple wavelengths to transmit data, where each wavelength represents an individual channel. As illustrated in Figure 1.3, each channel comprises a single mode laser source that generates an optical signal where the information is encoded, in this Figure through external modulation. These channels are combined together for transmission over a single optical fibre. The frequency separation between two adjacent wavelengths in WDM is known as the channel spacing and typically accounts for the information bandwidth and guard bands, that are unused parts of the spectrum between channels for the purpose of preventing interference. Current deployed WDM systems typically operate at a 50 GHz grid spacing, standardised by the International Telecommunication Union (ITU) [16] and referred to as Dense WDM (DWDM). During transmission, the multiplexed signal can be amplified via EDFAs, and individual optical channels can be inserted or removed from the network as desired, using optical add-drop multiplexers. At the receiver side, the optical signal is demultiplexed into individual channels, distributed to the intended destination where the optical signal is photodetected and the data recovered.

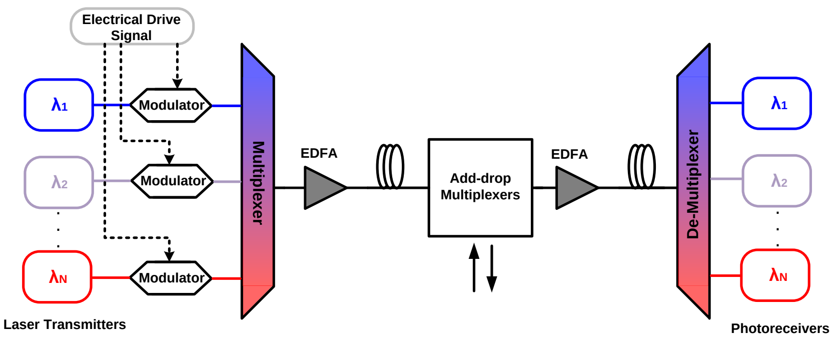

Figure 1.3: Generic WDM architecture.

WDM was mainly enabled by the development of EDFAs that allow simultaneous amplification of all WDM optical channels and compensation for losses in multiplexers, de-multiplexers and during fibre transmission. The utilization of numerous wavelengths, as opposed to the exclusive use of the 1550 nm wavelength, allows bi-directional data transfer through one fibre, and increased system capacities maintaining mature low speed electronics. In 1995 the first commercial WDM system was deployed with a total bandwidth transmission of 20 Gb/s consisting of 8 WDM channels at a bit rate of 2.5 Gb/s [17], and a regenerator span of 360 km. In 1996, research experiments proved an overall transmission of 1 Tb/s [18] (55 WDM channels at 20 Gb/s) over 150 km [19].

Since the first WDM system implementations, technology developments allowed the channel count and the bit rate per WDM channel to continually increase, from 2.5 to 100 Gb/s per wavelength [18] with a total number of 80 channels (separated by a channel spacing of 50 GHz), thus boosting the overall capacity over a fibre. The combination of both technological breakthroughs, EDFAs and WDM, certainly boosted the $B \cdot L$ product and facilitated long-haul systems with potential for further scalability.

1.2.3 State of the art: Towards 100 Gb/s and Beyond

Figure 1.4 shows the global Internet traffic for 1990-2015 estimated by Cisco Systems [20], along with their forecast for the period between 2016 and 2020 [21]. Although the Internet traffic growth rate has decelerated compared to the previous decade, it remains robust at an intensive 23 % increase per year largely driven by the emergence of smart Internet-connected devices, and bandwidth-hungry services and applications, such as on-demand High Definition Television (HDTV), cloud storage and high quality online games.

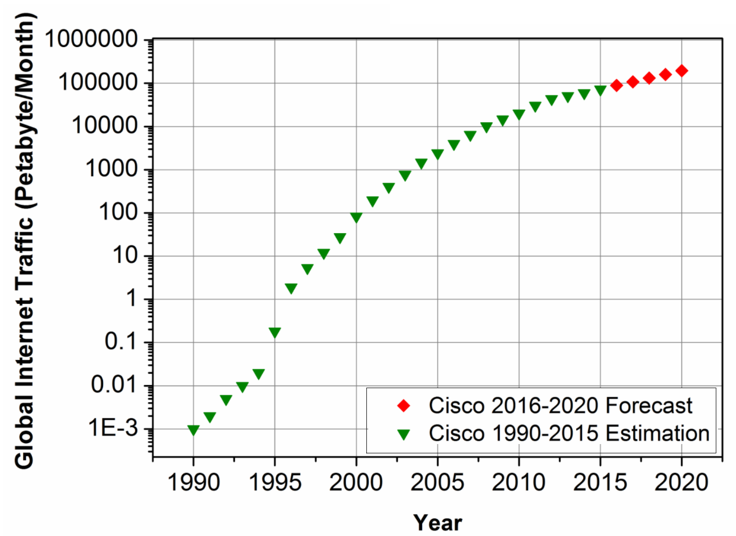

Figure 1.4: Global Internet traffic growth for period 1990-2020.

The capacity growth of commercial optical systems, enabled by WDM, exceeded the requirements of network bandwidth during the first decade. However, as the Internet traffic keeps growing exponentially and the technology matures, it becomes more difficult to increase the systems capacity [22]. In fact, some studies have concluded that the network traffic will grow 10 times faster than current systems capacity over the next decade [23]. In order to satisfy the ever-increasing demand for bandwidth, optical networks must evolve towards higher performance and spectral efficiency, and reduced power consumption [24].

Novel scaling techniques, that are being introduced progressively by the industry, are focusing on improving the spectral efficiency by two main scaling methods: increasing the data rate per optical channel, and reducing the channel spacing which implies a larger number of usable channels. The spectral efficiency is the information rate that can be transmitted over a given bandwidth or channel spacing and it is measured as the ratio *Bit Rate/Channel Spacing* in (bit/s)/Hz. It indicates how efficiently the available fibre bandwidth is being utilised. WDM systems with 10 Gb/s per channel, spaced by 50 GHz, presented a spectral efficiency of 0.2 (bit/s)/Hz.

The first step towards high spectral efficient systems was the implementation of coherent optical communications where higher-order modulation formats are used to increase the data rate per optical channel. Early commercial WDM systems employed, with a high degree of success, a 2 level amplitude modulation format referred to as On/Off Keying (OOK). Even though the possibility of practical implementation of 40 Gb/s OOK systems was demonstrated [25], as data rates are required to exceed 10 Gb/s per channel, this modulation format presents dispersion impairments that can be prohibitive [26] and its spectral efficiency is limited for further scaling. On the other hand, advanced modulation formats, explained in detail in section 1.3, can modulate the amplitude and phase components of both linear polarisations of the optical signal. Therefore, more information can be transmitted when these three parameters are modulated and the spectral efficiency can be at least quadrupled, compared to OOK systems.

The initial introduction of coherent communications allowed 40 Gb/s per channel [27] and a spectral efficiency of 0.8 (bit/s)/Hz. As shown in Figure 1.5, 40 Gb/s has been soon followed in the industry by 100 Gb/s per channel [28] that is able to run at the same 50 GHz channel spacing as 10 Gb/s systems but provides a 10X higher spectral efficiency, namely 2 (bit/s)/Hz.

While commercial coherent 100 Gb/s systems are currently being deployed in long-haul links, research and industry are already moving forward and considering a new spectrally efficient approach for next generation optical transport networks with higher-speed per channel (i.e. 400 Gb/s and 1 Tb/s): the coherent superchannel [29], [30].

A superchannel is an adaptation of DWDM where multiple optical carriers (or sub-channels) are

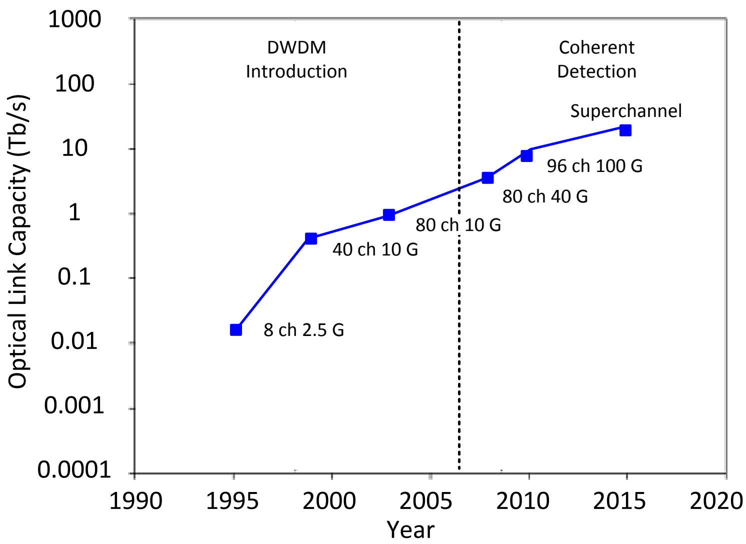

Figure 1.5: Technology roadmap of fibre link capacity in commercial networks. After: [31]

combined to create an aggregated and unified high data rate channel. Therefore, superchannels are multi-wavelength signals that further maximize the spectral efficiency and throughput of installed optical fibres by minimizing the frequency spacing between sub-channels and even eliminating guard bands.

At the time of this writing, research studies have demonstrated superchannel transmissions with spectral efficiencies of up to 8.67 (bit/s)/Hz [32] and claim a possible overall bit rate of 40 Tb/s over 1000 km links when using the total bandwidth of a single optical fibre, which results in a $B \cdot L$ product of 40,000 (Tb/s)·km. Commercial superchannel field trials have also recently started and shown a real-time 2 Tb/s superchannel transport over 727 km [33].

1.3 Advanced Modulation Formats

In optical communications, signal modulation is achieved by imposing the information data on the amplitude, wavelength, phase or polarization of a laser lightwave.

The electric field at the output of a monochromatic laser can be expressed as:

$$E(t) = A(t) \cdot e^{j(w_0 t + \phi(t))} = A(t) \cdot e^{j\phi(t)} \cdot e^{jw_0 t} \tag{1.1}$$

where A is the amplitude, w_0 is the angular frequency and ϕ the phase of the electric field. As observed in Equation 1.1, the amplitude and phase of the complex optical signal could be represented as a phasor. The real and imaginary components of this phasor are also referred to as the In-phase (I) and the Quadrature (Q) components. Thus, amplitude and phase modulations can be represented in an IQ constellation diagram, as depicted in Figure 1.6. The vectorial length from the origin to each of the points of the constellation diagram (symbols) relates to the amplitude of the electric field with the angular component representing the phase. Hence, the IQ plane shows the baseband I and Q signals required to produce the modulated signal.

Conventional optical systems use a remarkably simple and effective 2-level form of intensity modulation: OOK. It consists on turning the laser light on and off to represent a binary 1 or 0, respectively. Due to its simplicity, OOK has been used with data rates up to 10 Gb/s in the entire optical industry for decades. The constellation diagram of OOK presents a symbol at the origin with a zero amplitude, while a second symbol is found at the amplitude of the E-field on the I-axis, indicating that the phase is not changed, as depicted in Figure 1.6 (a). For OOK, the bit rate and symbol rate (or baud rate) are the same since one optical symbol represents only one bit.

Advanced modulation formats allow the number of bits encoded per symbol to be increased. As such, larger information transmissions are achieved with the same symbol (baud) rate, resulting in an enhanced spectral efficiency. The simplest way to do this is to transmit multiple bits per symbol using multilevel amplitude modulation. 4-level Pulse Amplitude Modulation (PAM) is a modulation technique that has been recently attracting a lot of attention whereby 4 distinct pulse amplitudes are used to convey the information. The transmission of four amplitudes allows the encoding of 2 bits of binary data per symbol and thus, PAM-4 enables twice the transmission capacity in comparison to OOK systems. PAM-4 is currently being considered a promising solution for short intra-datacentre links, mainly due to its implementation simplicity, cost-effectiveness and low power consumption [34], [35].

Quadrature Phase Shift Keying (PSK) (QPSK) is a form of phase modulation, where the phase of the laser optical light is used for encoding data. The constellation formed by four symbols is shown in Figure 1.6 (c). Each symbol, or constellation point, corresponds to a discrete phase value that will be imposed on the optical carrier, but maintains the same amplitude. The transmission of four phases also enables the encoding of 2 bits of binary data per symbol. Consequently, QPSK doubles the bit rate transmitted by OOK in the same bandwidth, obtaining a doubling of the spectral efficiency. For any modulation format the relationship between the number of available symbols,

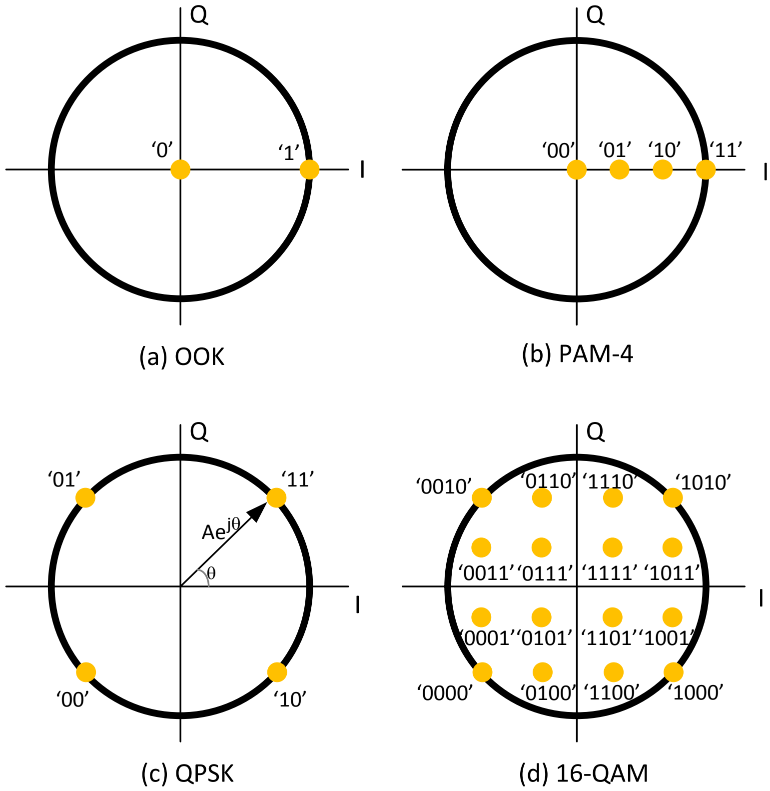

Figure 1.6: Examples of advanced modulation format constellations: (a) OOK, (b) PAM-4, (c) QPSK and (d) 16-QAM.

m, and the number of bits transmitted per symbol, M, is given by:

$$M = \log_2(m) \tag{1.2}$$

It should be noted that higher-order modulation formats also allow the use of lower symbol (baud) rates for a certain overall bit rate. This means that not only the signal spectral width is reduced, but lower cost electronic devices that are commercially available and mature can be used to transmit the same bit rate.

The encoding efficiency can be escalated by employing a combination of phase and multilevel amplitude modulation that extend the number of bits transmitted per symbol. This modulation format is referred to as Quadrature Amplitude Modulation (QAM) and it is often denoted as m-QAM, where m represents the overall number of symbols. The constellation of a 16-QAM is illustrated in Figure 1.6 (d). As it can be seen, each symbol has a unique combination of amplitude and phase and it can convey 4 bits of information, hence the use of 16-QAM quadruples the transmitted bit rate and the resultant spectral efficiency compared to OOK systems.

Additionally, Polarization Division Multiplexing (PM) is generally used in conjunction with high order PSK or QAM to double the transmitted data by carrying different information in two orthogonal light polarization modes independently, allowing the development of 100 Gb/s in the ITU DWDM standard 50 GHz grid using 25 Gbaud PM-QPSK which has been the preferred format for 100 Gb/s applications by the industry. The major problems with the practical use of PM are continuous drifts and dispersion in the polarization states during fibre-optic transmission. As a result, PM requires digital signal processing at the coherent receiver to estimate and decode the signal, eliminating polarization-related artefacts [36].

The symbol size, and thereby the spectral efficiency, of m-QAM systems can be further increased by using a larger number of amplitude and phase levels, as 32-QAM (5 bits per symbol), 64-QAM (6 bits per symbol) or higher m [37], [38]. However, as the order of modulation continuously increases, the requirement for higher Optical Signal-to-Noise Ratio (OSNR) becomes more stringent and the transmission reach may get limited, which can be prohibitive for some communication systems [39].

The constellations in Figure 1.6 show a black circle that exemplifies the maximum peak power that can be launched into a fibre before optical non-linearities, taking place in the fibre, appear and distort the signal. Therefore, as the modulation order increases, the constellation points are situated closer, making them less distinguishable and hence, more susceptible to noise in transmission systems [40]. This has a direct impact in the reachable transmission distance before dispersion and added noise in the system create interferences that make the symbols non recognizable and decoded erroneously at the receiver. As such, the noise purity of the transmitter optical source (in terms of intensity and phase noise) becomes crucial and a major limiting factor in spectrally efficient coherent systems [36]. This will be further detailed later in this thesis.

In conclusion, advanced modulation formats offer a significant enhancement of the spectral efficiency of optical transmission systems. As such, in some scenarios the signal spectral width is notably reduced, resulting in an inefficient use of the ITU 50 GHz grid. Furthermore, when channel rates above 100 Gb/s are considered, a continual increase of the modulation order might not suffice as the noise requirements and transmission distance penalties may be impracticable. In pursuance of better utilisation of the available bandwidth of a fibre, advanced modulation formats can be combined with the use of superchannels and multicarrier techniques, explained in section 1.4. These methods aim to fit more optical sub-channels and decrease channel spacings and guard bands for higher performance and throughput.

The following subsections describe in detail the various processes to generate and detect these advanced modulation formats over optical signals.

1.3.1 External modulation

In external modulation, the laser diode bias current is kept constant and thereby, the laser is on a Continuous Wave (CW) operation where its emitting output power is constant. The laser light is then passed through a modulator that manipulates amplitude and/or phase of the light according to an electrical data drive signal, also applied to the modulator. This modulation is isolated from the driving conditions of the laser and thus, the performance, noise properties and behaviour of the laser remain constant. Furthermore, the use of external modulation enables complex modulation formats, such as QPSK or QAM, to be imposed on an optical carrier.

Two main optical modulators are here revised due to their relevance in optical fibre transmission systems: Mach-Zehnder Modulator (MZM) and IQ MZM.

1.3.1.1 Mach-Zehnder Modulator

The schematic of a MZM structure is shown in Figure 1.7. It comprises two couplers and two electro-optic modulators placed in the MZM arms (some MZMs may have only one electro-optic modulator in one arm). The principle of operation of an electro-optic modulator is based on the electro-optic effect, also known as Pockels effect. It consists of a linear variation in the refractive index of a waveguide according to the strength of an applied electric field [45]. As a consequence, the propagation speed of the light travelling through the waveguide is affected and phase delays, proportional to the electric signal, are induced. By controlling the external voltages applied, the phase of the incoming optical field can be modulated and so, such electro-optic modulators are sometimes referred to as phase modulators.

The incoming beam light from a laser diode operating in CW mode is equally divided into the two arms. An independent drive voltage is applied across each phase modulator and so the optical signals in either path are subjected to different changes in phase. The two signals are then recombined. By controlling the relative phase shift between the two arms, the interference between the two signal varies from constructive to destructive and so the output signal can be also modulated in terms of amplitude. Different configurations of optical modulators exist, but in general they all can be reduced to a combination of phase modulators and/or MZMs. Considering a dual-drive MZM, where

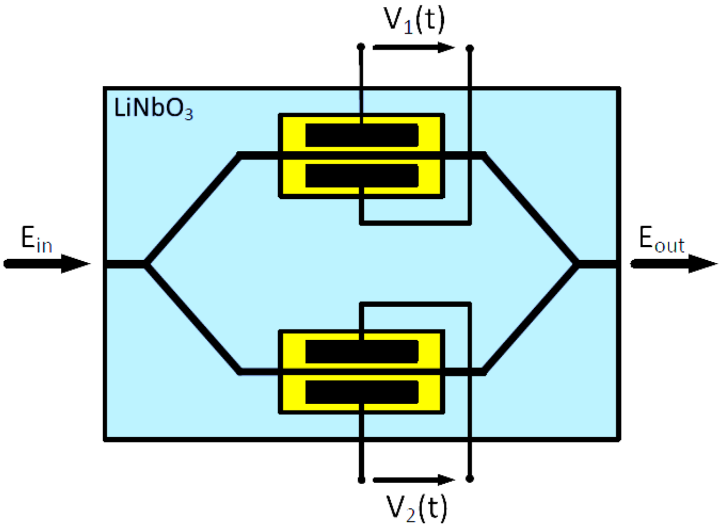

Figure 1.7: Mach-Zehnder Modulator structure.

there is a phase modulator in each arm that can be controlled independently, the optical output is mathematically described as [45]:

$$E_o(t) = \frac{1}{2} \cdot \left(e^{j\phi_1(t)} + e^{j\phi_2(t)}\right) \cdot E_i(t) \tag{1.3}$$

where $E_i(t)$ is the input optical field, $E_o(t)$ is the output optical field and $\phi_1(t)$ and $\phi_2(t)$ are the phase shifts applied to the upper and lower paths of the modulator. Manipulating this equation, it can be observed that the transfer characteristic of a MZM allows amplitude and phase modulation of the input electric field according to $\phi_1(t)$ and $\phi_2(t)$:

$$E_o(t) = E_i(t) \cos\left(\frac{\phi_1(t) - \phi_2(t)}{2}\right) \cdot e^{j\left(\frac{\phi_1(t)+\phi_2(t)}{2}\right)} = A(\phi_1(t), \phi_2(t)) \cdot e^{j(\phi_1(t), \phi_2(t))} \tag{1.4}$$

The voltage difference needed to create a relative phase shift between the two optical paths equal to π is called the half-wave voltage V_π and thus, the phase shifts can be defined as:

$$\phi_{1,2}(t) \approx \frac{\pi \cdot V_{1,2}(t)}{V_\pi} \tag{1.5}$$

where $V_{1,2}(t)$ is the applied voltage composed of a DC voltage, V_b corresponding to the operating bias of the device, and the AC signal $s(t)$ with the data information to transmit [13]:

$$V(t) = V_b + s(t) \tag{1.6}$$

In the ideal case, a shift of V_π in the voltage difference ΔV between the two arms of the modulator is capable of changing the output optical power from minimum to maximum, as illustrated in Figure 1.8 where the transfer function for the electric field and optical power of the MZM are illustrated. In order to obtain intensity modulation, the operating bias point is set to be in the linear region between minimum and maximum transmission points to achieve a linear relationship between driving voltages and optical output power. This is known as the quadrature bias point. Phase modulation

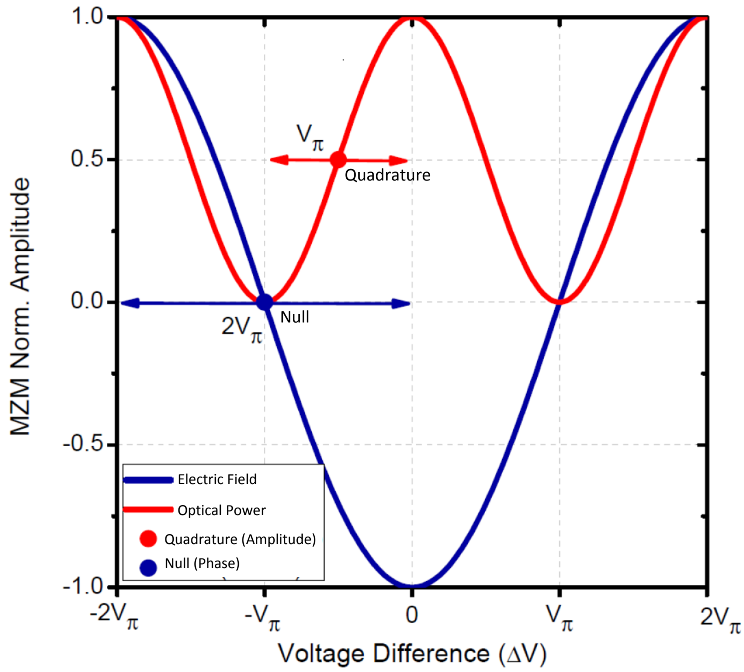

Figure 1.8: Normalised field (blue) and power (red) transfer functions of a dual-drive Mach-Zehnder modulator. Operation bias points for amplitude (quadrature) and phase (null) modulation are also shown. After: [2]

can also be achieved when the operating bias is set to the minimum transmission point, known as the null point. This can be observed visually in Figure 1.8. In this case, a more complicated receiver, capable of detecting phase change, is required as it will be later shown.

Although a single MZM can generate amplitude and phase modulation of the input light by choosing $V_{1,2}$ appropriately, it does not have the capability of modulating I and Q independently.

1.3.1.2 IQ Mach-Zehnder Modulator

An optical complex field modulator, also known as IQ modulator, consists of two nested MZMs with an additional 90° phase shifter in one of the arms as illustrated in Figure 1.9. By choosing the applied voltages appropriately, one can cover the entire complex IQ plane in the constellation diagram and generate higher order modulation formats such as QPSK and 16-QAM that require independent modulation of I and Q components.

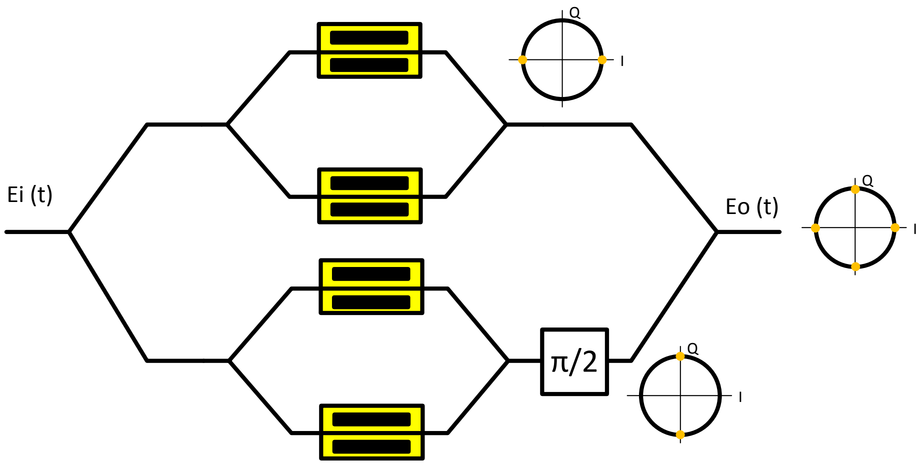

Figure 1.9: Schematic of an IQ MZM. An example of QPSK modulation with the correspondent constellation diagrams is also shown.

As an example, consider a QPSK modulation. Each MZM should be biased at null to generate a binary phase modulation in each of the arms, corresponding to phase shifts of 0 and π. The signal in the lower arm is then phase shifted by $\frac{\pi}{2}$ relative to the other arm. As a result, the two I and Q components are generated.

1.3.2 Direct detection

After fibre transmission, the optical signal needs to be detected and the electrical data information extracted, or de-modulated, from the optical carrier in an optical receiver.

As explained in section 1.3.1 the optical power of a laser lightwave can be modulated to carry information. In a direct detection receiver, the optical signal is detected by a photodiode that generates a photocurrent, proportional to the power of the optical incident signal. Hence, the induced electric current variations correspond to the recovered modulating data [13].

The performance of direct-detection receivers is predominantly affected by intensity noise.

1.3.3 Coherent detection

Direct detection is a simple and cost-efficient optical receiver, however, it allows only amplitude modulated formats to be recovered as the detected average optical power is phase independent.

Modulation formats that use the optical carrier phase to transmit information require more complicated receivers, called coherent detectors. In these, phase variations are converted into intensity changes by coupling the modulated optical signal with a reference signal, known as Local Oscillator (LO), creating constructive or destructive interferences depending on the relative phase differences.

The phase diversity quadrature frontend, depicted in Figure 1.10, comprises a 90° hybrid and a pair of balanced photodetectors allows the amplitude and phase de-modulation of both IQ components [46]. The generated photocurrents are mathematically expressed as [36], [46]:

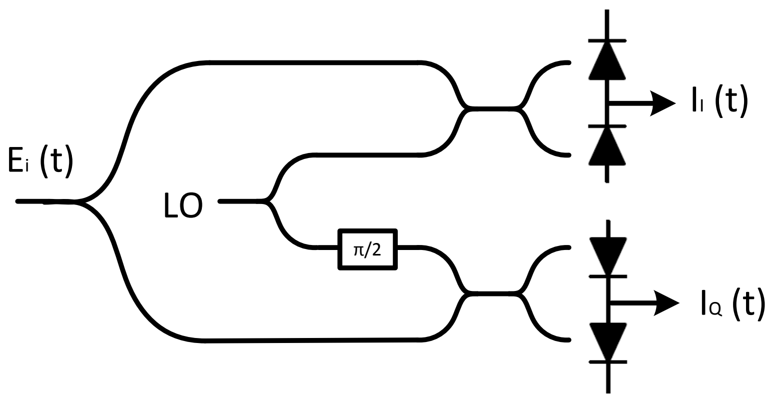

Figure 1.10: Schematic of a phase diversity coherent receiver, formed by a 90° hybrid and two of balanced photodetectors.

$$I_I(t) \approx \frac{R}{2}|E_i||E_{LO}|\cos\Big(w_i(t) - w_{LO}(t) + \phi_i(t) - \phi_{LO}(t)\Big) \tag{1.7}$$

$$I_Q(t) \approx \frac{R}{2}|E_i||E_{LO}|\sin\Big(w_i(t) - w_{LO}(t) + \phi_i(t) - \phi_{LO}(t)\Big) \tag{1.8}$$

where $I_I(t)$ and $I_Q(t)$ represent the photocurrents for the I and Q components respectively, R is the responsivity of the photodetector, $|E_i(t)|$, w_i and ϕ_i are the electric field amplitude, frequency and phase of the modulated optical signal and $|E_{LO}(t)|$, w_{LO} and ϕ_{LO} are the electric field amplitude, frequency and phase of the local oscillator reference. The signal phase ϕ_i contains the phase of the optical carrier and the phase of the encoded data. Therefore, phase modulation and coherent receivers are sensitive to phase noise so future high capacity transmitters and require low noise optical transmitters. Additionally, low phase noise LOs and high-speed digital signal processing are required to perform phase and frequency tracking [46].

1.4 Superchannel

Superchannels have been considered as key enablers for high capacity next generation optical transport networks by both the research community and industry [47]- [53].

Superchannels are formed by multiple combined optical carriers, or sub-channels, typically encoded with high order modulation formats and spectrally close-spaced thereby, fulfilling the bandwidth demands with transmissions of $>$100 Gb/s per channel while keeping pace with the spectral efficiency.

The motivation behind superchannels comes as an evolution of DWDM after the employment of advanced modulation formats. As previously explained, combinations of amplitude, phase and polarization modulations can dramatically increase the network capacity. However, by employing optical carriers spaced by the current DWDM 50 GHz grid, the spectrum is not efficiently used as these high order modulations schemes occupy narrower bandwidths. Superchannels seek to alleviate this spectrum waste and further increase the throughput by decreasing the channel spacings, allowing more channels to be fitted, and by using in conjunction, multicarrier modulation transmission techniques that allow the reduction and even elimination of guard bands, as explained in subsection 1.4.2.

In Figure 1.11 an example of the potential spectrum savings is illustrated. Figure 1.11 (a) shows a 1 Tb/s superchannel formed by using ten optical carriers at 100 Gb/s each employing 12.5 Gbaud polarization multiplexed 16-QAM. The sub-channels are separated by the fixed 50 GHz grid and as a result, the superchannel occupies a bandwidth of 500 GHz. On the other hand, Figure 1.11 (b) shows a spectrally efficient 1 Tb/s superchannel comprised of ten optical carriers with the same modulation format and baud rate, polarization multiplexed 16-QAM. In this case, the sub-channels are placed contiguously, using a multiplexing technique named Nyquist WDM that allows the reduction of the bandwidth of each sub-channel to 12.5 GHz, and 500 MHz guard bands are in place. Hence, a total bandwidth of 129.5 GHz is needed, obtaining a 74.1 % in spectral usage.

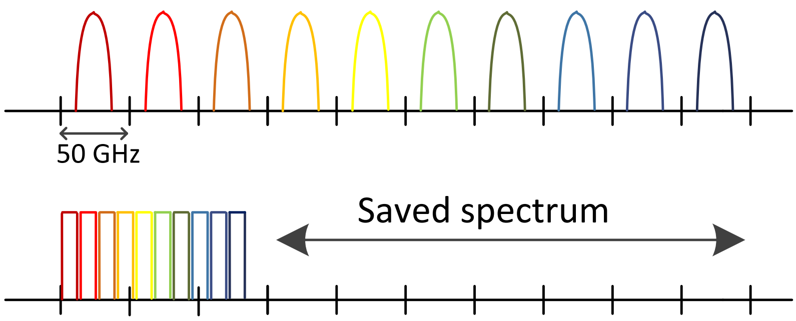

Figure 1.11: 1 Tb/s superchannel illustration. Upper, superchannel in existing 50 GHz grid. Lower, same superchannel employing Nyquist WDM, with 13 GHz of frequency spacing between sub-channels.

Superchannels were first demonstrated by S. Chandrasekhar [47] in 2009. The superchannel consisted on 24 optical carriers with PM-QPSK spaced by 12.5 GHz, where an overall transmission of 1.2-Tb/s over 7200 km was obtained. Numerous research works and field trials by companies such as NEC, Infinera and Alcatel-Lucent soon followed with early commercially available products by 2012. NEC first demonstrated the transmission of 1.15 Tb/s superchannels over 10,000 kilometres of existing transoceanic fibres with 23 optical carriers, each with 12.5 Gbaud PM-QPSK [50] and the first Infinera 500 Gb/s superchannel was brought into market, comprising ten optical carriers modulated with PM-QPSK, in 2012. Since then, superchannels gained a lot of attention and numerous works have successfully proved their suitability for high performance and capacity transmissions [51]- [52]. Currently, Infinera offers commercial products for superchannel transmissions of up to 1.2 Tb/s employing PM-16-QAM [53]. Remarkable recent achievements include a superchannel transmission with 8.67 (bit/s/Hz) of spectral efficiency [32], and the late field trial demonstrations of real-time superchannels of 5.6 Tb/s over 359 km and 2 Tb/s over a live 727 km network by British Telecommunications and Huawei Technologies [33].

1.4.1 Flexible Networks

The fibre bandwidth is currently divided in a 50 GHz grid defined by the ITU standards that, although successfully allowed 100 Gb/s to be commercially deployed, will have difficulties allocating higher bit rates (400 Gb/s, 1Tb/s, etc.). Furthermore, an arbitrary number of smaller frequency slots could allow the creation of bandwidth-fitted superchannels avoiding misuse of the available spectrum, as illustrated by Figure 1.11. Thus, there is a necessity for the grid to evolve towards finer granularities or even gridless [54] and new standards as the *Flexible grid* defined by the ITU-T in the G.694.1 recommendation [55] are emerging to support their deployment. The new flexible grid defines channels having a granularity of 12.5 GHz, combined with the ability to define an aggregate superchannel spectral width of 12.5 GHz multiples.

Flexible optical networks, also referred as elastic networks, make use of these flexible grids and are gaining a lot of attention to allow 400 Gb/s and 1Tb/s superchannels as they additionally enable a superb efficient usage of the available spectrum by dynamically allocating the bandwidth (elastic spectrum allocation) according to temporal traffic demands. Furthermore, an optimized spectral efficiency and performance can be achieved by dynamically adjusting transmission parameters such as sub-channel bandwidths, information rates and modulation formats depending on the unoccupied bandwidth, required capacity, optical link reach or other operating specifications.

1.4.2 Enabling Multicarrier modulation techniques

As previously mentioned, superchannels utilize multicarrier modulation techniques that allow the multiple sub-channels to be closely frequency spaced and reduce the overall transmitted bandwidth. These techniques rely on spectral and temporal shaping of the pulses that carry the data. The initial use of signal shaping techniques [56] in optical communications was motivated by the reduction of inter-symbol interference (ISI), a form of distortion of a signal in which one symbol interferes with subsequent symbols, and improvement of the transmission performance of the signal [40], [49].

In this work, we focus on two specific techniques: Nyquist WDM and all-optical Orthogonal Frequency Division Multiplexing (OFDM).

1.4.2.1 Nyquist WDM

In Nyquist WDM each sub-channel is spectrally shaped to occupy the minimum bandwidth that ensures ISI-free transmission, defined by the *Nyquist ISI criterion* and coincides with the baud rate [57]. Such narrow sub-channels can then be multiplexed very tightly, with minimum guard bands that ensure sub-channel filtering at the receiver without incurring in crosstalk (inter-channel interferences) [58], as observed in the ideal spectrum in Figure 1.12 (a).

These ideal non-overlapping rectangular-shaped sub-channel spectra correspond to an overlapped sinc-shaped response in the time domain [59], as observed in Figure 1.12 (b).

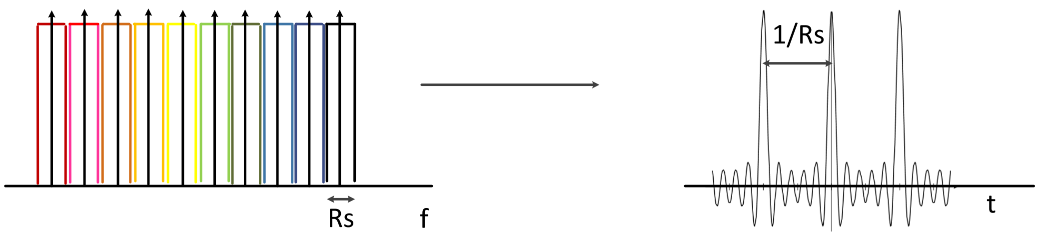

Figure 1.12: Left, a typical spectrum of a Nyquist WDM multicarrier signal. Right, time response of the Nyquist WDM multicarrier signal, with QPSK modulation and where the period corresponds to the baud rate used.

Nyquist WDM, therefore, requires a specific optical spectral rectangular shaping which can be performed at the transmitter using digital, analog electrical or optical filtering. However, perfect rectangular signals (sinc pulses) are not physically realisable and alternatively, practical implementations widely use raised-cosine pulses, illustrated in Figure 1.13, for Nyquist pulse shaping. The sharpness of the spectral filtering is determined by the roll-off factor, β, where $0 < \beta \leq 1$ [60].

Hence, Nyquist WDM reduces the total superchannel bandwidth allowing a better spectral efficiency by tightly packing the sub-channels and minimizing their bandwidth. This poses wavelength stability and low phase noise (that translates into frequency noise) requirements on the optical subcarriers to avoid drift and interference.

1.4.2.2 All optical OFDM

All optical OFDM transmits data on many sub-channels that are spectrally overlapped [57]. Analogous to Nyquist WDM, all optical OFDM involves temporal shaping of the signal and thus, the

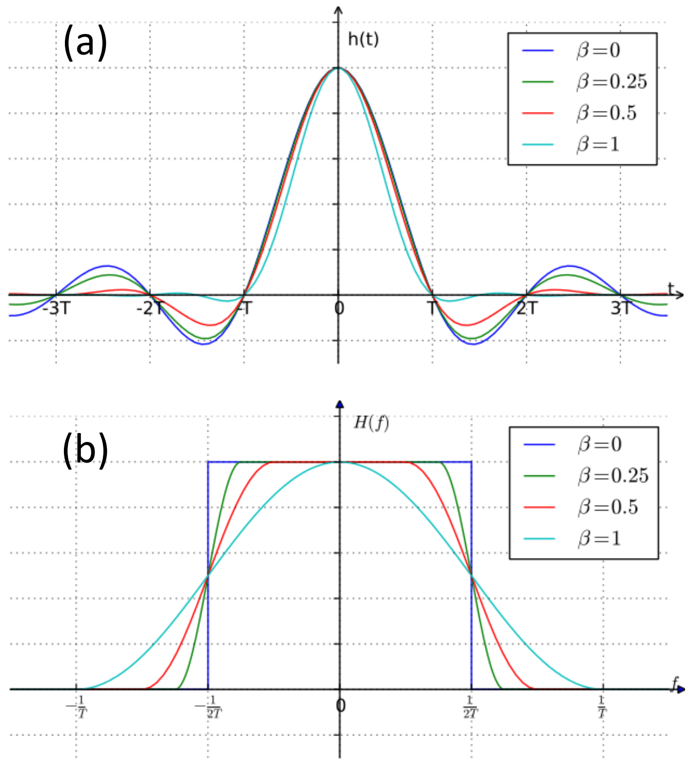

Figure 1.13: (a) Raised-cosine pulse in the time domain (b) Frequency response of raised-cosine pulse. After: [61]

transmitted pulses are ideal rectangular pulses. Therefore, the spectrum of the sub-channels correspond to sinc-shaped functions precisely spaced at multiples of the inverse of the symbol periods. These shaped spectra strongly overlap but are mathematically orthogonal with the peaks of the sub-channel spectra coinciding with the nulls of the spectra from neighbouring sub-channels, as illustrated in Figure 1.14.

In all optical OFDM crosstalk is clearly presented in the spectrum but it can be eliminated at the receiver if the sub-carriers have a strong phase correlation [57], [62], i.e. their phase noises are correlated and can be cancelled out. If, on the contrary, the sub-carriers present arbitrary phase noises that translates into frequency noise, the sub-channels will interfere in an unpredictable way.

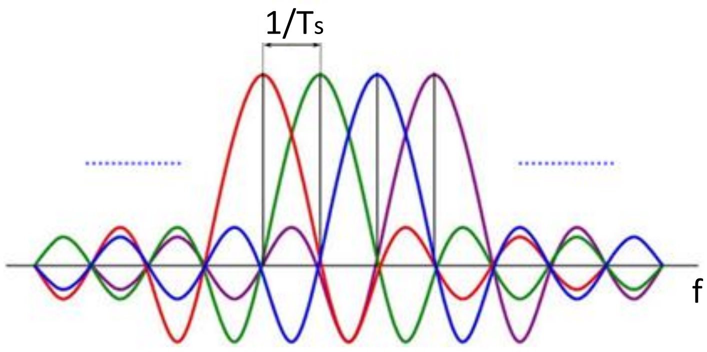

Figure 1.14: All optical OFDM ideal spectrum with overlapped sinc sub-carriers.

1.5 Optical Multicarrier Sources

The generation of superchannels that uses advanced modulation formats and multicarrier modulation techniques, require an optical multi-wavelength transmitter capable of creating multiple, closely frequency spaced and stable optical carriers.

1.5.1 Bank of lasers

A conventional approach to generate optical multicarrier sources is to use a bank of single mode lasers, which can be implemented with discrete lasers or with an integrated laser array [63], [64]. Each laser is adequately set to a certain wavelength to create the desired frequency spacing.

A single Photonic Integrated Circuit (PIC) can host numerous lasers allowing a large number of optical carriers from a single chip. Nevertheless, laser banks struggle to provide a constant frequency spacing between the carriers as each laser emission wavelength can arbitrarily drift over time. Clearly, as the spacing between sub-channels is reduced and guard bands omitted or become very small, this wavelength drift becomes problematic, causing undesired interference between adjacent sub-channels, and therefore, their use limit the achievable spectral efficiency. In order to maintain an acceptable stability each laser needs additional complicated control mechanisms [65], as well as independent biasing circuits which increases the complexity, cost and power consumption. Moreover, modifying the frequency spacing requires all lasers to be precisely tuned individually.

Finally, the independent lasers are not phase correlated to each other, which is an enabling condition for all-optical OFDM modulation technique and an indispensable requirement to reverse the non-linear distortions through fibre transmission, which also enables power above the non-linear barrier to be launched into fibres and consequently, longer record-breaking transmission distances [66].

1.5.2 Optical Frequency Comb Source (OFCS)

OFCSs have shown significant promise for use in wide ranging applications among numerous disciplines, such as millimetre wave and THz signal generation [67], microwave photonics, spectroscopy [68] and, particularly, next generation spectrally efficient optical transceivers [69], [70].

An OFCS simultaneously generates, from a single device or subsystem, a number of precisely spaced and equidistant spectral carriers that share a strong phase correlation. Hence, OFCSs have attracted much interest and have proven to be key components in spectrally-efficient advanced multicarrier modulation techniques, thanks to their inherently precise and stable frequency spacing which enables the reduction or elimination of guard bands. Moreover, a single OFCS can replace multiple independent lasers reducing the power consumption and complexity.

OFCSs may also offer tunable frequency spacing and wavelength that allows a single source to be dynamically and easily adapted to suit the chosen symbol rate and to allocate a superchannel simultaneously to a specific wavelength band, according to traffic demands [70]. Finally, recent research studies have demonstrated that the phase correlation between the optical carriers presented in OFCSs is essential to push the fibre transmission capacity and distance over previous estimated limits [66]. The input power to a fibre is typically limited to a certain power level, beyond that threshold, additional power irreparably creates non-linearities that distort the information travelling through the fibre. The phase correlation between the multiple optical carriers, can be used to cancel these non-linearities and substantially recover the transmitted information. Consequently, the study demonstrated a record 12,000 km transmission [66].

Due to these beneficial characteristics, this thesis is focused on OFCS for next generation optical transmission applications.

The advanced modulation techniques that have been discussed in this Chapter offer a large fibre capacity and throughput enhancement by dramatically improving the spectral efficiency. Depending on the network topology and application, diverse requirements and specifications (such as transmission lengths, overall superchannel bandwidth, modulation formats and complexity) are stipulated.

Additionally, at the time of writing, there are no defined standards for the implementation of these emerging technologies. Therefore, a single compact OFCS with the potential to meet the stringent requirements of various optical networking scenarios, from intra-datacentre to long-haul optical transport, would be highly desirable.

Large number of carriers capable of allocating a superchannel, with good spectral flatness, stability, frequency spacing and wavelength flexibility, low Relative Intensity Noise (RIN), high Optical Carrier to Noise Ratio (OCNR), low phase noise and strong phase correlation between the carriers are all advisable qualities for versatile OFCSs that successfully allow the deployment of advanced modulation formats and superchannels. Furthermore, optical comb sources are expected to reduce component count and power consumption at the optical transmitters, so in order to yield further compactness and cost-efficiency, the photonic integration of these sources has lately become crucial.

A number of OFCS have been proposed, such as Mode-locked lasers (MLLs), electro-optic modulator based, parametric and gain-switched OFCSs that will be reviewed in Chapter 2.

1.6 Conclusions

From the first fibre optic link at Mb/s over several kilometres, optical communications have transformed to a complex high-capacity network spanning the globe that has facilitated the evolution of the Information Age. Modern society relies on inter-connected mobile devices and fast data exchange for communication, entertainment, mobility, education, business operations and health. Numerous emerging services and bandwidth-hungry applications are further contributing to the incessant and relentless traffic growth.

As such, various capacity scaling and spectrally efficient methods have been proposed recently to cope with bandwidth demands. High-order modulation formats, such as QPSK and QAM, improve the spectral efficiency by multi-level encoding of the information in the optical carrier amplitude, phase and polarization while maintaining the bandwidth. Simultaneously, the multicarrier modulation techniques presented, Nyquist WDM and all optical OFDM, reduce the frequency spacing and guard bands between adjacent optical channels, optimizing the bandwidth usage. In conjunction, these techniques will enable spectrally efficient optical superchannels to reach data rates beyond Tb/s. The implementation of these technologies require compact multi-carrier optical sources in the transmitter with wavelength stability, good spectral and noise properties as well as cost efficiency.

Optical frequency comb sources are key candidates that simultaneously generate multiple phase correlated optical carriers with an outstanding stable and equidistant frequency separation.

This work is focused on a specific kind of optical frequency comb sources: externally injected gain switched optical frequency comb sources (GS-OFCS). This thesis investigates novel experimental configurations to enhance their potential for network deployment, with improved flexibility and expanded bandwidth coverage. This work also studies the need for de-multiplexing of these comb sources and, in order to yield further compactness and cost-efficiency, a detailed characterization of two photonic integrated devices for GS-OFCS generation and de-multiplexing is reported. Finally, the integrated GS-OFCS is implemented into two spectrally efficient transmission systems that denote the quality and relevancy of these devices for future optical networks.

References

[1] R. Ramaswami, K. N. Sivarajan, and G. H. Sasaki, “Optical Networks: A Practical Perspective,” Morgan Kaufmann, 2010.

[2] V. Vujicic, “Optical multicarrier sources for spectrally efficient optical networks,” Thesis, Available: http://doras.dcu.ie/20981/1/Thesis_Vidak_Vujicic_Final_version.pdf

[3] S. J. B. Yoo, Y. Yin and K. Wen, “Intra and inter datacenter networking: The role of optical packet switching and flexible bandwidth optical networking,” 16th International Conference on Optical Network Design and Modelling (ONDM), Colchester, 2012, pp. 1-6.

[4] T. H. Maiman, “Stimulated Optical Radiation in Ruby,” *Nature*, vol. 187, pp. 493–494, 08/06/print 1960.

[5] K. C. Kao and G. A. Hockham, “Dielectric surface waveguides for optical frequencies,” in *Proceedings of the Institution of Electrical Engineers*, vol. 133, pp. 1151–1158, July 1966.

[6] F. P. Kapron, D. B. Keck, and R. D. Maurer, “Radiation losses in glass optical waveguides,” *Applied Physics Letters*, vol. 17, pp. 423–425, 1970.

[7] I. Hayashi, M. B. Panish, P. W. Foy, and S. Sumski, “Junction Lasers which Operate Continuously at Room Temerature,” *Applied Physics Letters*, vol. 17, pp. 109–111, 1970.

[8] H. Kogelnik, “High-capacity optical communications: personal recollections,” *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 6, no. 6, pp. 1279–1286, Nov. 2000.

[9] R. J. Sanferrare, “Terrestrial lightwave systems,” *AT&T Technical Journal*, vol. 66, pp. 95–107, 1987.

[10] J. I. Yamada, S. Machida, and T. Kimura, “2 Gbit/s optical transmission experiments at 1.3 um with 44 km single-mode fibre,” *Electronics Letters*, vol. 17, pp. 479–480, 1981.

[11] S. Abbott, “Review of 20 years of undersea optical transmission system development and

deployment since TAT-8," in *34th European Conference on Optical Communication*, Brussels, Belgium, 2008, pp. 1-4.

[12] A. H. Gnauck, B. L. Kasper, R. A. Linke, R. W. Dawson, T. L. Koch, T. J. Bridges, E. G. Burkhardt, R. T. Yen, D. P. Wilt, J. C. Campbell, K. C. Nelson, and L. G. Cohen, "4-Gbit/s transmission over 103 km of optical fibre using a novel electronic multiplexer/demultiplexer," *Journal of Lightwave Technology*, vol. 3, pp. 1032–1035, 1985.

[13] G. P. Agrawal, Fiber-Optic Communication Systems, 3rd ed.: Wiley, 2002.

[14] R. J. Mears, L. Reekie, I. M. Jauncey, and D. N. Payne, "High-gain rare-earth-doped amplifier at 1.54 µm," in *Proceedings of Optical Fiber Communication Conference*, Nevada, USA, paper WI2, Jan. 1987.

[15] E. Desurvire, J. Simpson, and P.C. Becker, "High-gain erbium-doped traveling-wave amplifier," *Optics Letters*, vol. 12, No. 11, pp. 888–890, Nov. 1987.

[16] International Telecommunications Union (ITU), "G.694.1 spectral grids for WDM applications: DWDM frequency grid", Series G: Transmission Systems and Media, Digital Systems and Networks, 2012

[17] R. C. Alferness, H. Kogelnik, and T. H. Wood, "The Evolution of optical systems: optics everywhere," *Bell Labs Technical Journal*, vol. 5, pp. 188–202, Mar. 2000.

[18] A. H. Gnauck, R. W. Tkach, A. R. Chraplyvy and T. Li, "High-Capacity Optical Transmission Systems," *Journal of Lightwave Technology*, vol. 26, no. 9, pp. 1032–1045, May, 2008.

[19] H. Onaka, H. Miyata, G. Ishikawa, K. Otsuka, H. Ooi, Y. Kai, S. Kinoshita, M. Seino, H. Nishimoto, and T. Chikama, "1.1 Tb/s WDM transmission over a 150 km 1.3 µm zero-dispersion single-mode ," in *Proceedings of Optical Fiber Communications Conference*, San Jose, California, USA, Paper PD-19, 1996.

[20] Cisco Systems, Available: http://en.wikipedia.org/wiki/Internet_traffic#cite_note-CSCO-15

[21] Cisco Systems, "The Zettabyte Era: Trends and Analysis", White paper, Jun. 2016. Available: http://www.cisco.com/c/en/us/solutions/collateral/service-provider/visual-networking-index-vni/vni-hyperconnectivity-wp.html

[22] E. Desurvire, "Capacity demand and technology challenges for lightwave systems in the next two decades," *Journal of Lightwave Technology*, vol. 24, no. 12, pp. 4697–4710, 2006.

[23] R. Essiambre and R. W. Tkach, "Capacity Trends and Limits of Optical Communication Networks," *Proceedings of the IEEE*, vol. 100, pp. 1035–1055, March 2012.

[24] S. Gringeri, E. B. Basch, and T. J. Xia, "Technical considerations for supporting data rates beyond 100 Gb/s," *IEEE Communications Magazine*, vol. 50, no. 2, pp. 21–30, Feb. 2012.

[25] M. Birk, L. Raddatz, D. A. Fishman, P. Magill, S. Woodward, "Field Trial of End-to-End OC-768 Transmission Using 9 WDM Channels over 1000km of Installed Fiber," in *Proceedings of Optical Fiber Communications Conference*, Atlanta, Georgia, USA, paper TuS4, 2003.

[26] T. Foggi, E. Forestieri, G. Colavolpe, G. Prati, "Maximum-Likelihood Sequence Detection With Closed-Form Metrics in OOK Optical Systems Impaired by GVD and PMD," *Journal of Lightwave Technology*, vol. 24, no. 8, pp. 3073–3087, Aug. 2006.

[27] H. Sun, K.-T. Wu, and K. Roberts, "Real-time measurements of a 40 Gb/s coherent system," *Optics Express*, vol. 16, pp. 873–879, 2008.

[28] P. J. Winzer, G. Raybon, H. Song, A. Adamiecki, S. Corteselli, A. H. Gnauck, D. A. Fishman, C. R. Doerr, S. Chandrasekhar, L. L. Buhl, T. J. Xia, G. Wellbrock, W. Lee, B. Basch, T. Kawanishi, K. Higuma, Y. Painchaud, "100-Gb/s DQPSK Transmission: From Laboratory Experiments to Field Trials," *Journal of Lightwave Technology*, vol. 26, no. 20, pp. 3388–3402, Oct. 2008.

[29] P. J. Winzer, "Beyond 100G Ethernet," *IEEE Communications Magazine*, vol. 48, no. 7, pp. 26–30, July 2010.

[30] Infinera, "Super-channels: DWDM Transmission at 100 Gb/s and Beyond," White Paper, Available: https://www.infinera.com/wp-content/uploads/2015/07/SuperChannel_WhitePaper.pdf

[31] Fiber optic components, "What is the Meaning of 100G Channels Networks to Service Providers", Article, April 2014. Available: http://www.-optic-components.com/what-is-the-meaning-of-100g-channels-networks-to-service-providers.html

[32] A. Nespola, S. Straullu, G. Bosco, A. Carena, J. Yanchao, P. Poggiolini, F. Forghieri, Y. Yamamoto, M. Hirano, T. Sasaki, J. Bauwelinck, and K. Verheyen, "1306–km 20x124.8–Gb/s PM–64QAM Transmission over PSCF with Net SEDP 11,300 (b·km)/s/Hz using 1.15 samp/symb DAC," *Optics Express*, vol. 22, pp. 1796–1805, Jan. 2014.

[33] Y. R. Zhou, K. Smith, S. West, M. Johnston, J. Weatherhead, P. Weir, J. Hammond, a. lord, J. Chen, W. Pan, C. Cao, R. Yang, N. Zhou, and S. Wu, "Field Trial Demonstration of Real-Time

Optical Superchannel Transport up to 5.6Tb/s over 359km and 2Tb/s over a Live 727km Flexible Grid Optical Link using 64GBaud Software Configurable Transponders," *Journal of Lightwave Technology*, vol.PP, no.99, pp.1-1, July 2016.

[34] F. Karinou, C. Prodaniuc, N. Stojanovic, M. Ortsiefer, A. Daly, R. Hohenleitner, B. Kogel, and C. Neumeyr, "Directly PAM-4 modulated 1530-nm VCSEL enabling 56 Gb/s/λ data-center interconnects," *IEEE Photonics Technology Letters*, vol. 27, no. 17, pp. 1872–1875, Sept. 2015.

[35] D. Sadot, G. Dorman, A. Gorshtein, E. Sonkin, and O. Vidal, "Single channel 112 Gbit/sec PAM4 at 56 Gbaud with digital signal processing for data centers applications," *Optics Express*, vol. 23, pp. 991–997, Jan. 2015.

[36] K. Kikuchi, "Coherent Optical Communications: Historical Perspectives and Future Directions," in *High Spectral Density Optical Communication Technologies*, Springer, 2010.

[37] X. Zhou, L. E. Nelson, P. Magill, R. Isaac, B. Zhu, D. W. Peckham, P. I. Borel, K. Carlson, "PDM-Nyquist-32QAM for 450-Gb/s Per-Channel WDM Transmission on the 50 GHz ITU-T Grid," *Journal of Lightwave Technology*, vol. 30, no. 54, pp. 553–559, Feb. 2012.

[38] A. H. Gnauck, P. J. Winzer, A. Konczykowska, F. Jorge, J.-Y. Dupuy, M. Riet, G. Charlet, B. Zhu, D. W. Peckham, "Generation and Transmission of 21.4-Gbaud PDM 64-QAM Using a Novel High-Power DAC Driving a Single I/Q Modulator," *Journal of Lightwave Technology*, vol. 30, no. 4, pp. 532–536, Feb. 2012.

[39] P. J. Winzer, "High-Spectral-Efficiency Optical Modulation Formats," *Journal of Lightwave Technology*, vol. 30, no. 24, pp. 3824–3835, Dec. 2012.

[40] R.-J. Essiambre, G. Kramer, P. J. Winzer, G. J. Foschini, B. Goebel, "Capacity limits of optical fiber networks," *Journal of Lightwave Technology*, vol. 28, no. 4, pp. 662–701, Feb. 2010.

[41] S. Lindgren, H. Ahlfeldt, L. Backlin, L. Forssen, C. Vieider, H. Elderstig, et al., "24-GHz modulation bandwidth and passive alignment of flip-chip mounted DFB laser diodes," *IEEE Photonics Technology Letters*, vol. 9, pp. 306-308, 1997.

[42] Y. Matsui, "55-GHz bandwidth short-cavity distributed reflector laser and its application to 112-Gb/s PAM-4," in *Proceedings of Optical Fibre Communication Conference*, Postdeadline Paper, Th5B.4, 2016.

[43] Y. Matsui, R. Schatz, G. Carey, T. Sudo and C. Roxlo, "Direct modulation laser technology toward 50-GHz bandwidth," *International Semiconductor Laser Conference*, Kobe, Japan, pp.

1–2, 2016.

[44] T. L. Koch and J. E. Bowers, "Nature of wavelength chirping in directly modulated semiconductor lasers," *Electronics Letters*, vol. 20, pp. 1038–1040, 1984.

[45] M. Seimetz, "High–Order modulation for Optical Fiber Transmission Systems," Springer, Atlanta, GA, 2009.

[46] K. Kikuchi, "Fundamentals of Coherent Optical Fiber Communications," *Journal of Lightwave Technology*, vol. 34, no. 1, pp. 157–179, Jan. 2016.

[47] S. Chandrasekhar, X. Liu, B. Zhu, and D. Peckham, "Transmission of a 1.2-Tb/s 24-Carrier No-Guard-Interval Coherent OFDM Superchannel over 7200-km of Ultra-Large-Area Fiber," in *Proceedings of European Conference on Optical Communications*, Vienna, Austria, Post deadline paper PD 2.6, 2009.

[48] G. Bennett, "Superchannels to the rescue!," Lightwave magazine Article. Available: http://www.lightwaveonline.com/articles/print/volume-29/issue-2/features/superchannels-to-the-rescue.html

[49] J. Fischer, M. Nolle, L. Molle, C. Schmidtlanghorst, J. Hilt, R. Ludwig, C. Schubert, "Beyond 100G - high-capacity transport technologies for next generation optical core networks," *Future Network & Mobile Summit*, Berlin, pp. 1–9, 2012.

[50] Y. Huang, M. Huang, D. Qian, Y. Shao, E. Ip, T. Inoue, Y. Inada, T. Ogata, Y. Aoki, and T. Wang, "4 × 1.15-Tb/s DP-QPSK Superchannel Transmission Over 10,181-km of EDFA Amplified Hybrid Large-Core/ Ultra Low-Loss Fiber Spans with 2-dB FEC Margin," in *Proceedings of Asia Communications and Photonics Conference and Exhibition (ACP)*, Shanghai, Post-deadline paper, pp. 1-6, 2011.

[51] F. P. Guiomar, S. B. Amado, J. D. Reis, S. M. Rossi, A. Chiuchiarelli, J. R. F. Oliveira, António L. Teixeira and A. N. Pinto, "Ultra-long-haul 400G superchannel transmission with multi-carrier nonlinear equalization," in *Proceedings of European Conference on Optical Communication*, Valencia, pp. 1-3, 2015.

[52] J. Renaudier, R. R. Müller, L. Schmalen, P. Tran, P. Brindel and G. Charlet, "1-Tb/s PDM-32QAM superchannel transmission at 6.7-b/s/Hz over SSMF and 150-GHz-grid ROADMs," in *Proceedings of European Conference on Optical Communication*, Cannes, pp. 1-3, 2014.

[53] Infinera Multi-terabit Product Brochure. Available: https://www.infinera.com/wp-content/

uploads/2015/10/Infinera-BR-DTN-X-Family.pdf

[54] G. Shen and Q. Yang, “From coarse grid to mini-grid to gridless: how much can gridless help contentionless?”, in *Proceedings of Optical Fiber Communication Conference/National Fiber Optic Engineers Conference*, paper OTuI3, 2011.

[55] ITU-T Recommendation G.694.1, “Spectral grids for WDM applications: DWDM frequency grid”, Available: http://www.itu.int/rec/T-REC-G.694.1/en

[56] J. Leuthold, W. Freude, “Chapter 9: Optical OFDM and Nyquist Multiplexing”, Optical Fiber Telecommunications VIB, Academic Press, 2013.

[57] G. Bosco, A. Carena, V. Curri, P. Poggiolini and F. Forghieri, “Performance limits of Nyquist-WDM and CO-OFDM in high-speed PM-QPSK systems,” *IEEE Photonics Technology Letters*, vol. 22, no.15, pp. 1129–1131, 2010.

[58] G. Bosco, V. Curri, A. Carena, P. Poggiolini and F. Forghieri, “On the performance of Nyquist-WDM terabit superchannels based on PM-BPSK, PM-QPSK, PM-8QAM or PM-16QAM subcarriers,” *Journal of Lightwave Technology*, vol. 29, no.1, pp. 53–61, 2011.

[59] R. Schmogrow, M. Winter, M. Meyer, D. Hillerkuss, S. Wolf, B. Baeuerle, A. Ludwig, B. Nebendahl, S. Ben-Ezra, J. Meyer, M. Dreschmann, M. Huebner, J. Becker, C. Koos, W. Freude, and J. Leuthold, “Real-time Nyquist pulse generation beyond 100 Gbit/s and its relation to OFDM,” *Optics Express*, vol. 20, no. 1, pp. 317–337, Jan. 2012.

[60] J. Proakis, and M. Salehi, “Digital Communications, 5th Edition,” McGrow Hill, 2007.

[61] Raised-Cosine Filter Article, Wikiwand. Available: http://www.wikiwand.com/en/Raised-cosine_filter

[62] D. Hillerkuss, R. Schmogrow, T. Schellinger, M. Jordan, M. Winter, G. Huber, T. Vallaitis, R. Bonk, P. Kleinow, F. Frey, M. Roeger, S. Koenig, A. Ludwig, A. Marculescu, J. Li, M. Hoh, M. Dreschmann, J. Meyer, S. Ben Ezra, N. Narkiss, B. Nebendahl, F. Parmigiani, P. Petropoulos, B. Resan, A. Oehler, K. Weingarten, T. Ellermeyer, J. Lutz, M. Moeller, M. Huebner, J. Becker, C. Koos, W. Freude, J. Leuthold, “26 Tbit/s line-rate super-channel transmission utilizing all-optical fast Fourier transform processing,” *Nature Photonics*, vol. 5, no. 6, pp. 364–371, May 2011.

[63] J.H. Ke, Y. Gao, and J.C. Cartledge, “400 Gbit/s single-carrier and 1 Tbit/s three-carrier superchannel signals using dual polarization 16-QAM with look-up table correction and optical pulse

shaping," *Optics Express*, vol. 22, pp. 71–84, 2014.

[64] Z. Xiao, S. Fu, S. Yao, M. Tang, P. Shum and D. Liu, "ICI Mitigation for Dual-Carrier Superchannel Transmission Based on m-PSK and m-QAM Formats," *Journal of Lightwave Technology*, vol. 34, no. 23, pp. 5526-5533, Dec. 2016.

[65] K. Igarashi, T. Tsuritani, I. Morita, K. Katoh, K. Kikuchi, "Frequency stabilization of multiple semiconductor lasers for Nyquist-WDM transmission systems," in *Proceedings of Optical Fiber Communication Conference/National Fiber Optic Engineers Conference*, Anaheim, CA, USA, paper OTu2I.6, Mar. 2013.

[66] E. Temprana, E. Myslivets, B.P.-P. Kuo, L. Liu, V. Ataie, N. Alic, and S. Radic, "Overcoming Kerr-induced capacity limit in optical fiber transmission," *Science*, vol. 348, no. 6242, pp. 1445–1448, Jun 2015.

[67] T. Shao, H. Shams, P. M. Anandarajah, M. J. Fice, C. C. Renaud, F. van Dijk, A. J. Seeds, and L. P. Barry, "Phase Noise Investigation of Multicarrier Sub-THz Wireless Transmission System Based on an Injection-Locked Gain-Switched Laser," *IEEE Transactions on Terahertz Science and Technology*, vol. 5, no. 4, pp. 590–597, July 2015.

[68] Michael J. Thorpe, David Balslev-Clausen, Matthew S. Kirchner, and Jun Ye, "Cavity-enhanced optical frequency comb spectroscopy: application to human breath analysis," *Optics Express*, vol. 16, pp. 2387–2397, 2008.

[69] V. Vujicic, C. Calo, R. Watts, F. Lelarge, C. Browning, K. Merghem, A. Martinez, A. Ramdane and L. P. Barry, "Quantum Dash Mode-Locked Lasers for Data Centre Applications," *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 21, no. 6, pp. 53–60, Dec. 2015.

[70] P. Zhu, J. Li, L. Niu, Y. Xu, Y. Chen, X. Xie, X. Chen, B. Guo, Z. Chen, and Y. He, "Optical Comb-enabled Cost-effective ROADM Scheme for Elastic Optical Networks," in *Proceedings of Optical Fiber Communication Conference*, San Francisco, CA, paper W3B.5, 2014.