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Self-Homodyne Coherent Systems using Advanced Modulation Formats

MARTIN SJÖDIN

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Photonics Laboratory, Department of Microtechnology and Nanoscience,
Chalmers University of Technology, SE-412 96 Göteborg, Sweden
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Abstract

Modulation formats that offer high spectral efficiency will be of great importance in future fiber optic communication systems. Currently, a lot of research efforts are ongoing to investigate the best ways of generating and detecting modulation formats in which both the phase and the amplitude of the light are used to carry information, such as 16-QAM.

The conventional way of detecting the phase of a signal is known as intradyne coherent detection. The signal is mixed with light from a free running local oscillator laser in the receiver and the intermediate frequency between the two lasers is tracked with digital signal processing.

This thesis deals with another coherent detection approach known as self-homodyne detection, in which a polarization multiplexed pilot tone is co-propagated with the signal and used as local oscillator in the receiver. Self-homodyne systems offer an interesting alternative to intradyne and have some distinct advantages and disadvantages that are quantified to some extent in this work. The optical signal-to-noise ratio requirements of self-homodyne systems have been investigated and compared to intradyne systems. The beneficial effect of band-pass filtering of the pilot tone was demonstrated and it was shown that the performance limits for self-homodyne and intradyne systems become equal as the filter bandwidth is made small.

Furthermore, we demonstrated the unique ability of self-homodyne systems to compensate for nonlinear phase distortion that distorts the received constellation diagram. We also demonstrated a novel interleaved polarization division multiplexing method to decrease the penalty in spectral efficiency of self-homodyne systems compared with intradyne systems that is due to the fact that conventional polarization division multiplexing cannot be used in the former case. The performance of the scheme was evaluated and suggestions for future improvements were made. Finally, a novel 16-QAM transmitter was presented that uses two IQ-modulators in series. Based on this scheme, we generated the first 16-QAM signal at 40 Gbaud.

Keywords: coherent detection, self-homodyne, intradyne, 16-QAM, QPSK, self phase modulation, wavelength division multiplexing, polarization division multiplexing, pilot tone
Thesis for the degree of licentiate of engineering

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Photonics Laboratory, Department of Microtechnology and Nanoscience, Chalmers University of Technology
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Photonics Laboratory, Department of Microtechnology and Nanoscience, Chalmers University of Technology, SE-412 96 Göteborg, Sweden
Phone: +46 (0) 31 772 1000

Front cover illustration: Signal spectra in a self-homodyne interleaved polarization division multiplexing system.

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List of papers

This thesis is based on the following appended papers:


Publications by the author not included in this thesis:


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Martin Sjödin

Göteborg
May 2010
### Abbreviations used in the text

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>ADC</td>
<td>Analog-to-digital converter</td>
</tr>
<tr>
<td>ASE</td>
<td>Amplified spontaneous emission</td>
</tr>
<tr>
<td>ASIC</td>
<td>Application-specific integrated circuit</td>
</tr>
<tr>
<td>BER</td>
<td>Bit-error rate</td>
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<tr>
<td>BPF</td>
<td>Band-pass filter</td>
</tr>
<tr>
<td>BPSK</td>
<td>Binary phase shift keying</td>
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<td>DCF</td>
<td>Dispersion compensating fiber</td>
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<td>DEMUX</td>
<td>Demultiplexer</td>
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<td>DFB</td>
<td>Distributed feedback</td>
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<tr>
<td>DI</td>
<td>Delay interferometer</td>
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<tr>
<td>DPSK</td>
<td>Differential phase shift keying</td>
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<tr>
<td>DQPSK</td>
<td>Differential quadrature phase shift keying</td>
</tr>
<tr>
<td>DSP</td>
<td>Digital signal processing</td>
</tr>
<tr>
<td>EDFA</td>
<td>Erbium-doped fiber amplifier</td>
</tr>
<tr>
<td>FEC</td>
<td>Forward error correction</td>
</tr>
<tr>
<td>GVD</td>
<td>Group velocity dispersion</td>
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<tr>
<td>IF</td>
<td>Intermediate frequency</td>
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<tr>
<td>IPDM</td>
<td>Interleaved polarization division multiplexing</td>
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<tr>
<td>IQM</td>
<td>IQ modulator</td>
</tr>
<tr>
<td>ISI</td>
<td>Intersymbol interference</td>
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<tr>
<td>LO</td>
<td>Local oscillator</td>
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<tr>
<td>MMF</td>
<td>Multi-mode fiber</td>
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<tr>
<td>MUX</td>
<td>Multiplexer</td>
</tr>
<tr>
<td>MZM</td>
<td>Mach-Zehnder modulator</td>
</tr>
<tr>
<td>OOK</td>
<td>On-off keying</td>
</tr>
<tr>
<td>OSNR</td>
<td>Optical signal-to-noise ratio</td>
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<tr>
<td>PBC</td>
<td>Polarization beam combiner</td>
</tr>
<tr>
<td>PBS</td>
<td>Polarization beam splitter</td>
</tr>
<tr>
<td>PC</td>
<td>Polarization controller</td>
</tr>
<tr>
<td>PDM</td>
<td>Polarization division multiplexing</td>
</tr>
<tr>
<td>PLL</td>
<td>Phase-locked loop</td>
</tr>
<tr>
<td>PMD</td>
<td>Polarization-mode dispersion</td>
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<tr>
<td>QAM</td>
<td>Quadrature amplitude modulation</td>
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<tr>
<td>QPSK</td>
<td>Quadrature phase shift keying</td>
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<tr>
<td>Abbreviation</td>
<td>Description</td>
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<tr>
<td>RS</td>
<td>Reed-Solomon</td>
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<tr>
<td>SE</td>
<td>Spectral efficiency</td>
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<tr>
<td>SPM</td>
<td>Self-phase modulation</td>
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<tr>
<td>SSMF</td>
<td>Standard single-mode fiber</td>
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<tr>
<td>WDM</td>
<td>Wavelength-division multiplexing</td>
</tr>
<tr>
<td>XPM</td>
<td>Cross-phase modulation</td>
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</table>
5 Future directions

5.1 Real-time self-homodyne systems

5.2 Intradyne systems

5.2.1 Parallelized coherent detection

5.2.2 Nonlinear effects in systems using PDM and WDM

5.3 Future is elsewhere?

6 Summary of papers
1 Introduction

The transmission of messages over significant distances for communication purposes is called telecommunications. It has a huge impact on both the social life of people and on the world economy. The early communication systems had low bit rates as they were relying on such simple technologies as drumbeats, smoke, hand-waving or signal flags, but the development has taken us to a point where information can be transmitted with hundreds of Gbit/s with a single signal. This is possible thanks to fiber optic communication systems in which, as the name implies, data is transported through optical fibers.

Fiber optic communication systems are not a competitor to systems using microwaves to transmit information, but a perfect complement since they are unmatched when it comes to point-to-point transmission. On the other hand, it is inconvenient to be wire-bound to people with fibers, and that is why fibers will never replace mobile phones. The reason for the high bandwidth is a combination of having a medium with low loss over a wide wavelength band (centered around 1.55 µm) and the high carrier frequency of light (193 THz @ λ=1.55 µm). Microwave-based systems have carrier frequencies four orders of magnitude smaller, which also reduces their bandwidth with about the same factor.

Two crucial steps towards where we are today were taken in the sixties: The low-loss optical fiber was proposed by Kao and Hockham in 1966 [1] and the first semiconductor laser working at room temperature was invented in 1970 [2]. In the early seventies the attenuation in state-of-the-art fibers was 20 dB/km [3], but modern commercial fibers have losses of only about 0.20 dB/km around λ=1.55 µm. This permits transmission over very long distances (~100 km) before the signal needs to be detected or amplified. The intrinsic bandwidth of the standard single-mode optical fiber is about 35 THz and it also has many other great advantages, such as being immune towards electromagnetic interference, a common problem in communication systems using microwaves as information carrier.

In the early systems, a weak signal had to be detected, converted to an electrical signal, amplified and then re-transmitted as an optical signal. This made it difficult and costly to take full advantage of the fiber bandwidth. However, the invention of the erbium-doped fiber amplifier (EDFA) [4, 5] in the eighties solved this problem and high data rates could now be transmitted over long distances using wavelength
division multiplexing (WDM). In research laboratories today, transmission of 69.1 Tbit/s [6] and 64 Tbit/s with a spectral efficiency (SE) of 8 bit/s/Hz [7] have been demonstrated. However, both these experiments used offline processing of data, and the record for a real-time experiment is still the 25.6 Tbit/s that was demonstrated in 2007 [8,9]. This experiment was based on non-coherent differential quadrature phase shift keying (DQPSK) modulation.

Even though the capacity of fiber optic networks already is huge, the demand for more is unlikely to cease within the near future. More and more people use internet for both entertainment and professional purposes. Music and movies are downloaded and in the future it is expected that high definition television will be streamed live over the internet, which will require enormous amounts of bandwidth. The bit rates therefore need to be increased further. To do this, a lot of research efforts are being focused on multilevel modulation formats that outperforms binary formats in terms of SE, as they carry multiple bits per symbol. They utilize the phase of the light to carry information and require more complicated generation and detection schemes than systems using on-off keying (OOK) or differential phase shift keying (DPSK) [10]. In addition, they require higher optical signal-to-noise ratio (OSNR) at the receiver due to the smaller symbol spacing and this in turn means that higher power levels in the systems are needed, which increases the impact of nonlinear effects. What most of these modulation formats have in common is that they require coherent detection at the receiver to preserve the phase information of the light.

Coherent detection provides the highest receiver sensitivity and makes it possible to mitigate transmission impairments such as group velocity dispersion (GVD) and polarization-mode dispersion (PMD) by using post-processing. The most common coherent detection approach is intradyne coherent detection [11], in which a free running local oscillator (LO) laser serves as a phase reference in the receiver, and digital signal processing (DSP) is used to perform various tasks, such as tracking the intermediate frequency (IF) between the two lasers. The intradyne approach shows a lot of promise but requires high speed application-specific integrated circuits (ASICs), which are difficult and expensive to develop. To date, there has only been one demonstration of a real time intradyne coherent system operating at a high baud rate (10 Gbaud) [12,13]. There are also concerns about the power consumption of future receivers and the development of systems that consumes low power is getting increasingly higher priority.

The main focus of this thesis is on self-homodyne coherent systems [14], which have some distinct advantages and disadvantages compared to intradyne systems. In self-homodyne systems, a pilot tone is co-propagated with the signal using the orthogonal polarization mode. Since the pilot tone and the signal come from the same laser they are correlated in phase and thus, there is no need for high speed ASICs or highly coherent laser sources. On the other hand, the pilot tone becomes deteriorated by optical amplifier noise, its quality is degraded if significant nonlinear effects are present and conventional polarization division multiplexing (PDM) can not be used.
Both experiments and simulations have been conducted to investigate the properties and evaluate the performance of self-homodyne coherent systems. In addition, work has been performed on generation, transmission and detection of signals using multilevel modulation formats that are likely to be used in future fiber optic systems.

The thesis is outlined as follows. Chapter 2 gives a description of a typical fiber optic communication system together with some important phenomena in the fiber. Chapter 3 describes some important modulation formats. Chapter 4 is about coherent detection and describes both the self-homodyne and the intradyne approaches. Chapter 5 is about future research directions and the papers are summarized in Chapter 6.
2  Fiber optic communication systems

Three primary units are always present in some form in any telecommunications system [15]:

I. A transmitter that takes information and converts it to a signal.

II. A transmission medium, also called the "physical channel" that transports the signal.

III. A receiver that takes the signal from the channel and converts it back into usable information.

Fig. 2.1 shows a block diagram of such a general communication system. In a fiber optic system, the transmitter usually consists of a semiconductor laser which can be directly modulated by changing the bias current or be operated in continuous wave mode to give a constant output power. In the latter case, modulation is performed by using an external modulator. The signal is transported through the optical fiber to the receiver, and on its way it might encounter components such as EDFAs, optical filters etc. In the receiver, the detection method depends on the modulation format. In the simplest case with OOK, the optical signal is converted to an electrical signal, a photocurrent $I(t)$, by a single photodiode according to $I(t) = R_d P_{in}$, where $R_d$ is the responsivity of the detector and $P_{in}$ is the signal power.

![Figure 2.1: A general communication system.](image-url)

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 Signals can be either analog or digital. An analog signal varies continuously with respect to the information and is therefore sensitive to noise. In a digital signal, the information is encoded as a set of discrete values (a set of ones and zeros). A great advantage with digital signals is that, unless the additive noise disturbance exceeds a certain threshold, the information remains intact. The resistance to noise represents a key advantage over analog signals. Fiber optic systems generally use digital signals.

2.1 The optical fiber

This section does not describe all phenomena that are important for fiber optic transmission, but those that have been most important for the work performed in this thesis.

The optical fiber is the channel in which the signal propagates, guided by total internal reflection. There are many advantages with using optical fibers for information transport; the attenuation in standard single-mode fibers (SSMF) can be as low as 0.151 dB/km [16] at 1.55 µm (but is usually about 0.20 dB/km), the bandwidth is large (≈ 35 THz), fibers are flexible and have low weight, they are easy to install and insensitive to moisture and they are immune to electromagnetic interference (no crosstalk between fibers). They are not perfect though. GVD, PMD, stimulated Brillouin scattering and the Kerr nonlinearity are four phenomena that the designer of a fiber optic communication system has to deal with. Also, despite the very low attenuation, the loss becomes substantial after some distance and the signal then needs to be amplified. The amplification adds amplified spontaneous emission (ASE) noise which degrades the OSNR.

It is worth mentioning that there are many different types of fibers. For example, multi-mode fibers (MMFs) are used for transmission over short distances, such as within buildings or vehicles. MMFs are inexpensive and easy to couple light into, but suffer from intermodal dispersion: The energy is carried by several different modes, which are solutions to Maxwell’s equations and a set of boundary conditions. Since the modes have quite different speed, there will be significant pulse broadening even after short distances. However, for transmission over a few hundred meters, MMFs are useful.

Then there are dispersion-shifted fibers, with very low dispersion around 1.55 µm, polarization-maintaining fibers, who preserve the polarization of light during propagation, and allwave fibers, who have higher bandwidth than SSMFs due to the removal of the OH-absorption peak around 1.4 µm. For long-haul applications, single mode fibers are indispensable as they have no intermodal dispersion.
2.1.1 Group velocity dispersion

The group velocity is given by [17]

\[ v_g = \left( \frac{d\beta}{d\omega} \right)^{-1}, \]  

(2.1)

where \( \beta \) is the propagation constant, defined as \( \beta = n(\omega) \omega/c \) and \( \omega \) is the angular frequency. The effective mode refractive index is denoted \( n(\omega) \) and \( c \) is the speed of light. The different spectral components of a pulse with a finite spectral width \( \Delta\omega \) travel at different speeds due to the frequency dependence of the group velocity. This results in signal distortion and typically in pulse broadening, which is a problem for fiber optic communication systems since the bit-error rate (BER) increases due to the intersymbol interference (ISI) introduced by the broadening. The pulse broadening \( \Delta T \) in the fiber is given by [17]

\[ \Delta T = L\beta_2 \Delta\omega, \]  

(2.2)

where the group velocity dispersion parameter is given by

\[ \beta_2 = \frac{d^2\beta}{d\omega^2}. \]  

(2.3)

The dispersion parameter \( D \) is related to \( \beta_2 \) by

\[ D = -\frac{2\pi c}{\lambda^2} \beta_2, \]  

(2.4)

a typical value of \( D \) in an SSMF at \( \lambda=1550 \text{ nm} \) is \( D=17 \text{ ps/\text{nm-km}} \). As an example of the impact of dispersion, the difference in traveling time of neighboring channels in a WDM system with 50 GHz channel spacing is about 0.5 ns if the SSMF span is 75 km long and the wavelengths are in the vicinity of 1.55 \( \mu \text{m} \).

A common approach to deal with pulse broadening is to use all-optical dispersion compensation by using dispersion compensating fibers (DCFs) with opposite sign of \( D \) compared to SSMFs. For a DCF, \( D \) is about -100 ps/\text{nm-km}. A large negative dispersion is desirable since it allows shorter DCFs to be used. The disadvantages with this compensation scheme are that DCFs give additional loss and have higher nonlinear coefficient than SSMFs, and thus can worsen the impact of nonlinear effects. In any case, after each SSMF span, there usually is some DCF that compensates for the dispersion in the span. This might not be the case in future fiber optic systems though, since with coherent detection and subsequent over-sampling of the signal to fulfil the Nyquist criterion [18] it is possible to compensate for dispersion after transmission and detection. The reason is that coherent detection preserves the phase information of the signal, while direct detection results in a photocurrent proportional to the signal power. With DSP-based GVD-compensation, the maximum transmission distance can be increased, since the additional DCF losses are avoided. Fig. 2.2 shows measured
constellation diagrams, representations of the optical field in the complex plane, of a 10 Gbaud quadrature phase shift keying (QPSK) signal (QPSK is described in section 3.2) back-to-back (Fig. 2.2a), after 50 km SSMF without dispersion compensation (Fig. 2.2b) and after 50 km SSMF with dispersion compensation using DCF (Fig. 2.2c). The performance degradation due to the GVD is easily seen by comparing Fig. 2.2b with Fig. 2.2a or Fig. 2.2c, as the spreading of the symbols is significantly larger in the former case, which increases the BER. The constellations in Fig. 2.2a and Fig. 2.2c look very similar which is expected if nonlinear effects due to the Kerr nonlinearity and higher order dispersion are negligible. For signals with large enough bandwidth, higher order dispersion has an impact and in that case it may not be sufficient to use DCF to compensate for all dispersion effects. The same reasoning is valid if high signal power is used so that the Kerr nonlinearity influences the transmission.

2.1.2 Self-phase modulation

One of the consequences of the Kerr effect (the intensity dependence of the refractive index) is that a signal propagating in a fiber induces a phase shift on itself according to [19]

$$\Delta \Phi_{SPM} = \gamma PL_{eff}$$

(2.5)

where $\gamma$ is the fiber nonlinearity coefficient, $P$ is the optical power and $L_{eff}$ is the effective length of the fiber, given by $L_{eff} = (1 - \exp(\alpha L))/\alpha$. $L_{eff}$ is used to account for the fiber loss, which is due to the attenuation described by the attenuation coefficient $\alpha$. As mentioned, the attenuation in an SSMF is about 0.2 dB/km≈4.5% per km. Since the signal imposes the phase shift on itself, the phenomena is known as self-phase modulation (SPM). SPM is a limiting factor for
long-haul systems, since it puts a constraint on the power level of a signal. To maintain a high OSNR, it is good to have high input power to each fiber span. However, due to nonlinear effects such as SPM, an optimum launch power exists that gives the lowest BER in the receiver.

SPM imposes a frequency chirp on the signal; the leading edge of an optical pulse is down-shifted in frequency and the trailing edge is up-shifted. Under certain circumstances, this gives rise to interesting phenomena such as optical solitons [20, 21] and it can also be used for pulse compression. The disadvantages include increased crosstalk in WDM systems due to the broadened spectra and for modulation formats with multiple amplitude levels, the intensity dependence of the refractive index gives different phase shifts for symbols of different amplitudes. This is illustrated by Fig. 2.3. Furthermore, when interacting with ASE noise, SPM creates nonlinear phase noise [22] which is most critical for long-haul systems with many optical amplifiers. Each symbol is phase rotated in accordance to its own amplitude level. As a result, the probability density functions of the symbols will not be Gaussian and they tend to obtain a spiral-like shape. The nonlinear phase noise effect is also visible in Fig. 2.3, as the symbols with higher amplitude have larger spreading in the radial direction.

2.1.3 Cross-phase modulation

Cross-phase modulation (XPM) is similar to SPM but involves at least two waves at different wavelengths or two orthogonally polarized waves at the same wavelength. Each of the waves modulates the refractive index of the other and introduces a nonlinear phase shift. If there are two waves at different wavelengths, wave 2
induces a phase shift on wave 1 according to [19]
\[ \Delta \Phi_{XPM} = 2 \gamma P_2 L_{eff}, \]  
(2.6)

where \( P_2 \) is the power of the second wavelength. The factor of 2 in 2.6 shows that the XPM effect is twice as strong as SPM for a given power. However, for two orthogonally polarized waves at the same wavelength and a fiber with rapidly and randomly varying birefringence, such as an SSMF, the XPM and the SPM phase shifts are approximately equally strong [23]. This has interesting implications for self-homodyne coherent systems [24], as described in section 4.2.2.

XPM is an important limitation for WDM systems since the different channels modulate each others phases. In OOK systems, the phase shift itself would not be a big problem in absence of dispersive effects, but with dispersion, the phase shift is converted to power fluctuations which degrades performance. When information is encoded in the phase, the situation is different since the phase shifts induce bit-errors even in the absence of effects such as dispersion. On the other hand, the impact of XPM depends on the interaction time between pulses at different wavelengths and on the patterns of the interacting data streams so it is a lot more complicated to give predictions about its impact than in the SPM case. Traditionally, XPM has been mitigated by using fiber with nonzero dispersion to induce pulse walkoff [25]. Work has also been presented in which compensation of XPM and other nonlinear effects is performed by solving the nonlinear Schrödinger equation in the receiver [26] after coherent detection. This approach is called digital backpropagation and is unlikely to be implemented in real systems any time soon, since it is very computationally demanding.

2.2 System components

Various components are used in a fiber optic communication system. Some of the most important for this work are described in this section.

2.2.1 The semiconductor laser

Semiconductor lasers are used in fiber optic systems since they are easy to integrate and have high coupling efficiency to the fiber. In addition, they have attractive features such as low power consumption, high reliability and compatibility with electronic circuits. As with all lasers, they produce highly coherent light through stimulated emission. The gain region consists of a double heterostructure pn-junction in which the active region has a smaller bandgap and higher refractive index than the p- and n-type materials. There are two major advantages with this. The active region effectively confines electrons and holes due to its smaller bandgap and the higher refractive index makes it act like a dielectric waveguide, similar to the optical fiber.

To have only one lasing mode, it is common to use a grating close to the active
region which gives a periodic variation of the refractive index. Instead of using two reflective facets, optical feedback is provided by the whole cavity. Fig. 2.4 shows the structure of a distributed-feedback (DFB) laser that utilizes such a grating to achieve single-mode operation. This laser type has been used with great success in OOK-systems, in which it does not matter that its linewidth traditionally has been quite broad [27]. However, recent advances will also make DFB-lasers useful for coherent systems requiring lasers with narrow linewidths. In [28], a tunable DFB-laser array having linewidths of 100-200 kHz in the entire C-band was reported at 30 mW output power.

### 2.2.2 The Mach-Zehnder Modulator

There are three basic ways to modulate a signal in a fiber optic system: direct modulation by changing the laser bias current, electroabsorption modulators and Mach-Zehnder modulators (MZMs) [29]. The MZM is the most common modulator in high speed fiber optic systems due to its excellent modulation performance and the possibility to modulate phase and amplitude independently. It consists of a Mach-Zehnder interferometer in which the refractive index can be changed in one or both of the arms by applying an electrical field. The most common material used to fabricate MZMs is lithium niobate (LiNbO$_3$), in which an electrical field applied along the z-axis of the crystal changes the refractive index. The voltage required to give a $\pi$ phase shift in an MZM-arm is denoted by $V_\pi$. Fig. 2.5 shows a single-drive MZM, in which the refractive index can be changed in only one of the arms of the interferometer. Such a device can be used as a pulse carver or to generate OOK. To generate phase modulated signals, it is necessary to be able to change the refractive index in both arms, since only amplitude modulation can be obtained otherwise. Such modulators are referred to as dual-drive MZMs. The

![Figure 2.4: Structure of a DFB semiconductor laser.](image)
ideal peak-to-peak voltage swing needed to generate a binary phase shift keying (BPSK) signal is $2V_\pi$. A smaller swing can be used, but in that case the optical signal will be more sensitive to noise and ISI in the driving signals.

To take full advantage of the nonlinear parts of the MZM transfer function, a swing of $2V_\pi$ is needed. Two or more dual-drive MZMs can be used in parallel to generate modulation formats such as QPSK or 16-quadrature amplitude modulation (16-QAM). A modulator consisting of two dual-drive MZMs in parallel is commonly referred to as an IQ-modulator (IQM). Independent data streams are applied to each modulator to generate BPSK-signals and a relative phase shift of 90° creates a QPSK signal when the two BPSK signals are combined. Fig. 2.6 shows a schematic
of an IQM and how it can be used to generate QPSK.

### 2.2.3 The erbium-doped fiber amplifier

EDFAs are indispensable parts of fiber optic communication systems. They were invented in the mid eighties [4,5] and gained a lot of interest as they are capable of amplifying light in the low loss wavelength window centered around 1550 nm without using expensive opto-electronic regenerators. The EDFA has benefits such as polarization independent gain, high pumping efficiency, modulation format transparency, low noise figure and it enables WDM transmission. In addition, thanks to its slow response time (ms) it does not give problems with cross gain saturation and can be operated in saturated mode. EDFAs are pumped with lasers at 980 nm and 1480 nm and apart from being able to operate in the C-band (1530-1570 nm), amplifiers with gain in the L-band (1570-1610 nm) and S-band (1480-1530 nm) have been fabricated.

Like a laser, EDFAs rely on the principle of stimulated emission of light. The signal photons stimulates the emission of new photons having the same phase, frequency, polarization and traveling direction. A schematic of an EDFA is shown in Fig. 2.7.

As every optical amplifier, the EDFA also generates ASE noise which degrades the OSNR and limits the transmission distance. The amount of ASE power per polarization at the output of an EDFA is given by

\[
P_{\text{ASE}} = S_{\text{ASE}} \Delta \nu_0 = n_{sp} h \nu_0 (G - 1) \Delta \nu_0. \tag{2.7}
\]

This amount of ASE power is generated each time the signal passes an amplifier. The OSNR is defined as

\[
\text{OSNR}_{0.1 \text{nm}} = \frac{P_S}{2P_{\text{ASE}}}, \tag{2.8}
\]

where \(P_S\) is the optical signal power. There is a factor of 2 in the denominator because equal amounts of ASE power are generated in the two orthogonal polarization modes. The OSNR is usually measured with an optical spectrum analyzer.

![Schematic of an EDFA](image)

**Figure 2.7: Schematic of an EDFA.**
and normalized to 0.1 nm bandwidth. The gain in EDFAs can be as high as 54 dB while having a noise figure as low as 3.1 dB [30].

2.3 Polarization division multiplexing

The transverse propagation mode of an SSMF exists in two degenerate polarization modes, because of the circular symmetry of the fiber. Both these modes can be used simultaneously to double the data rate compared to the case in which only a single polarization state is used to transmit information. This technique is known as polarization division multiplexing (PDM) and is likely to become a standard in future fiber optic systems. To create a PDM data stream, the outputs from two separate modulators are combined with a polarization beam-combiner (PBC). However, in most experiments, PDM is emulated by using a single modulator, splitting its output equally and then recombining the two resulting data streams with a PBC with a relative time delay to de-correlate them.

Modulators dedicated to generate PDM data are likely to be implemented in future systems. In these devices, a polarization beam-splitter (PBS) at the input is integrated with two IQMs and a PBC at the output. This is the optimum solution as it does not require any polarization control before the output of the modulator, only before its input to make sure that the power splitting by the PBS is equal.

Problems with PDM include that power can leak from one polarization to another, PMD may degrade the performance for long distance transmission, and the complexity in the receiver is increased. XPM crosstalk between the orthogonally polarized data streams is also an issue which has to be dealt with. As mentioned in 2.1.3, the XPM shift given by a signal is in this case approximately equal to its SPM shift.

Nevertheless, the prospect of increasing the throughput with a factor of two makes PDM very attractive.

2.4 Wavelength division multiplexing

Since the EDFA has such a wide gain bandwidth, many channels can be amplified simultaneously. In a WDM system, channels at different wavelengths are multiplexed together into the same fiber and amplified by the same EDFAs. C-band EDFAs have a bandwidth of about 4 THz (30 nm), which permits amplification of 80 WDM channels in a 50 GHz grid. In general, a WDM system has a uniform frequency spacing between its channels. The channel frequencies of WDM systems are standardized by the International Telecommunication Union to cover the S-, C- and L-bands and the available spacings are 25 GHz, 50 GHz and 100 GHz. The low-loss window in state-of-the-art fibers extends over 400 nm (from 1.3 µm to 1.7 µm) [31], making it possible to accommodate 1086 WDM channels on a 50 GHz grid. This means that with 40 Gbaud PDM 16-QAM, the total bit rate in a single fiber could be 350 Tbit/s. However, the number of channels is not only limited by
the fiber itself but also by the bandwidth over which optical amplifiers can provide uniform gain. This bandwidth is considerably smaller than 400 nm, but with Raman amplification it can be more than 100 nm [32]. There are some problems with Raman amplifiers though, as they require a lot of pump power to achieve high gain. Currently, they are mainly used as a complement to EDFAs to improve noise performance in systems.

Other factors that limit the bandwidth of WDM systems are available laser sources covering the whole wavelength region, signal impairments during transmission due to XPM and other effects, and crosstalk during demultiplexing.

Fig. 2.8 shows a schematic of a WDM system. To combine and separate the WDM channels, a multiplexer (MUX) and a demultiplexer (DEMUX) are used, respectively. The same device can be used for both purposes, depending on the direction of propagation. A MUX/DEMUX can be diffraction-based or interference-based. A diffraction-based DEMUX uses a diffraction grating to disperse the incoming light into different wavelength components, while an interference-based uses optical filters and directional couplers. In a non-coherent system, the rejection of crosstalk is highly dependent on the DEMUX, but in a coherent system it is actually possible to omit it since only a WDM channel close in frequency to the LO laser gives a beating signal within the receiver bandwidth. In a coherent system, a passive splitter can therefore be used to separate the channels. However, this would give more loss than a real WDM DEMUX and could also result in too high power entering the photodiode.

### 2.5 Forward error correction coding

Forward error correction (FEC) coding is used to improve the BER in fiber optic systems. Historically, the target BER after detection of the signal has been $10^{-9}$ or $10^{-12}$, but when utilizing FEC coding a much higher BER can be acceptable.
By adding redundant bits to the data, the net BER can be reduced after detection. Use of Reed-Solomon (RS(255,239)) [33], the most common FEC code in fiber optic systems, allows a BER of $10^{-3}$ in the receiver with only 7% overhead (the payload is 239 bytes and there is 16 bytes overhead). This BER is then corrected to a very low value and regarded as "error free". With RS(255,239), eight bytes can be fully corrected. In each byte, there are eight bits, which means that the code can correct from eight up to sixty-four erroneously detected bits.

The implication of FEC-coding for fiber optic systems is that much lower signal-to-noise ratio is tolerated in the receiver, which enhances transmission distance. In the latest experimental demonstrations of high-capacity transmission over a single fiber, the BER is usually measured only down to $10^{-4}$ or so, mainly due to the very long acquisition time required to measure lower BER when using sampling oscilloscopes and off-line processing. The detected signal is declared to be error-free if its BER is below the threshold for the given FEC code. However, it is important to keep in mind that a FEC code only corrects a given input BER if the bit-errors are uncorrelated. If nonlinear effects are significant, they change the signal statistics and may cause burst errors. This can give tougher BER requirements in the receiver [34]. In dense WDM systems, there may also be coherent crosstalk due to beating between adjacent WDM channels. Such crosstalk can also result in burst errors, since the effects are strongly correlated over a large number of bits [35].

The drawback with using FEC codes is the overhead that needs to be used. For RS(255,239), the overhead is 7% which, for example, means that a 10 Gbit/s system needs to operate at 10.7 Gbit/s. In some submarine systems, codes with about 25% overhead are used. These require a BER of $2 \cdot 10^{-2}$ at the FEC input [36].
3 Multilevel modulation formats

In fiber optic communication systems, OOK is the dominating modulation format since many years. It is simple to generate and to detect and the system bit rates could be increased thanks to inventions such as the EDFA and the WDM-technique, so there was no real motivation to use other formats. The exception was DPSK, which also is quite simple and was used in some systems, mainly due to its better receiver sensitivity. Both these modulation formats are binary and transmit only one bit per symbol.

An important figure-of-merit for a WDM communication system is the SE, defined as

\[
SE = \left( \frac{B}{\Delta f} \right)
\]

where \( B \) is the per-channel bit rate and \( \Delta f \) is the channel spacing. For a long time, advances in high-speed electronics (higher \( B \)) and in the stability of lasers and optical filters (narrower \( \Delta f \)) enabled the required increase in SE to meet the market demands. However, further improvements in these areas are considered to be very difficult and to continue increasing the SE, more advanced modulation formats than binary are needed. An overview of binary formats and of differential quadrature phase shift keying (DQPSK) is provided in [37]. To increase the SE beyond what can be accomplished by using those formats, coherent detection is needed, as this allows the use of more general multilevel formats.

The optical field has three attributes that can be used to carry information. These are the amplitude, the phase and the polarization. In state-of-the-art experiments performed today, all these attributes are used simultaneously, in contrast to some years ago when only the amplitude or the differential phase were used. The most popular modulation format in research laboratories the last years has been QPSK, but today square 16-QAM attracts most attention and some experimental results have been reported also for 128-QAM [38]. These modulation formats are not new, they have been used in the wireless community for many years, albeit at lower bit rates. However, utilizing them in fiber optic systems requires a lot of work at both the transmitter and the receiver side, together with investigations about their tolerance towards impairments in the optical fiber. The number of bits \( b \) per symbol is given by \( b = \log_2(M) \) where \( M \) is the total number of symbols for
Figure 3.1: OSNR required for BER=10\(^{-3}\) and the number of bits/symbol for some well-known modulation formats, assuming ASE noise bandwidth of 0.1 nm and 10 Gbaud in a single polarization. Coherent detection is assumed for all modulation formats except OOK. The data is taken from [31].

Figure 3.2: Qualitative picture on how the BER in the receiver varies with the input power to each fiber span for OOK and a multilevel modulation format.
a particular modulation format. The data rate increases quite slowly as a function of the number of symbols in a constellation. Fig. 3.1 shows the theoretical OSNR requirements to obtain a BER of $10^{-3}$ and the number of bits/symbol for some well known modulation formats, assuming an ASE noise bandwidth of 0.1 nm, 10 Gbaud and data in a single polarization. These values were derived using curves for BER as a function of SNR found in [31] and then SNR and OSNR were related by

$$\text{OSNR} = \frac{pR_s}{2B_{ref}} \text{SNR},$$

which was also found in [31]. In 3.2, $p$ is a factor which is 1 in the single polarization case, $R_s$ is the symbol rate and $B_{ref}$ is the ASE noise bandwidth.

In terms of SE it is good to have many bits/symbol, but this has to be balanced against the increased system complexity and the higher OSNR requirements for the more complex modulation formats. An obvious complication with modulation formats that use more than one amplitude level is that the sensitivity to SPM and XPM is higher. For example, it is important to have high SE in long-haul systems, and to obtain a long reach it is advantageous to use high input power to the fiber spans. This in turn increases the impact of nonlinearities.

On the other hand, it is also likely that multilevel formats will be used in metro-networks in the future, and the problems with nonlinearities should not be as severe in these.

Fig. 3.2 shows a general picture on how the performance in a fiber optic system varies as a function of optical input power to the fiber spans for OOK and a multilevel modulation format. For low input powers, the systems are OSNR limited and the signal mainly deteriorated by ASE noise. For high input powers to the fiber spans, less ASE noise is generated but on the other hand there is a greater impact of nonlinearities. There is an optimum input power to the spans that gives best receiver performance. The optimum input power for any multilevel format is lower than for OOK since multilevel formats are more sensitive to nonlinearities. Furthermore, for a given OSNR value, a multilevel format has higher BER due to its tighter symbol spacing. That is why the BER-curve of the multilevel format is up-shifted compared to the OOK case.

### 3.1 Differential formats

While the most popular modulation formats in research laboratories today use the absolute phase to carry information, there are also differential formats in which the data is encoded in the phase difference between two consecutive symbols. These formats are denoted as DnPSK, where n stands for the number of symbols in the constellation and DPSK for differential phase shift keying. The greatest advantage with DnPSK is that it is compatible with direct detection, so there is no need for using an LO laser in the receiver. Instead, one or more (depending on n) Mach-Zehnder delay interferometers (DIs) are used to demodulate the data by creating
interference between neighboring symbols. The signal entering a DI is splitted equally into two paths, and then recombined with a relative time delay of one symbol slot $T_S$. The data has to be pre-coded in the transmitter to map the data to the correct symbols. Pre-coders for DPSK ($n=2$) and DQPSK ($n=4$) can be found in [39].

A drawback with differential detection compared to coherent detection is that there are only limited possibilities of performing DSP-based mitigation of transmission impairments, as this requires capture of the absolute phase of the optical field. It is therefore necessary to perform GVD compensation in the optical domain in D$n$PSK systems, and when PDM is used, a polarization control system must be implemented in the receiver.

DPSK has almost the same performance as PSK, which makes it hard to motivate use of the latter format due to the higher complexity of coherent receivers compared to direct detection receivers. The constellations of these two formats look exactly the same, the difference lie in the detection method and the pre-coding. They are both most conveniently generated by using a dual-drive MZM.

DQPSK is an attractive modulation format carrying two bits/symbol. It is the only multilevel modulation format which can be generated with binary driving signals and still fully utilize the nonlinear parts of the MZM transfer function, while not needing coherent detection in the receiver. To demodulate DQPSK, two asymmetric DIs are used to obtain the differential phase of each quadrature component, as shown in Fig. 3.3. A 45° phase shift in the DIs is needed to demodulate the signal, resulting in a sensitivity penalty of 2.2 dB compared to QPSK at low BER [39, 40].

Regarding higher order D$n$PSK formats, such as D8PSK and D16PSK, the increased complexity in both pre-coders and receivers (more DIs needed for demodulation) together with larger sensitivity penalties make them less interesting for future fiber optic networks.
3.2 QPSK

The signal constellation of quadrature phase shift keying (QPSK) is shown in Fig. 3.4, and is exactly the same as for DQPSK. QPSK/DQPSK are preferably generated with an IQM driven by binary electrical signals at $2V_{\pi}$ as shown in 2.2.2, although it is possible to use various other approaches, such as cascading a dual-drive MZM with a phase modulator. The IQM is clearly the optimum solution though, since it apart from the advantage with the MZM transfer function is a single integrated device, which reduces cost. With an IQM, the QPSK data also becomes naturally grey-coded, which means that a symbol error normally only gives one bit-error.

In contrast to DQPSK, QPSK data does not need to be pre-coded in the transmitter as coherent detection is used in the receiver. QPSK has better sensitivity than DQPSK due to the absence of differential demodulation and post-processing of data can be used to compensate for GVD, PDM and other impairments. The polarization can be tracked and corrected after detection, which means that there is no need to use polarization tracking before the receiver.

Compared to BPSK or OOK, QPSK provides twice the SE and is regarded as a good candidate for being used in 100 Gbit Ethernet networks [41]. It is considered to be quite mature since it has been studied extensively, but until now the only company who has demonstrated a real time coherent QPSK system is Nortel (now Ciena) [12,13].

3.3 16-QAM

16-QAM is a 16-level modulation format and therefore transmits 4 bits per symbol. This format has been given a lot of attention recently and was used to set a new world record for high capacity transmission [6]. There are in fact many different 16-QAM constellations but in the fiber optic community, 16-QAM normally refers to the rectangular variant.

16-QAM can be generated with many different modulator schemes, the most
common is to apply four-level electrical signals to an IQM [42] or a dual-drive MZM [43]. It is also possible to use two IQMs in parallel driven by binary electrical signals [44], but such devices are difficult to fabricate. They are however the ideal solution, since they take full advantage of the nonlinear parts of the transfer functions of the MZMs, which is beneficial for the signal quality. Fig. 3.5 shows a schematic of this transmitter scheme together with a constellation of a 16-QAM signal. The IQMs both generate QPSK signals. One of these is attenuated with 6 dB and they are then combined to create a 16-QAM signal.

In this thesis, a novel scheme for generating 16-QAM is presented in paper C. It is based on using two cascaded IQMs driven by binary signals. One of the IQMs generates QPSK and the other generates a small quadratic constellation in one quadrature, which is mapped onto the QPSK constellation to create a 16-QAM signal.

16-QAM needs lasers with narrower linewidth than QPSK and several studies have been performed to investigate the requirements. In [45] it was reported that a combined signal and LO laser linewidth of 120 kHz gives an OSNR penalty of 2 dB at a BER of $10^{-4}$ for a 10 Gbaud 16-QAM signal. However, in [46], it is reported that for the same baud-rate as in the previous example, a combined linewidth of 1.4 MHz is sufficient to obtain an OSNR penalty of 1 dB compared to the theoretical limit at a BER of $10^{-3}$. "Combined linewidth" means the sum of the LO and the signal laser linewidths.

These results show the importance of using the optimum IF recovery algorithm in a coherent receiver, as the latter algorithm permits the use of DFB-lasers in systems using 16-QAM without inducing a large penalty. This is highly attractive because of the low cost of these devices. Furthermore, it is stated in [46] that the mentioned 1.4 MHz value can be approximately doubled in a system using PDM.

Figure 3.5: Constellation of a rectangular 16-QAM signal and how it can be generated with two parallel IQMs.
and the same IF recovery for both polarizations.

It can easily be understood intuitively that 16-QAM is sensitive to nonlinear effects such as SPM. SPM distorts the constellation and gives rise to nonlinear phase noise when interacting with ASE noise. This makes it more difficult to perform IF recovery, which is critical to be able to demodulate the data. Modern systems will use PDM, which also adds XPM distortion from the other channel at the same wavelength. Thus, it can be expected that future fiber optic systems with multilevel modulation formats have to operate at small power levels. This is a drawback since the OSNR requirements are higher for the new formats.

In [42], several long-haul transmission experiments for PDM 16-QAM were performed, and the total nonlinear phase shift per channel was kept low (around 0.05 rad, assuming $\delta = 1.5/(W \cdot \text{km})$ and not taking into account how the Raman amplification affects the phase shift).

### 3.4 64-QAM

64-QAM, whose constellation is shown in Fig. 3.6, is a 64-level modulation format (6 bits per symbol). The optimum way of generating it is to use six parallel dual-drive MZMs driven by binary driving signals, such as in [47]. The reason is again that with this scheme, the MZMs are forgiving against noise and ISI in the driving signals. There are many other possible transmitter implementations as well, including the use of a single IQM driven by eight-level electrical signals. To generate such driving signals at high symbol rates is a great challenge, though. 64-QAM naturally has more stringent linewidth requirements than 16-QAM, due to its tighter symbol spacings. In [46] it was reported that a combined linewidth of the LO and the signal of 400 kHz is required to get a 1 dB penalty compared to the theoretical limit at a BER of $10^{-3}$.

64-QAM is more sensitive than 16-QAM to nonlinearities, since it has smaller symbol spacing and more amplitude levels. To use 64-QAM in long-haul systems presents a real challenge, taking into account its high OSNR requirements and complexity.

![Figure 3.6: Constellation of a 64-QAM signal.](image-url)


4 Coherent detection

Coherent optical communications is a huge research topic today, but it was proposed already in the eighties by various researchers [48–55]. The reason for the interest at that time was the superior receiver sensitivity of coherent systems compared to systems using OOK and direct detection. However, when the EDFA entered the stage [4,5] very high sensitivity could be obtained without using coherent detection and there was no longer a motivation to work on the topic. However, in recent years, the capacity limits of systems using binary modulation formats such as OOK and DPSK have been reached and coherent systems are a hot topic once again. The reason is that spectrally efficient modulation formats that use the phase to carry information require more advanced detection schemes than direct detection. As mentioned in section 3.1, DnPSK signals can be detected by using DIs before the photodetectors together with pre-coding of the data. The drawback with this approach is that for n>2, there is a sensitivity penalty due to DIs that increases with n [40], and also that the pre-coders get quite complicated for large n [56]. Due to its improved sensitivity and other promising aspects, such as post-processing of data to compensate for signal impairments, it is preferable to use coherent detection. In any case, modulation formats that uses both the phase and the amplitude to carry information require coherent detection to achieve the best possible performance. Especially, formats that have uneven phase spacing, such as rectangular QAM-

![Figure 4.1: BPSK receiver using an optical PLL.](image-url)
formats, can not be detected with DIIs.

Although there are many possible implementations of coherent receivers, all of them utilize beating of the incoming signal with a local oscillator (LO) which serves as a phase reference. To track the phase of the signal it is possible, but not preferable, to use a phase-locked loop (PLL) [57]. This approach requires lasers with very narrow linewidths which are locked in phase, something that is difficult to achieve [58]. Fig. 4.1 shows a schematic of a coherent receiver using an optical PLL.

4.1 Intradyne coherent systems

Intradyne coherent detection is the dominating approach and a lot of research efforts have been made in the last years to investigate these systems. In the intradyne receiver, the incoming signal is mixed with light from a LO laser in a 90° optical hybrid, which provides output signals for the I and the Q quadratures. The photocurrents are sampled by analog-to-digital converters (ADCs) and DSP is used to perform clock recovery, track the IF between the lasers and perhaps also compensate for transmission impairments such as GVD. The first demonstration of coherent detection using DSP was made in 2004 [11]. Intradyne receivers usually have both phase and polarization diversity [59], meaning that the signal can be demodulated no matter what phase orientation or polarization state it has at the receiver input.

4.1.1 Digital signal processing

In an intradyne system, once the I- and Q-photocurrents have been sampled by the ADCs, it is possible to perform post-processing of the data. Fig. 4.2 shows a

![Figure 4.2: Schematic of the front-end and the signal processing blocks in an intradyne coherent receiver.](image-url)
Fig. 4.3: Constellations of QPSK and 16-QAM before (a) and after (b) IF-recovery.

schematic of the signal processing blocks that are typically used in an intradyne receiver, together with the receiver front-end. The first step is to perform digital clock recovery to be able to resample the signal at the optimum sampling instant, thereby reducing ISI. Feedback and feedforward clock recovery schemes for digital receivers are described in [60]. The second step is to equalize the signal and track its state of polarization (SOP). Equalization is used to compensate for linear transmission impairments such as GVD and for any ISI induced by receiver and/or transmitter. Polarization tracking/demultiplexing is performed by an algorithm that tracks the SOP of the signal and corrects it. The constant modulus algorithm (CMA) is frequently used to perform this task [61] but independent component analysis has also been suggested [62]. A comparison of the two algorithms for PDM demultiplexing can be found in [63].

Since the LO laser in an intradyne system is free running, the IF frequency always needs to be tracked to be able to retrieve the data. The IF frequency \( f_{\text{IF}} \) is given by \( f_{\text{IF}} = f_{\text{sig}} - f_{\text{LO}} \), where \( f_{\text{sig}} \) and \( f_{\text{LO}} \) are the carrier frequencies of the signal laser and the LO laser, respectively. Fig. 4.3 show simulations of constellations for QPSK and 16-QAM before and after IF-recovery. The frequency separation between the lasers results in the signal samples being uniformly distributed in the angular direction over time. QPSK therefore obtains a ring-like shape in the complex plane. In the 16-QAM case, there are three rings, due to the fact that there are three different
amplitude levels for the symbols in 16-QAM. After the IF frequency is tracked and removed from the samples, the true constellations are recovered. IF recovery can be performed in many different ways, which depend on the modulation format, laser linewidths, symbol rate and the OSNR of the signal. Overviews of IF recovery in intradyne systems are given in [46] and [58].

A concern for systems using intradyne detection is the resolution of ADCs. In [42] it was reported that an ADC resolution of 4-5 bits is required to avoid OSNR penalties in excess of 1 dB for 16-QAM at a BER of $10^{-3}$.

### 4.2 Self-homodyne coherent systems

In self-homodyne systems, a polarization multiplexed pilot tone is used as LO in the receiver. The greatest advantage with this scheme is that the signal and the pilot tone are perfectly phase correlated. It is therefore possible to perform coherent detection without using DSP in the receiver and a high speed ASIC is not needed (even though it is still possible to implement one and perform post-processing of the data). Another advantage with self-homodyne systems is that narrow linewidth lasers are not required due to the phase correlation. In [64], a DFB-laser with 30 MHz linewidth was used to demonstrate 10 Gbaud 16-QAM transmission with real-time BER measurements. Real time measurements of BER have also been presented for 10 GBaud QPSK and 5 GBaud 64-QAM signals [65,66]. In all these experiments, integrated transmitter and receiver components were used, which is necessary in order to avoid relative phase drifts (due to e.g. temperature variations).

![Figure 4.4: The transmitter in a self-homodyne system.](image)
fluctuations) between the pilot tone and the signal when they travel in separate fibers. This happens, for example, after they are split in the receiver.

A drawback with the self-homodyne approach is that there is an OSNR penalty if EDFAs are used in the system, as is shown in paper A. This is due to the ASE noise in the same polarization as the pilot tone. Also, it is not possible to use conventional PDM in self-homodyne systems due to the pilot tone. To make self-homodyne systems attractive for commercial use, it is important to find new schemes to increase the SE, as a factor of 2 is lost compared to intradyne systems if only one polarization can be used for data transmission.

Fig. 4.4 shows the schematic of the transmitter in a self-homodyne system. The output from a laser is equally split by a PBS into two branches. In one of them there is, preferably, an IQM that generates the signal, while the other branch is for the pilot tone and is passive. The signal and the pilot tone are then recombined with a PBC which ensures that their polarizations are orthogonal to each other. Ideally, the transmitter is fully integrated as in [64–66] but such devices were not available in the experiments performed in this work. Fully integrated components facilitate the generation of self-homodyne signals and solve the problem with the relative phase drift between the signal and the pilot tone.

4.2.1 Pilot tone filtering

In paper A, we also show that the sensitivity of self-homodyne systems can be improved by performing a narrow band-pass (BPF) filtering of the pilot tone in the receiver, after the signal and the pilot tone have been split by the PBS. This is illustrated in Fig. 4.5, which shows the receiver used in an experimental setup. With very narrow filtering and optimization of the power ratio between pilot tone and signal, the OSNR requirements are lowered and in fact the performance approaches that of intradyne systems. Since both the center frequency of the signal and of the narrowband optical filter drift with time it is important to implement a control system in the receiver that maximizes the pilot tone power after the filter.

Figure 4.5: The receiver in a self-homodyne system using pilot tone filtering.
Figure 4.6: Simulations to illustrate the SPM canceling effect in self-homodyne systems: a) 16-QAM constellation affected by SPM and by XPM from the co-propagating pilot tone. b) The pilot tone is affected by SPM and by XPM from the signal. c) When the signal and the pilot tone interact in the photodetection process, an undistorted constellation is obtained.

4.2.2 SPM cancellation

One interesting feature of self-homodyne systems is the ability to cancel nonlinear phase shifts. In a fiber with rapidly and randomly varying birefringence, the XPM phase shifts between two orthogonally polarized signals with the same center frequency is approximately the same as the signals SPM phase shifts, according to the Manakov approximation. This implies that the signal and the pilot tone in a self-homodyne system obtain the same nonlinear phase shifts. The SPM shift of the signal is therefore canceled after photodetection. However, this is only true when considering a single channel. The situation becomes more complicated in a WDM system. In particular, the SPM cancelation is not compatible with interleaved polarization division multiplexing (IPDM), since IPDM requires narrow filtering of the pilot tone in the receiver to suppress crosstalk between adjacent channels. The filtering removes most of the nonlinear modulation on the pilot tone.

The cancelation also depends on the dispersion in the fiber, as is shown in paper B. It is beneficial to have as small value of accumulated dispersion as possible when the optical power is high. Fig. 4.6 shows simulations illustrating the SPM cancelation. The constellations are shown for the pilot tone and for the signal before the receiver, when they are affected by ASE noise and nonlinear phase shifts due to SPM and XPM from one on another. Since the phase reference has the same nonlinear phase shift as the signal, the symbols are rotated back and obtain their correct positions after the coherent detection.

4.2.3 Interleaved polarization division multiplexing

The largest drawback with self-homodyne systems may be their incompatibility with conventional PDM. Until recently, data transmission has been limited to only one polarization, which reduces the SE with a factor of two compared to intradyne
Figure 4.7: Wavelength spectra for: a) an intradyne system using PDM. b) a self-homodyne system with data in a single polarization. c) a self-homodyne system using IPDM.

systems. Such a penalty is not acceptable and a solution to this problem is needed.

In paper D, a novel interleaved polarization division multiplexing (IPDM) approach is demonstrated, which enables an increase of the SE of self-homodyne systems. Fig. 4.7a shows the spectrum of a WDM signal using PDM and intradyne detection. The co-propagating pilot tone in a self-homodyne system does not permit a spectrum like this. Fig. 4.7b shows a typical signal spectrum in a self-homodyne WDM system: Only one polarization is used to transmit data. However, by placing the signals as in Fig. 4.7c, it is possible to enhance the SE. The channel spacings are the same for both the x- and the y-polarization, but a relative wavelength shift is made that allows the pilot tones to fit in between the data spectra. Measured results indicate that to obtain as high SE as possible in a system using IPDM, pre-filtering of the data spectra is required. This is due to that any overlap between the pilot tone and the data spectra surrounding it is detrimental for the performance, since it is critical to have a high quality phase reference in a coherent system. The obtained increase in SE compared to the single polarization case was 33%, measured at 2 dB OSNR penalty compared to the single channel case. It should however be possible to improve this value with the above-mentioned filtering.
IPDM systems are also sensitive to nonlinear effects such as SPM and XPM. When the data spectra are broadened by SPM, their overlap with the neighboring pilot tones increase, which affects the coherent detection negatively. Furthermore, XPM from all channels in the system affects the pilot tones. Clearly, it is important to have as small impact as possible of nonlinear effects in self-homodyne IPDM systems. On the other hand, systems using intradyne detection and multilevel modulation formats are also sensitive to effects such as SPM, since it causes constellation distortion and nonlinear phase noise that make IF recovery very difficult. There are some additional complications compared to systems using PDM and intradyne detection. All channels in a self-homodyne WDM system need to be aligned in polarization to minimize crosstalk. Polarization maintaining fibers should be used in the transmitter to deal with this. Furthermore, IPDM systems are incompatible with conventional optical add-drop multiplexers and new solutions are required to use IPDM in optically routed networks.
5 Future directions

This chapter discusses possible future research directions with the ultimate aim to increase the capacity of fiber optic communication systems.

5.1 Real-time self-homodyne systems

The greatest advantage with self-homodyne systems is that they do not need DSP in the receiver. As has been demonstrated [64–66], it is possible to perform real-time experiments without using high speed ASICs. To demonstrate long distance transmission with high SE and BER measurements in real-time would be a good next step. To do this, integrated receiver and transmitter components are needed, or the slow phase drift between the pilot tone and the signal due to thermal fluctuations needs to be tracked. One way to do this could be to use a fiber stretcher in the receiver. If the phase drift can be minimized by other means, i.e. temperature stabilization and use of as short fiber pigtails as possible, it might also be possible to perform real time experiments. To reach high SE, IPDM should be used, preferably in combination with pre-filtering of the data spectra to minimize interference with the pilot tones.

5.2 Intradyne systems

If high-speed ASICs that can perform necessary tasks, such as IF recovery, are realized at a reasonable cost, there is no doubt that intradyne systems will dominate the market. It might therefore be wise to spend more efforts on those systems and investigate their performance limits.

5.2.1 Parallellized coherent detection

As the symbol rates increase, the requirements on the ASICs and the ADCs become more demanding. As a result, parallellized coherent detection is getting more attention. The scheme is based on utilizing several coherent receivers in parallel to be able to reduce the speed of each individual receiver. For example, if two parallel
receivers are used, such as in [67,68], the speed of the DSP circuits can be reduced with a factor of two. The next generations of fiber optic systems are expected to work at symbol rates of 56 Gbaud or more and to develop ASICs with such speeds is very challenging.

5.2.2 Nonlinear effects in systems using PDM and WDM

In a system using PDM, there will be XPM between the channels at the same wavelengths. This gives a nonlinear phase shift that is equally dependent on the power of both symbols that are overlapping in time. It could be interesting to try out a compensation scheme for this. To the author’s knowledge, this has not been done for modulation formats such as 16-QAM.

5.3 Future is elsewhere?

People have put a lot of faith in coherent systems and advanced modulation formats in recent years, but one should not forget that not so long ago it was a widespread belief that soliton transmission was the next big thing. That research field faded away after the introduction of WDM in the nineties, and it is not impossible that some new invention puts coherent systems on the shelf. There seem to be a lot of problems with realizing real-time coherent receivers. Nortel succeeded in developing a 10 Gbaud receiver for PDM QPSK but there are concerns about the development cost and the power consumption of coherent systems. Another issue is that it might be problematic to use multilevel modulation formats in long-haul systems due to problems with nonlinearities. The OSNR requirements increases rapidly as a function of the number of symbols in a constellation, and somewhere there is a limit to when it is no longer feasible to try to increase the SE by using more advanced modulation formats.

In any case it is clear that a lot of efforts need to be made and money to be spent before we see any real time 16-QAM systems operating at high symbol rates.
6 Summary of papers

The thesis includes four appended papers, which will be outlined below.

Paper A
A theoretical and experimental study of the OSNR requirements for self-homodyne coherent systems is performed. It is shown that self-homodyne systems have a 6 dB OSNR penalty compared to intradyne systems for a unity power ratio between the signal and the pilot tone. This is due to the pilot tone being deteriorated by amplified spontaneous emission noise and also that it is included in the OSNR measurement. However, narrow band-pass filtering of the pilot tone and optimization of the mentioned power ratio give the same performance limit as for intradyne systems.

Paper B
Due to the rapidly and randomly varying birefringence of standard single-mode fibers, the pilot tone and the signal in a self-homodyne system acquire the same nonlinear phase shifts. In this letter we investigate the possibility to cancel nonlinear phase distortion in self-homodyne transmission systems. Numerical simulations are used to quantify the impact of dispersion and noise and the concept is also validated in an experiment for 16-QAM signals at both 5 Gbaud and 10 Gbaud.

Paper C
A novel 16-QAM transmitter using two IQ-modulators in series is proposed and evaluated experimentally by using a high speed constellation analyzer. The advantages with the proposed transmitter are that binary electrical signals and already existing components can be used. Clear constellations were observed without any digital ISI compensation even at 40 Gbaud, which indicates the feasibility of the scheme.
Paper D

Conventional polarization division multiplexing cannot be used in self-homodyne systems due to the co-propagating pilot tone. This causes an SE loss of a factor of two compared to intradyne systems. In this paper, a novel interleaved polarization division multiplexing scheme is proposed and investigated in an experiment. The channel spacings are the same in both the x- and the y-polarization, but a relative wavelength shift is made that allows the pilot tones to fit in between the data spectra. The performance of the scheme is evaluated and a 33% increase in SE is measured at an OSNR penalty of 2 dB compared to the case in which data is transmitted in a single polarization. Suggestions for improvements of the scheme are also made.
References


Papers A–D
Paper A

OSNR Requirements for Self-Homodyne Coherent Systems

M. Sjödin, P. Johannisson, Z. Tong, M. Karlsson, and P. Andrekson,

Paper B

Cancellation of Nonlinear Phase Distortion in Self-Homodyne Coherent Systems

P. Johannisson, M. Sjödin, M. Karlsson, E. Tipsuwannakul, and P. Andrekson,

Paper C

40-Gbaud 16-QAM Transmitter using Tandem In-phase/Quadrature Modulators driven by Binary Electrical Signals


Submitted to European Conference on Optical Communication (ECOC) 2010, Turin, Italy, 2010.
Paper D

Interleaved Polarization Division Multiplexing in Self-Homodyne Coherent WDM Systems

M. Sjödin, E. Agrell, Guo-Wei. Lu, P. Johansson, M. Karlsson, and P. Andrecson,