DPSK modulation format for optical communication using FBG demodulator

By F. Jacobsson
DPSK modulation format for optical communication using FBG demodulator

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Abstract

In optical communication is the Mach-Zehnder interferometer (MZI) a well-used tool, for instance as demodulator for differential phase shift keying (DPSK) modulated signals. The DPSK is a fast and stable modulation format and well suited for many optical applications. It has some advantages to the binary PSK, as a lower phase error rate and a no need to know the absolute phase. But for the demodulation of DPSK signals is the MZI a difficult component to use in practice because of stabilization problems. The signals in the two arms of the MZI are easily distorted by temperature and movement affecting the polarization.

The task of this M.Sc. graduation project was to, in simulations and experiments, evaluate a DPSK demodulation technique replacing the MZI with an optical filter. The function of adding the signal to itself but delayed one bit as done in the MZI gives, when the signal is coded as a duobinary signal, in the spectrum domain a function with the same shape of a band-pass filter. The phase modulated signal can therefore be converted to an amplitude modulated signal with a band-pass filter and detectable for a photodiode.

This function was confirmed to work when simulated for single DPSK transmission using a Gaussian shaped Fiber Bragg grating as demodulator. The filter was placed at the receiver side of the transmission since it was found that the DPSK signal was more resistant to dispersion caused by the fiber than the ASK signal that it was converted to by the filter. Simulations were made in 10 Gbit/s and with a filter bandwidth of 6 GHz were an error free 160 km transmission achieved. A successful transmission at 40 Gbit/s was achieved, but for low distance because of dispersion.

To test the FBG solution in optical network application were a four channel wavelength division multiplexing system and a combined system of angle/intensity modulation for a label switching application simulated. For the multi channel WDM transmission with DPSK was a power penalty found compared to similar ASK system of 2 dBm. But with lower dispersion sensitivity could a longer, 160 km, transmission be reached. A possibility was found to integrate the FBG demodulation function into the WDM demultiplexer, since the optical filters did the demultiplexing. The result was a simpler system, but with a power penalty of 1 dBm and an error free transmission of 150 km. In higher bitrates was it found to use an AWG for demultiplexing and for DPSK demodulation with a channel spacing of 100 GHz.
The combined DPSK/ASK application was simulated with a DPSK signal in 10 Gbit/s and an ASK signal in 2.5 Gbit/s. The ASK signal was found to be very sensitive to the dispersion in the fiber which limited the error free transmission to only a few kilometers. For the DPSK part was longer transmission successful with the filter demodulator.

In the experiments that were done to verify the simulated results for DPSK transmission using the FBG demodulator was it found that the available filters had too wide bandwidth for a 10 Gbit/s transmission. A result was seen showing that the demodulation technique worked, but with much distortion because of the filter shape. No other narrower filters were available so some solutions were tried to increase the bitrate and to combine filters for a narrower function. It gave not a satisfactory result but verified that the width of the filter was the problem. The size of the available filters was more suitable for a bitrate of 15 Gbit/s, but equipment for faster experiments were not available.
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Chapter 1

Introduction

1.1 Background

This report is made as a graduation project at the end of my Master of Science studies in Electronics design engineering at Linköping University, Sweden. The project has been made as exchange studies in the department of Electro-optical communication at the Eindhoven University of Technology (TU/e) in the Netherlands between August 2003 and February 2004. The work has been supervised by Dr. Idelfonso Tafur Monroy and ing. Frans Huijskens, and assisted by PhD student Juan Jose Vegas Olmos.

1.2 Purpose

The work presented in this report is performed within the framework of the STOLAS project within the electro-optical communication research field at TU/e. The graduation project focuses on the use of differential phase modulated signals for labeling of optical signals and for networking. This work has been done to evaluate the demodulation technique for optical DPSK transmission in general in simulations and experiments, and to implement the result in optical labeling of signals and network systems.

1.3 Method

The work has been based on documents in the research field of optical communication and phase modulation published via the organization IEEE. To assert the performance of the proposed transmission system, simulations were made in the software VPI transmissionmaker & VPI componentmaker ver-

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sion 5.5 provided by VPI photonics. For testing and validating the results of the simulations, corresponding experiments were performed in the optical communication laboratory at TU/e. The simulations were also used as a way to get an understanding about the behavior and properties of an optical transmission.
Chapter 2

DPSK theory

2.1 Phase shift keying

There are several techniques for encoding digital data to an analog signal. Three basic types are amplitude shift keying (ASK), frequency shift keying (FSK) and phase shift keying (PSK). The differences between them are pictured in figure 2.1.

![Figure 2.1: Differences in three modulations techniques, amplitude shift keying, frequency shift keying and phase shift keying.]

In ASK an amplitude difference is used of the carrier frequency to send the bits. In FSK there is a frequency difference around a center frequency, and in PSK the signal’s phase is changed.
The phase-shifted modulation shown above is more likely to be called binary phase shift keying (BPSK) since the binary digits are represented by two different phases. The difference in phase of the two states is $\pi$. This gives us an expression for the representation of:

$$s(t) = \begin{cases} 
A \cos(2\pi f_c t) & \text{for binary 1} \\
A \cos(2\pi f_c t + \pi) = -A \cos(2\pi f_c t) & \text{for binary 0}
\end{cases}$$

There is also a possibility to let a phase represent a multiple number of bits. In Quadrature phase shift keying (QPSK) each phase state represents two binary bits and the phase difference between the states are $\pi/2$ [6].

### 2.2 Differential phase shift keying

With PSK you need a receiver that can detect the absolute phase of the signal coming. Sometimes is that not possible or too difficult to achieve since then both the modulator in the transmitter and the detector needs to be very stable.

An alternative to the BPSK can then be the differential phase shift keying (DPSK) method. The difference between the binary and the differential PSK is that in the DPSK the bits are not represented by a certain phase, but by a change of phase. When a binary one is sent the phase is unchanged from the previous bit, and a binary zero is represented by a change of the phase [6]. An example is shown in figure 2.2.

![Differential phase shift keying](image)

**Figure 2.2: Differential phase shift keying.**

The DPSK method has some advantages compared to PSK. Since the information is stored in the phase change and not in the phase itself it is very good for systems where the precise phase is not known [7]. For that reason, and if the system is affected by phase noise, the detection of the
signal is made easier with DPSK. But at the same time you lose about 3 dB of power by using DPSK instead of PSK.

2.3 Demodulation of optical DPSK signals

To detect an optical DPSK signal sent thru a fiber, several different kinds of receivers can be used. Common for all the receivers is that the main translation of the optical signal into an electrical signal is done by a photodiode. The incoming photons are absorbed in the diode and a current is created [2]. After the photodiode come electrical filters and decision circuits [7]. For DPSK detection there are two kinds of receivers, the direct detection and the heterodyne, where the heterodyne are the more complex one and the direct detection are simpler and can not detect absolute phase but only changes in the phase. The latter ones are those treated here.

With the photodiode alone, only differences in the optical signal’s amplitude can be detected. Since the information sent by DPSK transmission is stored in the phase of the signal, with the amplitude constant, something need to convert the phase to intensity.

The main idea behind a direct demodulation of a DPSK signal can be viewed with a Mach-Zehnder Interferometer (MZI). A MZI can be seen in figure 2.3.

The incoming signal is split in two parts and sent into two different arms. The signals look the same with half of the original power each. In one of the arms the signal is delayed with a time equal to the time for one bit (1/bitrate). The two signals are then added back together again and sent further on. What happens with the phase-modulated signal when delayed and then added back to itself can be seen in figure 2.4.

The phase information is converted to intensity and can be sent on to the photodiode for conversion of the light to electrical current. This simple kind
CHAPTER 2. DPSK THEORY

Figure 2.4: Function of DPSK demodulation.

of DPSK receiver is called an additive direct detection DPSK receiver and consists mainly only by a MZI and a photodiode as shown in figure 2.5.

But this simple receiver has some drawbacks compared to more advanced receiver. For instance that it wastes 3 dB of power in the second splitter when the two signals are added back together [7].

One little more advanced receiver is the balanced direct detection receiver. It solves the drawback of the additive receiver mentioned above. The balanced receiver look like figure 2.6 shows, but further on in this paper an
additive direct detection DPSK receiver will be used as receiver for DPSK signals using a Mach-Zehnder Interferometer.

\[ \text{Figure 2.6: Balanced direct detection receiver.} \]

2.4 Duobinary coding of the DPSK signal

It has been shown that some advantages can be reached by doing a duobinary coding of the signal in a DPSK transmission system [3]. To make a binary signal to a duobinary, the signal is first precoded by, in a modulo 2 way, counting the number of zeros, and then coded by adding the precoded signal to itself but delayed with one bit and then removing one. The coding is what is done in the Mach-Zehnder Interferometer. A normal DPSK transmission system could therefore look like in figure 2.7 [3].

\[ \text{Figure 2.7: Coding in DPSK transmission.} \]
The coded signal that comes out from the MZI is then identical to the original binary signal, and as mentioned earlier the phase information is converted to intensity for the photodiode.

The function to add a signal to itself delayed with one bit can also be described as a convolution in the time domain by $\delta(t) + \delta(t - T)$. $T$ is here the bit period and $\delta$ the Dirac distribution. If instead the spectral domain is considered, the same function is represented by a multiplication of the spectrum by $1 + e^{i2\pi fT} = 2e^{i\pi fT}\cos(\pi fT)$ [3]. This gives a function as in figure 2.8.

![Figure 2.8: Optical spectrum of Mach-Zehnder function.](image)

It has been shown that when duobinary coding is used, instead of binary coding, only the first, center, arch of the function is used according to the Nyquist theory [3]. This means that the same function can be realized with a band-pass filter with the same bandwidth. A filter like that could distort the signal a little bit, but it also removes much optical noise.

But the biggest advantage of using an optical filter instead of the MZI is that the MZI is difficult to realize in practice. For the function of the MZI to work in a good way, the two arms need to be precisely alike, only that one of them is one bit longer. This can be hard to realize, especially because of the polarization matching required. The polarization changes very easily for instance because of movement of the fiber and temperature. If the polarization is different in the both arms when they are added together in the second coupler one effect could be that the signal level for a zero bit is not really zero. This would degrade the performance and could be hard to control when it changes over time. A photonic integrated circuit may however be a solution.

Because of the above issues, would it be very good if a filter could be used instead, it would offer several advantages. An optical filter has the potential of being a much simpler and more stable component to realize.
Chapter 3

Simulations

A first step to evaluate the use of a filter as optical DPSK demodulator was made with simulations in the software VPI transmission maker, a program for simulation of optical transmission systems. The main questions that needed to be treated were the following:

- Will it work at all to replace the MZI with a filter?
- What kind of filter should be used?
- How should the filter be shaped?
- How wide should the filter be?
- Are there other parameters that affect the transmission and demodulation?

Since the system later was supposed to be tested in experiments, the first goal was to find the specifications for the needed filter. That information would then be sent to colleagues at the Universited Politecnica de Valencia, Spain, for them to make the filter. All other components needed were available.

3.1 Setup

A system was set up and simulated to find the answers. That the theory worked was quickly found and the system looked like in figure 3.1.

Description of the blocks used in the simulation:

1. A pseudo random bit sequence generator. Generates a stream of ones and zeros to be sent in the system.
2. Logical components for the precoding part of the duobinary coding of the signal.

3. A non-return to zero coder. Converts the bit stream to electrical pulses.

4. Rise time adjustment, adjusts the rise time of the pulse with a default value of \(0.25/\text{BitRate}\) seconds.

5. DFB laser that generates an optical continuous wave signal. The used emission frequency of the laser is 193.1 THz.

6. A phase modulator. Modulates the phase of light from the laser according to the incoming electrical data signal. The parameter phase deviation in the module sets the difference in phase between ones and zeros. The start value for the difference is 180 degrees (\(\pi\)).

7. Fiber used to simulate a transmission of different length. It has some parameters that have big influence at the optical signal such as attenuation \((0.2e-3 \, \text{dB/m})\), dispersion \((16e-6 \, \text{s/m}^2)\) and the non-linear index \((2.6e-20 \, \text{m}^2/\text{W})\).

8. The filter used for the demodulation, more specifications below.

9. An optical PIN receiver containing of a PIN photodiode and a low-pass Bessel filter.

10. A visualizer to view the scope of the received signal.

All simulations have been made with a bit rate of 10 Gbit/s.
3.2 The filter

To find out a suitable shape of the band-pass filter needed for the demodulation, simulations were made with the filters provided by VPI. It was found that a Gaussian shaped Fiber Bragg Grating (FBG) worked best and gave an error free transmission. The Gaussian transfer function that represented the filter in the simulation looked like figure 3.2.

![Gaussian filter transfer function](image)

Figure 3.2: Gaussian filter transfer function.

The filter’s center frequency needs to be the same as the laser’s emission frequency and \( \Delta f \) is the 3-dB bandwidth of the function. For the filter to have the right width as described in chapter 2.4, the bandwidth should be in the order of 0.5-0.8 times the bitrate [3]. Since the simulations are made at 10 Gbit/s should it be between 5-8 GHz. A simulation sweep was therefore made and the bit error rate (BER) measured. Based on the results shown in figure 3.3 was a bandwidth of 6 GHz chosen as a target value for the filter.

The information needed for the collaborators at the Universidad Politecnica de Valencia to make the filters is now decided. They should be Gaussian shaped FBG and with a bandwidth of around 6 GHz.

3.3 Placing of the filter

In the literature it has been discussed where in a system the filter should be placed, on the receiver side or on the transmitter side [3, 5]. The filter converts the phase information into intensity, from PSK to ASK. So the question becomes whether the transmitted signal should be modulated with PSK or ASK. It has been shown that with the filter at the transmitter side the signal gets a larger amount of chirp compared to normal DPSK transmission.
3.4 Phase deviation

To determine if a change of the parameter phase deviation could improve the result of a transmission with the demodulating filter at the transmitter side, simulations were made where the deviation was changed and the BER measured. In a back-to-back system (no transmission fiber between transmitter and receiver) the optimal phase deviation was found to be about 190 degrees (1.06*π). But it was also discovered that the optimal phase deviation changed with the transmission length. In figure 3.4 can the phase deviation giving the lowest BER depending on the transmission length be seen, both for systems with the filter at the transmitter side and the receiver side.
Figure 3.4: Phase modulator’s phase deviation giving lowest bit error rate as function of transmission length.

The conclusion becomes that the phase deviation can be changed to improve the behavior of the system and the optimal phase deviation depends on the transmission length. But the improvement is not very large.

3.5 Transmission length

When the optical signal is transmitted thru a fiber, several parameters affect the signal that limits the possible length of transmission. The most natural one is the attenuation, the loss of signal power caused by the fiber. This decreasing of light power can for instance depend on bending of the fiber so that the condition of total internal reflection in the fiber not is fulfilled, or because of absorption, the material of the fiber absorbs energy from the transmitted light [2]. In the simulations have an attenuation value of 0.2 dB/km been used. So then for each kilometer the light travels 0.2 dB of the original power is lost.

The other important factor is the dispersion. The dispersion mainly causes a spreading of the transmitted pulse. The light that the laser produces is rather narrow (a linewidth of 10 MHz) with a specified center frequency. But light of different wavelengths travels with different velocities [2]. This makes the pulse to spread since light with some frequencies reach the destination earlier than other. The same thing can happen when light (even if all
of it has the same wavelength) travels thru different parts of the fiber core. There can be some changes in the material’s refractive index along the fiber that make the light go with different velocities and the pulse spreads. The in the simulation’s fiber specified dispersion of $16 \text{e}-6 \text{ s/m}^2$ is a dispersion coefficient at a reference wavelength giving a dispersion of $16 \text{ ps/nm/km}$ [4]. This is only the part of the dispersion caused by the different velocities of the wavelengths. The part caused by the differences of the refractive index in the core is specified in the non-linear index, in the simulations given the value $2.6\text{e}-20 \text{ m}^2/\text{W}$. All these simulation values are default values from the used fiber.

All these things limit the performance of the transmission system. To see how long fiber the system can handle, a simulation were made where the receiver sensitivity was measured. This value gives information about how much power is needed for the receiver to be able to detect a signal with a BER of $1\text{e}-9$. Result in figure 3.5 shows that the system can perform an error free transmission with a fiber length of up to 160 km when the filter is on the receiver side. After that a BER of $1\text{e}-9$ could not be reached.

![Figure 3.5: Receiver sensitivity as a function of transmission length.](image)

The curve also shows that the detection actually is getting better the first 80 km. The conclusion is that the dispersion is not only bad here. It makes the pulse wider throughout the fiber and this makes it more suitable for the shape of the demodulating FBG. At around 75 km the laser’s pulse and the filter match each other the best, then it gets worse. This result is for a transmission with the filter at the receiver side. With the filter placed at the
transmitter side only a transmission length of 120 km could be reached. This confirms what mentioned earlier that the DPSK signal better can resist the affects of the fiber compared to the ASK. But there is a small power penalty using the receiver filter. More power is lost during the transmission in the fiber when the signal is DPSK modulated in the fiber than when it is ASK modulated. But the penalty is small and the big dispersion sensitivity in the ASK signal is more important. The dispersion effects is also seen in figure 3.6 at the eye diagrams for the system with filter after transmission (a), and filter before transmission (b) with 120 km long fiber. The eye diagram in b) is much distorted due to the dispersion introduced by the fiber. In later simulations will only systems with demodulating filters placed at the receiver side be used.

![Eye diagrams for simulation system at 120 km transmission with filter after the fiber (a), and before the fiber (b).](image)

Figure 3.6: Eye diagrams for simulation system at 120 km transmission with filter after the fiber (a), and before the fiber (b).

### 3.6 40 Gbit/s transmission

The main work has been done with a bitrate of 10 Gbit/s. But in future experiments in the project might it be interesting to know how the system behaves at higher bitrates. It is also known that in experiments is a filter with a bandwidth of 6 GHz rather narrow. It is easier to make filters that are wider. Therefore were simulations made with a bitrate of 40 Gbit/s. The system was not modified any more than that the filter’s bandwidth now was 0.6*40e9=24 GHz. The result was a successful, error free (a BER below 1e-9) transmission for a back-to-back system, and for a transmission up to 14 km. The eye diagram in figure 3.7 shows a 40 Gbit/s transmission, much distorted by dispersion. It has not been investigated how to improve the result.
3.7 Conclusions

It has been found that it is possible to replace the MZI with a filter in optical DPSK demodulation. The filter should be a Gaussian shaped Fiber Bragg grating with a 3dB-bandwidth of 6 GHz in a 10 Gbit/s transmission system. The filter converts the PSK signal to an ASK signal, and since the PSK better can resist the negative effects of the fiber, the grating should be placed after the fiber. It can then also filter some optical noise caused by the fiber. An error free transmission of 160 km has been achieved by simulation.
Chapter 4

Experiments

When the fabricated gratings from the colleagues at the Universitat Politècnica de València arrived the work in the laboratory started. The goal was to find out whether it was possible to achieve a result similar to the simulated with the filter DPSK demodulation. Three different gratings were used with these specifications:

- Grating 1: Center wavelength $\lambda_c=1552.37$ nm, 3dB-bandwidth 0.047 nm, 5.85 GHz.
- Grating 2: Center wavelength $\lambda_c=1552.44$ nm, 3dB-bandwidth 0.043 nm, 5.35 GHz.
- Grating 3: Center wavelength $\lambda_c=1553.12$ nm, 3dB-bandwidth 0.047 nm, 5.85 GHz.

4.1 Experimental setup

The first setup for the experiments looked like figure 4.1 shows.

The laser first meant to use was a DFB (Distributed Feedback) laser with a temperature controller attached to be able to change the emission wavelength. Two problems were however found using this. First it was not possible to get a wavelength below 1553 nm, which made grating one and two unusable. The second problem was that the system was very sensitive to have the exact right stable wavelength. The center frequency of the emission of the laser needed to be a very good match to the filter’s center frequency. With the temperature and current controllers for the laser it was difficult to adjust the wavelength precise enough. This led to the decision to instead use a tunable laser with a wide range and a tunability of 0.0001 nm. With such
CHAPTER 4. EXPERIMENTS

Data

Figure 4.1: First experimental setup.

high precision in the laser it was only able to give a maximum power of 2.9 dBm. Therefore was an Erbium-doped fiber amplifier introduced in order to pump the signal up to the required dBm. It was placed before the filter so some possible noise introduced by the EDFA could be removed.

The PSK modulated signal goes thru the circulator into the grating and the reflected filtered signal go back thru the circulator to the receiver. There were two different receivers available for the experiments. One specially made for a bitrate of 10 Gbit/s, and one usable for variable bitrates. The first one contained a threshold function that slightly reshaped the signal before sending the electrical signal further on.

4.2 Results

The experimental setup was modified a little bit to look like in figure 4.2.

Figure 4.2: Experimental setup with added tunable filter.

A wide tunable band-pass filter, with a bandwidth of 1 nm, was attached to help filter residual amplified spontaneous emission (ASE) noise, and an
isolator put before the receiver to avoid reflections from the receiver to affect the system. With a good fine-tuning of the laser wavelength a better result was found, but still not as good as expected, according to the simulations.

4.2.1 System spectrums

To get a closer look at what happened with the signal when sent thru the system was the spectrum viewed at several points in the setup in figure 4.2. The spectrums were taken with grating number two inserted and the two first pictures of the laser’s sent signal and the spectrum after the phase modulator can be seen in figure 4.3.

![Figure 4.3: Spectrum from the tunable laser with center wavelength 1552.0009 nm and output power 2.889 dBm (a), and spectrum after phase modulator (b).](image)

The spectrum for the laser signal is very narrow, but it is broadened much after the phase modulation. The information is stored in the whole wide pulse and should now be demodulated by the grating. The spectrum of the filtered signal is shown in figure 4.4. As found above should the demodulating filter be rather narrow, according to the fact $0.6-0.8 \times$ bitrate.

The 3dB-bandwidth in the spectrum of the DPSK signal in figure 4.4 was much wider than the wanted 6 GHz. A look at the filter’s transfer function was needed.

4.2.2 Filter spectrums

With a look at the spectrum of the reflection of the grating without any laser signal it was found that the 3dB-bandwidth was wider than it was
supposed to be, according to the 6-9 GHz for 10 Gbit/s. The pictures from the spectrum analyzer for the three gratings are shown in figure 4.5.

The measured 3dB-bandwidths were here for grating one 0.080 nm or 9.93 GHz, for grating two 0.073 nm or 9.02 GHz and for grating three 0.075 nm or 9.4 GHz. The wanted bandwidth found in the simulations was 6 GHz. This was found as a probable cause for the results. Since no other, narrower gratings were available was it tried to verify that the too wide shape of the filters were the problem.

The simulations that found the filter bandwidth of 6 GHz were performed with a 10 Gbit/s bitrate. But the bandwidth also depends on the bitrate, in the simulations it was 0.6*Bitrate. So a higher bitrate would make the proper filter bandwidth wider. An experiment where the bitrate was raised is shown in figure 4.6.

In figure 4.6 a) the eye diagram and pulse for a transmission of 10 Gbit/s
is shown. Compared to the pictures of 4.6 b) with a transmission of 11 Gbit/s, you can see a small improvement in the latter one. The eye opening is slightly bigger and the shape of the pulses is a little bit better. But a raise of the bitrate to 11 Gbit/s does not make a filter bandwidth of 9 GHz good for the detection. For that a bitrate of at least 15 Gbit/s is needed. But experiments like that were not possible with the available equipment. The phase modulator was not made for more than 10 Gbit/s and the error detection unit used for the generation of the signal and calculation of the errors in the received signal was not made for more than 12.5 Gbit/s.

The experiment above was made with the receiver specially made for 10 Gbit/s and with the reshaping function built in. To see if the same result was found when the bitrate increased with the wide range, analoge, receiver, the experiment was repeated. The eye diagrams and pulses in figure 4.7 confirm the result from the previous figure. Since no reshaping is made in this receiver, the result looks worse than before. But it is possible to see that the eye opening is increasing and that the ripple on the pulses is decreasing when the bitrate is raised.

The other gratings with wider bandwidths were even worse suited for a bitrate of 10 Gbit/s but the same tendency could be seen.
4.3 Combining with band-stop filter

Since the only available filters were too wide an attempt was made to combine one of the band-pass filters with a tunable Fabry-Perot band-stop filter. If the band-stop filter could be tuned to the edge of the band-pass’ active part, the result would be a narrower filter function that might work for the desired purpose. Fiber Bragg grating number 2 was used with the tunable Fabry-Perot filter in a setup as in figure 4.8.

With the use of a spectrum analyzer was the band-stop filter tuned to give a narrower spectrum. In figure 4.9 are the spectrums for the band-pass filter alone (a) and for the combination of the two filters (b).

The shape of the spectrum is not very good, but it is narrower. The experiment was made at 10 Gbit/s with the 10 Gbit/s receiver, and the received eye diagram in figure 4.10 shows that a small improvement was achieved. The solution to use two filters to change the filtering spectrum is although not a good one.

However, the eye diagram is still far from good, and more experiments needs to be made to find out how to improve the results, with narrower gratings or equipment for higher bitrates.
Figure 4.8: Experimental setup with FBG grating and Fabry-Perot band-stop filter.

Figure 4.9: Transfer function for grating two alone (a) and in combination with FP band-stop filter (b).
4.4 Bit error rate

When the bit error rate measurements of the experimental setup were made, a saturation value of the BER was found. A value of $2 \times 10^{-9}$ was the lowest error rate possible for the system, which was achieved for the maximum input power. In figure 4.11 the BER for the first setup with grating 2 and the setup with the combination of band-pass and band-stop filters are displayed.

It can be seen that although the eye diagram for the double filter setup looks better, the measured bit error rate is not better.
4.5 Conclusions

It has been shown that it was possible to realize a DPSK transmission using a FBG as a demodulator. However, the result was not satisfactory. The original plan was to test the behavior of the setup with longer transmission fiber, in bigger systems and networks. But it was found that with the available resources it was not possible to get a good back-to-back transmission as needed. The experiment results showed that narrower filters and/or the possibility to do experiments in higher bitrate were needed to go further with the system.
Chapter 5

Applications

5.1 Combined angle/intensity modulation

Since the information sent with optical differential phase shift keying is completely stored in the phase and intensity of the light is constant, a possibility opens up to use the amplitude for transport of additional information, for example by a intensity modulator. In this extra channel can for instance labeling information in label switching applications be sent together with the payload information.

It will here be shown how an electroabsorption modulation can be used at the optical DPSK signal to send label data in the amplitude. A comparison was made between using a balanced direct detection receiver containing a MZI and a Gaussian shaped FBG for demodulating the DPSK payload signal.

5.1.1 Setup

The simulation setup looked like in figure 5.1. The DPSK data was sent with 10 Gbit/s and the amplitude was modulated with a digital ASK signal in 2.5 Gbit/s.

For the ASK modulation was an electroabsorption external modulator chosen. That one has some advantages compared to the Mach-Zehnder (MDM) modulator, which could be another choice [2]. One of them is lower insertion loss in the former one. The EA modulator consists of a semiconductor material waveguide that the incoming light from a laser passes thru. The absorption property of the semiconductor waveguide can be change if a voltage is applied. This is due to that the bandgap of the material decreases as the voltage increases, which makes the waveguide absorb the light from the laser. With this fact the intensity constant incoming light can be modulated with an electrical signal containing the information that is to be sent.
The modulator has a modulation index parameter that defines the difference in amplitude between a transmitted zero and a one. The index can vary from zero to one as showed in figure 5.2.

The modulation index, m, describe how much lower in power a transmitted zero should be compared to one's full value of the incoming light. A low value would here give better conditions for the DPSK signal since the amplitude is wanted to be as stable as possible for the demodulation. On the other hand, a high modulation index makes the results better for the ASK signal. A compromise is ought to be found.
5.1.2 Back-to-back system

First was a system simulated that used a balanced direct detection receiver, shown above in figure 2.6. The DPSK signal is generated in the phase modulator according to the data bit pattern. The light is then once again modulated in the electroabsorption modulator. At the receiver side, the signal is split with a 50/50 coupler. One part goes to the DPSK demodulator, and the other part to the receiver for the intensity modulated signal, which is detected direct with a photodiode.

The first back-to-back simulation was made first without and then with the ASK modulation attached to see how the extra channel affected the received DPSK signal. The modulation index was required to be as little as possible since fluctuations in the amplitude were especially sensitive with the MZI receiver. A value of 0.05 was found to give a good result for a back-to-back system. As the eye diagrams in figure 5.3 show was the signal very little affected and both the angle and the amplitude modulated signals were error free.

![Figure 5.3: Eye diagram for DPSK transmission, with MZI receiver, without added ASK modulation active (a) and with ASK modulation active (b). Eye diagram for ASK data (c)](image)

The same parameter values for the system was used when the MZI receiver was replaced with the earlier discussed FBG with a bandwidth of 6 GHz. The result was very similar, in figure 5.4, a small affect on the DPSK signal but still error free signals.

This shows that for a back-to-back transmission is the FBG a good demodulator for the DPSK signal in a combined angle/intensity modulation system. The stabilization problems of the MZI could therefore be avoided.
5.1.3 Transmission

When a transmission fiber of some distance was attached to the setup became the modulation index in the electroabsorption modulator to be a very important. It was found that the ASK signal was very sensitive to the dispersion in the fiber and needed a higher modulation index to be able to give an error free amplitude modulated signal. That affected the result of the DPSK signal and with the FBG demodulator was a transmission length of 3.6 km the longest possible to achieve with a BER of below 1e-9 for both signals. Figure 5.5 shows the dependence between BER and modulation index for the FBG system at a fiber length of 3.6 km.

This was a low result and it seemed that the biggest limitation was the ASK signal’s sensitivity to the dispersion. A simulation with a modulation index of 0.2 was made to see how the DPSK and ASK signals’ BER behaved with longer transmission length, including more dispersion. From figure 5.6 it is clear that the angle modulated signal can handle the effects of the fiber much better than the amplitude modulated. It was found that the nonlinear index in the fiber did not affect the behavior of the ASK signal to speak of. But when the dispersion value was lowered longer transmissions became possible. With the dispersion completely removed in the simulation model was the ASK signal error free thru the complete 30 km simulation.

The same behavior for the DPSK signal was found with the MZI receiver. The conclusion is that some kind of dispersion compensation is needed in the fiber or at the receiver to make it possible to combine DPSK and ASK signal for longer transmissions in a system like this.
Figure 5.5: Bit error rate measurement as a function of EA modulation index for transmission length 3.6 km.

Figure 5.6: Bit error rate measurement as a function of transmission length for different dispersion values in transmission fiber.
5.1.4 Conclusions

It has been shown that the FBG can successfully be used for DPSK demodulation in a combined system with DPSK and ASK signals. It was however found that the ASK signal in the simulated system was very sensitive to dispersion which therefore limited the possible transmission length. The DPSK signal was not that affected by the fiber effects.
5.2 Multi-channel system

In this chapter it will be determined how the earlier simulated single transmission system behaves when put into a larger multi channel system. This was simulated with a four-channel wavelength division multiplexing (WDM) transmission using DPSK. The result was also compared to a similar system using ASK format. The question to answer was whether the FBG demodulation technique worked well in a WDM system, and if it was possible to integrate the filter demodulation with the demultiplexer unit.

5.2.1 WDM

The wavelength division multiplexing is based on splitting the transmission bandwidth in several channels, the light of each laser emits on different wavelengths [2]. The, in this case four, incoming wavelengths is by the multiplexer sent in parallel channels on the same transmission fiber. Each channel is given a separate band in the spectrum. The demultiplexer receives the signals and split the four wavelengths into different fibers again. The spectral distance between signal wavelengths is given by the channel spacing.

5.2.2 DPSK multiplexing

When the simulation work started for the multi-channel system, the first setup using DPSK and WDM looked like figure 5.7 presents, simulating in 10 Gbit/s.

The four channel’s lasers emit in individual wavelengths, and in the multiplexer are the phase modulated incoming signals combined and sent WDM multiplexed thru the fiber. Each channel is spectrally separated with a distance from peak to peak given by the channel spacing. The channel spacing must be declared both in the laser, multiplexer, demultiplexer and the Fiber Bragg grating. This because the laser emission frequency and the demodulating filter’s center frequency must match, and the multiplexers must know the center frequency of each channel. In the simulations was the channels sent with a distance of 100 GHz between the center frequencies. The optical spectrum in the transmission fiber therefore looked like figure 5.8.

The channels are well separated so crosstalk between the channels is avoided. The channel spacing could be smaller if it is necessary to make space for more channels in the same bandwidth. After the demultiplexing is the demodulating of the DPSK signals made by the FBG. The filters for each channel have different center frequencies but the same shape and a
Figure 5.7: Wavelength division multichannel system used for the first simulations.

Figure 5.8: Optical spectrum in the WDM multiplexed transmission fiber.
bandwidth of 6 GHz. With this system was a successful transmission with a BER of 1e-9, for channel 1, simulated for 160 km.

In the WDM demultiplexer is the channel separation of channels made by a filter in a setup like figure 5.9 [4].

![Figure 5.9: The wavelength division demultiplexer.](image)

This show that in the simulations that were made was the signals filtered twice in a row. First to separate the channels in the wavelength division multiplexed signal with a filter bandwidth of 40 GHz, and then to demodulate the DPSK signal with a 6 GHz bandwidth. It is easily seen that these function can be combined using only one filter, the one integrated in the demultiplexer. Since filters also are located in the multiplexer in a reversed scheme of the one for the demultiplexer in figure 5.9, could it be a possibility to do the demodulating there instead. But according to the results in section 3 was the DPSK signal more resistant against the affects from the fiber than the ASK signal, so it is better to use the demultiplexer filters for the demodulating. The filters in the multiplexer are therefore left with the bandwidth 40 GHz and the filters in the demultiplexer are changed to 6 GHz. This gives a simulation setup viewed in figure 5.10.

This makes the system much easier when no external filters are needed as the system in 5.7. The system was simulated with an error free received signal over 150 km for channel 1. Figure 5.11 show the receiver sensitivity for the two systems with external and internal demodulating filter. It is seen that apart from a shorter transmission of 10 km is there a power penalty in longer transmissions in the range of 1 dBm when using the internal filter.

### 5.2.3 ASK multiplexing

To compare the DPSK system's simulation results with an ASK multi channel system simulations were made with a similar system except for the modulation part. Instead of the phase modulator an amplitude modulator was used,
CHAPTER 5. APPLICATIONS

Figure 5.10: Wavelength division multichannel system using the demultiplexer as demodulator.

Figure 5.11: Receiver sensitivity as a function of length for WDM simulation using external and internal filter for DPSK demodulation.
and the precoding logic used with the DPSK was not needed. The detection was done directly by the photodiode. The multiplexing technique was the same but the filters in the demultiplexer were not needed for anything else than the demultiplexing so the bandwidth was again 40 GHz. It has earlier been found that the DPSK modulated signals was more resistant to the dispersion in the fiber than the ASK signals. The same tendency can be seen in this system as viewed in figure 5.12. The ASK transmission has a better result for short transmissions in respect of power, a power penalty for the DPSK of 2 dBm. But the ASK signal cannot handle the longer transmissions above 90-100 km.

Figure 5.12: Receiver sensitivity as a function of length DPSK and ASK modulated transmission.

5.2.4 Arrayed waveguide grating

Another way to multiplex signals in a multi channel system and still using wavelength division multiplexing can be to use an arrayed waveguide grating (AWG) instead of the WDM multiplexer used above. The AWG consists of two WDM couplers, arrayed waveguides between them and the incoming and outgoing waveguides [2]. In a AWG demultiplexer is the input to the first coupler one waveguide with light of different wavelengths. That light is split into the arrayed waveguides that have different lengths. This makes the wavelengths to get different phase shift in the waveguides and in the output coupler they interfere to maximum intensities that goes into different directions and into different outgoing fibers depending on wavelength.
AWG's is good in matters of handling large number of channels with low loss in multiplexing applications and therefore popular in WDM systems [1].

Simulations were made with the AWG multiplexer to see how it could be used in a DPSK multi channel system. The AWG do not include any filter as the multiplexer used above so the external demodulating filter cannot directly be replaced by the function of the demultiplexer. But it was found that when the channel spacing in the system was narrowed was a filtering done in the multiplexing. A channel spacing of 100 GHz was found to be too wide to give the right function. For a good demodulating of the DPSK signal was a spacing of about 30 GHz needed. That small value is however not really commercial available today for 10 Gbit/s data transmission.

The conclusion becomes that to use an AWG multiplexing technique without any external filter for the DPSK demodulation is a very low channel spacing needed, unless a higher bitrate are used.

5.2.5 40 Gbit/s transmission

As seen earlier in section 3.6 were simulations in 40 Gbit/s successful for back-to-back transmission and up to a few kilometers. The same result was seen when 40 Gbit/s simulations were made with multi channel systems.

Using the WDM multiplexer was a transmission of 12 km made error free. That is a little deterioration from the single channel, but it is a reasonable result since it is a rather high bitrate and a sensitive multi channel system. As discussed above could a higher bitrate be a way to make it possible to have a more normal channel spacing of 100 GHz when using a AWG multiplexer. With a transmission in 40 Gbit/s was that confirmed. A good result with 100 GHz spacing was achieved in a back-to-back system and for a transmission of up to 6 km. This is lower than for the other transmissions, but in this case when no actual filtering is done can crosstalk between the channels be a cause since the spacing is low in relation to the bitrate. In figure 5.13 is the eye diagram seen using AWG for 6 km transmission. It is found that the dispersion is a big issue in 40 Gbit/s.

5.2.6 Conclusions

It has been found in this chapter that the DPSK demodulation technique with a FBG gives a successful transmission for up to 160 km in a multiplexing system. The simulated four channel system could be made easy with wavelength division multiplexing using the internal filters in the demultiplexer also for demodulating the DPSK signal by giving them a narrow
bandwidth of 6 GHz. For that solution a power penalty of 1 dBm compared to the external filter version is observed.

Another power penalty of 2 dBm was found when using DPSK compared to ASK as modulation format in this four channel system. But the DPSK signal was more resistant against dispersion and could transmit in longer distances.

Simulations for 40 Gbit/s was made successfully for very short distance with the DPSK system. 12 km transmission was made with the internal filter in the demultiplexer in single mode fiber and no dispersion compensation. At this high bitrate was it possible to use an arrayed waveguide grating for the multiplexing. This gave the conclusion that a direct DPSK demodulation can be done by an AWG at high bitrates with a channel spacing of 100 GHz. In 10 Gbit/s was very narrow spacing of 30 GHz needed for a successful internal DPSK demodulation by the AWG.
Chapter 6

Conclusions

It has been found that a Gaussian shaped Fiber Bragg grating can be used for DPSK demodulation. This was found to be a useful result in optical transmission applications, such as multi channel and subcarrier systems. The filter can replace the Mach-Zehnder interferometer in DPSK receivers when having a bandwidth of 0.6*bitrate. This has been found both for 10 and 40 Gbit/s. For the higher bitrate is dispersion compensation needed to get longer transmission than 14 km.

A transmission of 160 km has been simulated for both single transmission and for a four channel wavelength division multiplexing system. With the WDM was it possible to use the internal filters in the demultiplexer for the DPSK demodulation. But by moving the demodulation from an external filter to the demultiplexer occurred a power penalty of 1 dBm. The DPSK signal has been found to be more resistant to dispersion than an ASK signal. Since the demodulating filter converts the phase information to intensity should the transmission be made with a DPSK signal and the filter therefore placed at the receiver side. The same fact showed in comparing the DPSK WDM system with an ASK WDM system. A power penalty occurred with the DPSK but the ASK system showed more sensitivity to dispersion and could not handle longer transmissions. At a higher bitrate of 40 Gbit/s was it possible to use an AWG for multiplexing and DPSK demodulation with a channel spacing of 100 GHz.

Also in the combined DPSK/ASK transmission was the ASK signal found to be very sensitive to the dispersion caused by the fiber. That limited the possible error free transmission to only a few kilometers. To use this kind of system for longer transmissions are some kind of dispersion compensation needed.

In experiments were only a back-to-back transmission tested. It was seen that the FBG demodulation technique worked, but the result was not good.
The available gratings were found to be too wide for a DPSK demodulation in 10 Gbit/s. They had a bandwidth in the area of 9 GHz, which was much wider than the wanted 6 GHz. This made the gratings more suitable for demodulating a DPSK signal in around 15 Gbit/s. Equipment for experiments in higher bitrates was not available and could not be tested.
Chapter 7

Future work in the project

To use this results further on in the project are these thing recommended.

- More experiments should be done to verify that a good result can be found in practice. For this is other narrower gratings needed, or equipment for higher bitrates than 10 Gbit/s.

- If equipment for higher bitrates get available can the bitrate first be raised to 15 Gbit/s with the 9 GHz filters for demodulation to see how the results improves.

- To use the combined system with DPSK/ASK signals further on in experiments should the dispersion compensation for the ASK channel be investigated. Maybe could another technique than the electroabsorption modulation be used for the intensity modulation.

- A subcarrier system using analoge ASK signal combined with the DPSK signal should be tested for use in optical label switching applications.

- Do more simulations in 40 Gbit/s to see how a the systems can be improved for for higher bitrates. Perhaps start with simulations in 20 Gbit/s to see the behavior in more details.

- If equipment is available for 40 Gbit/s could transmission be tested in experiments using wider, and easier to produce, filters for the DPSK demodulation.
Appendix A

Bit error rate

The bit error rate is the result of a comparison between the originally sent bits and the received bits. The definition of the BER is 'number of erroneous bits/total number of bits' [2]. The error consist of receiving a sent zero as a one or vice versa.

In normal situations are a BER of 1e-9 considered as a result for an error free transmission. However, in some industry situations are a result of 1e-6 accepted. With error correction techniques can than lower values be reached.

Sensitivity for a receiver is often measured. This gives the minimum power that a receiver need to detect a given bit error rate, often 1e-9.
Appendix B

Eye diagrams

The eye diagram is a way to evaluate the performance of optical and electrical data transmission [2]. It is formed by viewing the received pulse for a 010 and a 101 signal. An ideal eye diagram would therefore look like figure B.1.

![Ideal eye diagram](image)

Figure B.1: Ideal eye diagram.

The eye diagram is wanted to be as open as possible. The behavior of the system can make the opening smaller and distort the shape. For example, jitter, small variations in the digital signal with respect of the reference time, make the signal diffuse, and slow rise or fall times would close the eye.
Bibliography


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