MASTER

A high bitrate direct-detection DPSK optical transmission system

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A high bitrate direct-detection DPSK optical transmission system (February 6, 1998)

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Abstract

For high speed data transmission over an optical fibre is both the 1500 nm and the 1300 nm regions can be used. In the 1300 nm region the polarisation insensitive Semiconductor Optical Amplifier (SOA) is available to optically amplify the signal. These amplifiers have a low saturation input power. Due to saturation, pattern effects occur when using intensity modulation. The pattern effect causes a closure of the eye pattern resulting in a low Bit Error Rate (BER). A solution to this problem is decreasing the signal power so saturation will not occur. This will decrease the achievable length of the link because the signal to noise ratio will become too low.

A second solution is making use of Differential Phase Shift Keying (DPSK) or Frequency Shift Keying (FSK) modulation. Due to the constant envelope of the modulated signals the saturation of the SOA's does not cause the pattern effect. The DPSK seems to be the best choice because it can be easily modulated using a $LiNBo_3$ phase modulator (commercially available in speeds up to 40 Gbit/s) and has a high receiver sensitivity.

A new problem introduced when using DPSK is the phase noise which influences the data stored in the phase. The advantage of *Differential* PSK is that only the phase change during two bits is of interest. The effect of phase noise is expressed in the factor $\Delta\nu \cdot T$. Where $\Delta\nu$ is the Full Width at Half Maximum (FWHM), also called linewidth, of the optical spectrum of an unmodulated signal at the input of the demodulator. The factor T is the bit time.

To be able to estimate the desired value of this factor a simulation program is written to calculate the BER-curve for different values of $\Delta\nu \cdot T$. Since error probability has a Poisson distribution the saddle point approximation method is used to calculate the BER. The demands of $\Delta\nu \cdot T$, found as well in literature as by the simulations, are $\Delta\nu \cdot T = 0.01$ for a balanced receiver and $\Delta\nu \cdot T = 0.005$ for an unbalanced receiver. Interesting to see is when the bit rate becomes larger the demands on the linewidth decrease.

Every laser has a finite linewidth ranging from 20 MHz for a normal communication laser to 1 MHz for CATV lasers. The linewidth is broadened by the SOA's in the link. To get an insight in the broadening of the linewidth an analysis was performed to describe the linewidth broadening due to an SOA. To verify the results of the analysis, measurement where performed measuring the linewidth of a link with a laser and up to four amplifiers. The resulting linewidth after a link highly depends on the input linewidth of the laser. The demands of $\Delta\nu \cdot T$ can easily be met for links with up to 20 amplifiers ($\approx$ 1000 km).

Another important noise factor is the Amplified Spontaneous Emission (ASE) -noise, which is a broadband noise caused by spontaneous emission in the SOA's. To describe its effect a simulation program was written, calculating the BER-curve for a different number of amplifiers and for different optical input powers of the link. The simulation shows, that the best

way to deal with the ASE-noise is to increase the signal power so the signal to noise ratio will stay high enough. A link of more than 20 SOA's can be reached. When increasing the signal power the amplifiers will saturate but this is no problem with DPSK.

Both the phase-noise and ASE-noise simulations predict a link of 20 amplifiers can be reached. To study what happens when both noises are combined, a simulation program was written which calculates the BER of the entire system. Due to the lack of a method for calculating the BER analytical, the system is simulated bit-by-bit.

The result of this simulation confirms it is, at least theoretical, possible to make links with lengths up to 1000 km using 20 segments of 50 km fibre and a SOA with an average gain of 20 dB.

Preface

This report is written as the final part of my graduate study at the Eindhoven University of Technology. In a period of at least 6 months an assignment has to be performed to prove your capabilities.

The assignment I received was:

- Explore the possibilities of optical transmission using Frequency Shift Keying Direct Detection (FSK-DD) and Differential Phase Shift Keying Direct Detection (DPSK-DD) at bit rates of 10-20 Gbit/s. Acquire knowledge in combination with an literature investigation into the latest developments. Get insight in the feasibility of these transmission systems using simulations.
- Choose the preferred modulation technique to perform experiments (FSK-DD versus DPSK-DD) based on the study and simulations.
- Characterise and evaluate the components of the system. Perform transmission experiments and show (possible) advantages of FSK-DD or DPSK-DD with respect to Intensity Modulated Direct Detection (IM-DD). Target bit rate: at least 2.5 Gbit/s.

Hereby, I want to express my thanks to the people who supported me during my study:

In the first place my family for supporting me during my study.

Dr.ir. H. de Waardt and ir. J.G.L. Jennen for the support during my graduation period.

Prof. G.D. Khoe for enabling me to graduate at the division professorial chair of electro optical communications.

Prof.G. Acket for reviewing my work.

A special thanks goes to all people programming Linux (a free Unix-like operating system), X-Windows and programs running in these environments. Without these it would have been impossible to perform the tasks described in this report in the same time frame.

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Chapter 1

Introduction

Optic fibres are used to transport high speed data over long distances. In the entire world over 100 million kilometres of Standard Single Mode Fibre (SSMF) is installed. The SSMF has two suitable wavelength windows where data can be transported. These windows are located at 1300 nm and 1550 nm. At 1550 nm the fibre has the lowest loss whereas at 1300 nm the dispersion is almost zero.

Although Dispersion Shifted Fibre (DSF) has been developed with zero dispersion at 1550 nm, the interest in the 1300 nm region still is not lost. The first reason is the costs, the DSF fibres are more expensive and more importantly millions of kilometres of SSMF fibre would have to be replaced. Secondly, it is to be expected that in the future both windows of 1300 nm and 1550 nm will be used to fully exploit the capacity of the optical fibre.

To get sufficient performance in the 1300 nm region investigation is necessary. The most important problem of this region is the optical amplification. For the 1550 nm window an Erbium Doped Fibre Amplifier (EDFA) is available which has very good characteristics. Investigation is being performed to find an amplifier with similar characteristics for the 1300 nm window. There are three candidates, the Praseodymium Doped Fibre Amplifier (PrDFA), the Raman Amplifier and the Semiconductor Optical Amplifier (SOA). This report will focus on the use of the SOA. The characteristics of this amplifier are not as good as those of the EDFA. Especially for high bit rate ($\approx$10Gbit/s) intensity modulation, also called Amplitude Shift Keying (ASK), the SOA has some severe disadvantages. For high bit rate ($\approx$10Gbit/s) ASK modulation the pattern effects occur. This causes a closure of the eye-pattern and hereby a high BER.

A solution is to use a modulation technique with constant envelope instead of intensity modulation. Remains the choice between frequency modulation called Frequency Shift Keying (FSK) or phase modulation called Differential Phase Shift Keying (DPSK).

To be able to develop an FSK or DPSK modulation system the following tasks have to be performed:

- A literature investigation to compare the advantages and disadvantages of the FSK versus the DPSK modulation techniques.
- A further analysis of the chosen modulation technique.
- The simulation of the chosen modulation technique
- Measurements on the chosen system.

As will be shown in the next chapter, were the advantages and disadvantages of the FSK and DPSK modulation are studied, the DPSK tends to give the best result. Next, the two most important optical noise factors, phase and Amplified Spontaneous Emission (ASE) noise, are studied. The entire system is simulated taking the combination of these two noise factors into account. In the simulations the electric circuit is assumed to be ideal. In the last chapter conclusions and recommendations are given.

Chapter 2

Modulation techniques

2.1 Judgement factors

As mentioned in the previous chapter, two different modulation techniques, DPSK and FSK, have to be analysed to be able to predict which one will give the best result for a 10-20 Gbit/s direct detection transmission system. To collect information on these modulation techniques, a literature investigation was performed. An index of the most important articles can be found in appendix A. A general overview of fibre optic communication systems can be found in [1].

The most important factors on which the prediction is based are:

- receiver sensitivity;
- noise factors;
- modulation;
- demodulation.

The optical transmission system will look like the one shown in figure 2.1, the system can be directly modulated on the laser or by an external modulator. An important demand

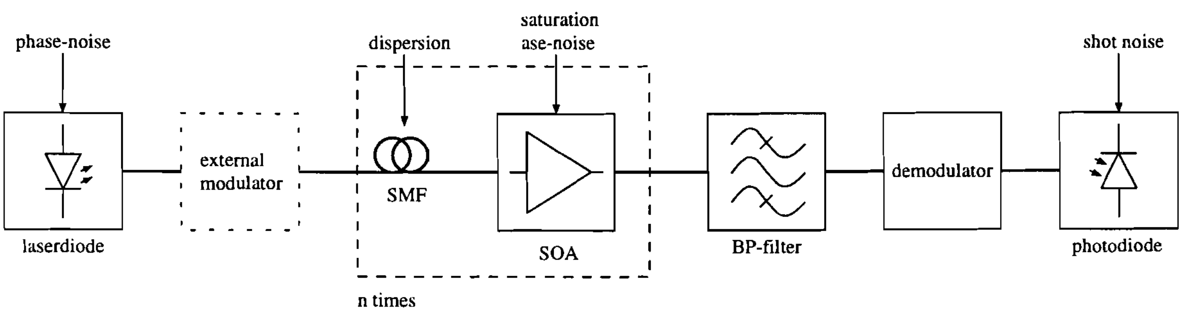


Figure 2.1: General system setup for high speed optical transmission employing FSK-DD or DPSK-DD.

is that the different components needed to modulate and demodulate the signal must be commercially available.

The *demodulation* has to be performed optically, which basically means the signal has to be converted from FSK or DPSK to ASK. The ASK signal can be detected by the receiver. The receiver consists of an optical to electrical conversion (photo diode), clock recovery and an integrate and dump filter.

The most important optical noise sources are:

- saturation effects
- phase noise
- shot noise
- ASE-noise
- dispersion

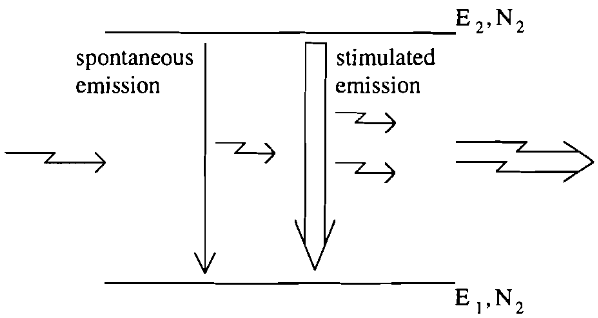


Figure 2.2: Two kinds of emission occurring in an SOA

2.1.1 Saturation effects in the SOA

To have stimulated emission there has to be a population inversion which means N_2 must be greater than N_1 (figure 2.2). There is a finite number of electrons which can contribute to the stimulated emission before $N_1 = N_2$ and the amplification stops. The electrons at E_2 are electrically pumped to this level and there number and the speed to get them there are limited. Without an input signal in steady state the level E_2 will be filled to a certain level.

When the SOA receives a high power input signal, the steady state will be determined by the equilibrium where the number of electrons per second contributing to the stimulated and spontaneous emission is equal to the maximum number of electrons per second which can be pumped to E_2. This means there is a maximum output power based on the supply of electrons per second to E_2.

When a pattern is launched into the SOA where '1' is a high intensity signal and '0' a low intensity signal, a '1' after a number of '0' 's will cause a high output signal which decays until eventually the equilibrium is reached. This effect can be seen in figure 2.3.

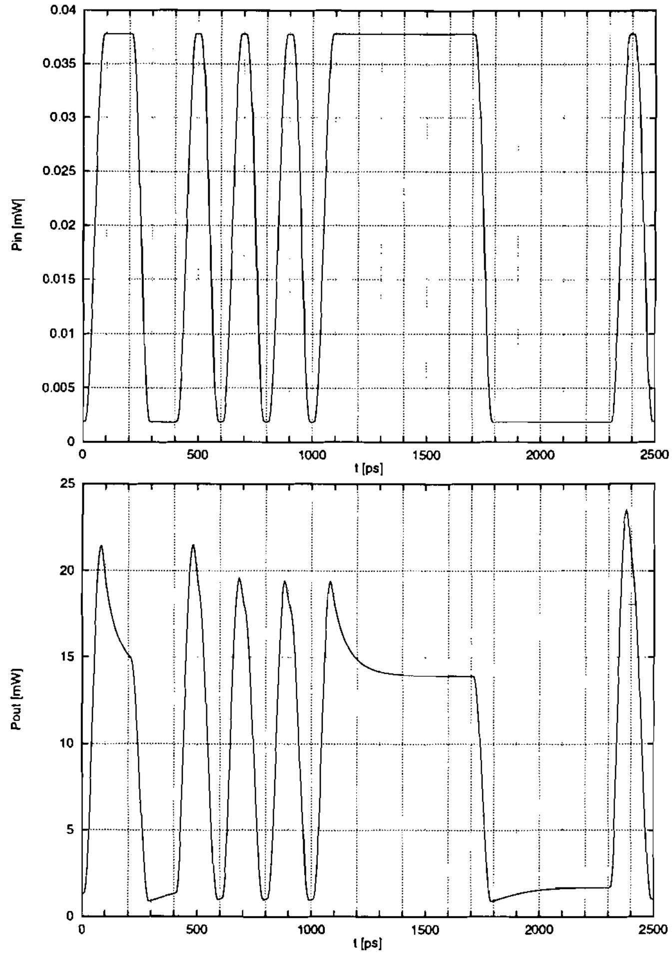


Figure 2.3: Illustration of pattern effects caused by saturation in SOA's

When the pattern '101' is launched into the SOA and the time between the two '1' 's is not long enough the SOA will not fully recover (the steady state where E_2 is filled to its maximum is not reached); the second '1' will be lower than the first. This effect can be seen in figure 2.3 with the first high intensity signal at 500, a '0' at 600 and a lower '1' at 700.

These two effects are called pattern effects. The second effect occurs when the carrier life time τ_c is exceeds the bit time T.

Figure 2.3 shows a pattern effect occurring after one SOA. One can imagine what happens in a link with several SOA's. The *distorted* signal travels through a second amplifier where exactly the same effects take place.

2.1.2 Phase noise

The phase noise is caused by spontaneous emission in the laser and SOA's (see chapter 4). This spontaneous emission influences the signal in two ways:

- A direct phase change due to a change in the number of photons;

- A phase change due to a change of the refractive index. The change occurs because the refractive index is a function of the carrier density.

The phase-noise is expressed in the linewidth, this is the width of the optical spectrum, at the output of the device, at which the power is at the half of its maximum (Full Width at Half Maximum (FWHM)).

2.1.3 Shot noise

The shot noise is generated in the photo diode. The arrival of photons at the photo diode are random discrete events. The average number of photons arriving is known. The deviation from this average is called the shot-noise. For all the modulation techniques described here, the shot noise is equal.

2.1.4 ASE noise

The ASE noise is exactly what its name describes Amplified Spontaneous Emission. It is caused by spontaneous emission in the amplifier which is amplified by the stimulated emission. The result is a random noise with a large bandwidth (64 nm, see chapter 6).

2.1.5 Dispersion

There are two contributions to the dispersion D, namely the waveguide dispersion and the material dispersion. The first is caused by frequency dependence of the phase constant β. The second is caused by the frequency dependence of the refractive index n on the frequency.

In the considered system both are very small, in fact the material dispersion is zero at 1310 nm.

The effect of dispersion is:

- $D < 0$ High frequency components travel slower;
- $D > 0$ High frequency components travel faster.

2.1.6 Noise in electric system

The entire electric circuit which contains the integrate and dump filter, the clock recovery and a bit error tester is assumed ideal. The eventual amplification and detection is supposedly ideal. This is not conform the real situation but the effects are the same for the different modulation schemes and can later be added.

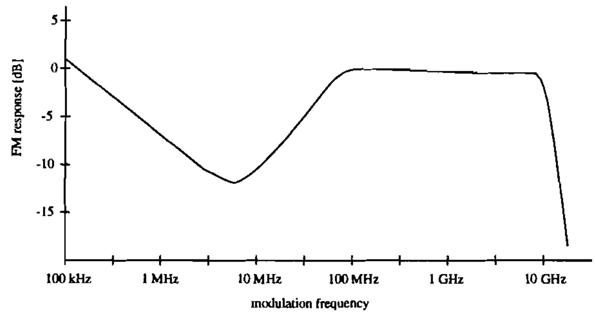


Figure 2.4: FM response of a semiconductor laser

2.2 FSK modulation

In FSK modulation bits are translated to a frequency:

$$'1' := f_1$$
$$'0' := f_0$$

The envelope of the signal is constant so no pattern effects will occur.

The easiest way to perform FSK modulation is directly on the laser. A disadvantage of this scheme is the frequency response of the laser. The frequency response of a laser looks like figure 2.4.

The first problem is the roll off at high frequencies which determines the maximum modulation frequency. Lasers which can be modulated at frequencies over 10 GHz are not yet commercially available. The second problem is a dip at lower frequencies which will cause a pattern effect for low frequency components. The last problem is the residual ASK. The frequency signal is modulated by changing the laser current, so not only the frequency, but also the intensity will change. This can cause pattern effects.

To externally modulate the signal using an acousto optic modulator is not possible because the maximum reachable frequency shift is 1 GHz which is not enough for our application. The second option is to use a $LiNbO_3$ phase modulator with a sawtooth or triangular input signal. These signals are difficult to create at 10 Gbit/s.

Demodulation can be done by filtering one of the frequencies out of the spectrum, or by using a delay-line interferometer with a delay of $\frac{T}{2}$ as shown in figure 2.5.

The chance that the phase noise will cause an error is very small. An error will occur if the signal falls outside the filter in an unbalanced receiver, or in the wrong filter with a balanced receiver.

The ASE-noise effects all modulation techniques described here in a similar fashion. It effects the signal to noise ratio and will always cause a BER-floor. Not only will the noise increase as more amplifiers are added, but the signal level will also decrease because the amplifiers will saturate on the ASE-noise. It is possible to use optical filters to decrease the bandwidth and with this the ASE power.

Dispersion has a negative effect on FSK because the frequency components shift in time. The chance exists that the signal will fall outside the passband of the filter and cause an error. The effect in the systems described here is very limited because the dispersion is almost zero.

2.3 DPSK modulation

In DPSK-modulation the data is put in the phase difference between two bits:

'1'	:=	180°	phase shift
'0'	:=	0°	phase shift

The envelope of the signal is constant so no pattern effects will occur.

Although it is possible to directly modulate the laser by applying a sawtooth or triangular signal, the same laser response problems will arise as with the FSK-direct modulation. On top of this, these signals are difficult to realise.

An external $LiNbO_3$ phase modulator is available from different manufactures for speeds up to 40 Gbit/s.

Demodulation is very simple, since it only consists of a delay-line and two couplers. The scheme can be seen in figure 2.6.

The phase noise does effect the system since the transmitted information is held in the phase. Using *Differential* PSK has the advantage that the information is held in the phase difference between two consecutive bits, so only the phase-noise between these two bits will effect the performance of the system. The demand that can be put on a DPSK system to have acceptable transmission is $\Delta\nu \cdot T = 0.01$ for a balanced receiver and $\Delta\nu \cdot T = 0.005$ for an unbalanced receiver. Where $\Delta\nu$ is the linewidth measured at the FWHM of the optical spectrum and T is the bit time.

Due to the way of demodulation the ASE-noise power is 3 dB higher as for the FSK and ASK modulation, so its effect is larger.

The effect of dispersion on a DPSK signal is very limited because the frequency is constant.

2.4 Choice of modulation technique

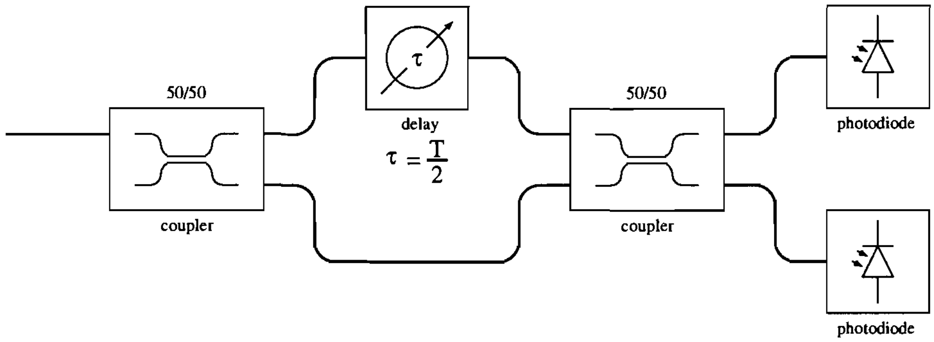
Taking the information in the previous sections into account a decision which modulation scheme to use was made. In table 2.1 the advantages and disadvantages are summarised. To get a complete overview also the ASK performance is added to the table although no special investigation is done to this modulation technique. The signs describe:

$--$	: negative effect which is hard to overcome;
$-$	: negative effect which demands extra attention;
$+$	: positive effect which needs attention;
$++$	: positive effect.

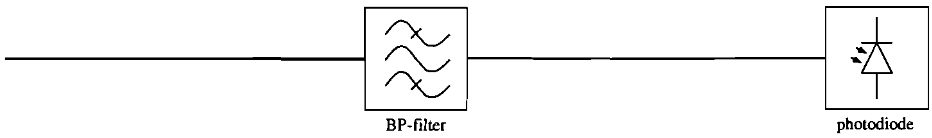
From the above it was concluded that the best modulation scheme to investigate further is the DPSK modulation. This conclusion is mainly based on the easy modulation, the extra 3dB receiver sensitivity and of course the lack of the pattern effect. The DPSK modulation scheme can only be used if the demand of $\Delta\nu \cdot T = 0.01$ can be met. Since there is very little known about linewidth broadening in a link with SOA's this is the first point of interest.

Table 2.1: Comparison between the considered modulation techniques

factors	ASK	FSK	DPSK
modulation	++	– –	++
demodulation	++	+	+
receiver sensitivity	+	+	++
phase-noise	++	++	–
ASE-noise	–	–	–
saturation effects	– –	+	++

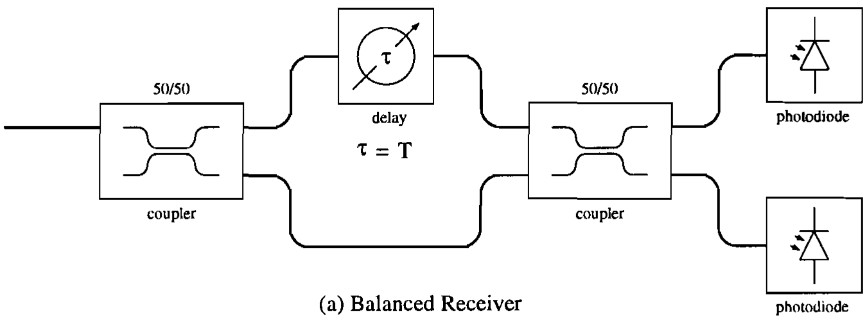


(a) Balanced Receiver

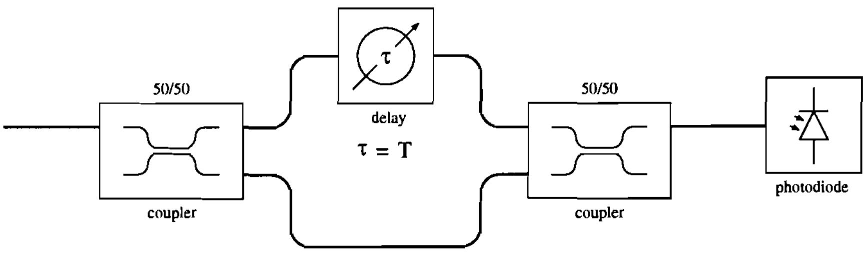


(b) Unbalanced receiver

Figure 2.5: Demodulation of optical FSK signal



(a) Balanced Receiver



(b) Unbalanced receiver

Figure 2.6: Demodulation of optical DPSK signal

Chapter 3

The DPSK transmission system

3.1 Theoretical setup

The DPSK system looks like the setup shown in figure 3.1. The system can be split in three optical parts:

- The transmitter consisting of an laser diode and a phase modulator;
- The link consisting of n times a length of fibre and an SOA;
- The receiver consisting of an optical demodulator and the photo-diodes.

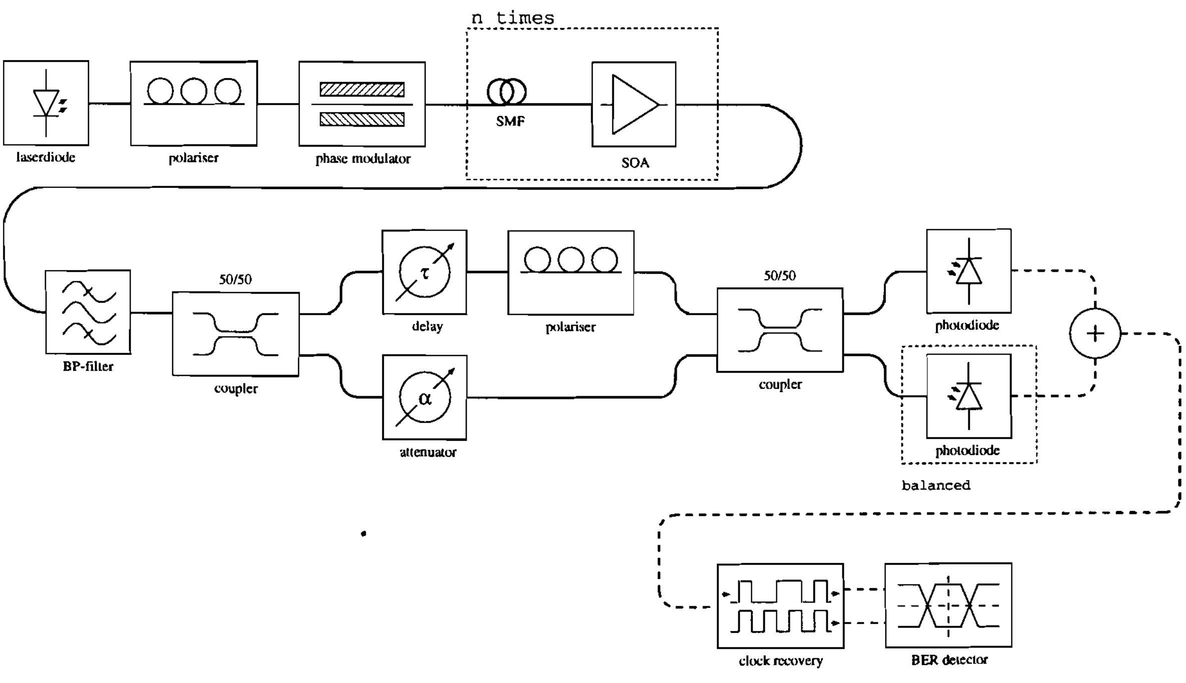


Figure 3.1: Setup of the high speed DPSK optical transmission system

The main optical noise sources are:

- ASE-noise;
- phase noise;
- non ideal phase modulation;
- non ideal delay.

The optical filter is used to remove the noise outside the signal bandwidth. This is primarily the ASE-noise. A second option would be the placement of filters inside the link to reduce the ASE-noise before the next SOA is reached. Since the ASE-noise power decreases, the SOA's will not saturate on the ASE-noise. However employment of filter in the link reduces the net signal power after each SOA filter combination due to the insertion loss of the filters. This could mean more amplifiers are necessary. This leads to an optimising problem of finding the best combination of filters and amplifiers.

In the theoretical approach used here, the electric system is assumed to be ideal. However in the electrical system a number of important noise sources can be identified:

- temperature noise in electrical receiver;
- none ideal timing;
- non ideal decision threshold α_{opt};
- noise of electrical amplifier in receiver.

3.2 (De)modulation of DPSK

As mentioned before, when using the DPSK modulation technique, the data is modulated by changing the phase between consecutive bit intervals:

'1'	:=	180°	phase shift
'0'	:=	0°	phase shift

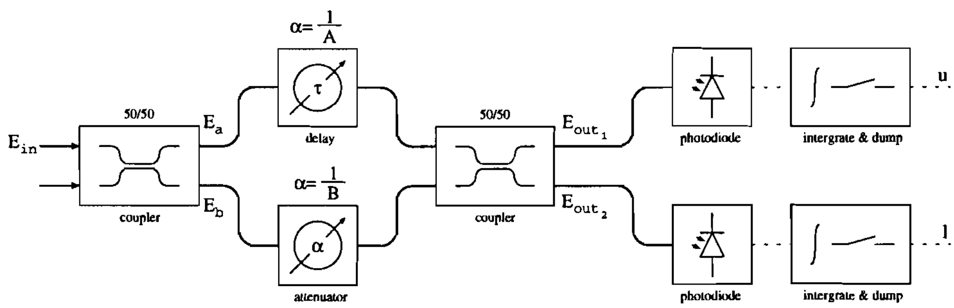


Figure 3.2: Setup of the Interferometric delay-line demodulator for DPSK demodulation

For demodulation two consecutive bit intervals have to be compared, a phase difference of 180° means a '1' , 0° means '0'. Comparison of these intervals is done in the interferometer circuit shown in figure 3.2.

The 50/50 couplers split the power of the signal in half giving each branch 50% power. The delay is used to delay the signal one bit time. After which the two signals are *compared* in the second coupler. The DPSK (de)modulation is shown in figure 3.3.

In the figure the importance of a stable and exact delay can be seen because the two signals with a frequency $f = 2.3 \cdot 10^{14}$ (the laser frequency) have to fit exactly over each other.

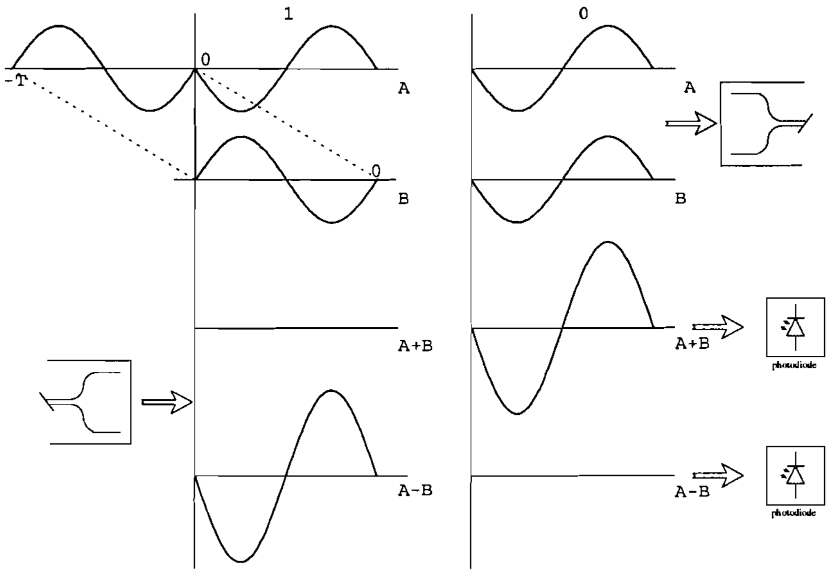


Figure 3.3: Schematic presentation of the DPSK (de)modulation technique

The demodulation can be expressed in equations as follows:

For the 3dB coupler the following formula (3.1) can be derived.

$$\begin{pmatrix} E_{out_1} \\ E_{out_2} \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & \exp\left(j\frac{\pi}{2}\right) \\ \exp\left(j\frac{\pi}{2}\right) & 1 \end{pmatrix} \cdot \begin{pmatrix} E_{in_1} \\ E_{in_2} \end{pmatrix} \tag{3.1}$$

$$E_a = \frac{1}{\sqrt{2}} E_{in_1} \tag{3.2}$$

$$E_b = \frac{1}{\sqrt{2}} E_{in_1} \exp\left(j\frac{\pi}{2}\right) \tag{3.3}$$

$$\begin{aligned} E_{out_1} &= \frac{A}{\sqrt{2}} E_a(t-\tau) + \frac{B}{\sqrt{2}} E_b(t) \exp(j\frac{\pi}{2}) && (3.4) \\ &= \frac{A}{2} E_{in_1}(t-\tau) + \frac{B}{2} E_{in_1}(t) \exp(j\pi) \\ &= \frac{A}{2} E_{in_1}(t-\tau) - \frac{B}{2} E_{in_1}(t) \\ E_{out_2} &= \frac{A}{E_a} \sqrt{2}(t-\tau) \exp(j\frac{\pi}{2}) + \frac{B}{\sqrt{2}} E_b(t) && (3.5) \\ &= \frac{A}{2} E_{in_1}(t-\tau) \exp(j\frac{\pi}{2}) + \frac{B}{2} E_{in_1}(t) \exp(j\frac{\pi}{2}) \\ &= \frac{A}{2} E_{in_1}(t-\tau) + \frac{B}{2} E_{in_1}(t) \end{aligned}$$

3.3 The experimental setup

The setup with which the experiments will be performed is drawn in figure 3.1.

The transmitter consists of a PHILIPS laser at 1310 nm a polariser and a SUMICEM phase modulator. The polariser is needed because the phase modulator is polarisation sensitive. The input signal for the phase modulator is generated by an Pseudo Random Bit Sequence (PRBS) generator.The voltage at which the phase has shifted 180 degrees is $V_\pi = 4.7, V$. Since the PRBS-generator could not deliver this much, an amplifier is used to generate the desired voltage.

The link consists of 4 times 50 km 1310 nm optimised fibre and a PHILIPS polarisation insensitive SOA. There is one filter placed at the end of the link. The electrical receiver consists of a clock recovery and a BER-tester

The delay is realised by an air gap consisting of two collimating lenses which couple the light from the fibre into the air and from the air back into the fibre. The length of the air gap can be regulated to adjust the delay. In the air gap a $\frac{\lambda}{2}$ and a $\frac{\lambda}{4}$ retardation plate is placed to be able to control the polarisation so it is equal in both branches of the coupler. In the second arm of the interferometer an attenuator is placed to make sure both branches have equal input intensity.

3.4 Coding and Decoding

Since the phase modulator is modulated binary with $'1' = V_\pi = 180°$ and $'0' = V_0 = 0°$ the signal after the modulator is not the same binary sequence. This because a '1' should be a 180° phase change with reference to the previous bit.

The DPSK demodulator output r_n is a function of its input signal s_n and the delayed signal s_{n-1}:

s_{n-1}	s_n	r_n
0	0	0
0	1	1
1	0	1
1	1	0

This can be expressed in a equation as follows:

$$r_n = s_n + s_{n-1} \tag{3.6}$$

The + is the modulo 2 addition which means:

$$\begin{aligned} 1+1 &= 2 \mod 2 = 0 \\ 1+0 &= 1 \mod 2 = 1 \end{aligned}$$

To get the right binary sequence at the output there are to possibilities:

- code the input signal of the phase modulator;
- decode the output signal of the receiver.

c_{n-1}	s_n	l_{n-1}	r_n	$ln = cn$
0	0	0	0	0
0	1	0	1	1
1	0	1	0	1
1	1	1	1	0

s_n	bit to be send
c_n	*coded* bit at input modulator
c_{n-1}	previous *coded* bit at modulator
l_n	bit at input last coupler
l_{n-1}	delayed bit at coupler
r_n	received bit should be s_n

The coded signal is:

$$c_n = c_{n-1} + s_n \tag{3.7}$$

s_{n-1}	s_n	r_n	d_{n-1}	d_n
0	0	0	0	0
0	1	1	0	1
1	0	1	1	0
1	1	0	1	1

s_n signal at input modulator
s_{n-1} previous signal at modulator
r_n received signal
d_n decoded signal should be s_n
d_{n-1} previous decoded signal = s_{n-1}

The decoded signal is:

$$d_n = r_n + d_{n-1} \tag{3.8}$$

Coding and decoding is not necessary during the experiments because we use of a PRBS-sequence.

PRBS-sequences can be represented by in primitive polynoms. For example 3-, 7- and 23-bit (**PBRS!**)-sequences look as follows:

$$\begin{aligned} x^3 + x^1 &= x^0 \quad \text{3-bit PRBS sequence} && (3.9)\\ x^7 + x^1 &= x^0 \quad \text{7 bit PRBS sequence} && (3.10)\\ x^{23} + x^5 + x^1 &= x^0 \quad \text{23-bit PRBS sequence} && (3.11) \end{aligned}$$

The theory behind this is called the Galois theory ([2]).

In the formulas x^n means the bit n-bits ago, so x^1 means the previous bit and x^0 means the current bit. So in the above equations the current bit x^0 is expressed as a modulo 2 addition of previous bits.

To start an n-bits PRBS-sequence an arbitrary sequence of n bits can be taken except the sequence of all '0' 's. The number of bits after which the n-bit PRBS-sequence repeats itself is $2^n - 1$.

An example of a 3-bit PRBS sequence starting with 010:

0100111 0100111 0100111 010

$$\begin{aligned} x^3 + x = 0 + 0 &= 0\\ 1 + 0 &= 1\\ 0 + 1 &= 1\\ 0 + 1 &= 1\\ 1 + 1 &= 0\\ 1 + 0 &= 1 \end{aligned}$$

etc.

If an ex-or of two following bits in the PRBS-sequence is taken the only change is a shift in the PRBS-sequence. For example if a bit sequence of $2^7 - 1$ is taken:

$$
\begin{array}{ll}
1 & 1001101\ 0001001\ 1110001\ 0100001\ldots \\
 & \underline{1100110\ 1000100\ 1111000\ 1010000\ 1\oplus} \\
 & 0101011\ 1001101\ 0001001\ 1110001
\end{array}
$$

The same bit sequence only shifted 7 bits. It can be shown this is also true for the sequence of $2^{23} - 1$, a commonly used bit sequence in transmission experiments.

$$
\begin{aligned}
x^{23} + x^{17} &= 1 \\
\underline{x^{24} + x^{18}} &= \underline{x \quad\quad} + \\
x^{24} + x^{23} + x^{18} + x^{17} &= x + 1
\end{aligned} \tag{3.12}
$$

$$
\begin{aligned}
& x^{24} + x^{23} + x^{18} + x^{17} = x + 1 \\
\Leftrightarrow\ & (x+1)(x^{23} + x^{17}) = x + 1 \\
\Leftrightarrow\ & x^{23} + x^{17} = x + 1
\end{aligned} \tag{3.13}
$$

This means a modulo 2 addition only means a shift of the PRBS sequence. From equation 3.7 it is seen:

$$r_n = s_{n-1} + s_n$$

So the received PRBS-sequence is only delayed a number of bits. The BER-tester synchronises itself on its input sequence so the delay in the PBRS has no effect on the measurement. It can be concluded that to perform the measurement nothing has to be changed in the data sequences.

Chapter 4

Phase-noise in a link with SOA's

4.1 Phase noise

Like mentioned before, the lasers and SOA's produce phase noise. This phase-noise is caused by spontaneous emission. Due to the random character of this process the spectrum of the phase noise is Gaussian. The spectrum of the phase-noise is drawn in figure 4.1.

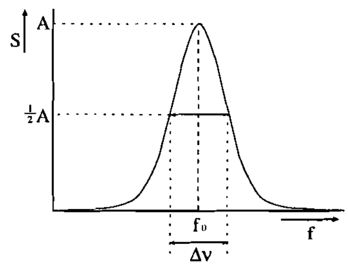


Figure 4.1: The Gaussian linewidth spectrum caused by phase noise.

The spectrum can be approximated in an equation as follows:

$$S(\omega) = E_0^2 \frac{\Delta\omega}{\left(\frac{\Delta\omega}{2}\right)^2 + (\omega_0 - \omega)^2} \tag{4.1}$$

$\Delta\omega = 2\pi\Delta\nu$

Very little investigation has been performed in the effects of the linewidth in a link with SOA's. For this reason, extensive investigation and experiments are performed to be able to describe the linewidth broadening in the link.

4.2 Laser linewidth

The linewidth of a laser can be expressed as:

$$\triangle v = \frac{R}{4\pi I}(1+\alpha_H^2) \tag{4.2}$$

This equation can be rewritten as:

$$\triangle v = \frac{v_g^2\, n_{sp}\, h\, v\,(1+\alpha_H^2)\, ln(\frac{1}{R_m})^2}{8\,\pi\, P_0\, \eta\, L^2} \propto \frac{1}{P_0} \tag{4.3}$$

This equation gives the linewidth as function of the laser power P_0. In the equation, v_g represents the group velocity and n_{sp} is the spontaneous emission factor which accounts for incomplete population inversion. The factor R_m represents the facet power reflectivity, *eta* the quantum efficiency and L the cavity length of the laser. The energy of the photons is given by $h\nu$ with h Planck's constant and ν the laser frequency.

To estimate the laser-linewidth, it is easier to rewrite 4.2 in the form:

$$\triangle v = \frac{\beta\,(1+\alpha_H^2)}{4\,\pi\,\tau_p\,(\frac{I}{I_{th}}-1)} = \frac{C}{\frac{I}{I_{th}}-1} \tag{4.4}$$

The exact values of the different device parameters seen in this equation are not known. However, an estimated guess for these values can be made.

Table 4.1: Estimated values of device parameters laser, needed to calculate laser linewidth

name	explanation	value	unit
β	spontaneous emission factor	$3\cdot10^{-5} - 1\cdot10^{-4}$	
α	linewidth enhancement factor	$3-5$	
τ_p	photon lifetime (see 4.5)	$1.26\cdot10^{12} - 1.28\cdot10^{-12}$	s
I_{th}	threshold current	$27.5\cdot10^{-3}$	A
I_{ld}	pumping current flowing to active region		A

Next, a maximum, minimum, and average linewidth can be calculated. With the estimated values C becomes:

$C_{min} = 18.7\cdot10^6$ Hz

$C_{avg} = 69.1\cdot10^6$ Hz

$C_{max} = 163.8\cdot10^6$ Hz

The photon lifetime is given by:

$$\tau_p = \frac{n}{c[\alpha_L + \frac{1}{2L}ln\frac{1}{\Gamma_1\Gamma_2}]} \cong 1.26\cdot10^{-12}\ s \tag{4.5}$$

Table 4.2: Estimated values of device parameters laser, needed to calculate photon lifetime

name	explanation	value	unit
n	refraction index	3.3	
c	light speed in vacuum	3.10^8	ms^{-1}
α_L	loss	$200 - 300$	m^{-1}
L	length of cavity	$250 \cdot 10^{-6}$	m
$\Gamma_{1,2}$	mirror reflectivity coefficients	$0.05, 0.3$	

The estimated values for the parameters are:

The values of these parameters are not exactly known so the maximal, minimal, and average value of τ_p is calculated:

$\tau_{p,min} = 1.26 \cdot 10^{-12}$ s

$\tau_{p,ave} = 1.27 \cdot 10^{-12}$ s

$\tau_{p,max} = 1.29 \cdot 10^{-12}$ s

4.3 Linewidth broadening due to SOA

The output of an SOA is in the first place an function of its input linewidth, as showed in an article by K. Hinton [3]. In this article an equation of the output linewidth of an SOA as function of the input-linewidth is derived:

The contributions to the phase noise are:

- input phase noise: phase noise induced by previous laser and SOA's;
- electron density fluctuations due to input intensity fluctuations;
- phase noise induced in amplifier due to internal spontaneous emission.

The dominant terms are the first and last, for DPSK with limited intensity noise the second term is small and may be neglected, as can be seen in [3, 4].

Using this data an equation can be derived which describes the output linewidth $\Delta\nu_{out}$ of an SOA:

$$\Delta v_{out} \cong \Delta v_{in}(1 + \frac{\pi F}{\gamma}\Delta v_{in}) \tag{4.6}$$

The first term on the right hand side of the equation merely represents the input phase noise $\Delta\nu_{in}$. The second term represents the effect of the amplifier. This is a function of the input linewidth, the spontaneous noise as expressed by F and the carrier lifetime as expressed by γ. The effects of intensity noise are neglected since the density fluctuations are neglected.

Theoretically, this equation is only usable for a laser with one amplifier because of the fact that the line shape changes form and does not stay Gaussian. Nevertheless, the change is so small that it is possible to approximate the linewidth of the signal after n amplifiers with this equation.

The spontaneous noise factor can be described as:

$$F = \left[\frac{\alpha_H G_n G_0}{\alpha_0}\right]^2 \frac{R_t L_A g^2}{2\gamma A \ln(g)} \tag{4.7}$$

The estimated values for the parameters are:

Table 4.3: Estimated values of device parameters SOA, needed to calculate linewidth broadening

name	description	value	unit
α_H	linewidth enhancement factor	$5-8$	
G_n	$=\frac{\delta G}{\delta N}$	$2.4\cdot 10^{-12}$	m^3s^{-1}
G_0	steady state material gain	calculate	s^{-1}
N	electron density in the conduction band $=\frac{\alpha_0+\kappa}{\Gamma}$		m^{-3}
α_0	steady state net gain	calculate	s^{-1}
κ	material loss	$3\cdot 10^{10}-3.75\cdot 10^{10}$	s^{-1}
Γ	optical confinement factor	0.3	
v_g	group velocity	$75\cdot 10^6$	ms^{-1}
	$=\Gamma G_0-\kappa=\frac{v_g\, ln(g)}{L}$		
R_v	average spontaneous emission rate in mode v		
n_{sp}	spontaneous emission factor	$1.3-2$	s^{-1}
	$=\frac{n_{sp}\,\alpha_0}{V}$		
R_t	average spontaneous emission rate into all guided modes	4.10	$m^{-3}s^{-1}$
L_A	cavity length SOA	$800\cdot 10^{-6}$	m
g	input to output power gain $=\exp\left(\frac{\alpha_0 L}{v_g}\right)$		
γ	inverse spontaneous carrier lifetime $=\frac{1}{\tau_c}$	$5\cdot 10^9$	s^{-1}
τ_c	spontaneous carrier lifetime	$200\cdot 10^{-12}$	s
A	cross section area of active region	$2.25\cdot 10^{-13}$	m^2
W	width of active region	$1.5\cdot 10^{-6}$	m
d	thickness of active region	$0.15\cdot 10^{-6}$	m

The factor R_t is the average spontaneous emission rate over all possible modes in the amplifier and can be derived, from the ASE-noise power P_{ASE}, as:

$$\delta P_{ASE} = h\nu n_{sp}(g-1)\delta\nu \tag{4.8}$$

The number of photons per Hz equal:

$$\frac{P_{ASE}}{h\nu} = n_{sp}(g-1) \tag{4.9}$$

The factor R_t becomes:

$$R_t = \frac{n_{sp}(g-1)B_o}{V}\overline{\eta} \tag{4.10}$$

The fraction describes the total spontaneous emission rates over all modes, with B_o the optical bandwidth and V the volume of the active region. The factor $\overline{\eta} \approx 0.24$ gives the rate between all the modes and the possible modes in the amplifier.

F can be expressed as a function of the gain like:

$$F(g) = \left[\frac{\alpha_H G_n\left(\frac{ln(g)}{L} + \kappa\right)}{\Gamma\frac{\ln(g)}{L}}\right]^2 \frac{n_{sp}(g-1)B_o g^2\overline{\eta}}{2\gamma A^2\ln(g)} \tag{4.11}$$

As can be seen, the spontaneous noise factor is only a function of the gain even in saturation. The values of G_n and α_H depend on the saturation but the product $\alpha_H \cdot G_n$ is not since:

$$\alpha_H = -\frac{4\pi}{\lambda}\frac{\frac{dn}{dN}}{\frac{dG}{dN}} \tag{4.12}$$

The factor $\frac{dn}{dN}$ is constant as function of injection current even in saturation. Which means $\alpha_H \cdot G_n$ is independent of saturation.

4.4 Measuring the linewidth

To check the equations and estimated values, a measurement has to be performed. This measurement had to be performed using the available equipment in a short time-frame. The outcome was crucial for the continuation of the project. The linewidth analysis was the first step in the investigation of the DPSK system and depending on the results, the next step, the ordering of a phase modulator was performed.

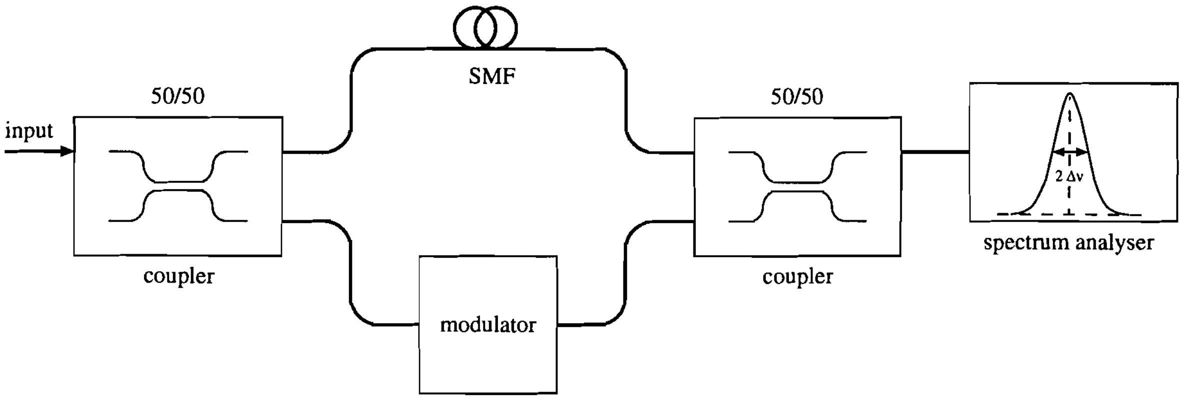


Figure 4.2: Theoretical setup for self-heterodyne linewidth measurement.

For measuring the linewidth, the spectrum of the signal has to be made visible on a spectrum analyser after which the linewidth, defined as the FWHM, can be read. The problem is that the frequency of the laser ($2.29 \cdot 10^{14}$ Hz) is too high to be measured with a spectrum analyser. The spectrum has to be shifted to a lower frequency which is in the range of the spectrum analyser.

A way to do this is self-heterodyne-detection. The scheme is drawn in figure 4.2. The idea is to modulate the signal with a lower frequency and subtract the original centre frequency so the spectrum is shifted to the modulation frequency. The signal is split at the coupler after which one signal is modulated and the other delayed. At the input of the second coupler the frequency components of the signals look like:

$$\omega(t)_1 = \omega_0 + \frac{d\Phi_1(t)}{dt} + \Omega \tag{4.13}$$

$$\omega(t)_2 = \omega_0 + \frac{d\Phi_2(t)}{dt} \tag{4.14}$$

To lose the laser frequency and just keep the low frequency signal the two signals are subtracted by the second coupler. If $\frac{d\Phi_1(t)}{dt}$ and $\frac{d\Phi_2(t)}{dt}$) are uncorrelated, in other words $\frac{d\Phi_1(t)}{dt} \neq \frac{d\Phi_2(t)}{dt}$ we get the following:

$$\begin{aligned} \omega(t) &= \Omega(t) + \frac{d\Phi_1(t)}{dt} - \frac{d\Phi_2(t)}{dt} \\ &= \Omega(t) + 2\Delta\phi(t) \end{aligned} \tag{4.15}$$

This is the desired signal with a Gaussian signal with a FWHM of 2 times the linewidth, at the centre frequency Ω.

When $\frac{d\Phi_1(t)}{dt}$ and $\frac{d\Phi_2(t)}{dt}$ are correlated, in other words $\frac{d\Phi_1(t)}{dt} = \frac{d\Phi_2(t)}{dt}$ we get:

$$\omega(t) = \Omega \tag{4.16}$$

This causes only a Dirac peak at the modulation frequency Ω.

To make sure the two signals are uncorrelated a length of fibre is placed in the upper branch of the link. This fibre has to have a minimum length to decorrelate the phase noises in the two branches:

$$\Delta\nu \cdot \tau_d > \frac{10}{2\pi} \tag{4.17}$$

Where $\Delta\nu$ is the laser linewidth and τ_d the delay in the fibre. The equation can be rewritten to determine the length (L_{fibre})of the fibre when the minimum linewidth $\Delta\nu = 1$ MHz.

$$\Delta\nu \frac{L_{fibre}}{v_{fibre}} > \frac{10}{2\pi} \tag{4.18}$$

$$L_{fibre} > \frac{10 v_{fibre}}{2\pi\Delta\nu} = \frac{10 \cdot 2 \cdot 10^8}{2\pi \cdot 10^6} = 318 \text{ m} \tag{4.19}$$

In most cases the modulation is performed by an acousto optic modulator. In our case only an intensity modulator was available.

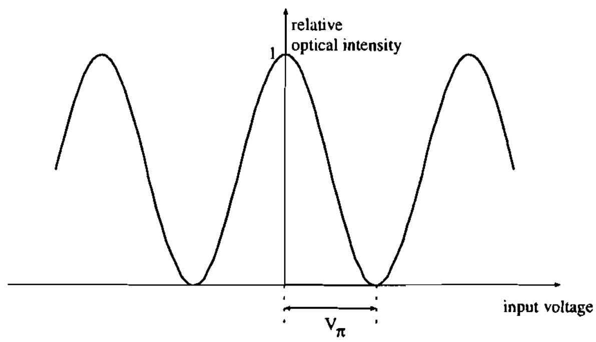


Figure 4.3: Response of the optical intensity modulator as function of the input voltage

The intensity modulator has a response as shown in figure 4.3. To get an appropriate sinusoidal signal there are two possibilities. The first is to fully modulate the modulator with a triangular signal as shown in figure 4.4. Using this method a high extinction ratio can be achieved.

The second possibility is to modulate a sinusoidal signal on a linear part of the modulator response. This method is shown in figure 4.5. The disadvantage of this method is a low extinction ratio which will cause a higher signal at DC-level and a remaining signal at the laser frequency ω_0. This causes no problem as long as the modulation frequency Ω does not come near these signals. In practice this means the modulation frequency should be chosen well above zero.

Since no function generator is available which can deliver the appropriate triangular signal the second method is used.

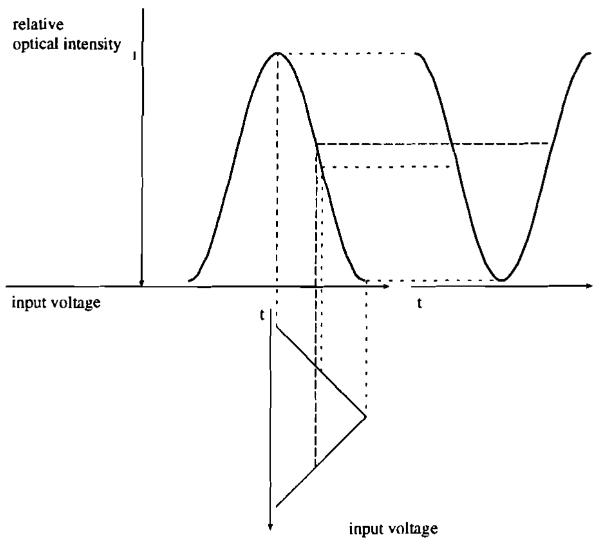


Figure 4.4: Modulation response of the intensity modulator using a triangular input signal

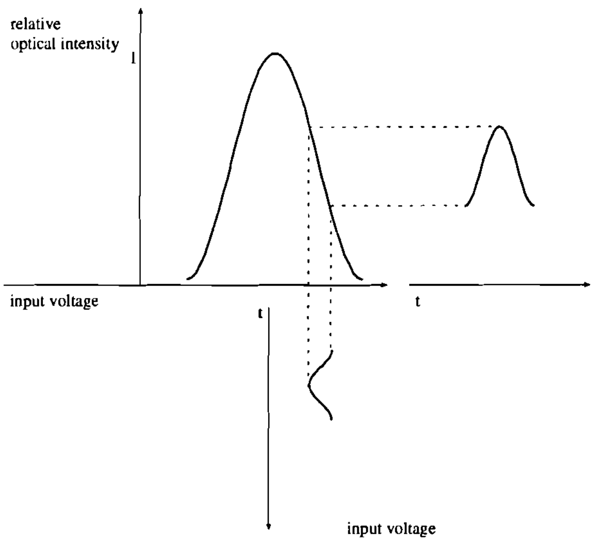


Figure 4.5: Modulation response of the intensity modulator using a sinusoidal input signal.

The measurement circuit is drawn in figure 4.6

The spectrum at the spectrum generator is described by equation 4.20.

$$S_I(\omega) \propto \frac{9}{4}\delta(\omega) + \frac{\pi}{8}\delta(\omega - \Omega) + \frac{1}{4}\frac{2\Delta\omega}{\Delta\omega^2 + \omega^2} + \frac{a}{2}\frac{2\Delta\omega}{\Delta\omega^2 + (\omega - \Omega)^2} \tag{4.20}$$

The deduction of this equation can be found in appendix A.

In the equation the different components are seen as predicted:

- The DC-component;

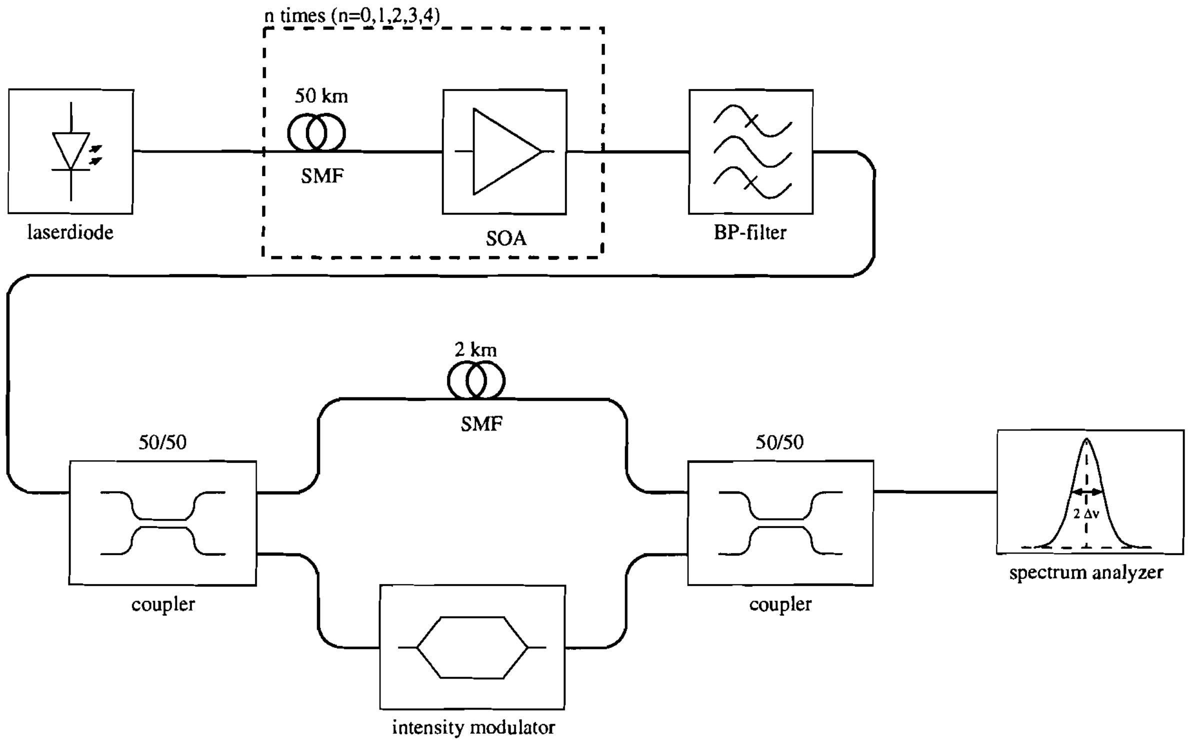


Figure 4.6: Setup of circuit to measure the linewidth of the laser-diode and the links consisting of a laser-diode and 1,2,3 or 4 SOA's

- A Gaussian signal at DC with FWHM= $2\Delta\nu$;
- A Dirac peak as residual of the modulation frequency;
- The Gaussian signal at Ω with FWHM= $2\Delta\nu$.

4.5 The measurements

The performed linewidth measurements are:

- $\Delta\nu$ of laser as function of laser output power;
- $\Delta\nu$ of laser and 1 SOA as function of laser output power;
- $\Delta\nu$ of laser and 2 SOA's as function of laser output power;
- $\Delta\nu$ of laser and 3 SOA's as function of laser output power;
- $\Delta\nu$ of laser and 4 SOA's as function of laser output power;
- $\Delta\nu$ of laser and SOA as function of the number of SOA's. (1,2,3,4) with constant input linewidth.

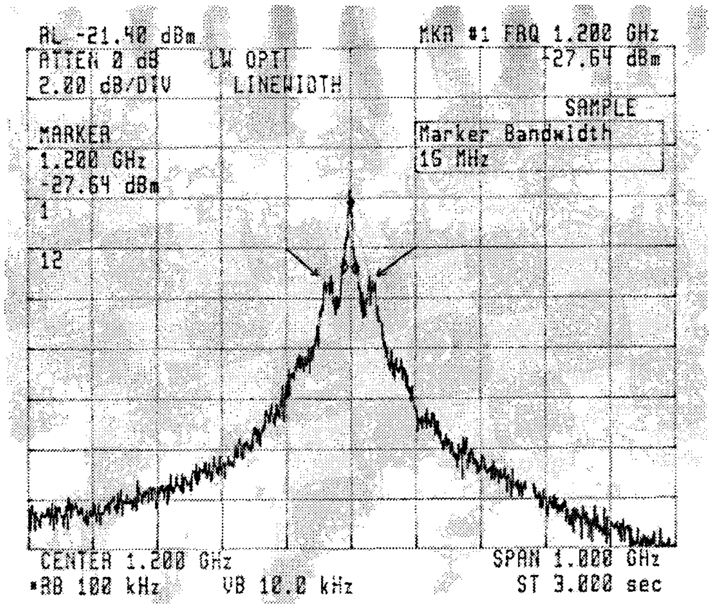


Figure 4.7: Plot of the measured optical spectrum of the laser-diode, showing two peaks due to the unwanted cavity effect in a connection

The main goal of this measurement is to determine if the derived equations where correct. The change of the linewidth after four amplifiers is very small. It lays within the maximum reachable accuracy as can be seen in last measurement.

By measuring the linewidth of the laser and SOA's as function of the laser output power a lot of data is received in one measurement. The linewidth of a laser depends on its output power. The gain of a SOA changes as function of its input power. This means as well the input linewidth as the gain of an SOA change when the output power of the laser changes. The data received in a measurement are:

- Dependence of the linewidth on the gain;
- Dependence of the linewidth on input linewidth;
- Independence of the linewidth on saturation.

The results of these measurements are found in Appendix B. All the measurements were performed twice. The first measurement is not as accurate as the second because of a problem with a connection between the laser and the rest of the circuit. In this connection a cavity was formed which caused peaks near the maximum of the optical spectrum (see figure 4.7). The occurrence of these peaks where temperature and polarisation dependent. This made accurate measurements difficult.

Between the first and second measurement the connection was fixed. Figure 4.8 shows a non-distorted spectrum of the linewidth measurement.

In figure 4.9 a measurement of the laser linewidth as function of the output power is drawn. In the figure also the calculated minimum, maximum and average linewidth, as described in 4.1, are drawn. It can be seen that the measured linewidth lies between the calculated

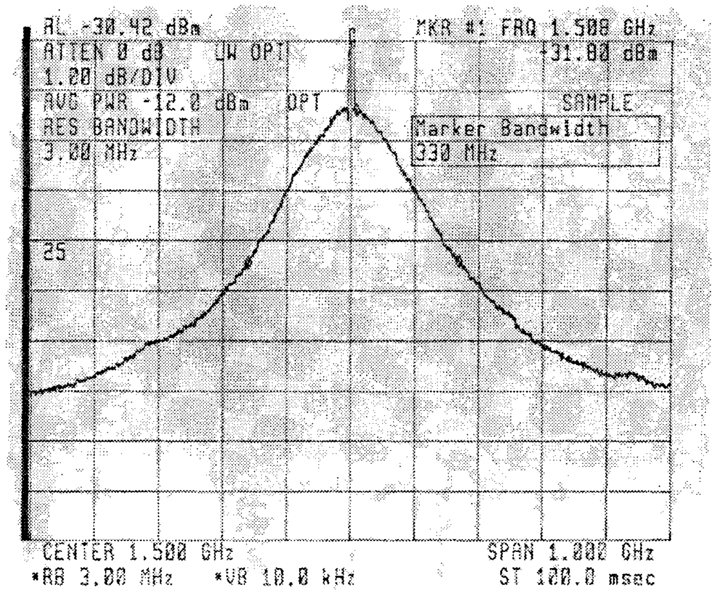


Figure 4.8: Plot of the measured optical spectrum which shows the spectrum of a link consisting of a laser-diode and 4 SOA's ($I_{ld} = 32mA$)

maximum and minimum. The last line drawn in the graph is the matched linewidth where a C-factor is determined so the calculated and measured line are as close as possible.

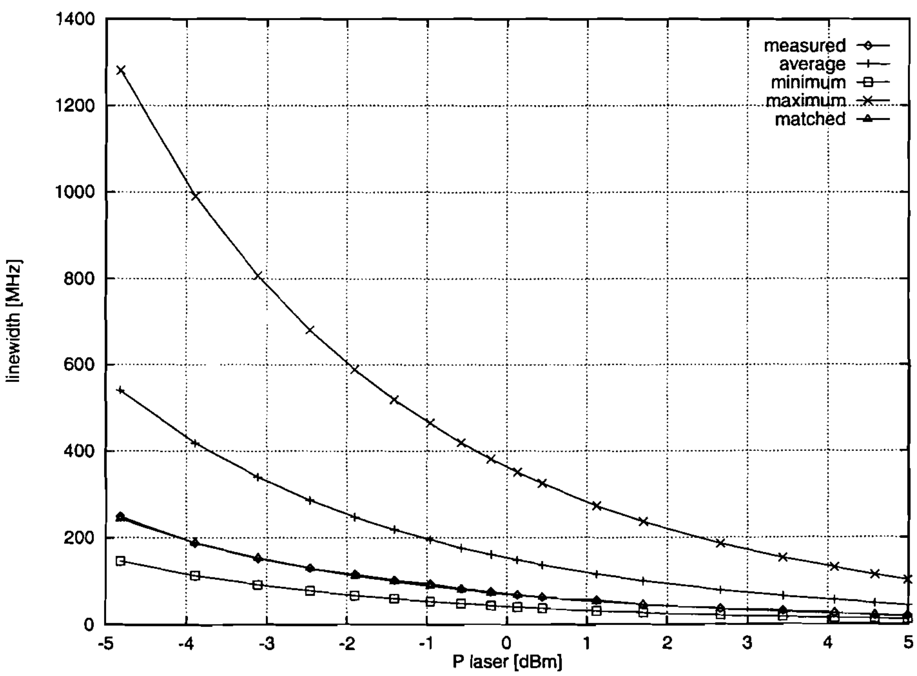


Figure 4.9: Comparison between calculation and measurement of the laser linewidth

This C-factor equals: $C = 31.2$.

In figure 4.10 the measurement of the link with 4 SOA's is drawn. Only the calculated average linewidth is drawn because the minimum, average and maximum linewidth are very close to each other. The accuracy of the measurement with SOA's is less, because the noise on the spectrum makes it more difficult to make a good readout of the linewidth. The noise is caused by ASE. It can be seen in the graph that the measured linewidth matches the calculated one with a high degree of accuracy.

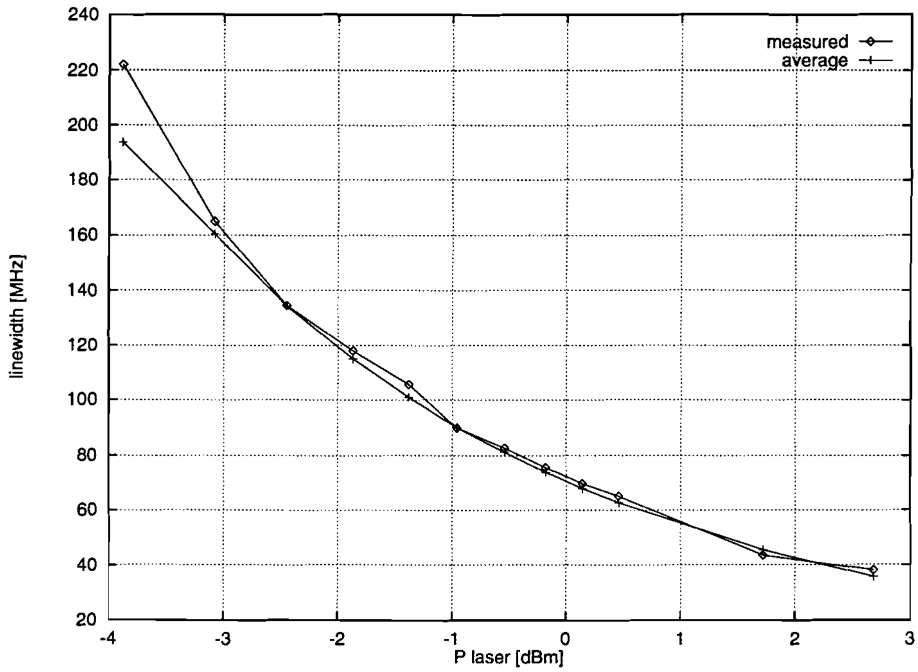


Figure 4.10: Comparison between calculation and measurement of a link consisting of a laser-diode and 4 SOA's

The error at low powers is caused by the fact that there is not enough power at the output to measure the linewidth accurately.

Looking at all measurements it is correct to assume that the calculations are correct and can be used for calculating the effect of SOA's on the linewidth.

To further inspect the calculations a simulation was performed for different linewidths keeping the amplifier gain constant. The results are plotted in the table below.

Table 4.4: Comparison between calculation and measurement of the linewidth broadening due to 1, 2, 3, and 4 SOA's

I_ld $[mA]$	$\Delta\nu_{ld}$ MHz	measured $\Delta\nu_{1SOA}$ MHz	calculated $\Delta\nu_{1SOA}$ MHz	measured $\Delta\nu_{2SOA}$ MHz	calculated $\Delta\nu_{2SOA}$ MHz	measured $\Delta\nu_{3SOA}$ MHz	calculated $\Delta\nu_{3SOA}$ MHz
40	61.93	61.95	62.06	63.50	62.10	63.45	62.22
50	35.47	38.50	35.51	38.65	35.52	38.25	35.56
60	24.85	24.15	24.87	24.95	24.87	25.15	24.89

gain amplifier 1: 20 dB

gain amplifier 2: 18.26 dB

gain amplifier 3: 20 dB

The results are close to the theoretical values, although the broadening of the linewidth by adding amplifiers cannot be seen because it lays below the accuracy of the measurement.

4.6 Effect of SOA's on the linewidth

Since the calculation of the linewidth of lasers and SOA's are correct, a number of interesting calculations can be made.

In figure 4.11 the effect of the number of amplifiers on the linewidth as function of the gain can be seen. The input linewidth is $\Delta\nu = 19$ MHz, which is the laser linewidth at $I_{ld} = 70$ mA.

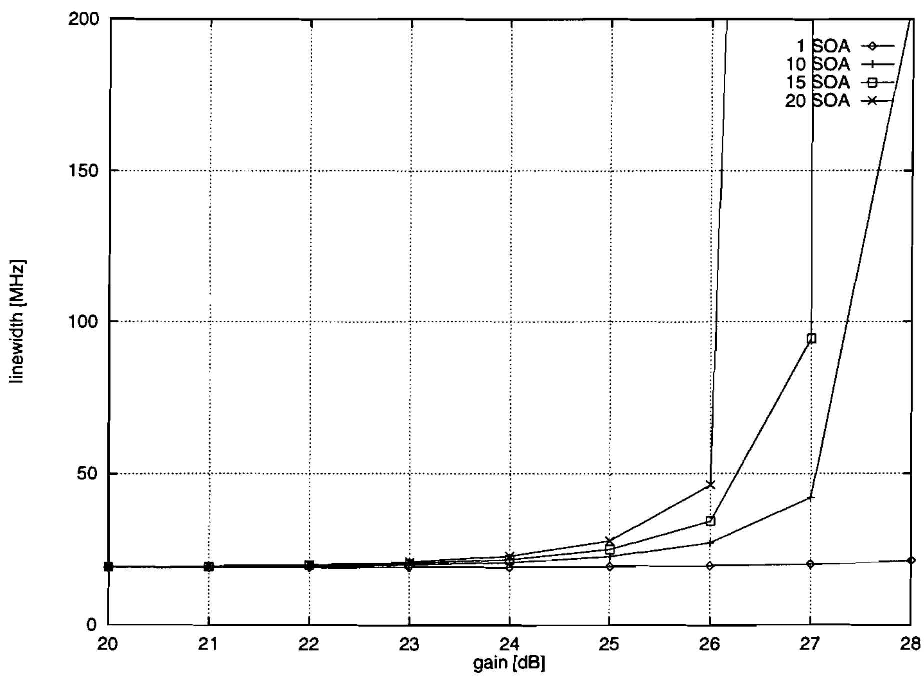


Figure 4.11: The linewidth as function of gain for a link consisting of 1, 10, 15 or 20 SOA's. The input linewidth of the link is 19 MHz.

For a balanced receiver the factor $\Delta\nu \cdot T$, which is the linewidth times the bit time, should be 0.01 (see chapter 5).

If the fibre-to-fibre gain of the SOA is assumed to be 20 dB, based on the link used for the ASK experiments with 50 km fibre segments and an average amplifier gain of 20 dB the following results can be obtained:

For an unbalanced receiver $\Delta\nu \cdot T = 0.005$ is required (see chapter 5).

In the above tables it is seen that for all except the 2.5 Gbit/s unbalanced receiver the linewidth requirements can be met for over 20 amplifiers which is a distance of a 1000 km.

Table 4.5: Number of possible amplifiers of an optical DPSK transmission system with balanced receiver, under the influence of phase-noise.

Bit rate Gbit/s	$\Delta\nu = 0.01 \cdot Bitrate[MHz]$	Number of amplifiers
2.5	25	> 20
5	50	> 20
10	100	> 20
20	200	> 20

Table 4.6: Number of possible amplifiers of an optical DPSK transmission system with balanced receiver, under the influence of phase-noise.

Bit rate Gbit/s	$\Delta\nu = 0.005 \cdot Bitrate[MHz]$	Number of amplifiers
2.5	12.5	not possible to realize
5	25	> 20
10	50	> 20
20	100	> 20

This linewidth is highly dependable on the laser used. The laser used in this experiment is a normal 2.5 Gbit/s communication laser. Lasers with a much lower linewidth are commercially available.

The length of links reported here is not the actual length which can be reached, as in this section only the effect of phase-noise is taken into account. As will be shown later in this report (chapter 6), the ASE-noise will also have an effect on the number of amplifiers which can be used.

Chapter 5

Analysing the effect of the phase-noise on a DPSK-system

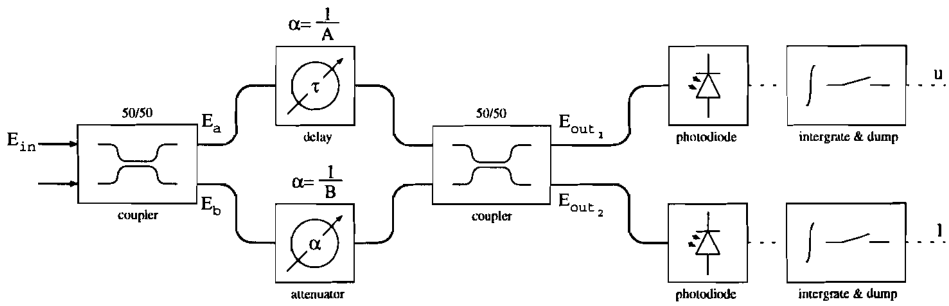


Figure 5.1: Setup of the interferometric Delay-line demodulator

As can be seen in section 3.2 E_{out_1} and E_{out_2} equal:

$$E_{out_1} = \frac{1}{2}AE_{in_1}(t-\tau) - \frac{1}{2}BE_{in_1}(t) \tag{5.1}$$

$$E_{out_2} = \frac{1}{2}AE_{in_1}(t-\tau) + \frac{1}{2}BE_{in_1}(t) \tag{5.2}$$

$$E_{in_1} = \exp(j[\omega(t) + \phi(t) + \theta(t)]) \tag{5.3}$$

With $\theta(t)$ the phase shift by the phase modulator and $\phi(t)$ the phase noise.

The photo current equals:

$$I_{pd} = \frac{\eta q}{2h\nu_0}\left|E\right|^2 \tag{5.4}$$

$$
\begin{aligned}
|E|^2 &= \left|\frac{1}{2}A\exp(j[\omega_0 t + \phi(t) + \theta(t)]) + \frac{1}{2}B\exp(j[\omega_0(t-\tau) + \phi(t-\tau) + \theta(t-\tau)])\right|^2 \\
&= \left\{\frac{1}{2}A\cos(\omega_0 t + \theta(t) + \phi(t)) + \frac{1}{2}B\cos(\omega_0(t-\tau) + \theta(t-\tau) + \phi(t-\tau))\right\}^2 \\
&+ \left\{\frac{1}{2}A\sin(\omega_0 t + \theta(t) + \phi(t)) + \frac{1}{2}B\sin(\omega_0(t-\tau) + \theta(t-\tau) + \phi(t-\tau))\right\}^2 \\
&= \frac{1}{4}A^2 + \frac{1}{4}B^2 + \frac{1}{2}AB\cos(\omega_0\tau + \theta(t) - \theta(t-\tau) + \phi(t) - \phi(t-\tau))
\end{aligned}
\tag{5.5}
$$

In this equation τ represents the delay of the delay-line which should be exactly the bit time T in which case $\omega_0\tau = n2\pi$. The factor $\theta(t) - \theta(t-\tau) = \Delta\theta$ represents the phase difference between two bits, this should be $0°$ or $180°$. The factors A and B represent the amplitude of the two fields at the input of the modulator and should be equal.

It is assumed that A=B and $\omega\tau_0 \approx 2n\pi$.

$$
|E|^2 = \frac{1}{2}A^2 + \frac{1}{2}A^2\cos(\Delta\phi(t)) + \cos(\Delta\theta(t)) + \frac{1}{2}A^2 sin(\Delta\phi(t))sin(\Delta\theta(t)) \tag{5.6}
$$

with $\Delta\phi = \phi(t) - \phi(t-\tau)$ and $\Delta\theta = \theta(t) - \theta(t-\tau)$

The BER cannot be calculated using the Gaussian approximation because this yields an inaccurate result, the Poisson approximation has to be used. A method to calculate this is the saddle point approximation method as described in [5].

5.1 The saddle point approximation method

A DPSK received signal can be expressed as (see [5]):

$$
\sum_k a_l A(t-kT)\exp(j\omega_0 t + \phi(t)) \tag{5.7}
$$

With ϕ(t) the phase noise. After detection and integration of the signal, the phase-noise can be described as:

$$
X = \int_{t-T}^{t} \exp(j\phi(t))dt \approx \int_{t-T}^{t} (1 + j\phi(t) - \frac{1}{2}\phi^2(t))dt \tag{5.8}
$$

$$
\Phi(s) = E\{\exp(sX)\} \tag{5.9}
$$

This function is called the moment generation function (mgf). The phase function can be created:

$$\varphi(s) = \ln|\Phi(s)| - \alpha_{opt}s - ln|s| \tag{5.10}$$

with α_{opt} the optimal decision threshold of the receiver.

Once the phase function $\varphi(s)$ can be determined for the balanced and unbalanced receiver the BER can be determined:

$$P_e = \frac{1}{2}q_+ + \frac{1}{2}q_- \tag{5.11}$$

with:

$$q_+ \approx \frac{\exp(\varphi(s_+)}{\sqrt{2\pi\varphi''(s_+)}} \tag{5.12}$$

$$q_- \approx \frac{\exp(\varphi(s_-)}{\sqrt{2\pi\varphi''(s_-)}} \tag{5.13}$$

The values of s_+ and s_- are determined by the positive and negative root of

$$\varphi'(s) = 0 \tag{5.14}$$

or the minima of φs. These can easily be determined by the golden routine as described in [6]. The golden routine determines the minimum of a parabolic function.

To calculate these functions a program is written which can be found in appendix C.

5.2 Unbalanced receiver

The output of the integrate and dump filter equals (see figure 5.1.

$$u = Poisson\left\{\int_0^T I_{pd}\right\} = Poisson\left\{\frac{m}{2}(1+W)\right\} \tag{5.15}$$

with W:

$$
\begin{aligned}
W &= \int_0^T \frac{1}{2}\cos(\Delta\theta(t))\cos(\Delta\phi(t)) + \frac{1}{2}\sin(\Delta\theta(t))\sin(\Delta\phi(t))dt \\
&= \int_0^T \frac{1}{2}\cos(\omega_0\tau + \Delta\theta(t))\cos(\Delta\phi(t))dt \\
&= \frac{1}{2}\cos(\Delta\theta(t))\int_0^T \cos(\Delta\phi(t))dt
\end{aligned} \tag{5.16}
$$

In the above equation it is assumed that $\Delta\theta$ is constant during the bit time T. Furthermore is is assumed that:

$$
\int_0^T \sin(\Delta\phi(t))dt = 0 \tag{5.17}
$$

The average of the phase noise $\Delta\phi$, with $\Delta\varphi$ a small value, equals zero. The interval of the integral is large enough to make the above assumption.

The deduction of the phase-function is described in [5].

$$
\begin{aligned}
\varphi(s) = &\frac{m}{2}(\exp(s)-1)(1+p) + \\
&-\frac{1}{2}\ln\left(\cosh\sqrt{\gamma mp(\exp(s)-1)}\right) + \\
&- s\alpha - ln|s|
\end{aligned} \tag{5.18}
$$

$$
\begin{aligned}
\varphi'(s) = &\frac{m}{2}\exp(s)(1+p) + \\
&-\frac{\sinh\left(\sqrt{\gamma mp(\exp(s)-1)}\right)\sqrt{\gamma mp}\cdot\exp(s)}{4\sqrt{\exp(s)-1}\cdot\cosh\left(\sqrt{\gamma mp(\exp(s)-1)}\right)} + \\
&-\alpha - \frac{1}{s}
\end{aligned} \tag{5.19}
$$

$$
\begin{aligned}
\varphi''(s) = &\frac{m}{2}\exp(s)(1+p) - \frac{\gamma mp\exp(2s)}{8(\exp(s)-1)} + \\
&+\frac{\sinh\left(\sqrt{\gamma mp(\exp(s)-1)}\right)\sqrt{\gamma mp}\cdot\exp(2s)}{8(\exp(s)-1)^{\frac{3}{2}}\cosh\left(\sqrt{\gamma mp(\exp(s)-1)}\right)} + \\
&-\frac{\sinh\left(\sqrt{\gamma mp(\exp(s)-1)}\right)\sqrt{\gamma mp}\cdot\exp(s)}{4\sqrt{\exp(s)-1}\cdot\cosh\left(\sqrt{\gamma mp(\exp(s)-1)}\right)} + \\
&+\frac{\sinh^2\left(\sqrt{\gamma pm(\exp(s)-1)}\right)\gamma mp\exp(2s)}{8(\exp(s)-1)\cosh^2\left(\sqrt{\gamma mp(\exp(s)-1)}\right)} + \frac{1}{s^2}
\end{aligned} \tag{5.20}
$$

with:

$$p = \cos(\Delta\theta)$$

$$m = \frac{\eta T}{2h\nu_0} A^2$$

The factor m is equivalent to the number of photons arriving at the photo-detector in one bit time. For the calculation of the BER curve not only q_+ and q_- have to be calculated as function of m, but also the optimal decision threshold α_{opt}. The BER is a parabolic function with respect to α_{opt}. The minimum of the BER determines the optimal threshold value. The calculation of this value can be done with the golden routine already realised in the program to calculate the minimum of φ.

Figure 5.2 shows the BER of a system with an ideal delay and modulator. The BER for different values of $\Delta\nu$ are calculated.

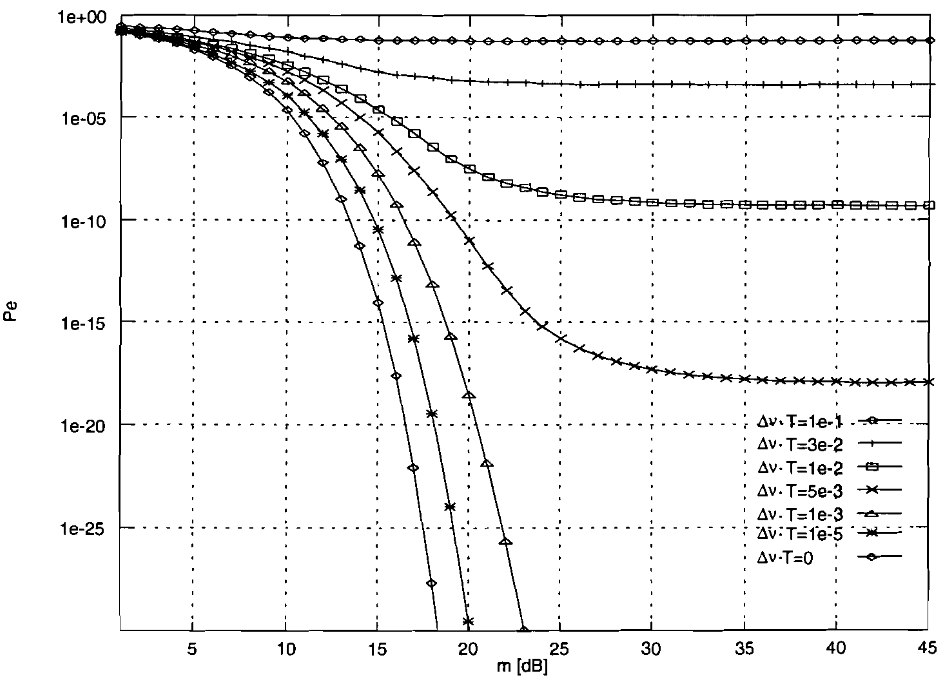


Figure 5.2: The BER of a unbalanced receiver under the influence of phase noise

Two problems which can occur are a phase shift at the modulator of less than 180° and a delay which is not equal to the bit time.

Simulations are performed to see the effect of these problems. In figure 5.3 the effects of an incomplete phase shift are seen, in figure 5.4 the effect of a non ideal delay.

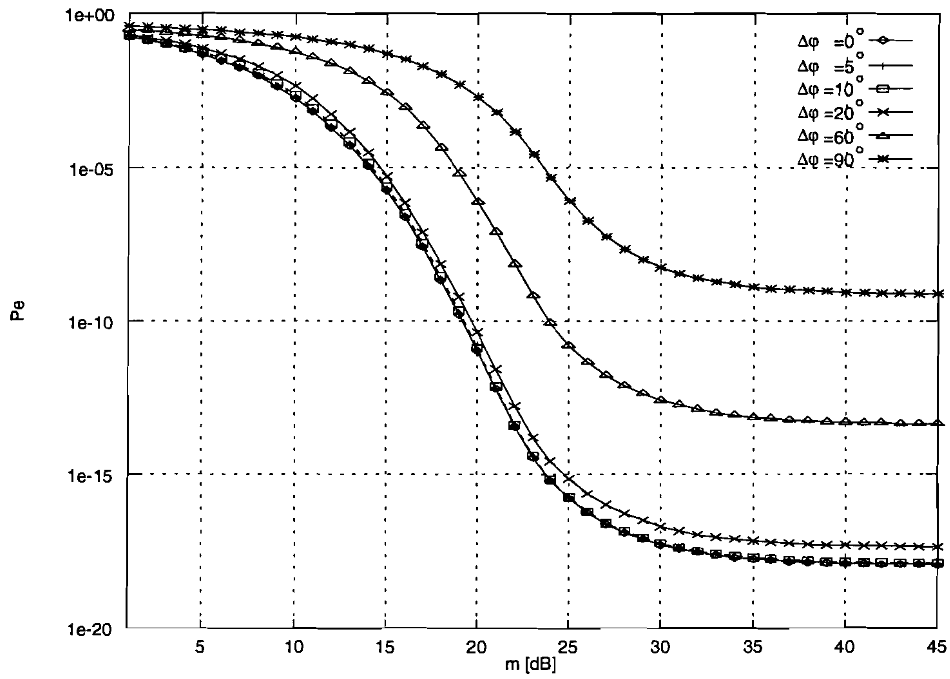


Figure 5.3: The BER of a unbalanced receiver under the influence of phase-noise and an incomplete phase shift at the modulator. Calculated for $\Delta\nu = 5 \cdot 10^{-3}$.

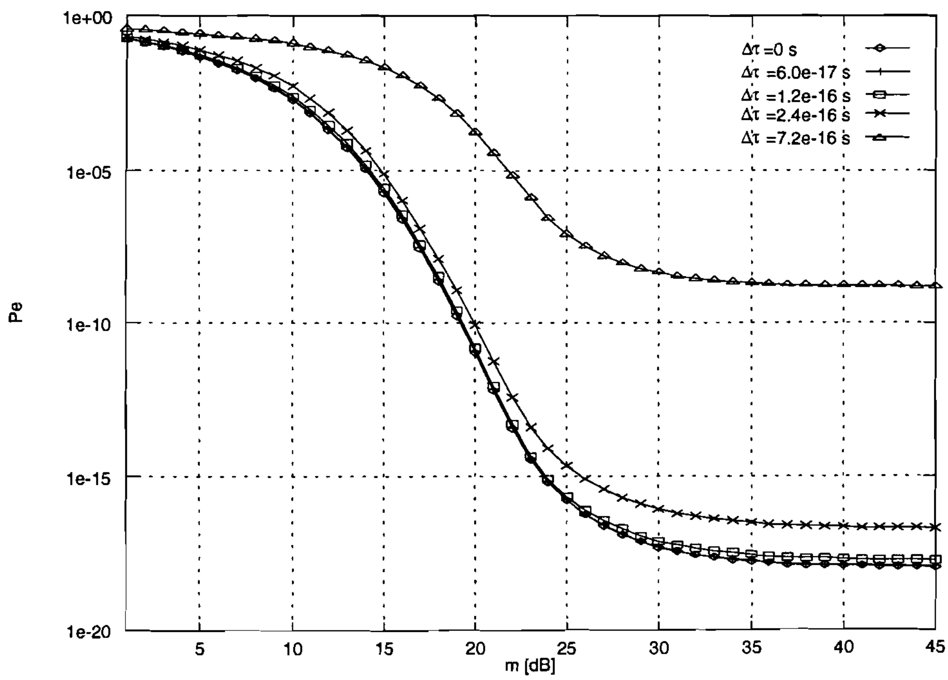


Figure 5.4: The BER of a unbalanced receiver under the influence of phase-noise and an incorrect delay at the demodulator. Calculated for $\Delta\nu = 5 \cdot 10^{-3}$.

5.3 Balanced receiver

The first and second output of the integrate and dump filter equal (see figure 5.1):

$$u = Poisson\left\{\int_0^T \frac{\eta q}{2h\nu_0}|E_{out_1}|^2\right\} = Poisson\left\{\frac{m}{2}(1+W)\right\} \tag{5.21}$$

$$l = Poisson\left\{\int_0^T \frac{\eta q}{2h\nu_0}|E_{out_2}|^2\right\} = Poisson\left\{\frac{m}{2}(1-W)\right\} \tag{5.22}$$

with W:

$$W = \frac{1}{2}\cos(\Delta\theta(t))\int_0^T \cos(\Delta\phi(t))dt \tag{5.23}$$

The phase function becomes [5]:

$$\begin{aligned}\varphi(s) &= \frac{m}{2}(\exp(s) - 2 + \exp(-s)) + \\ &+ \frac{1}{2}mp(\exp(s) - \exp(-s)) + \\ &- \frac{1}{2}\ln\left|\cosh\left(\sqrt{\gamma mp(\exp(s)-1)}\right)\right| - \ln|s|\end{aligned} \tag{5.24}$$

$$\begin{aligned}\varphi'(s) &= \frac{1}{2}m(\exp(s) - \exp(-s)) + \frac{1}{2}mp(\exp(s) + \exp(-s)) + \\ &- \frac{\sinh\left(\sqrt{\gamma mp(\exp(s)-1)}\right)\sqrt{\gamma mp}\cdot\exp(s)}{4\sqrt{\exp(s)-1}\cdot\cosh\left(\sqrt{\gamma mp(\exp(s)-1)}\right)} + \\ &+ \frac{\sinh\left(\sqrt{-\gamma mp(\exp(-s)-1)}\right)\sqrt{-\gamma mp}\cdot\exp(s)}{4\sqrt{\exp(-s)-1}\cdot\cosh\left(\sqrt{-\gamma mp(exp(-s)-1)}\right)} - \frac{1}{s}\end{aligned} \tag{5.25}$$

$$\begin{aligned}
\varphi''(s) = & \frac{1}{2}m(\exp(s) + \exp(-s) + \frac{1}{2}pm(\exp(s) - \exp(-s)) + \\
& - \frac{\gamma mp \exp(2s)}{8(\exp(s) - 1)} + \frac{\sinh\left(\sqrt{\gamma mp(\exp(s) - 1)}\right)\sqrt{\gamma mp} \cdot \exp(2s)}{8(\exp(s) - 1)^{\frac{3}{2}} \cosh\left(\sqrt{\gamma mp(\exp(s) - 1)}\right)} + \\
& - \frac{\sinh\left(\sqrt{\gamma mp(\exp(s) - 1)}\right)\sqrt{\gamma mp} \cdot \exp(s)}{4\sqrt{\exp(s) - 1} \cdot \cosh\left(\sqrt{\gamma mp(\exp(s) - 1)}\right)} + \\
& + \frac{\sinh^2\left(\sqrt{\gamma mp(\exp(s) - 1)}\right)\gamma mp \exp(2s)}{8(\exp(s) - 1)\cosh\left(\sqrt{\gamma mp(\exp(s) - 1)}\right)} + \\
& + \frac{\gamma mp \exp(-2s)}{8(\exp(-s) - 1)} - \frac{\sinh\left(\sqrt{-\gamma mp(\exp(s) - 1)}\right)\sqrt{-\gamma mp} \cdot \exp(-2s)}{8(\exp(-s) - 1)^{\frac{3}{2}} \cosh\left(\sqrt{-\gamma mp(\exp(-s) - 1)}\right)} + \\
& - \frac{\sinh\left(\sqrt{-\gamma mp(\exp(-s) - 1)}\right)\sqrt{-\gamma mp} \cdot \exp(-s)}{4\sqrt{\exp(-s) - 1} \cdot \cosh\left(\sqrt{-\gamma mp(\exp(-s) - 1)}\right)} + \\
& - \frac{\sinh^2\left(-\sqrt{\gamma mp(\exp(-s) - 1)}\right)\gamma mp \exp(-2s)}{8(\exp(-s) - 1)\cosh\left(\sqrt{-\gamma mp(\exp(-s) - 1)}\right)} + \frac{1}{s^2}
\end{aligned} \tag{5.26}$$

with

$$p = \cos(\Delta\theta)$$

$$m = \frac{\eta q T}{2h\nu_0} A^2$$

The decision threshold α_{opt} is always zero for a balanced receiver, it does not appear in the equations for $\varphi(s)$.

The simulation result of the system with ideal phase modulation and delay can be found in figure 5.5.

For the simulations including the phase and delay error see the figures 5.6 and 5.7.

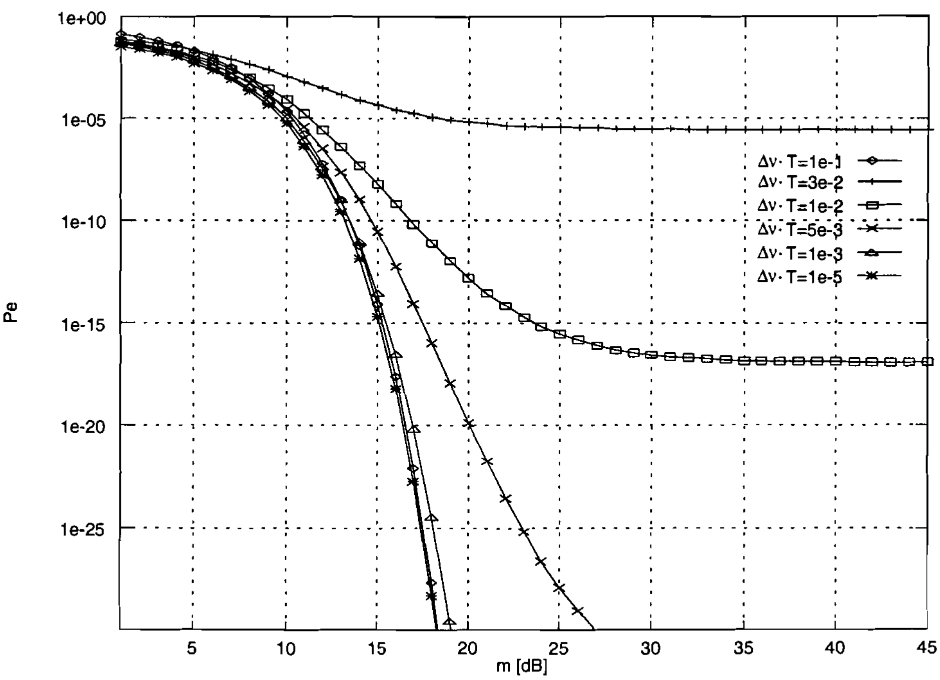


Figure 5.5: The BER of a balanced receiver under the influence of phase noise

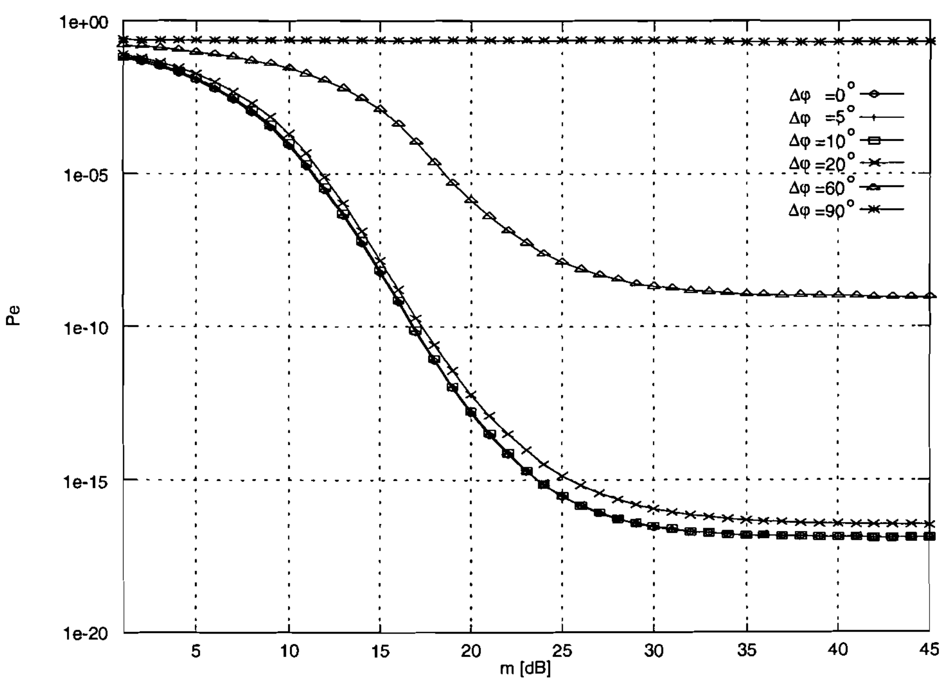


Figure 5.6: The BER of a balanced receiver under the influence of phase-noise and an incomplete phase shift at the modulator. Calculated for $\Delta\nu = 5 \cdot 10^{-3}$.

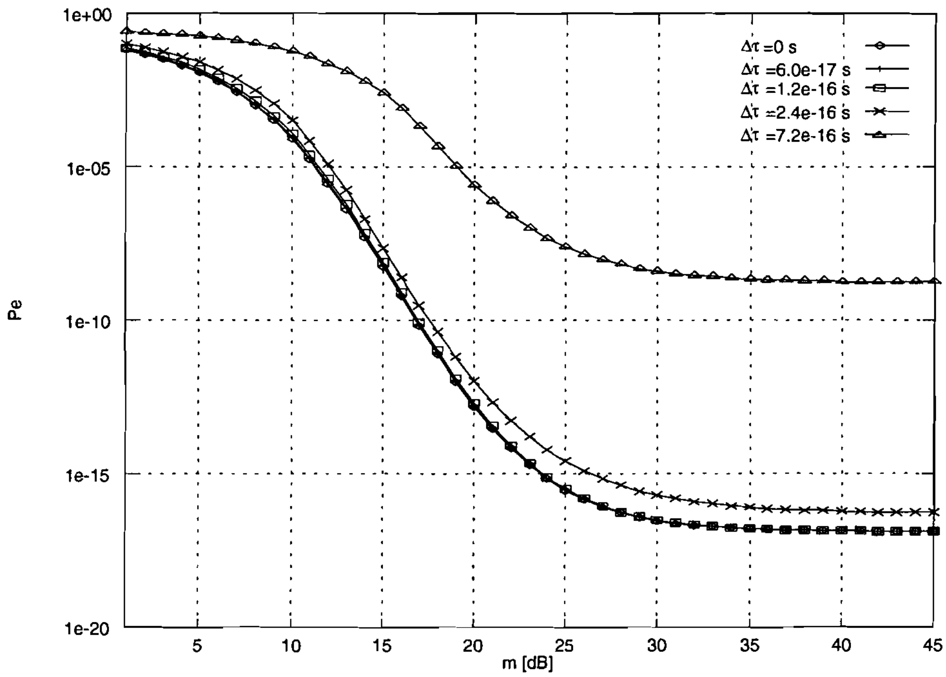


Figure 5.7: The BER of a unbalanced receiver under the influence of phase-noise and an incorrect delay at the demodulator. Calculated for $\Delta\nu = 5 \cdot 10^{-3}$.

5.4 Results of the phase noise simulations

Due to the phase noise a BER-floor is formed. The level of this floor is a function of the factor $\Delta\nu \cdot T$. The factor $\Delta\nu \cdot T$ represents the phase shift per second times the time in which the phase should stay constant to get an ideal detection.

The use of an unbalanced receiver means 3 dB less receiver sensitivity and a factor of $\Delta\nu \cdot T$ which should be smaller than 0.005. For the balanced receiver the same factor $\Delta\nu \cdot T$ only has to be less than 0.01. The same value as can be found in literature.

For the previous values a BER-floor of 10^{-18} is reached; this means a large safety margin is taken as opposed to the demanded BER of 10^{-9}. This is done because the simulation only accounts for phase noise and not for ASE (chapter 6), electrical noise and other neglected noise sources.

As can be seen in the figures 5.3 and 5.3 a phase error of 20° is acceptable. For the phase modulator it means a reasonable error is permitted. Even the non-flat FM response of the phase modulator will hardly effect the BER.

In the delay-line an error of $1.2 \cdot 10^{-16}$ for the unbalanced and $2.4 \cdot 10^{-16}$ for the balanced receiver are acceptable, as can be seen in the figures 5.4 and 5.7.

The minimum delay error means the distance in the delay line (in air) must be stable:

For an acceptable delay ($\Delta\tau$) the stability of the delay-line can be expressed in a distance (Δs) of the air gap:

$$\Delta s = \Delta\tau \cdot \nu$$

Table 5.1: Permitted errors in phase modulator and delay line demodulator

	$\Delta\tau$ [s]	Δs [nm]	$\Delta\varphi$ [°]
unbalanced	$1.2 \cdot 10^{-16}$	36	10
balanced	$2.4 \cdot 10^{-16}$	72	20

Chapter 6

Simulations incorporating ASE-noise

ASE-noise is caused by spontaneous emission in the amplifier. This emission will cause stimulated emission so amplifying the noise. The spontaneous emission is a stochastic process where an electron drops from a high to a low energy band emitting a photon. The frequency is determined by $\nu = \frac{E_g}{h}$, with E_g the energy gap between the conduction and valence band. Because the drop can occur over a wide range of energies and the lack of a filter in the SOA the noise has a large bandwidth. In figure 6.1 an example of two ASE-spectra can be seen. The peak is caused by an externally injected signal.

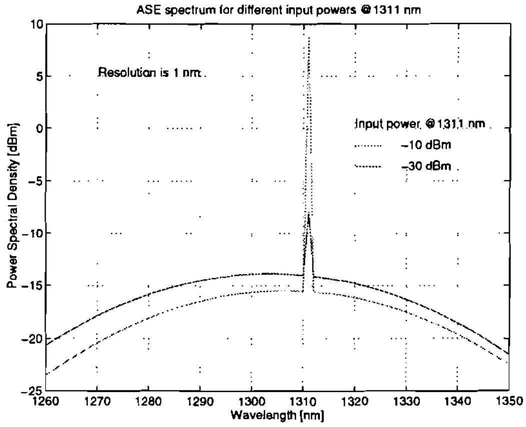


Figure 6.1: An example of the ASE-noise spectrum for to different input powers of the SOA.

A number of articles have been written about ASE-noise in a link with SOA's. An important article is written by Olsen [7]. The simulations, are based on this theory.

First, the output of the DPSK-demodulator with ASE-noise is calculated (see figure 6.2

For the 3dB coupler the following formula can be derived:

$$\begin{pmatrix} E_{out_1} \\ E_{out_2} \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & \exp(j\frac{\pi}{2}) \\ \exp(j\frac{\pi}{2}) & 1 \end{pmatrix} \cdot \begin{pmatrix} E_{in_1} \\ E_{in_2} \end{pmatrix} \tag{6.1}$$

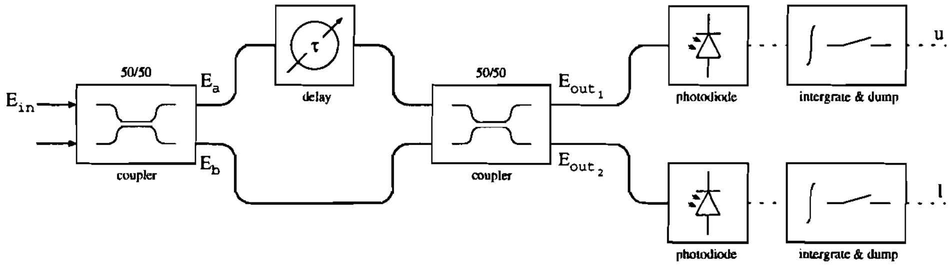


Figure 6.2: Setup of the interferometric Delay-line demodulator.

Like can be seen in figure 6.2 the loss in the upper and lower branch of the demodulator is assumed to be zero. The factor n_{sp} is the stochastic signal which describes the ASE-noise.

$$E_a = \frac{1}{\sqrt{2}}E_{in_1}(t) + \frac{1}{\sqrt{2}}n_{sp}(t) \tag{6.2}$$

$$E_b = \frac{1}{\sqrt{2}}E_{in_1}(t)\exp(j\frac{\pi}{2}) + \frac{1}{sqrt2}n_{sp}(t) \tag{6.3}$$

$$\begin{aligned} E_{out_1} &= \frac{1}{\sqrt{2}}E_a(t-\tau) + \frac{1}{\sqrt{2}}E_b(t)\exp\left(j\frac{\pi}{2}\right) \\ &= \frac{1}{2}E_{in_1}(t-\tau) + \frac{1}{2}E_{in_1}(t)\exp(j\pi) + \frac{1}{2}n_{sp}(t-\tau) + \frac{1}{2}n_{sp}(t)\exp(j\pi) \\ &= \frac{1}{2}E_{in_1}(t-\tau) - \frac{1}{2}E_{in_1} + \frac{1}{2}n_{sp}(t-\tau) - \frac{1}{2}n_{sp}(t) \\ &= \frac{1}{2}E_{in_1}(t-\tau) - \frac{1}{2}E_{in_1} + n_{sp}(t) \end{aligned} \tag{6.4}$$

$$\begin{aligned} E_{out_2} &= \frac{1}{\sqrt{2}}E_a(t-\tau)\exp\left(j\frac{\pi}{2}\right) + \frac{1}{\sqrt{2}}E_b(t-\tau) \\ &= \frac{1}{2}E_{in_1}(t-\tau)\exp\left(j\frac{\pi}{2}\right) + \frac{1}{2}E_{in_1}\exp\left(j\frac{\pi}{2}\right) \\ &= \frac{1}{2}E_{in_1}(t-\tau)\exp\left(\frac{j\pi}{2}\right) + \frac{1}{2}E_{in_1}\exp\left(j\frac{\pi}{2}\right) + \\ &+ \frac{1}{2}n_{sp}(t-\tau)\exp\left(\frac{j\pi}{2}\right) + \frac{1}{2}n_{sp}(t)\exp\left(j\frac{\pi}{2}\right) \\ &= \frac{1}{2}E_{in_1}(t-\tau) + \frac{1}{2}E_{in_1} + n_{sp}(t) \end{aligned} \tag{6.5}$$

The random signals $n_{sp}(t)$ and $n_{sp}(t-\tau)$ are independent, this means $\frac{1}{2}n_{sp}(t) + \frac{1}{2}n_{sp}(t-\tau) = n_{sp}(t)$.

The current i after the photo-detector equals:

$$\begin{aligned} i &= \frac{q}{h\nu}\overline{E^2} + n_{shot} \\ &= \frac{q}{h\nu}\overline{E_s^2 + E_s n_{sp} + n_{sp}n_{sp}} + n_{shot} \\ &= E + E_s n_{sp} + n_{sp}n_{sp} + n_{shot} \end{aligned} \tag{6.6}$$

The photo-current is build out of the signal E_s, the signal-spontaneous beat-noise $E_s n_{sp}$, the spontaneous-spontaneous beat-noise n_{sp} and the shot-noise n_{shot}.

The average signal power in the receiver is:

$$S = \left(G\frac{P_s q}{h\nu}\eta_{in}\eta_{out}L_s\alpha_L\right)^2 \qquad (6.7)$$

The variable G describes the fibre to fibre gain, P_s the signal power at the input of the amplifier, η_{in} and η_{out} the input and output coupling efficiencies. The loss of the fibre segment before the amplifier is described by $L_s\alpha_L$, with L_s the fibre length and α_L the loss per meter of the fibre.

The total average noise power in the receiver is:

$$N_{tot} = N_{shot} + N_{s-sp} + N_{sp-sp} \qquad (6.8)$$

With $N_s hot$ the shot-noise, N_{s-sp} the signal spontaneous beat-noise and N_{sp-sp} the spontaneous spontaneous beat-noise, described by:

$$N_{shot} = 2B_e q\eta_{out}\alpha_L\left(G\frac{P_s q}{h\nu}\eta_{in} + \frac{P_{sp}q}{h\nu}\right) \qquad (6.9)$$

$$N_{s-sp} = 4G\frac{P_s q}{h\nu}\eta_{in}\eta_{out}\alpha_L^2\frac{B_e}{B_0} \qquad (6.10)$$

$$N_{sp-sp} = \left(\frac{P_{sp}q}{h\nu}\alpha_L\right)^2 B_e\frac{2B_o - B_e}{B_0^2} \qquad (6.11)$$

In these equations B_e is the electrical bandwidth, B_o the optical bandwidth and P_{sp} the ASE-noise power of the amplifier. For the BER calculation with the ASE-noise the Gaussian approximation can be used.

$$P_e = \frac{1}{2}erfc\left(\frac{Q}{\sqrt{2}}\right) \qquad (6.12)$$

The erfc function, is the complementary error function of Q, with:

$$Q = \frac{\sqrt{S(1)} - \sqrt{S(0)}}{\sqrt{N_{tot}(1)} + \sqrt{N_{tot}(0)}} \qquad (6.13)$$

$S(1)$	: signal power for logical '1'
$S(0)$	: signal power for logical '0'
$N_{tot}(1)$	: noise power for logical '1'
$N_{tot}(0)$	: noise power for logical '0'

6.1 The simulations

The simulation program (Appendix D) calculates the Q factor as function of the signal power per bit time m. For the simulation of a link with a number of amplifiers it is assumed that the loss in the fibre equals the gain of the amplifiers. Although this is a simplification, it still shows the effects of the ASE-noise and gives an idea of the number of amplifiers which can be used. The same assumption was made when the number of amplifiers as function of the phase-noise was calculated (see section 4.6).

An important effect of saturation is in this case a decrease of the gain, this is not taken into account in the simulations. To get realistic results the input power is chosen such that saturation does not occur.

6.1.1 Balanced receiver

For the balanced receiver the average signal powers for '1' and '0' equal:

$$S(1) = \frac{1}{2}S \tag{6.14}$$

$$S(0) = -\frac{1}{2}S$$

The simulation is performed for input powers of the first amplifier of -15 dBm and -10 dBm. Both values are realistic, although for the second value a preamplifier has to be used or the first section of fibre in the link has to be shortened. The first simulation is seen in figure 6.3 and the second in 6.4.

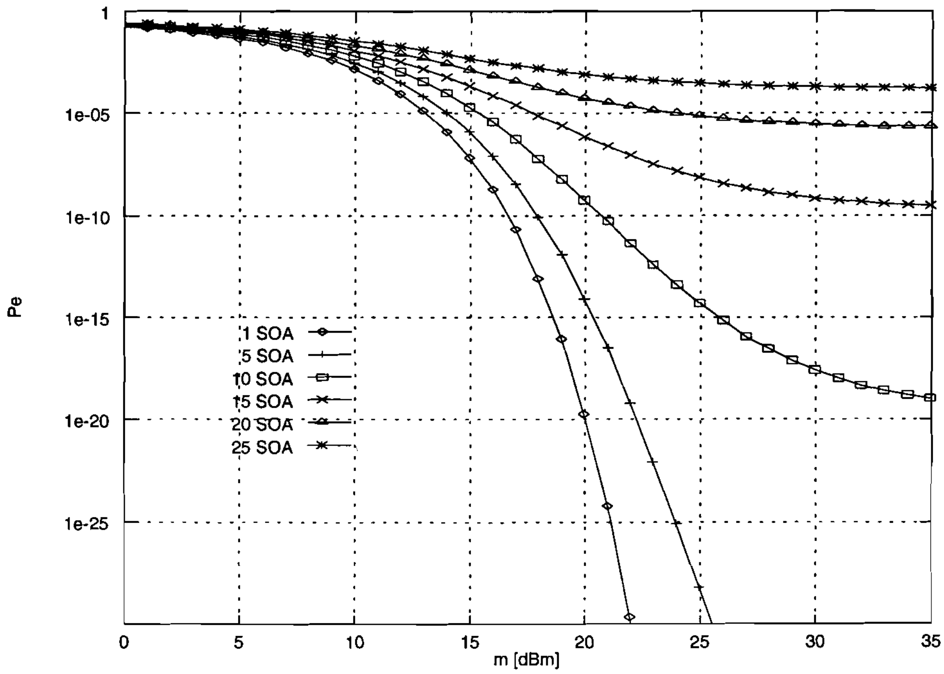


Figure 6.3: BER of a balanced receiver under the influence of ASE- noise. The input power of the link is: $P_{in_{soa1}} = -15$ dBm.

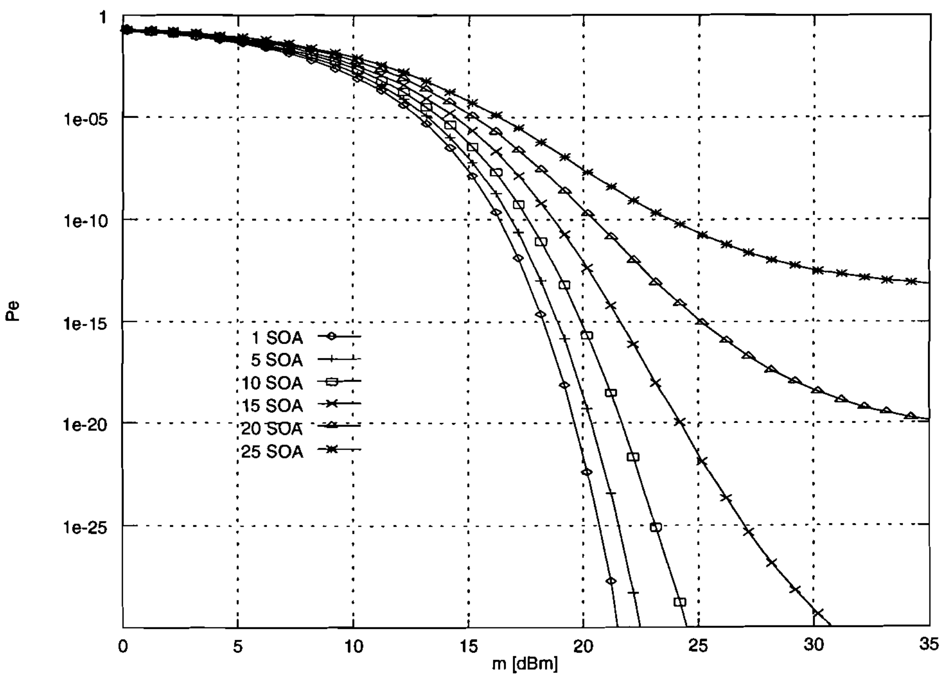


Figure 6.4: BER of a balanced receiver under the influence of ASE- noise. The input power of the link is: $P_{in_{soa1}} = -10$ dBm.

6.1.2 Unbalanced receiver

For the unbalanced receiver the average signal powers for '1' and '0' equal:

$$S(1) = \frac{1}{2}S \qquad (6.15)$$

$$S(0) = 0$$

The simulation is also performed for the input power of the first amplifier of -15 dBm and -10 dBm. The first simulation is seen in figure 6.5 and the second in 6.6.

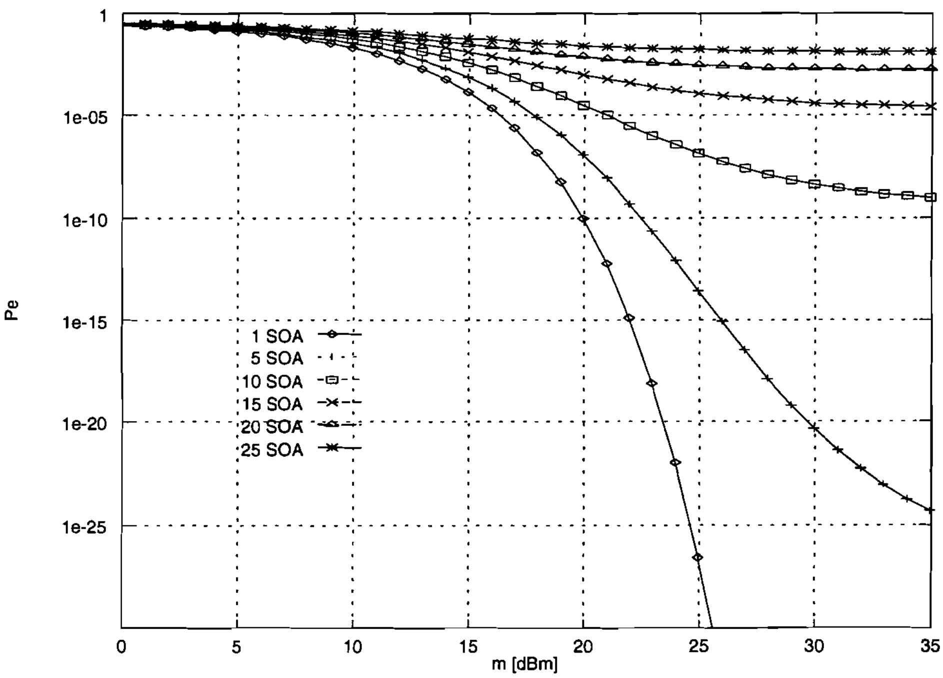


Figure 6.5: BER of an unbalanced receiver under the influence of ASE- noise. The input power of the link is: $P_{in_{soa1}} = -15$ dBm.

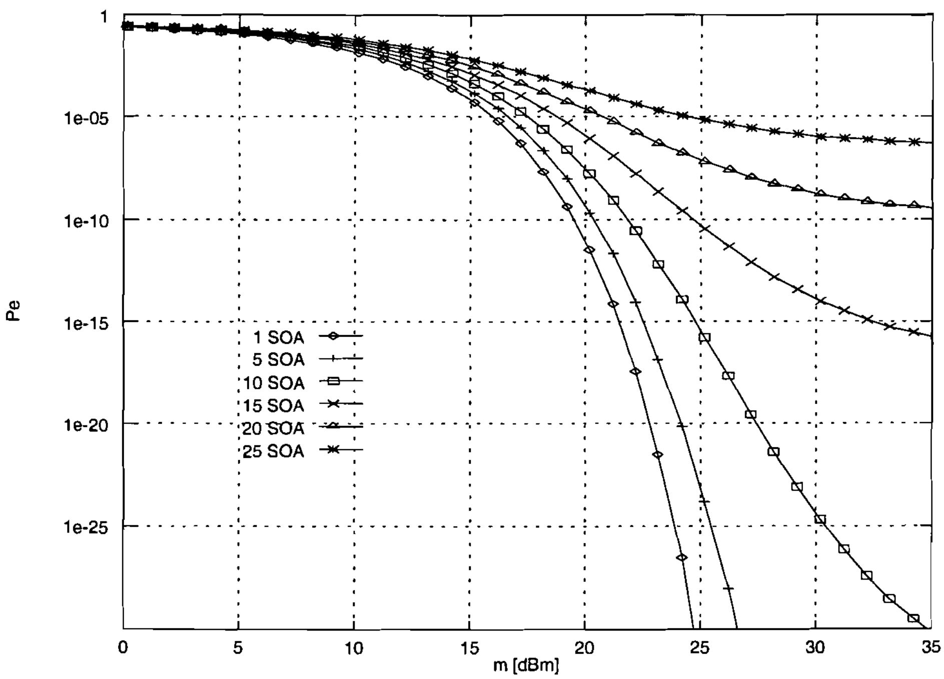


Figure 6.6: BER of an unbalanced receiver under the influence of ASE- noise. The input power of the link is: $P_{in_{soa1}} = -10$ dBm.

6.1.3 Simulation results

The results of the balanced receiver are better than the unbalanced receiver which is expected due to the better signal to noise ratio of the balanced receiver. Secondly, a higher input signal power improves the BER-curves also due to a higher signal to noise ratio.

As can be seen in figure 6.4 a link of at least 20 SOA's can be made using a balanced receiver and 15 (see figure 6.6) using the unbalanced one. Taking the floor 10^9 below the desired 10^{-9} to be on the save side.

The results can be improved by increasing the signal because for higher signal powers the amplifiers will saturate and the gain of the different amplifiers in the link will not be equal. In the simulation program it is assumed the gain of all programs is the same and equal to the loss in the fibres.

Comparing the limit of SOA's due to the phase-noise (section 4.6) and the ASE, it can be seen that it is not predetermined which noise will limit the number of amplifiers and thus the length of the link.

In a real link saturation will occur. Due to saturation the gain will decrease. This has the positive effect that the ASE-noise will decrease but the negative effect that the signal is amplified less.

If the signal power budget at the input of the link is high enough so the decrease in amplification of the signal does not matter, saturation will have a positive effect. But it is also possible that due to the saturation of the SOA the amplification of the signal will become to low. When the last occurs bandpass filters can be placed in the link, to decrease the ASE-noise power, but the filters also have a loss in the passband.

Chapter 7

Simulation of the DPSK transmission system

To be able to simulate the system with ASE and phase noise taken into account, a different approach is needed. It is not yet possible to calculate the DPSK-system with ASE-noise and phase-noise analytically with the saddle point approximation used in section 5.1 the mgf of

$$\int_0^T \frac{1}{2} \cos\left(\Delta\Phi(t)\right) dt \tag{7.1}$$

is calculated. This can only be done for small values of $\Delta\Phi(t)$ and not for the phase of the ASE-noise. The trick is to find the mgf of equation 7.1 which also applies for great values of $\Delta\Phi$. Work on finding this expression is in progress.

To be able to calculate the BER of the DPSK system with ASE and phase-noise, a different approach is taken. The system is simulated *bit* by *bit*. A very big disadvantage of this method is that the simulations are heavily time consuming. For calculating a BER of 10^{-9} at least 5 times 10^9 bits have to be calculated to get a reasonable result. A calculation of a factor of 10^{-9} takes about 72 hours on a Pentium at 166 MHz.

The structure of the calculation looks like:

1. Calculate the output signal power P_s, ASE-noise power P_{ASE} and linewidth $\Delta\nu$ after the link (at the input of the demodulator).
2. Calculate one bit out of the PRBS sequence.
3. Add phase noise.
4. Add ASE noise.
5. Calculate photo current adding the shot-noise.
6. Determine what bit was sent and if it is received correctly

This calculation is done recursively counting the number of bits needed for five errors. The BER equals five divided by the number of bits. Doing this for different values of the input signal power per bit m a BER-curve is calculated.

A flowchart of the program is shown in figure 7.1. The source code of the program can be found in Appendix E.

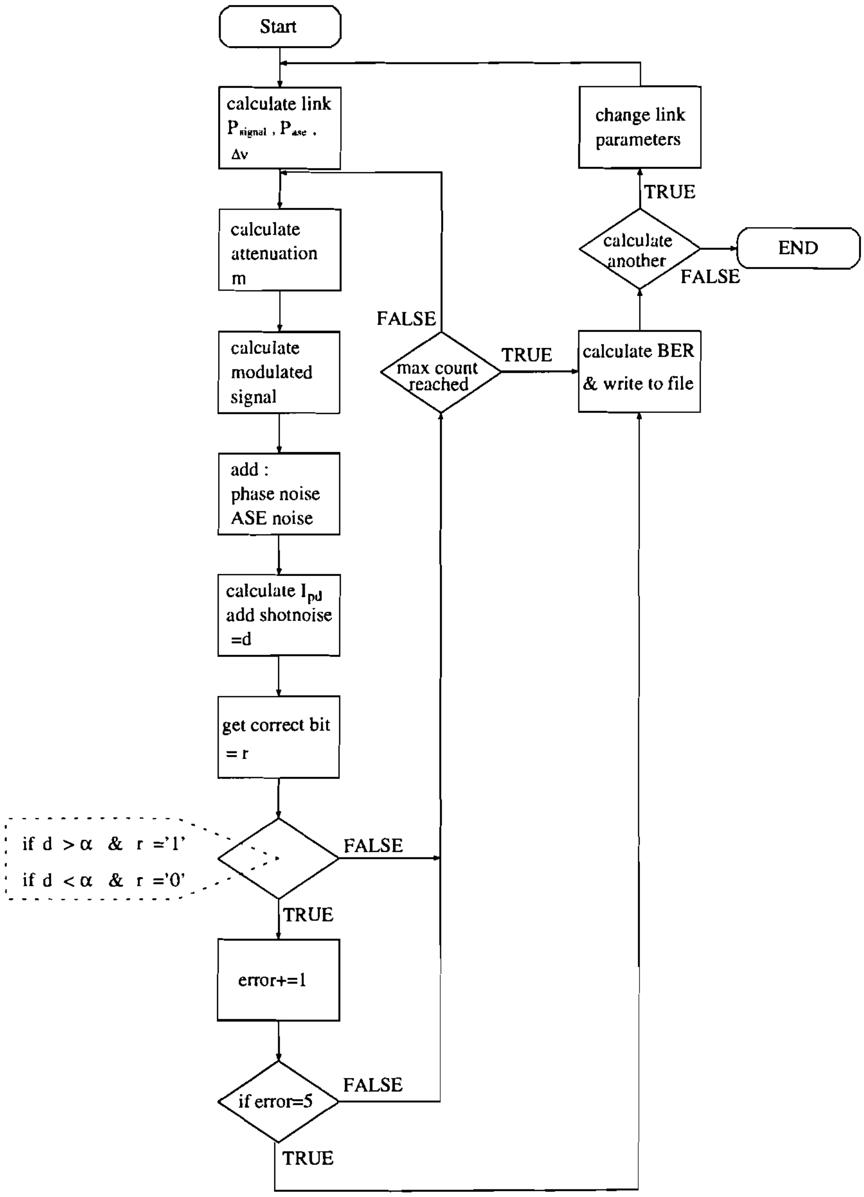


Figure 7.1: Flowchart describing the program simulating the high bit rate DPSK optical transmission system.

There is no user interface in the program. If values have to be changed they have to be changed in the program, after which the program has to be compiled again.

7.1 Calculation of the link

To calculate the influence of the link, the output signal power P_s , output ASE noise power P_{ASE} and the linewidth $\Delta\nu$ have to be calculated after each amplifier. To be able to do this, first the gain of the amplifier has to be calculated.

The gain can be calculated using:

$$g = G_0 \cdot 2^{-(g-1)\frac{P_{in}}{P_{sat}(1-\frac{1}{g})}} \tag{7.2}$$

Next the powers and linewidth are calculated:

$$P_s = gP_{s_{in}} \tag{7.3}$$

$$P_{ASE} = gP_{ASE_{in}} + n_{sp}(g-1)h\mu_0 B_o \tag{7.4}$$

$$\Delta\nu_{out} = \Delta\nu_{in}\left(1 + \frac{\pi F}{\gamma}\Delta\nu_{in}\right) \tag{7.5}$$

7.2 Adding the noise to the simulation

The calculation of the noise is done for an entire bit, in other words only the envelope of the noise is taken into account. The reason for this is the highly needed increase in speed, the program would else take years to complete the calculation of a BER curve.

7.2.1 The phase noise

The phase noise can be modelled by

$$E = A\exp(\omega(t) + \varphi(t)) \tag{7.6}$$

with $\varphi(t)$ the phase noise:

$$\varphi(t) = \sqrt{\pi\Delta\nu T} \cdot n_{gauss} \tag{7.7}$$

with n_{gauss} a Gaussian distributed variable:

$$E\{n_{gauss}\} = 0$$

$$E\{n_{gauss}^2\} = 1$$

The $\varphi(t)$ is a Gaussian distributed variable. This is only true looking at the phase noise after an entire bit. If the real laser signal where to be sampled and this approach was used to calculated the phase-noise, it would result in a spectrum of white noise with a delta peak at ω. The phase changes are gradual and cannot *jump* over the entire linewidth during one sample period which would be assumed possible using this approach. It is however possible to *jump* over the entire linewidth during an entire bit.

7.2.2 The ASE noise

The field of the ASE-noise can be expressed as:

$$E_{ASE} = A_{ASE} \exp(j\varphi(t)) \tag{7.8}$$

with $\varphi(t)$ a random phase.

After the link a receiver a bandpass filter is placed to filter most of the ASE noise out of the signal. The remaining ASE-power equals:

$$P_{ASE} = \frac{B_o}{B_f} N_{sp} \tag{7.9}$$

$$A_{ASE} = \sqrt{\frac{B_o}{B_f} N_{sp}} \tag{7.10}$$

The remaining ASE-noise has an almost flat frequency spectrum and can be seen as white noise.

The ASE noise is summed during an entire bit resulting in a signal with a Gaussian distributed noise. Which can be expressed as the phase:

$$\varphi(t) = \pi n_{gauss} + \frac{\pi}{2} \tag{7.11}$$

The factor n_gauss is a Gaussian distributed variable with mean 0 and variance 1.

7.2.3 The shot noise

The shot-noise is a Poisson distributed noise caused by the arrival of photons at discrete time intervals (see section 2.1.3). After one bit time an average of $\frac{I_{avg}T}{q}$ electrons have been received. The number of received electrons and the current can be expressed as:

$$n = Poisson\left(\frac{I_{avg}T}{q}\right) \tag{7.12}$$

$$I = Poisson\left(\frac{I_{avg}T}{q}\right)\frac{q}{T} \tag{7.13}$$

7.3 The simulations

Due to the limited time available and the long time it takes to perform a simulation, just a small number of simulations have been performed. The intention of these simulation was to predict the performance of the laboratory setup. The simulation results will later be compared with the experiments after which the program may have to be adapted.

One simulation is done to look if the number of 20 SOA's, which means a link of a 1000 km can be realised as predicted in sections 4.6 and 6.1.3. The simulated DPSK system is drawn in figure 7.2.

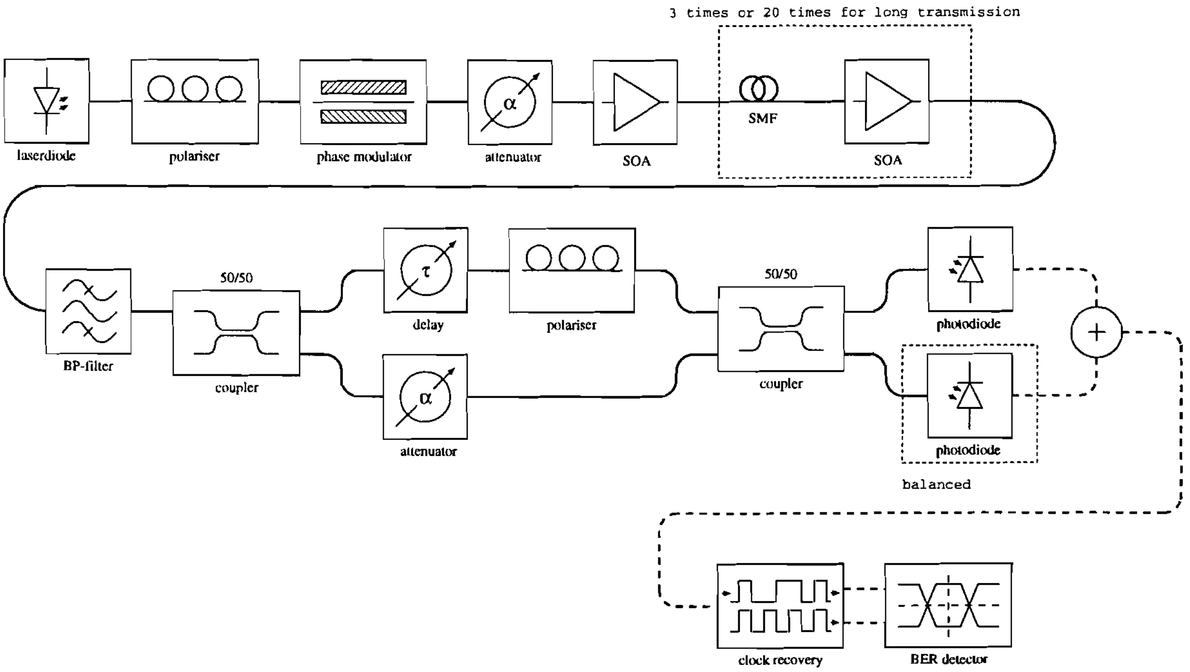


Figure 7.2: The scheme of the DPSK optical transmission system which is simulated.

7.3.1 Balanced receiver

The idea was to simulate the performance of the laboratory link (build for ASK modulation experiments). Due to a high value for n_{sp} used in the simulations, the calculation of the simulated link (P_{ASE}, P_s and $\Delta\nu$) will not match the laboratory link.

The signals in the figure have the following values:

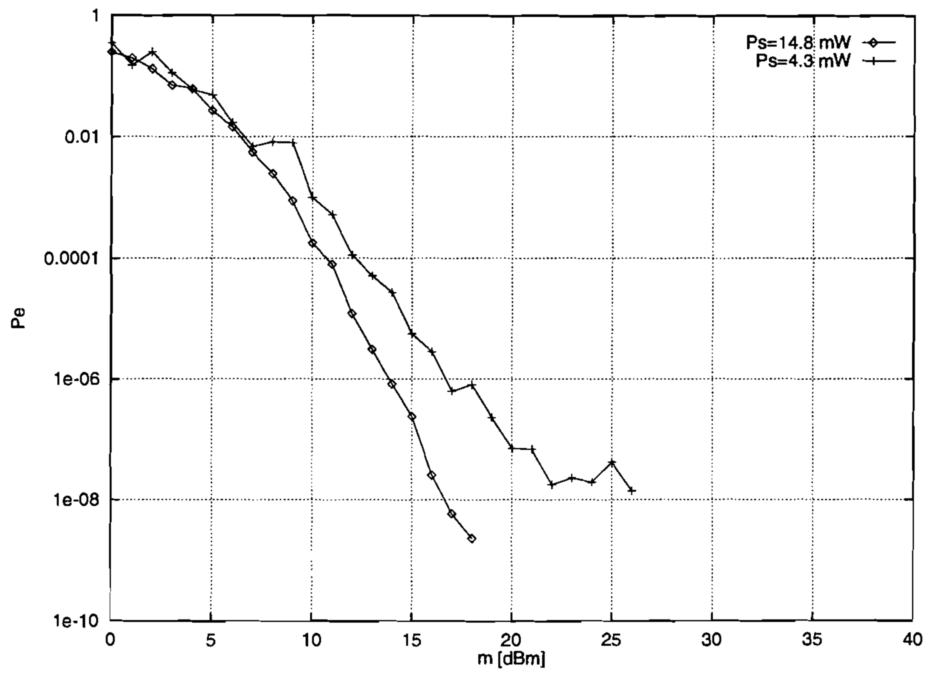


Figure 7.3: BER of the balanced receiver under influence of as well ASE as phase-noise.

P_s $= 4.27$ mW
$\Delta\nu$ $= 100$ MHz
P_{ase} $= 11.6$ mW

P_s $= 14.8$ mW
$\Delta\nu$ $= 100$ MHz
P_{ase} $= 3.12$ mW

The first power can be obtained by the laser, the second can be obtained by a pre-amplifier or shortening the first fibre in the link.

7.3.2 Unbalanced receiver

This simulation is meant to simulate the laboratory link in which the first experiments will take place. Unfortunatly, the value for n_{sp} in the simulation is too high. The real link will probably perform better than simulated here. The further simulation and conclusions are correct.

The signals in the graphic have the folowing values:

P_s $= 4.27$ mW
$\Delta\nu$ $= 50$ MHz
P_{ase} $= 11.6$ mW

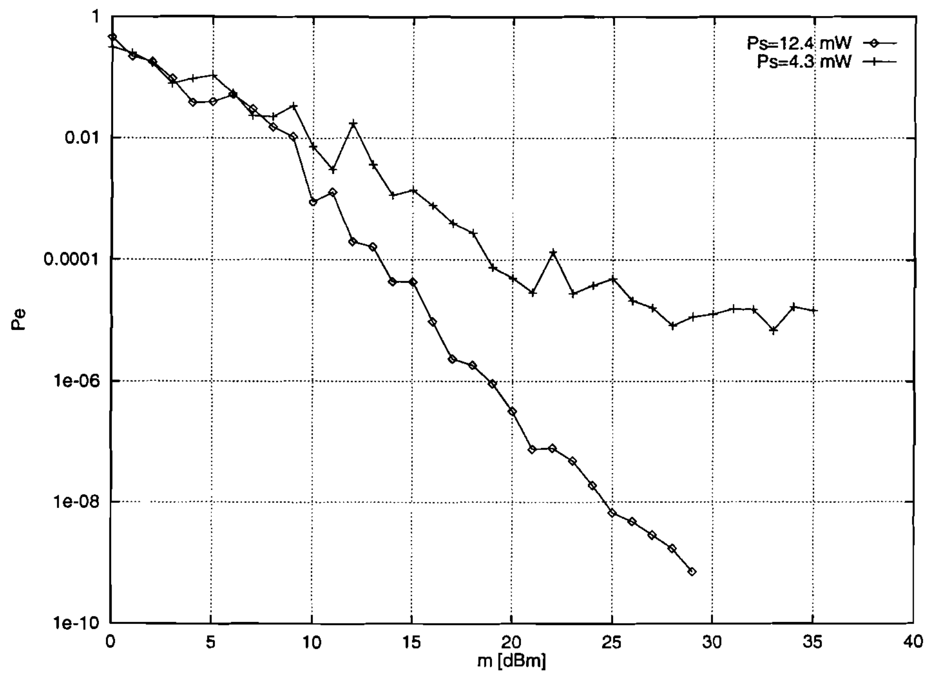


Figure 7.4: BER of the unbalanced receiver under influence of as well ASE as phase-noise.

$P_s \quad = 12.4$ mW

$\Delta\nu \quad = 50$ MHz

$P_{ase} \quad = 4.84$ mW

The first power can be obtained by the laser, the second can be obtained by a pre-amplifier or shortening the first fibre in the link.

7.3.3 A 1000 km long link

In this simulation a correct value for n_{sp} is used. The link in this simulation consists of a preamplifier and 20 segments of 50 km of fibre and a SOA. The result of the simulation in shown in figure 7.5

$P_s \quad = 12.7$ mW

$\Delta\nu \quad = 11.3$ MHz

$P_{ase} \quad = 4.18$ mW

In this simulation the link is simulated with a laser current $I_{ld} = 100$ mA.

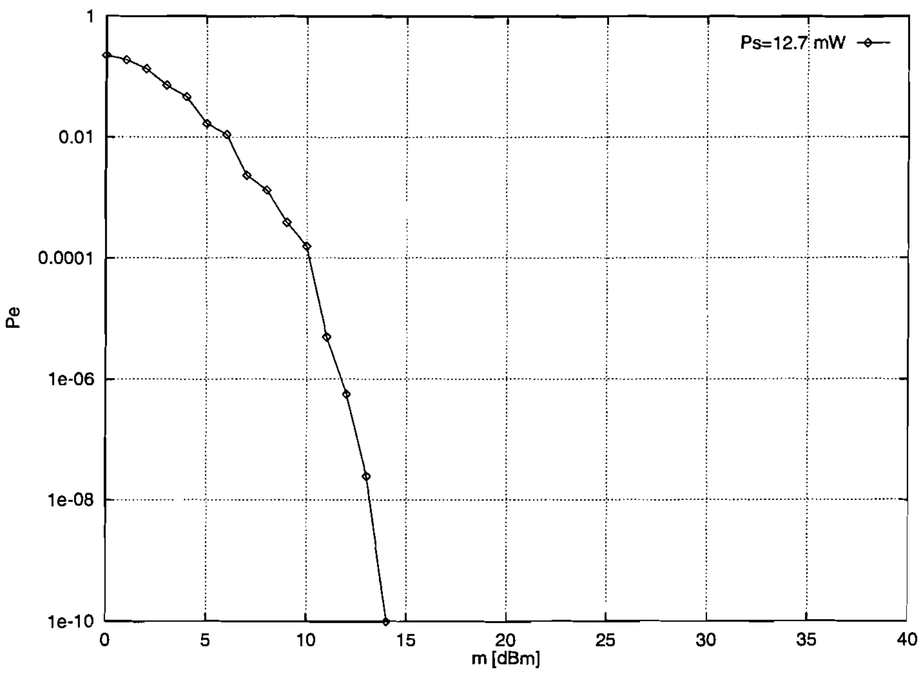


Figure 7.5: The BER of a high speed optical DPSK transmission system, transmitting over a distance of a 1000 km.

7.4 Results of the simulation

The simulation results are as predicted in sections about phase 5.4 and ASE-noise 6.1.3.

To get an good idea of the location of the BER-floor, it is advised to use seperate phase (section 5.4) and ASE-noise simulations (section 6.1.3). The dominant noise will be a good estimate for the real BER floor.

Seperate simulations were also used to check the seperate noise terms in the simulation program, making the other noise term zero.

Furthermore, it can be seen in figure 7.5 that a link of a 1000 km is theoretically possible. The calculation is performed till 10^{-10} and the BER floor is not yet vissible. If this can be realised, it would mean a real improvement over the acheivible link length when using ASK.

The next important step is to compare the simulations with measurements after which further simulations have to be performed.

Chapter 8

Conclusions

As can been seen by the previous chapters, not the entire assignment is finished; no experiments were conducted. The main reason for this is the delivery time of the components needed to perform the experiments.

The bit-by-bit simulation program was finished just before the end of my graduation period. Simulations still have to be performed to get more insight in how the ASE and phase noise influence each other. The simulation program shows that a DPSK system with a link of 20 segments, consisting of 50 km of fibre and a SOA, has a BER below 10^{-9}. This means a link of **1000 km** is, at least theoretically, possible.

Although there was no time to finish the assignment a good base is realised to continue the investigation of the DPSK system. The theoretical work shows very promising results: a longer link (1000 km) could be realised than is possible for ASK (500 km).

Both the phase and ASE-noise play an important role in the DPSK system although their effects can be kept limited. The linewidth broadening in a link with SOA's can be kept limited by a small input linewidth. Small enough input linewidths can already be achieved with *normal* communication lasers. CATV lasers with even smaller linewidths are also commercially available. The input power of the link can be increased without the fear of signal degradation due to saturation. Saturation by the signal power even has a positive effect on the ASE-noise. A second positive effect of saturation is that the SOA's in saturation are less polarisation dependent.

In the near future, the actual system measurements have to be performed and the results have to be compared with the ASK-results. After this the DPSK system can be judged.

There is still a lot of work to be done. This work includes:

- Perform measurements on the DPSK system.
- Compare DPSK and ASK performance.
- Compare measurements with simulations and if necessary update the model.
- Perform simulations to investigate how ASE and phase noise influence each other.
- Perform simulations with different links (e.g. a different number of amplifiers, filters between the amplifiers, different linewidths, etc.).
- Investigate delay-line with feedback. The feedback will be necessary for a commercial DPSK communication system.
- Investigate how to realize a balanced receiver (demands, make or buy, etc).
- Try to realize an analytical simulation for the DPSK system.
- Write a simulation program to calculate the optimal number of amplifiers, gain and fibre lengths, minimising the ASE noise and signal linewidth.

In the near future, I will perform the measurements on the DPSK-system and hopefully help a new graduate student to start further investigations.

Abbreviations

FSK-DD Frequency Shift Keying Direct Detection

DPSK-DD Differential Phase Shift Keying Direct Detection

IM-DD Intensity Modulated Direct Detection

PRBS Pseudo Random Bit Sequence

EDFA Erbium Doped Fibre Amplifier

SOA Semiconductor Optical Amplifier

ASK Amplitude Shift Keying

FSK Frequency Shift Keying

DPSK Differential Phase Shift Keying

BER Bit Error Rate

FWHM Full Width at Half Maximum

ASE Amplified Spontaneous Emission

mgf moment generation function

SSMF Standard Single Mode Fibre

DSF Dispersion Shifted Fibre

PrDFA Praseodymium Doped Fibre Amplifier

Nomenclature

α_0 $[m^{-1}]$ steady state net gain coefficient

α_H Linewidth enhancement factor

α_L $[m^{-1}]$ loss per meter

α_{opt} $[s^{-1}]$ Optimal decision threshold of receiver

β Spontaneous emission factor

η quantum efficiency

Γ optical confinement factor

γ $[s^{-1}]$ inverse carrier lifetime

γ inverse carrier lifetime

$\Gamma_{1,2}$ mirror reflectivity coefficients

κ $[s^{-1}]$ material loss

λ $[m]$ wavelength

ν $[Hz]$Laser frequency

$\triangle v_{in}$ $[Hz]$ input linewidth SOA

$\triangle v_{out}$ $[Hz]$ output linewidth SOA

A $[m^2]$ cross section area of active region

B_0 $[Hz]$ Optical bandwidth of SOA

B_f $[Hz]$ Passband of optical filter

c $[ms^{-1}]$ light speed in vacuum

F phase noise term

g input to output power gain

G_0 $[m^{-1}]$steady state material gain

$G_n = \frac{\delta G}{\delta n}$ $[m^{-2}]$

h $[Js]$ Planck's constant $(= 6.63 \cdot 10^{-34} Js)$

I $[W]$light intensity

I_{ld} $[A]$ Pumping current flowing to active region

I_{th} $[A]$ Threshold current

L $[m]$ laser cavity length

L_A $[m]$ cavity length of SOA

L_s $[m]$ length of fibre segment

m number of photons arriving at photodetector in one bit time

N $[m^{-3}]$ electron density in conduction band

n refractive index

N_{sp} $[W]$ Total ASE-noise power

n_{sp} $[s^{-1}]$spontaneous emission factor

P_0 $[W]$ Output Power

P_{in} $[W]$ input power

P_{sat} $[W]$ saturation power of SOA

R Spontaneous emission rate

R_m Facet power reflectivity

R_t $[m^{-3}]$total average spontaneous emission rate into all guided modes

v_g $[ms^{-1}]$ group velocity

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Appendix A

Article reference guide

Table A.1: Overview of the articles used to study the preformance of FSK and DPSK optical transmission systems

points of interest	FSK modulation	literature	DPSK modulation	literature
theoretical receiver sensitivity	-	-	3dB (FSK) 1.5-2dB (CP-FSK)	[8]
carrier recovery	-	-	very easy	[9]
modulator	direct on laser	[10, 11]	direct on laser	[9, 12, 13]
		[14, 13]	LiNBO3 straight line (availible SUMICEM)	[9, 14]
	Mach-Zehner	[15]	Mach-Zehner → IM modulation	[9, 16] [15]
	SLA /freq. lock laser		SLA / freq. lock laser	[17]
fibre dispersion	-	[18, 14]	more tolerant	[19, 20] [18, 14]
fibre non-linearities	-	[18]	-	[18]
SLA		[21, 22]		[21, 21]
demodulator	Mach-Zehner delay-line $\tau = \frac{T}{2}$	[15] [14]	Mach-zehner delay-line τ = T	[23] [14]
	injection locked laser	[24, 25]	frequency locked laser	[26]
	filter	[27]	-	
biggest disadvantage	AM-modulation of FM signal	[28, 29, 13] [32, 14]	phase noise → $\Delta\nu T \approx 0.01$	[30, 31, 16] [33, 34, 35] [32, 14]
solutions	-appropriate encoding (AMI) - laser with flat FM-response - equalisation of driving signal		- Frequency feedback - laser with small linewidth - filtering ??	[36, 31] [21]
AMI	better as MC for low frequencies	[28]		
Manchester (MC)	prefered because of experience	[28]	prefered because of expeience	
NRZ		[28]		
bipolar	bigger bandwitdth		easy to realize	[37]

Appendix B

Measurement report linewidth

B.1 Linewidth laser

B.1.1 First measurement of linewidth laser

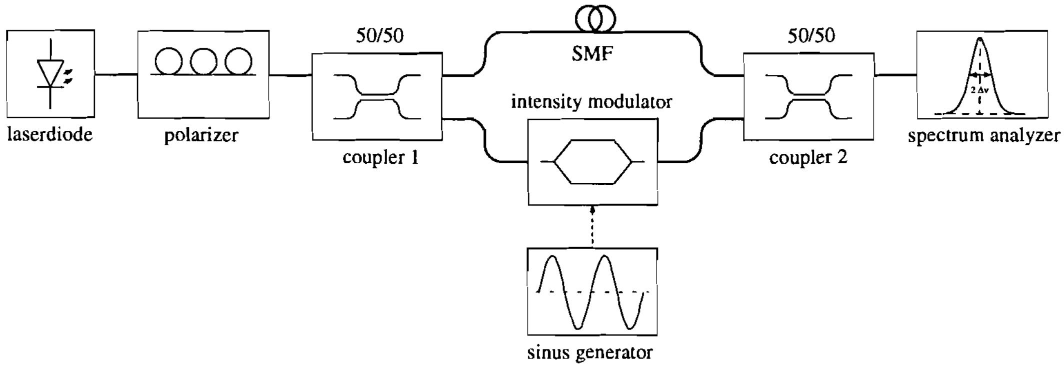

Figure B.1: Measurement circuit

Used equipment

laser:	#2284 PHILIPS CQF92/D
modulator:	EC355L; SUMICEM P/N:T-MZ 1.3-10
S/N:MZ4-256-24 #3146	
coupler 1-2:	50/50
SMF 2:	2268 m 1300nm, loss=0.36dB/km
spectrum analyzer:	Display EC130G; HP 70004A
	RF Section ECO27A HP 70908A
	lightwave section EC020A; HP 70810B
	local oscilator EC021A; HP 70900A

I_{ld} [mA]	P_{ld}[dBm]	$\Delta\nu$ [MHz] *measured*	$\Delta\nu$ [MHz] for $C = C_{min}$	$\Delta\nu$ [MHz] for $C = C_{avg}$	$\Delta\nu$ [MHz] for $C = C_{max}$	$\Delta\nu$ [MHz] for $C = C_{matched}$
30.0	-4.95	215.00	146.07	540.61	1281.49	244.09
32.5	-2.84	125.00	84.03	311.01	737.24	140.43
35.0	-1.43	100.00	58.98	218.30	517.47	98.57
37.5	-0.41	75.00	45.56	168.63	399.73	76.14
40.0	0.41	60.00	36.98	136.86	324.43	61.80
42.5	1.11	54.00	31.21	115.53	273.86	52.16
45.0	1.67	50.00	26.99	99.89	236.80	45.10
47.5	2.20	42.80	23.74	87.86	208.27	39.67
50.0	2.65	36.90	21.20	78.45	185.96	35.42
52.5	3.05	35.90	19.15	70.89	168.03	32.01
55.0	3.42	31.75	17.47	64.65	153.26	29.19
57.5	3.75	28.20	16.07	59.48	141.01	26.86
60.0	4.05	25.40	14.86	55.02	130.41	24.84
65.0	4.44	20.30	12.93	47.84	113.41	21.60
70.0	4.90	18.80	11.44	42.33	100.35	19.11

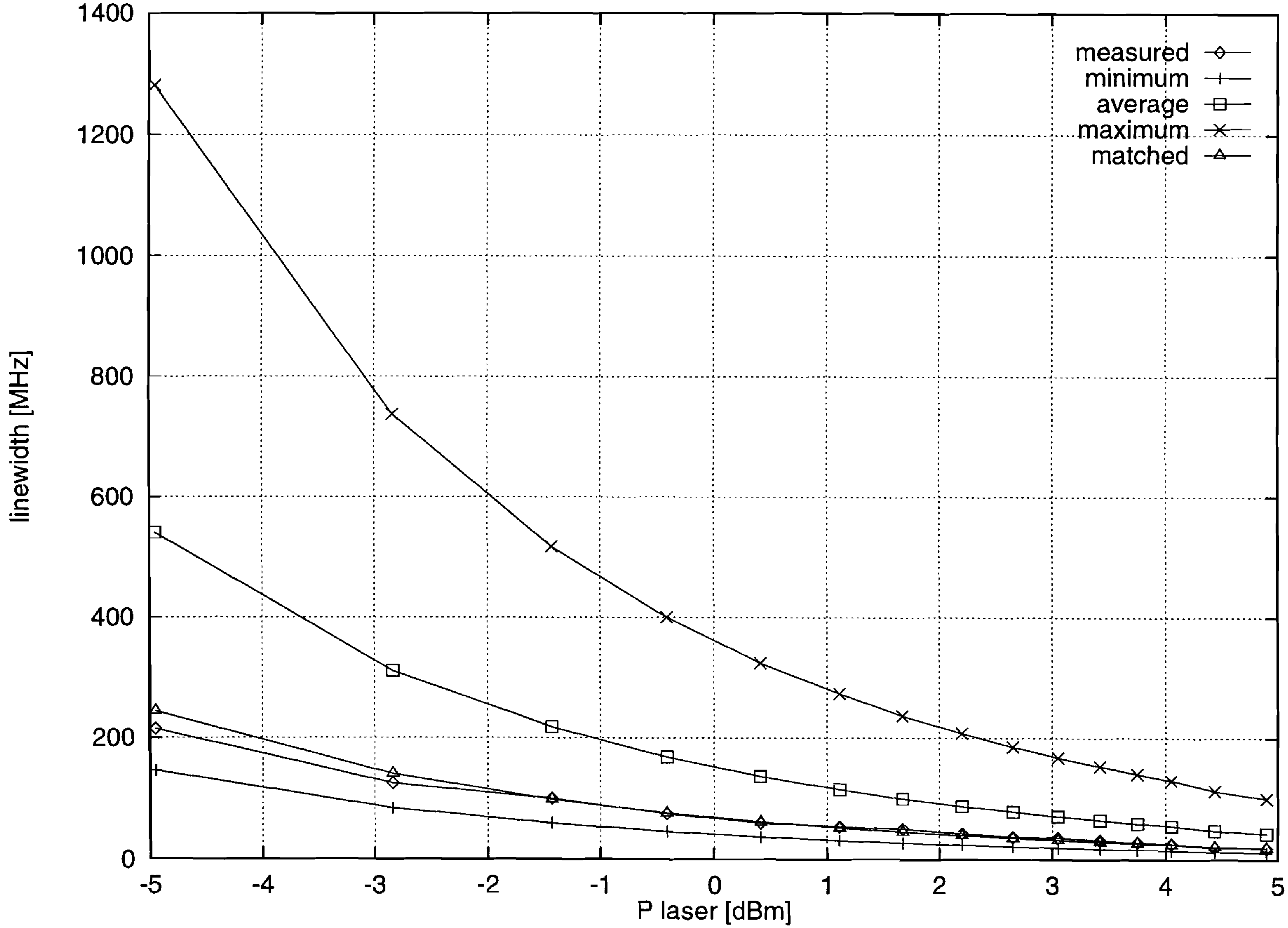

Figure B.2: Linewidth of laser (first measurement)

B.1.2 Second measurement of linewidth laser

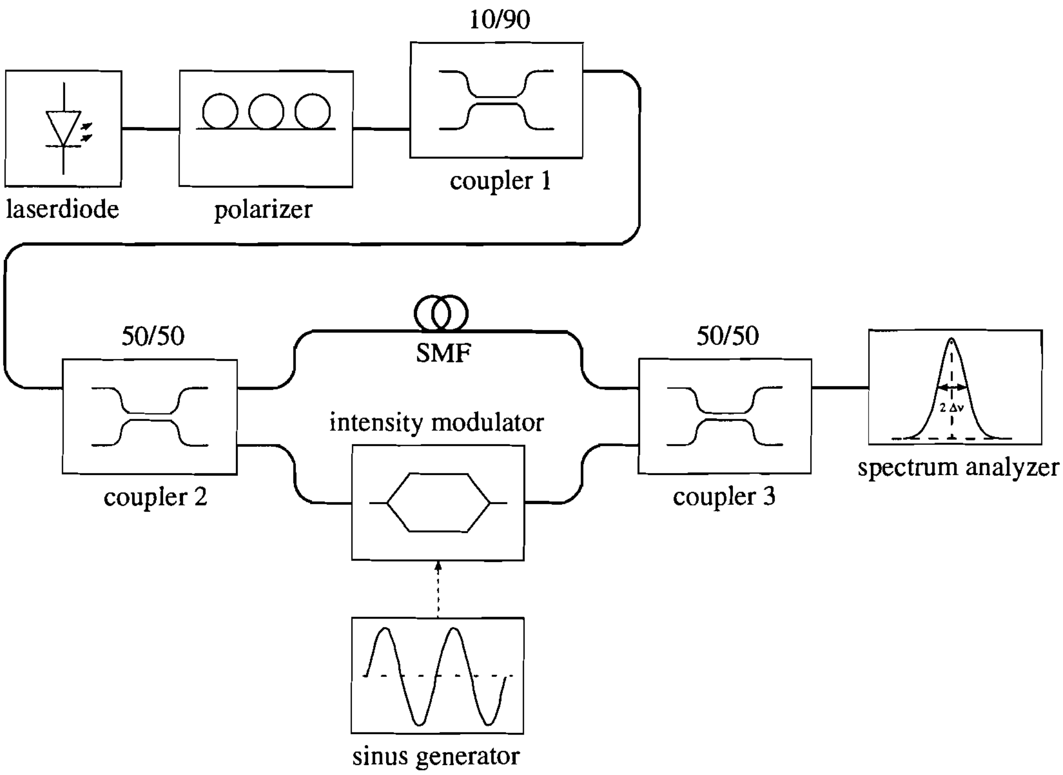

Figure B.3: Measurement circuit

Used equipment

laser:	#2284 PHILIPS CQF92/D
modulator:	EC355L; SUMICEM P/N:T-MZ 1.3-10
S/N:MZ4-256-24 #3146	
coupler 1-3:	50/50
SMF :	2268 m 1300nm, loss=0.36dB/km
spectrum analyzer:	Display EC130G; HP 70004A
	RF Section ECO27A HP 70908A
	lightwave section EC020A; HP 70810B
	local oscilator EC021A; HP 70900A

I_{ld} [mA]	P_{ld}[dBm]	$\Delta\nu$ [MHz] *measured*	$\Delta\nu$ [MHz] for $C = C_{min}$	$\Delta\nu$ [MHz] for $C = C_{avg}$	$\Delta\nu$ [MHz] for $C = C_{max}$	$\Delta\nu$ [MHz] for $C = C_{matched}$
30.0	-4.82	249.80	540.61	146.07	1281.49	244.09
31.0	-3.89	187.70	417.74	112.87	990.25	188.62
32.0	-3.11	152.25	340.38	91.97	806.87	153.69
33.0	-2.46	129.40	287.20	77.60	680.79	129.68
34.0	-1.90	115.50	248.39	67.11	588.79	112.15
35.0	-1.41	102.25	218.82	59.12	518.70	98.80
36.0	-0.96	93.50	195.54	52.83	463.52	88.29
37.0	-0.57	82.00	176.74	47.75	418.95	79.80
38.0	-0.20	75.75	161.23	43.56	382.20	72.80
39.0	0.13	67.50	148.23	40.05	351.38	66.93
40.0	0.44	62.40	137.17	37.06	325.16	61.93
42.5	1.12	55.45	115.60	31.23	274.03	52.20
45.0	1.70	44.90	99.89	26.99	236.80	45.10
50.0	2.66	36.90	78.55	21.22	186.20	35.47
55.0	3.44	31.75	64.72	17.49	153.42	29.22
60.0	4.08	25.40	55.03	14.87	130.45	24.85
65.0	4.58	20.30	47.87	12.93	113.47	21.61
70.0	4.99	18.80	42.35	11.44	100.39	19.12

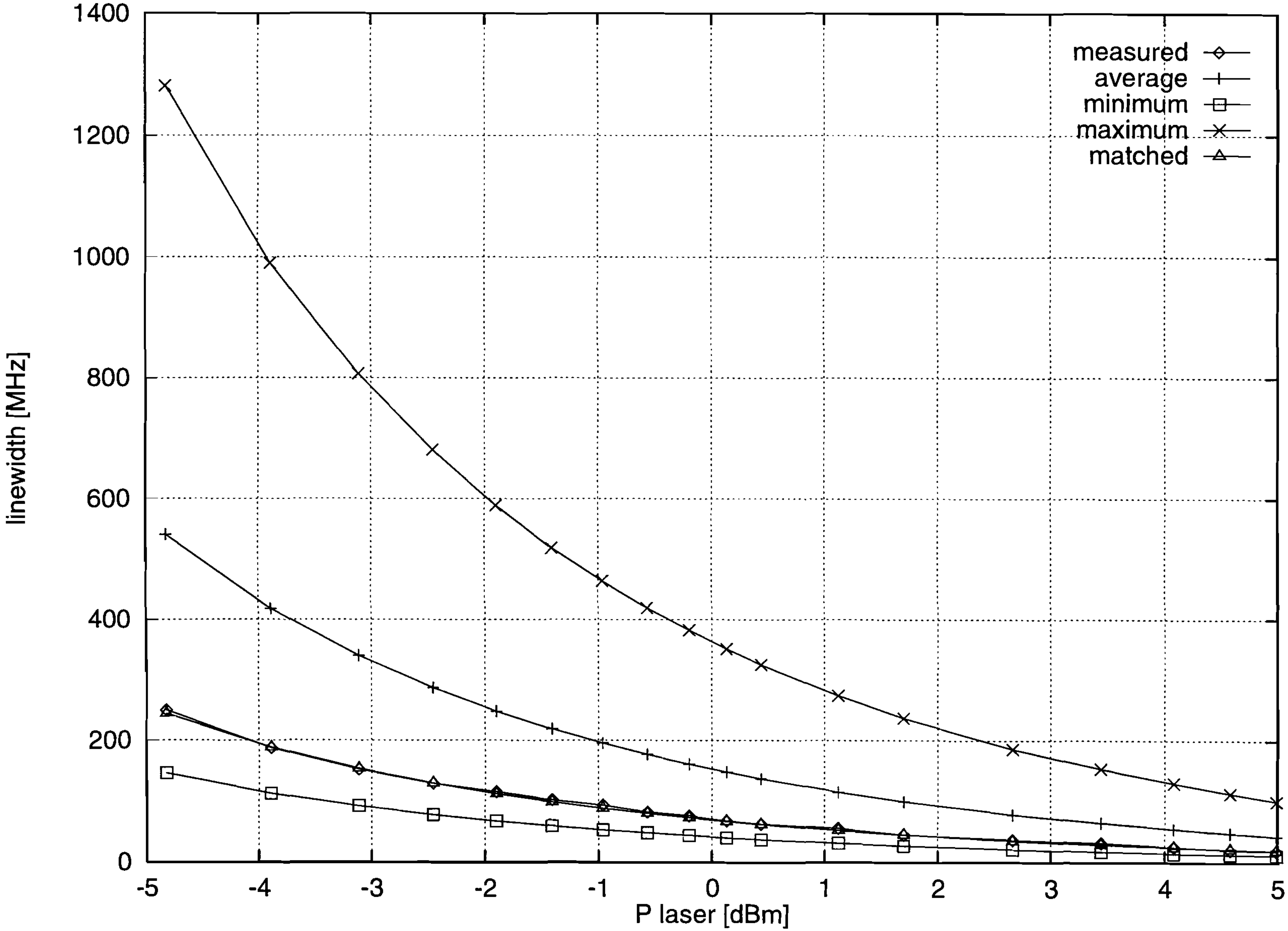

Figure B.4: Linewidth of laser (second measurement)

B.2 Linewidth of laser & 1 SOA

B.2.1 First measurement of linewidth laser & 1 SOA

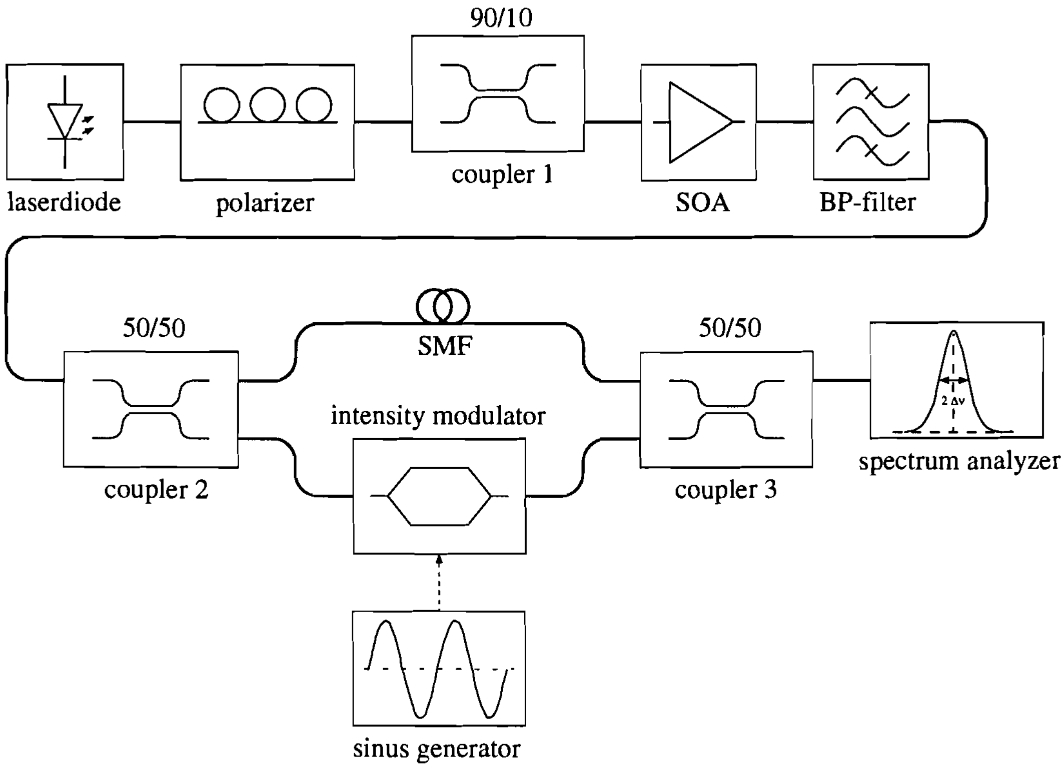

Figure B.5: Measurement circuit

Used equipment

laser:	#2284 PHILIPS CQF92/D
SOA:	#14 PHILIPS CQF882/E
modulator:	EC355L; SUMICEM P/N:T-MZ 1.3-10
S/N:MZ4-256-24 #3146	
coupler 1:	90/10
coupler 2-3:	50/50
SMF 1:	50 km 1300nm, loss=17.8 dB
SMF 2:	2268 m 1300nm, loss=0.36dB/km
spectrum analyzer:	Display EC130G; HP 70004A
	RF Section ECO27A HP 70908A
	lightwave section EC020A; HP 70810B
	local oscilator EC021A; HP 70900A

I_{ld}[mA]	P_{ld}[dBm]	$P_{soa_{in}}$[dBm]	$P_{soa_{out}}$[dBm]	g_{ff}[dB]	$\Delta\nu_{ld+1soa}$[MHz] measured	$\Delta\nu_{ld}$	$\Delta\nu_{ld+1soa}$[MHz] $f = f_{avg}$	$\Delta\nu_{ld+1soa}$[MHz] $f = f_{min}$	$\Delta\nu_{ld+1soa}$[MHz] $f = f_{max}$
30.0	-4.84	-16.89	5.32	16.16	227.00	244.09	244.10	244.10	244.10
31.0	-3.88	-15.93	6.10	28.03	178.00	188.62	192.93	190.60	196.52
32.0	-3.12	-15.17	6.62	27.79	143.50	153.69	156.12	154.81	158.15
33.0	-2.46	-14.51	7.15	27.66	129.00	129.68	131.27	130.41	132.61
34.0	-1.90	-13.95	7.49	27.44	118.00	112.15	113.19	112.63	114.05
35.0	-1.41	-13.46	7.89	27.35	105.00	98.80	99.55	99.15	100.19
36.0	-0.96	-13.01	8.13	27.14	97.00	88.29	88.82	88.53	89.26
37.0	-0.57	-12.62	8.34	26.96	88.50	79.80	80.18	79.98	80.50
38.0	-0.21	-12.26	8.39	26.65	82.00	72.80	73.06	72.92	73.28
39.0	0.13	-11.92	8.55	26.47	69.00	66.93	67.13	67.02	67.29
40.0	0.44	-11.61	8.70	26.31	66.50	61.93	62.09	62.00	62.21
42.5	1.12	-10.93	8.97	25.90	53.50	52.20	52.28	52.23	52.35
45.0	1.70	-10.35	9.22	25.57	47.00	45.10	45.15	45.13	45.20
50.0	2.66	-9.39	9.45	24.84	36.50	35.47	35.49	35.48	35.50
55.0	3.44	-8.61	9.67	24.28	31.00	29.22	29.23	29.23	29.24
60.0	4.08	-7.97	9.65	23.62	28.00	24.85	24.85	24.85	24.86
65.0	4.58	-7.47	9.39	22.86	25.50	21.61	21.61	21.61	21.62

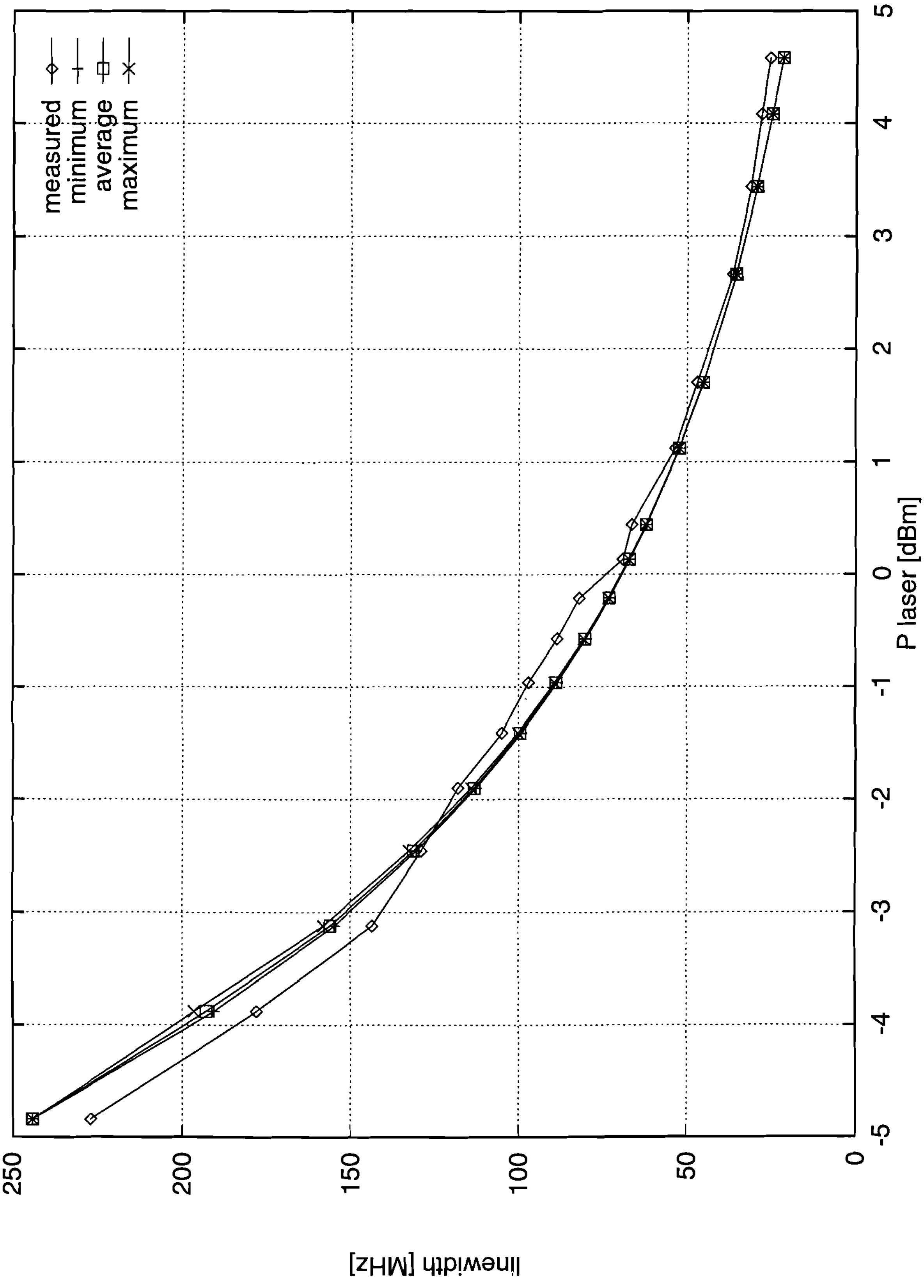

Figure B.6: Linewidth of laser & 1 SOA (second measurement)

B.2.2 Second measurement of linewidth laser & 1 SOA

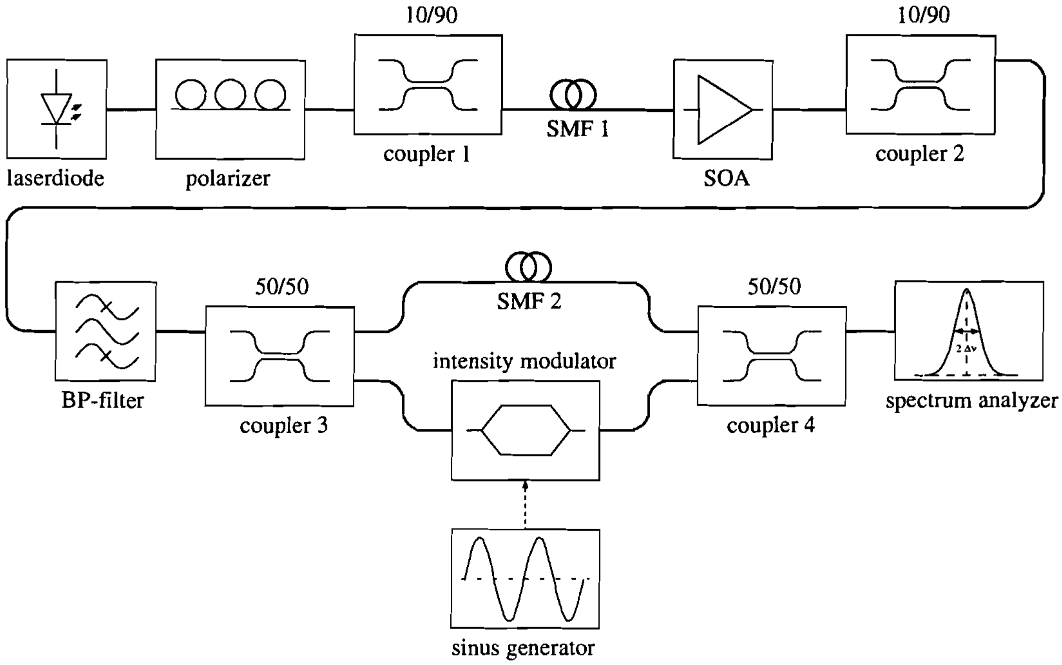

Figure B.7: Measurement circuit

Used equipment

laser:	#2284 PHILIPS CQF92/D
SOA:	#14 PHILIPS CQF882/E
modulator:	EC355L; SUMICEM P/N:T-MZ 1.3-10
S/N:MZ4-256-24 #3146	
coupler 1-2:	90/10
coupler 3-4:	50/50
SMF 1:	50 km 1300nm, loss=17.8 dB
SMF 2:	2268 m 1300nm, loss=0.36dB/km
spectrum analyzer:	Display EC130G; HP 70004A
	RF Section ECO27A HP 70908A
	lightwave section EC020A; HP 70810B
	local oscilator EC021A; HP 70900A

I_{ld}[mA]	P_{ld}[dBm]	$P_{soa_{in}}$[dBm]	$P_{soa_{out}}$[dBm]	g_{ff}[dB]	$\Delta\nu_{ld+1soa}$[MHz] measured	$\Delta\nu_{ld}$	$\Delta\nu_{ld+1soa}$[MHz] $f = f_{avg}$	$\Delta\nu_{ld+1soa}$[MHz] $f = f_{min}$	$\Delta\nu_{ld+1soa}$[MHz] $f = f_{max}$
30.0	-4.85	-16.90	7.23	18.08	226.50	244.09	244.11	244.10	244.12
31.0	-3.90	-15.95	7.85	29.80	184.00	188.62	202.26	194.91	213.63
32.0	-3.12	-15.17	8.48	29.65	156.00	153.69	161.90	157.47	168.75
33.0	-2.48	-14.53	9.00	29.53	137.50	129.68	135.07	132.16	139.56
34.0	-1.91	-13.96	9.32	29.28	122.00	112.15	115.59	113.73	118.45
35.0	-1.41	-13.46	9.60	29.06	108.00	98.80	101.11	99.87	103.04
36.0	-0.97	-13.02	9.84	28.86	100.00	88.29	89.91	89.04	91.26
37.0	-0.57	-12.62	10.05	28.67	90.00	79.80	80.97	80.34	81.94
38.0	-0.20	-12.25	10.25	28.50	84.05	72.80	73.67	73.20	74.40
39.0	0.13	-11.92	10.42	28.34	76.25	66.93	67.59	67.23	68.14
40.0	0.44	-11.61	10.58	28.19	69.80	61.93	62.45	62.17	62.88
45.0	1.70	-10.35	11.21	27.56	49.05	52.20	52.44	52.31	52.64
50.0	2.75	-9.30	11.65	27.00	37.50	45.10	45.23	45.16	45.33

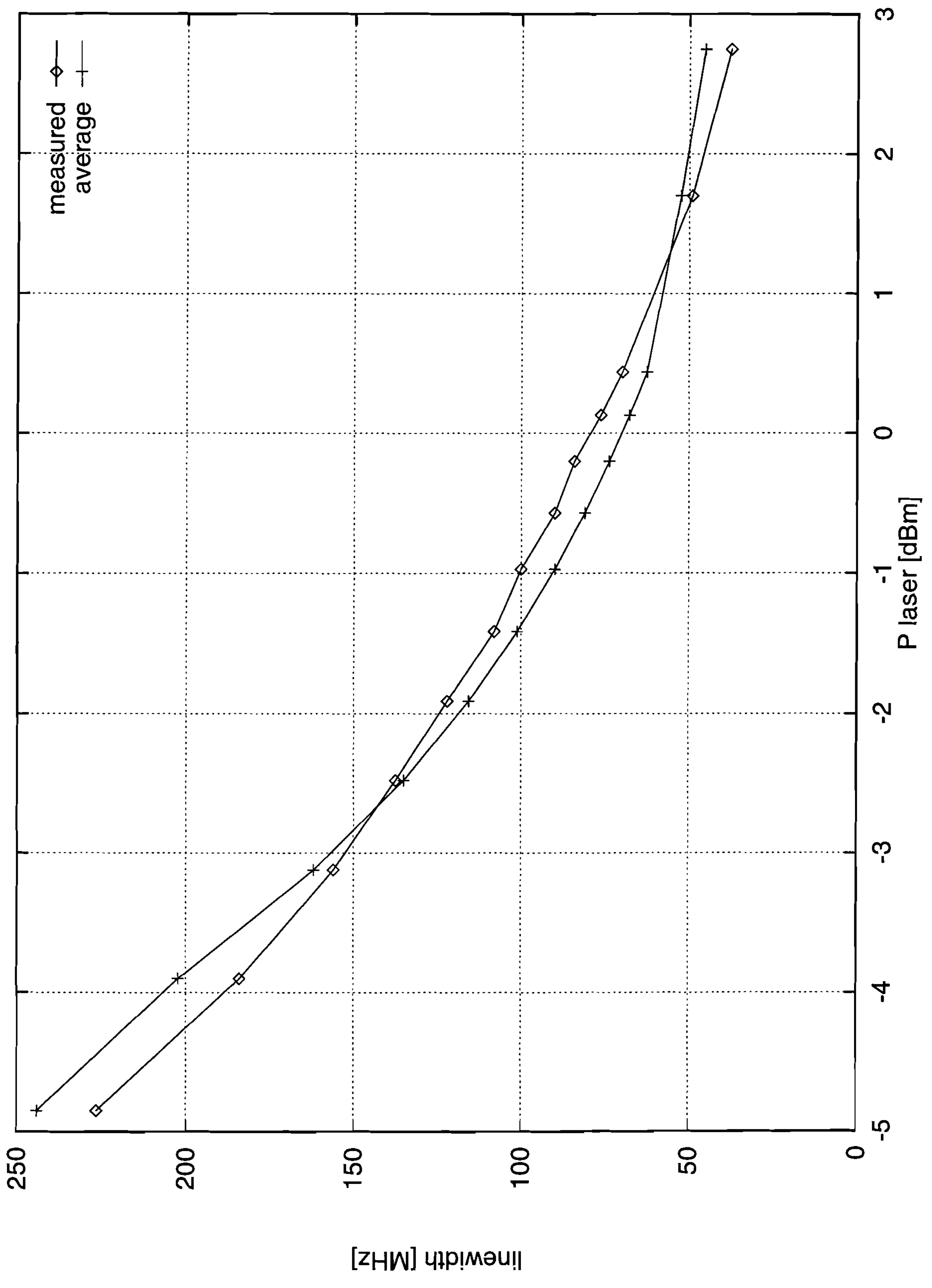

Figure B.8: Linewidth of laser & 1 SOA (second measurement)

B.3 Linewidth of laser & 2 SOA's

B.3.1 First measurement of linewidth laser & 2 SOA'2

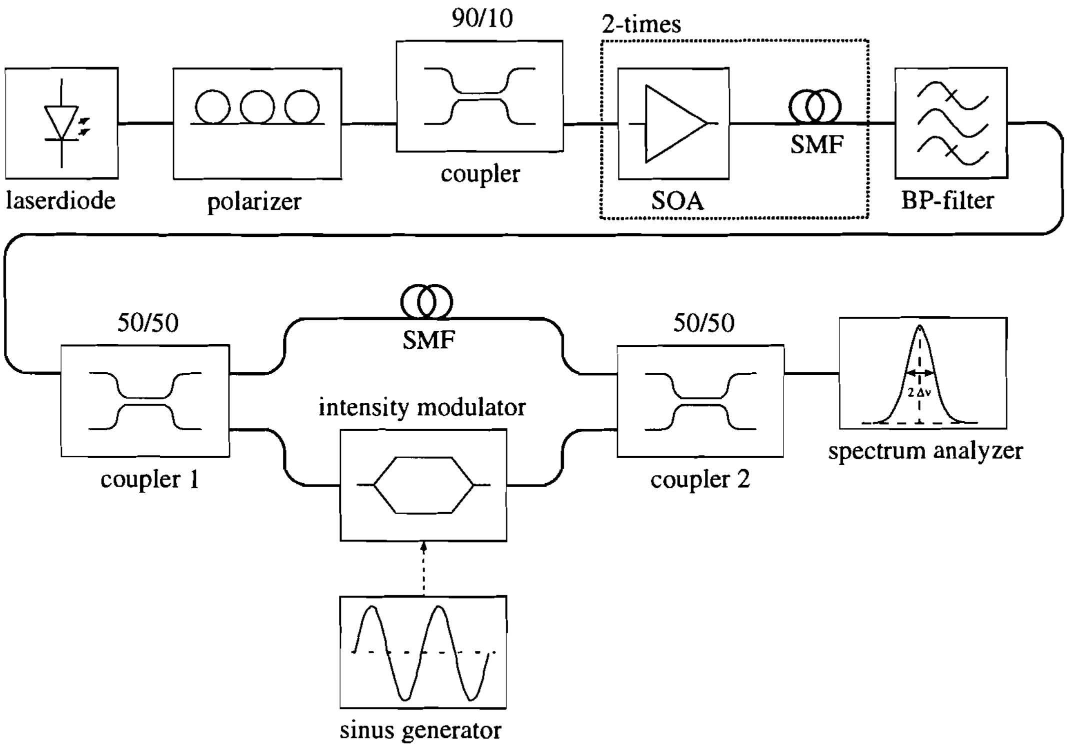

Figure B.9: Measurement circuit

Used equipment

laser:	#2284 PHILIPS CQF92/D
SOA 1:	#14 PHILIPS CQF882/E
SOA 2:	#12 PHILIPS CQF882/E
modulator:	EC355L; SUMICEM P/N:T-MZ 1.3-10
S/N:MZ4-256-24 #3146	
coupler 1:	90/10
coupler 2-3:	50/50
SMF 1:	50 km 1300nm, loss=17.8 dB
SMF 2:	2268 m 1300nm, loss=0.36dB/km
spectrum analyzer:	Display EC130G; HP 70004A
	RF Section ECO27A HP 70908A
	lightwave section EC020A; HP 70810B
	local oscilator EC021A; HP 70900A

I_{ld}[mA]	P_{ld}[dBm]	$P_{soa_{in}}$[dBm]	$P_{soa_{out}}$[dBm]	g_{ff}[dB]	$\Delta\nu_{ld+2soa}$[MHz] measured	$\Delta\nu_{ld}$	$\Delta\nu_{ld+2soa}$[MHz] $f = f_{avg}$	$\Delta\nu_{ld+2soa}$[MHz] $f = f_{min}$	$\Delta\nu_{ld+2soa}$[MHz] $f = f_{max}$
31.0	-3.89	-15.50	6.93	28.43	194.00	192.93	198.69	195.58	203.63
32.0	-3.11	-14.98	7.33	28.31	160.50	156.12	159.61	157.73	162.60
33.0	-2.46	-14.45	7.78	28.23	134.00	131.27	133.61	132.35	135.62
34.0	-1.90	-14.11	8.00	28.11	113.00	113.19	114.80	113.93	116.18
35.0	-1.41	-13.71	8.20	27.91	106.00	99.55	100.65	100.06	101.59
36.0	-0.96	-13.47	8.33	27.80	93.00	88.82	89.63	89.19	90.32
37.0	-0.57	-13.26	8.47	27.73	86.00	80.18	80.81	80.47	81.35
38.0	-0.20	-13.21	8.57	27.78	78.50	73.06	73.60	73.31	74.07
39.0	0.13	-13.05	8.68	27.73	72.50	67.13	67.57	67.33	67.95
40.0	0.44	-12.90	8.78	27.68	68.00	62.09	62.45	62.25	62.77
42.5	1.12	-12.63	8.96	27.59	56.50	52.28	52.52	52.39	52.73
45.0	1.70	-12.38	9.08	27.46	48.50	45.15	45.32	45.23	45.47
50.0	2.67	-12.15	9.05	27.20	37.50	35.49	35.57	35.53	35.65
55.0	3.44	-11.93	9.03	26.96	31.50	29.23	29.28	29.26	29.33
60.0	4.08	-11.95	9.02	26.97	29.50	24.85	24.89	24.87	24.92
65.0	4.58	-12.21	8.80	27.01	25.50	21.61	21.64	21.63	21.67

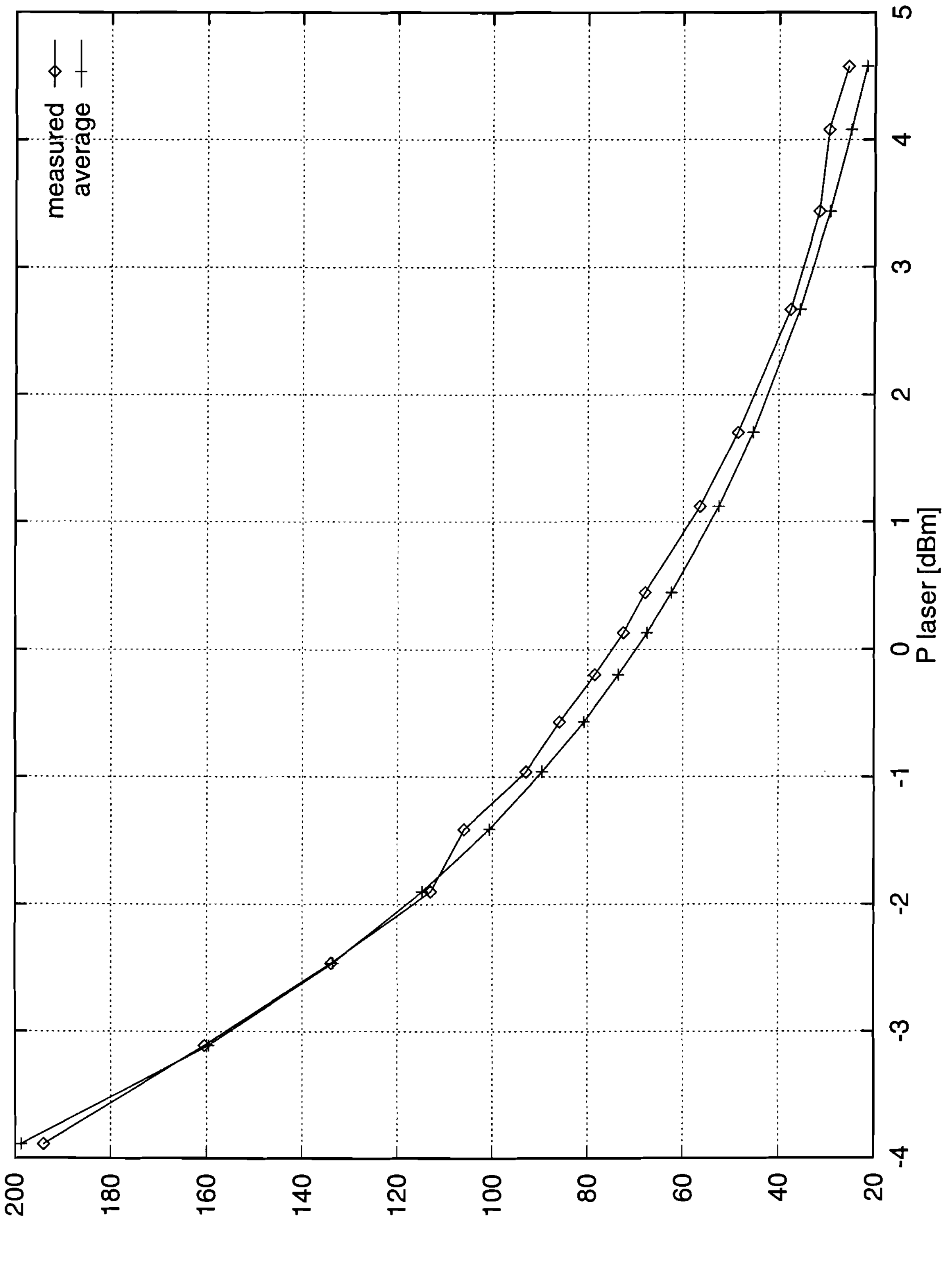

Figure B.10: Linewidth of laser & 2 SOA's (first measurement)

B.3.2 Second measurement of linewidth laser & 2 SOA's

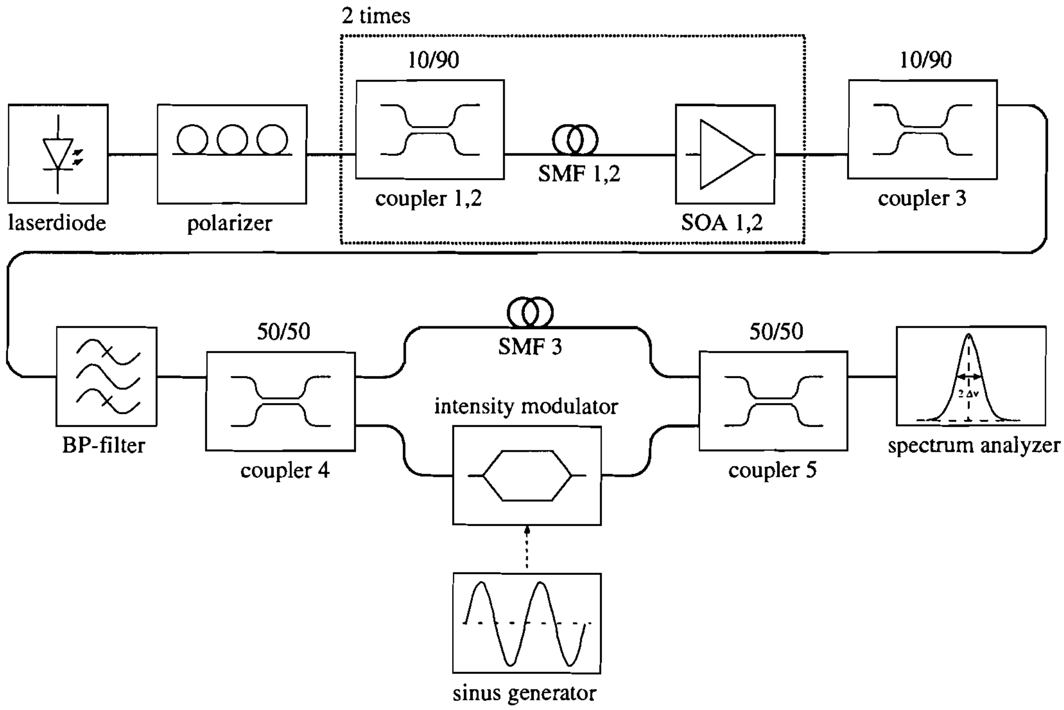

Figure B.11: Measurement circuit

Used equipment

laser:	#2284 PHILIPS CQF92/D
SOA 1:	#09 PHILIPS CQF882/E
SOA 1:	#13 PHILIPS CQF882/E
modulator:	EC355L; SUMICEM P/N:T-MZ 1.3-10
S/N:MZ4-256-24 #3146	
coupler 1-3:	90/10
coupler 4-5:	50/50
SMF 1:	50 km 1300nm, loss=17.8 dB
SMF 2:	50 km 1300nm, loss=17.9 dB
SMF 3:	2268 m 1300nm, loss=0.36dB/km
spectrum analyzer:	Display EC130G; HP 70004A
	RF Section ECO27A HP 70908A
	lightwave section EC020A; HP 70810B
	local oscilator EC021A; HP 70900A

I_{ld}[mA]	P_{ld}[dBm]	$P_{soa_{in}}$[dBm]	$P_{soa_{out}}$[dBm]	g_{ff}[dB]	$\Delta\nu_{ld+2soa}$[MHz] measured	$\Delta\nu_{ld}$	$\Delta\nu_{ld+2soa}$[MHz] $f = f_{avg}$	$\Delta\nu_{ld+2soa}$[MHz] $f = f_{min}$	$\Delta\nu_{ld+2soa}$[MHz] $f = f_{max}$
30.0	-4.83	-13.57	7.20	26.77	252.00	244.10	247.23	245.54	249.92
31.0	-3.90	-12.95	7.65	26.60	190.00	194.91	196.69	195.73	198.23
32.0	-3.13	-12.32	8.02	26.34	156.00	157.47	158.46	157.93	159.31
33.0	-2.48	-11.80	8.26	26.06	135.20	132.16	132.74	132.43	133.24
34.0	-1.91	-11.48	8.48	25.96	124.40	113.73	114.14	113.92	114.48
35.0	-1.42	-11.20	8.66	25.86	111.55	99.87	100.16	100.00	100.40
36.0	-0.97	-10.96	8.77	25.73	98.45	89.04	89.25	89.13	89.43
37.0	-0.57	-10.75	8.83	25.58	88.75	80.34	80.49	80.41	80.63
38.0	-0.21	-10.55	8.93	25.48	80.75	73.20	73.32	73.26	73.43
39.0	0.13	-10.38	9.03	25.41	73.00	67.23	67.33	67.28	67.42
40.0	0.44	-10.22	9.10	25.32	66.75	62.17	62.25	62.21	62.32
45.0	1.70	-9.59	9.40	24.99	50.25	52.31	52.35	52.33	52.39
50.0	2.66	-9.15	9.49	24.64	38.35	45.16	45.19	45.17	45.21

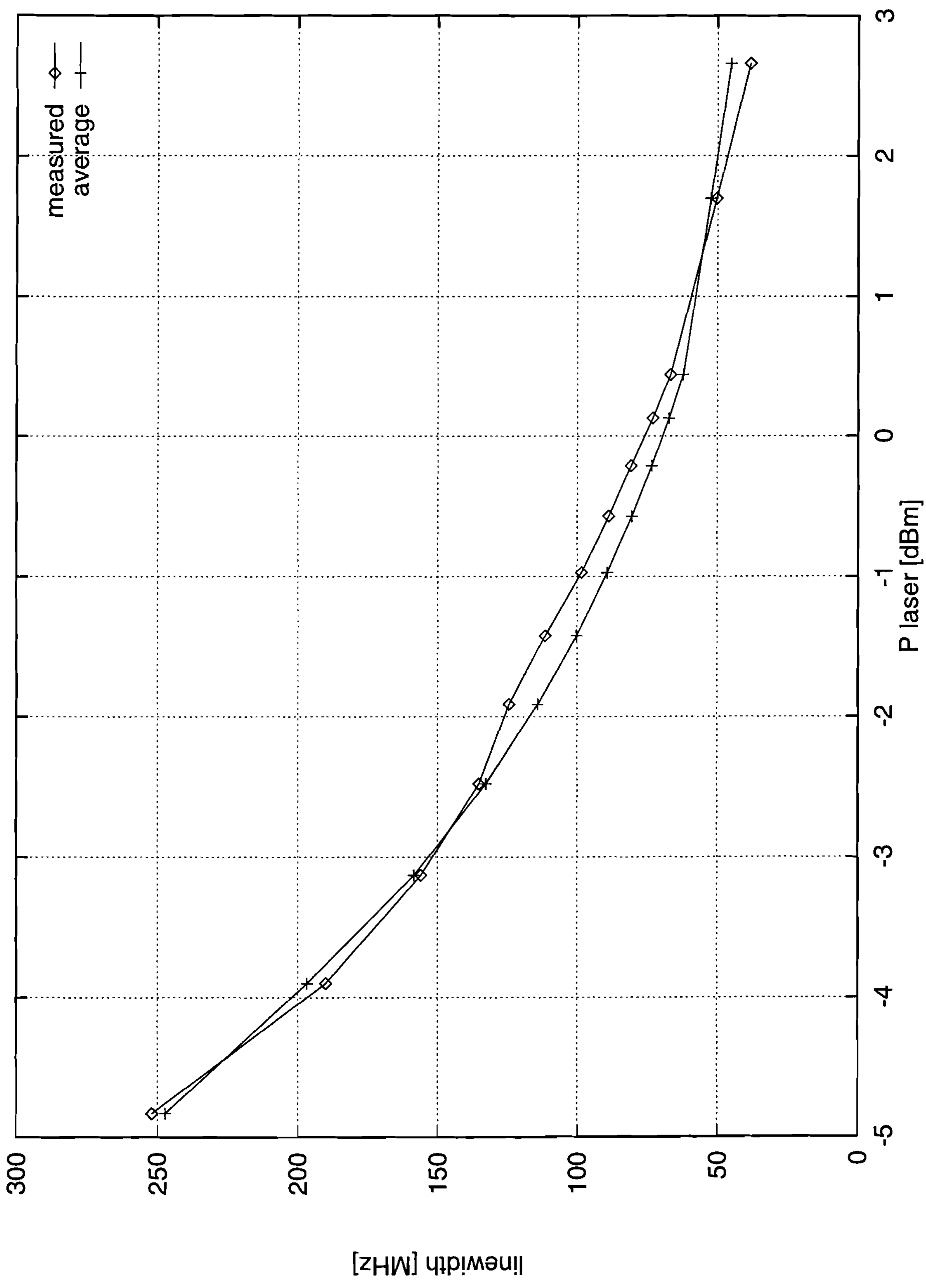

Figure B.12: Linewidth of laser & 2 SOA's (second measurement)

B.4 Linewidth of laser & 3 SOA's

B.4.1 First measurement of linewidth laser & 3 SOA's

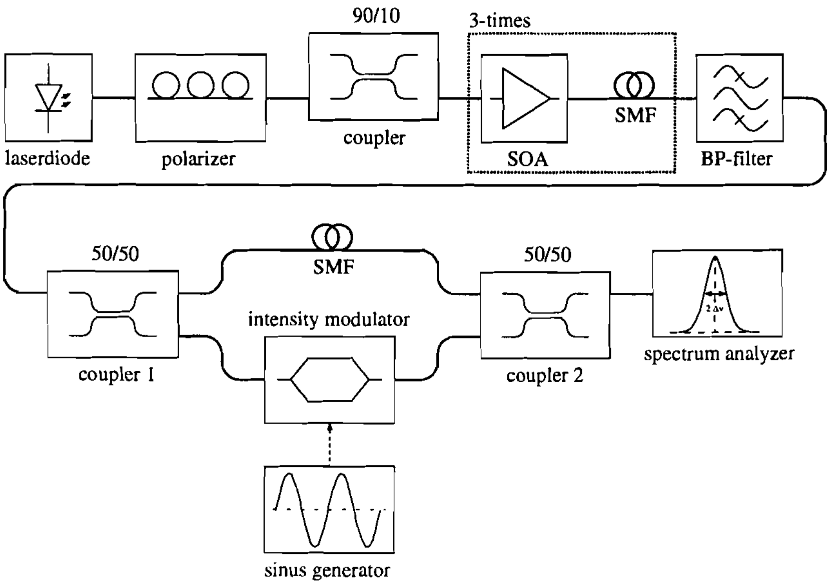

Figure B.13: Measurement circuit

Used equipment

laser:	#2284 PHILIPS CQF92/D
SOA 1:	#14 PHILIPS CQF882/E
SOA 2:	#12 PHILIPS CQF882/E
SOA 3:	#11 PHILIPS CQF882/E
modulator:	EC355L; SUMICEM P/N:T-MZ 1.3-10
S/N:MZ4-256-24 #3146	
coupler 1:	90/10
coupler 2-3:	50/50
SMF 1:	50 km 1300nm, loss=17.8 dB
SMF 2:	50 km 1300nm, loss=17.9 dB
SMF 3:	50 km 1300nm, loss=18.8 dB
SMF 4:	2268 m 1300nm, loss=0.36dB/km
spectrum analyzer:	Display EC130G; HP 70004A
	RF Section ECO27A HP 70908A
	lightwave section EC020A; HP 70810B
	local oscilator EC021A; HP 70900A

I_{ld}[mA]	P_{ld}[dBm]	$P_{soa_{in}}$[dBm]	$P_{soa_{out}}$[dBm]	g_{ff}[dB]	$\Delta\nu_{ld+3soa}$[MHz] measured	$\Delta\nu_{ld}$	$\Delta\nu_{ld+3soa}$[MHz] $f = f_{avg}$	$\Delta\nu_{ld+3soa}$[MHz] $f = f_{min}$	$\Delta\nu_{ld+3soa}$[MHz] $f = f_{max}$
30.0	-4.84	-11.40	7.94	25.34	235.50	245.54	246.79	246.12	247.87
31.0	-3.90	-10.95	8.29	25.24	185.00	195.73	196.48	196.07	197.12
32.0	-3.12	-10.58	8.57	25.15	157.50	157.93	158.39	158.14	158.78
33.0	-2.48	-10.34	8.78	25.12	138.75	132.43	132.74	132.57	133.01
34.0	-1.91	-10.12	8.93	25.05	123.00	113.92	114.14	114.02	114.33
35.0	-1.42	-9.94	9.05	24.99	104.40	100.00	100.16	100.08	100.31
36.0	-0.97	-9.83	9.14	24.97	94.00	89.13	89.26	89.19	89.37
37.0	-0.57	-9.77	9.19	24.96	84.00	80.41	80.52	80.46	80.61
38.0	-0.20	-9.67	9.26	24.93	79.50	73.26	73.34	73.30	73.42
39.0	0.13	-9.57	9.35	24.92	73.15	67.28	67.35	67.31	67.41
40.0	0.44	-9.50	9.40	24.90	68.65	62.21	62.27	62.24	62.32
45.0	1.70	-9.20	9.61	24.81	48.90	52.33	52.37	52.35	52.40
50.0	2.66	-9.11	9.66	24.77	38.15	45.17	45.20	45.19	45.23

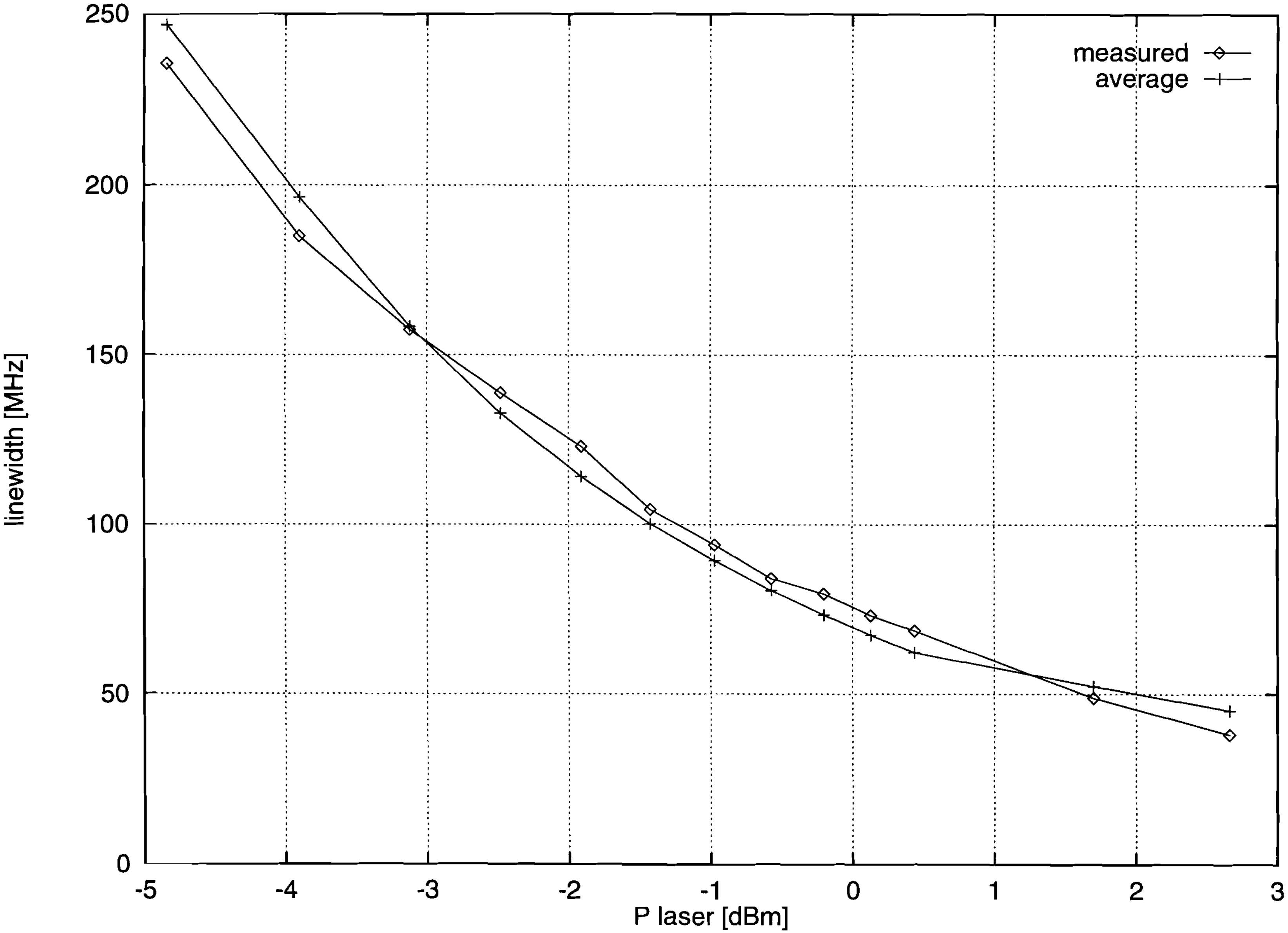

Figure B.14: Linewidth of laser & 3 SOA's (first measurement)

B.4.2 Second measurement of linewidth laser & 3 SOA's

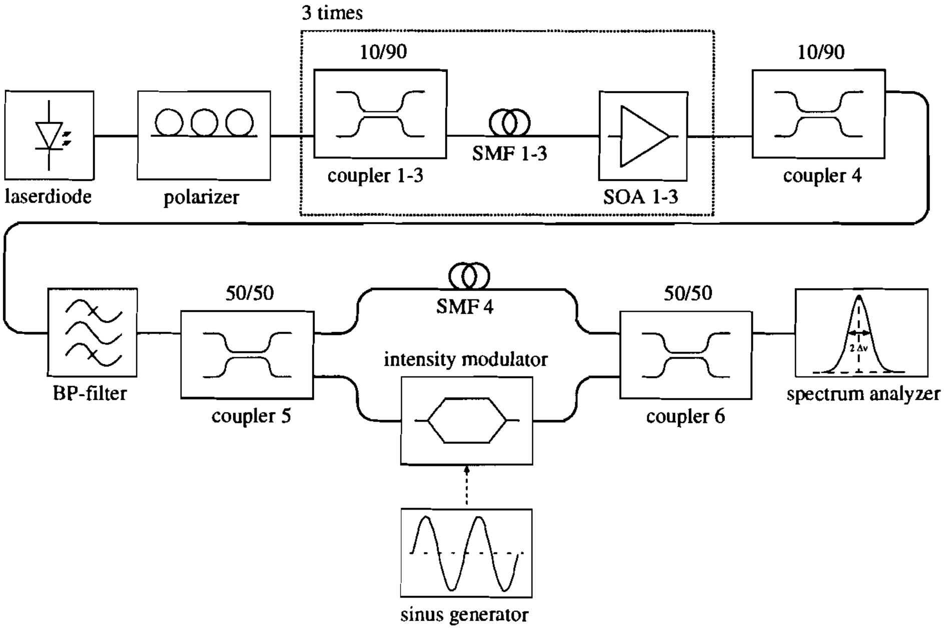

Figure B.15: Measurement circuit

Used equipment

laser:	#2284 PHILIPS CQF92/D
SOA 1:	#09 PHILIPS CQF882/E
SOA 2:	#13 PHILIPS CQF882/E
SOA 3:	#12 PHILIPS CQF882/E
modulator:	EC355L; SUMICEM P/N:T-MZ 1.3-10
S/N:MZ4-256-24 #3146	
coupler 1-4:	90/10
coupler 5-6:	50/50
coupler 6:	50/50
SMF 1:	50 km 1300nm, loss=17.8 dB
SMF 2	50 km 1300nm, loss=17.9 dB
SMF 3:	50 km 1300nm, loss=18.8 dB
SMF 4:	2268 m 1300nm, loss=0.36dB/km
spectrum analyzer:	Display EC130G; HP 70004A
	RF Section ECO27A HP 70908A
	lightwave section EC020A; HP 70810B
	local oscilator EC021A; HP 70900A

I_{ld}[mA]	P_{ld}[dBm]	$P_{soa_{in}}$[dBm]	$P_{soa_{out}}$[dBm]	g_{ff}[dB]	$\Delta\nu_{ld+3soa}$[MHz] measured	$\Delta\nu_{ld}$	$\Delta\nu_{ld+3soa}$[MHz] $f = f_{avg}$	$\Delta\nu_{ld+3soa}$[MHz] $f = f_{min}$	$\Delta\nu_{ld+3soa}$[MHz] $f = f_{max}$
31.0	-3.88	-22.30	-0.21	28.09	224.50	189.08	193.51	191.12	197.31
32.0	-3.11	-20.62	0.16	26.78	165.00	158.98	160.32	159.60	161.47
33.0	-2.46	-20.30	0.43	26.73	136.50	133.19	134.10	133.61	134.88
34.0	-1.89	-19.73	0.53	26.26	114.50	114.49	114.98	114.72	115.41
35.0	-1.42	-19.17	0.88	26.05	97.50	100.62	100.96	100.78	101.24
36.0	-0.96	-18.89	1.16	26.05	93.45	89.69	89.95	89.81	90.18
37.0	-0.56	-18.50	1.17	25.67	87.50	81.00	81.17	81.08	81.31
38.0	-0.19	-18.48	1.47	25.95	76.90	73.70	73.87	73.78	74.01
39.0	0.14	-18.38	1.72	26.10	68.15	67.70	67.85	67.77	67.99
40.0	0.45	-18.31	1.88	26.19	61.95	62.52	62.66	62.59	62.79
45.0	1.71	-17.92	1.96	25.88	44.00	45.35	45.41	45.38	45.47
50.0	2.68	-17.52	2.32	25.84	36.35	35.58	35.62	35.60	35.65
60.0	4.09	-17.70	2.16	25.86	26.50	24.91	24.92	24.91	24.94

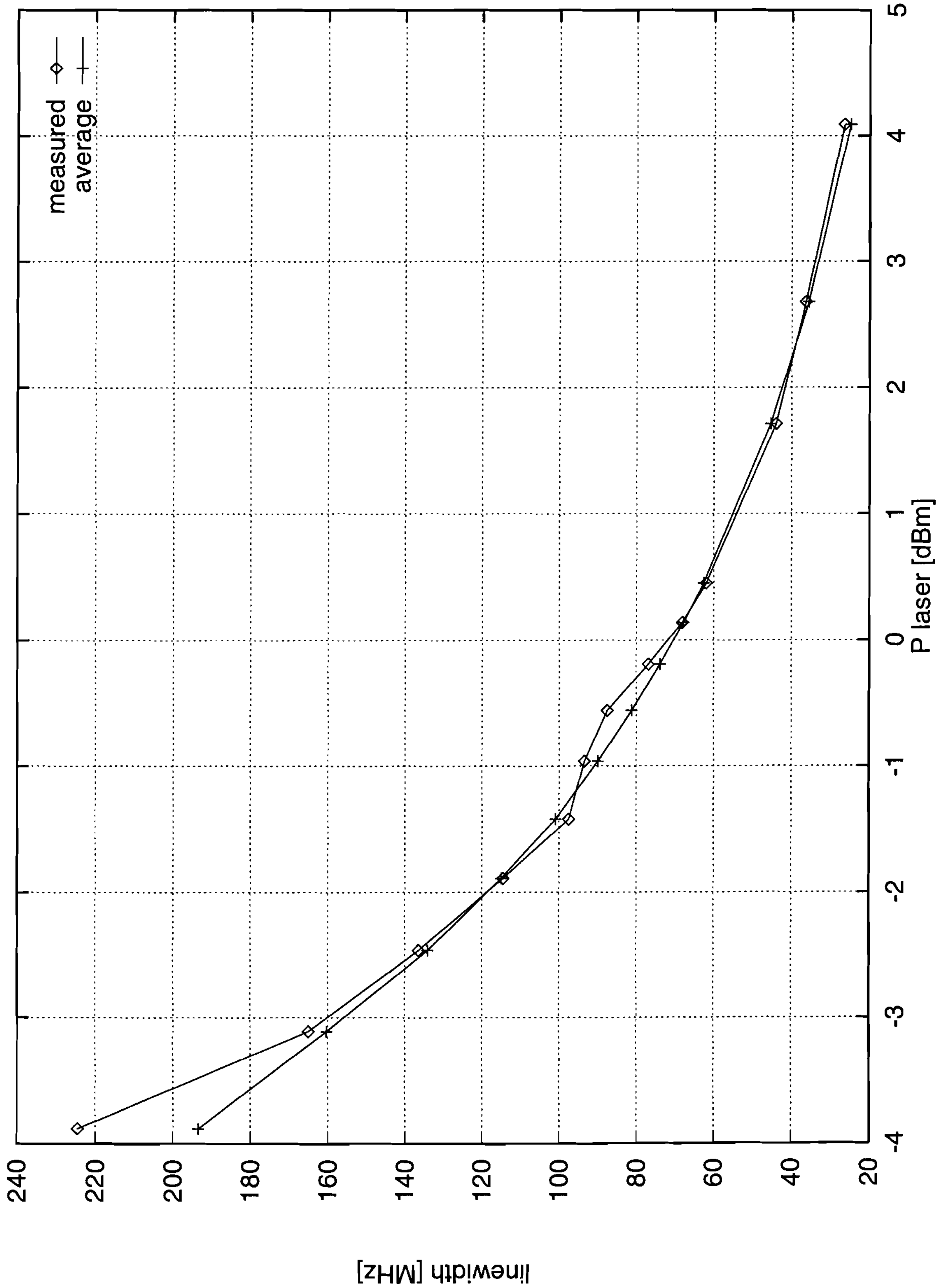

Figure B.16: Linewidth of laser & 3 SOA's (second measurement)

B.5 Linewidth of laser & 4 SOA's

B.5.1 First measurement of linewidth laser & 4 SOA's

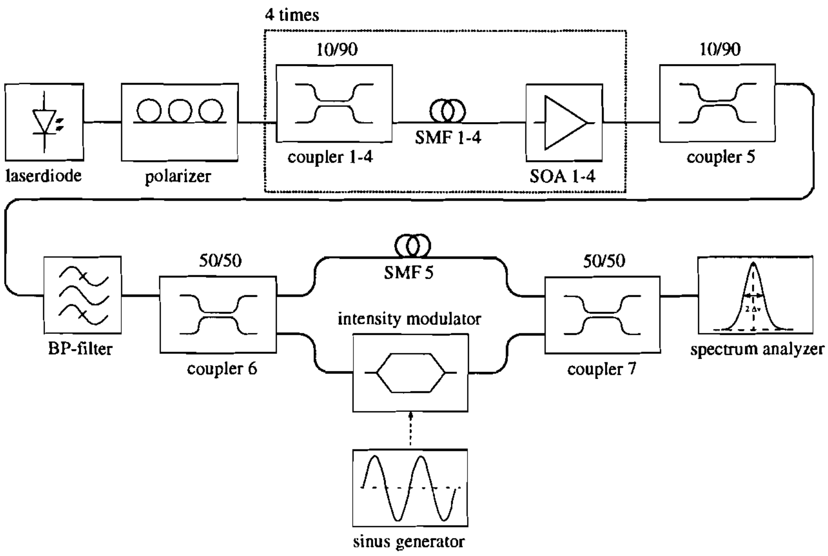

Figure B.17: Measurement circuit

Used equipment

laser:	#2284 PHILIPS CQF92/D
SOA 1:	#09 PHILIPS CQF882/E
SOA 2:	#13 PHILIPS CQF882/E
SOA 3:	#12 PHILIPS CQF882/E
SOA 4:	#14 PHILIPS CQF882/E
modulator:	EC355L; SUMICEM P/N:T-MZ 1.3-10
S/N:MZ4-256-24 #3146	
coupler 1-5:	90/10
coupler 6-7:	50/50
SMF 1:	50 km 1300nm, loss=17.8 dB
SMF 2	50 km 1300nm, loss=17.9 dB
SMF 3:	50 km 1300nm, loss=18.8 dB
SMF 4:	50 km 1300nm, loss=18.9 dB
SMF 5:	2268 m 1300nm, loss=0.36dB/km
spectrum analyzer:	Display EC130G; HP 70004A
	RF Section ECO27A HP 70908A
	lightwave section EC020A; HP 70810B
	local oscilator EC021A; HP 70900A

I_{ld}[mA]	P_{ld}[dBm]	$P_{soa_{in}}$[dBm]	$P_{soa_{out}}$[dBm]	g_{ff}[dB]	$\Delta\nu_{ld+4soa}$[MHz] measured	$\Delta\nu_{ld}$	$\Delta\nu_{ld+4soa}$[MHz] $f = f_{avg}$	$\Delta\nu_{ld+4soa}$[MHz] $f = f_{min}$	$\Delta\nu_{ld+4soa}$[MHz] $f = f_{max}$
31	-3.88	-24.11	-6.12	23.99	282.50	193.51	193.84	193.66	194.12
32	-3.10	-23.74	-5.76	23.98	168.00	160.32	160.54	160.42	160.73
33	-2.43	-23.47	-5.45	24.02	140.00	134.10	134.26	134.17	134.40
34	-1.89	-23.37	-5.32	24.05	115.95	114.98	115.10	115.04	115.21
35	-1.40	-23.02	-4.92	24.10	100.00	100.96	101.05	101.00	101.13
36	-0.95	-22.74	-4.69	24.05	95.00	89.95	90.03	89.99	90.09
37	-0.56	-22.73	-4.63	24.10	82.20	81.17	81.23	81.20	81.28
38	-0.19	-22.43	-4.40	24.03	75.30	73.87	73.92	73.89	73.96
39	0.14	-22.18	-4.22	23.96	70.30	67.85	67.89	67.87	67.93
40	0.46	-22.02	-4.02	24.00	65.30	62.66	62.70	62.68	62.73
45	1.72	-21.94	-3.90	24.04	46.55	45.41	45.43	45.42	45.45
50	2.68	-21.58	-3.53	24.05	33.30	35.62	35.63	35.62	35.64

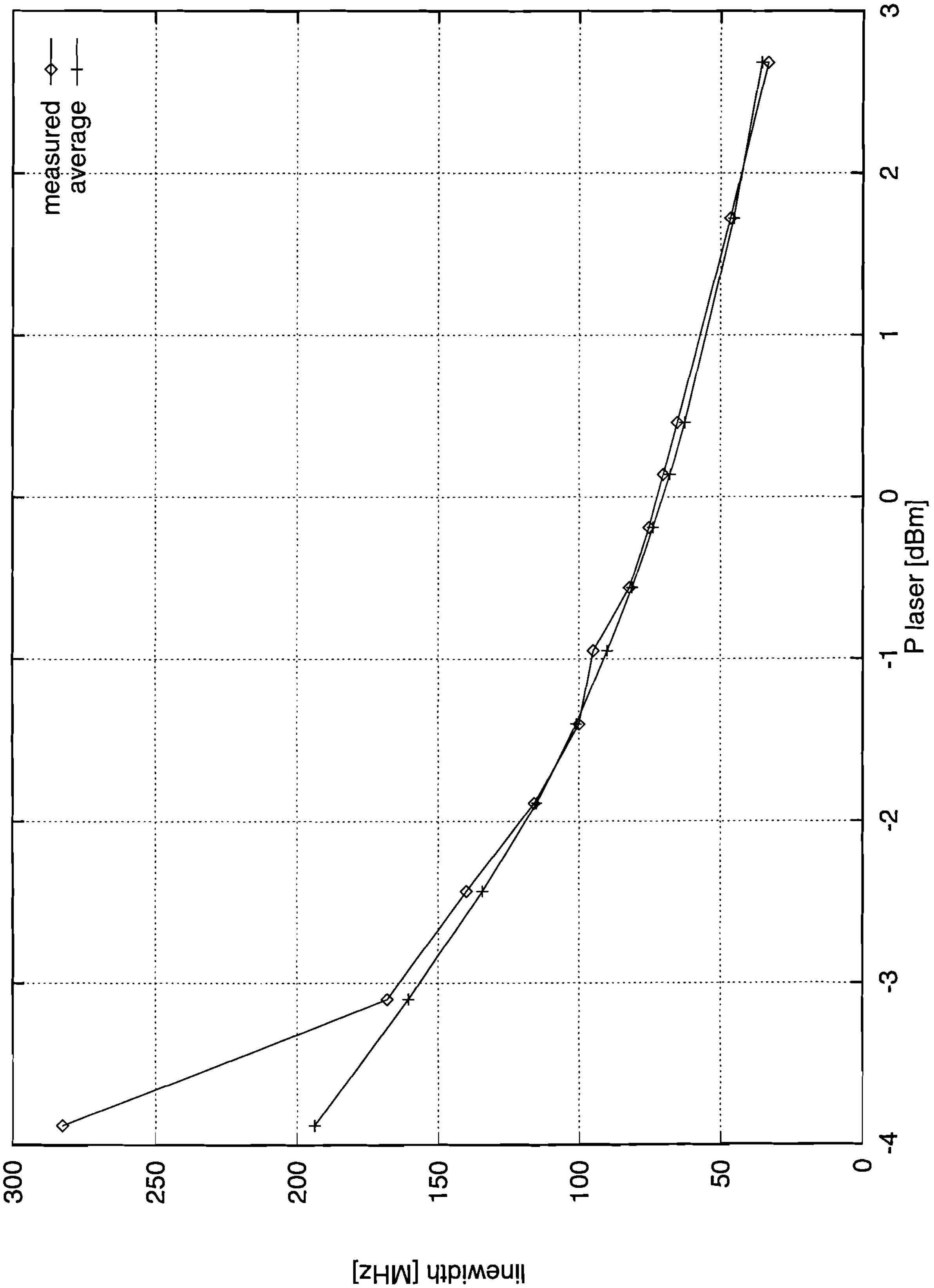

Figure B.18: Linewidth of laser & 4 SOA's (second measurement)

B.5.2 Second measurement of linewidth laser & 4 SOA's

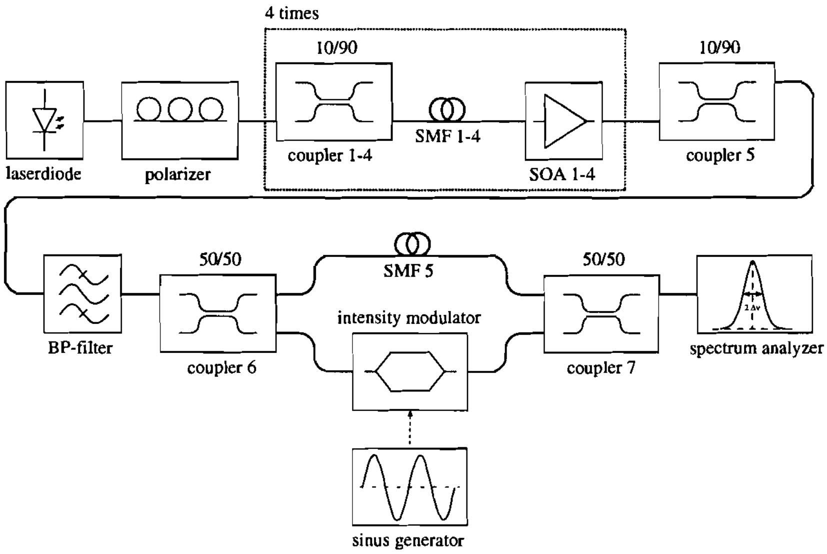

Figure B.19: Measurement circuit

Used equipment

laser:	#2284 PHILIPS CQF92/D
SOA 1:	#09 PHILIPS CQF882/E
SOA 2:	#13 PHILIPS CQF882/E
SOA 3:	#12 PHILIPS CQF882/E
SOA 4:	#14 PHILIPS CQF882/E
modulator:	EC355L; SUMICEM P/N:T-MZ 1.3-10
S/N:MZ4-256-24 #3146	
coupler 1-5:	90/10
coupler 6-7:	50/50
SMF 1:	50 km 1300nm, loss=17.8 dB
SMF 2:	50 km 1300nm, loss=17.9 dB
SMF 3:	50 km 1300nm, loss=18.8 dB
SMF 4:	50 km 1300nm, loss=18.9 dB
SMF 5:	2268 m 1300nm, loss=0.36dB/km
spectrum analyzer:	Display EC130G; HP 70004A
	RF Section ECO27A HP 70908A
	lightwave section EC020A; HP 70810B
	local oscilator EC021A; HP 70900A

I_{ld}[mA]	P_{ld}[dBm]	$P_{soa_{in}}$[dBm]	$P_{soa_{out}}$[dBm]	g_{ff}[dB]	$\Delta\nu_{ld+4soa}$[MHz] measured	$\Delta\nu_{ld}$	$\Delta\nu_{ld+4soa}$[MHz] $f = f_{avg}$	$\Delta\nu_{ld+4soa}$[MHz] $f = f_{min}$	$\Delta\nu_{ld+4soa}$[MHz] $f = f_{max}$
31	-3.88	-24.11	-6.75	23.36	222.00	193.51	193.73	193.61	193.91
32	-3.08	-23.74	-6.13	23.61	165.00	160.32	160.49	160.40	160.64
33	-2.45	-23.47	-5.66	23.81	134.50	134.10	134.24	134.17	134.36
34	-1.87	-23.37	-5.31	24.06	118.00	114.98	115.10	115.04	115.21
35	-1.38	-23.02	-4.97	24.05	105.65	100.96	101.05	101.00	101.13
36	-0.96	-22.74	-4.62	24.12	89.95	89.95	90.03	89.99	90.10
37	-0.54	-22.73	-4.37	24.36	82.80	81.17	81.24	81.20	81.30
38	-0.18	-22.43	-4.15	24.28	75.65	73.87	73.92	73.89	73.97
39	0.14	-22.18	-3.95	24.23	69.70	67.85	67.90	67.87	67.94
40	0.46	-22.02	-3.89	24.13	65.00	62.66	62.70	62.68	62.73
45	1.72	-21.94	-3.67	24.27	43.50	45.41	45.44	45.42	45.45
50	2.68	-21.58	-2.60	24.98	38.00	35.62	35.64	35.63	35.66

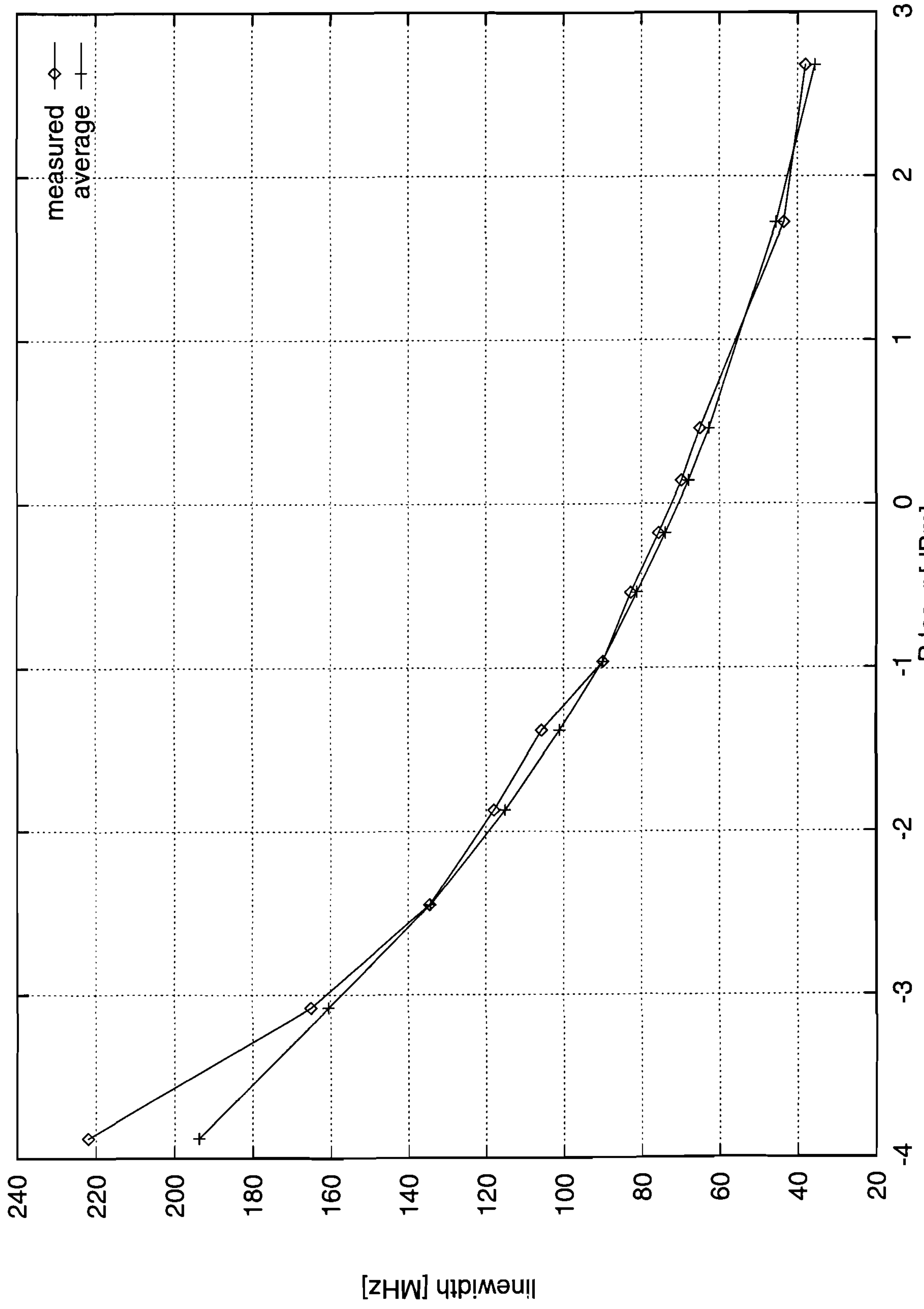

Figure B.20: Linewidth of laser & 4 SOA's (second measurement)

Appendix C

Phase-noise simulation code

C.1 Balanced receiver

C.1.1 Makefile

```
objects=ber-balanced.o golden1.o golden2.o

ber-balanced: $(objects)
gcc -g -o ber-balanced $(objects) -lm

ber-balanced.o: ber-balanced.c
gcc -g -c ber-balanced.c

golden1.o: golden1.c
gcc -g -c golden1.c

golden2.o: golden2.c
gcc -g -c golden2.c

clean:
rm $(objects)
```

C.1.2 ber-balanced.c

```
#include<stdio.h>
#include<math.h>

/* define external functions */
double golden1(double ax, double bx, double cx, double (*f)(double), double tol,double
double golden2(double ax, double bx, double cx, double (*f)(double), double tol,double

const double tol=1e-12;
```

```
double gamma=2*PI*1E-2;
double alpha;
double p;
double m;
double h;
double Pos_pValue;
double Neg_pValue;

/* calculate double derivative of the characteristic function */
double ddPhi(double s)
{
  double g12,g22,c1,c2,y;

  g12=sqrt(fabs(gamma*m*p*(exp(s)-1)));
  g22=sqrt(fabs(gamma*m*p*(exp(-s)-1)));
  c1=gamma*m*p;
  c2=sqrt(fabs(gamma*m*p));

  if (p>0)
    {
      y=0.5*m*(exp(s)+exp(-s))+0.5*p*m*(exp(s)-exp(-s))-
c1*exp(2*s)/(8*(exp(s)-1))-
sin(g12)*c2*exp(2*s)/(8*pow(1-exp(s),(double)3/2)*cos(g12))-
sin(g12)*c2*exp(s)/(4*sqrt(1-exp(s))*cos(g12))-
pow(sin(g12),2)*c1*exp(2*s)/(8*(exp(s)-1)*pow(cos(g12),2))+
c1*exp(-2*s)/(8*(exp(-s)-1))+
sin(g22)*c2*exp(-2*s)/(8*pow(exp(-s)-1,(double)3/2)*cos(g22))+
sin(g22)*c2*exp(-s)/(4*sqrt(exp(-s)-1)*cos(g22))+
pow(sin(g22),2)*c1*exp(-2*s)/(8*(exp(-s)-1)*pow(cos(g22),2))+
pow(s,-2);
    }
  else
    {
      y=0.5*m*(exp(s)+exp(-s))+0.5*p*m*(exp(s)-exp(-s))-
c1*exp(2*s)/(8*(exp(s)-1))-
sin(g12)*c2*exp(2*s)/(8*pow(exp(s)-1,(double)3/2)*cos(g12))+
sin(g12)*c2*exp(s)/(4*sqrt(exp(s)-1)*cos(g12))-
pow(sin(g12),2)*c1*exp(2*s)/(8*(exp(s)-1)*pow(cos(g12),2))+
c1*exp(-2*s)/(8*(exp(-s)-1))-
sin(g22)*c2*exp(-2*s)/(8*pow(1-exp(-s),(double)3/2)*cos(g22))-
sin(g22)*c2*exp(-s)/(4*sqrt(1-exp(-s))*cos(g22))+
pow(sin(g22),2)*c1*exp(-2*s)/(8*(exp(-s)-1)*pow(cos(g22),2))+
pow(s,-2);
    }
  return(y);
}
```

```
/* the characteristic function */
double Phi(double s)
{
  double y;

  y=0.5*m*(exp(s)-2+exp(-s))+0.5*p*m*(exp(s)-exp(-s))-
    0.5*log(cos(sqrt(fabs(gamma*m*p*(exp(s)-1)))))-
    0.5*log(cos(sqrt(fabs(gamma*m*p*(exp(-s)-1)))))-log(fabs(s));
  return(y);
}

/* calculate error chance */
double Pe(double x)
{
  double xlo,xhi,xavg;
  double qp,qm;
  double base;
  double s,y,phi;

  alpha=x;
  /* values where in between minimum lies */
  xlo=0;
  xavg=0.95*log(pow(PI,2)/(4*m*gamma)+1);
  xhi=log(pow(PI,2)/(4*m*gamma)+1);
  /* positive root */
  p=Neg_pValue;
  /* get minimum */
  phi=golden2(xlo,xavg,xhi,Phi,tol,&s);
  qp=exp(Phi(s))/sqrt(2*PI*ddPhi(s));
  xlo=0;
  xavg=-0.95*log(pow(PI,2)/(4*m*gamma)+1);
  xhi=-log(pow(PI,2)/(4*m*gamma)+1);
  /* negative root */
  p=Pos_pValue;
  /* get minimum */
  phi=golden2(xlo,xavg,xhi,Phi,tol,&s);
  phi=Phi(s);
  qm=exp(Phi(s))/sqrt(2*PI*ddPhi(s));
  y=(0.5*qp+0.5*qm);
  return(y);
}

/* calculate BER */
void CalcBer(char PeName[])
{
  double xlo,xavg,xhi,xmin;
  double BER;
```

```
  double mdB;
  FILE *fptr;

  /* open file to save BER */
  fptr=fopen(PeName,"w");
  for (mdB=0;mdB<50;mdB++)
    {
      /* calculate m */
      m=pow(10,mdB/10.0);
      /* values where in between minimum lies */
      xlo=0.01*m;
      xavg=0.5*m;
      xhi=m;
      /* calculation for line-width=0 phase-turn=180*/
      if ((gamma==0)&(Neg_pValue==-1))
{
  BER=0.5*exp(-1.0*m);
}
      /* calculation for other values line-width or phase-turn */
      else
{
  /*calculate BER */
  BER=Pe(0);
}
      /* print m,Ber to file */
      fprintf(fptr,"%e %e\n",mdB,BER);
    }
  fclose(fptr);
}

void main(void)
{
  char PeName[]="Peb1_1.data3";
  /* define line-width * bittime */
  double Garray[]={1e-1,3e-2,1e-2,5e-3,1e-3,1e-5,0.0};
/*  double Garray[]={1e-2,9E-3,8e-3,7e-3,6e-3,5e-3};*/
  /* 180,175,170,160,120,90 */
  /* define cos(incomplete phase turns) (less -1=180 degrees) */
  double Neg_Values[]={-1,-0.9962,-0.9848,-0.9397,-0.5,0};
  double Pos_Values[]={1,0.9962,0.9848,0.9397,0.5,0};
  int i,x;

  /* calculate BER-curve */
  for (x=0;x<6;x++)
    {
      /* change \omega\tau means  Neg_pValue=-Pos_PValue */
      /* complete phase turn */
```

```
      /* Pos_pValue=1;*/
      /* incomplete phase turn no 180 degrees */
      Pos_pValue=1;
      /* complete phase turn */
      /*     Neg_pValue=-1;*/
      /* incomplete phase turn no 180 degrees */
      Neg_pValue=Neg_Values[x];
      for (i=0;i<7;i++)
{
  gamma=2*PI*Garray[i];
  PeName[3]=i+49;
  PeName[5]=x+49;
  CalcBer(PeName);
}
    }
}
```

C.2 Unbalanced receiver

C.2.1 Makefile

```
objects=ber-unbalanced.o golden1.o golden2.o

ber-unbalanced: $(objects)
gcc -g -o ber-unbalanced $(objects) -lm

ber-unbalanced.o: ber-unbalanced.c
gcc -g -c ber-unbalanced.c

golden1.o: golden1.c
gcc -g -c golden1.c

golden2.o: golden2.c
gcc -g -c golden2.c

clean:
rm $(objects)
```

C.2.2 ber-unbalanced.c

```
#include<stdio.h>
#include<math.h>

/* define external functions */
double golden1(double ax, double bx, double cx, double (*f)(double), double tol,double
```

```
double golden2(double ax, double bx, double cx, double (*f)(double), double tol,doul

const double tol=1e-12;
double gamma=2*PI*1E-2;
double alpha;
double p;
double m;
double h;
double Pos_pValue;
double Neg_pValue;

/* calculate double derivative of the characteristic function */
double ddPhi(double s)
{
  double g,c,d,y;

  g=sqrt(fabs(gamma*m*p*(exp(s)-1)));
  c=0.5*gamma*m*p;
  d=sqrt(-gamma*m*p);

  if (p>0)
    {
      y=m/2.0*exp(s)*(1+p)-c*exp(2*s)/(4*(exp(s)-1))
-sin(g)*sqrt(2*c)*exp(2*s)/(8*pow(1-exp(s),3/2)*cos(g))
-sin(g)*sqrt(2*c)*exp(s)/(4*sqrt(1-exp(s))*cos(g))
-pow(sin(g),2)*c*exp(2*s)/(4*(exp(s)-1)*pow(cos(g),2))
+1.0/pow(s,2);
    }
  else
    {
      y=m/2.0*exp(s)*(1+p)-c*exp(2*s)/(4*(exp(s)-1))
-sin(g)*d*exp(2*s)/(8*pow(exp(s)-1,(double)3/2)*cos(g))
+sin(g)*d*exp(s)/(4*sqrt(exp(s)-1)*cos(g))
-pow(sin(g),2)*c*exp(2*s)/(4*(exp(s)-1)*pow(cos(g),2))
+1.0/pow(s,2);
    }
  return(y);
}

/* the characteristic function */
double Phi(double s)
{
  double y;

  y=(m/2.0)*(exp(s)-1)*(1+p)-0.5*log(cos(sqrt(fabs(gamma*p*m*(exp(s)-1)))))
    -s*alpha-log(fabs(s));
  return(y);
```

```
}

/* calculate error chance */
double Pe(double x)
{
  double xlo,xhi,xavg;
  double qp,qm;
  double base;
  double s,y,phi;

  alpha=x;
  /* values where in between minimum lies */
  xlo=0.0;
  xavg=0.95*log(pow(PI,2)/(4*m*gamma)+1);
  xhi=log(pow(PI,2)/(4*m*gamma)+1);
  /* positive root */
  p=Neg_pValue;
  if ((gamma==0) & (p==-1))
    {
      s=1/alpha;
    }
  else
    {
      /* get minimum */
      phi=golden2(xlo,xavg,xhi,Phi,tol,&s);
    }
      qp=exp(Phi(s))/sqrt(2*PI*ddPhi(s));
      if ((m*gamma)>(pow(PI,2)/2.0))
{
  base=log(1-pow(PI,2)/(4*m*gamma));
  xlo=0.0;
  xhi=0.99*base;
  xavg=0.95*base;
}
      else
{
  xavg=-1*m/alpha;
  xlo=0.0;
  xhi=-10;
}
  /* negative root */
  p=Pos_pValue;
  /* get minimum */
  phi=golden2(xlo,xavg,xhi,Phi,tol,&s);
  phi=Phi(s);
  qm=exp(Phi(s))/sqrt(2*PI*ddPhi(s));
  /* calculate Pe */
```

```
  y=(0.5*qp+0.5*qm);
  return(y);
}

/* calculate BER */
void CalcBer(char PeName[],char alpName[])
{
  double xlo,xavg,xhi,xmin;
  double BER;
  double mdB;
  FILE *fptr;
  FILE *aptr;

  /* open file to save BER */
  fptr=fopen(PeName,"w");
  fprintf(fptr,"#p+%i p-%i Dv.T%e\n",(int)acos(Pos_pValue)*360/(2*PI),
  (int)acos(Neg_pValue)*360/(2*PI),gamma/(2*PI));
  /* open file to save alpha */
  aptr=fopen(alpName,"w");
   for (mdB=0;mdB<50;mdB++)
    {
      /* calculate m */
      m=pow(10,mdB/10.0);
      xlo=0.01*m;
      xavg=0.5*m;
      xhi=m;
      /* calculation for line-width=0 phase-turn=180*/
      if ((gamma==0)&(Neg_pValue==-1))
{
  BER=0.5*exp(-1.0*m);
}
      /* calculation for other values line-width or phase-turn */
      else
{
    /* calculate BER */
  BER=golden1(xlo,xavg,xhi,Pe,tol,&xmin);
  /* print m,alpha/m to file */
  fprintf(aptr,"%e %e\n",m,xmin/m);
}
      /* print m,Ber to file */
      fprintf(fptr,"%e %e\n",mdB,BER);
    }
  fclose(fptr);
  fclose(aptr);
}

void main(void)
```

```
{
  char PeName[]="Pe1_1.data3";
  char alpName[]="alp1_1.data3";
  /* define line-width * bittime */
  double Garray[]={1e-1,3e-2,1e-2,5e-3,1e-3,1e-5,0.0};
 /*double Garray[]={1e-2,9E-3,8e-3,7e-3,6e-3,5e-3};*/
  /* 180,175,170,160,120,90 */
  /* define cos(phase) */
  double Neg_Values[]={-1,-0.9962,-0.9848,-0.9397,-0.5,0};
  /* 0,5,10,20,60,90 */
  /* define cos(phase) */
  double Pos_Values[]={1,0.9962,0.9848,0.9397,0.5,0};
  int i,x;

  for (x=0;x<6;x++)
    {
      /* calculate BER-curve */
      /* change \omega\tau means  Neg_pValue=-Pos_PValue */
      /* complete phase turn */
      /* Pos_pValue=1;*/
      /* incomplete phase turn no 180 degrees */
      Neg_pValue=Neg_Values[x];
      /*      Pos_pValue=1;*/
      /* incomplete phase turn no 0 degrees */
      Pos_pValue=1;
      for (i=0;i<7;i++)
{
  gamma=2*PI*Garray[i];
  PeName[2]=i+49;
  PeName[4]=x+49;
  alpName[3]=i+49;
  alpName[5]=x+49;
  CalcBer(PeName,alpName);
}
    }
}
```

Appendix D

ASE-noise simulation code

D.1 Makefile

```
objects=ase.o

ase: $(objects)
gcc -g -o ase $(objects) -lm

ase.o: ase.c
gcc -g -c ase.c

clean:
rm $(objects)
```

D.2 ase.c

```
#include<stdio.h>
#include<math.h>

/* plancks constant [J s]*/
#define h 6.6256E-34
/* elmatary charge */
#define q 1.6E-19
/* laser frequency (needed to calculate power) */
#define v0 2.28847E14
#define BitRate 10E9

int main(void)
{
  double Nshot0,Nshot1;
  double Ns_sp0,Ns_sp1;
  double Nsp_sp;
```

```
  double S0,S1;
  double Is0,Is1;
  double Isp;
  double Q,Pe;
  double A;
  int i,x;
  FILE *fileptr;

  /* Optical gain 26 [dB] */
  double G=398;
  /* ASE noise power */
  double Isp1soa=1.4*(G-1)*q*1.76E11;
  /* SOA output coupling efficiency */
  double eta_out=0.5;
  /* SOA input coupling efficiency */
  double eta_in=0.5;
  /* loss between SOA and receiver */
  double L=0.01;
  /* electrical Bandwidth */
  double Be=BitRate;
  /* optical Bandwidth */
  double Bo=1.77E11;
  /* signal power */
  double Ps=1E-4;
  int FileNum=0;
  char filename[]="aseQx.data";

  /* reveiver signal power '0' */
  Is0=0;
  /* receiver signal power '1' unbalanced */
  Is1=0.5*Ps*q/(h*v0);
  /* receiver signal power '1' balanced */
  A=1;

  /* x SOA's -> assumed loss between SOA's = amplification SOA's */
  for (x=0;x<6;x+=1)
    {
      A+=x*5;
      Isp=Isp1soa*A;
      filename[4]='0'+FileNum;
      FileNum++;
      fileptr=fopen(filename,"w");
      for (i=-80;i<=-25;i+=1)
{
  L=pow(10,(double)i/10.0);
  /* calculate signal (S0=0) */
  S0=G*Is0*eta_in*eta_out*L*G*Is0*eta_in*eta_out*L;
```

```
  S1=G*Is1*eta_in*eta_out*L*G*Is1*eta_in*eta_out*L;

  /* shot-noise '0' */
  Nshot0=2*Be*q*eta_out*L*(G*Is0*eta_in+Isp);
  /* signal-spontaneous beat noise '0' */
  Ns_sp0=4*G*Is0*eta_in*eta_out*eta_out*Isp*L*L*Be/Bo;
     /* shot-noise '1' */
  Nshot1=2*Be*q*eta_out*L*(G*Is1*eta_in+Isp);
  /* signal-spontaneous beat noise '1' */
  Ns_sp1=4*G*Is1*eta_in*eta_out*eta_out*Isp*L*L*Be/Bo;
  /* spontaneous-spontaneous beat noise '0' and '1' */
  Nsp_sp=((Isp*eta_out*L)*(Isp*eta_out*L)*Be*(2*Bo-Be))/(Bo*Bo);

  /* calculate Q */
  Q=(sqrt(S1)-sqrt(S0))/(sqrt(Nshot1+Ns_sp1+Nsp_sp)
 +sqrt(Nshot0+Ns_sp0+Nsp_sp));

  /* estimation */
  /* Pe=(1.0/sqrt(2*PI))*exp(-Q*Q/2)/Q; */
  /* print m and Q */
  fprintf(fileptr,"%e %e\n",10*log10(0.5*Ps*1E2*L/(h*v0*BitRate)),Q);
}
      fclose(fileptr);
    }
}
```

Appendix E

Simulation code

E.1 Makefile

```
objects=poidev.o ran1.o gammln.o golden.o gasdev.o \
dpsk_main.o filter.o sender.o receiver.o link.o rtsafe.o
CC=gcc
FLAGS= -O3

dpsk: $(objects)
$(CC) $(FLAGS) -o dpsk $(objects) -lm

dpsk_main.o: dpsk_main.c
$(CC) $(FLAGS) -c dpsk_main.c

filter.o: filter.c
$(CC) $(FLAGS) -c filter.c

sender.o: sender.c
$(CC) $(FLAGS) -c sender.c

receiver.o: receiver.c
$(CC) $(FLAGS) -c receiver.c

link.o: link.c
$(CC) $(FLAGS) -c link.c

poidev.o: poidev.c
$(CC) $(FLAGS) -c poidev.c

ran1.o: ran1.c
$(CC) $(FLAGS) -c ran1.c

gammln.o: gammln.c
```

```
$(CC) $(FLAGS) -c gammln.c

golden.o: golden.c
$(CC) $(FLAGS) -c golden.c

gasdev.o: gasdev.c
$(CC) $(FLAGS) -c gasdev.c

rtsafe.o: rtsafe.c
$(CC) $(FLAGS) -c rtsafe.c

clean:
rm $(objects)
```

E.2 sender.h

```
#ifndef __SENDER_H
#define __SENDER_H

char getbit(void);
void LaserParam(double *I,double *Dv,double *A);
void Laser(double *E_re,double *E_im,double dt,double v_in);
double fi(int status);

#endif /* __SENDER_H */
```

E.3 send.c

```
#include"dpsk_main.h"

extern double ran3(long int *idum);
extern double gasdev2(long int *idum);

/* the bit pattern (NPattern+1), first bit must be zero !*/
char Pattern[NPattern]={0,1,0,1,0,0,1,1,0,0,1,0,1,1,0,0,1,0,0,0,1,0,1};

char getbit(void)
{
  int P[23][23]={
    {1},
    {1,1},
    {1,0,1},
    {1,0,0,1},
    {0,1,0,0,1},
```

```
    {1,0,0,0,0,1},
    {0,0,0,0,0,1,1},
    {1,0,0,0,1,1,0,1},
    {0,0,0,1,0,0,0,0,1},
    {0,0,1,0,0,0,0,0,0,1},
    {0,1,0,0,0,0,0,0,0,0,1},
    {0,0,1,1,0,0,1,0,0,0,0,1},
    {1,0,1,1,0,0,0,0,0,0,0,0,1},
    {1,0,0,0,0,0,0,0,0,0,1,1,0,1},
    {1,0,0,0,0,0,0,0,0,0,0,0,0,0,1},
    {0,1,1,0,1,0,0,0,0,0,0,0,0,0,0,1},
    {0,0,1,0,0,0,0,0,0,0,0,0,0,0,0,0,1},
    {0,0,0,0,0,0,1,0,0,0,0,0,0,0,0,0,0,1},
    {1,0,0,0,1,1,0,0,0,0,0,0,0,0,0,0,0,0,1},
    {0,0,1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,1},
    {0,1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,1},
    {1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,1},
    {0,0,0,0,1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,1},
  };
  int T,k;


  T=0;
  for (k=0;k<NPattern;k++)
    {
      T+=Pattern[NPattern-1-k]*P[NPattern-1][k];
    }
  /* shift pattern */
  for (k=0;k<(NPattern-1);k++)
  {
    Pattern[k]=Pattern[k+1];
  }
  Pattern[NPattern-1]=T%2;

  return(Pattern[0]);
}


void LaserParam(double *I,double *Dv,double *A)
/* calculate linewidth and optical power/field laser */
{
  /* variables or based on measurement */
  const double C=31.2E6;
  /* direction coefficient of linear part P(I) graph laser */
  const double r=0.074;
  /* threshold current */
  const double Ith=26.6E-3;
```

```
  if ((*I==0) & (*Dv!=0))
    {
      *I=C*Ith/ *Dv+Ith;
    }
  else
    {
    /* laser linewidth */
      *Dv=C/((*I/Ith)-1);
    }
  if (*I<=Ith)
    {
      printf("Please start using the laser as an laser, I(=%f)>Ith(=%f)",*I,Ith);
    }
  if (*I<40E-3)
    {
      printf("I<40 is not in the linear part of P(I), I(=%f) can't calculate P",*I)
    }
  if (*I>100E-3)
    {
      printf("Congratulations you just blew up the laser,I(=%f)<100",*I);
    }
      /* laser field */
      *A=(*I-25E-3)*r;
}
```

E.4 link.h

```
#ifndef __LINK_H
#define __LINK_H

void SLA(double *I,double *N,double *Dv, double gain);
void Loss(double *I,double *N,double loss);
double AmplifierGain(double Pin,int AmplifierSettings);
void Amplifier(double *E_re,double *E_im,long int NumOfSamples,
       double *v_in,double gain, double dt);
double FibreLoss(double length);
double RandomPhase(double B);

#endif /* __LINK_H */
```

E.5 link.c

```
#include "dpsk_main.h"
```

```
extern double gasdev(long int *);
extern double ran1(long int *);

double rtsafe(void *,double ,double,double,double,double);

void *AmplifierFunc(double x,double *f,double *df,double Pin, double G0)
{
  const double ln2=0.6931471;
  const double Psat=10E-3;

  *f=G0*pow(2,-(x-1)*Pin/(Psat-Pin))-x;
  *df=-G0*pow(2,-(x-1)*Pin/(Psat-Pin))*Pin/(Psat-Pin)*ln2-1;
}


/* calculate gain */
double AmplifierGain(double Pin,int AmplifierSetting)
{
  double G0[]={398,631,1000,1258,1584,1995,1995};
  const double Psat=10E-3;
  double G;

  /* calculate root of function AmplifierFunc in area [1,G0[]] */
  /* Pin an G0[] are needed to discribe amplifier in AmplifierFunc */
  G=rtsafe(AmplifierFunc,1,G0[AmplifierSetting],0.1,Pin,G0[AmplifierSetting]);

  return(G);
}

double  RandomPhase(double B)
{
  double phase;
  phase=(ran1(&seed1)-0.5)*2;
  return(phase);
}

/* calculate signal and ASE-noise amplification and linewidth */
void SLA(double *I,double *N,double *Dv, double gain)
{
  double f;
  double Nsp;
  const double alpha_h=6.5;
  const double G_n=3.2E-20;
  const double L=800E-6;
  const double k=450;
  const double T=0.3;
```

```
  const double n_sp=1.4;
  const double y=5e9;
  const double r=0.24;
  const double A=2.25E-13;
  const double Ba=1.136E13;

  *I *=gain;
  Nsp=n_sp*(gain-1)*h*v0*Ba;
  *N=gain* *N+Nsp;
  f=pow((( alpha_h*G_n*(log(gain)/L+k))/(T*log(gain)/L)),2)
    *(n_sp*(gain-1)*Ba*pow(gain,2)*r)/(2*y*pow(A,2)*log(gain))*PI/y;
  *Dv = *Dv *(1+f* *Dv);
}

/* calculate power loss of the link (loss measured) */
void Loss(double *I,double *N,double loss)
{
  /* convert from dB */
  loss=pow(10,loss/10);
  *I/=loss;
  *N/=loss;
}

/* calculate fibre loss */
double FibreLoss(double length)
{
  /* fibre loss in dB/km */
  const double fibre_loss=0.3;

  return(sqrt(length*pow(10,fibre_loss/10)));
}
```

E.6 receiver.h

```
#ifndef __RECEIVER_H
#define __RECEIVER_H

double BalancedBER(double alpha,double *Ipd1,double *Ipd2);
double UnbalancedBER(double alpha,double *Ipd);
void Balanced(double *E_re,double *E_im,double *Ipd1,double *Ipd2,double N,double D
void Unbalanced(double *E_re,double *E_im,double *Ipd, double N ,double Dv);

#endif /* __RECEIVER_H */
```

E.7 receiver.c

```
#include "dpsk_main.h"
#include "receiver.h"
#include "link.h"

extern char Pattern[NPattern];
extern double gasdev2(long *idum);


/* calculate phase noise due to finite linewidth */
void PhaseNoise(double *E_re,double *E_im,double Dv)
{
  double phase;

  /* when time-interval is long enough (e.g. 1*bittime T) */
  /*= gaussian phase */
  phase=sqrt(PI*Dv*1.0/(BitRate*SamplesPerBit))*gasdev2(&seed3);
  *E_re=*E_re*cos(phase);
  *E_im=*E_re*sin(phase);
}/* calculate phase noise due to finite linewidth */

void ASENoise(double *E_re, double *E_im,double Nsp,double Ba)
{
  double AsePhase;
  const double Bo=1.13E13;
  /* bandwidth behind filter ! */

  AsePhase=RandomPhase(Ba);
  *E_re+=sqrt((Nsp/Bo)*Ba)*cos(PI*AsePhase+PI/2.0);
  *E_im+=sqrt((Nsp/Bo)*Ba)*sin(PI*AsePhase+PI/2.0);
}

char DetectPbrs(char bit)
{
  /* first bit is zero */
  static char oldbit=0;
  char tbit;

  tbit=oldbit;
  oldbit=bit;
  bit=tbit^bit;
  return(bit);
}

/* calculate shotnoise (poisson ditribution) */
```

```
double ShotNoise(double Iavg)
{
  double shotnoise;
  FILE *fileptr;
  if (Iavg<0) exit(0);
  /*
    {
      shotnoise=-1*(poidev(fabs(Iavg)/(q*BitRate),&seed2)*q*BitRate);
    }
  else*/
    {
      shotnoise=(poidev(Iavg/(q*BitRate),&seed2)*q*BitRate);
    }
  return(shotnoise);
}

double UnbalancedBER(double alpha,double *Ipd)
{
  int error=0;
  int i;
  double bit=0;
  double t;

  for (i=0;i<SamplesPerBit;i++)
    {
      bit+=Ipd[i];
    }
  /* adding shotnoise here is simpler and faster as before he integrate */
  bit=ShotNoise(bit/SamplesPerBit);
  t=DetectPbrs(Pattern[0]);
  /* due to machine inaccuracy 0 might not be 0 */
  if ( ( (bit>alpha) & (t!=1.0) ) |
       ( (bit<=alpha+1E-20) & (t!=0.0) ) )
    {
      error=1;
    }
  return(error);
}

double BalancedBER(double alpha,double *Ipd1,double *Ipd2)
{
  int error=0;
  int i;
  double bit1=0;
  double bit2=0;
  double bit;
  double t;
```

```
  FILE *fileptr1;
  FILE *fileptr2;

  for (i=0;i<SamplesPerBit;i++)
    {
      bit1+=Ipd1[i];
      bit2+=Ipd2[i];
    }
  /* adding shotnoise here is simpler and faster as before he integrate */
  bit1/=(double)SamplesPerBit;
  bit2/=(double) SamplesPerBit;
  bit1=ShotNoise(bit1);
  bit2=ShotNoise(bit2);
  bit=bit1-bit2;
  t=DetectPbrs(Pattern[0]);
  if ( ( (bit>alpha) & (t!=1.0) ) |
       ( (bit<=alpha+1E-20) & (t!=0.0) ) )
    {
      error=1;
    }
  return(error);
}

/* unbalanced receiver */
void Unbalanced(double *E_re,double *E_im,double *Ipd,double Nsp,double Dv)
{
  const double Cdetect=PdEff*q/(h*v0);
  static double Eold_re[SamplesPerBit];
  static double Eold_im[SamplesPerBit];
  double Ere_out,Eim_out;
  int i;
  const double Ba=1.77E11;
  double A=0.5;
  double B=0.5;


  for (i=0;i<SamplesPerBit;i++)
    {
      /* add phase noise */
      PhaseNoise(&E_re[i],&E_im[i],Dv);
      /* add ASE noise */
      ASENoise(&E_re[i],&E_im[i],Nsp,Ba);
/*      *E_im+=sqrt(Nsp)*sin(AsePhase);*/
      Ere_out=A*Eold_re[i]-B*E_re[i];
      Eim_out=A*Eold_im[i]-B*E_im[i];
      /* keep last bit = delay line */
      Eold_re[i]=E_re[i];
```

```
      Eold_im[i]=E_im[i];
      Ipd[i]=Cdetect*(Ere_out*Ere_out+Eim_out*Eim_out);
    }
}

/* balanced receiver */
void Balanced(double *E_re,double *E_im,double *Ipd1,double *Ipd2,double Nsp,double
{
  const double Cdetect=PdEff*q/(h*v0);
  static double Eold_re[SamplesPerBit];
  static double Eold_im[SamplesPerBit];
  double Ere_out1,Ere_out2,Eim_out1,Eim_out2;
  int i;
  double A=0.5;
  double B=0.5;
/*  const double Nsp=1.78E-9;*/
/*  const double Ba=BitRate;*/
  const double Ba=1.77E11;
  double AsePhase;
  double phasenoise;

/*  PhaseNoise(&E_re[i],&E_im[i],Dv);*/
  /* get phasenoise */
  /*  phasenoise=GetPhaseNoise(Dv); */
  for (i=0;i<SamplesPerBit;i++)
    {
      /* add phase noise */
      /*      E_re[i]=E_re[i]*cos(phasenoise)-E_im[i]*sin(phasenoise);
      E_im[i]=E_re[i]*sin(phasenoise)+E_im[i]*cos(phasenoise);*/
      PhaseNoise(&E_re[i],&E_im[i],Dv);
      /* add ASE noise */
      ASENoise(&E_re[i],&E_im[i],Nsp,Ba);

      Ere_out1=A*Eold_re[i]-B*E_re[i];
      Ere_out2=A*Eold_re[i]+B*E_re[i];
      Eim_out1=A*Eold_im[i]-B*E_im[i];
      Eim_out2=A*Eold_im[i]+B*E_im[i];
      /* keep last bit = delay line */
      Eold_re[i]=E_re[i];
      Eold_im[i]=E_im[i];
      Ipd1[i]=Cdetect*(Ere_out1*Ere_out1+Eim_out1*Eim_out1);
      Ipd2[i]=Cdetect*(Ere_out2*Ere_out2+Eim_out2*Eim_out2);
/*      Ipd[i]=ShotNoise(Ipd[i]);*/
    }
}
```

E.8 dpsk main.h

```
#ifndef __DPSKMAIN_H
#define __DPSKMAIN_H

#include<stdlib.h>
#include<stdio.h>
#include<math.h>
#include<string.h>
#include<time.h>


/* define light speed in vacuum */
#define cv 3E8
#ifndef PI
#define PI M_PI
#endif
#define INIT 0
#define RESET 1
#define CALC 2
#define UNBALANCED 1
#define BALANCED 2

/* external declared functions */
/*========================================================================*/

/*extern   fft(int n, double xRe[], double xIm[], double yRe[], double yIm[]);*/
/*extern void prbs(int M,int N,int Pattern[],int *PRBS_OUT);*/
/*extern void detect(int M,int *PRBS_IN,int *DPSK_OUT);*/
double golden(double ax, double bx, double cx, double (*f)(double,double,double),double
double poidev(double xm, long *idum);

/* GLOBAL VARS */
/*========================================================================*/
#define NPattern 23
#define SamplesPerBit 1

/* plancks constant [J s]*/
#define h 6.6256E-34

/* elmatary charge */
#define q 1.6E-19
/* laser frequency (needed to calculate power) */
#define v0 2.28847E14
/* bit rate */
#define BitRate 10E9
```

```
/* efficiency photo diode */
#define PdEff 0.8


long int seed1;
long int seed2;
long int seed3;
/* total linewidth */
double Dv;

#endif /*__DPSK_MAIN_H */
```

E.9 dpsk main.c

```
/* This program calculataes the BER of a DPSK system */
/* The model simulates the different parts of the circuit as black boxes*/
/* The field is calculated over one bit at a time, this to save memory and cpu speec

#include"link.h"
#include"sender.h"
#include"receiver.h"
#include"filter.h"

/* calculate the optimal decision moment alpha for the unbalanced receiver */
/* alpha=0.5*(alpha_max-alpha_min) where alpha_max and alpha_min are */
/* the values at which a certain BER is reached */
double OptimizeAlpha(double A,double Dv,double N,double m)
{
  double AlphaStart1=0;
  double AlphaStart2=0.5*m*A*A;
  double ErrorStop;
  double alpha,MinAlpha,MaxAlpha;
  char bit;
  double E_re[SamplesPerBit];
  double E_im[SamplesPerBit];
  double Ipd[SamplesPerBit];
  double count=0;
  double Error;
  int i;
  double l;
  int j;
  double I;

  alpha=AlphaStart1;
  /* calculate alpha at which Pe>ErrorStop starting at min alpha */
  while ((Error/count) < ErrorStop)
```

```
    {
      count=0;
      Error=0;
      while (Error<10)
{
  /* get bit outof prbs */
  bit=getbit();
  for (i=0;i<SamplesPerBit;i++)
    {
      E_re[i]=A*(cos((int)bit*PI));
      E_im[i]=A*(sin((int)bit*PI));
    }
  count++;
  /* unbalanced receiver */
  Unbalanced(E_re,E_im,Ipd,N,Dv);
  /* Check error */
  Error+=UnbalancedBER(alpha,Ipd);
}
      /* set true alpha values with 0.01 steps */
      alpha+=0.01;
    }
  MinAlpha=alpha;
  /* calculate alpha until Pe>ErrorStop starting at max alpha */
  alpha=AlphaStart2;
  while ((Error/count)<ErrorStop)
    {
      count=0;
      Error=0;
      while (Error<10)
{
  bit=getbit();
  for (i=0;i<SamplesPerBit;i++)
    {
  E_re[i]=A*(cos((int)bit*PI));
  E_im[i]=A*(sin((int)bit*PI));
    }
  count++;
  Unbalanced(E_re,E_im,Ipd,N,Dv);
  Error+=UnbalancedBER(alpha,Ipd);
}
      alpha-=0.01;
    }
  MaxAlpha=alpha;
  /* alpha=0.5*(alpha_max-alpha_min) */
  return(0.5*(MaxAlpha-MinAlpha));
}
```

```
/* Calculate BER unbalanced system */
int UnbalancedSystem(void)
{
  char bit;
  double E_re[SamplesPerBit];
  double E_im[SamplesPerBit];
  double Ipd[SamplesPerBit];
  double count=0;
  double alpha;
  double Error;
  int i;
  int FileNum=0;
  double l;
  int j;
  double A,Abase,Nbase;
  double I,m,N,Int,Attenuation;
  double min,max,avg;
  FILE *fileptr;
  FILE *fileptr2;
  char filename[]="uberx.dat";
  double gain;
  double MaxError;
  double link1;

  Error=0;
  count=0;
  /* define laser current */
  I=40E-3;
  /* calculate linewidth Dv and ouput power Int for laser with current I */
  LaserParam(&I,&Dv,&Int);

  m=PdEff*q/(h*v0);
  for (j=4;j<6;j++)
    {
      N=0;
      /* initialize random number generators */
      seed1=-rand();
      seed2=-rand();
      seed3=-1L*time(NULL);
      gasdev2(&seed3);


      filename[4]='1'+FileNum;
      /* clear file */
      fileptr2=fopen(filename,"w");
      fclose(fileptr2);
```

```
      /* next run, next file */
      FileNum++;

      /* calculate link (here:the link in the lab) */
      /* Int=signal power */
      /* N=ASE-noise power */
      /* Dv=linewidth */
      /*==========================================*/
      /* loss modulator + connection [dBm] */
      Loss(&Int,&N,8);
      /* link 1 */
      link1=j*5;
      Loss(&Int,&N,link1);
      gain=AmplifierGain(Int+N,0);
      SLA(&Int,&N,&Dv,gain);
      /* link 2 */
      Loss(&Int,&N,20);
      gain=AmplifierGain(Int+N,0);
      SLA(&Int,&N,&Dv,gain);
      /* link 3 */
      Loss(&Int,&N,20);
      gain=AmplifierGain(Int+N,0);
      SLA(&Int,&N,&Dv,gain);
      /* link 4 */
      Loss(&Int,&N,20);
      gain=AmplifierGain(Int+N,0);
      SLA(&Int,&N,&Dv,gain);

      Abase=sqrt(Int);
      Dv=5E-3*BitRate;
      Nbase=N;
      fileptr2=fopen(filename,"a");
      fprintf(fileptr2,"# Psignal=%e Pase=%e Dv=%e\n",Int,N,Dv);
      fclose(fileptr2);

      /* attenuation at receiver !!! */
      Attenuation=sqrt((q*BitRate)/m)/Abase;
      for (l=0;l<=35;l++)
{
  A=Abase*Attenuation;
  N=Nbase*Attenuation*Attenuation;
  Attenuation*=1.122;
  Error=0;
  count=0;
  /* optimal discision value alpha */
  alpha=OptimizeAlpha(A,Dv,N,m);
  /* calculate bits until n errors have occured or Ber<1E-10 */
```

```
  MaxError=5;
  /* calculate bits until n errors have occured or Ber<1E-10 */
  while ((Error<MaxError)&(count!=5E10))
    {
      /* get bit outof prbs */
      bit=getbit();
      /* take SamplesPerBit samples per bit */
      /* 1 sample should be enough */
      for (i=0;i<SamplesPerBit;i++)
{
  E_re[i]=A*(cos((int)bit*PI));
  E_im[i]=A*(sin((int)bit*PI));
}
      count++;
      /* unbalanced receiver */
      Unbalanced(E_re,E_im,Ipd,N,Dv);
      /* Check error */
      Error+=UnbalancedBER(alpha,Ipd);
    }
  if (count==5E10)
    {
      /* don't calculate anything below Ber=1E-10 so exit */
      Error=MaxError;
      break;
    }
  else
    {
      /* write Ber to file*/
      fileptr2=fopen(filename,"a");
      fprintf(fileptr2,"%e %e\n",10*log10((m*A*A)/(q*BitRate)),Error/count);
      fclose(fileptr2);
    }
}
    }
  return 0;
}

int BalancedSystem(void)
{
  char bit;
  double E_re[SamplesPerBit];
  double E_im[SamplesPerBit];
  double Ipd1[SamplesPerBit],Ipd2[SamplesPerBit];
  double count=0;
  double alpha;
  double Error;
  int i;
```

```
int FileNum=0;
double l;
int j;
double A,Abase,Nbase;
double I,m,N,Int,Attenuation;
double min,max,avg;
double MaxError;
FILE *fileptr;
FILE *fileptr2;
char filename[]="lberx.dat";
double gain;
double var=0;
double link1;

Error=0;
count=0;
/* define laser current */
I=100E-3;
m=PdEff*q/(h*v0);

/* calculate linewidth Dv and ouput power Int for laser with cuurent I */
LaserParam(&I,&Dv,&Int);
/* calculate ber curve for different linewidths */
for (j=0;j<5;j++)
  {
    N=0;
    /* initialize random number generators */
    seed1=-rand();
    seed2=-rand();
    seed3=-1L*time(NULL);
    gasdev2(&seed3);
    /*initialize filename (ber1.dat,ber2.dat etc) */
    filename[4]='1'+FileNum;
    /* clear file */
    fileptr2=fopen(filename,"w");
    fclose(fileptr2);

    /* next run, next file */
    FileNum++;

    /* calculate link (here:the link in the lab) */
    /* Int=signal power */
    /* N=ASE-noise power */
    /* Dv=linewidth */
    /*==========================================*/
    /* loss modulator + connection [dBm] */
    Loss(&Int,&N,8);
```

```
      /* link 1 */
      link1=j*5;
      Loss(&Int,&N,link1);
      gain=AmplifierGain(Int+N,0);
      SLA(&Int,&N,&Dv,gain);
      /* link 2 */
      Loss(&Int,&N,20);
      gain=AmplifierGain(Int+N,0);
      SLA(&Int,&N,&Dv,gain);
      /* link 3 */
      Loss(&Int,&N,20);
       gain=AmplifierGain(Int+N,0);
      SLA(&Int,&N,&Dv,gain);
      /* link 4 */
      Loss(&Int,&N,20);
      gain=AmplifierGain(Int+N,0);
      SLA(&Int,&N,&Dv,gain);

      Abase=sqrt(Int);
      /* linewidth =x*T (define it when we want to keep linewidth fixed */
      /*  Dv=1E-2*BitRate;*/
      Nbase=N;
      fileptr2=fopen(filename,"a");
      fprintf(fileptr2,"# Psignal=%e Pase=%e Dv=%e\n",Int,N,Dv);
      fclose(fileptr2);
      /* output attenuation */
      /* the graphic should start at  10log(M)=0 (M=A*A*m/q*BitRate) */
      Attenuation=sqrt((q*BitRate)/m)/Abase;
      for (l=0;l<=35;l++)
{
  A=Abase*Attenuation;
  N=Nbase*Attenuation*Attenuation;
  Attenuation*=1.122;
  Error=0;
  count=0;
  /* optimal discision value is 0 for balanced receiver */
  alpha=0;
  MaxError=5;
  /* calculate bits until n errors have occured or Ber<1E-10 */
  while ((Error<MaxError)&(count!=5E10))
    {
      /* get bit outof prbs */
      bit=getbit();
      /* take SamplesPerBit samples per bit */
      /* 1 sample should be enough */
      for (i=0;i<SamplesPerBit;i++)
{
```

```
  E_re[i]=A*(cos((int)bit*PI));
  E_im[i]=A*(sin((int)bit*PI));
}
      count++;
      /* balanced receiver */
      Balanced(E_re,E_im,Ipd1,Ipd2,N,Dv);
      /* Check if error occured */
      Error+=BalancedBER(alpha,Ipd1,Ipd2);
    }
  if (count==5E10)
    {
      /* don't calculate anything below Ber=1E-10 so exit */
      Error=MaxError;
      break;
    }
  else
    {
      /* write Ber to file*/
      fileptr2=fopen(filename,"a");
      fprintf(fileptr2,"%e %e\n",10*log10((m*A*A)/(q*BitRate))
      ,Error/count);
      fclose(fileptr2);
    }
}
    }
  return 0;
}


/* calculate the signal, ASE noise and linwidths in a SOA link */
int link()
{
  double Int;
  double N;
  double Dv;
  double gain;
  int x;
  FILE *fileptr;

  fileptr=fopen("/temp/data/link.data","w");
  fclose(fileptr);
  for (x=0;x<7;x++)
    {
      fileptr=fopen("/temp/data/link.data","a");
      Int=0.01;
      Dv=25E6;
      N=0;
```

```
      fprintf(fileptr,"\nI=%i\n",x*50+100);
      fprintf(fileptr,"A=%e N=%e v=%e\n",Int,N,Dv);
      Loss(&Int,&N,1);
      fprintf(fileptr,"A=%e N=%e\n",Int,N);
      gain=AmplifierGain(Int+N,x);
      fprintf(fileptr,"G=%e\n",gain);
      SLA(&Int,&N,&Dv,gain);
      fprintf(fileptr,"A=%e N=%e v=%e\n",Int,N,Dv);
      Loss(&Int,&N,2);
      fprintf(fileptr,"A=%e N=%e\n",Int,N);
      gain=AmplifierGain(Int+N,x);
      fprintf(fileptr,"G=%e\n",gain);
      SLA(&Int,&N,&Dv,gain);
      fprintf(fileptr,"A=%e N=%e v=%e\n",Int,N,Dv);
      Loss(&Int,&N,3);
      fprintf(fileptr,"A=%e N=%e\n",Int,N);
      gain=AmplifierGain(Int+N,x);
      fprintf(fileptr,"G=%e\n",gain);
      SLA(&Int,&N,&Dv,gain);
      fprintf(fileptr,"A=%e N=%e v=%e\n",Int,N,Dv);
      fclose(fileptr);
    }
  return(0);
}

/* comment or uncomment one of the functions to preform the calculation */
/* the user interface is not finished */
int main(void)
{
  int rvalue;
  int i;

/*============================================================*/

/* calculate the signal, ASE noise and linwidths in a SOA link */
/*  rvalue= link();*/

/*============================================================*/

/* calculate amplifier curve */
/*  for (i=1;i<50;i++)
    {
      AmplifierGain(1E-5*i,0);
    }*/
/*=============================================================*/

/*calculate BER of unbalanced system */
```

```
 /*  rvalue=UnbalancedSystem(); */

/*============================================================*/

/*calculate BER of balanced system */
 rvalue=BalancedSystem();

/*==========================================================*/

  return(rvalue);
}
```