A NOVEL OPTICAL TRANSMISSION METHOD USING

AN INLINE PHASE MODULATOR

By

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This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the Division of Graduate Education.

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ABSTRACT

This thesis presents a novel optical communication technique that provides a second, low data rate channel on an existing high-speed fiber optic link. The second channel is derived using an acousto optic fiber phase modulator and interferometeric receiver. This method modulates the optical phase of the primary high speed optical signal with a low frequency sine wave. At the receiving end of the low speed path, an interferometer and band pass fiber are used to recover the low-speed signal. Information is carried on the low frequency sine wave by use of FSK modulation. The method is non-invasive in that the low-speed channel is derived without electrically, optically or physically affecting the performance of the high-speed optical path. The method is ideal for overlaying network management channels on a fiber network. The thesis includes both analysis and experimental verification of the technique

CHAPTER ONE

INTRODUCTION

Optical Fiber Transmission System

Optical fiber transmission systems have been widely deployed as infrastructure for backbone networks for more than two decades. Optical fiber can offer almost unlimited bandwidth and some other unique advantages over all previously developed transmission media, such as light weight, high signal quality, and low loss (0.2 dB/km). Currently almost every telephone conversation, cell phone call, and Internet packet has to pass through some piece of optical fiber from source to destination. Basically an optical fiber point-to-point transmission system consists of three parts: the optical transmitter, the optical fiber, and the optical receiver. The optical transmitter is responsible for converting an electrical analog or digital signal into a corresponding optical signal. The optical fiber guides the optical signal from source to destination over some distance. The optical receiver is responsible for converting optical signal back to an electrical signal. Figure 1 shows a basic optical fiber transmission system. The signal is typically transmitted by intensity modulation (On Off Keying).

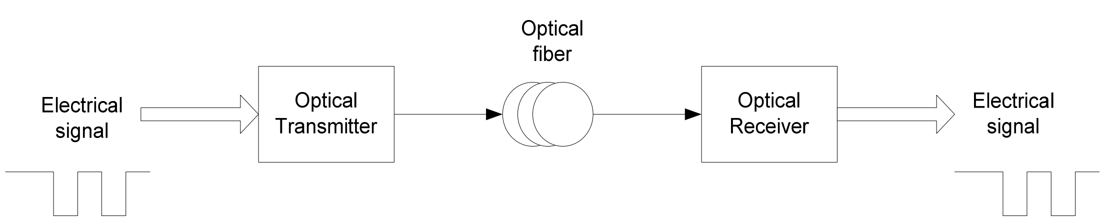


Figure 1.1 A basic optical transmission system

Modulation Technique in Optical Fiber Transmission System

Currently in an optical transmission system the most common modulation technique is On Off Keying (OOK) where ‘light on’ represents data 1, and ‘light off’ represents data 0. At the receiver end the light is directly detected by a photo-diode. This kind of modulation is also called Intensity Modulation and Direct Detection (IM/DD). The main advantage of OOK is its simplicity in implementing the design of modulators and demodulators. There are two types of modulators for OOK modulation: direct and external. When data rates are in the low gigabit range and transmission distances are less than 100 km, most fiber optic transmitters use direct modulators where lasers are directly turned on and off by the input electrical signals. As data rates and span lengths increase, waveguide chirp caused by turning a laser on and off, limits data rates. The solution is to use an external modulator such as a Mach-Zehnder (MZ) interferometer following the laser. The optical fields in the two arms of the MZ interferometer interfere constructively or destructively, which makes the optical intensity on or off.

Thesis Background

Currently, only the intensity of an optical signal is used to encode information for transmission [1]. Some other modulation techniques have been proposed in the past ten years as promising candidates for the next generation of optical transmission; but OOK will still be in use for a long time because of its simplicity [2-3]. OOK is an amplitude modulated technique and it does not make use of the optical phase. In other words, the optical phase of the optical transmission signal has been wasted. On the other hand, laser technology has developed very quickly, and much narrower linewidth and stable lasers are already used in optical fiber transmission systems [4-7]. It is now possible to make use of optical phase in intensity modulation systems.

In this thesis, a method using the optical phase of an optical carrier in an OOK system is proposed, analyzed and demonstrated. A second transmission channel can be created by using this method without affecting the primary OOK transmission. The additional channel created could be very useful in delivering system control, management, and monitoring signals [8].

The system model of the proposed method is described in Chapter 2. Chapter 3 shows the simulation results. Chapter 4 talks about the system considerations. Chapter 5 discusses system noise and Bit Error Rate (BER) estimations. The exploratory lab experiment is provided in Chapter 6. And the conclusion is given in Chapter 7.

CHAPTER TWO

SYSTEM MODEL

System Description

Figure 2.1 shows a typical long haul IM/DD optical fiber transmission system. In such a system information is modulated into light intensity by an external Mach Zehnder (MZ) interferometer. After the MZ modulator the optical signal passes through an Erbium Doped Fiber Amplifier (EDFA) to boost the optical power. EDFAs are also used periodically to compensate fiber loss. At the receiver end, the optical signal is converted to an electrical signal using a fast photodiode.

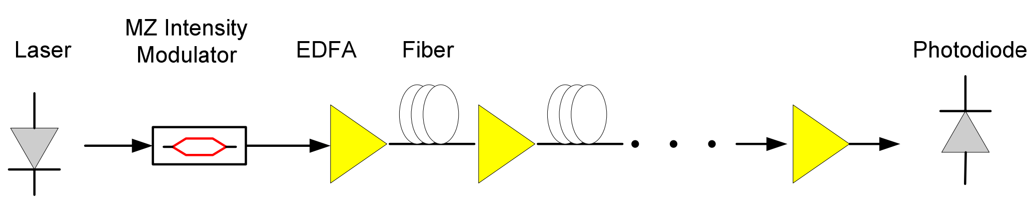


Figure 2.1 Typical configuration of an IM/DD system

The proposed phase modulation transmission system is based on the above IM/DD system. Figure 2.2 shows the proposed system configuration. After the intensity modulator we insert an optical phase modulator that modulates the optical phase of primary intensity modulated signals sinusoidally. The information data of the second channel is represented by different frequencies using Frequency Shift Keying (FSK). At the receiver end we pick off a portion of the transmitted signal by using an optical coupler. The signal is directed into an interferometer where the phase modulated signal is demodulated and converted to an intensity modulated signal. A photodiode is used to convert the optical signal to an electrical signal. The demodulated intensity signal consists of some harmonics, so an electrical band pass filter is used after the photodiode to eliminate higher order components and reduce the electrical noise. Since this modulation method is modulating the optical phase, it will not change the light intensity of the OOK transmission. In other words, it will not affect the primary OOK transmission.

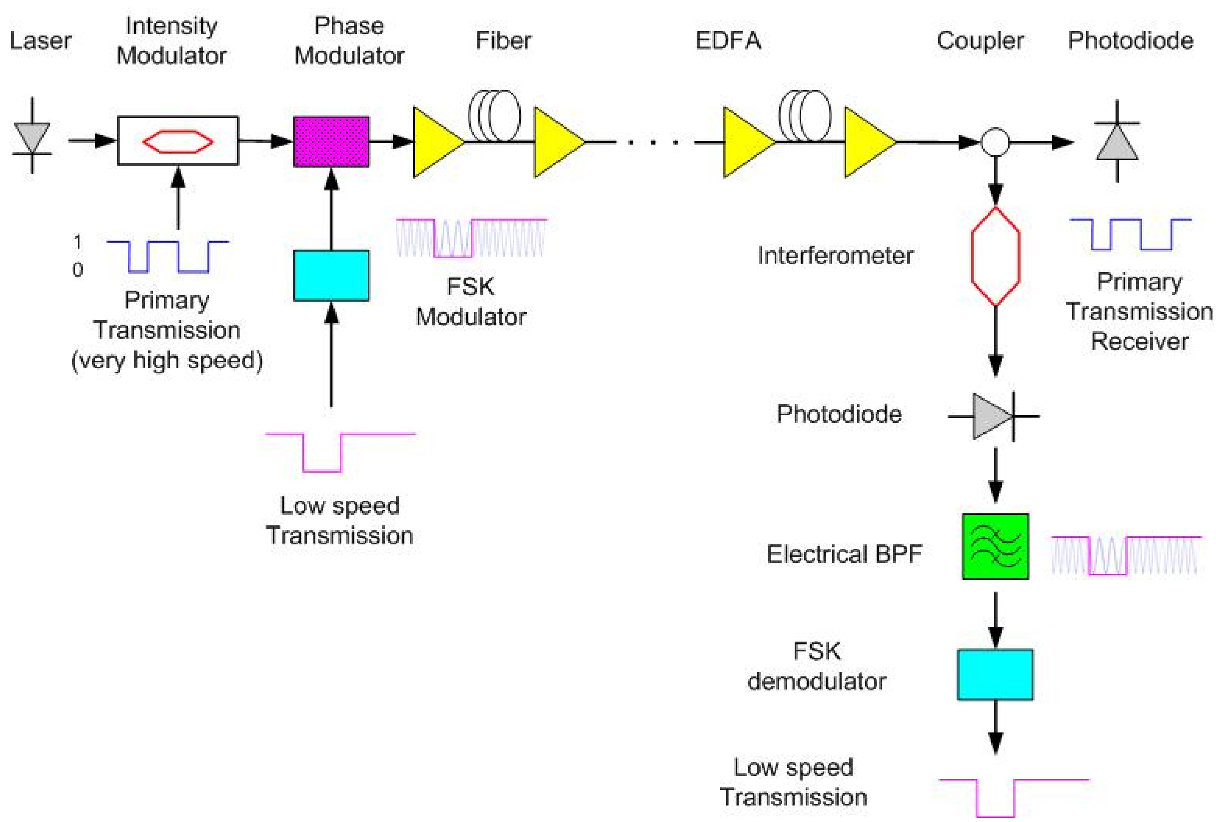


Figure 2.2 System configuration of the proposed modulation method

Modulation Format

OOK light pulses propagating in the optical transmission system can be described by

$$E(z,t) = \sum_k a_k A(z,t-T_b)\cos(\omega t - \beta z) \tag{2.1}$$

where E(z,t) is the electrical field of the light pulses, a_k represents the kth symbol in the message sequence, A(z,t) is the complex field envelope , ω is the light frequency, β is the light propagation constant equal to 2πn/λ, n is the effective refractive index and λ is the wavelength. Transmitted OOK light pulses are illustrated in figure 2.3.

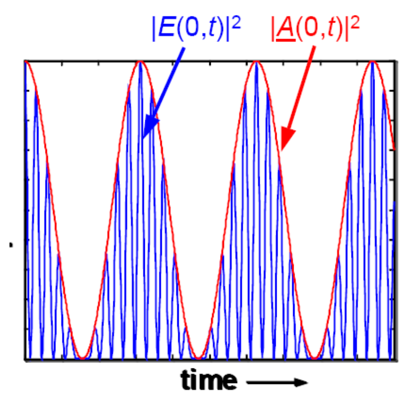


Figure 2.3 Light pulse

The data rate for the primary OOK transmission is typically several GHz or more, while the sine wave frequency for the proposed phase modulation method is several MHz or less. Therefore, the phase modulation method can be thought of as on a Continuous Wave (CW) light carrier, which can be described by the following equation [9-10].

$$E(z,t) = A\cos(\omega t - \beta z) \tag{2.2}$$

In this system, data 1 or 0 are represented by different frequencies f_i, so the electrical field of the modulated light signal can be expressed by

$$E(z,t) = A\cos(\omega t - \beta z + A_m \cos(2\pi f_i t + \psi_0)) \quad (2.3)$$

where A_m is the phase deviation ($A_m \leq \pi$) ; f_i is the frequency of the low speed sinusoidal wave; ψ_0 is the initial phase, which is an arbitrary value between 0 and 2π and can be thought of as 0 for simplicity. Equation 2.3 can be simplified to

$$E(z,t) = A\cos(\omega t - \beta z + A_m \cos(2\pi f_i t)) \quad (2.4)$$

We can also describe equation 2.4 in complex form

$$E(z,t) = \mathrm{Re}\{Ae^{j(-\beta z)} e^{jA_m \cos(2\pi f_i t)} e^{j\omega t}\} \quad (2.5)$$

Compared to Phase Shift Keying (PSK) modulations, such as Binary PSK, Quadrature PSK, and Differential PSK, this modulation method is novel. Conventional phase modulation techniques use discrete phase shift to represent 0 and 1. For this modulation method, the optical phase shift is a continuous sine wave, and we use different frequencies f_i to represent information.

Interferometer

An interferometer is used in the system to demodulate the phase modulated signal into an intensity modulated signal. When two mutually coherent light waves are present simultaneously in the same region, they will interfere with each other. The total wave function is the sum of individual electric fields. If these two light waves have the same frequency, the new complex amplitude is the superposition of individual complex amplitudes, and the intensity is the square of the new complex amplitude.

Let $U_1(z)$ and $U_2(z)$ be the complex amplitudes of two monochromatic light waves which are superposed.

$$U_1(z) = I_1^{1/2} e^{j\psi_1} \, ; \; U_2(z) = I_2^{1/2} e^{j\psi_2} \tag{2.6}$$

The new light wave is still a monochromatic light wave with the same frequency, and the new complex amplitude is given by [11]

$$U(z) = U_1(z) + U_2(z) . \tag{2.7}$$

The intensity is the square of new complex amplitude [11]

$$\begin{aligned} I &= |U|^2 = |U_1 + U_2|^2 = |U_1|^2 + |U_2|^2 + U_1 U_2^* + U_1^* U_2 \\ &= I_1 + I_2 + I_1^{1/2} I_2^{1/2} e^{j(\psi_1 - \psi_2)} + I_1^{1/2} I_2^{1/2} e^{j(\psi_2 - \psi_1)} \\ &= I_1 + I_2 + 2 I_1^{1/2} I_2^{1/2} \cos(\psi_2 - \psi_1). \end{aligned} \tag{2.8}$$

Now let's take a look at how an interferometer retrieves phase modulated signals in the proposed system. The interferometer shown in figure 2.4 is made up of two 50:50 couplers and two optical fiber paths with different lengths L_1, L_2. At the first coupler, the incoming light is equally split into two parts and these two light waves go through different paths. At the second coupler, these two light signals are superposed and interfere with each other. Since they have gone through different distances, there is a time shift or phase shift between them.

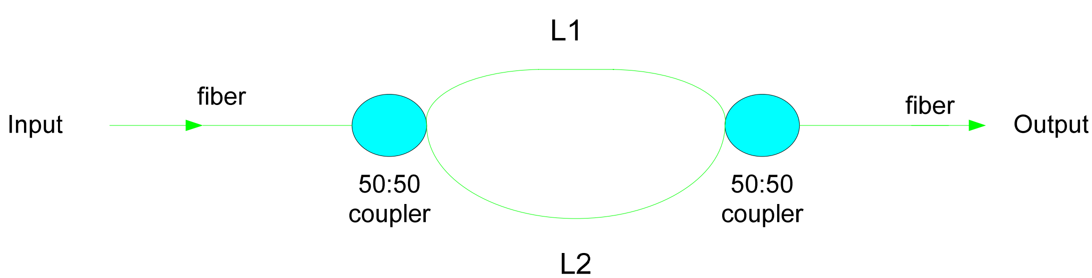


Figure 2.4 An interferometer with two 50:50 couplers

Let U_1 denote the complex amplitude of light at the point of the second coupler that has gone through the upper path of the interferometer and U_2 denote the complex amplitude of light that has gone through the lower path. U_1 and U_2 can be expressed by

$$\begin{aligned} U_1(t) &= \sqrt{I_0}\exp(j(-\beta L_1 + A_m\cos(\omega_m(t-\frac{nL_1}{c}))) \\ U_2(t) &= \sqrt{I_0}\exp(j(-\beta L_2 + A_m\cos(\omega_m(t-\frac{nL_2}{c}))) \end{aligned} \tag{2.9}$$

where I_0 is half of the input intensity, and $\omega_m=2\pi f_i$.

Let ψ_1 and ψ_2 denote the optical phase of these two light waves on the different paths, and we have

$$\begin{aligned} \psi_1 &= -\beta L_1 + A_m\cos(\omega_m(t-\frac{nL_1}{c})), \\ \psi_2 &= -\beta L_2 + A_m\cos(\omega_m(t-\frac{nL_2}{c})). \end{aligned} \tag{2.10}$$

After the second coupler the phase modulated signal is converted to an intensity modulated signal. From equation 2.8 the intensity after the interferometer is dependent on the phase difference of the two arms of the interferometer. The phase difference is given as

$$\psi_2 - \psi_1 = -\beta(L_2 - L_1) + A_m[\cos(\omega_m(t-\frac{nL_2}{c})) - \cos(\omega_m(t-\frac{nL_1}{c}))] \tag{2.11}$$

Simplifying the second term, we obtain

$$
\begin{aligned}
& A_m[\cos(\omega_m(t-\frac{nL_2}{c}))-\cos(\omega_m(t-\frac{nL_1}{c}))] \\
&= A_m[-2\sin(\frac{\omega_m(t-\frac{nL_2}{c})-\omega_m(t-\frac{nL_1}{c})}{2})\sin(\frac{\omega_m(t-\frac{nL_2}{c})+\omega_m(t-\frac{nL_1}{c})}{2})] \\
&= A_m[-2\sin(\frac{\omega_m(-(\frac{nL_2}{c}-\frac{nL_1}{c}))}{2})\sin(\frac{2\omega_m t-\frac{\omega_m nL_2}{c}-\frac{\omega_m nL_1}{c}}{2})] \\
&= 2A_m\sin(\frac{\omega_m n(L_2-L_1)}{2c})\sin(\omega_m t-\frac{\omega_m n(L_2+L_1)}{2c})
\end{aligned}
\tag{2.12}
$$

In this equation, the term before the second sine function is a constant dependent on the phase deviation of modulation, modulation frequency, and the length difference of the two interferometer arms. The second sine term is a time function with the modulation frequency. We simplify equation 2.12 by

$$A_{con}\sin(\omega_m t+\varphi_0) \tag{2.13}$$

$$\text{where } A_{con}=2A_m\sin(\frac{\omega_m n(L_2-L_1)}{2c})\ ;\ \varphi_0=-\frac{\omega_m n(L_2+L_1)}{2c} \tag{2.14}$$

Neglecting the initial phase of φ_0, the phase difference becomes

$$\psi_2-\psi_1=-\beta(L_2-L_1)+A_{con}\sin(\omega_m t) \tag{2.15}$$

If the light powers for each arm of the interferometer are identical, from equation 2.8 the intensity after interferometer can be described by

$$
\begin{aligned}
I(t) &= I_{in}(1+\cos(\psi_2-\psi_1)) \\
&= I_{in}[1+\cos(-\beta(L_2-L_1)+A_{con}\sin(\omega_m t))]
\end{aligned}
\tag{2.16}
$$

where I_{in} is the input light intensity and $-\beta(L_2-L_1)$ can be thought of as the initial phase.

Fundamental Component and Bessel Function

From equation 2.16 we can see that the intensity after the interferometer looks like a phase modulation function on a direct current (DC) signal. We can use the famous Bessel functions to expand it. Then we pick up the fundamental frequency component which has the same frequency as the modulating frequency at the transmitter end. We first expand the cosine function of equation 2.16 and describe it by

$$\begin{aligned} I(t) &= I_{in}[1+\cos(-\beta(L_2-L_1)+A_{con}\sin(\omega_m t))] \\ &= I_{in}[1+\cos(\beta(L_2-L_1))\cos(A_{con}\sin(\omega_m t)) \\ &+\sin(\beta(L_2-L_1))\sin(A_{con}\sin(\omega_m t))] \end{aligned} \tag{2.17}$$

Well known results from applied mathematics state that [12]

$$\begin{aligned} \cos(\beta\sin\omega_m t) &= J_0(\beta)+\sum_{neven}^{\infty}2J_n(\beta)\cos n\omega_m t \\ \sin(\beta\sin\omega_m t) &= \sum_{nodd}^{\infty}2J_n(\beta)\sin n\omega_m t \end{aligned} \tag{2.18}$$

where n is positive, β is the modulation index, and

$$J_n(\beta)\equiv\frac{1}{2\pi}\int_{-\pi}^{\pi}\exp(j(\beta\sin\lambda-n\lambda))d\lambda. \tag{2.19}$$

The coefficient $J_n(\beta)$ are Bessel functions of the first kind, of order n and argument β. By using the Bessel functions, we can expand the intensity by

$$\begin{aligned} I(t) &= I_{in}[1+\cos(\beta(L_2-L_1))\cdot(J_0(A_{con})+\sum_{neven}^{\infty}2J_n(A_{con})\cos n\omega_m t) \\ &+\sin(\beta(L_2-L_1))\cdot(\sum_{nodd}^{\infty}2J_n(A_{con})\sin n\omega_m t)] \end{aligned} \tag{2.20}$$

Let's take a look at the term inside the first sine function, $\beta(L_2-L_1)$. In this term, β represents the phase propagation constant $2\pi n/\lambda$. Because the wavelength is about 1.3 or 1.5 μm and the difference (L_2-L_1) is several meters or several centimeters, the term inside the sine function will be very big. On the other hand, if the fiber length of the interferometer changes a little, this term might vary a lot. Although this term looks unpredictable, it is easy and practical to put a mechanical phase modulator in one arm of the interferometer to adjust it, because the variation of the fiber length changes very slowly due to environmental effects. We may take the value of 0.5 for the whole sine function term in equation 2.20 for simplicity. Then equation 2.20 becomes

$$I(t) = I_{in}\{1 + 0.5J_0(A_{con}) + J_1(A_{con})\sin\omega_m t + J_2(A_{con})\cos 2\omega_m t + J_3(A_{con})\sin 3\omega_m t + J_4(A_{con})\cos 4\omega_m t + \cdots\} \tag{2.21}$$

Since the fundamental frequency component is our concern, we use a bandpass filter to eliminate DC and higher order components. Then the intensity becomes

$$I(t) = I_{in}J_1(A_{con})\sin\omega_m t \tag{2.22}$$

We get a sine wave signal at the receiver whose amplitude depends on the input light power, the length difference of interferometer arms, and the phase deviation of modulation.

<u>Intensity parameters optimization</u>

From equation 2.22 we can see that after the interferometer the phase modulated signal has been converted to an amplitude modulated sine wave signal with the same modulation frequency as the modulated sine signal at the transmitter end. The strength of this signal is dependent on the input light power, the length difference of interferometer arms, and a coefficient of Bessel functions of the first kind. To get the maximum signal to noise ratio (SNR), thus reducing the bit error rate (BER), it is very important to optimize the signal strength by adjusting these related factors: the length difference of the interferometer arms, modulation amplitude, and modulation frequency.

We consider the coefficient of the Bessel function $J_1(A_{con})$. Figure 2.5 shows the relationship between the coefficients of Bessel function of the first kind and modulation index, which is A_{con} here. From the figure we can see that for a modulation index from 0 to about 1.9, J_1 increases from 0 to 0.58. When the modulation index is bigger than 1.9, J_1 begins to decrease. The coefficient of Bessel function J_1 looks like a periodic wave. If we can make the modulation index A_{con} around the region of about 1.9, we can get the biggest value of J_1, thus increasing the strength of the received signal. From equation 2.14 we know the modulation index comprises three major factors: phase deviation of modulation, modulation frequency, and the length difference of the interferometer arms. To obtain a modulation index A_{con} around 1.9, the phase deviation that represents the maximum phase shift of the modulation A_m should be around 0.95 rad and the value of the following sine function should be close to 1. Now consider the term inside the sine wave of equation 2.14, $\omega_m n(L_2-L_1)/2c$. If the modulation frequency is about 100 MHz, and the refractive index of optical fiber is about 1.47, we can adjust the length difference of the interferometer's two arms to make the value of the whole term to be around $\pi/2$.

$$\frac{\omega_m n(L_2 - L_1)}{2c} = \frac{\pi}{2}. \tag{2.23}$$

$$L_2 - L_1 = \frac{c}{2 f_m n} = \frac{3 \cdot 10^8}{2 \cdot 1.47 \cdot f_m} = \frac{1.02 \cdot 10^8}{f_m}, \tag{2.24}$$

where the unit is meter.

From equation 2.24 we can see that to optimize J_1, the length difference of the interferometer arms is dependent on the modulation frequency.

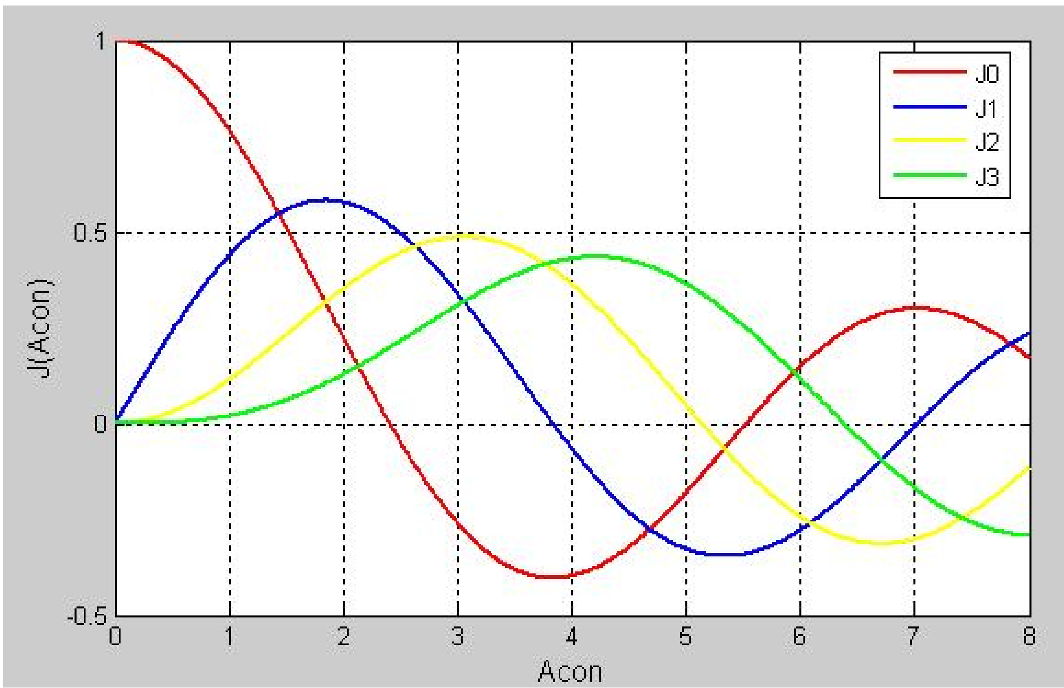


Figure 2.5 The relationship between coefficients of Bessel functions of the first kind and modulation index

CHAPTER THREE

SYSTEM SIMULATION

OptSim Introduction

The proposed system was simulated with RSOFT's OptSim software. OptSim is one of the most advanced optical communication system simulation software tools and gives us an intuitive modeling and simulation environment. It supports the design and the performance evaluation of the transmission level of optical communication systems and can be used to model WDM, DWDM, TDM, CATV, optical LAN, parallel optical bus, and other emerging optical systems. It also provides an easy-to-use graphical user interface and lab-like simulation results analysis instruments on both Windows and UNIX platforms. It has a large library of flexible component models and simulation algorithms providing a good trade-off between accuracy and speed.

Simulation Model

Figure 3.1 shows the OptSim simulation model for the proposed system. Because the OptSim software is not suited to simulate lower-data-rate FSK modulation, only sine wave verification is done in this model. On the left side of the figure is a typical CW laser, followed by a MZ external modulator that is modulated at a data rate of 10 Gb/s. Following the MZ modulator is an optical phase modulator that is modulated by a sine wave signal. The optical power is boosted using an EDFA before being launched into an optical fiber. The right side of the figure shows the primary 10 Gb/s OOK receiver and phase demodulator for the proposed system. First a splitter is used to pick off some light signal for the primary OOK transmission, then that light signal is directed into an interferometer where the phase modulated signal is demodulated into an intensity modulated signal as described in chapter 2. Following the interferometer a photo diode is used to convert the optical signal into an electrical signal. Six band pass filters (BPF) are put after the photo diode to observe the six harmonics in the electrical signal.

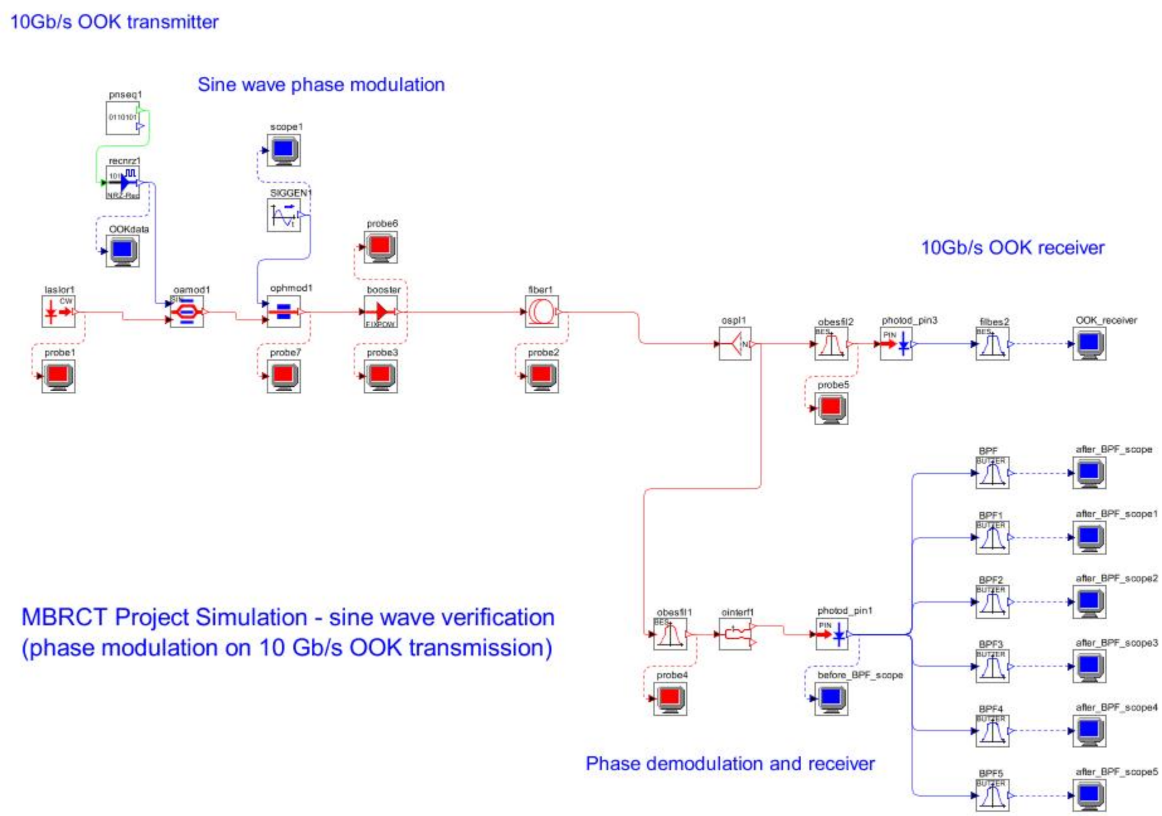


Figure 3.1 OptSim simulation model for the proposed system

Simulation Results

First to make sure that the phase modulation does work in the simulation model, we compare results with phase modulation on and off. Figure 3.2 shows the simulated oscilloscope figure before the BPF when the phase modulation is on, and figure 3.3 shows the comparison when the phase modulation is off. From these two figures we can see that when the phase modulation is on, there are three major components in the signal: DC, fundamental frequency, and the second harmonic. This result is similar to the results obtained using MATLAB as shown in figure 3.4. The source code is given in appendix A. When the phase modulation is off, we see a flat signal on the scope, which means the optical phase between two arms of the interferometer are identical. When we use a band pass filter, we can select the fundamental frequency and eliminate the other two. Figure 3.5 shows the sine wave we get after the band pass filter.

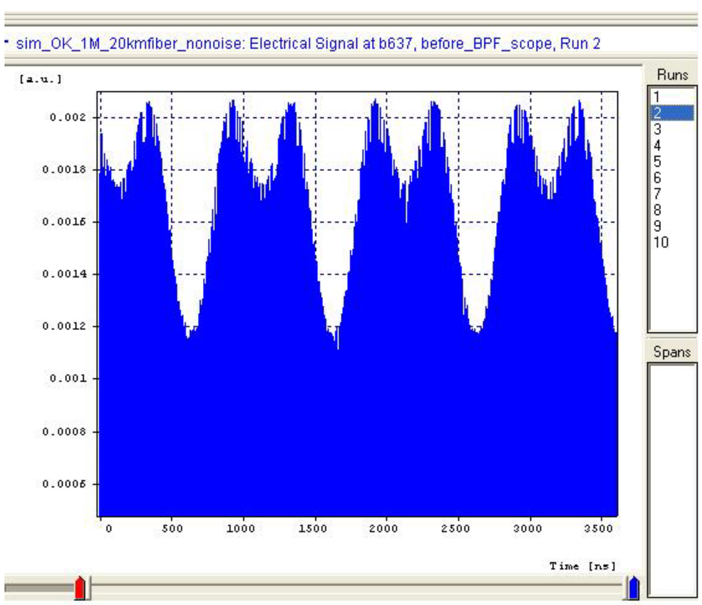


Figure 3.2 OptSim scope figure before BPF when phase modulation is on

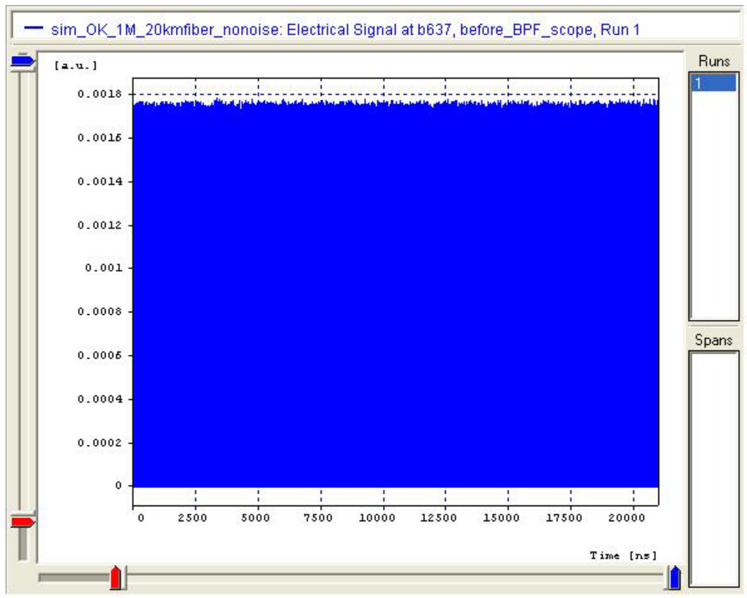


Figure 3.3 OptSim scope figure before BPF when phase modulation is off

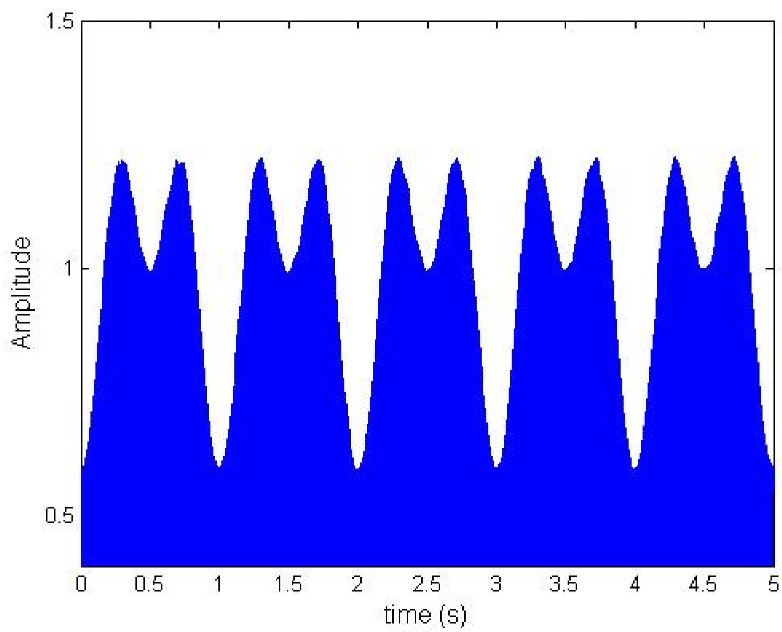


Figure 3.4 MATLAB plot for a signal in which DC, fundamental frequency, and the second harmonic are the major components

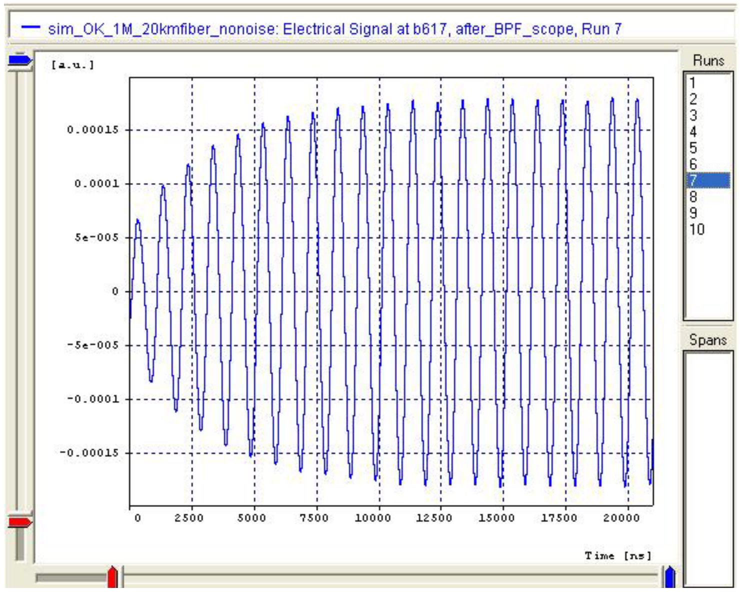


Figure 3.5 OptSim scope figure after BPF

The simulation has verified that sinusoidally modulating the optical phase of the primary high speed OOK optical signal at the transmitter end, we can easily recover the sine wave signal at the receiver end using the proposed method. The major components in the signal after interferometer and before the band pass filter are DC signal, the fundamental frequency, and the second harmonic. The simulation has also verified that the length difference of the interferometer two arms does not affect the frequency of the modulation sine wave signal, but it will affect the signal's strength at the receiver end. So by changing the length difference of the interferometer two arms, we can modify the signal's strength to get the best performance of the system.

CHAPTER FOUR

SYSTEM CONSIDERATIONS

Maximum Modulation Frequency

In chapter 2 we assumed that the phase modulation is put on a CW channel. This assumption is made because compared to the high speed primary OOK transmission, the optical phase modulation frequency is very slow. This section will demonstrate that this assumption is almost correct. This section will also give a quantitative explanation.

In the proposed system, the phase modulation sine wave signal which represents low speed information bits is put on the primary OOK light pulses. We may think of the primary OOK light pulses as the sampling points for the sine wave of the phase modulation signal. However, the sample period here is not constant. From Nyquist theory, to recover the original signal, the sampling frequency must be at least double the signal frequency [13]. To make sure that we have enough samples to retrieve the sine wave, the data rate for the primary OOK transmission should be much higher than the optical phase modulation frequency. In other words, for a given OOK channel, the optical phase modulation frequency should be far below the primary channel data rate.

In a typical digital transmission system, the probability of 1 or 0 occurrences is 0.5. Because light off represents information bit 0, we need to calculate the probability of successive zeros in the digital transmission. The probability of 50 successive zero bits is given by

$$P_e = (\frac{1}{2})^{50} = 8.88 \cdot 10^{-16} \tag{4.1}$$

These 50 successive zeros mean that the sampling frequency for the phase modulation signal is 2% of the OOK data rate. The sampling frequency must be double the signal frequency. So the maximum signal's frequency is 1% of the OOK data rate. From equation 4.1 we can see that if the modulation frequency is 1% of the data rate of the primary OOK transmission, we are likely to be able to recover the sine wave from the primary high speed OOK transmission. The probability of being unable to recover the original signal is below $8.88\text{x}10^{-16}$, which is far below the primary OOK system's bit error rate (BER). Figure 4.1 shows a MATLAB simulation with high speed pseudo random binary sequence (PRBS) OOK data as sample points and the frequency of the sine wave is 1% of the data rate of the OOK transmission. The source code is given in appendix A. We can clearly see that the sine wave can be retrieved from the primary OOK transmission signal when the maximum signal's frequency is 1% of the OOK data rate. We select 1% as the maximum ratio for the modulation frequency to OOK data rate for the proposed system.

For comparison, Figure 4.2 shows a MATLAB emulation where the frequency of the sine wave is 8% of the data rate of the OOK transmission. We can not see a clear sine wave from this figure. The reason is that there are not enough sampling points to retrieve the sine wave signal.

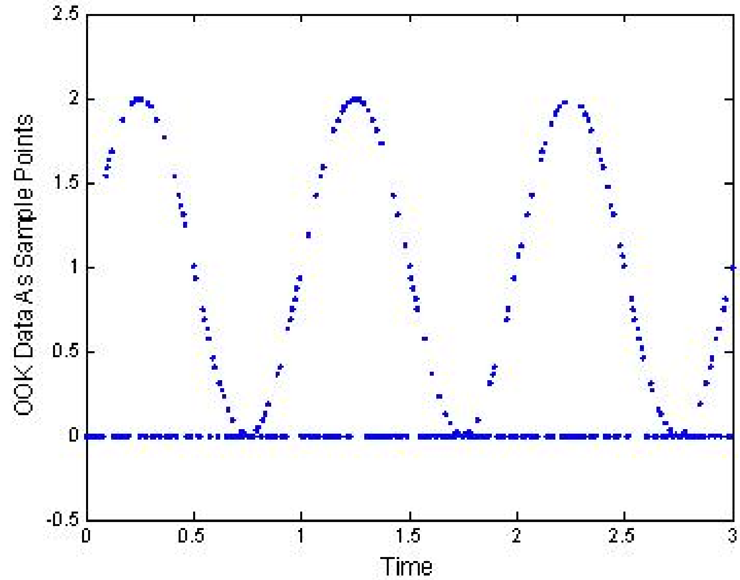


Figure 4.1 MATLAB calculation, a sine wave, whose frequency is 1% of the data rate of high speed OOK binary signals, is put in the primary OOK transmission

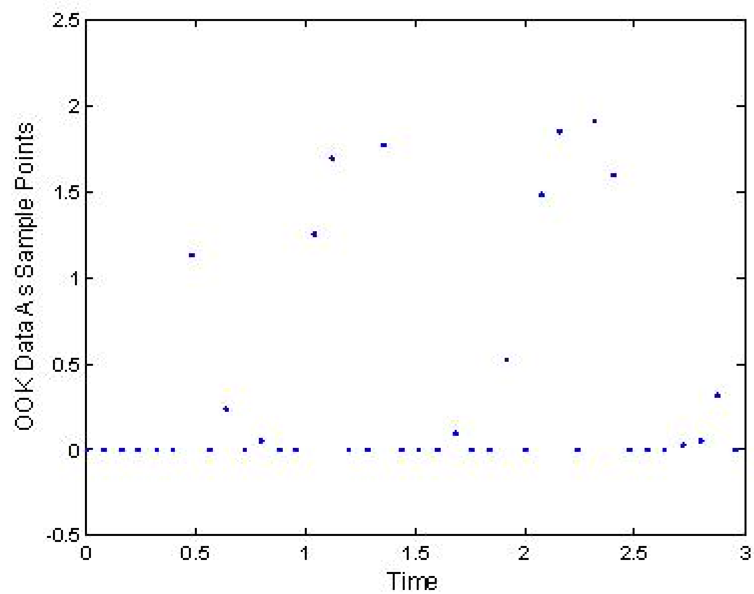


Figure 4.2 MATLAB calculation, a sine wave, whose frequency is 8% of the data rate of high speed OOK binary signals, is put in the primary OOK transmission

Chromatic Dispersion Increase

Since the variation of optical phase generates a frequency shift of the optical carrier, the frequency shift should be considered because it will add a little more dispersion to the primary transmission. This section will discuss how much the additional dispersion will be and will determine whether it will affect the primary transmission.

The frequency shift caused by phase variation of the optical phase modulation is given as

$$\Delta f_m = \frac{d(A_m \cos(2\pi f_i t + \psi))}{dt} = 2\pi A_m f_i . \tag{4.2}$$

Converting frequency shift to wavelength shift,

$$\frac{\Delta\lambda}{\lambda} = \frac{\Delta f}{f} . \tag{4.3}$$

From (4.3) we obtain

$$\Delta\lambda_m = \frac{\Delta f \lambda^2}{c} = \frac{2\pi A_m f_i \lambda^2}{c} , \tag{4.4}$$

where c is the speed of light in free space, which is equal to $3 \cdot 10^8$m/s.

The chromatic dispersion is given by

$$\Delta t_{chrom} = D(\lambda)\Delta\lambda_m L \tag{4.5}$$

where D(λ) is the chromatic dispersion coefficient (ps/nm·km), and L is the fiber length. The relative dispersion increase is given as

$$\frac{\Delta t_{increase}}{\Delta t_{original}} = \frac{D\Delta\lambda_m L}{D\Delta\lambda L} = \frac{\Delta\lambda_m}{\Delta\lambda} = \frac{\frac{2\pi A_m f_i \lambda^2}{c}}{\Delta\lambda} = \frac{2\pi A_m f_i \lambda^2}{c\Delta\lambda} \tag{4.6}$$

where $\Delta\lambda$ is the primary transmission spectral width.

From this equation we can see that the chromatic dispersion increase caused by using this method is dependent on the modulation phase deviation A_m and modulation frequency f_i. It has nothing to do with the primary data rate, which means if the primary bit rate increases, the relative chromatic dispersion increase by using this method will remain the same. This does not hold for self phase modulation (SPM). In other words, if the data rate is increased, SPM will cause a very serious problem by increasing chromatic dispersion. However the chromatic dispersion increase caused by this method will remain the same.

We have derived that the modulation phase deviation A_m should be about 0.95 radian, and the maximum phase modulation frequency should be 1% of the data rate of the primary OOK transmission. Now it is easy to calculate the relative chromatic dispersion for a given OOK channel. Figure 4.3 shows the relative chromatic dispersion increase on the primary OOK transmission system with data rate from 0.1 Gb/s to 10 Gb/s and spectral width 1 nm. From this figure we can see that the relative chromatic dispersion increases as the primary OOK data rate increases. As for a 10 Gb/s channel, the relative chromatic dispersion increase is about 0.48%. If the maximum tolerable ratio is 0.5%, as the data rate increase above 10 Gb/s, the phase modulation frequency should be decreased below 1% of the data rate of the primary OOK transmission to satisfy chromatic dispersion requirements.

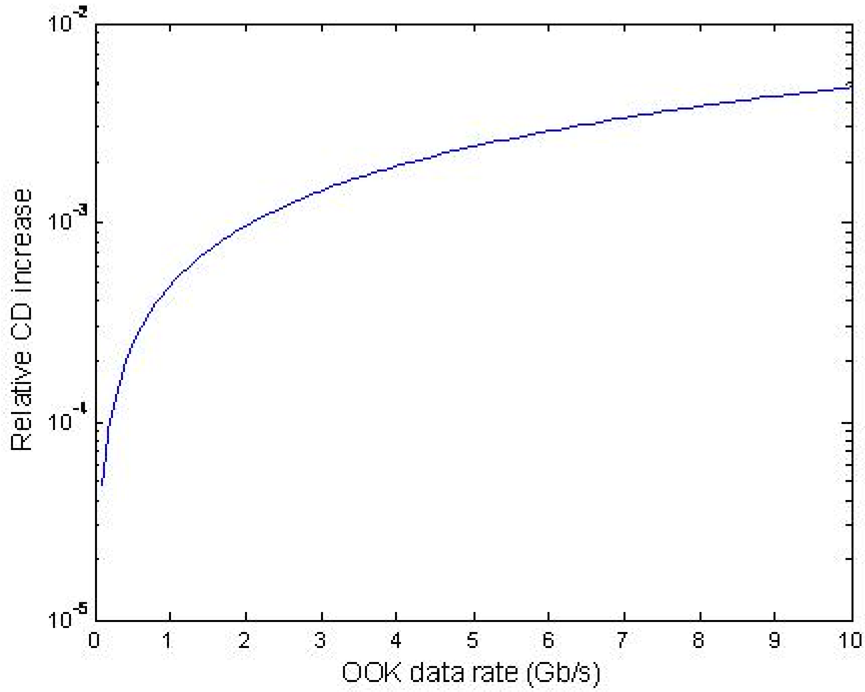


Figure 4.3 Relative chromatic dispersion increase for the proposed system on primary OOK transmission system with Δλ equal to 1 nm

System Capacity

In this section we consider the system capacity, which is the maximum data rate of the proposed second channel. In the proposed system, FSK has been used to represent information. In Sunde's FSK the data rate is equal to the frequency spacing f_1-f_0. The transmission data rate is given as [13]

$$r_b = f_1 - f_0 \tag{4.7}$$

The relationship between modulation frequency and data rate is given by [13]

$$f_i = r_b(n+i) \tag{4.8}$$

where r_b is the data rate and n and i are fixed integers. So the maximum data rate is given by

$$r_b \le f_1/2 \tag{4.9}$$

Since the maximum modulation frequency is 1% of the data rate of primary OOK transmission. For simplicity, the capacity for the proposed system is about 0.5% of the data rate of primary OOK transmission. Figure 4.3 shows the system capacity as the primary OOK data rate varies from 0.1 Gb/s to 10 Gb/s. This capacity is under the assumption of 0.5% relative CD increase tolerance for the primary OOK transmission system.

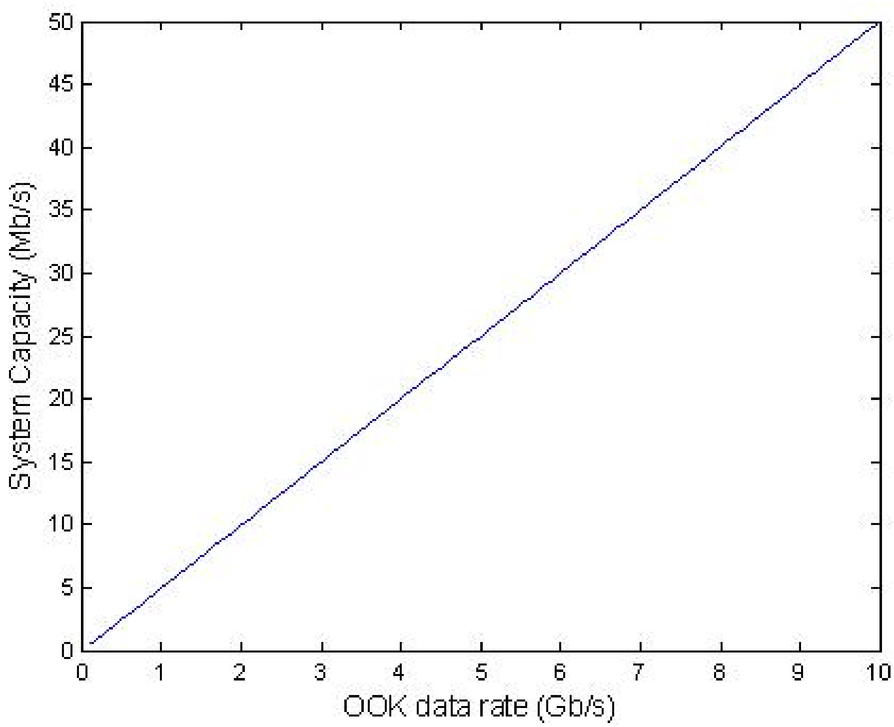


Figure 4.4 System capacities for the primary OOK data from 0.1 Gb/s to 10 Gb/s

Phase Shift Comparison with SPM and XPM

In this section we compare the phase shift of the proposed method with the phase shift caused by self phase modulation (SPM) and cross phase modulation (XPM).

The phase shift caused by SPM is given by [10]

$$\Delta \psi_{SPM} = \gamma P_{in} L_{eff} \ . \tag{4.10}$$

Where γ is the nonlinear propagation phase coefficient, P_{in} is the input optical power, and L_{eff} is the effective length for SPM given by [10]

$$L_{eff} = \frac{1}{a(1-e^{-aL})}, \tag{4.11}$$

where a is the fiber attenuation constant in 1/km, L is the fiber length, and L>>1/a, which results in L_{eff}=1/a. Typically, the attenuation is 0.2 dB/km and a is 0.046. So L_{eff}=21.7 km. Typically $\gamma=2.35\cdot10^{-3}$ 1/(m·W), and P_{in} is in the range of 1mW. The phase shift caused by SPM is given by

$$\Delta \psi_{SPM} = \gamma P_{in} L_{eff} = 2.35\cdot10^{-3} \times 1mW \times 21.7km = 0.05(rad) \tag{4.12}$$

In a WDM system we have to take into account XPM as there are multiple wavelengths sharing the bandwidth. The total phase shift is given by [10]

$$\Delta \psi = \gamma L_{eff} (P_{in} + 2\sum P_{other}) \tag{4.13}$$

If there are 50 channels, the phase shift will be about 5 radians. The above calculations are just for one span of optical transmission. If there are k spans in the system, the total phase shift we can simply multiply by k. Note that the phase shifts caused by SPM and

XPM can be thought of as the initial phase of the primary transmission system, which does not affect the proposed phase modulation for the second channel.

CHAPTER FIVE

SYSTEM NOISE ANALYSIS AND BER ESTIMATION

Introduction

The performance of a phase modulator system is very sensitive to phase noise. The overall phase noise in an optical transmission system is composed of several nearly independent components, such as semiconductor laser phase noise, additive amplifier amplified spontaneous emission (ASE) noise, and nonlinear optical fiber phase noise due to the interaction of additive amplifier ASE noise and the optical fiber nonlinear Kerr effect. The proposed phase modulator system also suffers from electrical noise because all optical signals have to be converted into electrical signals using a photo detector for post processing. This chapter will discuss all of these detrimental factors to analyze the system's signal to noise ratio (SNR) and estimate bit error rate (BER).

Optical Phase Noise

The optical phase noise sources include laser phase noise, optical amplifier phase noise, and optical fiber nonlinear phase noise. In this section we will review and analyze these various sources of optical phase noise and discuss the impacts on the proposed modulation system.

Light radiated by a laser diode fluctuates in its intensity and phase even when the bias current is ideally constant. These fluctuations are caused mostly by spontaneous emission and are random in nature. This phenomenon is called laser noise. The emission spectrum of a semiconductor laser may be viewed as being determined by its phase fluctuations. In particular, the laser linewidth Δf is determined by the magnitude of the phase noise. This connection between phase noise and linewidth is manifested analytically in the usual expression for the phase error accumulated in a time τ [14-15].

$$\sigma_{\phi}^{2}(\tau) = 2\pi\Delta f\tau \qquad (5.1)$$

where σ^2 is the variance of laser phase noise accumulated in a time τ. This is obtained by assuming that the phase undergoes a random walk where the steps are individual spontaneous emission events which instantaneously change the phase by a small amount in a random way.

Because the proposed phase modulation system is not a coherent detection system, we use an interferometer at the receiver end to retrieve the information signal. The accumulated time τ can be considered as the time difference of light going through the two arms of the interferometer. The time difference is given as

$$\tau = \frac{n(L_2 - L_1)}{c} \qquad (5.2)$$

The noise phenomena in a semiconductor optical amplifier (SOA) and in an erbium doped fiber amplifier (EDFA) have very much in common. When those amplifiers are used to compensate the fiber loss in optical transmission systems, they magnify the signal noise along with the signal itself. But the principal noise source for an optical amplifier is self-generated amplified spontaneous emission (ASE) noise. Since the spontaneous emitted and amplified photons are random in phase, they do not contribute to the information signal but generate noise within the signal's bandwidth. The average total power of ASE is given by [10]

$$P_{ASE} = 2n_{sp}hfGBW \tag{5.3}$$

where hf is photon energy, G is amplifier gain, BW is the optical bandwidth of the amplifier, and n_{sp} is spontaneous emission factor or population inversion factor and is given as

$$n_{sp} = \frac{N_2}{N_2 - N_1} \tag{5.4}$$

where N_2 and N_1 are populations of the excited and lower levels, respectively. The value of n_{sp} ranges typically from 1.4 to 4.

At the output of each amplifier, the ASE noise field is added to each pulse. Classically this noise field is approximated as additive and has a Gaussian distribution. Although some think the ASE noise is not a Gaussian distribution, a Gaussian approximation can serve as an upper bound and can be viewed as a good approximation, since the energy per pulse greatly exceeds one photon. The noise field can be thought of as two degrees of freedom (DOFs) [16]. They have the same form as the pulse. One is in phase with the pulse and the other is in quadrature, as shown in figure 5.1. The quadrature noise component produces an immediate phase noise, and the in-phase component alters the energy of the pulse. The pulse amplitude fluctuation caused by the in-phase ASE noise will interact with the fiber Kerr effect, which will generate an additional nonlinear phase noise. All of these phase noise components will add together and persist throughout the rest of the transmission.

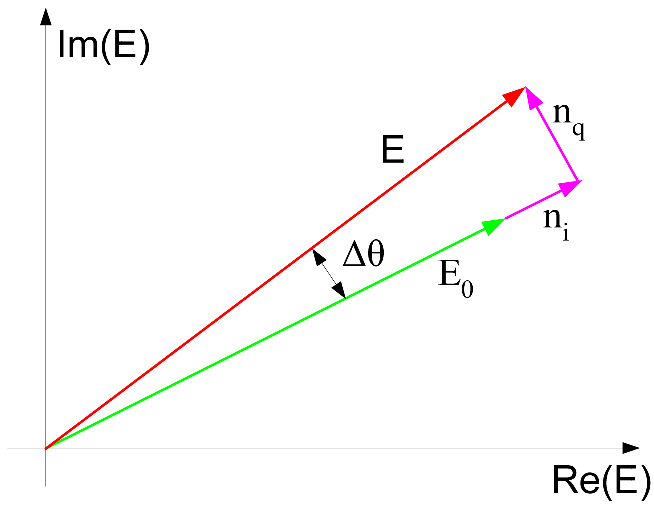


Figure 5.1 Phasor diagram for pulse propagation

Since the total ASE noise is comprised of in-phase and quadrature components, the variance for each degree of freedom of the noise is half of the total power of ASE noise

$$\sigma_I{}^2 = \sigma_Q{}^2 = \frac{1}{2} P_{ASE} = n_{sp} hfGBW. \tag{5.5}$$

From figure 5.1 we can see that the phase noise caused by the quadrature component of ASE noise can be approximated by

$$\sigma_{ASE-phase} = \Delta\theta = \frac{n_Q}{E} = \frac{\sigma_Q}{\sqrt{P}}, \tag{5.6}$$

where P is the output power of optical amplifier and also can be thought of as the launched power at the transmitter end. In an optical transmission system there may be several optical amplifiers deployed to compensate the fiber loss. For simplicity and without loss of generality, we assume these optical amplifiers are identical, which means that at each amplifier the phase noises generated are the same. To include all of the phase noise, recall that they are approximated with Gaussian statistics, and consequently, their variances can simply be added to represent the variance of the total phase noise

$$\Delta\theta_{all}^{\ 2} = \Delta\theta_1^{\ 2} + \Delta\theta_2^{\ 2} + \cdots + \Delta\theta_n^{\ 2} = n\Delta\theta^2, \tag{5.7}$$

and the standard deviation of the total phase noise can be described by

$$\sigma_{ASE-phase-total} = \sqrt{n}\Delta\theta = \sqrt{n}\frac{\sigma_Q}{P} = \sqrt{n}\sqrt{\frac{n_{sp}hfGBW}{P}}, \tag{5.8}$$

where n represents the number of amplifiers in the optical transmission system.

Nonlinear phase noise, also called Gordon and Mollenauer noise, is induced by the interaction of fiber Kerr effect and optical amplifier noise when optical amplifiers are used periodically to compensate for fiber loss [17-21]. In single channel transmission system nonlinear phase noise is induced by SPM and in a WDM system it is induced by SPM and XPM. First we discuss a single channel system.

At high optical power P, the index of refraction of optical fiber must include the nonlinear contribution [10]

$$n_r = n_{r0} + n_r'(P / A_{eff}), \tag{5.9}$$

where n_{r0} is the refractive index at small optical power, n'_r is the nonlinear index coefficient (n'_r is about 3×10^{-20} m^2/W for silicon fiber), and A_{eff} is the optical effective core area. Typically the nonlinear contribution to the refractive index is quite small (less than 10^{-7}). But, due to a long interaction length, the effect of nonlinear refractive index becomes significant, especially when optical amplifiers are used to boost the optical power. The phase (propagation) constant also becomes power dependent or nonlinear [10].

$$\beta = \beta_0 + \gamma P \tag{5.10}$$

where β_0 is the linear portion of the phase constant and γ is the nonlinear propagation coefficient which is given as [10]

$$\gamma = \frac{2\pi}{\lambda}\frac{n_r'}{A_{eff}}. \tag{5.11}$$

When the operating wavelength is at 1550 nm and the optical effective area is 55 μm^2, γ is equal to $2.35\text{x}10^{-3}$ 1/m•W. In each fiber span, the overall nonlinear phase shift is equal to [10]

$$\phi_{NL} = \int_0^L \gamma P(z)dz = \gamma L_{eff} P, \tag{5.12}$$

where P is the launched power, L is the fiber length and L_{eff} is the effective fiber length that we have given by equation 4.11.

We assume a system with multiple fiber spans using an optical amplifier in each span to compensate the fiber loss. For simplicity, we assume that each span is the same length, and an identical optical power is launched into each span. In the linear regime, the electric field for the kth span is equal to

$$E_k = E_0 + n_1 + n_2 + \cdots + n_k, \tag{5.13}$$

where n_k is the complex amplifier noise at the kth span, k=1,2, …, N, and $E\{|n_k|^2\}=2\sigma^2$, where σ^2 is the noise variance per span per dimension. The optical power is $P_k=|E_k|^2$ and SNR is $P_k/(2k\sigma^2)$. The nonlinear phase shift at kth span is given by

$$\phi_{NL-k} = \gamma L_{eff} \{| E_0 + n_1 + n_2 + \cdots n_k |^2\}. \quad (5.14)$$

At the kth span we get the mean phase shift of $\gamma L_{eff}|E_0|^2$ and phase noise of $\gamma L_{eff} k|n|^2$. Nonlinear phase is accumulated span by span, and the mean of overall nonlinear phase shift is approximately

$$\phi_{NL-mean} = k\gamma L_{eff} \ | E_0 |^2 \ . \quad (5.15)$$

To calculate the standard deviation of nonlinear phase noise at the receiver end, recall that we assume the nonlinear phase noise is a Gaussian distribution with zero mean. The variance of the nonlinear phase noise at the kth span is the sum of all phase noise variances before;

$$\begin{aligned} \sigma_{NL-k}{}^2 &= \sigma_1{}^2 + \sigma_2{}^2 + \cdots + \sigma_k{}^2 \\ &= (\gamma L_{eff})^2 \{(n^2)^2 + (2n^2)^2 + \cdots + (kn^2)^2\} \\ &= (\gamma L_{eff})^2 n^4 \{1 + 4 + \cdots + k^2\} \\ &= (\gamma L_{eff})^2 n^4 \frac{k(k+1)(2k+1)}{6}, \end{aligned} \quad (5.16)$$

and the standard deviation of nonlinear phase noise is given by

$$\sigma_{NL-k} = \gamma L_{eff} n^2 \sqrt{\frac{k(k+1)(2k+1)}{6}}. \quad (5.17)$$

Note that the mean nonlinear phase shift does not affect our phase modulation and can be considered as an arbitrary constant or initial phase of the primary transmission system. Only the nonlinear phase noise is the impairing factor for our phase modulation.

Optical Phase SNR and Bit Error Rate (BER) Estimation

We have reviewed the major phase noise factors in current optical transmission systems, which include semiconductor laser phase noise, optical amplifiers' ASE phase noise, and nonlinear phase noise. In this section, we will quantitatively discuss how much phase noise will affect the proposed modulation method and calculate the optical signal to noise ratio (OSNR) to determine the BER due to optical phase noise.

Since we use Gaussian statistics to approximate all sources of optical phase noise, the total variance of the phase noise can be obtained by simply adding those phase noise variances together:

$$\sigma^2{}_{total} = \sigma^2{}_{laser} + \sigma^2{}_{ASE-phase} + \sigma^2{}_{NL}. \qquad (5.18)$$

Although this method may overestimate the system performance, it can give us a direct insight and upper bound of the system.

We assume that a DFB laser is used in the primary OOK transmission system and its linewidth is 4 MHz. The difference of the two interferometer arm lengths is 10 cm. From equation 5.2 we find that the accumulated time is

$$\tau = \frac{n(L2 - L1)}{c} = \frac{1.47 \cdot 0.1}{3 \cdot 10^8} = 4.9 \cdot 10^{-10}\, s, \qquad (5.19)$$

and the variance of laser phase in this time period is given by

$$\sigma^2_{laser}(\tau) = 2\pi\Delta f \tau = 2\pi \cdot 4 \cdot 10^6 \cdot 4.9 \cdot 10^{-10} = 0.0123. \qquad (5.20)$$

Assume that there are 10 spans in the optical transmission system, n_{sp}=2, the operating wavelength is 1550 nm, the gain of optical amplifier is 25 dB, the launched power is 1 mW, and the bandwidth is 10 GHz. The photon's power is given by

$$hf = \frac{hc}{\lambda} = \frac{6.6\cdot 10^{-34}\cdot 3\cdot 10^{8}}{1550\cdot 10^{-9}} = 1.28\cdot 10^{-19}\,J. \tag{5.21}$$

Then the ASE phase noise is given by

$$\sigma^2{}_{ASE} = \frac{nn_{sp}hfGBW}{P} = \frac{10\times 2\times 1.28\cdot 10^{-19}\times 316\times 10\cdot 10^{9}}{1\cdot 10^{-3}} = 0.008.1 \tag{5.22}$$

To calculate the nonlinear phase noise, we use the same values as in the above calculation for the optical amplifier. The noise power is given by

$$n^2 = P_{ASE} = 2n_{sp}hfGBW = 2\times 2\times 1.28\cdot 10^{-19}\times 316\times 10\cdot 10^{9} = 1.62\cdot 10^{-6}W \tag{5.23}$$

Then the nonlinear optical phase noise is given by

$$\begin{aligned}\sigma^2{}_{NL} &= (\gamma L_{eff} n^2\sqrt{\frac{k(k+1)(2k+1)}{6}})^2 \\ &= (2.35\cdot 10^{-3}\times 21.7\cdot 10^{3}\times 1.62\cdot 10^{-6}\times\sqrt{\frac{10\times 11\times 21}{6}})^2 \\ &= 5.03\cdot 10^{-5}\end{aligned} \tag{5.24}$$

Finally the total variance of system phase noise is given by the sum of these three phase noise variances

$$\sigma^2{}_{total} = \sigma^2{}_{laser} + \sigma^2{}_{ASE} + \sigma^2{}_{NL} = 0.0123 + 0.0081 + 5.03\cdot 10^{-5} = 0.0204. \tag{5.25}$$

The standard deviation is the square root of the variance and equals

$$\sigma_{total} = 0.1428. \tag{5.26}$$

Compared with the laser phase noise, the amplifier's ASE noise and the nonlinear phase noise are negligible in a single channel system. In WDM systems the variance of nonlinear phase noise will increase by 100 times assuming 50 wavelengths. Then nonlinear phase noise is then comparable with the sum of the laser phase noise and ASE phase noise. The total phase noise is given by

$$\sigma^2{}_{total} = \sigma^2{}_{laser} + \sigma^2{}_{ASE} + \sigma^2{}_{NL} = 0.0123 + 0.0081 + 100 \times 5.03 \cdot 10^{-5} = 0.0254 \tag{5.27}$$

and the standard deviation is the square root of the variance

$$\sigma_{total} = 0.1594 \text{ (rad).} \tag{5.28}$$

We have calculated the standard deviation of phase noise for a typical system. We know that the phase deviation of the proposed system has been optimized to be 0.95 radian. Making an analogy to the electrical communication system, we note that the phase deviation is the same as electrical signal amplitude and the phase noise is the same as the electrical noise. Then we get the optical phase signal power given by

$$S_{opt-phase} = \frac{1}{2} A_m^2 , \tag{5.29}$$

and the optical phase noise power is given by

$$N = \sigma^2{}_{total} . \tag{5.30}$$

In digital communications, we more often use E_b/N_0, a normalized version of SNR, as a figure of merit. E_b is bit energy and can be described as signal power S times the bit time T_b. N_0 is noise power spectral density, and can be described as noise power N divided bandwidth W.

$$\frac{E_b}{N_0} = \frac{ST_b}{N/W} = \frac{S/R_b}{N/W} , \tag{5.31}$$

where R_b is the data rate.

For simplicity, we assume the date rate equal to the bandwidth to get

$$\frac{E_b}{N_0} = \frac{S}{N} = SNR \ . \tag{5.32}$$

For a typical system, we find that the optical phase SNR in a single channel is

$$\frac{E_b}{N_0} = SNR = \frac{S}{N} = \frac{\frac{1}{2}0.95^2}{0.0204} = 22.12 = 13.45dB \tag{5.33}$$

and the optical phase SNR in a typical WDM system is

$$\frac{E_b}{N_0} = SNR = \frac{S}{N} = \frac{\frac{1}{2}0.95^2}{0.0254} = 17.77 = 12.50dB. \tag{5.34}$$

As for the BER estimation, we also can use the equation for electrical Binary FSK which is given by [13]

$$P_B = Q\left(\sqrt{\frac{E_b}{N_0}}\right) \ , \tag{5.35}$$

where Q(x) is the co-error function.

We can estimate the BER for the typical system in a single channel, which is given by

$$P_B = Q\left[\sqrt{\frac{E_b}{N_0}}\right] = Q\left(\sqrt{\frac{\frac{1}{2}0.95^2}{0.0204}}\right) = 1.28 \cdot 10^{-6}, \tag{5.36}$$

and the BER in a typical WDM system is given by

$$P_B = Q\left[\sqrt{\frac{E_b}{N_0}}\right] = Q\left(\sqrt{\frac{\frac{1}{2}0.95^2}{0.0254}}\right) = 1.25 \cdot 10^{-5}. \tag{5.37}$$

Based on the above quantitative analysis, we can see that the major phase noise is semiconductor laser phase noise that is accumulated in a time period. This modulation method can not be used in a transmission system where an LED light source is used, because the linewidth for the LED is too big, generating lots of phase noise.

Electronic Noise

All electrical devices suffer from electrical noise. All optical transmission systems have optical to electrical conversion at the receiver end using photodetectors, where system performance may be corrupted by thermal noise, shot noise, and dark noise. In this section, all of these sources of noise will be reviewed and the system SNR and BER in the electrical domain will be calculated.

The shot noise is defined as the deviation of the actual number of electrons from the average number. The main cause of shot noise is that actual number of photon arrivals in a particular time is random variable. The number of electrons producing photocurrent will vary because of their random recombination and absorption. Therefore, even though the average number of electrons is constant, the actual number of electrons will vary. The spectral density for shot noise is given by [10]

$$S_s(f) = 2eI_p^* \tag{5.38}$$

Where I^*_p is the average photocurrent and e is the electron charge $1.6 \cdot 10^{-19}$ J. The RMS current is given by [10]

$$i_s = \sqrt{2eI_p^* BW_{PD}} \tag{5.39}$$

where BW_{PD} is the photo-detector's bandwidth.

The deviation of an instantaneous number of electrons from the average value because of temperature change is called thermal noise. Its spectral density is given by [10]

$$S_t(f) = 2k_B T / R_L, \tag{5.40}$$

where k_B is the Boltzmann constant ($1.38\bullet10^{-23}$ J/K), T is the absolute temperature and R_L is the load resistance. The RMS current is given by [10]

$$i_t = \sqrt{(4k_B T / R_L) BW_{PD}}. \tag{5.41}$$

Dark current noise usually is included in the shot noise. Its RMS current is given by [10]

$$i_d = \sqrt{2ei_d^* BW_{PD}}, \tag{5.42}$$

where i^*_d is the dark current.

Since each noise is an independent random process approximated by Gaussian statistics, the total noise power is given as the sum of the components

$$i_{noise}^2 = i_s^2 + i_t^2 + i_d^2 \tag{5.43}$$

Note that after the photo-detector we use an electrical band pass filter to reduce the noises and DC current, so we will use the bandwidth of the band pass filter instead of the photo-detector's bandwidth BW_{PD}.

Electrical SNR and BER Calculations

In this section we will take some typical values for the proposed system to calculate the electrical SNR and estimate the electrical BER. In the proposed system, after the interferometer, the phase modulated signal is converted to an intensity modulated signal, which is directed to a photodetector where the optical signal is converted to an electrical signal. We use a band pass filter to eliminate DC and higher order components. From equation 2.22 we see that the amplitude for the detected sine wave signal is given by

$$I_s = RI_{in} J_1(A_{con}), \tag{5.44}$$

where I_s represents the average current or amplitude of the detected sine wave signal, R is the responsivity of the photodetector, $J_1(x)$ is the coefficient of Bessel functions of the first kind, and I_{in} is the launched optical power. The electrical SNR can be given by

$$SNR = \frac{I_s^2}{i_{noise}^2} = \frac{(RI_{in} J_1(A_{con}))^2}{i_s^2 + i_t^2 + i_d^2}. \tag{5.45}$$

Let A_m=0.95, R=0.85 A/W, f_m=10 MHz, n=1.47, L_2-L_1=10 cm, then A_{con} is given by

$$A_{con} = 2A_m \sin(\frac{\omega_m n(L_2 - L_1)}{2c}) = 2\times 0.95 \times \sin(\frac{2\pi \times 10\cdot 10^6 \times 1.47 \times 0.1}{2\times 3\cdot 10^8}) = 0.0292 \tag{5.46}$$

and J_1 is given by

$$J_1(A_{con}) = J_1(0.0292) = 0.0146 \tag{5.47}$$

Let P_{in}=0.1 mW, then the detected current is

$$I_s = RI_{in} J_1(A_{con}) = 0.85 \times 0.1 \times 0.0146 = 0.0012 \text{ (mA)} \tag{5.48}$$

and detected signal power is given by the square of the current

$$S = I_s^2 = 1.44 \cdot 10^{-6} (mA)^2. \tag{5.49}$$

We then calculate the noise current and power. Let the data rate be 5 Mb/s and bandwidth of the filter be 2 times the data rate, which is 10 MHz. Let R_L=50 Ω, T=293 K, i^*_d = 3 nA. The noise power is then given by

$$N = i_{noise}^2 = i_s^2 + i_t^2 + i_d^2 = (2eI_p^* + (4k_B T / R_L) + 2ei_d^*)BW$$
$$= (2 \times 1.6 \cdot 10^{-19} \times 1.2 \cdot 10^{-6} + 4 \times 1.38 \cdot 10^{-23} \times 293 \div 50$$
$$+ 2 \times 1.6 \cdot 10^{-19} \times 3 \cdot 10^{-9}) \times 10 \cdot 10^{6} \quad (5.50)$$
$$= 3.24 \cdot 10^{-15} (A^2)$$
$$= 3.24 \cdot 10^{-9} (mA)^2.$$

Assuming the noise figure for the whole receiver is 10 dB, the noise power becomes

$$N = 3.27 \cdot 10^{-9} \times 10 = 3.24 \cdot 10^{-8} (mA)^2. \quad (5.51)$$

In a digital transmission system we usually use bit energy to noise spectral density ratio instead of SNR,

$$\frac{E_b}{N_0} = \frac{ST_b}{\frac{N}{BW}} = \frac{1.44 \cdot 10^{-6} \times \frac{1}{5 \cdot 10^6}}{3.24 \cdot 10^{-8} / 10 \cdot 10^6} = \frac{2.88 \cdot 10^{-13}}{3.24 \cdot 10^{-15}} = 88.9 = 19.5dB, \quad (5.52)$$

where T_b is the duration of one bit period, and N_0 is the noise spectral density. For a noncoherent FSK system the BER is given by [13]

$$P_{e,FSK,NC} = \frac{1}{2} \exp(-\frac{E_b}{2N_0}). \quad (5.53)$$

For this modulation system, if we only consider the electrical noise, the BER is

$$P_{e,FSK,NC} = \frac{1}{2} \exp(-\frac{E_b}{2N_0}) = \frac{1}{2} \exp(-88.9/2) = 2.48 \cdot 10^{-20}. \quad (5.54)$$

Compared with the optical phase BER estimation, this number is negligible. So for this modulation method the optical phase noise is the major detrimental factor that determines the system performance. In the optical phase noise, semiconductor laser phase noise is the major component at the current stage.

CHAPTER SIX

EXPERIMENT RESULTS

Acoustic Optical Phase Modulator

In our exploratory work, we used a piezoelectric actuator as a transducer, as shown in figure 6.1, to squeeze the optical fiber to change the optical phase of a light signal transmitted on the fiber. When the fiber is squeezed, the refractive index of the fiber is changed, thus modifying the optical path traversed by light propagating through the fiber and changing the light phase. Compared to high speed OOK transmission (several Gb/s), the squeezing frequency is very low.

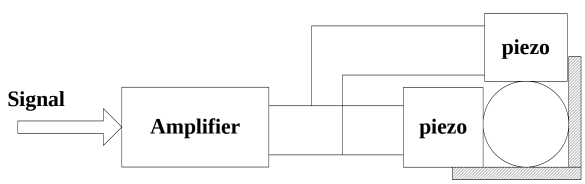


Figure 6.1 piezoelectric actuator squeezer

Optical phase of light transmitted on the fiber is given by [22]

$$\Phi = \beta L = knL \tag{6.1}$$

where β is the wave propagation constant; k is the free space optical wave number; n is the index of refraction of the fiber and L is the fiber length. Optical path length is given by

$$L_{opt} = nL. \tag{6.2}$$

The variation of optical path is given by

$$\Delta L_{opt} = \Delta nL + \Delta Ln . \quad (6.3)$$

Squeezing of the fiber generally changes both the refractive index and the fiber length. The change of fiber length is negligible. By ignoring the change of fiber length, the variation of optical path is given by

$$\Delta L_{opt} = \Delta nL . \quad (6.4)$$

If the light is propagating in the Z direction, the effective index of refraction (n_r) in the radial direction that delays the propagation of a transverse EM wave changes due to the photo-elastic effect. There have been several reported methods of modulating optical phase by altering the index of refraction of fiber. These include methods of stretching and squeezing [23-33]. None of these methods use the phase change to provide a communication channel. The photo-elastic effect appears as a change in the optical indicatrix

$$\Delta\left(\frac{1}{n_r^2}\right) = p_{11}\varepsilon_{xx} + p_{12}\varepsilon_{yy} + p_{13}\varepsilon_{zz} \quad (6.5)$$

where p_{11} and p_{12} are the strain optic coefficient, $\varepsilon_{xx} = \varepsilon_{yy} = \varepsilon_r < 0.01$ are the strains in r (xx, yy) direction, and $\varepsilon_{zz} = 0$ is the strain in Z direction.

The variation of the effective refractive index is given by

$$\Delta n = \Delta n_r = -\frac{1}{2} n^3 \left(p_{11} + p_{12}\right)\varepsilon_{r_r} \quad (6.6)$$

The variation of optical path then is given by

$$\Delta L_{opt} = \Delta nL = -\frac{1}{2} n^3 \left(p_{11} + p_{12}\right)\varepsilon_r L . \quad (6.7)$$

The maximum elastic strain ε_r for optical fiber is 0.01. Greater strain will damage the fiber. If a continuous sinusoidal squeeze is applied to the optical fiber, the strain can be given by

$$\varepsilon_r = \varepsilon \sin(\omega_m t), \tag{6.8}$$

where ε is a constant strain that is below 0.01 and ω_m is the modulating angular frequency of the squeezer.

By substituting equation 6.8 into equation 6.7, the optical path variation can be expressed by

$$\Delta L_{opt} = \Delta n L = -\frac{1}{2} n^3 (p_{11} + p_{12}) L \varepsilon \sin(\omega_m t). \tag{6.9}$$

The optical phase shift becomes a time function and is given by

$$\begin{aligned} \Delta\Phi &= k \Delta L_{opt} \\ &= -\frac{1}{2}\frac{2\pi}{\lambda} n^3 (p_{11} + p_{12}) L \varepsilon \sin(\varpi_m t). \end{aligned} \tag{6.10}$$

The displacement velocity is given by

$$v = \frac{d\Delta L_{opt}}{dt}. \tag{6.11}$$

From Doppler theory, the frequency shift is given as the equation

$$\Delta f = f_0 \frac{v}{c}. \tag{6.12}$$

From the above description it can be seen that if a sine wave is used to squeeze the optical fiber, the optical phase shift is a sine wave with the same frequency.

Experiment Setup

Figure 6.2 shows the experimental setup configuration, including transmitter and receiver block diagrams. The transmitter consists of an FSK modulator, a squeezer driver and a squeezer made of a piezoelectric actuator. The FSK modulator converts incoming digital information bits into different-frequency sine waves. The squeezer driver is a high voltage amplifier that amplifies the sine wave signal to drive the piezoelectric actuator and squeeze the optical fiber. The receiver includes an interferometer, photo-detector, band pass filter and FSK demodulator. The interferometer converts the phase modulated signal into an intensity modulated signal. The photo detector detects the light intensity signal and converts it into an electric signal. The band pass filter removes the DC and high order components. The FSK demodulator detects the different frequencies of the sine signal and recovers the transmitted information bits.

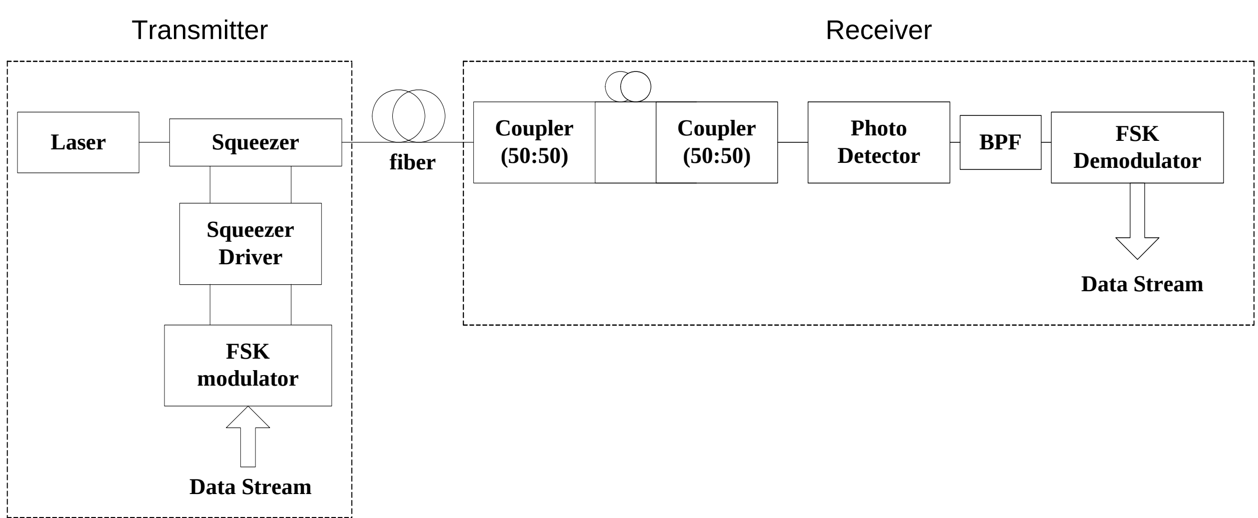


Figure 6.2 Lab configuration

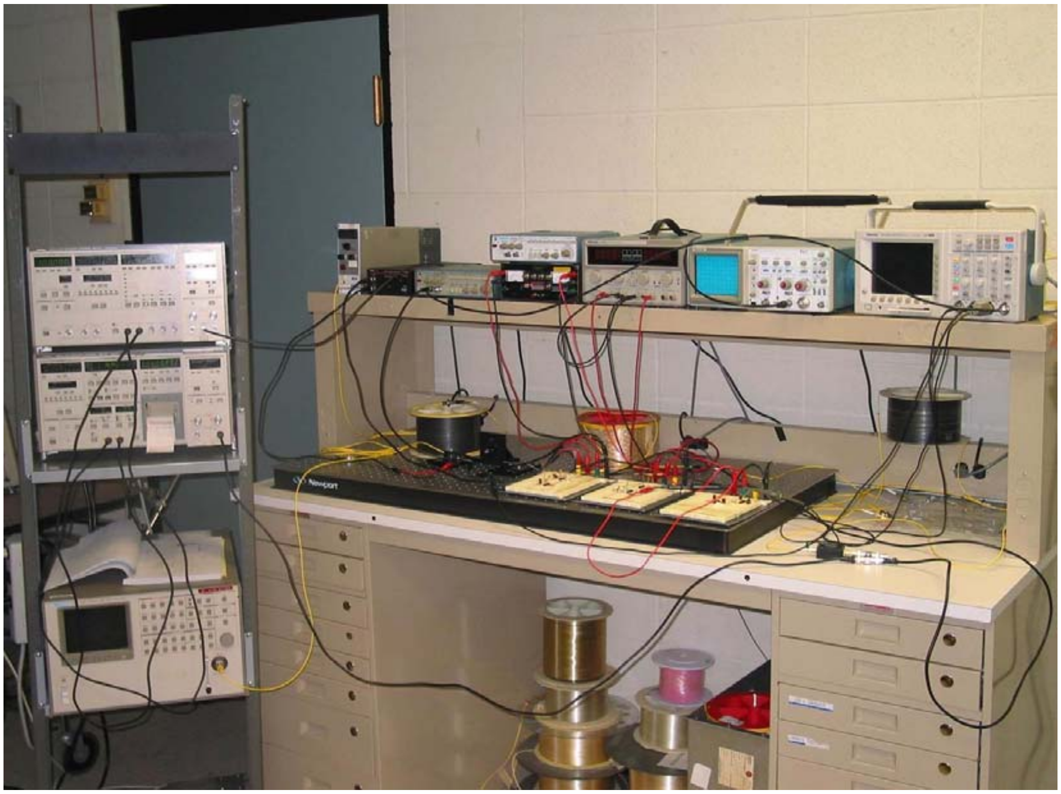
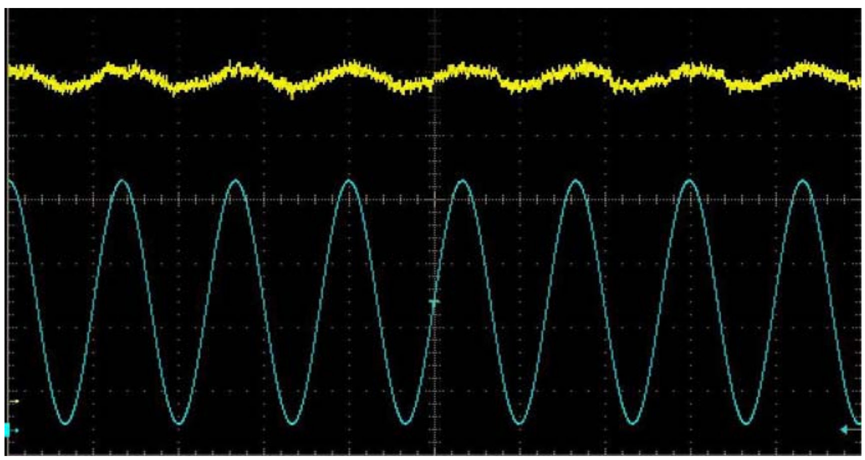


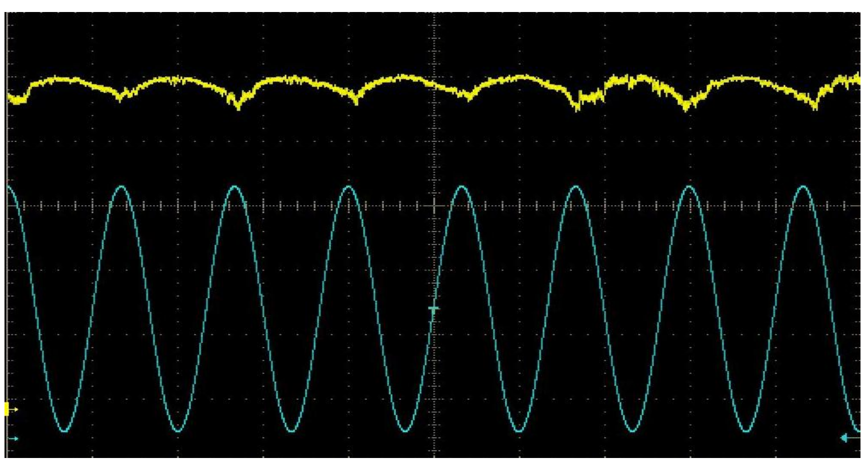
Figure 6.3 Experiment setup

Lab Results

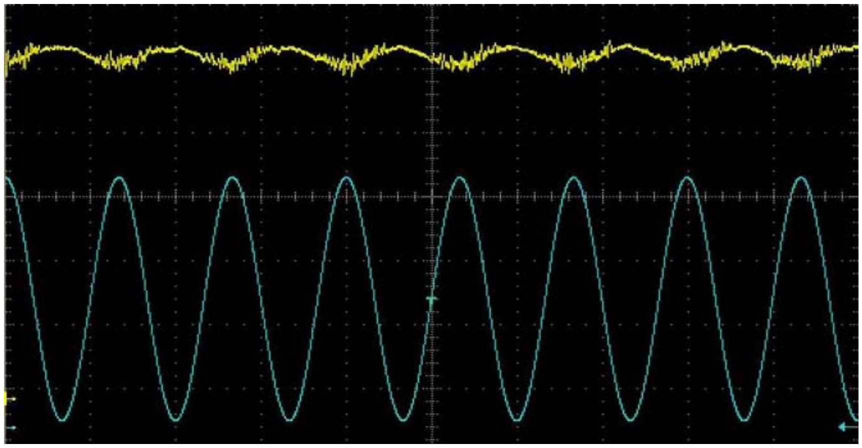
In the initial experiments the optical fiber was squeezed at 8 kHz to modulate the optical phase by a sine wave at 8 kHz. Figure 6.4 shows the sine wave signals detected at the receiver end at four different times. In this figure, the blue line represents the phase modulation sine wave signal which drove the squeezer to squeeze the optical fiber at the transmitter end, and the yellow line represents the sine wave detected at the receiver end. From figure 6.4 we can see that a some times the sine wave was very clear, but at other times the sine wave signal had considerable noise. This lack of repeatability is attributable to the mechanical squeezer becoming loose over time, and it could not modulate the optical phase with consistent, repeatable mechanical deflection. The sine wave signal detected at the receiver end verified the theory and basic method of transmitting and detecting a sine wave signal using the acousto-optic modulation approach, but the experiments also showed the limitations of the mechanical deflection technique.



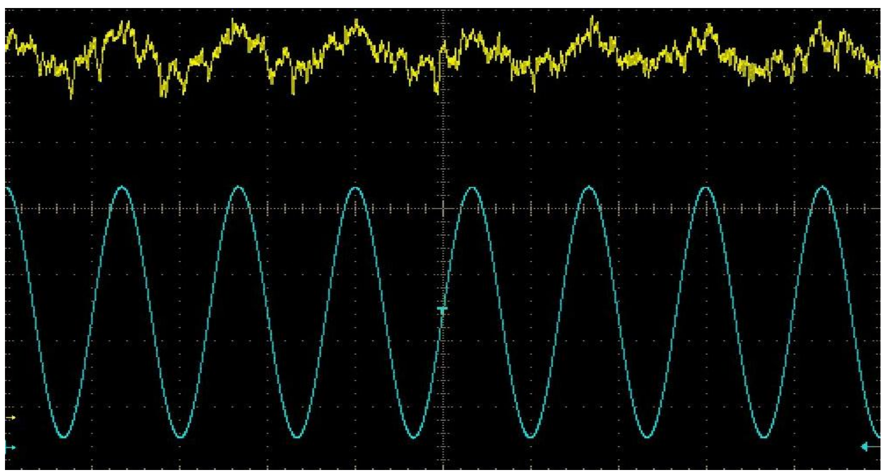
(1)



(2)



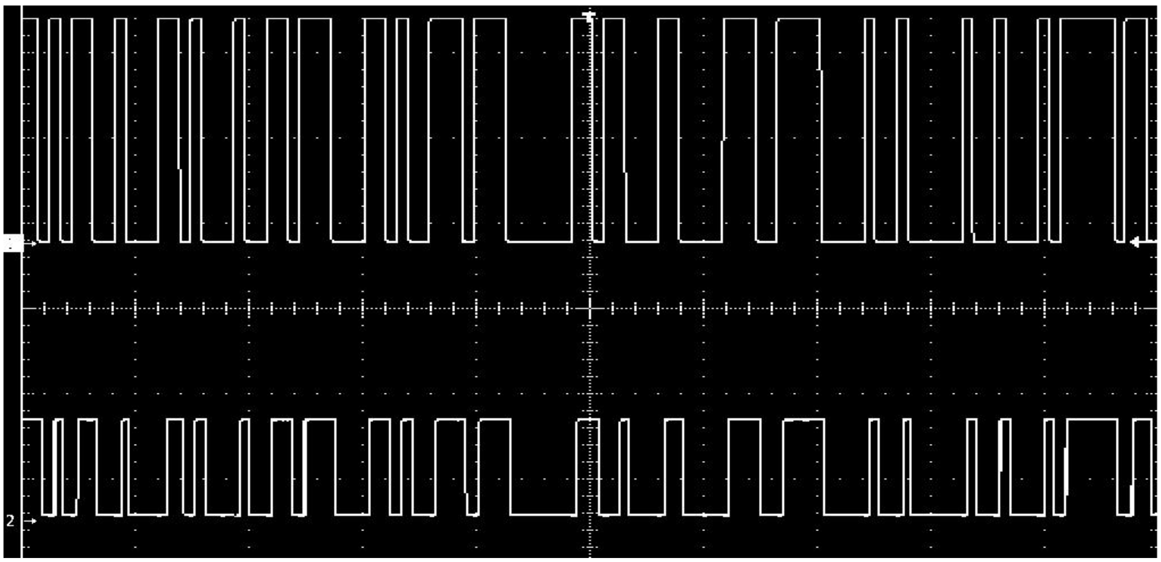
(3)



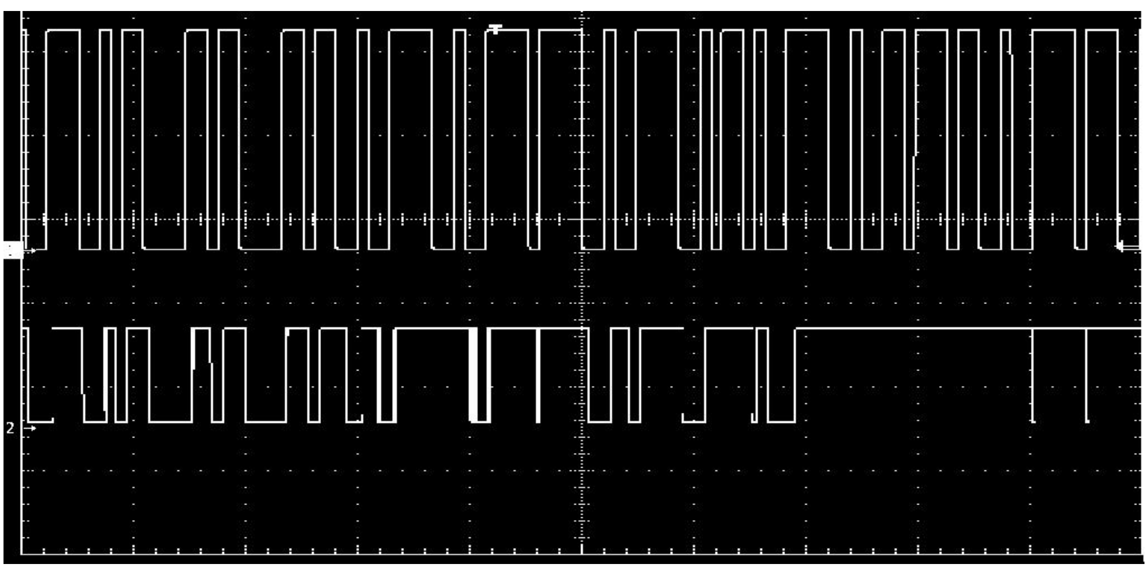
(4)

Figure 6.4 Experimental results, 8 kHz sine wave detected in four measurement periods

For the next step we used the system shown in figure 6.2 to transmit low-bit-rate data. Figure 6.5 shows the waveform of the received data when we transmitted a pseudo random bit sequence (PRBS) at a rate of 1 kbps, setting frequency for data 0 f_0 at 8 kHz and frequency for data 1 f_1 at 12 kHz. In figure 6.5 the upper waveform represents the transmitted PRBS signal, and lower waveform represents the received signal. From this figure we can see that at some times the system totally lost the ability to recover the data bits. The signal loss was due to noise on the sine wave signal before the FSK demodulator. The measured bit error rate was about 0.15.



(1)



(2)

Figure 6.5 Results of FSK modulation tests at 1 kbps

The lab results were not satisfactory for a real transmission system, but verified the modulation technique we proposed. More consistent and usable results can be achieved by using an optical phase modulator instead of the mechanical phase modulator,

CHAPTER SEVEN

CONCLUSIONS

This thesis has demonstrated a novel optical modulation method that can increase existing system utilization without perturbing the original high speed transmission by modulating the optical phase. The impressed signal can be easily detected at the other end of the link by using an interferometer and band pass filter. FSK modulation has been used to transmit low-speed data on the second channel. This second transmission channel can be used for network monitoring, measurements of path loss, subscriber to network signaling and other network operations and control functions.

This thesis has theoretically analyzed this transmission technique. Verification experiments were conducted using a mechanical optical phase modulator. The mechanical phase modulator is not the best choice. For the future work, we are developing an electrical optical phase modulator to improve the system's performance.

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APPENDICES

APPENDIX A

MATLAB SOURCE CODE

MATLAB Code 1: twosin.m

```
% MBRCT Project MATLAB code - twosin.m
% The figure for DC, fundamental,
% and the second harmonics together

clc;
t=0:.001:5;
f=1;
omiga=2*pi*f;
lowf_signal=1-(.2*cos(omiga*t)+.2*cos(2*omiga*t));
modulated_signal=abs(lowf_signal.*sin(10000*t));
plot(t,modulated_signal);
axis([0,5,0.4,1.5]);
xlabel('time','FontSize',12);
ylabel('Amplitude','FontSize',12);
```

MATLAB Code 2: sinOOK.m

```
% For MS thesis OOK as sampling point for the sin wave
% f=1
% OOK 100f

clc;
t=0:1e-2:3;

% Primary OOK pseudorandom binary signal
OOKdata=(idinput(length(t),'prbs')'+1)/2;
plot(t,OOKdata,'.');
axis([0,3,-.5,1.5]);
xlabel('Time','FontSize',12);
ylabel('PRBS OOK Data ','FontSize',12);

% Phase modulation frequency 2% data rate
% primary OOK transmission

figure;
ysin=sin(2*pi*t)+1;
plot(t,ysin,'.');
axis([0,3,-.5,2.5]);
xlabel('Time','FontSize',12);
ylabel('Modulation Sin signal 1% of OOK Data Rate','FontSize',12);

% the combination of these two
figure;
ysum=OOKdata.*ysin;
plot(t,ysum,'.');
axis([0,3,-.5,2.5]);
xlabel('Time','FontSize',12);
ylabel('OOK Data As Sample Points','FontSize',12);
```

MATLAB Code 3: relativeCDincrease.m

```
% Calculate relative Chromatic Dispersion increase on the
% primary OOK channel delta lamda = 1nm
clc;
Am=0.95;

% OOK data rate from 1Gb/s to 40Gb/s
rbOOK=(0.1:0.1:10)*1e9;

f=rbOOK*0.01;
c=3e8;
lamda=1.55e-6;
deltalamda=1e-9;

relCDinc=(2*pi*Am*f*lamda^2)/(c*deltalamda);
semilogy(rbOOK/1e9,relCDinc);
xlabel('OOK data rate (Gb/s)', 'FontSize',12);
ylabel('Relative CD increase', 'FontSize',12);

f1percent=(c*deltalamda)/(2*pi*Am*lamda^2)
```

MATLAB Code 4: capacity.m

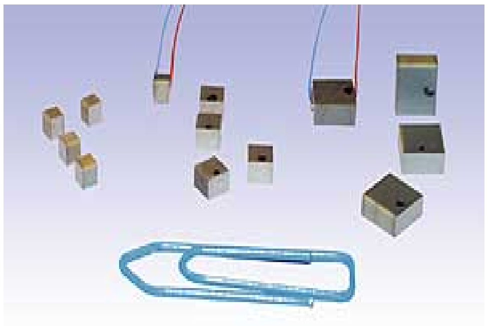
```
% Calculate capacity for the proposed system
clc;

% OOK data rate from 1Gb/s to 10Gb/s
rbOOK=(0.1:0.1:10)*1e9;

% modulation frequency is 1% of the OOK data rate
f=rbOOK*0.01;

rbFSK=f/2;
plot(rbOOK/1e9,rbFSK/1e6);
xlabel('OOK data rate (Gb/s)', 'FontSize',12);
ylabel('System Capacity (Mb/s)', 'FontSize',12);
```

APPENDIX B

LAB COMPONENTS

Piezoelectric actuator

PL022 from PI Corporation is chosen for the experiment for its high resonant frequency, low electrical capacitance and suitable displacement.



Technical Data / Ordering Numbers

Ordering Number*	Dimensions A x B x TH in mm	Displacement [µm ±20% @ 100V]	Blocking Force [N]	Electrical Capacitance [nF ±20%]	Resonant Frequency [kHz]
PL022.20	2 x 2 x 2	2.2	> 250	25	> 300
PL033.20	3 x 3 x 2	2.2	> 300	100	> 300
PL055.20	5 x 5 x 2	2.2	> 500	280	> 300

High voltage amplifier

Thorlabs's MDT694 amplifier is very suitable for driving piezo actuator and is chosen for this lab.

Input voltage: 0 to 10V

Output voltage: 0 to 150V
Max output current: 60mA
Bandwidth: 40 kHz

Photodetector

Thorlabs's D400FC 1GHz InGaAs Fiber Optic Photo Detector is used for this experiment.

- Spectral Range: 700 nm to 1800 nm
- Rise & Fall Times: 100ps Typ.
- Bandwidth: 1GHz
- Dark Current: 1nA Typical, 5nA Max
- 0.9 mA/mW Typical @ 1550nm
- 0.8 mA/mW Typical @ 1300nm
- Attach to Single Mode or Multimode Devices