OPTICAL TIME DIVISION MULTIPLEXING FOR OPTICAL COMMUNICATION SYSTEM

(PEMULTIPLEK PEMBAHAGI MASA OPTIK BAGI SISTEM KOMUNIKASI OPTIK)

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2008

ACKNOWLEDGEMENTS

First and foremost, I thank God, the Mighty for giving me the strength to be able to finish this project. I wish to thank the Ministry of Higher Education Malaysia and Research Management Centre, Universiti Teknologi Malaysia for their financial support during the full term of this research.

Many thanks to my colleagues Assoc. Prof. Dr Abu Sahmah, Dr Sevia and Mr Marwan, also to my research assistants Mr Hafiz and Ms Vida for their support.

I am grateful for the encouragement and support provided by the many friends in Wireless Communication Centre (WCC) UTM such as Mr Mohammed, Ms Yusnita and Mr Reza.

Last but not least, I want to say a heart-felt 'thank you' to my dear wife, parents and children, for their continuous prayer, support and love throughout the years.

ABSTRACT

Fibre nonlinearities are limiting factors for optical communications systems, in particular for wavelength division multiplexing (WDM). Among the nonlinearities effect is four wave mixing (FWM), which is a nonlinear process that generates new frequency components from existing frequency components. FWM is the main factor which ultimately limits the channel density and capacity of WDM systems. Many studies have been carried out on the fiber nonlinear effects in WDM baseband-optical modulated systems but very few have been published on radio-over-fiber (ROF)-WDM system.

Therefore, this research has put a core situation in studying the FWM effect in ROF-WDM systems which carry the modulated microwave carrier and baseband signal. In the ROF-WDM system, the optical modulation technique plays a vital role in amount of fiber nonlinearity effect. Therefore, in this regards, different types of ROF-WDM system in terms of optical modulation techniques are investigated and the drawback and advantages of these techniques are compared. Among these modulated technique, the most suspected optical modulation technique to fiber nonlinearity which is direct intensity modulation is chosen to be modeled for the ROF-WDM system.

The model of the WDM baseband optical modulated system is initially developed to investigate the effect of FWM. In this way, the FWM in conventional WDM system is firstly investigated. By using this model fiber nonlinearity effects in conventional optical system is observed and some effects of fiber nonlinearity by changing the parameters such as channel spacing and the power level are verified. After doing this procedure, a computer model of ROF-WDM system is developed to analyze the FWM effect in the system. In this regards a ROF-WDM system that uses 30 GHz millimeter wave signal to carry the baseband data rate of 2.5 Gb/s is modeled. The results have shown that, in terms of generating FWM component, ROF-WDM system with double sideband transmission is more productive. Therefore, the FWM effect is more destructive than baseband modulation optical system. However, single sideband transmission in ROF can alleviate the FWM impact in certain level. Finally, at the end of the project, some possible solutions and suggestions to mitigate the FWM effect in ROF-WDM system are proposed.

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ABSTRAK

Ketidak lelurus gentian adalah merupakan faktor penghalang dalam system perhubungan optik terutama bagi pemultiplek pembahagian panjang gelombang (WDM). Antara kesan tak lelurus itu adalah *four wave mixing* (FWM), yang merupakan proses penghasilan komponen frekuensi yang baru daripada komponen frequency yang asal. FWM merupakan faktor utama yang menghadkan kepadatan saluran dan keupayaan sistem WDM. Banyak kajian telah dilakukan yang mengkaji kesan tak lelurus gentian dalam sistem termodulat optik-jalurdasar WDM

Oleh sebab itu, tujuan penyelidikan ini adalah untuk mengkaji kesan FWM dalam sistem ROF-WDM yang membawa isyarat jalurdasar dan jugan pembawa gelombang mikro termodulat. Dalam sistem ROF-WDM, teknik pemodulatan optik memain peranan yang penting dalam menentukan kesan tak lelurus gentian. Untuk tujuan itu, beberapa jenis permodulatan optik digunakan dalam kajian ini dan perbandingan antara teknik-teknik pemodulatan dilakukan. Didapati teknik pemodulatan keamatan langsung memberikan prestasi yang terbaik, oleh sebab itu teknik ini dipilih dalam penyelidikan ini untuk digunakan dalam sistem ROF-WDM.

Sistem termodulat jalurdasar WDM dimodelkan terlebih dahulu untuk mengkaji kesan FWM. Dengan mengunakan model ini beberapa parameter penting seperti pisahan saluran dan aras kuasa diubah bagi mengkaji kesan FWM dalam sistem konvensional WDM. Kemudian model sistem ROF-WDM dibangunkan bagi mengkaji kesan FWM dalam sistem ini. Sistem ini menggunakan isyarat gelombang milimeter 30 GHz bagi membawa isyarat jalurdasar atau isyarat maklumat yang setiap satu mempunyai kadar bit 2.5 Gb/s. Keputusan menunjukan peningkatan kesan FWM dalam sistem penghantaran jalursisi kembar ROF-WDM berbanding sitem WDM konvensional. Walaubagaimanapun penghantaran jalursisi tunggal dapat mengurangkan kesan FWM. Beberapa cadangan bagi mengurangkan kesan FWM dalam sistem ROF-WDM dicadangkan.

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LIST OF ABBREVIATION

Symbol	Definition
WDM	Wavelength division multiplexing
DWDM	Dense wavelength division multiplexing
BER	Bit error rate
SNR	Signal-to-noise ratio
FWM	Four wave mixing
XPM	Cross phase modulation
SPM	Self phase modulation
SRS	Stimulated Raman Scatter
SBS	Stimulated Brilion Scatter
DCS	Dispersion compensation shifted
RZ	Return to zero
NRZ	Non Return to zero
SMF	Single mode fiber
GVD	Group Velocity Dispersion
LED	Light emitting diodes
ROF	Radio over fiber
RAU	Remote access unit
RBS	Remote base station
LO	Local oscillator
IMDD	Intensity Modulation direct detection
DBF-LD	Double feedback laser diode
EAM	Electro-absorption modulator
MZM	Mach Zehnder modulator

CHAPTER 1

INTRODUCTION

1.1 Introduction

As the capacity of fiber transmission systems increases, the spacing between wavelength division multiplexing (WDM) channels needs to decrease to make optimal use of limited optical low loss spectrum window. Furthermore, high data rates of 10 or 20 Gb/s and long spans between amplifiers in a chain require high optical powers to inject into the fiber to meet signal-to-noise ratio (SNR) requirements. These high-power values as well as the close spacing between channels increase nonlinear crosstalk between the channels due to the nonlinear properties of the transmission fiber. The most important nonlinear property of fiber which can limit the data rate of the system are Self phase modulation (SPM) Cross phase modulation (XPM) Four wave mixing (FWM), Stimulated Raman Scattering (SRS) and Stimulated Brillion scattering (SBS) [1]. Therefore, to increase the data rate of any WDM optical communication system theses nonlinear effect of fiber need to be mitigated. As a mater of the fact, the fiber nonlinearity is present in any communication system which uses the fiber optics as a media. Therefore, Radio-Over-Fiber (ROF) system also is affected by this undesirable phenomenon.

In this research the FWM as a most dominant fiber's nonlinearity in radio over fiber (ROF) systems incorporating wavelength division multiplexing (WDM) is investigated. The comparison is made with conventional optical WDM system which uses the baseband modulated data. In this regard, we present a simple ROF-WDM simulation model that uses 30 GHz millimeter wave signal to carry the baseband data rate of 2.5 Gb/s. The results have shown that, in terms of generating FWM component, ROF-WDM system with double sideband transmission is more productive. Therefore, the FWM effect is more destructive than baseband modulation optical system. However, single sideband transmission in ROF can alleviate the FWM impact in certain level.

1.2 Problem statement

Fiber nonlinearity is the main destructive phenomena in high data rate optical communication systems. Because of limited low loss optical spectrum, DWDM is an efficient technique to increase spectral efficiency. To have more channels in the low loss optical spectrum, the channel spacing must decrease. As channel spacing decrease the fiber nonlinearity effects increase and cause to performance degradation of optical system. This degradation even is more critical for the long haul transmission where we need to supply high level of power to the fiber. Feeding the high power to the fiber not only increase the XPM and FWM effect but also cause to activate the effect of other fiber nonlinearity phenomena like SRS and SBS. Many techniques have been proposed to resolve and mitigate the fiber nonlinearity issues. Among theses method we can refer to unequal channel spacing and dispersion compensation shifted (DCS) fiber as well as applying high bandwidth optical amplifier. However, the problem of fiber nonlinearity in the ROF system is a quit new issues and it needs to be investigated more.

Therefore, it is essential to investigate and analyze the different fiber nonlinearity phenomena in the ROF system. Many investigations are carried out to mitigate fiber nonlinearity effects in baseband modulated optical system [2], [3], [4]. The question is that whether those solutions and finding can be applied into ROF system or not. In multi-channel systems, FWM in optical fibers induces channel crosstalk and possibly degrades system performance. Now, we need to know how much FWM effect can degrade the performance of ROF system, when the optical carrier carry the modulated microwave frequency instead of baseband RZ or NRZ pulses. In this research, we investigate this issue, and our focus is on FWM effect as a fiber most dominant nonlinear effect in zero dispersion fiber.

1.3 Objectives of the project

The objectives of the project can be classified into four sections as below.

- Study the effects of fiber nonlinearity on performance of optical system with Wavelength Division Multiplexing (WDM) Technique.
- Study the effects of fiber nonlinearity on performance of Radio-Over-Fiber (ROF) system with Wavelength Division Multiplexing (WDM) Technique.
- Simulation of FWM fiber nonlinearity on ROF-WDM system and comparison with baseband modulation optical systems.

1.4 Report outline

The following sections of these report is consist of four chapters. Chapter one reviews the literature of fiber nonlinearity. The ROF system, base on its modulation technique is elaborated in chapter three. The simulation model of ROF-WDM system is presented in chapter four. In chapter five, the simulation results are presented. Finally report concludes in chapter six.

CHAPTER 2

FIBER OPTICS AND FIBER NONLINEARITIES

2.1 Introduction

To further enhance and explore the advantages of the high bandwidth provided by optical fiber, multiplexing is an effective solution which combines multiple numbers of wavelengths into the same fiber in the region of 1300-1600 nm spectrums. With the invention of lasers with extremely narrow line widths, more channels can be multiplexed into the same fiber which provides the basis for Dense Wavelength Division Multiplexing (DWDM). As it shown in Figure-2.1, the main components of the DWDM system are the multiplexer at the transmitting end and the demultiplexer at the receiving end. The multiplexer combines the different wavelengths and they are separated back at the receiving end with a demultiplexer.

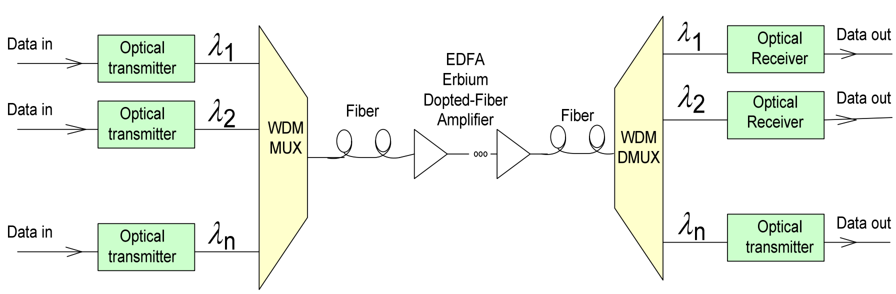

Figure 2.1 Optical system using WDM technique

In the transmitter side, different light source are modulated individually by signal. For good link quality, the frequency spectrum of individual channel should be as narrow as possible. By now, laser carrier line width 4M/250 MHZ can be achieved by external / directly modulating optical wave using double feedback laser diode (DBF-LD) As it can be seen from the Figure-2.1, for long-haul transmission optical amplifier needed to compensate the fiber loss. Desirable optical amplifier is EDFA since it has high gain, large saturated output power and wide bandwidth.

Theoretically, the number of channel within low loss window (1330nm-1580nm) is 1250, therefore, Potential capacity of WDM is

$$C = 1250 \times 10 = 12.5 \text{ Tb/s}$$

However, many factor limits, the total number of channel in WDM including bandwidth limitation of optical amplifier and fiber nonlinearity. The existence broadband optical amplifier just has 50nm spectrum flat gain. *EDFA* probably can be considered ideal amplifier since it has high gain, broad bandwidth, and also it works on population inversion principle. Gain variation of optical amplifier is detrimental because It leads to supply insufficient optical power to some WDM channel and supply too much optical power feed to other channel. Too much optical power increase the nonlinearity effect of fiber (XPM-FWM-SRS) while insufficient optical power degrade the system signal to noise ratio (SNR). Therefore, gain flattened amplifier is needed to alleviate the fiber nonlinearity effects. In this way, also we need to apply some techniques to equalize the gain of amplifier.

Fiber nonlinearity is another technical challenge which limits the number of channel in WDM. The fiber nonlinearity causes to high interference and channel cross-talk between WDM channels. Therefore, Extra channel spacing is essential. In addition, the simplest approach to avoid fiber nonlinearity effects is keeping the light intensity low. This action nonetheless, is detrimental due to decreasing the system SNR.

2.2 Fiber characteristics, losses and non-linear effects

2.2.1 Overview

The fundamental component that makes the optical communication possible is the optical fiber. The phenomenon which guides the light along the optical fiber is the total internal reflection. It is an optical phenomenon which occurs when the incident light is completely reflected. Critical angle is the angle above which the total internal reflection occurs. In case of materials with different refractive indices, light will be reflected and refracted at the boundary surface. This will occur only from higher refractive index to a lower refractive index such as light passing from glass to air. This phenomenon forms the basis of optical communication through fibers. An optical fiber is a dielectric waveguide, it is cylindrical, and guides the light parallel to the axis. The cylindrical structure is dielectric with a radius "a" and refractive index of "n1". This is the called the *core* of the fiber the fiber and the layer that encompasses this structure is called the *cladding*. Cladding has a refractive index "n2" which is lesser than "n1". This helps in providing mechanical strength and helps reducing scattering losses. It also prevents the core from surface contamination. Cladding doesn't take part in light propagation.

2.2.2 Types of fibers

Fibers can be classified according to the core's material composition. If the refractive index of the core is uniform and changes abruptly at the cladding boundary, then it is called as Step-index fiber. If the refractive index changes at each radial distance, then it is called as Graded-index fiber. These fibers can be divided into Single mode and multi mode fibers. Single mode fibers operate in only one mode of propagation. Multimode fibers can support hundreds of modes. Both laser diodes and light emitting diodes (LED) can be used as light wave sources in fiber-optical communication systems. When compared to Laser diodes, LEDs are less expensive, less complex and have a longer lifetime, however, their optical powers are typically small and spectral line-widths are much wider than that of laser diodes. In Multimode fibers different modes travel in different speed, which is commonly referred to as inter-modal dispersion, giving room to pulse spreading. In single mode fibers, different signal frequency components travel in different speed within the fundamental mode and this result in chromatic dispersion. Since the effect of chromatic dispersion is proportional the spectral linewidth of the source, laser diodes are often used in high-speed optical systems because of their narrow spectral linewidth.

2.2.3 Fiber Losses

For efficient recovery of the received signal, the signal to noise ratio at the receiver must be considerably high. Fiber losses will affect the received power eventually reducing the signal power at the receiver. Hence optical fibers suffered heavy loss and degradation over long distances. To overcome these losses, optical amplifiers were invented which significantly boosted the power in the spans in between the source and receiver. However, optical amplifiers introduce amplified spontaneous emission (ASE) noises which are proportional to the amount of optical amplifications they provide. Low loss in optical fibers is still a critical requirement in long distance optical systems to efficiently recover the signal at the receiver. Attenuation Coefficient is a fiber-loss parameter which is expressed in the units of dB/Km. The optical power traveling inside the fiber changes along the length and is governed by Beer's law:

$$\frac{dp}{dz} = \alpha . p \qquad 2.1$$

"α" is the attenuation constant in Neper. If Pin and Pout are the power at the input and output of the fiber and L is the length of the fiber, then the power at the output is

$$p_{out} = p_{in} . \exp(-\alpha . L) \qquad 2.2$$

For short wavelengths, the loss may exceed 5 dB/Km and makes it unsuitable for long Distance transmission [4]. These losses are mainly due to material absorption and Rayleigh scattering. Material absorption is the phenomenon exhibited by fibers material. The intrinsic absorption is caused by fused silica, and extrinsic absorption is caused by impurities in silica. The other contributing factor is the Rayleigh scattering which is caused by the density fluctuations in the fiber. These fluctuations change the refractive index on a smaller scale. Light scattering in such medium is called Rayleigh scattering [6]. The intrinsic loss of silica fibers due to this scattering is expressed as,

$$\alpha_R = C / \lambda^4 \qquad 2.3$$

C is a constant in the range of 0.7 – 0.9 (dB/Km)-μm^4 and depends on the fiber core. This constitutes the scattering loss to be 0.12 – 0.16 (dB/Km) at λ = 1.55 µm [5].

2.2.4 Chromatic Dispersion

In multi-mode fibers, intermodal dispersion is the dominant contributor of signal waveform distortion. Although intermodal dispersion is eliminated in single mode fibers, different frequency component of optical signal carried by the fundamental mode still travel in slightly different speed giving rise to a wavelength-dependent group delay. As group delay depends on wavelength, different amount of time is taken for the different spectral components to reach a certain distance. Due to this effect the optical signal with a certain spectral width spreads with time when it travels through the fiber. This pulse spreading is important and needs to be determined. The following Equation gives the value for pulse spreading.

$$D = -\frac{2\pi c}{\lambda^2}\beta_2 \qquad 2.4$$

where D is the dispersion parameter, c , the light velocity, λ , the wavelength and β is the GVD (Group Velocity Dispersion) parameter. It is measured in ps/nm/km. Dispersion can also be measured by adding the material and waveguide dispersion together unless a very precise value is needed. Thus material dispersion and waveguide dispersion can be calculated separately and summing up these values will gives the dispersion value.

2.3 Fiber Nonlinearities

The non-linear effects of the fibers play a detrimental role in the light propagation. Nonlinear Kerr effect is the dependence of refractive index of the fiber on the power that is propagating through it. This effect is responsible for SPM, XPM and FWM. The other two important effects are stimulated SBS and SRS.

2.3.1 Self Phase modulation

In fibers, the refractive index always has some dependence on the optical intensity which is the optical power per effective area. This relation can be given as Equation 2.5,

$$n = n_0 + n_2 I = n_0 + n_2 \frac{p}{A_{eff}} \qquad 2.5$$

where n_0 is the ordinary refractive index , n_2 is the non-linear refractive index coefficient equal to 2.6×10-20m2/W for silica fibers,A_{eff} is the effective core area, and P is the power of the optical signal. This non-linearity is called as Kerr nonlinearity. This produces Kerr effect in which the propagating signal is phase modulated by the carrier. This leads to a phenomenon is called Self-phase modulation that converts power fluctuations into phase fluctuations in the same channel [5]. The nonlinear refraction index results in a phase change for the propagating light.

$$\varphi_{NL} = \gamma \, . \, P \, . \, L_{eff} \qquad 2.6$$

$$\gamma = \frac{2\pi n_2}{\lambda A_{eff}} \qquad 2.7$$

γ is the nonlinear coefficient. The phase change becomes significant when the power times the length of the system equals 1W-km. SPM occurs when an intensity-modulated signal travels through a fiber. The signal is broadened in frequency domain by Equation 2.8.

$$\Delta\beta = \gamma.\ \mathrm{L}_{\mathrm{eff}}\ .\frac{dp}{dt} \qquad 2.8$$

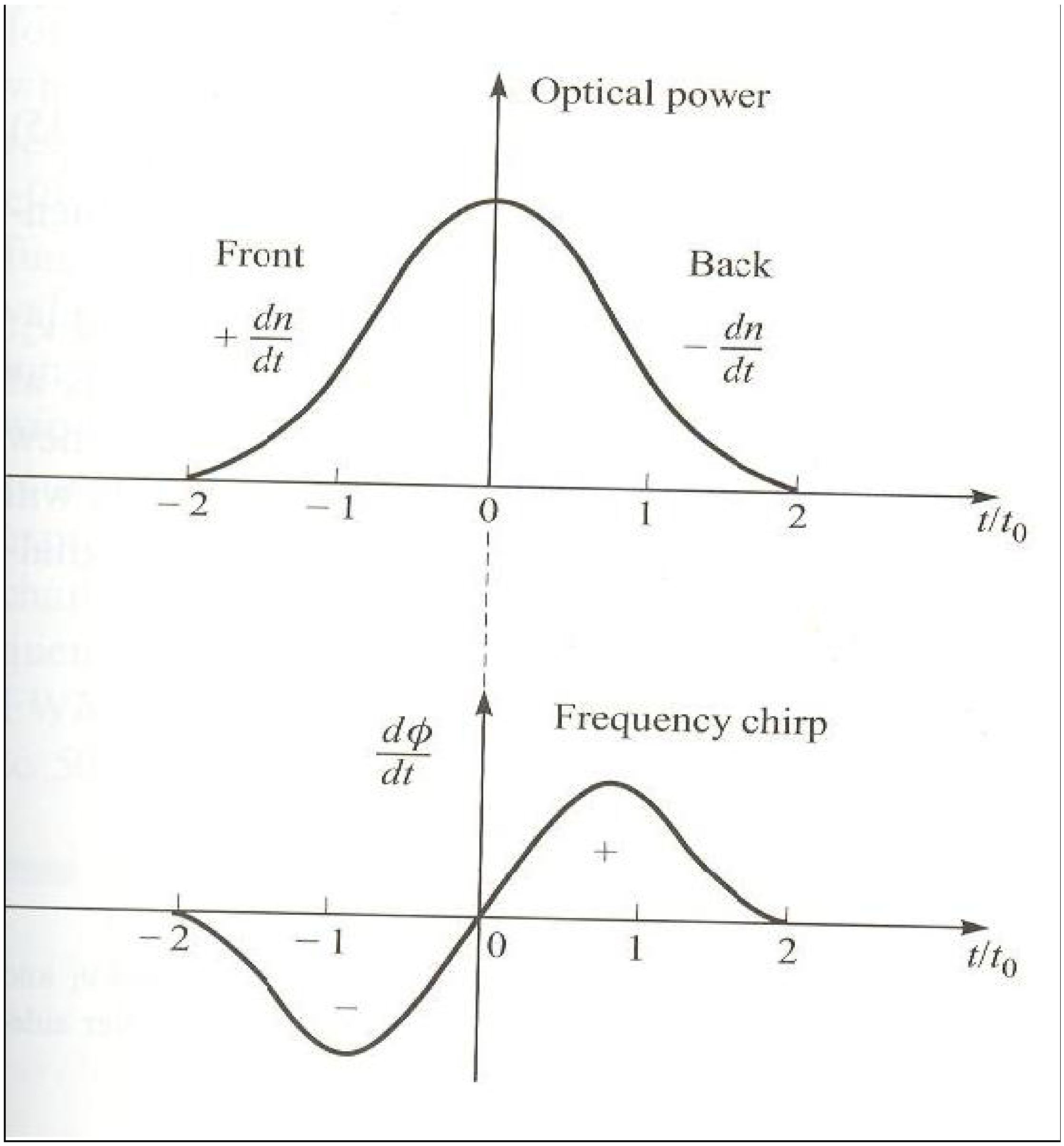

Figure 2.2 Frequency chirping effect [4]

In a material in which the refractive index depends on the intensity of the signal, and as this time varying signal intensity propagates along the fiber, it will produce time varying refractive index. This produces higher refractive index at the peak of the pulse when compared to the edges of the pulse. This produces a time varying phase change $d\theta/dt$. Due to this change, the frequency of the optical signal undergoes a frequency shift from its initial value. This effect is known as frequency chirping, in which different parts of the pulse undergo different phase change [4]. The rising edge experiences a shift towards the higher frequency and the trailing edge experiences a shift towards the lower frequency. Since this effect depends heavily on the signal intensity, SPM has more effect on high intensity signal pulses. In case of fibers which have the GVD effects, the pulse broadens which leads to difficulty in the receiver side to decode the signal. When the chromatic dispersion is negative, the edges of frequencies which experienced higher shifts tend to move away from the centre of the pulse. The edges of frequencies which experienced lower shifts tend to move away from the centre in the opposite direction. Thus this GVD affected pulse will be broadened at the end of the fiber. The chirping worsens due to this effect. Thus SPM can degrade the performance of the optical system in case of long haul transmission.

2.3.2 Cross phase modulation

As with Equation 2.5, the refractive index of the fiber depends on the time varying signal intensity and this result in time varying refractive index. This also leads to an effect called Cross phase modulation (XPM). XPM has more pronounced effect in case of WDM systems in which more optical channels are transmitted simultaneously. In case of XPM, the phase shift depends on the power of other channel. The total phase shift can be represented as [6],

$$\phi_j^{NL} = \gamma . \mathrm{L_{eff}} \,.(P_j + 2\sum_{m \neq j} p_m) \qquad 2.9$$

Φ is tthe non-linear phase shift for the *jth* channel, P_j and P_m are the power are the power for the channels i and j and m vary from one to $N^2(N-1)/2$, N is the total number of channel. On the right-hand-side of Equation (2.9), the first term represents effect of SPM and the second term represents that of XPM. In Equation 2.9 implies that XPM is twice as effective as SPM for the same amount of power [4]. The phase shift which is directly created by XPM at the end of the fiber depends on the bit patterns and powers of the neighboring channels. The effect of XPM also depends on the wavelength separation between the signal channel and the neighboring channel. If the channels are separated widely, then the XPM effects are relatively weak because the two bit streams walk-off from each other quickly. In case of the DWDM systems, the channel wavelength separation is very narrow which leads to strong XPM effect. Since XPM results in a inter channel crosstalk, its effect, to some extent, also depends on the bit pattern of the two channels. This will be shown in later sections. To analyze the effect of XPM and SPM, the nonlinear Schrödinger Equation can be used which is represented as Equation 2 .10 [6].

$$i\frac{\partial A(z,\tau)}{\partial z}-i\frac{\beta_3}{6}.\frac{\partial^3 A(z,\tau)}{\partial \tau^3}+\gamma.|A(z,\tau)|^2.A(z,\tau)=0 \qquad 2.10$$

The Equation 2.10 neglects the third-order dispersion and the term α is added for fiber losses. By increasing the effective area, nonlinearities can be reduced. A_{eff} is about 80 μm2 for standard fibers and is 50 μm2 for dispersion shifted fibers [2-3].

2.3.3 Four wave mixing

Both XPM and FWM cause interference between channels of different wavelengths resulting in an upper power limit for each WDM channel .The most severe problems are imposed by Four-wave mixing (FWM), also known as four-photon mixing, is a parametric interaction among optical waves, which is analogous to inter modulation distortion in electrical systems. In a multi-channel system, the beating between two or more channels causes generation of one or more new frequencies at the expense of power depletion of the original channels. When three waves at frequencies f_P, f_q,and f_r are put into a fiber, new frequency components are generated at $f_{FWM} = f_P+f_q- f_r$. In a simpler case where two continuous waves (cw) at the frequencies f_1 and f_2 are put into the fiber, the generation of side bands due to FWM is illustrated in Fig 1 The number of side bands due to FWM increases geometrically, and is given by

$$M = \frac{N^2(N-1)}{2} \quad 2.11$$

where N is the number of channels and M is the number of newly generated sidebands For example, eight channels can produce 224 side bands. Since these mixing products can fall directly on signal channels, proper FWM suppression is required to avoid significant interference between signal channels and FWM frequency components. The power of FWM product is inversely proportional to the square of the channel spacing .when all the channels have the same input power FWM efficiency is give by Equation (2.12).

$$\eta = \left(\frac{n_2}{A_{eff} \cdot D \cdot (\Delta\lambda)} \right)^2 \quad 2.12$$

Where A_{eff} is the effective area of the fiber and D is the dispersion parameter.

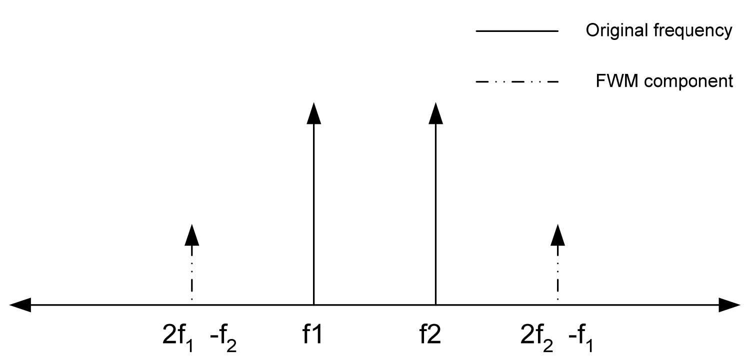

Figure 2.3 Four wave mixing effect for two channels

2.3.4 Stimulated Brillouin Scattering

SBS falls under the category of inelastic scattering in which the frequency of the scattered light is shifted downward [5]. This results in the loss of the transmitted power along the fiber. At low power levels, this effect will become negligible. SBS sets a threshold on the transmitted power, above which considerable amount of power is reflected. This back reflection will make the light to reverse direction and travel towards the source. This usually happens at the connector interfaces where there is a change in the refractive index. As the power level increases, more light is backscattered since the level would have crossed the SBS threshold. The parameters which decide the threshold are the wavelength and the line width of the transmitter. Lower line width experiences lesser SBS and the decrease in the spectral width of the source will reduce SBS. In case of bit streams with shorter pulse width, no SBS will occur [5]. The value of the threshold depends on the RZ and NRZ waveforms which are used to modulate the source. It is typically 5 mW and can be increased to 10 mW by increasing the bandwidth of the carrier greater than 200 MHz by phase modulation [5].

2.3.5 Stimulated Raman Scattering

SRS occurs when the pump power increases beyond the threshold, however in SRS it can happen in either direction, forward and backward. The molecular oscillations set in at the beat frequency and the amplitude of the scattering increases with the oscillations. The Equations that govern the feedback process are [6],

$$\frac{dI_P}{dz} = -g_R I_P I_S - \alpha_P I_P \qquad 2.13$$

$$\frac{dI_S}{dz} = -g_R I_P I_S - \alpha_S I_S \qquad 2.14$$

Where, g_R is the SRS gain, I_P and I_S are intensities of Pump and stokes field. the threshold power, the is given by Equation (2.15)

$$P_{th} = 16\alpha(\pi w^2)/g_R \qquad 2.15$$

πw^2 is the effective area of the fiber core and w is the spot size. Even though there are some detrimental effects posed by these two effects, SBS and SRS can also be used in a positive way. Since both deal with transferring energy to the signal from a pump, they can be used to amplify the optical signal. Raman gain is also used in compensating losses in the fiber transmission.

Table 2.1 Comparison between SBS and SRS

property	SBS	SRS
Direction of	Only in backward direction	In both backward and forward direction
Spectrum width	Narrow band	Broadband
Frequency shift	About 10 GH	About 13 TH

CHAPTER 3

ROF SYSTEM AND OPTICAL MODULATION

3.1 Introduction

ROF is one of the promising techniques for four generation (4G) of mobile wireless cellular system [7]. By using this technique the process of cell optimization become easily feasible. In the concept of cell optimization, pico and micro cell are defined in order to take advantage of frequency reusing technique. Without ROF technique, cell optimization is very costly; since each Pico cell needs a separate base station. By using ROF, this problem can be resolved [8]. In this technique, the microwave frequency signal from remote antenna is directly transferred to the central base station over an optical fiber. So, all signal processing is done in the central base station. By doing so, the base station structure is simplified and it just substitutes by a cost-effective, small and compact remote access unit (RAU) which is transparent to the air.

This chapter presents the different modulation techniques to optically generate micro and millimeter wave for Radio over Fiber (ROF) systems. The investigation of modulation technique in ROF system is very vital in the amount of fiber nonlinearity effect in the system. By applying the appropriate optical modulation, the cause of fiber nonlinearity can be efficiently compensated. The optical modulation of the millimeter wave can be divided into three classes: Intensity modulation direct detection, sub-harmonic up-conversion and heterodyning techniques. The context of this chapter can be organized as three broad sections. Each section gives a theoretical background about the specific methods to generate the micro and millimeter wave optical signal.

3.2 Intensity modulated direct detection

This method can be classified into two techniques: direct modulation and external modulation. The most simple transmitter configuration for the optical generation of microwave signals uses intensity modulation of a laser. The modulated optical carrier is transmitted through optical fiber and is detected using the photodetector as shown in Figure-3.1 The photodetector convert the optical carrier to electrical DC and AC component with the local RF oscillator frequency. This technique is referred as intensity modulation and direct detection (IMDD). The laser can be directly or externally modulated.

3.2.1 Direct modulations

Figure 3.1 shows an IMDD scheme that uses a directly modulated laser diode. An RF local oscillator LO is modulated with base band data stream. The subsequent mixed signal is used to modulate the current injected into laser diode. The intensity modulated optical signal is transmitted over fiber-optic cable, and detected by a photo detector. Provided that the bandwidth of the photodetector exceeds the modulated bandwidth of the laser diode, an electrical signal oscillating at RF LO, modulated with the baseband data is generated at the photodetector.

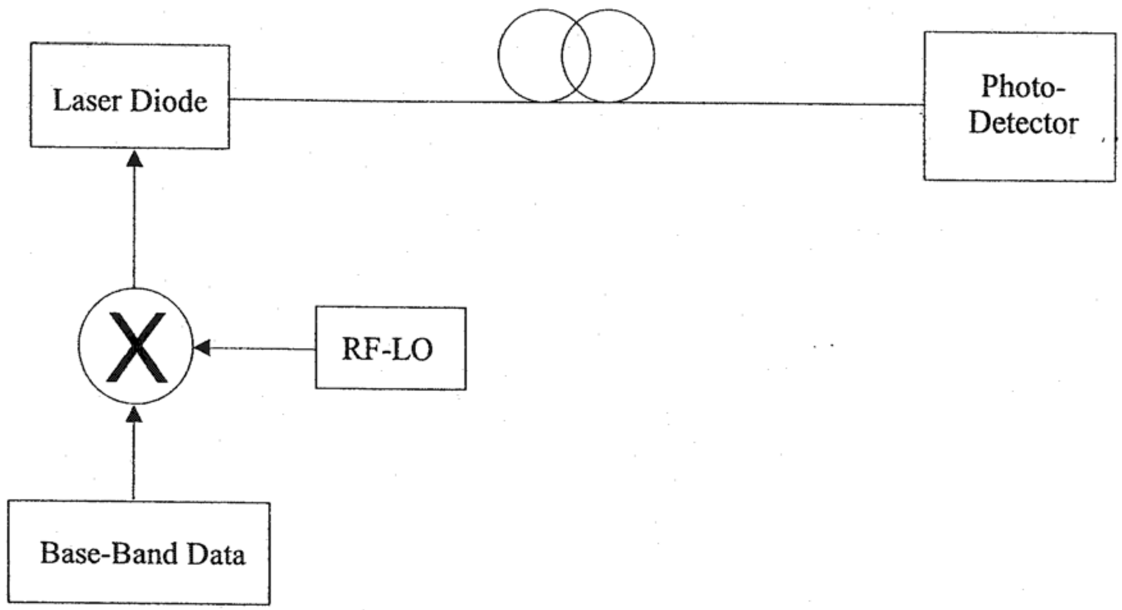

Figure 3.1: direct modulation block diagram. The laser injection current is modulated with the RF carrier mixed with base-band data

The direct modulation scheme is used in commercialized ROF application for 2nd and 3rd generation wireless systems. This configuration is widely used because of the low-cost and high reliability of laser diodes. However, there are limitations to laser diode modulation speeds. This limitation put the boundaries on the generation of higher RF frequency signals. Despite much effort, the laser diode cannot be easily modulated after than 30 GHz [9]. The commercialized laser on the current market is in the range of several GHz. This is because of natural resonance frequency of laser diode. Generally, the problems and challenges due to direct modulation can be outlined as: Laser relaxation oscillation, chromatic dispersion and chirp.

3.2.1.1 Relaxation oscillation

The relaxation oscillation of the laser diode is a time lag between the cause and effect, creating the oscillations that severely distort the modulation waveforms. The oscillation can very with amplitude, frequency and duration. The oscillation is depending upon to the carrier lifetime and gain of the semiconductor [10]. In conventional semiconductor the carrier life time is in the order of few nanoseconds inducing a relaxation oscillation in order of few GHz.

3.2.1.2 Chromatic dispersion

In addition to limitation of laser diode, the transmission span of millimeter wave signals in system with intensity modulation is limited due to chromatic dispersion [11]. In directly modulated or externally modulated transmitter, the microwave signal is carried in the sidebands of the optical carrier. The sidebands and the carrier are shifted in frequency, and thus contains slightly different wavelengths, all of which travel at different velocity through the fiber, causing the signal spreads along the transmission length. The relative time delay between the two restored modulation signals can be translated as phase delay which can be expressed as Equation 3.1.

$$\theta(2\omega_s, L) = \frac{1}{2\pi} DL \frac{\lambda^2}{c} \omega_s^2 \qquad (3.1)$$

Where $\omega_{s}=\omega_{RF}$ is the central frequency of the modulation signal, L is the length of the link, D is the dispersion coefficient of the optical fiber, c is speed of light and λ is the wavelength of the optical carrier. The phase delay causes interference between the two RF modulation signal coming from two optical sidebands. The RF photocurrent from the photodetector can be represented in Equation 3.2.

$$I_d(t) = \underbrace{k \cos\left(\frac{\theta}{2}\right)}\cos[\omega_s t + \frac{\theta(2\omega_s, L)}{2} + ... \qquad (3.2)$$

The underlined term reflects the optical power penalty due to dispersion of the optical fiber. Therefore, after detection power reduction of the recovered microwave or millimeter wave carrier is resulted, consequently it causes to reduction of signal to noise ratio.

3.2.1.3 Chirp

Modulating the output power of the laser by varying the electrical current causes a change in output power and output frequency. The change in output frequency is called chirp. There are two effects contributing to chirp. First the carrier concentration due to increase in current, reduce the refractive index. Second, increasing the drive current can increase the temperature of the device, altering the refractive index and causing the chirp to expand. Since the refractive index is changing, the lasing wavelength within a single modulating pulse will vary as the injection current is changed. This creates an output that is chirped, or changing wavelength over time. The multi-wavelength nature of chirped signal causes them to experience more chromatic dispersion than that of an un-chirped signal.

3.2.2 External modulation

The other popular technique in IMDD link is external modulation. An external modulator is a device that is placed between the laser and RF modulated signal. A block diagram of an external modulation IMDD link is shown in Figure-3.2

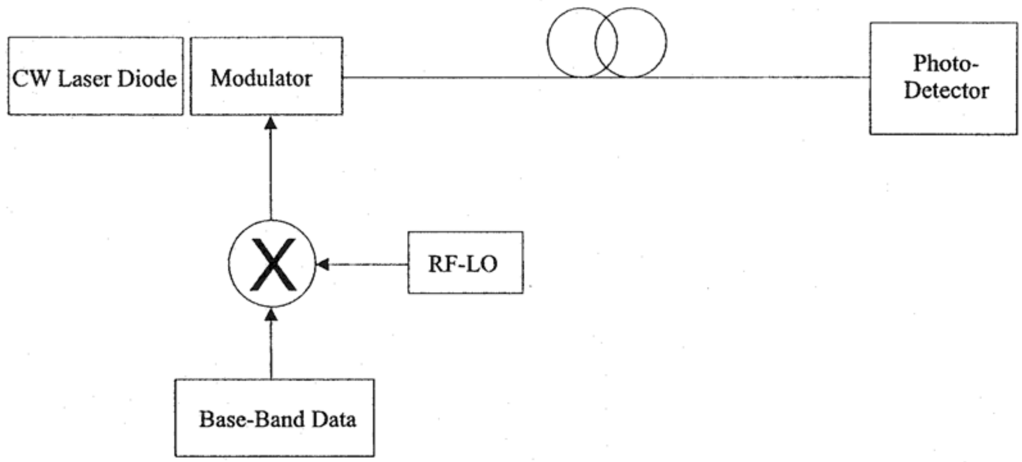

Figure 3.2 external modulation block diagram. The laser diode is run continues-wave (CW), and the output optical signal is modulated externally

In an externally modulated IMDD link, the electrical current applied to the laser is kept constant at the level above lasing threshold, providing a constant continues wave CW optical output. Since the current of the laser is constant, link degradation due to laser relaxation oscillation are eliminated [12]. Nonetheless, the disadvantages of external modulation are the cost and it requires the relatively high drive voltage and it introduces large insertion losses [13]. There are two types of commonly used external modulator: The electro-refractive modulator and electro-absorption modulator.

3.2.2.1 Electro-refractive Modulator

The refractive index of a material in an electro-optic modulator is changed by the electro-optic effect, by means of applying a sufficient electric field to the waveguide [14]. The refractive index n of an electro-optic medium is a function of the applied electrical field which represented by Equation 3.3.

$$n(E) = n + a_1.E + \frac{1}{2}a_2.E^2 + \ldots \quad (3.3)$$

Where a_1. a_2,…a_n are material-related coefficients. Since, the refractive index changes with an electrical field passing through these materials a phase shift will be created. A phase shift will not directly affect the intensity of the light beam. In principle, the CW laser beam is split equally into two arms of interferometer can provide the intensity modulation. An electric field applied to one or both arms in order to shift the phase of the light, and the light is recombined into a single wave guide. The light from each arm combines either in phase $\Delta\theta = 2\pi n, \quad n = 0,1,2...$, where $\Delta\theta$ represents the change in phase between the light in each arm, which generate a light optical output, or out of phase $\Delta\theta = \pi n, \quad n = 0,1,2...$ which generate a low optical output. Theses devise called Mach-Zender interferometer.

3.2.2.2 Electro-Absorption Modulator

Electro-absorption modulators are based on a semiconductor structure whereby light is absorbed when voltage is applied to the semiconductor. They are often fabricated out of the same materials as semiconductor lasers, making them useful in forming elegant integrated devices. Since, it occupies very little space. The modulator is operating in reverse bias, so the power consumption can be very low. In addition, they have high modulation efficiency, and they can work with IF frequency less than 10GHz while the MZM is able to work with IF frequency less than 1GHz. Moreover, the biased voltage from 1-3V usually is enough for EAM whereas for MZM the DC voltage from 4-5 V is required. EAM has been demonstrated with extinction ratio per device length exceeding 20 dB/mm at a voltage of 4 V [15]. Figure-3.3 is a block diagram of external modulation using an electro-absorption modulator. The baseband data modulates the RF signal with frequency of ω_s. The RF signal then modulates the optical source with the frequency of ω_1.

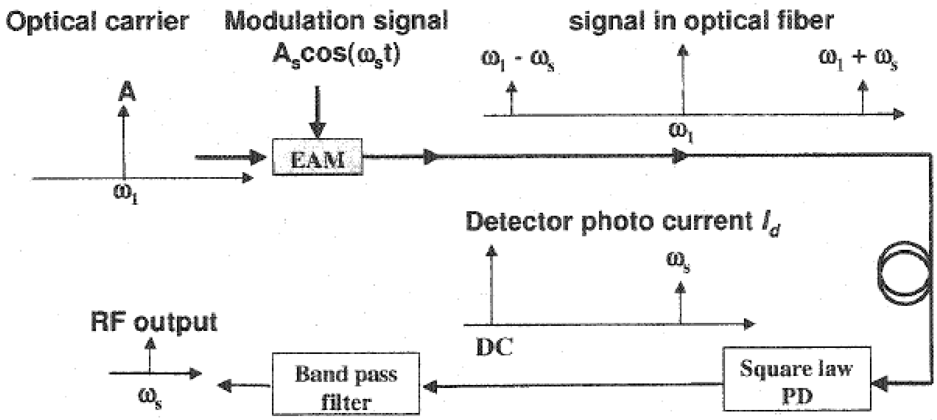

Figure 3.3 An external modulation technique using EAM

The outputs of the electro absorption modulator are two sidebands which are located at $\omega_1 + \omega_s$ and $\omega_1 - \omega_s$. Finally base on the square law photo detection the output of the photodiode will be just the modulated RF carrier and DC value. The optical carrier and the other created frequency are canceled out after photo detection operation.

3.3 Sub-Harmonic Up-Conversion

In this technique, [16], a sub-harmonic of the desired RF carrier frequency is generated in the control-station. This subharmonic is optically transmitted using a low-cost directly modulated laser diode and detected by a fast diode. The electrical output from the photodetector is then multiplied by the RF local oscillator in the base-station as shown in Figure 3.4.

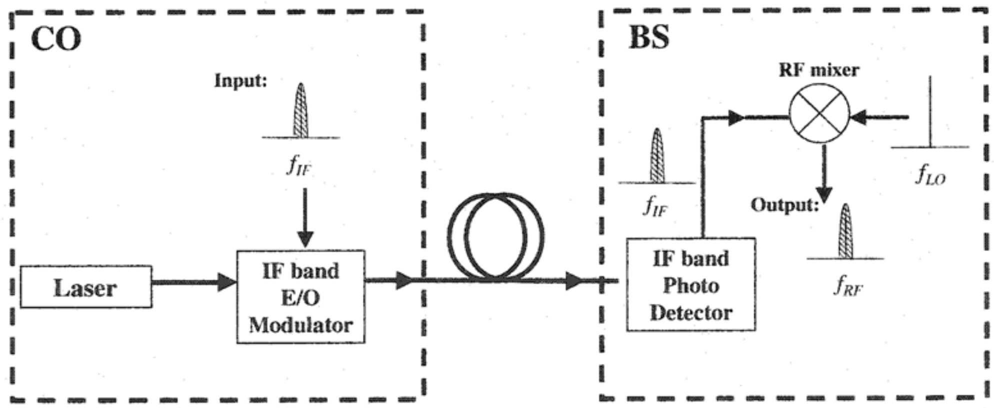

Figure 3.4 The IF signal is sent to the BS by the optical fiber link. At the BS the IF signal is up converted to RF band by an electrical RF mixer.

Sub-harmonic configuration uses a low cost laser to generate sub-harmonic of the RF frequency. In addition, by using IF frequency the induced dispersion fiber will be less than the RF modulated signal over fiber. Therefore the system encounters less power penalty. Since, the phase delay can be expressed as following Equation.

$$\theta(2\omega_s, L) = \frac{1}{2\pi} DL \frac{\lambda^2}{c} \omega_s^2$$

$$\omega_s = \omega_{RF} < \omega_{RF} \qquad (3.4)$$

Nonetheless, this technique has two drawbacks; first, the phase-noise of the system is enhanced by the multiplication of the signal in the base-station. When multiplying the signal, the phase noise increases as shown in Equation 3.5.

$$noise = 10\log(k^2) + 3dB \qquad (3.5)$$

Where k is the multiplication factor needed to create the RF carrier from the sub-harmonic. Second drawback is the complexity of the remote base station (RBS) because of high electrical RF mixer.

Some schemes are proposed to remove the MMW local oscillator at the BS [17]. for example, LO signal is distributed from the control station (co). After detection, the LO signal and IF signal are separated. They then drive an electrical RF mixer at the BS to up convert the IF to the RF band.

3.4 remote heterodyning

There are many different techniques that use remote heterodyning to optically generate micro and millimeter wave signals. The most common techniques are presented in this section.

Photodetector respond are insensitive to optical phase and they just detect the intensity of the optical field. However, it is possible to obtain the information about the both magnitude and phase of the optical field by using a reference optical field. Due to interference between the two fields when combined and shone on a square-law photodetector, the output electrical current contains information about both amplitude and the phase of the signal field. This is called the optical heterodyning. When one performs optical heterodyning in the receiver of a base station, this can be called remote heterodyning. The block diagram of remote heterodyning is shown in Figure-3.5. When two lasers shining at two separated wavelengths, the photodetector output will produce an electrical signal which oscillating at exactly the frequency difference between the two sources.

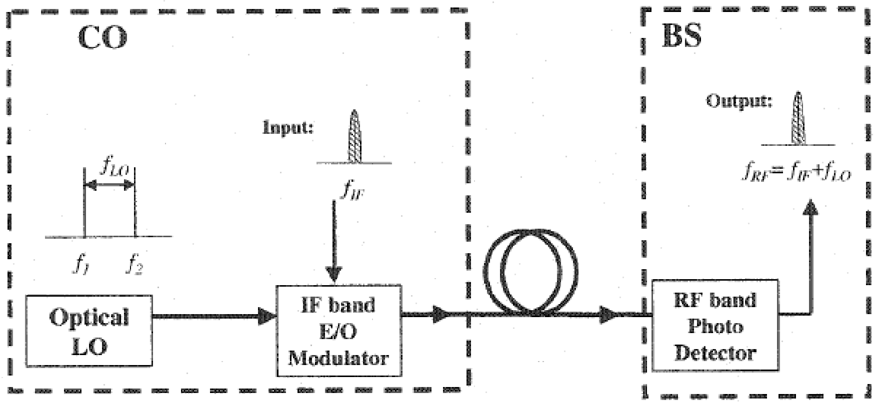

Figure 3.5 Conventional optical heterodyned link

The IF modulation signal modulates the optical LO. The square law detection of photodetector up-convert the IF signals to the RF band. The phase delay of the system in this case can be calculated using Equation 3.6.

$$\theta(2\omega_s, L) = \frac{1}{2\pi}\left(DL\frac{\lambda^2}{c}\omega_{RF}^2\right)\frac{\omega_{IF}}{\omega_{RF}}$$

$$\omega_s = \omega_{RF} < \omega_{RF} \qquad (3.6)$$

Similar to IMDD scheme, dispersion can limit the transmission span of the link. To reduce the effect of chromatic dispersion in a remote heterodyning technique, only one optical carrier is modulated with base-band data. In this situation, since the signal is spread over a smaller bandwidth than if both carriers are modulated with the base-band data, the negative effect of chromatic dispersion can be reduced.

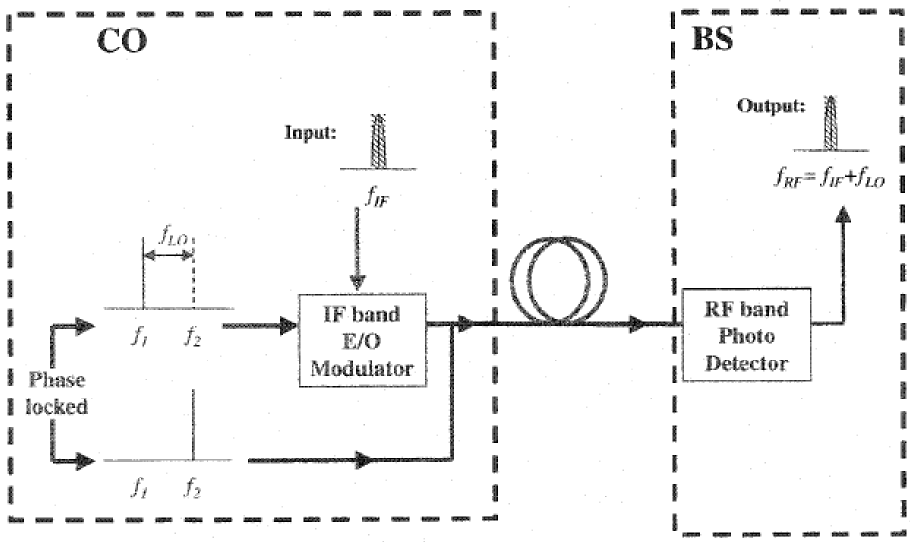

Figure 3.6 An optical heterodyned link with the decoupled optical sideband transmission property. The IF modulation signal only modulate one carrier of the optical signal LO

The RF photocurrent of the link by modulating just one optical carrier with the IF data can be expressed by Equation 3.7. It can be seen that the power penalty due to dispersion can be eliminated completely.

$$I_d(t) = k.\ 1\ .\cos[\omega_{RF}t + \theta(\omega_{RF}, L)] + ... \qquad (3.7)$$

3.4.1 square-law photodetector

Most of the heterodyning techniques discussed in the following section require the use of square-law photodetector in order to optically generate the millimeter-wave signal.

The optical fields of two signal incident upon a photodetector can be represented by Equations 3.8 and 3.9.

$$s_1 = E_1 \cos(\omega_1 t + \theta_1) \tag{3.8}$$

$$s_2 = E_2 \cos(\omega_2 t + \theta_2) \tag{3.9}$$

Where E_1 and E_2 are the optical electric-field amplitude, ω_1 and ω_2 are the radial frequencies, and θ_1 and θ_2 are the respective phases. The optical intensity I_{opt} is proportional to the absolute-square of the complex amplitudes.

$$I_{opt} = |s_1 + s_2|^2 \tag{3.10}$$

Substituting (3.8) and (3.9) to (3.10) obtains

$$I_{opt} = E_1^2 \cos^2(\omega_1 t + \theta_1) + E_2^2 \cos^2(\omega_2 t + \theta_2) + 2E_1^2 E_2^2 \cos(\omega_2 t + \theta_2)\cos(\omega_1 t + \theta_1) \tag{3.11}$$

Using trigonometric identities, Equation (3.11) can be written as Equation 3.12.

$$\begin{aligned} I_{opt} = {} & \frac{E_1^2}{2}[1 + \cos(2\omega_1 t + 2\theta_1) + \frac{E_2^2}{2}[1 + \cos(2\omega_2 t + 2\theta_2)] \\ & + E_1 E_2 \left\{ \cos[(\omega_1 - \omega_2)t + (\theta_1 - \theta_2)] + \cos[(\omega_1 + \omega_2)t + (\theta_1 + \theta_2) \right\} \end{aligned} \tag{3.12}$$

Commercial photodetector are limited to bandwidth on the order of several tens of GHz, meaning any signal oscillating faster than this upper limit will be rejected. Since ω_1 and ω_2 are optical frequencies oscillating at several hundreds of the, terms containing theses, and the summation (ω_1+ω_2) may be ignored. They will only contribute to DC level of the electrical output signal as shown in Equation 3.13.

$$I_{opt} = \frac{E_1^2}{2} + \frac{E_2^2}{2} + E_1E_2\left\{\cos[(\omega_1 - \omega_2)t + (\theta_1 - \theta_2)]\right\} \tag{3.13}$$

The optical power collected by the detector is the optical intensity integrated over the surface area of the detector, A. Assuming a uniform intensity over the detector area, the optical power P_{opt} can be represented by Equation 3.14.

$$I_{opt} = A\frac{E_1^2}{2} + A\frac{E_2^2}{2} + AE_1E_2\left\{\cos[(\omega_1 - \omega_2)t + (\theta_1 - \theta_2)]\right\} \tag{3.14}$$

The detector current i(t) generated is

$$i(t) = \frac{R.A}{Z_C}\left\{\frac{E_1^2}{2} + \frac{E_2^2}{2} + E_1E_2\left\{\cos[(\omega_1 - \omega_2)t + (\Phi)]\right\}\right. \tag{3.15}$$

Where Φ , z_c is the characteristic impedance of the front end of the detector, and R is the detector responsively. We can write Equation 15 in terms of incident optical P_1 and P_2.

$$i_{IF}(t) = 2R\sqrt{P_1P_2}COS[(\omega_1 - \omega_2)t + (\Phi)] \tag{3.16}$$

The electrical power output P_{el} from the photodetector is then

$$p_{el} = i(t)^2.R_L \tag{3.17}$$

Where R_l is the load resistance of the photodetector. Change in the phase is the results of non-coherent phase fluctuations in each optical field, and contributes to the finite linewidth of the heterodyned output signal.

3.4.2 Single source heterodyning

There are two techniques for single source heterodyning: phase modulation and Multi cavity lasers heterodyning. Brief explanation will be given about both techniques in this section. There are inherently advantages of using single heterodyning technique than two source heterodyning techniques. In single source heterodyning, since the modes used to heterodyne with each other on the photodetector come from the same semiconductor chip, the orientation of polarization is stable, and the heterodyned signal is less sensitive to ambient temperature and mechanical vibrations [18]. However, the drawback of this technique is mode competition. Mode competition occurs when a power increase in one mode cause a reduction of power in the other mode.

3.4.2.1 Phase modulation

A single laser source can be used to provide two modes that mix with each other on the photodetector. A CW laser can be coupled into external modulator that alters the phase of the light as opposed to the intensity modulation. Phase modulators introduce a voltage dependent phase on linearity polarized input beam. A voltage at the RF frequency is applied across the electrodes which induces a change in the refractive index via electro-optic effect, and thereby causes a phase shift in the optical signal. The control signal can be DC or time varying RF signal, $V(t) = V_0 \sin \omega_m t$ the electric field induces after optical modulation by external modulator can be written as Equation 3.18.

$$E(t) = E_0 \cos(\omega t + m \sin \omega_m t) \tag{3.18}$$

After expanding the Equation, it can be written as following relation in the Equation 3.19.

$$\begin{aligned} E(t) = E_0[\, j_0(m)\cos \omega t + j_1(m)\cos(\omega + \omega_m)t - j_1(m)\cos(\omega - \omega_m)t \\ \mathrm{j}_2(m)\cos(\omega + 2\omega_m)t - j_2(m)\cos(\omega - 2\omega_m)t + ...] \end{aligned} \tag{3.19}$$

If the single sideband modulation (SSB) [19] is used the first two components of the optical current at the photodetector mix together base on square-law photodetector it can be write in Equation 3.20.

$$i_{opt}(t) = (\, j_0(m)\cos \omega t + j_1(m)\cos(\omega + \omega_m)t)^2 \tag{3.20}$$

In contrast, if the suppressed carrier double sideband (SC-DSB) is used, the optical current can be written as Equation 3.21.

$$i_{opt}(t) = [E_0\, j_1(m)\cos(\omega + \omega_m)t - E_0\, j_1(m)\cos(\omega - \omega_m)t]^2 \tag{3.21}$$

As an example to generate 60 GH RF carrier signal using frequency modulation, the RF oscillator required would need to oscillate at either 30GHz for SC-DSB or 60GHz for the SSB technique.

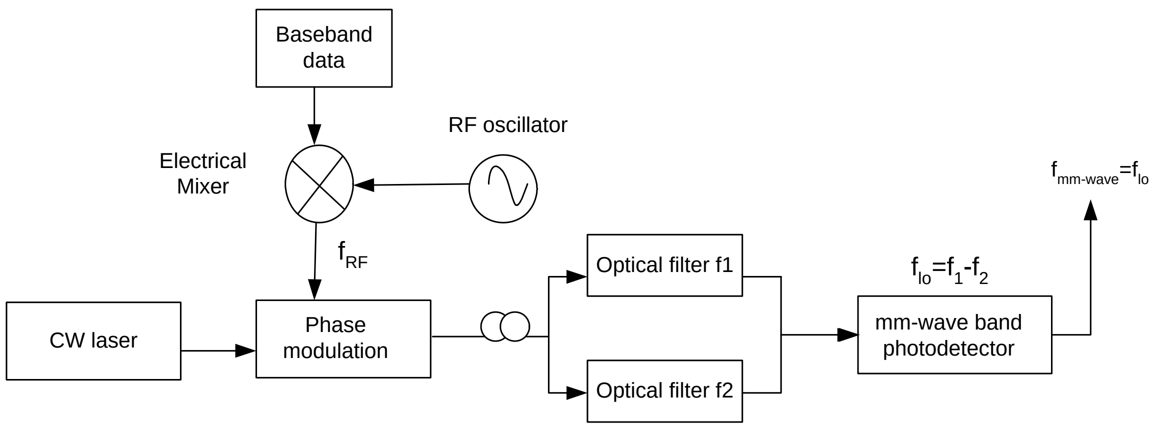

Figure 3.7 Single source heterodyning using CW laser

Baseband information modulates at the subharmonic of mm-wave frequency. Then the induced RF frequency phase modulates the optical laser source. The results would be the array of sidebands of optical source and RF frequency. Two sideband of these array separated by the desired mm-wave frequency are picked up by two optical filter which are after detected by the square-law photodetector.

3.4.2.2 Multi cavity lasers heterodyning

Two optical modes are produced in a single device with their separation equal to desired millimeter wave signal. The modes are produced in separate cavities grown on the same chip. An additional section is often incorporated in order to match the phase of the outputs.

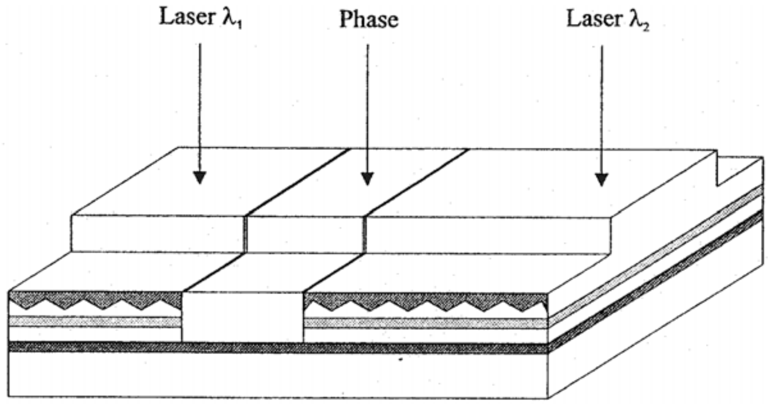

Figure 3.8 Dual-mode multi-cavity laser diode

The laser oscillates at two distinct wavelengths as directed by the sections and cavity length. An additional section is usually incorporated to provide phase matching between two cavities.

3.4.3 Multi-laser configuration for remote heterodyning

Another broad category of remote heterodyning makes use of multiple laser configurations. Multiple lasers can be used to generate two modes that can be heterodyned on a photodetector. The simplest configuration is two independent laser cavities, which have a shift in oscillation equal to required millimeter-wave frequency. This however generates two modes that are uncorrelated. The technique of locking the properties of one laser onto another in an attempt to reduce the phase noise between two modes is called optical injection locking.

3.4.3.1 Optical injection locking

Optical injection is the process of coupling light from one lasing device, usually called master laser, into second laser devise called the slave laser. The master laser is isolated from the slave laser using an optical isolator to prevent optical feedback from the slave laser into master laser. Photons injected into the slave laser from the master will generate stimulated emission of photon with the same polarization, wavelength, and phase. In this way the slave will oscillate with the same wavelength and phase characteristics of the master laser. The phenomenon, whereby a slave laser adopts or 'locks' onto the injected wavelength and phase of master laser is called optical injection locking.

Because the slave laser adopt the phase properties of the master laser, using a master laser and slave laser to generate two mode for millimeter wave generation can results in reduced phase noise. Techniques published include sideband injection locking, which uses two slave lasers and one master and one slave laser injection locked by a master.

3.4.3.2 Sideband injection locking

Sideband injection locking is a technique whereby the master laser is phase modulated at a subharmonic of the desired millimeter-wave frequency to create an optical spectrum containing an array of sidebands from the master lasers [20].The master laser output signal is split and coupled into two slave lasers. By varying current and temperature, each slave laser is separately tuned to lock onto the sideband of the master laser, which is separated by the desired frequency. Because the two slave laser have adopted the phase properties of a single master laser, the modes generated in each cavity will provide a heterodyned signal with less phase-noise than that of two lasers that are not injected to a master laser [21].

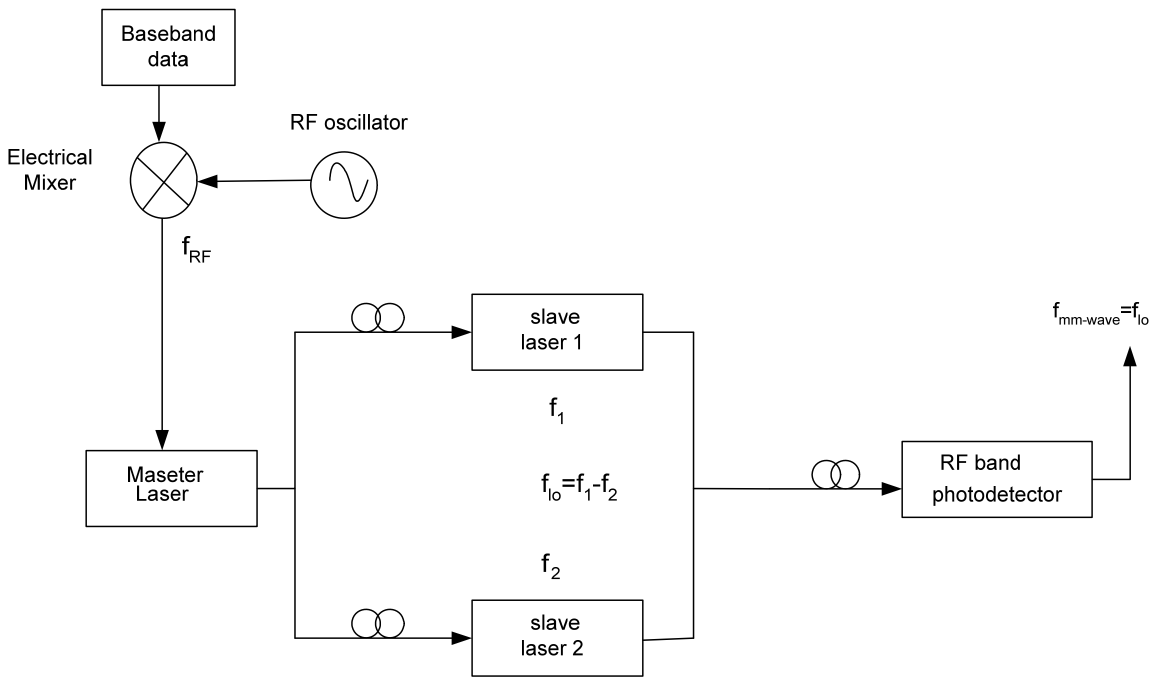

Figure 3.9 Slave laser1 and slave laser 2 are injection locked onto a sideband of master laser result in F_{lo} to generate the mm-wave frequency.

3.4.3.3 Master/slave laser distributed feedback lasers

A master/slave configuration uses optical heterodyned of two single-mode lasers. More specifically, a master DFB laser, and a slave DFB laser are coupled such that the slave laser is injection locked onto the master laser. An RF electrical drive is applied to the slave laser at a subharmonic of the desired millimeter-wave frequency. The master laser is subsequently temperature tuned until injection-locks onto one of the slave laser sidebands, which results in some phase-noise cancellation in the output signal. The main practical limitation on optical injection locking is that the range of frequencies in which the master laser can vary before the slave laser become unstable is small. This is known as the locking range. The stability required for the laser operate within a typical locking range demands that the slave laser temperatures be controlled with milli- Kelvin precision. Alternatively, laser must be monolithically integrated to keep temperature changes constant between each laser [22].

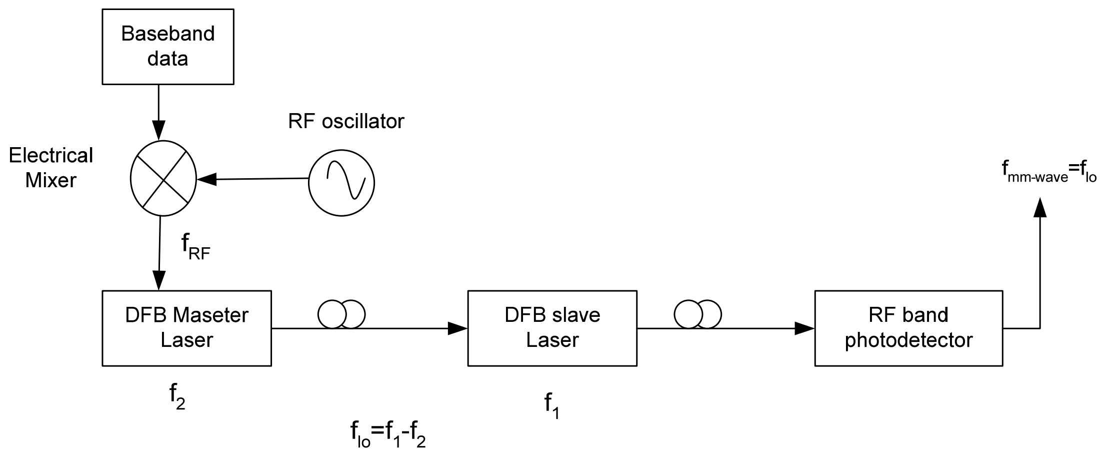

Figure 3.10 Slave laser is injection locked onto one the sideband of master laser result in F_{lo} to generate the mm-wave frequency.

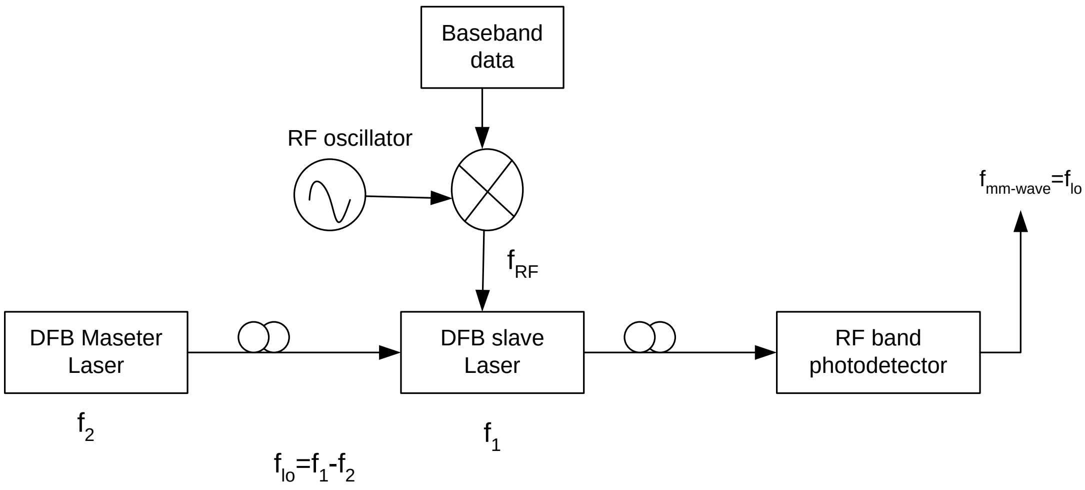

Figure 3.11 master laser is injection locked onto one the sideband of slave laser to generate the mm-wave frequency

The experimental structure of this configuration has been in [23] which is shown in Figure-3.12.

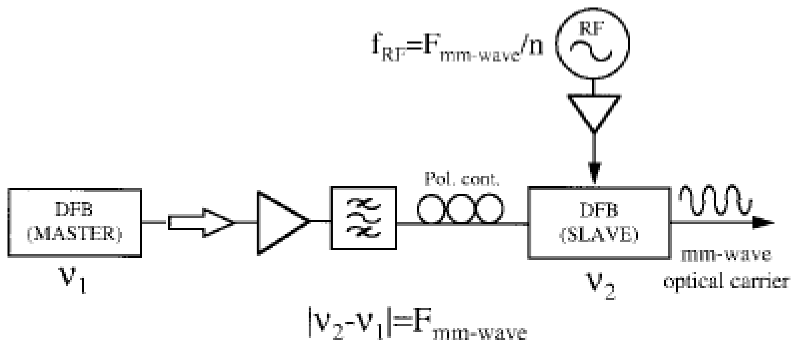

Figure 3.12 Experimental arrangement of master/slave DFB to generate mm-wave carrier [24]

3.4.3.4 EAM modulator for Multi-laser configuration heterodyning technique

Another possible solution could be the structure shown in the Figure-3.13. the mm-wave optical carrier, ω_{lo} can be produced by either using one master/two slave lasers structure or by master/slave DFB configuration. ω_2 and ω_1 are correlated to one other. Because they are generated by using phased lock techniques. The modulated IF frequency, $A_S\cos(\omega_s t)$ modulates the optical carrier by using an electro-absorption modulator.

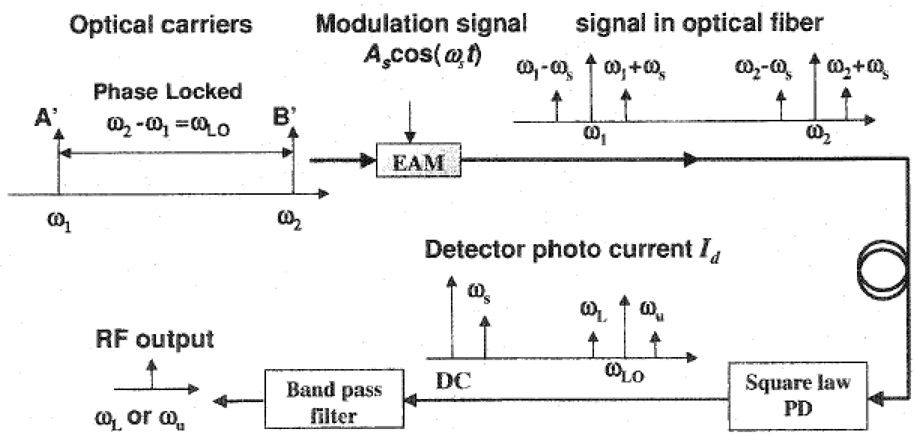

Figure 3.13 Modulator/mixer using an optical LO consisting two phased-locked optical carriers.

In the previous structure shown in Figure-3.13 both optical carrier are modulated by the IF frequency. If one optical carrier is modulated with the IF frequency the dispersion-induced power penalty will be dramatically reduced, and it is because of single sideband transmission of this structure. Therefore the following structure in Figure-3.14 is introduced.

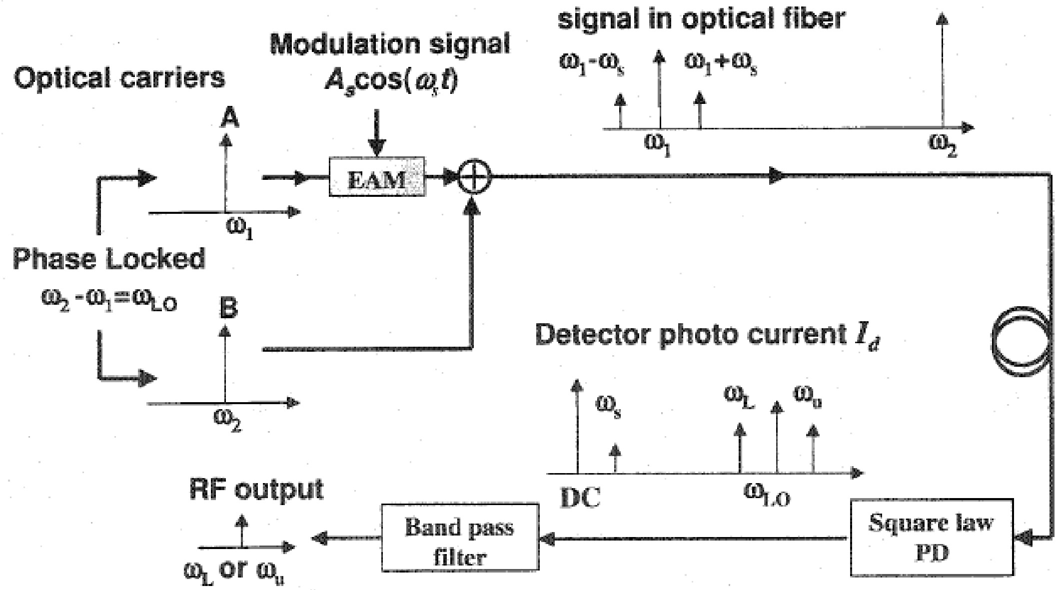

Figure 3.14 Heterodyned modulator/mixer with one optical carrier bypassing the EAM

The experimental results have been achieved in [23]. The structure of the works is depicted in appendix A.

CHAPTER 4

METHODOLOGY AND SIMULATION MODEL

4.1 Introduction

We present a simple ROF-WDM simulation model that uses 30 GHz millimeter wave signal to carry the baseband data rate of 2.5 Gb/s. In this chapter, a simulation model using Optisystem software has been used to analyze the fiber FWM nonlinearity effect on ROF system. Then the results have been compared with the effect of FWM on the conventional optical system.

4.2. System model

Block diagram of the system is shown in the Figure-4.1. The major components of the system are remote access unit (RAU), optical modulators, WDM multiplexer, fiber optic link, WDM demultiplexer and ROF receiver.

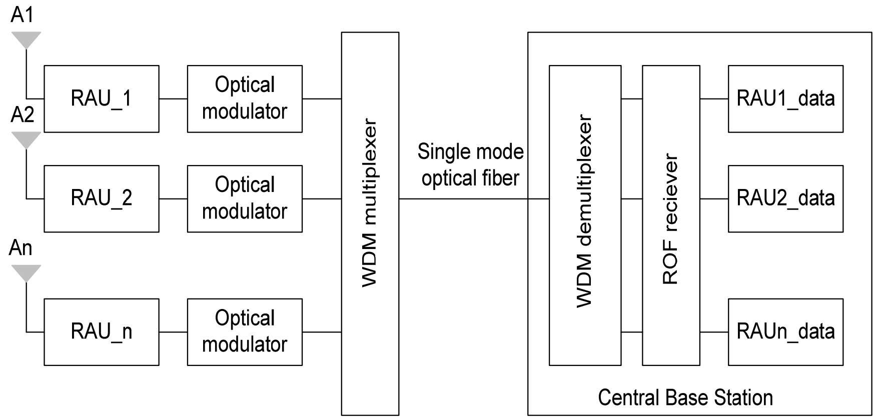

Figure 4.1 Block diagram of ROF system

4.2.1 ROF transmitter

The ROF transmitter can be considered as a devise including N number of RAU, optical modulator and WDM multiplexer. So, for this discussion the transmission happen from RAU to central base station (CBS). In this research no wireless standard is considered. The data receiving from RAU can be in the form of CDMA, OFDM, TDMA or any combination of these schemes. From ROF point of view, all of these analog signals receiving by RAU are modulated RF or millimeter wave frequency. Therefore, base station can be modeled as a source of information in the form of zeros and ones which are modulated using RF carrier signal as it’s shown in Figure 4.2.

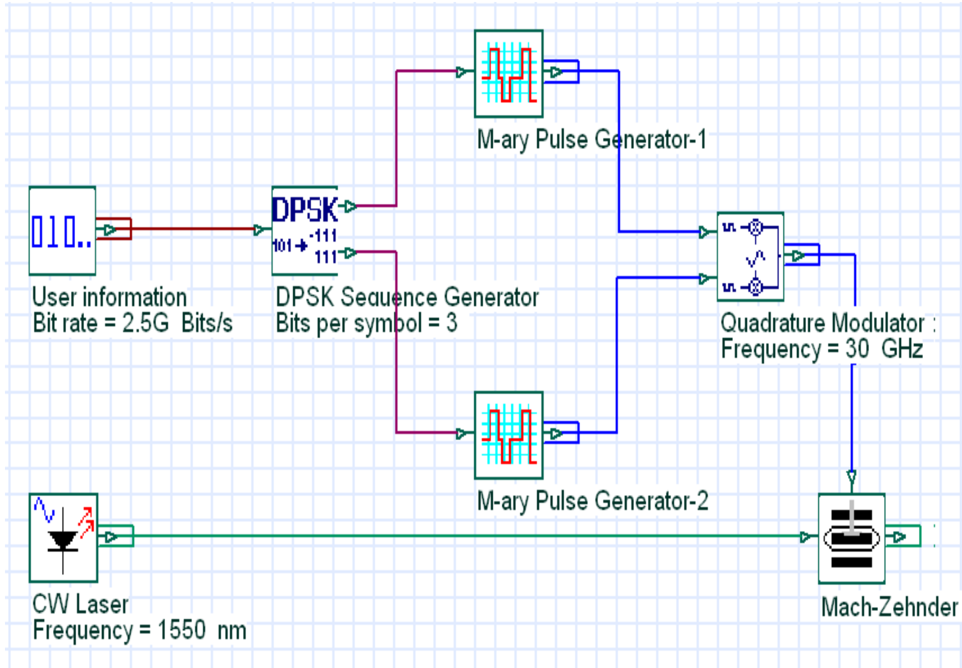

Figure 4.2 ROF transmitter

Here, we assume that, the outgoing data rate of each RAU station is about 2.5 Gb/s which possibly can be a good estimation of a RAU capacity. To increase the spectral efficiency of the system the DPSK modulation scheme is added into the system, I and Q signal coming from the DPSK modulator are convert to M-ray pulse using M-ray pulse generator. The resulting pulses from M-ray generator then are modulated using 30GHz RF carrier. By doing the aforementioned steps a RAU is simply modeled. Now it is a turn for modeling ROF transmitter. The transmitter can be easily constructed using collection of external optical modulation scheme which could be consisting of a laser diode with 10MHz line-width in the arrangement with a Match Zehnder. The laser diode is radiating in the range of 1550 nm. This range is chosen since it is low loss window of optical frequency band [25]. In the next step to make a complete use of optical link, WDM multiplexing scheme is added to the model. Now, the ROF transmitter is almost modeled. It means that for ROF transmitter, each RAU can be just considered as a single wavelength in the system. It should be mentioned that we assume all RAU are working at the same frequency band which is the worse case.

4.2.2 ROF Receiver

The collections of N RAU modeled in section 4.2 are multiplexed using WDM multiplexer as shown in Figure 4.3 and then are transmitted through a single mode fiber (SMF) into central base station. The fiber length assumed to be 50 kilometers which is good estimation of macro cell radius [25].

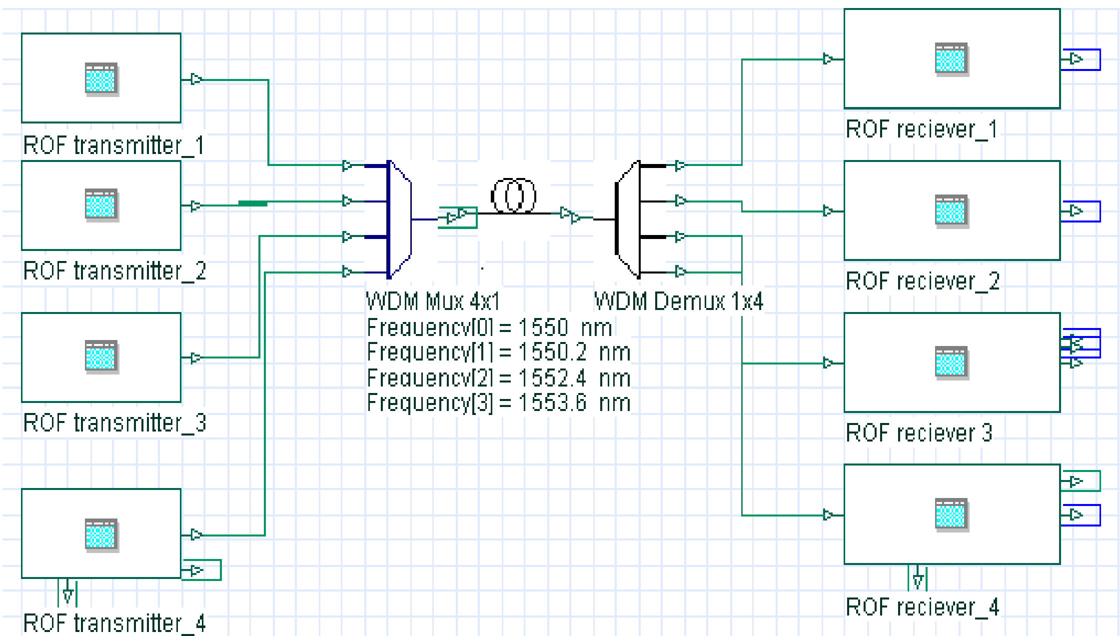

Figure 4.3 ROF-WDM system model

In the CBS then each base station signal are demultiplexed through WDM demultiplexer and then detected using a ROF receiver as it is represented in Figure 4.4. As it is shown in Figure 4.4, the ROF receiver is consist of a 30 GHz local I and Q oscillator, M-ray detector, DPSK decoder and a NRZ pulse generator.

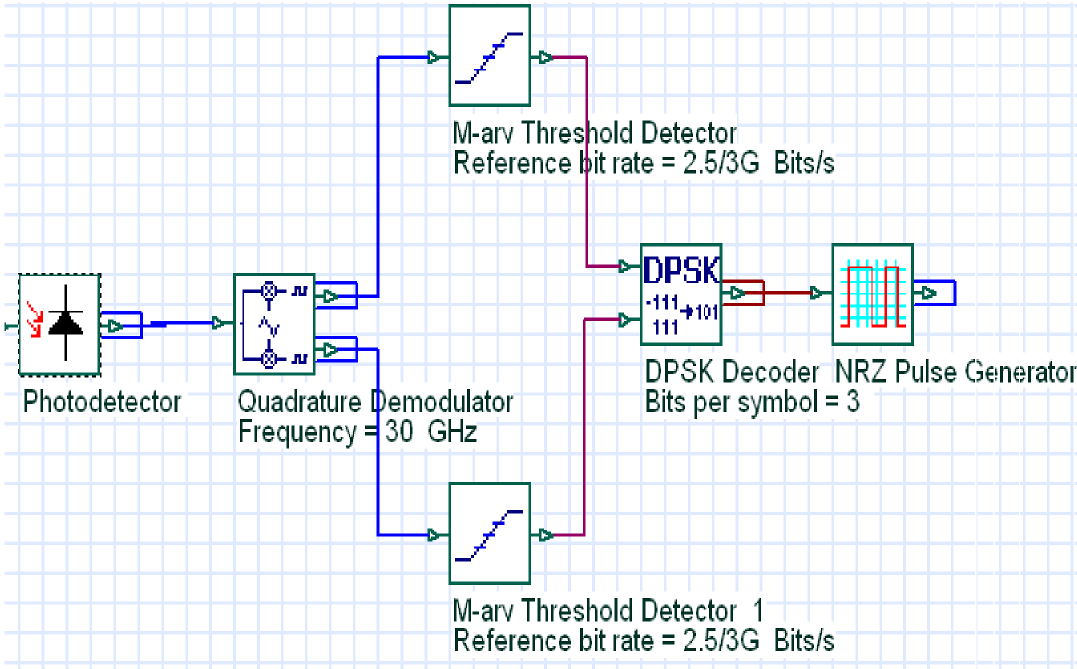

Figure 4.4 ROF receiver

The complete ROF-WDM system is completely modeled in the next section the results will be presented.

4.3 Simulation parameters

Figure 4.3 represents the general model of the simulation in this project. The simulation parameters are indicated in Table 4.1.

Table 4.1 Simulations parameters

Parameters	**value**
Number of RAU	4
Baseband modulation	DPSK
Data rate	2.5Gb/s
Number of bit in each symbol	3
RF carrier frequency	30GHz
Optical fiber length	50km
Type of optical fiber	Single mode fiber (SMF)
Fiber dispersion	1ps/km/nm
Fiber attenuation	0.2dB/km
Fiber nonlinear coefficient(n2)	2.6×10^{-20}
Optical modulation	External modulation
Photo detector type	PIN
Fiber effective area	$64\mu^2$

CHAPTER 5

SIMULATION RESUTS AND DISCUSSION

5.1 Baseband modulated results

The results for optical baseband modulation are presented in Figure 5.1, 5.2, 5.3, 5.4, 5.5. The optical spectrum of individual base station with baseband modulation can be seen in Figure 5.1. The baseband data rate is set to 2.5 Gb/s for this case. The resulting FWM component for baseband modulated optical system is portrayed in Figure 5.3.

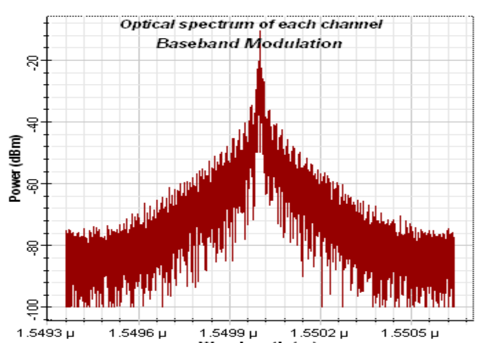

Figure 5.1 The optical spectrum of individual channel with baseband modulation

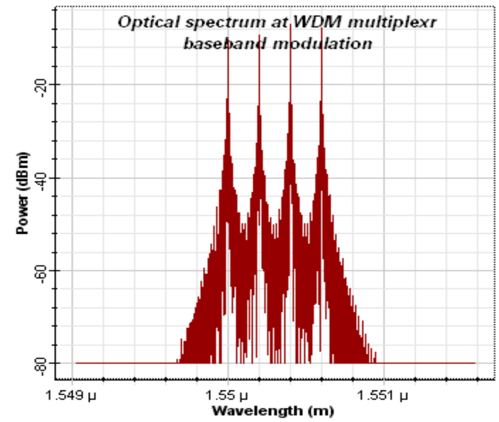

Figure 5.2 Optical spectrum of 4 channel WDM with baseband modulation at transmitter side

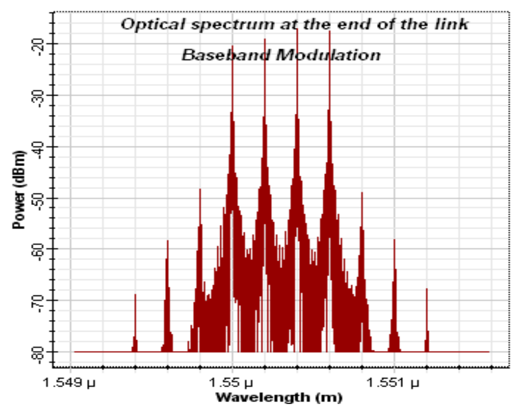

Figure 5.3 Optical spectrum of 4 channel WDM with baseband modulation at the end of the link

In compare with Figure 5.2 which shown the optical spectrum at the first of the optical link, six components can be clearly seen that added into the original spectrum. However, we expect 24 component as it is indicated in this equation $N^2\times (N-1)/2$, where N is the number of channels. The fact is that 18 invisible FWM components are probably mach or fall into original channels. However, even by this sort of distortion the error free signal can be detected in the receiver for each channel. The eye diagram graph for this case is portrayed at Figure 5.4. The resulting eye height is 7.34×10^{-5}.

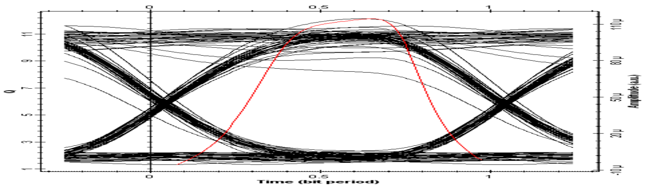

Figure 5.4 Eye diagram for 4 channel baseband modulate WDM signal

The above simulations have been repeated for optical baseband modulation but this time for data rate 10 Gb/s. Also for this case the error free signal is detected in the receiver. The resulting eye height for this case was 5.32×10^{-5}. However, for higher bit rate the system will not perform well, since the channel spacing must be more than as 2 time as higher frequency in electrical signal which is 20 GB for this case equivalent to 0.2nm. Means for higher bit rate than 10 Gb/s , the channel spacing must be more than 0.2 nm or 20 GHz. In the next section the results for RF modulated signal is presented.

5.2 RF and millimeter-wave modulated results

In the same way to previous section the results for RF modulation are presented at Figure 5.5, 5.6, 5.7, 5.8, 5.9. The optical spectrum of individual channel with RF modulation is shown in Figure 5.5. Two sidebands resulting from RF electrical carrier is present in the optical spectrum of individual channel. The baseband data rate is set to 2.5 Gb/s for this case. The resulting FWM component for baseband modulated optical system is portrayed in Figure 5.7. For this case channel spacing is 0.2 nm. The resulting eye diagram can be seen in Figure 5.8. Therefore in this case the information can not be detected.

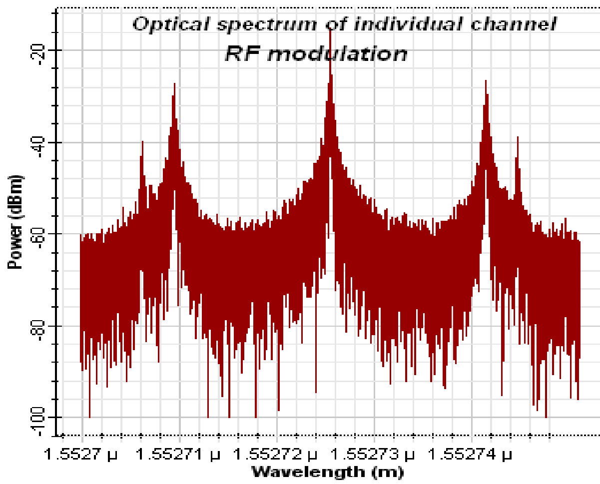

Figure 5.5 the optical spectrum of individual channel with RF modulation

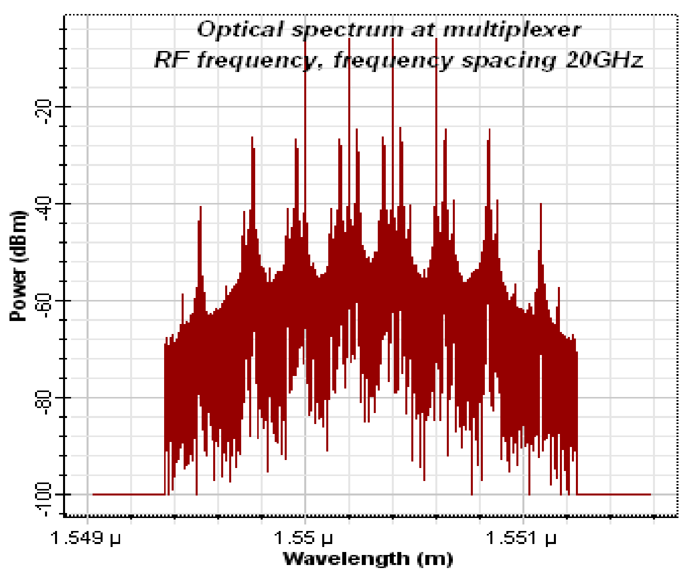

Figure 5.6 optical spectrum of 4 channel WDM with RF modulation at transmitter side

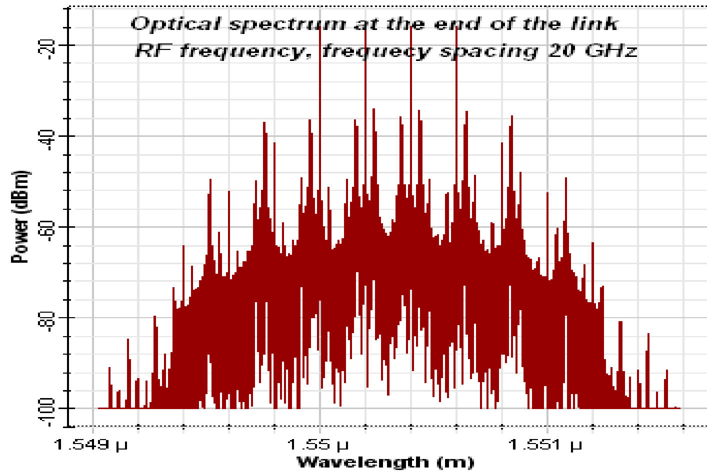

Figure 5.7 optical spectrum of 4 channel WDM with RF modulation at the end of the link

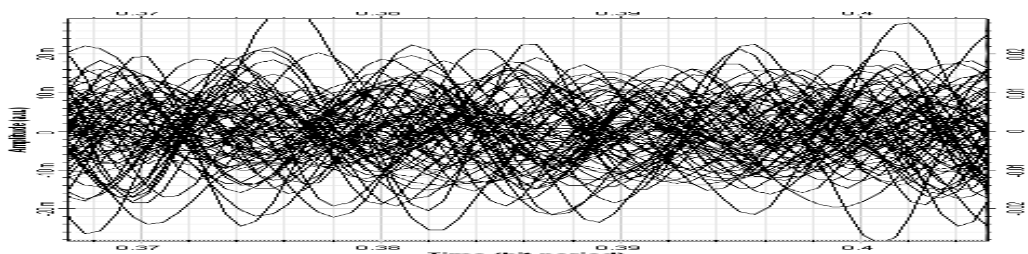

Figure 5.8 Eye diagram for 4 channel RF modulated WDM signal

Technically, to successfully recovering the data we need to increase the channel spacing to 0.6 nm as a rule of thumb in addition we must use single sideband transmission. The channel spacing therefore must be chosen as much as 60 GHz. by doing this modification the information of individual channel can be recovered error freely. The eye diagram resulting from the latest arrangement is shown in below.

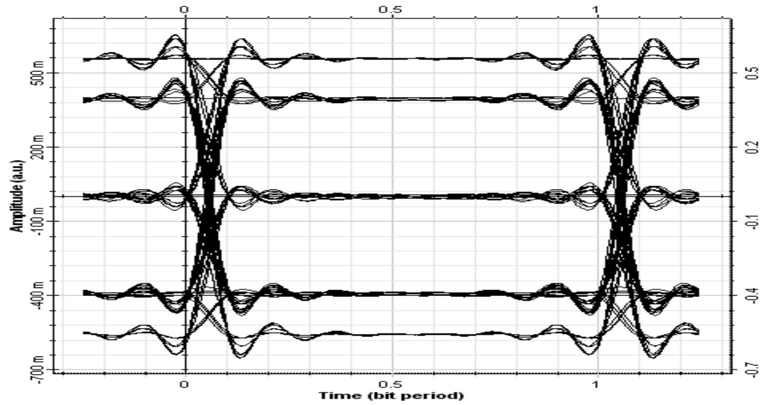

Figure 5.9 Eye diagram for 4 channel RF modulated WDM signal, with single sideband transmission and channel spacing of 60 GHz.

5.3 Discussion

The optical modulation of RF or millimeter-wave carrier produces double sideband signals. For the case when the data rate was about 2.5Gb/s with the RF carrier frequency of 30Ghz and optical channel spacing of more than 3 nm with double sided transmission the information could not be recovered. The reasons can be found from Figure 5.10 and 5.11. Figure 5.10 shows the optical spectrum at the end of the link for 4 channels WDM supply by four lasers lasing at 1550 nm with 0.2 nm channel spacing. Figure 5.11 is the case when one the laser is substitute with a ROF transmitter with the 1 GHz RF signal.

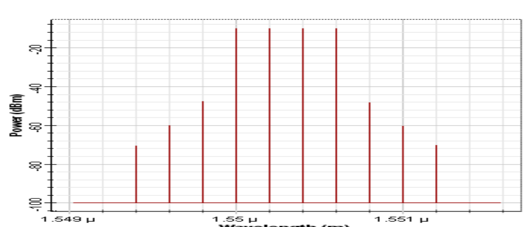

Figure 5.10 optical spectrum of 4 channel WDM with 4 CW laser with zero linewidth.

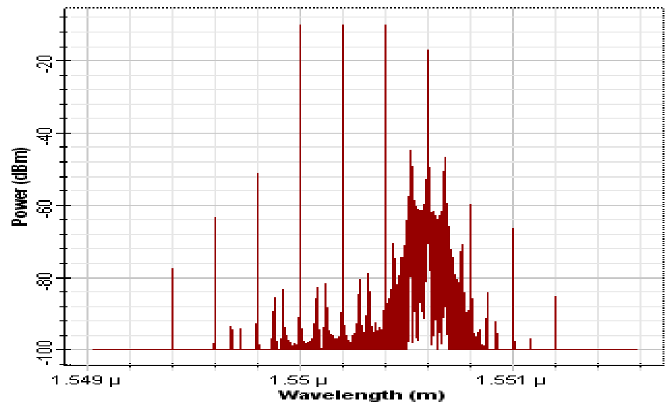

Figure 5.11 optical spectrum of 4 channels WDM with one RF modulated signal and three CW laser

By the way of comparison, it can be concluded the sidelobes producing from the RF carrier contribute in generating of new FWM component. This phenomenon can be clearly seen in Figure 5.11. The number of visible FWM component from 6 in Figure-5.10 increases to 22 visible FWM components. This reason can justify, the case when channel spacing of even 3nm is not sufficient to recovering the data in above mention scenario. Therefore, in ROF system, when the data rate is high and millimeter wave carrier is considered, to reduce the FWM effect one of the sideband must be filtered out

CHAPTER 6

CONCLUSION AND FUTURE WORKS

6.1 Conclusion

The results shown the FWM effect in both baseband and RF modulated optical signal is destructive. The much discrepancy between these two systems in terms of FWM impact is because of double sideband nature of optical spectrum generated by RF or millimeter wave carrier. If double sideband optical carrier transmitted through the link in addition to optical carrier each individual sideband of optical carrier also contribute to generate FWM component. Therefore, the number of FWM component increases dramatically and it causes to transfer energy from the main component to new component. Also most of these components are overlapped directly with original channel and causes high level of interferences and performance degradation. In addition, the nonlinearity effect of optical fiber causes phase shifting on both sidebands of each channel. And because the frequency of each sideband is different, the phase delay of each sideband might be different, in worse case this two phase might be in opposite of each other, and in the photodiode they may completely fade each other. Therefore, to increase the power and bandwidth efficiency of ROF-WDM system the single sideband transmission strongly recommended. In the case of single sideband transmission the channel spacing of more than two time of higher RF frequency seems to be efficient to recover the data in the receiver.

6.2 Future works

In this research, we investigate the effect of FWM nonlinearity in ROF zero dispersion single mode fiber. Many questions about this issue left unanswered when the assumption of the problem changes. As an example, investigation of FWM in multimode fiber, since much current-in-use optical system is using this type of fiber. In zero dispersion fiber, the FWM is the predominant fiber nonlinearity; however, this condition is not valid for non-zero dispersion index fiber. Therefore, the other type of fiber nonlinearity should also be taken into the account in designing the ROF-WDM system.

In addition, structure of ROF-WDM system, has a key role to reduce the fiber nonlinearity. Hence, we should also find the appropriate structure of ROF-WDM system which is less susceptible to fiber nonlinearity. As an example, there are many ROF structures in terms of optical modulation technique which should be investigated in terms of fiber nonlinearity. So, one of the future works could be investigating ROF-WDM system with optical modulation techniques mentioned in chapter three in terms of fiber nonlinearity.

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APPENDICES

Appendix A. Measurement setup of the heterodyned modulator/mixer using EAM