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Photonics Based Techniques for Millimeter-Wave Generation, Transmission and  
Multiplexing

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A Thesis

Presented to

The Faculty of Engineering and Computer Science

University of Denver

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In Partial Fulfillment

of the Requirements for the Degree

Master of Science

---

by

Daw Asderah

June, 2009

Advisor: Dr. M. A. Matin

Author: Daw Asderah

Title: Photonics Based Techniques for Millimeter-Wave Generation, Transmission and Multiplexing

Advisor: Dr. M. A. Matin

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## **ABSTRACT**

Millimeter-waves have found wide application in various fields. In this research, MMW generation, transmitting and receiving, multiplexing techniques are investigated. Three ways of MMW generation based on photonics are discussed. By modeling these three techniques and applying different situations of transmission links up to 100 km and fixed bit rate of 2.5 Gb/s, different results were found and compared to each other. Also, the effect of chromatic dispersion is discussed in addition to the phase conjugation way of dispersion compensation. Dispersion compensation based on phase conjugation was also simulated and applied to OSSB millimeter-wave generator in order to transmit the generated signals through 100 km of fiber and data rate of 10 Gb/s without dispersion effect.

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For giving me the chance to get my master’s degree in the US, I would link to thank “Gaddafi International Charity and Development Foundation.”

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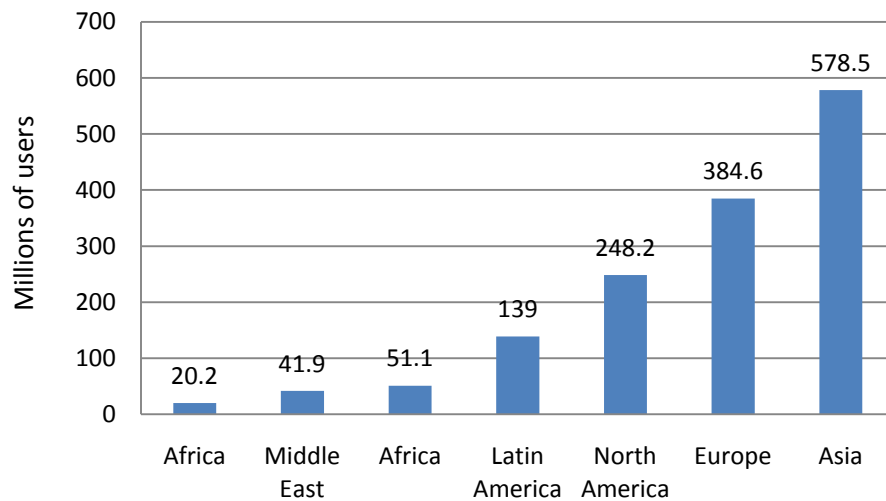
## [ CHAPTER 1 ]

### 1. INTRODUCTION

#### 1.1 Background

The high-speed broadband diffusion and the continuing increase of the Internet traffic among housing and business users have required a massive bandwidth demand on the underlying telecommunications infrastructure. Worldwide internet users have increased from 2.1 million users in 1990 to about 1,850 million users in 2010. Fig 1.1 shows the worldwide internet users as in 2008. Global IP traffic in 2007 stands at more than 6 exabytes every month, it is expected to reach 29 exabytes per month in 2011. Meanwhile, traffic patterns have been propelled from voice and text based services to user-generated interactive video services. As Internet video streaming and downloads will grow from 9% of all consumer internet traffic in 2006 to 30% in 2010 (Cisco Systems, 2008). Nowadays, Peer-to-peer (P2P) traffic is still the largest share of internet traffic, but approximately 70% of peer-to-peer traffic is due to the exchange of video files (Duffy, 2007). YouTube is one example, and it is just the beginning. In the near future, the networks will experience real-time video communications and dynamic video content more than pre-recorded video content. As a result of this astonishing development, the metro and core networks of the telecommunication infrastructure have experienced a great growth in bandwidth and capacity with the wide use of optical fiber technology in the past decade (Cisco Systems, 2008).

In the near future, the requirements of a bandwidth that enable us to host many channels of high definition TV (HDTV) signals is expected to grow up to many gigabits per second. In order to keep away from restricted access in last miles of metro networks, and develop both wired and wireless technologies, carriers and service providers are actively seeking combined network architectures to deliver the wide range of services to both fixed and mobile devices' users. In this regard, millimeter wave wireless that is based on photonics technologies have been considered the most promising solution to enhance the capacity, coverage, bandwidth, and mobility in environments and applications. This is including; telemedicine devices, local area networks, conference centers, airports, shopping malls and also homes and small offices (NEC Corporation, 2005).



**Fig. 1.1 World Internet users until 2008**

## **1.2 Wideband wireless access networks**

Wireless networks are recently becoming more widely used. This growth is mainly accelerated by well developed wireless communication techniques, cheap wireless

hardware, and a wider range of coverage. The use of these networks is changing the way we use computers and other electronic devices at work, home, and when traveling.

There are many aspects such as data rate and the coverage area which would result in different applications for wireless communication systems as shown in figure 1.2. These categories range from wireless wide area networks (WWANs), which cover the widest geographic area, to wireless personal area networks (WPANs), which cover less than 10 meters. End-users and service providers are deploying diverse types of wireless networks to complement and substitute for wired infrastructure. All of these wireless technologies are changing the landscape for broadband access (Quinn, 2005).

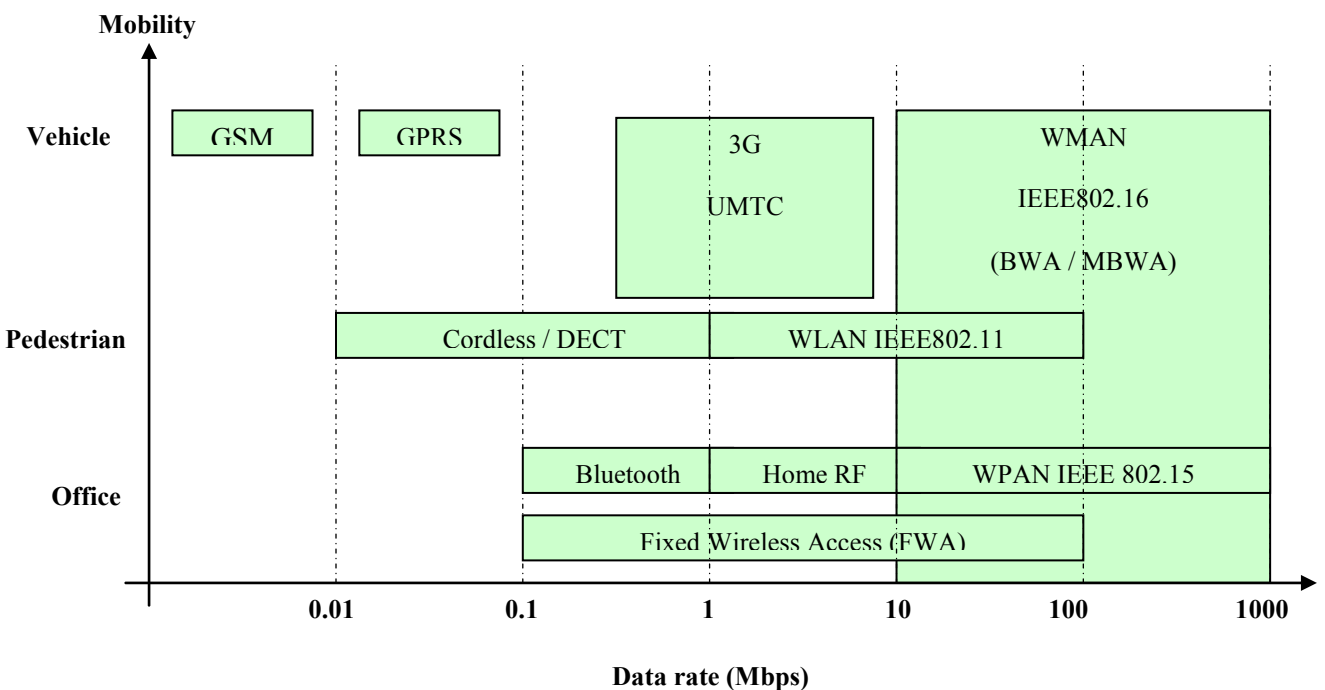


Fig. 1.2 An overview of wireless access systems and their bit rates

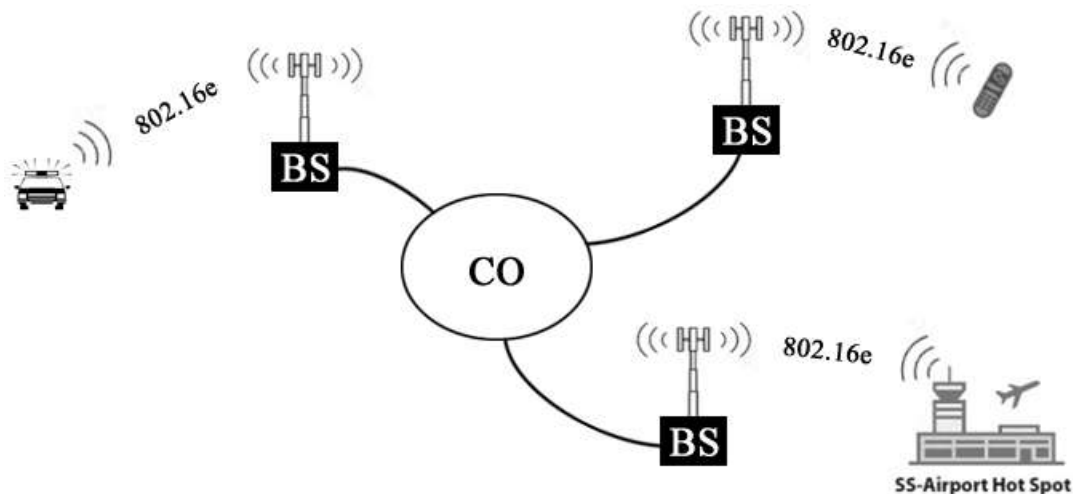
### 1.2.1 Overview of Broadband Wireless Networks

One of the most widely used wireless networks is a wireless local area network (WLAN) that adopts the standard series (IEEE 802.11). These networks are popular

because of their convenience, cost efficiency, and their flexibility to share data with other networks in one building. As shown in table 1.1, the measured coverage of WLAN is approximately 30 meters indoors and 100 meters outdoors. In the last couple of years, all computers come totally prepared to work with WLAN technology. Operating in the RF spectrum of 2.4 GHz and 5-GHz bands and providing data rates up to 54 Mb/s, IEEE 802.11 a/b/g cover the specification of physical and data link layers in ad-hoc mode or access point for current wide use. IEEE 802.11n standard has the raw data rate of 248 Mb/s resulting from the Multiple Input Multiple Output (MIMO) function (Perahia & Stacey, 2008).

A WPAN presents wireless networks have coverage of about 10 meters, and these networks are used for the connection of consumer electronic devices with each other such as personal digital assistants (PDAs). The ad-hoc connection is one kind of these networks. Bluetooth, standardized in IEEE 802.15.1 with data rates up to 3 Mb/s, allows the connection of mobile devices to send and receive multimedia, computers, and other electronic applications between each other. The other categories of WPAN are ultra wide band (UWB), which depends on the standard IEEE 802.15.3a and low data rate WPAN-ZigBee, that associate with the standard IEEE 802.15.4. The basic principles of the UWB technology are using a wide range of frequency band without interfering with the original technologies and low-power usage. In the USA, this system was permitted in 2004 in the frequency band of 3.1 GHz - 10.6 GHz and up to 0.5-Gb/s data rate with the -42.3 dbm/MHz power signal. The UWB has many applications in fast home networks for video or audio data transmission, high-resolution printers, and digital camcorders. The ZigBee technology is founded for low data rate up to 250 kb/s wireless sensor networks.

That has great possibilities in applications from home and building automation to industrial control (IEEE 802, 2008) (wirelesslans, 2004).



**Fig 1.3 802.16e Broadband Wireless Packet-Based Network**

Wireless metro area network (WMAN) is the officially used name of the IEEE 802.16 Working Group on Broadband Wireless Access (BWA) standards for wireless metro area internet access. The Worldwide Interoperability for Microwave Access (WiMAX) works in the frequency band between 10-66 GHz with a line of sight condition at 802.16 or in the frequency band of 2 - 11 GHz with a non line of sight at 802.16d. In addition, WiMAX supports high data rates up to 75 Mb/s for fixed access and 30 Mb/s for mobile access (WiMaxForum).

WWANs are the cellular networks used for data service and mobile phone networks. WWANs provide connectivity over a wide geographical area through handover mobility support and cell roaming. Around the world, there are two WWAN technologies. They are called Global System for Mobile Communications (GSM) and Code Division Multiple Access (CDMA). These two technologies are going forward to adopt third

generation (3G) mobile networks for enhanced packet-based QoS, providing increased bandwidth, improved spectrum efficiency and mobility. While Europe mobile systems based on GSM, CDMA technology is adopted in the U.S (Quinn, 2005) (Andersson, 2001).

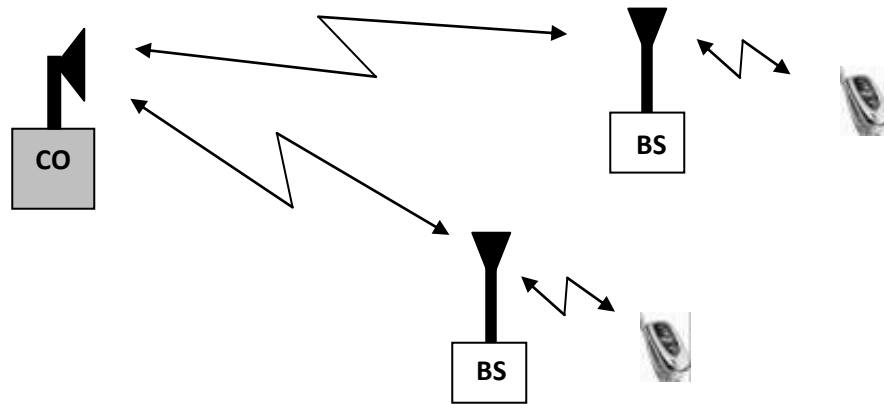
**Table 1.1: Characteristics of broadband wireless networks standards**

<b>Name</b>	<b>Origin</b>	<b>Frequency band</b>	<b>Bit rate</b>	<b>Signal range</b>
Bluetooth	2004	2.4 GHz	2.1 Mb/s	10 m
UWB	2007	3.1-10.6 GHz	500 Mb/s	10 m
ZigBee	2004	2.4 GHz	250 kb/s	10 m
802.11a	1999	5 GHz	54 Mb/s	100(outdoor)/30 m
802.11b	1999	2.4 GHz	11 Mb/s	110(outdoor)/35 m
802.11g	2003	2.4 GHz	54 Mb/s	110(outdoor)/35 m
802.11n	2006	2.4/5 GHz	150 Mb/s	160(outdoor)/70 m
802.16	2001	10-66 GHz	134 Mb/s	5 km
802.16a	2003	2-11 GHz	75 Mb/s	10 km
802.16d	2004	2-11 GHz	75 Mb/s	8 km
802.16e	2005	2-6 GHz	30 Mb/s	5 km
GSM	1992	900/1800 MHz	9.6 kb/s	35 km
GPRS	1997	900/1800 MHz	80 kb/s	35 km
EDGE	2004	900/1800 MHz	200/100 kb/s	30 km
UMTS	2000	873/1900 MHz	2048 kb/s	2 km
HSDPA	2004	900/1800 MHz	14.4 Mb/s	6 km

Table 1.1 describes the main abilities of all the mentioned wireless technologies and standards above. Researchers are still investigating to improve the wireless access technologies. That will result in higher bit rates for wireless technologies and wider range of coverage.

### 1.2.2 The challenges of recent wireless communications networks

Fig.1.4 shows a basic design of narrowband wireless communication system. The central office (CO) is processing the calls and acts as a switch, while the Base Stations (BSs), which are linked to the CO through wireless links or fibers, handle the signals coming from and to Wireless Terminal Units (WTU), or the mobile units (MU). The radius covered by the signal from the BS is called the cell radius. Also, all the WTU inside one cell are sharing the radio frequency spectrum.



1.4 Simple narrowband wireless communication system

In general, low frequency of carrier presents narrow bandwidth. For instance GSM systems adopt frequencies around 900 or 1800 MHz with a frequency range of 200 kHz for each carrier. Moreover, universal mobile telephone system (UMTS), one of the 3G systems, runs at frequencies around 2 GHz and has only 5 MHz bandwidth for each channel (3G and UMTS FAQ).

In order to increase the capacity of wireless communication systems, the carrier frequencies need to be increased. This improvement is required to avoid the congestion at employed frequency bands. Even though, higher carrier frequencies offer greater



bandwidth, they lead to increased costs of radio front-ends in the BSs and the mobile units. In addition, the efficiency of RF active devices such as transistors is lower at high frequencies than that at low frequencies. Moreover, due to the ability of longer propagation of the radio waves, low-frequency RF signals lead to the ability of designing larger cells. The larger cells enable high mobility, however they lead to poor channel capacity of the wireless communication system, as the spectrum is shared by all WTUs that are operating within the cell's region. Therefore, the easiest way to increase capacity of wireless communication systems at low microwave carriers is to design micro- or pico-cells. Narrowing cell size with keeping the low frequency operated is difficult to accomplish, however it is possible when the radiated power at the antenna is reduced.

It is true, that smaller cell sizes result in improving spectral efficiency. However, the number of base stations needs to be increased to cover wide areas. In addition, the large number of base stations needs to be serviced and powered through an extensive feeder networks. That would raise the cost of such a system's hardware in addition to the high maintenance cost. Furthermore, serious issues of fading, distortion, and interference, they clarify the necessity of convenient systems that are immune to the effects for public use and reduce the cost of installation and maintenance. As it presents the simplicity of construction and the ability of convergence with other technologies, Radio-over-Fiber (RoF) technology has the ability to play that role (Al-Raweshidy & Komaki, 2002).

## **1.3 Millimeter-Waves over Wireless/Fiber Links**

### **1.3.1 Technology of wireless millimeter-wave**

At present, there is a rising need in developing wireless technologies for higher speeds, at data rate of 10 Gbps and up (Asyrmatos). For example, there is an ever increasing use of uncompressed high definition cameras across a broad range of applications. In some applications, an efficient wireless broadband communication path, such as a wireless millimeter wave link, will provide important advantages for connectivity. Applications for wireless connected high definition cameras are expected to be applied in national security, broadcast television, and surveillance (CSIRO, 2007). Other example of high data transfer uses of a high bit rate communication between space platforms, PC to PC and server to server communications, and temporary backup of fiber links in a disaster recovery scenario. This necessity of more bandwidth allocation places heavy load on the current operating radio spectrum and causes spectral overcapacity at lower microwave frequency bands. Millimeter-wave communication systems offer the right solution to maintain these issues. Beside the wide bandwidth availability and the perspective of multi-gigabit to terabit networks, the potential of the millimeter-wave spectrum has many other advantages; such as, enabling densely packed communication link networks from very short range to medium range, integrating efficient radiating elements at the millimeter bands, and leading to compact, adaptive and portable integrated systems. In a very broad term, millimeter-wave can be identified as an electromagnetic spectrum that is located between 30 GHz to 300 GHz, which

corresponds to the wavelengths from 10 mm to 1 mm (Yong & Chong, 2007) (Dawn, Sarkar, Perumana, & Padmanava, 2007). In 2001, the Federal Communications Commission (FCC) allocated 7 GHz in the 57 - 64 GHz band for unlicensed use (Yong & Chong, 2007). Using that free spectrum, combined with the advantage of low cost fabrication technology and low loss packaging materials, have renewed interest in this piece of wireless spectrum. WirelessHD™ is an industry-led effort to define a design for the coming generation wireless digital network interface for wireless high-definition signal transmission for users of electronics products using 60-GHz band. The function of the range for the first products will be in-room, point-to-point, none-line-of-sight (NLOS) at distance of up to 10 meters (WirelessHD).

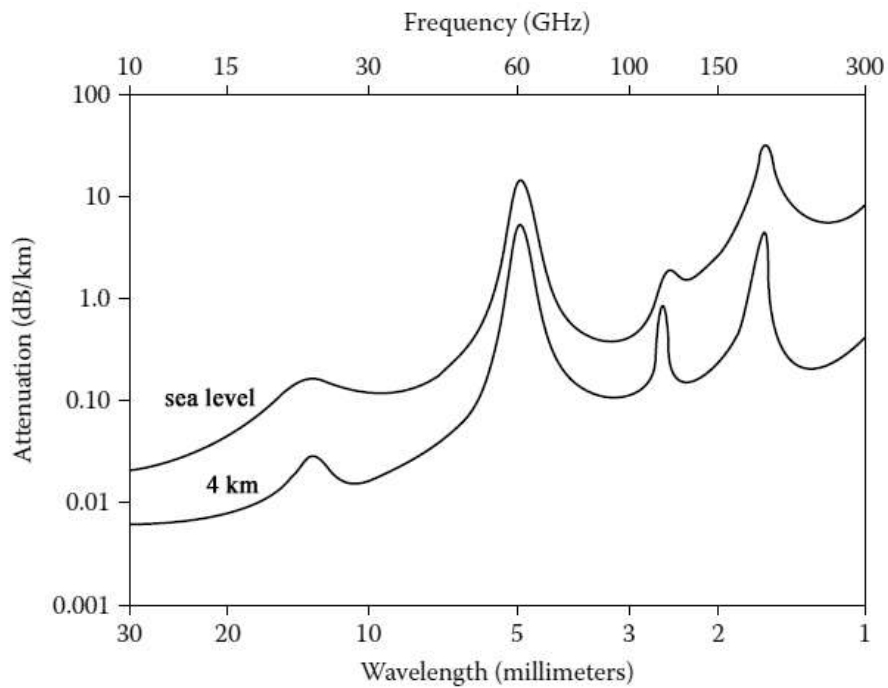


Figure 1.5 Average atmospheric absorption of frequency (Xiao, Zhou, & Zhang, 2008)

Compared to lower bands, the radio signals in millimeter-wave band are extremely prone to atmospheric attenuation, making them of very little use over long distances. In particular, signals in the 60-GHz region are subject to a resonance of the oxygen molecule and are severely attenuated (10-16 dB/km). In addition, the free space path loss increases quadratic with signal frequency which means the free space attenuation at 60-GHz band is too much higher than that at lower and higher frequencies. High propagation attenuation at some frequencies as shown in fig. 1.5 actually requires a set of short-range wireless applications, but it also means dense frequency reuse patterns. Higher frequencies also require smaller sizes of RF components such as antennas.

The WirelessHD<sup>TM</sup> specification defines a novel wireless protocol that enables directional connections that adapt very rapidly to changes in the environment. This is accomplished by dynamically steering the antenna beam at the transmitter while at the same time focusing the receiver antenna in the direction of the incoming power from the transmitter. This dynamic beam forming and beam steering utilize not only the direct path, but allow the use of reflections and other indirect paths when the LOS connection is lost (Xiao, Zhou, & Zhang, 2008) (Kitayama, 2000).

The economic aspect is primarily related to the transceiver RF front-ends. Usually, the III-V semiconductors such as gallium arsenide (GaAs) are required for millimeter-wave systems; however, GaAs is an expensive material. According to the reports about recent progress in developing the 60-GHz front-end chip sets, IBM engineers have demonstrated the first experimental 60-GHz transmitter and receiver chips using a high-speed alloy of silicon and germanium (SiGe). Temporarily, researchers are using a widely

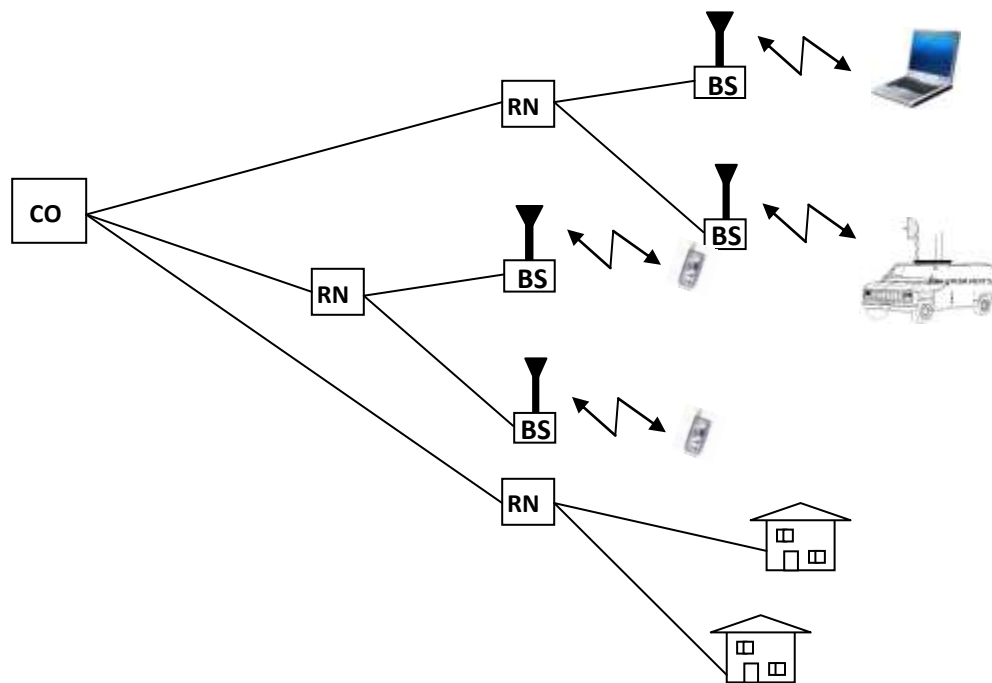
available and inexpensive metal oxide semiconductor (CMOS) technology to make 60-GHz transmitter and receiver components (Smulders, 2002).

### **1.3.2 Millimeter waves-over-fiber systems**

With all the improvements in the technology of wireless communications and the optical fiber communications as well, they do not completely meet some needs to communicate in a very convenient way. In some applications we need the speed of light and ability of transmitting a high bit rate per second without being connected physically with cables. That is why the idea of merging the technology of wireless with the optical fiber communications, will help to come up with highly convenient applications.

While microwave and millimeter wave links have excellent mobility characteristics that are impossible to achieve for other transmission media (wireless optical links have qualified performance if compared with microwave ones), they still suffer from a number of constraints. Most of them are resulted from EMC (electromagnetic compatibility) requirements, in order to avoid the interference and the crosstalk. Also, the wireless links suffer from the attenuation of the signal due to air characteristics, weather, smog, and the local shape of terrain or the occurrence of trees and buildings. The line of sight between the transmitter and receivers is usually an essential requirement for a reliable transmission. Also, the microwave spectrum is expensive and limited. On the other hand, wireless based access solutions offer portability and flexibility to users (Al-Raweshidy & Komaki, 2002).

In order to get benefits of the wide frequency spectrum offered by optical fiber and the flexibility features offered by the wireless techniques, as mentioned above, the networks that are based on both radio-over-fiber (RoF) and wireless techniques have been considered the most capable solution to the challenges facing wideband wireless networks. The merge of optical fiber and wireless communications in the range of millimeter-wave lengths can increase the channel capacity, covered areas, and mobility in environments such as airports, conference centers, media stations, outdoor events, super shopping malls, and homes. Furthermore, employing photonic technologies in fiber/wireless networks can significantly reduce the requirement of high-frequency electrical components for millimeter-wave signal processing (Kitayama, 2000).



**Figure 1.6 A schematic of basic radio-over-fiber system**

As above mentioned, the idea of RoF is to merge the use of two technologies such as radio frequency (RF) for wireless and optical fiber for wired transmissions. As shown in

Fig. 1.6, a basic RoF system consists of a CO for multiplexing, signal generation and processing, optical fiber network to transparently deliver the radio signals to remote nodes (RN), and then to a large number of base stations (BSs). The perfect distances between the CO and the BSs and between BS and the end users is going to be studied and presented in this research (Xiao, Zhou, & Zhang, 2008).

### **1.3.3 Strengths of RoF Technology**

The main advantage of RoF systems is the very wide broadband services offered with high flexibility. Incorporating with other technologies such as wavelength division multiplexing, the capacity of RoF can be greatly increased. Moreover, applying optical fiber to distribute millimeter-wave signals to the base stations and then through wireless links to the end user, can offer better coverage and higher transmission performance because of many advantages for the fiber links. Some of the advantages and benefits of the RoF technology compared with electronic signal distribution are explained below (Nakasyotani, Toda, Kuri, & Kitayama, 2006). The advantages of millimeter-waves-over-fiber can be briefly described in these points:

- I. Low Attenuation
- II. Immunity to electromagnetic interference
- III. Low power consumption
- IV. Easy installation and maintenance

### **1.3.4 Challenges of RoF Technology**

RoF is basically has analog signal characteristics in modulation, transmission, and detection of light even though the data being propagated is in digital form. As a result, the

aspects of noise and distortion that affect analog systems can identically affect RoF systems. These factors are able to control the dynamic range (DR) and noise figure (NF) of the RoF links. DR is a very important parameter for mobile (cellular) communication systems such as GSM because the power received at the BS from the mobile units varies widely which is usually about 80 dB. In the same cell, the RF power received from a mobile unit which is several hundreds of feet away should be much lower than the RF power received from a mobile unit which is close to the BS, but within the same cell.

The sources of noise in analog optical fiber links include the laser's relative intensity noise (RIN), the phase noise, the shot noise of photodiodes, thermal noise of amplifiers, optical return loss (ORL), and the dispersion of fiber links. In RoF systems' links that are based on multi-mode fiber (MMF), modal dispersion severely limits the available link bandwidth and distance. In RoF systems' links that are based on single mode fiber (SMF), chromatic dispersion may limit the fiber link length and may also cause phase de-correlation which results in high RF carrier phase noise (Al-Raweshidy and Komaki 2002).

#### **1.4 The Significance of the Research**

The technology of MMW communications based on photonic techniques for generation, transmission, and multiplexing and demultiplexing has more strength and fewer limitations than the technology of MMW based on electronics. This research showed us the limitations and strengths of each technique of photonic millimeter-wave generation in addition to the comparison between these techniques will help designers and researchers to choose the right technique of generation depending on available



environment of transmission. From the approached comparison and the other investigated parts in this research, many applications can be perfectly showed up or developed. These possible or expected applications are:

#### **1.4.1 Transmission of multiple HD-TV Signals**

The recent developments and the ability of handling multi-gigabit/sec of the radio-over-fiber systems have supported the rapid spread of wired broadband service. In contrast, one of the most important requirements for the end users is offering convenient wireless connections between base stations and mobile unites which requiring wide bandwidth for their services. It is true that the fiber or wired communication links offer wide bandwidth; however, the recent wireless links are not capable to provide that bandwidth. As presented in table 1.1, the highest bit rate of all the shown wireless standards does not reach 1 Gb/s. It is clearly seen that this bandwidth does not fit the requirements of the future technologies of high resolution multimedia services. As a result, new techniques of wired/wireless communicating are significantly requiring developments to meet the high demand of wider bandwidth for wireless links (Quinn 2005, Andersson 2001).

Recently, millimeter-wave-over-fiber or radio-over-fiber technology of the frequencies above 40 GHz and bit rate higher than 1 Gb/s is the most promising candidate for high speed wireless access networks. Even though all the effort have been spent to develop this technology, it still require a lot of research to be done in order to offer a completely designed system for multichannel multimedia communicating system

for the public use such as high definition television systems (HD-TV) (Chung, et al. 2007).

#### **1.4.2 Private Networks**

Many challenges are facing network administrators such as the speed of network connection or the nature of ground between buildings that connected together. For that reason, networks administrations need a high speed and convenient connection between some points of their LAN and the MMW wireless connection is the right solution for that challenge.

#### **1.4.3 Fiber Extensions**

It is great to find an extension for fiber line such as the MMW that based on photonic technology to avoid many problems in connecting to points of optical fiber links. As mentioned before the nature could be a reason of cutting links of networks especially in places we cannot setup a fiber link through them.

#### **1.4.4 Military Communications and Surveillance Systems**

Wireless communications are very important for military operations because of the short time for its systems to be installed. Also, the high bit rate is important to send and receive high amount of data in parts of second. That is going to help for giving these systems administrators a real time picture for the surrounding situation in an easy and fast way.

### **1.5 Objectives and Research Approach**

Despite to the aforementioned parts of introduction, the demand of improving the wireless access networks has to get more attention from researchers in order to develop it.

So far, many studies have been done by researchers focusing on generation techniques of MMW signals based on photonics. Depending on papers and journals that I have searched in, and to the best of my knowledge, previous studies focus on one or multiple ways of generation techniques; however, they do not compare these techniques with each other in the same situation of data rate and transmission links. To offer this kind of study, the main objective of this study was to investigate with comparisons, by theoretical study or simulations, the best photonic based techniques for millimeter-wave generation and transmission. In addition, other techniques for optical millimeter-wave communications such as multiplexing and data modulation are investigated.

In this research, many aspects of the stated objectives were approached. Depending on the available software of simulation, three ways of MMW generation techniques are covered, simulated using “OptiSystem<sup>©</sup> and OptSim<sup>©</sup>” software, and compared to each other depending on the results of different distances and links of transmission in addition to a study and simulation of fiber dispersion compensation.

### **1.6 Brief Statement of the limits of Research**

One of the main limits of this research is that only software was used for implementation even though it gives nearly real results. This is because of the software’s flexibility to set all required parameters such as, attenuation, distance of transmission links, dispersion of fiber links, insertion loss, and applied frequency. Moreover, the investigated technique of wavelength interleaved WDM using NxN arrayed wave grating (AWG) could not be achieved because this technique requires a specific AWG which is not available at the simulation software. Recently, orthogonal frequency division

multiplexing (OFDM) cannot be optically achieved. This is because it requires fast Fourier transform FFT and quadrature amplitude modulation QAM and these can only be achieved away of photonics.

### **1.7 Thesis Organization**

This research organized based on the general construction of optical millimeter-wave systems. Usually, the first stage of each system is starting with signal generation. This is why the investigated techniques of MMW generation are presented in chapter 2. Also, novel designs transceivers are presented in the same chapter. In chapter 3, fiber and free space optical links characteristics are studied and used to compare the mentioned generation techniques to each other. Furthermore, one solution for dispersion effect caused by fiber links is simulated. Theoretical study of the technology of wavelength interleaved wavelength division multiplexing (WI-WDM) is presented in chapter 4 in addition to a study and simulation of WDM technique with using different techniques of MMW generation. As a proposal for future work, chapter 5 includes theoretical study of digital data modulation technique that can be used a multiplexer for transmitting multiple MMW signals with reduced or eliminated intersymbol interference (ISI).

## [ CHAPTER 2 ]

# 2. MILLIMETER-WAVE GENERATION AND TRANSMISSION TECHNIQUES

### 2.1 Introduction

Millimeter-waves have found wide application in the fields of communications, radar, radiometry, spectroscopy, and radio astronomy, etc. Electronic generation of millimeter-waves using oscillator and frequency multiplexers has been achieved; however, such millimeter-wave sources are usually huge and heavy. In addition, due to the serious air propagation loss, the free space transmission distance of millimeter-wave signals is generally limited. These facts limit the use of millimeter waves in many modern systems (Xiao, Zhou and Zhang 2008). However, the fixed wireless access (FWA) links are very attractive for the last-one-mile networks and wide networks because they are saving time and cost of installation in addition to being more flexible and physically uncomplicated. Recently, the speed of FWA is still less than 1 Gbit/s, that is why FWA links still need more effort in research for more improvement (Hirata, Harada and Nagatsuma 2003).

Generation and transmission of millimeter-wave signals based on photonic techniques are capable of declining the abovementioned limitations effectively. Also, the generation of millimeter waves based on photonics, provides low-phase noise, high

output power, and wide frequency tunability (Nagatsuma, et al. 2007). Many photonic generation techniques for millimeter-wave were achieved; however, each one of them has its own advantages and disadvantages that would affect their applications. In this chapter we will examine a selection of some techniques achieved so far. These techniques of generation are external intensity modulation of RF signal based on mach-zehnder modulators and optical heterodyning are presented.

To take advantage of the wide bandwidth that is offered by fiber and technology of millimeter-wave based on photonics, the mixing of wireless and optical networks is a key for rising the ability of higher bit rates per second transmitted and mobility. This also will decrease the costs in the access networks. Thus, the radio-over-fiber (ROF)-based optical–wireless networks came into play and has emerged as an affordable alternative solution in the aforementioned applications (Jia, et al. 2007).

## **2.2 Millimeter-wave Generations by Direct and External Intensity Modulation**

The easiest way for optically distributing millimeter-wave signals, in space or through a fiber, is to modulate the laser source's intensity with the RF signal which could be recovered by photodetector to regenerate the original RF signal at the receiver side. This method is called intensity modulation. The modulation of laser source might be done by two ways. The first way is shown in Fig. 2.1.a which is achieved by applying an RF signal to one of the laser's terminals. The result will be many optical spectral lines which are called sidebands. They are all spaced by the drive frequency as shown in figure 2.4. Only two sidebands, which are separated by the required millimeter-wave frequency as mentioned, are then selected.

The other method of modulation is to operate the laser in continuous wave (CW) mode and by using an external modulator such as the Mach-Zehnder Modulator (MZM), to externally modulate the output current of the light source as shown in Fig 2.1.b (Jianjun, et al. 2006).

The MZM behavior could be mathematically described as;

$$E_{out}(t) = E_{in}(t) \cdot \cos(\Delta\theta(t)) \cdot \exp(j \cdot \Delta\phi(t))$$

Where:  $\Delta\theta$  is the phase difference between the two branches and is defined as;

$$\Delta\theta(t) = \frac{\pi}{2} \cdot (0.5 - ER \cdot (RF(t) - 0.5))$$

With

$$ER = 1 - \frac{4}{\pi} \cdot \arctan\left(\frac{1}{\sqrt{extrat}}\right)$$

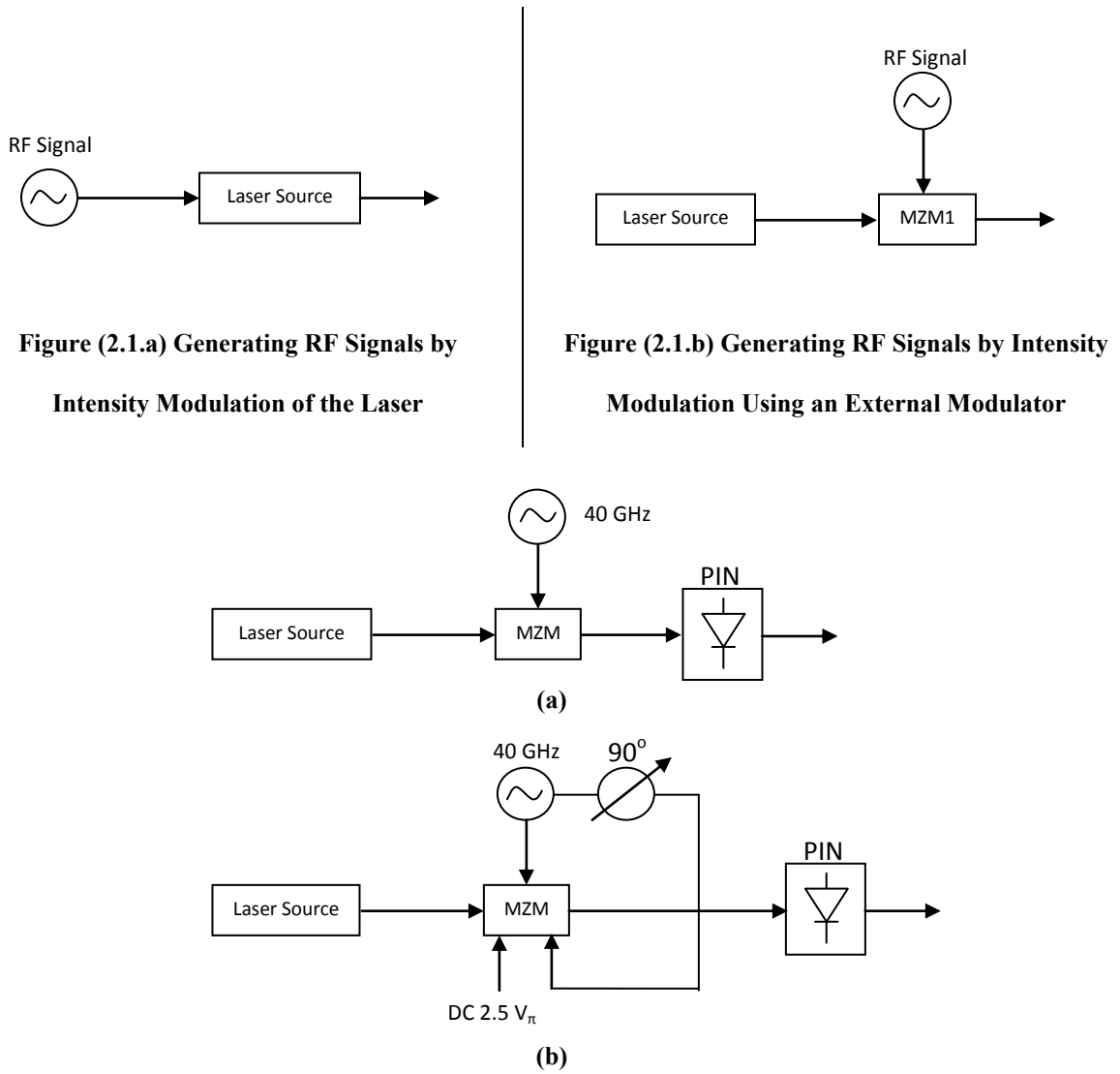
And  $\Delta\phi$  is the signal phase change defined as;

$$\Delta\phi(t) = SC \cdot \Delta\theta(t) \cdot (1 + SF)/(1 - SF)$$

Where: the parameter **SC** is  $-1$  if negative signal chirp is true, or  $1$  if negative signal chirp is false. **extrat** is the extinction ratio, **SF** is the symmetry factor, and **RF(t)** is the electrical input signal. The electrical input signal is normalized between 0 and 1 (OptiSystem Component Library 2008).

The generated double sideband (DSB) signals do not have the ability to travel longer distance because of the chromatic dispersion in the fiber. To reduce the effect of dispersion, optical single sideband (SSB) modulation technique should be used which could be approached by using a single dual-arm Mach-Zehnder modulator (MZM) as

shown in Fig 2.2. In all the above-mentioned cases, the RF signal to be transmitted is the actual modulating signal (Jia, et al. 2007).



**Fig. 2.2 Optical up-conversion using (a) DSB and (b) SSB with bit rate of 2.5 Gb/s**

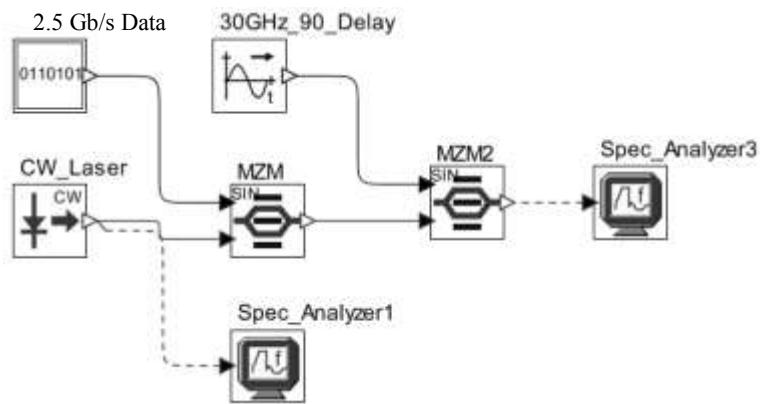
After the transmission through the fiber or wireless channel and direct detection on a photodiode, the photocurrent is a duplication of the modulating RF signal applied either directly to the laser or to the external modulator at the central office (CO). If we modulated the RF signal with data before modulating the transmitter, the detected RF



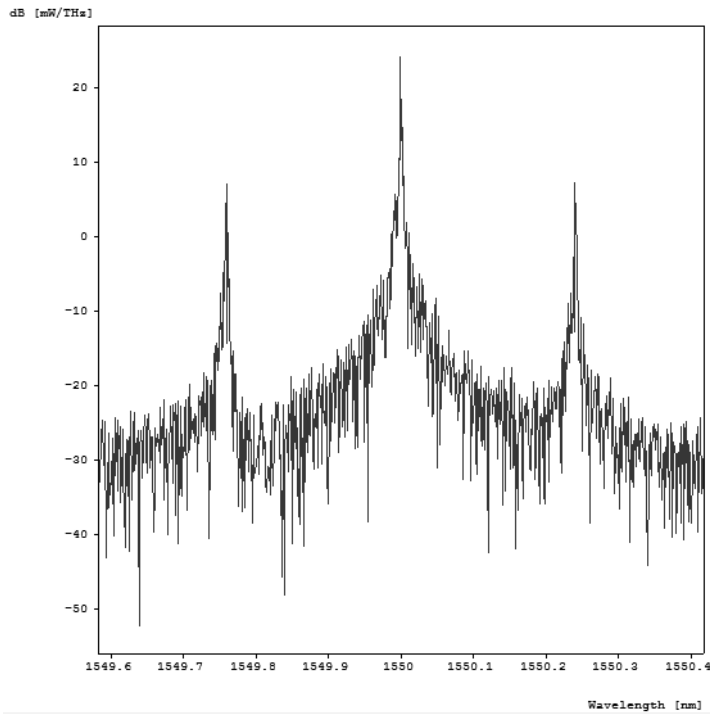
signal at the receiver side will be carrying the same data. There are many modulation techniques with different characteristics for this approach will be discussed later in this research (Jia, et al. 2007, Jianjun, et al. 2006).

### 2.2.1 Implementations and Results

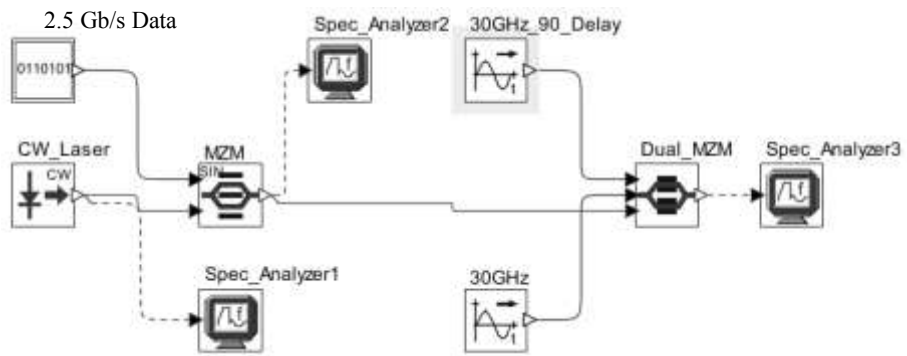
In the experimental setup shown in Fig. 2.3, the generation of optical double sideband (ODSB) of 30 GHz signal is illustrated. The generated millimeter-wave signal has a data bit rate of 2.5 Gb/s.



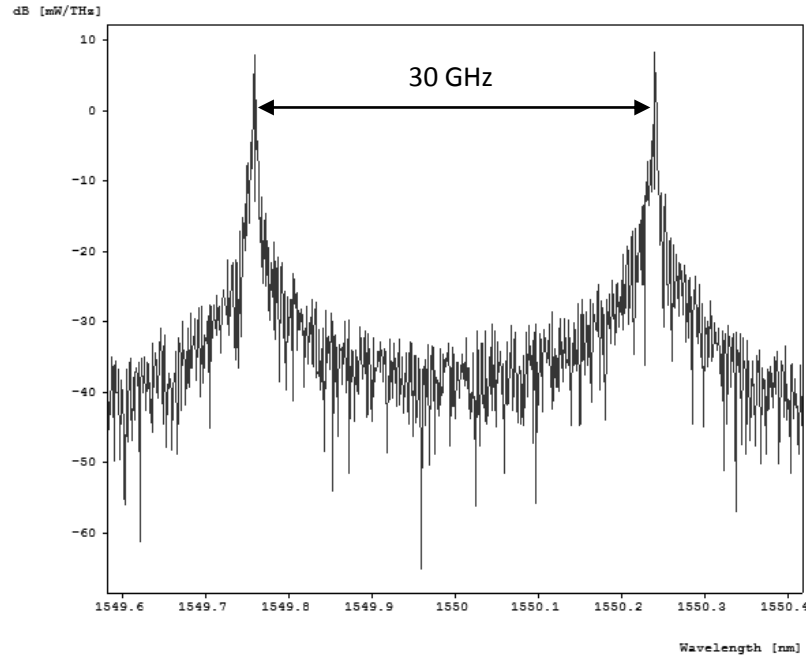
**Fig. 2.3 Experimental setup of ODSB+C of 30 GHz generation**



**Fig. 2.4 Optical spectrum of 30 GHz ODSB millimeter-wave**



**Fig. 2.5 Experimental setup of OSSB of 30 GHz generation**



**Fig. 2.6 Optical spectrum of 30 GHz OSSB millimeter-wave**

### **2.2.2 Advantages of Direct and External Intensity Modulation**

The first advantage of this way of millimeter-wave generation is that it is very simple. In addition, if low dispersion fiber is adopted together with a linear external modulator, the whole system becomes linear. The optical link through fiber or wireless channel is transparent to the used modulation technique for the original RF signal, which also acts as an attenuator. In other words, these simple systems need little or no upgrades at any changes in the modulation format of the original RF signal. Direct laser diode modulation and external modulation techniques are both tunable with microwave sources. Since the same laser generates both optical fields, the phase noise is highly correlated resulting in very narrow linewidth millimeter-waves. In fact, the performance of these methods in terms of phase noise is comparable to more advanced techniques such as the OPLL system (Quinn 2005, Jianjun, et al. 2006).

### **2.2.3 Disadvantages of Direct and External Intensity Modulation**

One of the noticeable problems of the direct and external intensity modulation techniques is the limitation of using them in high millimeter-wave frequency applications. The reason of that is to generate higher frequency signals, the modulating signal must be also at that high frequency as well. Because of the limited bandwidth of signals generated by direct laser modulation, distortion will occur. In contrast, external modulators such as the Mach-Zehnder modulator (MZM) are able to support high frequency RF signals. However, they need high drive voltages, which lead consequently to very expensive drive amplifiers.

A further disadvantage of the external modulation based technique is that it is affected by chromatic dispersion caused by the fiber, especially when double side band modulation of the optical signal is adopted (Jia, et al. 2007, Nagatsuma, et al. 2007)

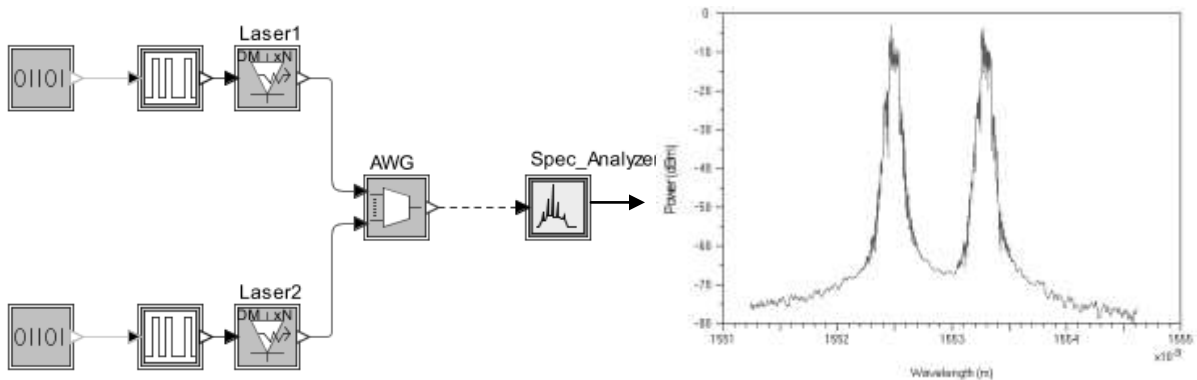
## **2.3 Millimeter-Wave Generation by Remote Heterodyning**

### **2.3.1 The principle of Remote Heterodyning**

The principles of remote heterodyning (RHD) techniques are quite different from those of direct and external intensity modulation techniques (IM). The major difference is that the IM systems transmit the millimeter-wave signals as sidebands on a single laser signal; however, the RHD systems generate the millimeter-wave signals by heterodyning of two laser signals. In this process, the phase noise of the two laser signals directly affects the generated millimeter-wave signal. Therefore, it is essential either to remove the actual laser-signal phase noise or to correlate the phase noise of the two laser signals.

Either methods or a combination ideally ensures the generation of a highly phase-stable MMW carrier.

A simplified schematic of the RHD principle is shown in Fig. 2.7. “At the transmitter end, two phase-correlated laser signals with a frequency offset of  $f_c = |f_1 - f_2|$  are generated by a dual-frequency laser transmitter. Both laser signals are transmitted through the fiber/wireless links to the receiver end where heterodyning takes place in an O/E-converter (photodiode). Assuming that the phase correlation between the two laser signals is not changed by the fiber link, the resulting beat signal is a highly phase-stable MMW carrier with a frequency of  $f_c$ . However, the phase correlation is altered to some extent by the fiber link which, besides transmission attenuation, may limit the system performance due to dispersion effects and fiber nonlinearities. Both chromatic dispersion (CD) and polarization mode dispersion (PMD) limit the obtainable transmission-distance times MW-carrier frequency product of the link. Further, at high optical input powers, fiber nonlinearities may cause significant problems.” (Gliese, et al. 1998).



**Fig. 2.7 Schematic of remote heterodyning**

In order to keep the frequency of the generated signal by RHD stable, it is required to control the instantaneous frequency difference accurately. In other words, absolute shifts in emission frequencies are not as important as the offset between them.

Because the laser emission frequency is highly sensitive to temperature variations, phase noise, and other effects, techniques were established to fix the required frequency offset and phase noise performance. Recently, there are many ways to control the frequency offset between the two lasers. These methods include:

- Optical Phase/Frequency Locked Loop (OPLL/OFLL)
- Optical Injection Locking (OIL) and Optical Injection Phase-Locked Loop (OIPLL)

Very high frequencies can be generated by using optical heterodyning which are restricted by the photodetector bandwidth. Because the optical powers of the two optical fields both contribute to the power of the generated millimeter-wave signal, heterodyning results in high-detected power and higher carrier-to-noise ratio (CNR) (Ng'oma 2002).

In remote heterodyning detection systems (RHD), it is important to eliminate chromatic dispersion effects which are very significant in phase noise sensitive modulation formats (16-QAM and 32-QAM), where dispersion results in a power problem. Remote heterodyning has natural advantage relating to chromatic dispersion. System sensitivity to chromatic dispersion can be greatly reduced, if one of the two optical carriers is modulated with data. However, this advantage does not exist in direct intensity modulation based methods, where the two optical sidebands are modulated with data. (Song, Lee and Song 2004). In addition to the attributes of RHD, is its capability of accepting low-frequency data modulation at the central office (CO). As a result, this system does not require high-frequency electro-optical components which can reduce the

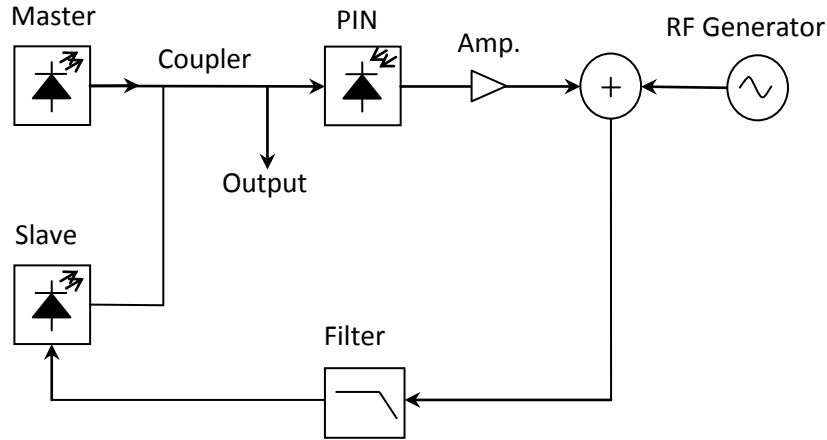
price using RHD techniques. In a comparison with intensity modulation techniques, the RHD modulator at the central office is able to be driven either by a low-frequency RF signal or with baseband data.

On the other hand, the major problem of RHD is the effect of laser phase noise and optical frequency variations on the stability that causes impurity of the generated RF carriers. Techniques used to reduce phase noise sensitivity such as, Optical Phase Locked Loops (OPLL) and Optical Injection Locking (OIL), are complex systems.

### **2.3.2 Optical Frequency/Phase Locked-Loops (OFLL/OPLL)**

The basic configuration of OFLL and OPLL techniques is shown in Figure 2.8. It consists of a free running master laser, a PIN photodiode, an amplifier, a frequency or phase discriminator, a loop filter, a slave laser and a millimeter-wave reference oscillator. The joint outputs of the two laser sources (master and slave) are split into two parts. One Part of the optical signal is used in the OPLL/OFLL at the central office (CO) while the other one is transmitted to the base station (BS). The optical signal at the CO is heterodyned on a photodiode to generate a millimeter-wave signal. The generated millimeter-wave signal is compared to the reference signal. In the system of OPLL, a phase error signal is generated and fed back to the slave laser. The same thing is happening with the OFLL systems. In this case, the slave laser is pushed to follow the master laser at a frequency offset that is equivalent to the frequency of the millimeter-wave reference oscillator. As mentioned before, the object of OFLL is to maintain the required mean frequency offset. It does not repress small scale frequency variations caused by phase noise as well as OPLL which is able to track small scale phase noise.

Since OFLL/OPLL techniques can maintain little frequency/phase variations, they are capable of producing high signal to noise ratio (SNR) of millimeter-wave (Kasai, et al. 2007, Ng'oma 2002).



**Figure 2.8: Schematic diagram of Optical Frequency/Phase Locked Loop**

On the other hand, OFLL's drawback is that the linewidth of the signal generated by the OFLL system is approximately the sum of the linewidths of the master and slave lasers. As a result, OFLL generates millimeter-wave signals with wide linewidths compared to the narrow linewidth generated by OPLL techniques. Also, the frequency of the generated millimeter-wave signal by OFLL is equal to the frequency difference between the two beating optical fields. Therefore, in order to produce narrow linewidth millimeter-wave signals using OFLL, lasers with narrow linewidths should be used. However, reducing the source linewidth will result in reducing the maximum power that will be transmitted in the fiber without experiencing attenuation. As a result, narrowing the laser source linewidth is limited.

Even though OPLL techniques are adopting inexpensive DFB lasers, they require complex laser structures in order to give better results. This condition is an important



because of the tuning rate of the slave laser must be satisfactorily high, thus the frequency noise of the master laser will be tracked. That means adequate feedback bandwidth must be available. The required feedback bandwidth is determined by the summation of the two laser linewidths, the requirements for loop stability and phase noise requirements. This is placed on the optical microwave signal generated by the system in which the OPLL is applied. Because they have a large amount of phase noise, semiconductor lasers require a wide feedback bandwidth when these lasers are used. In order to attain the wide feedback bandwidth, the loop-propagation delay must be reduced. In addition, to achieve the best results of OPLL system, both responses of the microwave components and the slave laser FM response, must be wide and uniform in both phase and magnitude even though it is not easy to accomplish. As a result, these requirements make the implementation of OPLL systems are difficult to accomplish (Ng'oma 2002).

#### **2.4 Novel Designs for Transceivers**

Optical wireless communication systems operate in specific ranges of wavelength as well as optical fiber communication systems. Depending on the used wavelength, the recent available optical wireless communication systems could be categorized into two categories depending on the operating wavelength. Some systems operate near the 800 nm wavelength band and others operate near the 1550 nm. Unlike optical fiber communication systems, the wavelength band of 1310 nm is not used as a transmitting wavelength because of the serious atmospheric absorption by water vapor around this wavelength (Matsomoto, et al. 2008).

In practical, there are many transmitters and receivers that have been developed to meet the channel requirements and to successfully transmit millimeter-wave signals.

These techniques are based on different designs depending on the application and data bit rate that they have been designed for. Several concepts and features for these transceivers are presented.

#### 2.4.1 Based On Photodetector and Antenna Integration

##### I. MMW Photonic Transmitter Based on UTC-PD

In this part of the research, a novel design and characteristics for transmitter based on uni-traveling carrier photodiode (UTC-PD), was investigated. This transmitter was designed for frequencies in the range of millimeter-wave and especially for higher than 100 GHz. This millimeter-wave component depends in its operation on the above mentioned UTC-PD which has a very fast chip and is able to provide high output power.

Fig.2.9.a and b show the diagram of the studied photonic millimeter-wave transmitter. The transmitter constructed by employing a planar antenna chip, a UTC-PD chip, a hemispherical Si lens, and an optical fiber with a collimating lens. The hemispherical Si lens is employed to improve the gain and directivity before propagating the millimeter-wave coming from the antenna (Hirata, Ishii and Nagatsoma 2001).

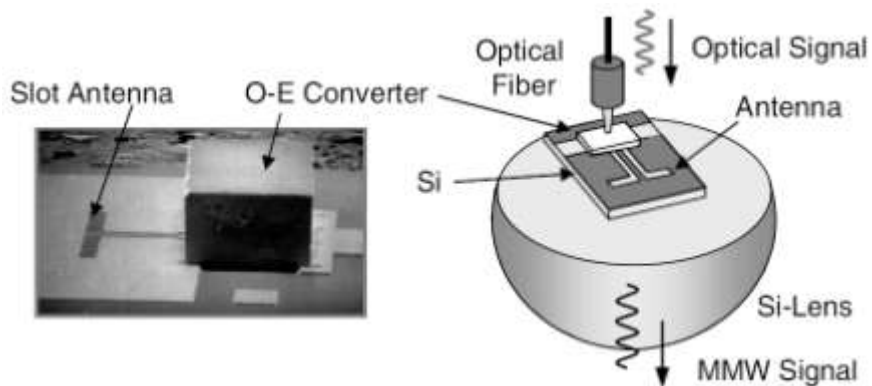
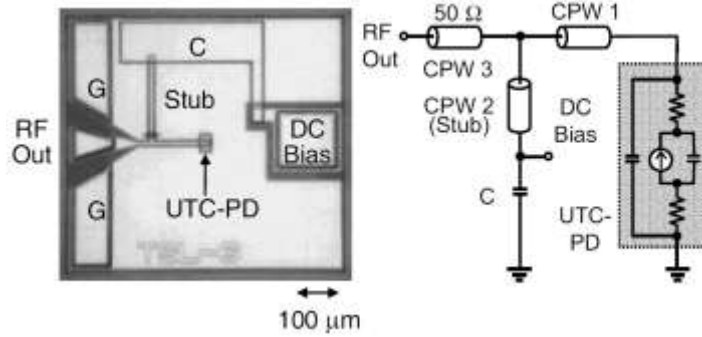


Fig. 2.9.a Conceptual diagram and microphotograph of the investigated MMW transmitter

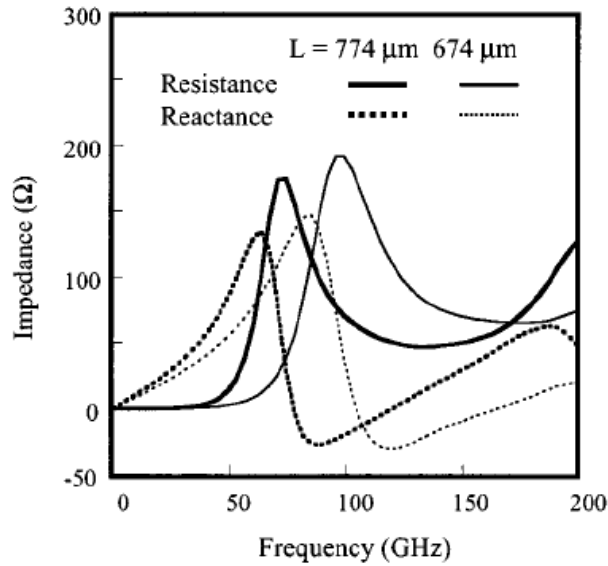


**Fig. 2.9.b microphotograph of the investigated MMW transmitter**

A coplanar-waveguide-fed (CPW-fed) slot antenna was employed for the planar antenna chip. The main reasons of using this antenna are simply because it is suitable for the connection of planar-active devices and has an antenna pattern perpendicular to the substrate (Kormanyos, et al. 1994). The slot antenna and CPW were created on a Si substrate with thickness of 0.4-mm and  $\epsilon_r=11.7$ . High-resistivity Si and thick gold were used in order to reduce the effects of dispersion and radiation loss that could be caused by the substrate. The thickness of the gold was 10  $\mu\text{m}$ , and the resistivity of the Si was 1  $\text{k}\Omega\cdot\text{cm}$ . The signal linewidth of the CPW was 20  $\mu\text{m}$ , the signal-ground space was 24  $\mu\text{m}$ , and the impedance of the CPW was 50 $\Omega$ . The fabrication process of this antenna was explained in details in (Hirata, Ishii and Nagatsoma 2001).

When optical signals were injected into the UTC-PD, the resulting electrical signals traveled to the slot antenna through the CPW. This produces MMW signals, which were collimated by the Si lens and propagated into free space. For the antenna design, two different 3-D electromagnetic simulators were used. One was based on the finite-element method (FEM), and the other was based on the finite-difference time-domain (FDTD)

method. First, the impedance of the slot antenna was simulated in order to determine the antenna geometry by using the method of FDTD.

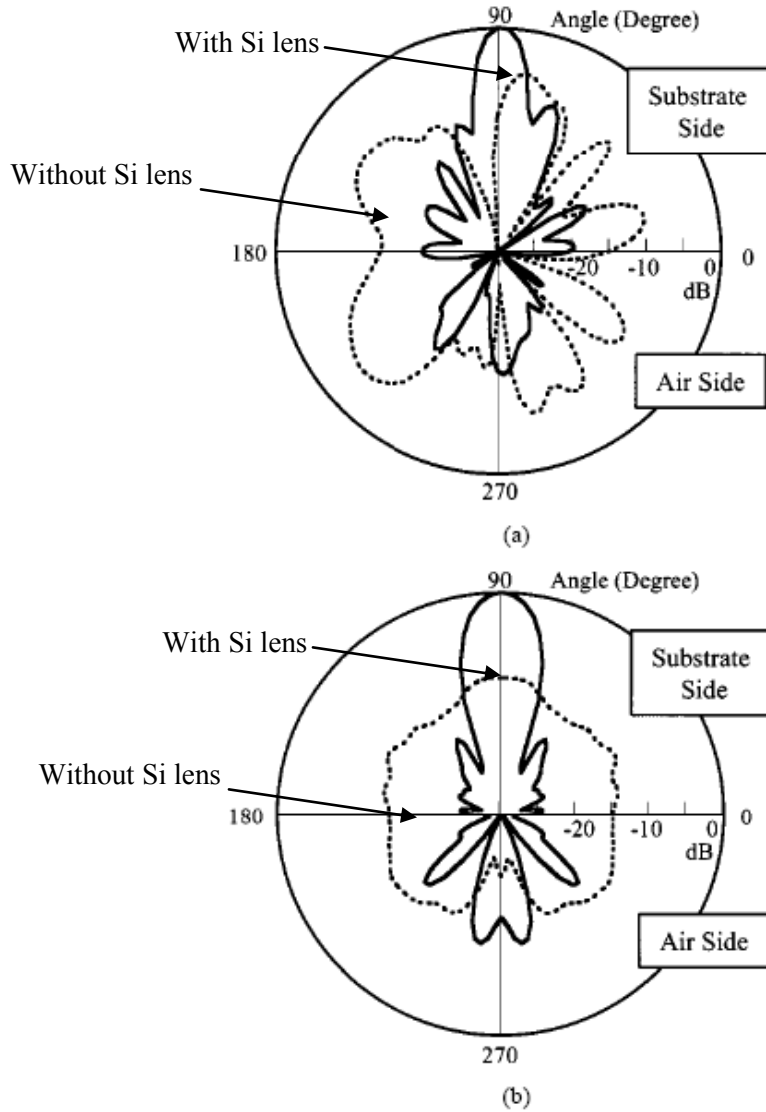


**Fig. 2.10 Antenna-impedance simulation results as a function of slot length using FDTD method (Hirata, Ishii and Nagatsoma 2001)**

The impedance of the CPW was assumed to be  $50\Omega$ , and the target frequency was 120 GHz. Thus, at the frequency of 120 GHz; the resistance should be  $50\Omega$ , and the reactance should be  $0\Omega$ . This condition could be clearly seen from the results of simulation done by FDTD method in Fig. 2.10 for different slot lengths. When the length of the slot was  $774\ \mu\text{m}$ , the width of the substrate was  $95\ \mu\text{m}$  and the resistance was  $50\Omega$ , the reactance value was fallen down to zero at 120 GHz.

Furthermore, the effects of the Si lens were investigated. The simulation results were recorded by Takalahata, et al. 2000. It shows that the slot antenna placed on the infinite Si substrate radiates preferentially into the substrate with a ratio of over the power radiated into the air side. The hemispherical lens collimates the millimeter-waves propagated from the slot antenna. The extension length of the hemispherical lens was

determined in the FEM simulation by Hirata, Ishii, and Nagatsoma 2001 to ensure the maximum directivity of the transmitter.



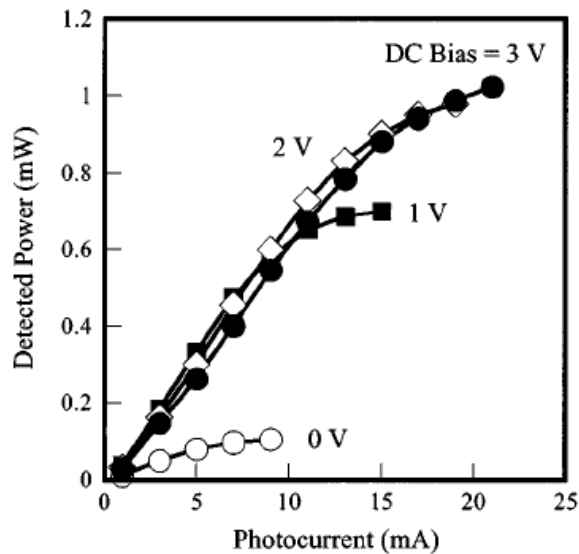
**Fig. 2.11. Radiation patterns of slot antenna with and without Si lens**

**(a) in the E-plane and (b) in the H-plane**

Fig. 2.11 shows radiation patterns of the antenna calculated by the FEM (Hirata, Ishii and Nagatsoma 2001). In the FEM simulation, the Si lens was modeled by a full space. This simulation showed that without using the Si lens, the power was propagated into the

sides of the air and substrate. When the Si lens was employed, most of the power radiated into the substrate side, and the beam was concentrated perpendicularly to the substrate. For instance, the gain of the simulated antenna was 4.3 dB without using the Si lens while it was 13.5 dB when the Si was used. Also, the same thing happened with the directivity. It was 4.9 dB without the Si lens and 16.9 dB with the Si lens. Because of the reflection loss at CPW, difference of 3 dB exists between the gain and directivity (Hirata, Kosugi, et al. 2003).

The output power of the UTC-PD was measured at a frequency of 120 GHz which was generated by the optical millimeter-wave source. It was concentrated onto the UTC-PD. The output power of the UTC-PD, which depends on the photocurrent ( $I_{ph}$ ), was propagated into the air and traveling to the waveguide detector which used a calibrated Schottky barrier diode.



**Fig. 2.12 Output power of the UTC-PD dependency as a function of the dc-bias voltage (Hirata, Ishii and Nagatsoma 2001)**

Fig. 2.12 shows the dependence of the detected UTC–PD output power on the photocurrent ( $I_{ph}$ ). It normally happens when detected power increases at the beginning with an increase in  $I_{ph}$ , and then the photodetector saturated. The saturation began at low ( $I_{ph}$ ), as the dc-bias voltage became lower. This mainly comes from the nonlinear saturation of the UTC–PD at frequencies beyond its 3-dB bandwidth (Hirata, Ishii and Nagatsoma 2001).

## II. MMW Photonic Based Receiver Based on Schottky-Diode (SBD)

To achieve designing a millimeter-wave receiver for a bit rate up to 10 Gbit/s, a broad band receiver is required with a large bandwidth and low-pass filter with high cut-off frequency. Because photonic components are more suitable than the electronic components, a photonic receiver depends on an InP Schottky barrier diode (InP SBD) was developed (Minotani, Hirata and Nagatsuma 2003).

A schematic of the investigated receiver is shown in Fig. 2.13. As can be seen it consists of Schottky barrier diode, slot ring antenna, CPW filter, and extended hemispherical Si lens. The filter and the slot ring are made of 10 $\mu$ m thick gold on a Si substrate with high resistivity of greater than 10k $\Omega$ .cm.

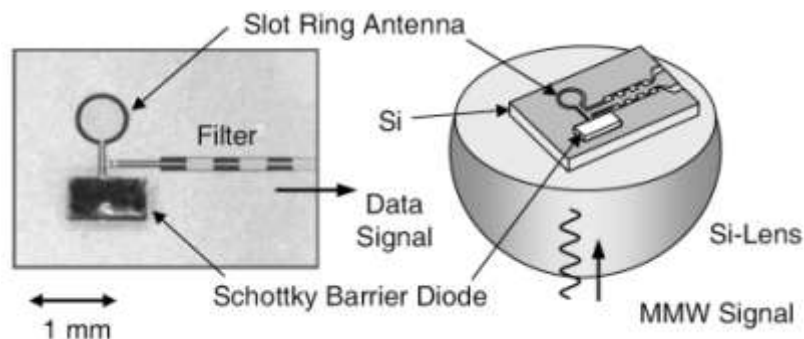
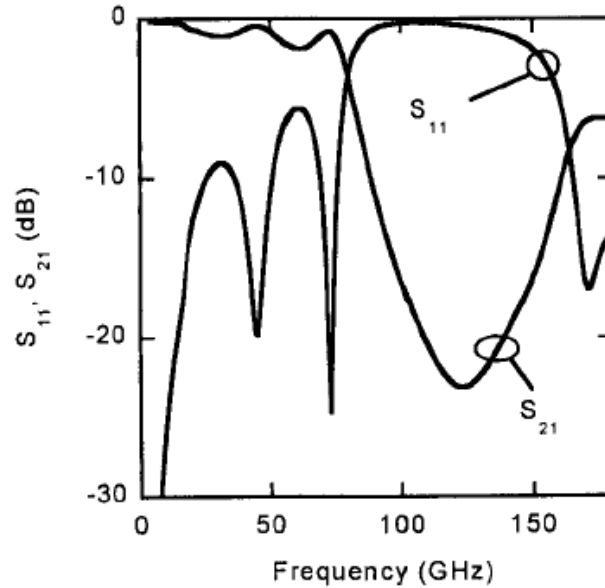


Fig. 2.13 MMW receiver based on SBD



**Fig. 2.14 S parameters of the CPW filter** (Minotani, Hirata and Nagatsuma 2003)

The received RF signals by the antenna, goes directly to the Schottky barrier diode (SBD) to be converted to baseband signals which go out through the CPW filter. The main rules of the CPW are to separate the RF signals from the baseband signals and also to a pass line for DC bias voltage. The CPW filter was designed to have a cut-off frequency at 70GHz. The CPW consists of four high impedance sections and three low impedance sections. Fig. 2.14 shows the performance of S parameters of the CPW filter whereas the  $S_{21}$  is smaller than -20dB in the frequency range of W-band.

#### **2.4.2 Based on PIN diodes**

The investigated photonic synthesizer or photonic oscillator concept is a novel technique for providing frequency tunable and low phase noise continuous wave signals. Comparing this synthesizer to other optical sources such as quantum cascade lasers and electrical transceivers, it shows a number of unique features such as frequency tunability, ultra wideband operation and the possibility to operate without cryogenic cooling as



(Stohr, et al. 2007) present depending on their research. These abilities strongly lead this photonic receiver to be promising candidate for several applications in the millimeter-wave communication systems. Also, photonic synthesizers are efficient candidates for broadband wireless communications, and millimeter-wave imaging.

A high-power pin waveguide photodetector with a rectangular WR10 waveguide output is investigated and presented in this part. What make this photodetector an interesting component to be focused on are the results that researchers in the University of Duisburg-Essen have gotten so far. Based on (Stohr, et al. 2007) this photonic component has the ability to synthesize frequencies in the range of millimeter-wave specifically within the range of 70 to 110 GHz and showed a flat response over the entire band. Along that frequency range, the output power variation of the photonic synthesizer was in the range below 3dB when the output power can vary between 0 and -35dB within other frequencies. Being a wideband tunable, this photonic millimeter-wave synthesizer is a unique component.

Technically, the photonic millimeter-wave synthesizer investigated in this research is based upon transforming the optically generated millimeter-wave to RF signals with tenability up to 50GHz. For instance, applying the output of the optical heterodyning of a two-mode 1.55 $\mu$ m laser signal in a high-power pin waveguide photodiode would generate millimeter-wave signals at a frequency range of 75 GHz to 110 GHz. In order to achieve stable frequency response when the source changes its frequency, a two stage limiting amplifier with an inter-stage isolator was further engaged as shown in Fig. 2.15 and Fig. 2.16

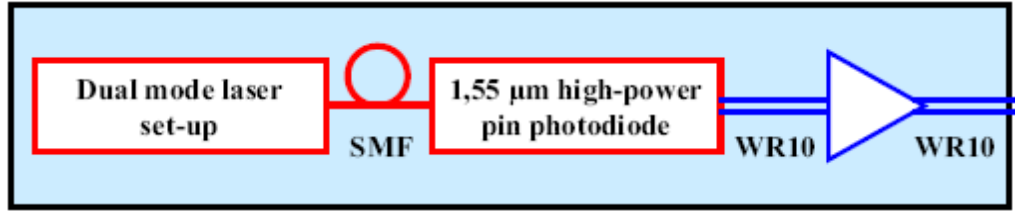


Fig. 2.15 Schematic diagram of the photonic millimeter-wave synthesizer based upon optical heterodyning (Stohr, et al. 2007).



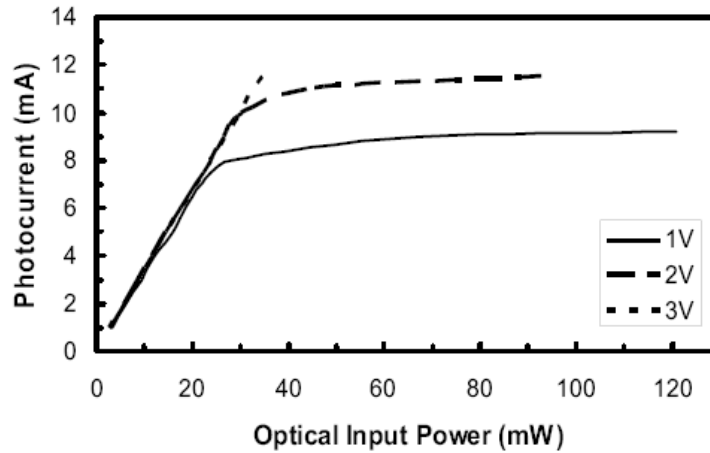
Fig. 2.16 photodiode chip featuring a passive optical waveguide, an integrated bias network and an LC circuit, creating an inductive peaking at 100GHz (Stohr, et al. 2007).

The current of the millimeter-wave signal generated by the photodiode is mathematically expressed as;

$$i = 2S_o P_{opt} + 2S_{fc} P_{opt} \cos(2\pi f_c t + \Delta\varphi),$$

Where:  $f_c$  and  $\Delta\varphi$  represent respectively the difference frequency and the difference phase of the two constituent optical input waves. Furthermore,  $S_o$  and  $S_{fc}$  indicate the generated DC and the RF components of the used photodiode. For testing the photonic synthesizer, researchers applied optical heterodyning to generate the millimeter-wave signals by using two individual lasers as shown above. Optical heterodyning is a simple way to generate a millimeter-wave signal and offers a wide frequency tunability as the output frequency can be simply tuned by controlling the wavelength of one of the lasers. For achieving more efficient millimeter-wave signals, other generation techniques could

be used which are explained in details in previous parts of this research. From the results in (Stohr, et al. 2007) at 1.55 $\mu\text{m}$  wavelength the waveguide coupled photodiode exhibits a response of about 0.3A/W.

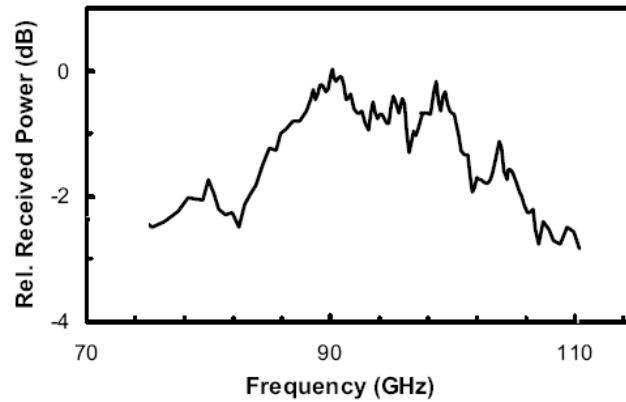


**Fig. 2.17 DC response of the used pin waveguide detector at different reverse bias voltages.**

As shown in Fig. 2.18, the photocurrent increases linearly with increasing optical input power. In addition, with rising up the reverse bias voltage the optical saturation point this can move towards higher optical input powers. From Fig.2.17, at a reverse bias voltage of 3V no saturation was observed up to 40mW while it was 30mW at the reverse bias voltage of 2V. Furthermore, an external W-band mixer and spectrum analyzer were used to measure the frequency response of the PIN photodiode. The results of this measuring could be shown in Fig.2.18.

As above-mentioned and depending on the graph of frequency response that shown in Fig.4, the investigated photodiode provides a stable frequency response for whole the W-band (75-110 GHz) with only 3dB of power disparity. It can be clearly noticed that the highest values of output power at 90 and 100 GHz is due to a partial compensation of

photodiode capacitance. The output power of the millimeter-wave signal can be controlled by changing the optical input power.



**Fig. 2.18** Frequency response of the pin photodiode related to the received power.

As explained above, one of the main components of this photonic synthesizer is an amplifier connected through a two-stage rectangular waveguide (WR10). The main rule for the amplifier here is to act as a limiting amplifier not as it seems to be for amplifying the output power of the photodiode. The purpose of that is to keep the frequency response stable at all the tunability range of the W-band (Stohr, et al. 2007).

### **2.4.3 Based On Beam Propagation Method**

A beam based wireless communication system is an optical beam that is directly propagated from a fiber side to free space using an optical antenna. At the receiver side, using the receiver optics, the transmitted optical beam is directly concentrated to a fiber and then to photodetector. Depending on the deployment situation, if the optical power of the transmitted signal is too low and not adequate for spread through the atmosphere, it

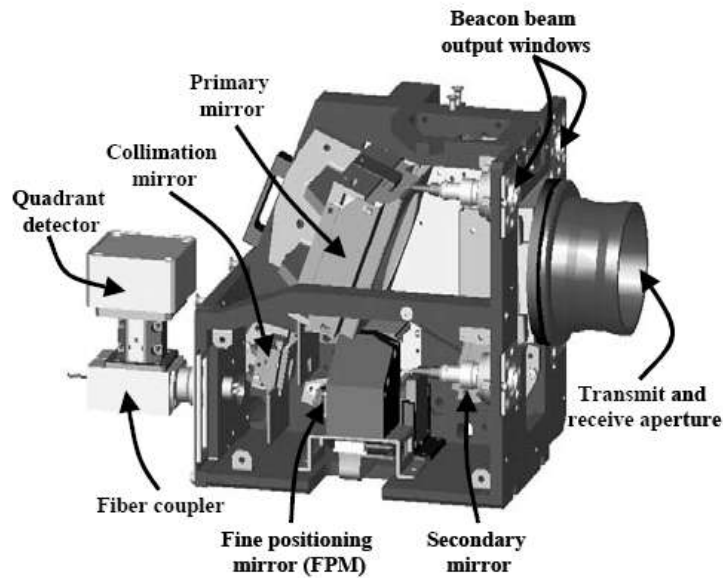
can be gained by an EDFA. The resulting will be high-powered optical signal can be efficiently transferred from the fiber termination to the atmosphere.

In completely photonic-based wireless communication systems, it is not required from the system to convert the signal from electrical to optical format for transmitting or receiving through the atmosphere. This is different from optical wireless communication systems. Also, it greatly enhances the photonic-based system's efficiency. Also, reconfiguring the transmitters or receivers is not necessary while bandwidth and protocol transparent communication links are realized even when the characteristics of the transmitted signal changes due to signal format changes from analog or digital, or varying bit-rate.

The above-mentioned advantages of full-optical wireless communication systems make them strong applicants for deployment as access technologies in the promised new generation networks (NGN). The major goal of the NGN is to offer a platform to make easy convergence of broadcasting and telecommunication infrastructure as well as combination of fixed and wireless networks. The photonic based antenna is considered to play an important role as an access technology able to deliver services regardless of the data rate or formats.

To meet the requirements of photonic based wireless communication link, a compact, light-weight antenna with superior beam tracking and acquisition capabilities is necessary. Most optical wireless communication links are considered to carry the generated millimeter-wave signals, which transport as much power as possible to the end point, of the beam which is usually narrow. The narrow transmission beam makes alignment of optical wireless communication terminals difficult compared to the wider

beam of the RF systems. This is a challenge for the optical wireless communications technology. However, the investigated beam that is based on propagation antenna has been specially designed to deal with this challenge. The structure of a photonic based wireless communication antenna is shown in Fig. 2.19.



**Fig. 2.19 Beam Propagation based wireless communication antenna**

The antenna uses a 1550 nm wavelength beam for data communication offering full-duplex (simultaneous bi-directional) 2.5 up to 10 Gb/s of data rates. Also, it uses a 980 nm wavelength for antenna alignment and tracking, which is automatically done. From the design concept and performance characteristics presented in (Matsomoto, et al. 2008) of the photonic based wireless communication system, it is considered to be a qualified alternative access technology for optical wireless communications in the promised new generation networks.

## [ CHAPTER 3 ]

### **3. FIBER AND FREE SPACE LINK CHARACTERISTICS FOR MMW TRANSMISSION**

#### **3.1 Millimeter-Wave Signals over Fiber Links**

The use of optical fiber technology in wireless networks leads to great potential for improving the channel capacity and the quality of services without the need of using additional radio spectrum. By employing the technology of Radio-over-Fiber (RoF), the flexibility and mobility of wireless access networks can be emerged with the large channel capacity of optical networks. The Radio-over-Fiber concept refers to the transportation of information over optical fiber by modulating the light with the radio signal, as shown in the previous parts of this research. This technique can be used as the backbone of the wireless access networks (Singh and Alphones 2007).

The ideal medium for long-distance millimeter-wave signal transmission is simply an optical fiber link with ultra-low loss. However, the effects of fiber dispersion types may cause signal problems when a signal fading happens. In order to solve the problem of the chromatic dispersion impact, optical single sideband modulation should be used. A RoF link is transparent to RF signals, this is why RoF links have the ability to be used in many state-of-the-art wireless communication systems.

### 3.1.1 RF Properties of RoF Links

From the aspect of RF signal transmission, an RoF link is a simple transducer and can be described by three characteristics which are; noise figure (NF), transducer power gain (TPG), and spurious-free dynamic range (SFDR).

Transducer power gain (TPG) is simply the ratio of the available power of a generator to power delivered to a load by a transducer. For an intrinsic RoF link, the TPG is described as:

$$g_i = S_{md}^2 r_d^2$$

Where;  $S_{md}^2$  is the slope efficiency of the modulation device (with dimensions of watts per ampere) and  $r_d^2$  is the responsivity of the detection device (with dimensions of amperes per watt). In the above equation, the input resistance of the modulation device has been assumed to equal the link's output load resistance (Cox III, et al. 2006).

In millimeter-wave RoF links with external modulation, the modulator slope efficiency is a derived parameter and can be improved by increasing the output power of the laser and reducing the bias voltage of the modulator (MZM). However, in millimeter-wave RoF links adopting direct-modulation with p-i-n photodiode, the TPG is independent of optical power and is less than or equal to one; positive gain can be achieved if cascade laser is used.

The noise figure NF of an intrinsic RoF link can be defined as degradation of the signal-to-noise ratio (SNR), when  $T_0$  is the input noise. If expressed in decibels, it is given by (Cox III, et al. 2006)

$$NF = 10 \cdot \log \left( \frac{n_{out}}{kT_0 B_N \cdot G_i} \right).$$



Where:  $k$  is Boltzmann's constant,  $T_0 = 290$  K,  $B_N$  is the noise bandwidth of the electronic receiver,  $G_i$  is the intrinsic TPG,  $n_{out} = G_i n_{in} + n_{link}$  is the total output noise, and  $n_{in}$  is the link input thermal noise. The link noise  $n_{link}$  includes thermal noise from the modulation device and photo-detection circuits, relative intensity noise (RIN) generated from the optical source, and shot noise generated from the statistical nature of photo-detection. Typically, these two noise sources control the output noise and their contributions to NF are both inversely relative to the intrinsic gain  $G_i$ . This is because, NF is defined as the ratio between the output noise and the amplified input thermal noise. Thus, reducing the intrinsic gain  $G_i$  can increase the NF.

In addition to the above, an intrinsic RoF link has nonlinear components and generates nonlinear distortion. Spurious-free dynamic range (SFDR) is a parameter characterizing the link nonlinearity and is defined as the output SNR when the power of the inter-modulation products equals the power of the link output noise. Also, the dynamic range can be quantified as the tow-tone SFDR. Because the third intermodulation frequencies  $2f_1 - f_2$  and  $2f_2 - f_1$  may appear within the system bandwidth, the most important SFDR is the third order. The SFDR can be improved by linearization techniques, such as pre-distortion in a direct modulation link or concatenation of modulators in external links (Fernando and Sesay 2005).

### **3.1.2 The Design of RoF Links**

Many factors are involved in the design of a fiber-wireless system. Signal-to-noise ratio is considered one of the most important factors. In the technology of radio over fiber, two signal-to-noise ratios (SNRs) need to be considered; the optical SNR (OSNR), and the electrical SNR, which represent the collective SNR in the concatenated fiber and

wireless channels. As mentioned, if other factors such as multipath spreading effect can be ignored, the quality of the data transmission mainly depends on the SNR at the RF terminal. This SNR depends on the OSNR, the optical receiver amplifier gain, and the wireless channel loss. The relationship is given as follows (Anpalagan and Fernando 2004)

$$SNR = OSNR \left[ \frac{1}{1 + \left(\frac{L_{wl}}{G_{op}}\right)^2} \right],$$

Where:  $L_{wl}$  is the wireless channel loss, and  $G_{op}$  is the optical receiver amplifier gain.

Therefore, the optical gain and the OSNR need to be carefully designed when the minimum SNR at an RF terminal to achieve certain transmission quality and the maximum wireless channel loss for certain connection distance are given. Indeed, the well designed optical gain, limits the OSNR.

In the fiber links, the OSNR is playing main rule in the modulation index, the connectors, electrical to optical, optical to electrical conversion losses, and the optical noise. The millimeter-wave power is limited by the nonlinear distortion due to the optoelectronic modulator. Because of impedance mismatch between the RF system and the laser diode at the E/O converter, the photodiode and the RF output at the O/E converter, the E/O and O/E conversion loss can be as high as 40 dB. Even though the bandwidth could be reduced, reactive matching techniques may decrease these serious losses (Xiao, Zhou and Zhang, Millimeter-Wave Technology in Wireless PAN, LAN, and MAN 2008).

### 3.1.3 Effects of Fiber Links on Optical Signals

Dispersion in an optical fiber is a phenomenon that occurs when the propagation velocities of the wave components, such as mode and frequencies, are different. As they support only the fundamental mode, single mode fibers are not affected by the relatively large intermodal dispersion found in multimode fibers. The main dispersion in single mode fibers is chromatic dispersion (CD) due to the slightly different propagation group velocities at different optical frequencies. Another type of dispersion is polarized mode dispersion (PMD) which occurs due to the non-ideal symmetry of fiber in which the orthogonally polarized components of the fundamental fiber mode have different mode indices. CD and PMD may affect the shape of the transmitted millimeter-wave signal along a single mode fiber (Xiao, Zhou and Zhang, Millimeter-Wave Technology in Wireless PAN, LAN, and MAN 2008).

### 3.1.4 The Effect of Chromatic Dispersion

From the closer point of view, chromatic dispersion can be defined as the wavelength pulse spreading that happens as the optical signal propagates along the fiber. There are two contributing factors to chromatic dispersion. The first one is the material dispersion which occurs as a result of the dependency of the fiber material's refractive index on the wavelength. The second factor is the waveguide dispersion, which is a result of the dependence of the propagation constant on the wavelength. The end result of CD is that different spectral components arrive at slightly different times. The pulse spreading due to chromatic dispersion is then given by

$$\Delta t_{chrom} = D(\lambda) \cdot \Delta\lambda \cdot L$$

Where:  $D(\lambda)$  is the dispersion parameter (in ps/nm.km),  $\Delta\lambda$  is the spectral width of the light source, and  $L$  is the length of the fiber. For silica fibers, the dispersion parameter,  $D(\lambda)$  may be approximated by the Sellmeier equation:

$$D(\lambda) = \frac{S_0}{4} \left[ \lambda - \frac{\lambda_0^4}{\lambda^3} \right]$$

Where;  $S_0$  is the zero dispersion slope, and  $\lambda_0$  is the zero dispersion wavelength, which occurs around 1300 nm. Typical dispersion parameter,  $D(\lambda)$  value of silica fiber is -3 ps/nm.km at 1310 nm while it is -17 ps/nm.km at wavelength of 1550 nm.

### 3.2 Free Space Links

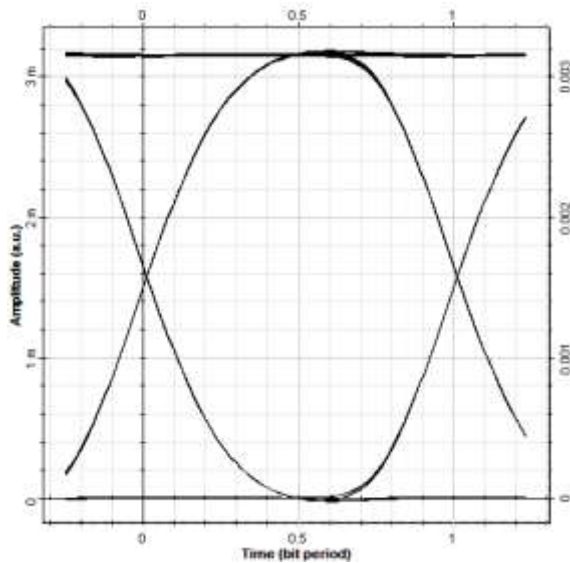
There is a similarity between transmitting light through a fiber and free space; however, there are differences between the effects of fiber glass and atmosphere. Further, similar bandwidth offered and bit rate per second are achievable when fiber glass or free space links are adopted since the same transmitters and receivers are used. However, there is an important difference between transmission through free-space and fiber links. It is the effect of the attenuation of laser power in the fiber compared to wireless links. Fiber optic cables attenuate at known and a constant value. For instance, multimode fiber cables attenuate at 2 to 3 dB/km, and single mode fibers attenuate at 0.5 to 0.2 dB/km. On the other hand, the wireless links' attenuation of light is unstable and difficult to calculate. Atmospheric attenuation varies from 0.2 dB/km in clear weather to 310 dB/km in a very dense fog (Kim, McArthur and Korevaar 2001).

Using a millimeter wave (MMW) along with the FSO transceivers are convenient alternative method to be used in wireless links. MMW systems have a large available spectrum ranging from 30GHz to 300GHz and can easily support high data rates up to

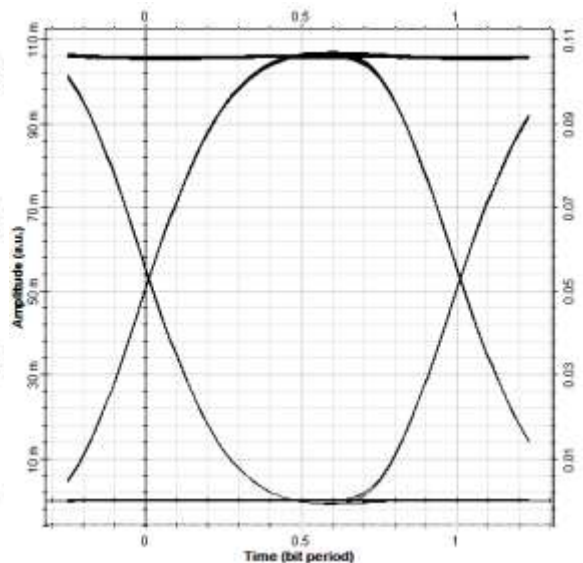
several G bit per second. These systems are ideal for short range point-to-point communications over distances not more than 20Km. Near 94GHz, the power absorption becomes a minimum and MMW systems can reach longer distances (T. Kamalakis 2007). For higher bit rates and longer distances, a specific transmitters and receivers should be employed. These transceivers are presented in details in the last chapter in figures 2.9 and 2.14.

### 3.3 Simulation and Results

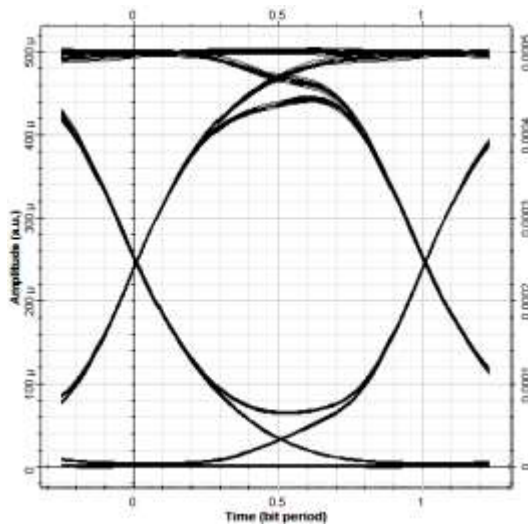
In this part, results of the three simulated techniques of generation are presented in order to give a clear vision of the advantages and disadvantages of each of them and compared to each other. Two ways of transmission (wireless and through fiber) were used on each system with different distances as well. Also fixed bit rate applied for all the cases.



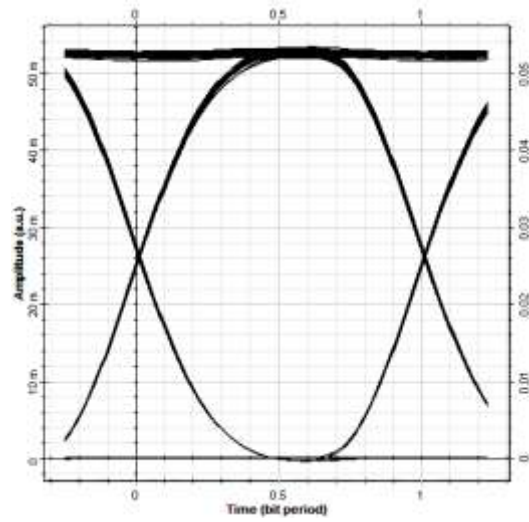
(a) DSB RoF after 10 Km



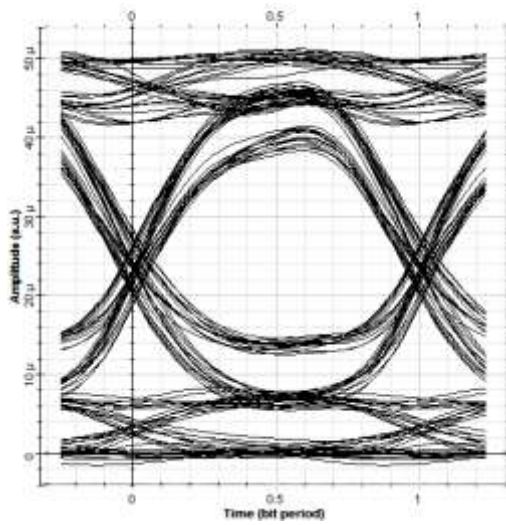
(d) DSB wireless after 200 m



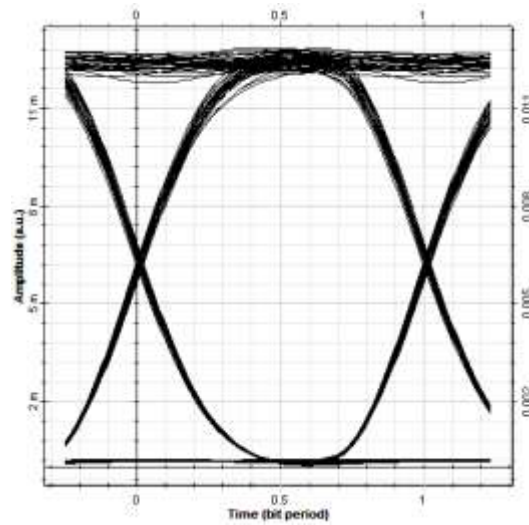
(b) DSB RoF after 50 Km



(e) DSB wireless after 400 m

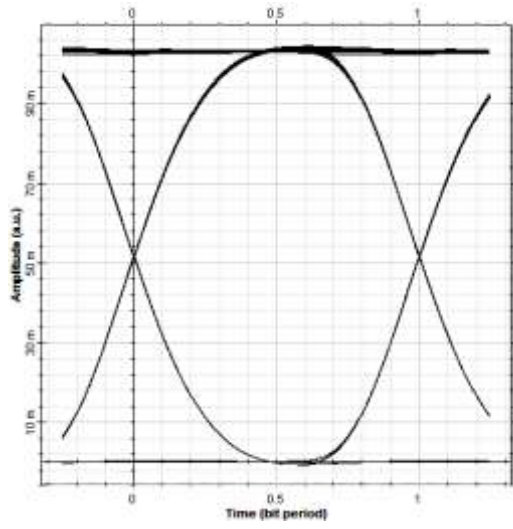


(c) DSB RoF after 100 Km

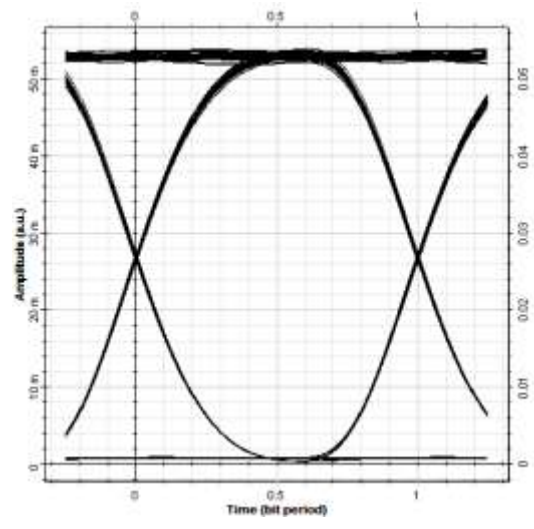


(f) DSB wireless after 600 m

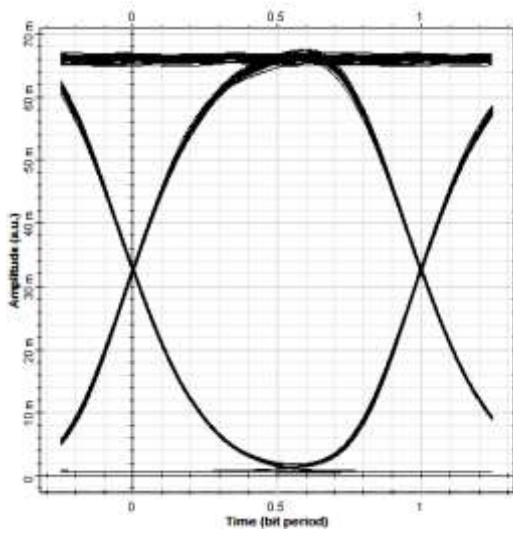
**Fig 3.2. The eye diagram of received signals were Up-converted by DSB technique and transmitted through a fiber and wireless links with bit rate of 2.5 Gb/s**



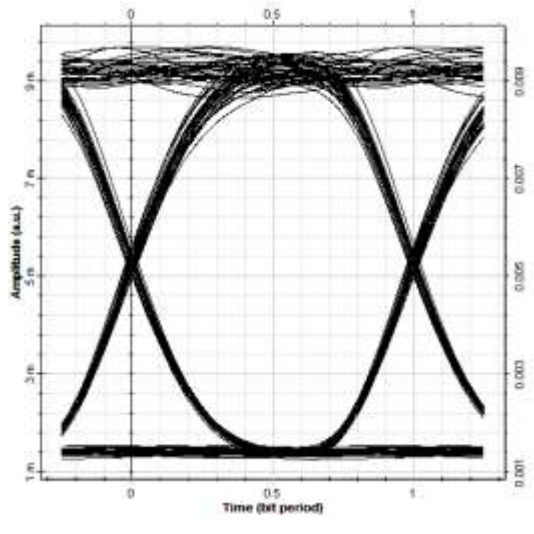
(a) SSB RoF after 10 Km



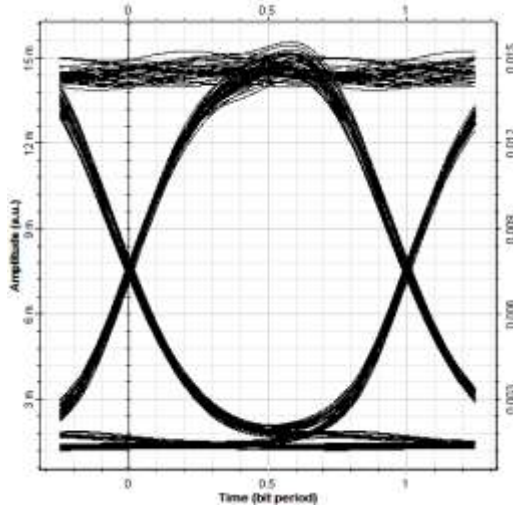
(d) SSB wireless after 200 m



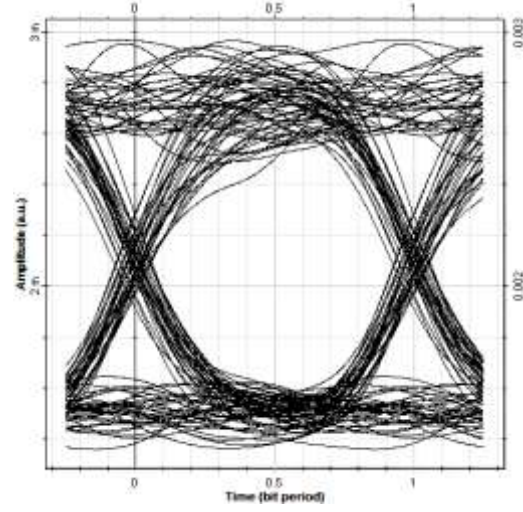
(b) SSB RoF after 50 Km



(e) SSB wireless after 400 m

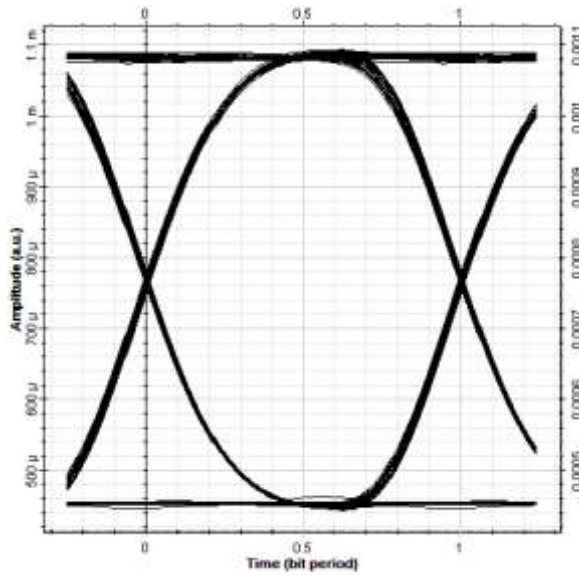


(c) SSB RoF after 100 Km

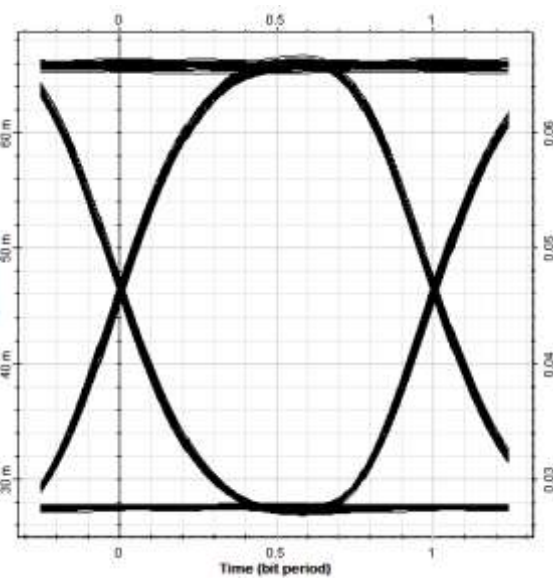


(f) SSB wireless after 600 m

**Fig 3.3. The eye diagram of received signals were Up-converted by SSB technique and transmitted through a fiber and wireless links with bit rate of 2.5 Gb/s**

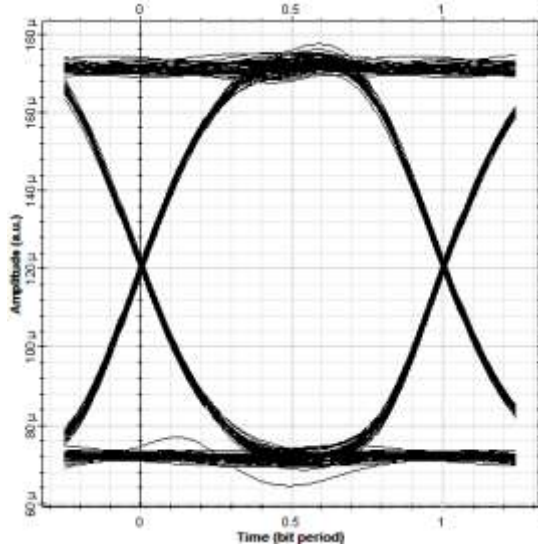


(a) RHD RoF after 10 Km

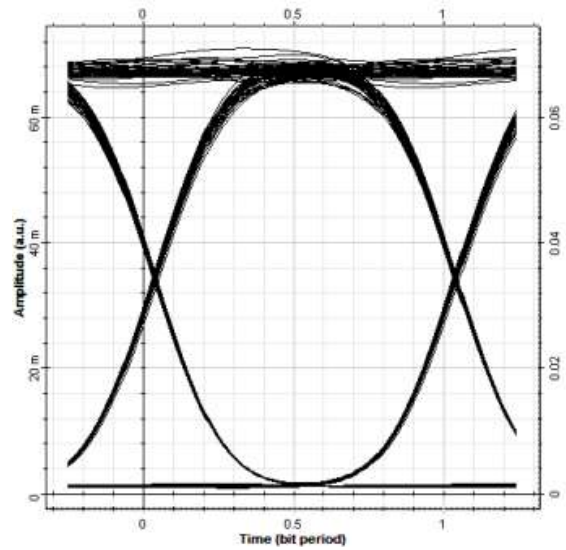


(d) RHD wireless after 200 m

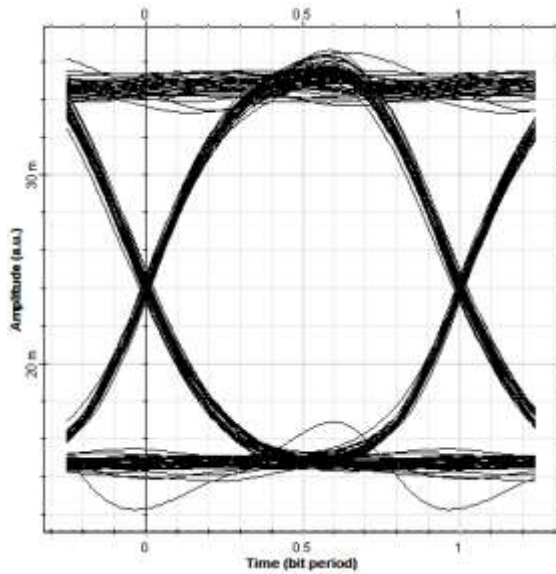




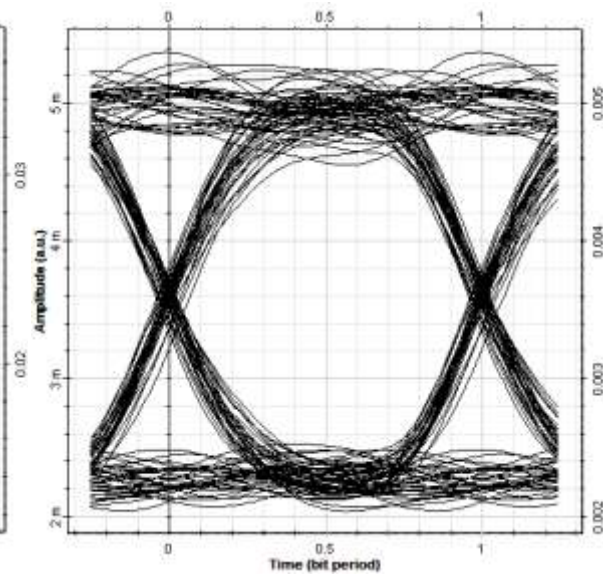
(b) RHD RoF after 50 Km



(e) RHD wireless after 400 m



(c) RHD RoF after 100 Km



(f) RHD wireless after 600 m

**Fig 3.4 The eye diagram of received signals were Up-converted by DSB technique and transmitted through a fiber and wireless links with bit rate of 2.5 Gb/s**

Each system showed different results from the others even though the fiber and atmospheric characteristics are the same. ODSB generation technique has improved that it has negative effect caused by fiber dispersion. On the other hand, ODSB transmitted

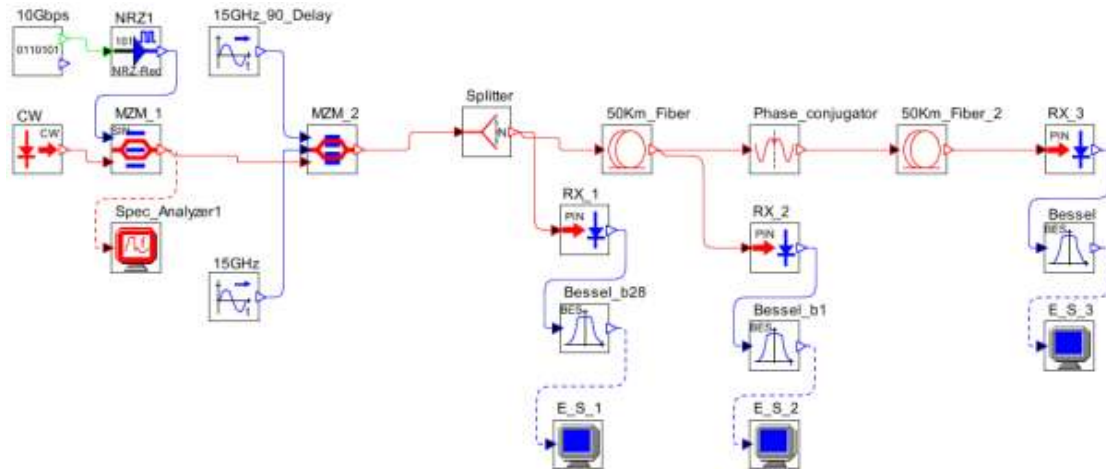
through free space have registered much better results than the other simulated techniques. The generation technique of SSB proved that it is the best way for transmitting MMW signals through fiber links. The generation technique of RHD experienced some problems when the signal transmitted through fiber link of length around 100 km, but it has well enough received signal after wireless link of a distance up to 400 m as same as the results of OSSB.

### **3.4 Dispersion Compensation Using Optical Phase Conjugate**

Optical phase conjugation (OPC), sometimes called a midspan spectral inversion, is an efficient technology to compensate the effect of chromatic dispersion in long-haul transmission systems. Basically, in order to get the best results of phase conjugate, it should be installed in the middle of fiber link. The idea of phase conjugating is to recover the transmitted signal in the second part of the link after conjugation from dispersion that happened in the first part of the transmission link before conjugation. In this part, long-haul transmission of millimeter-wave signal by using optical phase conjugate will be simulated (Jansen, et al. 2006).

#### **3.4.1 Simulation and Results**

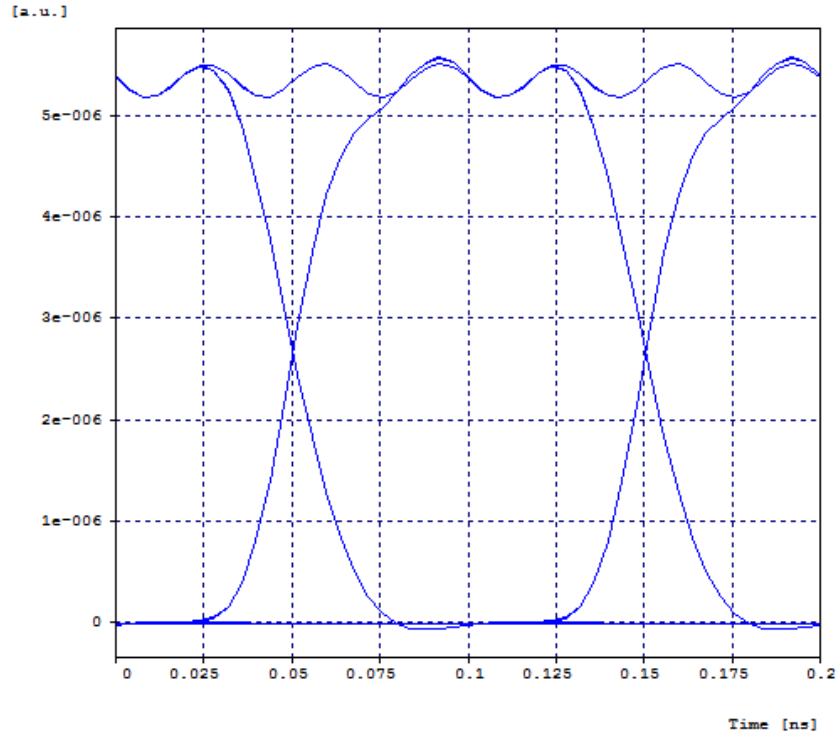
The schematic setup is given in Figure 3.4. The simulation setup consist optically modulated millimeter-wave signal with data rate of 10Gbps, a fiber span consisting of two links, a mid-span phase conjugate, and receiver. Fiber link dispersion is set to (16 ps/nm/km).



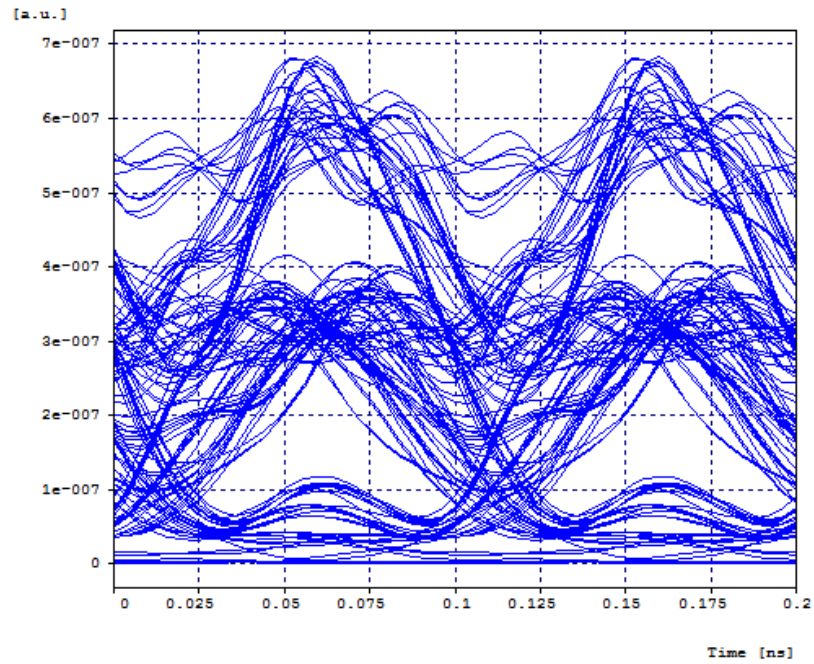
**Fig. 3.4 Schematic setup of dispersion compensation using phase conjugate**

Due to the effect of chromatic dispersion, the eye diagram shows a totally closed eye after 50 km. Then the signal goes through an OPC, and then to another 50 km long fiber link. At the output of the second link the received eye is totally open which means that the signal is recovered from the chromatic dispersion. Figure 3.5 demonstrates eye diagrams of the transmitted signal (a). after transmitter, (b). after first link and OPC, and (c). after the second fiber link.

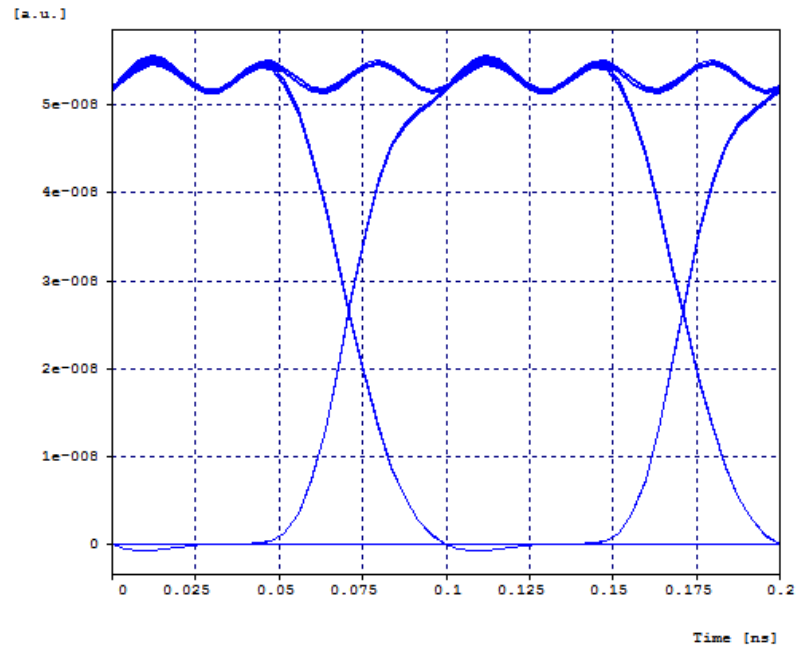
In details, the signal is being affected in the first half of the fiber resulting in distorted pulse shapes with the blue light leading the red light. This dispersed signal is then being phase conjugated. The OPC reverses or inverts the optical spectrum of the signal so that red becomes blue and blue becomes red. The shape of a pulse remains the same, but now the leading edge is red and the trailing edge is blue. Now the dispersion in the second half of the fiber reshapes the pulse so that, if the dispersion before the OPC matches the dispersion after it, then the original pulse shape will be restored at the end of the span.



**Fig.3.5 (a) Eye diagram of the generated signal**



**Fig.3.5 (b) Eye diagram of the signal after 100km of fiber**



**Fig.3.5 (c) Eye diagram of the signal after 100km of fiber and dispersion compensator**

## [ CHAPTER 4 ]

### **4. MULTIPLEXING/DEMULTIPLEXING OF MMW-OVER-FIBER**

In millimeter-wave over-fiber systems, multiple remote antenna base stations BSs are interconnected to a central office (CO) via an optical fiber network. Because of environmental effects that contain the surrounding ultra-high frequencies, the coverage of BSs could be reduced. Consequently, the number of BSs to be installed will increase and the system's cost will increase as well. Therefore, the challenge facing the designers of radio-over-fiber networks is to build simple and cost-effective fiber networks to feed that large number of base stations.

Reducing the required spectral-band for millimeter-wave channel, when optical single sideband modulation is adopted, is required also to increase the spectral efficiency. Furthermore, the effect of chromatic dispersion increased due to using optical single side band, which should be taken in mind while designing radio-over-fiber networks.

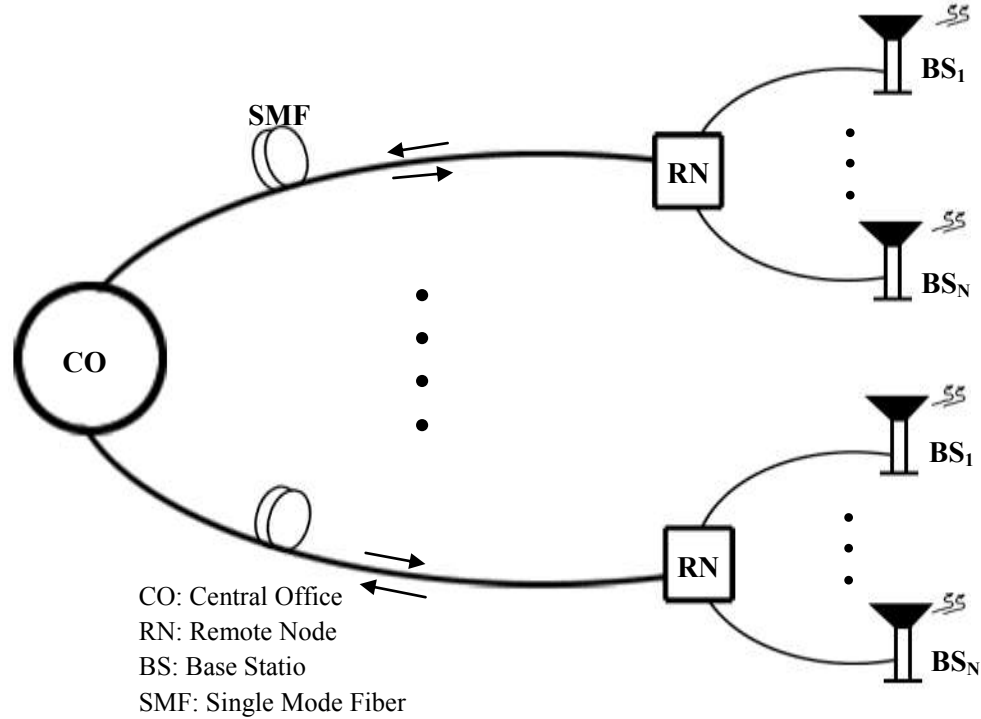
Despite the challenge of carrying as much data as we can through a single fiber to be distributed on many base stations, the technique of single sideband modulation efficiently duplicates the system's capacity of millimeter-wave over the fiber when it is compared with the optical double sideband based systems. On the other hand, employing techniques such as WDM or OFDM in fiber based networks can eliminate the challenge by enabling multiple optically modulated mm-wave signals to be transported through one fiber to feed many antenna base stations.

#### **4.1 Wavelength Division Multiplexed MM-Wave over-Fiber**

As mentioned above, the technique of WDM is an efficient method to increase the capacity of the fiber networks in mm-wave over fiber systems. With the WDM based fiber networks carrying optical mm-wave signals, each signal is carried by a separate wavelength, are transmitted to the base stations via the CO through a single fiber that provides an effective increase in network capacity without the need for installing new fiber. Having low number of laid fibers would result in simple networks to be maintained or upgraded as the number of BSs is increased in addition to the low cost of installing such networks.

As shown in Fig. 4.1 which presents a diagram of WDM based fiber/wireless network, from the aspect of downlink for the optical millimeter-wave, the used channels are spaced with a specific wavelength separation which are generated and multiplexed at the CO by employing WDM multiplexer. After signals were transmitted through the fiber, the remote node (RN) receives them. Millimeter-waves are demultiplexed at the RN and transferred to the base stations to be delivered to users through wireless links. On the other hand, at the side of uplink direction for mm-wave signals which are generated at the users' sites, received signals by antennas of base stations are converted from electrical to optical form and then sent to the RN, where the optically modulated signals are multiplexed before transmitted to the CO through fiber for further processing. Even though there is a large number of BSs in fiber networks incorporating WDM, it is still an effective system as it processes the whole signal at the CO and it uses passive multiplexers and demultiplexers at the RN side. Furthermore, fiber networks with WDM can independently process the transmitted signals. These advantages support the

technology of millimeter-wave fiber/wireless to be the promised one for the future wireless communications (M. Bakaul, et al. 2006).

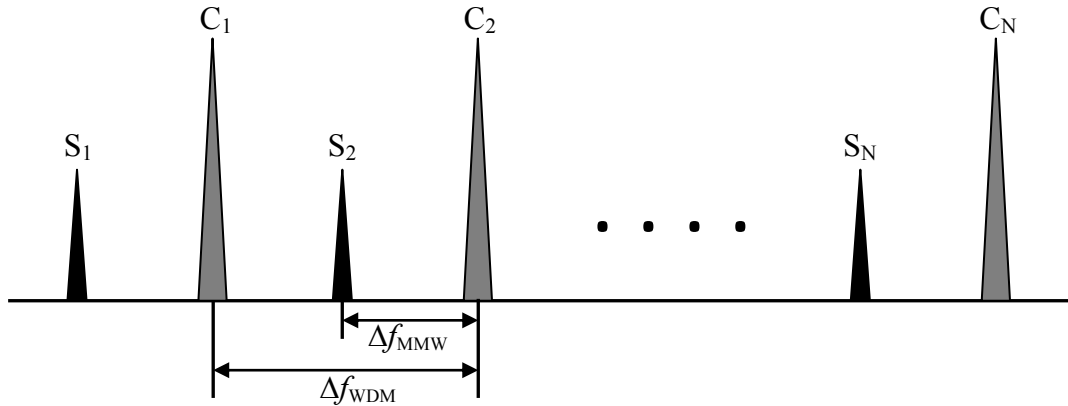


**Fig. 4.1 Schematic diagram of ROF system employing WDM**

With all the effective advantages of the technology of WDM, the channel spacing in the fiber metro network requires more efficient multiplexing technique which is dense-wavelength-division multiplexing (DWDM). Adopting DWDM as a multiplexing technique can increase the channel capacity. As a result of DWDM, a single fiber can transfer many millimeter-wave signals traveling to many base stations without a serious aliasing problems (Toda, Kuri and Kitayama 2005). DWDM usually has a channel spacing of 100GHz, 50 GHz, and 25 GHz depending on the characteristics of the transmitted millimeter-wave signals.



As shown in Fig. 4.2, the optical spectra of  $N$  optically modulated single sideband carrier millimeter-waves and multiplexed by the technique of WDM. These millimeter-wave channels are separated by frequency of  $\Delta f_{\text{WDM}}$  and  $\Delta f_{\text{mmw}}$  respectively, where  $\Delta f_{\text{mmw}} < \Delta f_{\text{WDM}}$ . As above-mentioned, in order to apply DWDM fiber based networks for millimeter-wave, it is necessary to reduce  $\Delta f_{\text{WDM}} < \Delta f_{\text{mmw}}$ . To meet the requirement of the DWDM by reducing the channel separations smaller than millimeter-wave carrier frequencies, the data bandwidth capacity of the millimeter-wave carriers have been considered (M. Bakaul, et al. 2006).



**Fig. 4.2 Optical spectra of  $N$  optical MMW channels in a WDM system**

As the bandwidth used for millimeter-wave carriers usually has unused spectra as shown in Fig. 4.2 between  $S_N$  and  $C_N$ , wavelength interleaving technique has been used to increase the number of millimeter-wave signals to be transmitted using the same bandwidth.

#### 4.1.1 Wavelength Interleaved WDM of MM-Wave Over-Fiber

In millimeter-wave over-fiber systems, as explained in chapter 2, the inter-channel spacing are generated when the RF signals are imposed on to the optical carrier and sidebands are generated with spacing equal to the drive frequency. Channel spacing to rise and restricts the effective WDM channel separation  $\geq 100$  GHz. The properties of an mm-wave over-fiber system incorporating a WDM channel separation of less than 100 GHz shows that the channel spacing is strongly dependent on the edge steepness quality of the WDM demultiplexing filter. There are studies prove that an effective reduction of WDM channel separation lower than the transmitted mm-wave frequency can be achieved when a very low side lobes by demultiplexing filter is accomplished. This channel separation reduction results in an overlap of the nearby sidebands of channels and consequently leading to a large increase in channels number that can be carried on a single fiber. The accomplishment of eliminating the channel spacing in millimeter-wave over-fiber systems introduces the techniques of DWDM compatible wavelength interleaving (WI-DWDM).

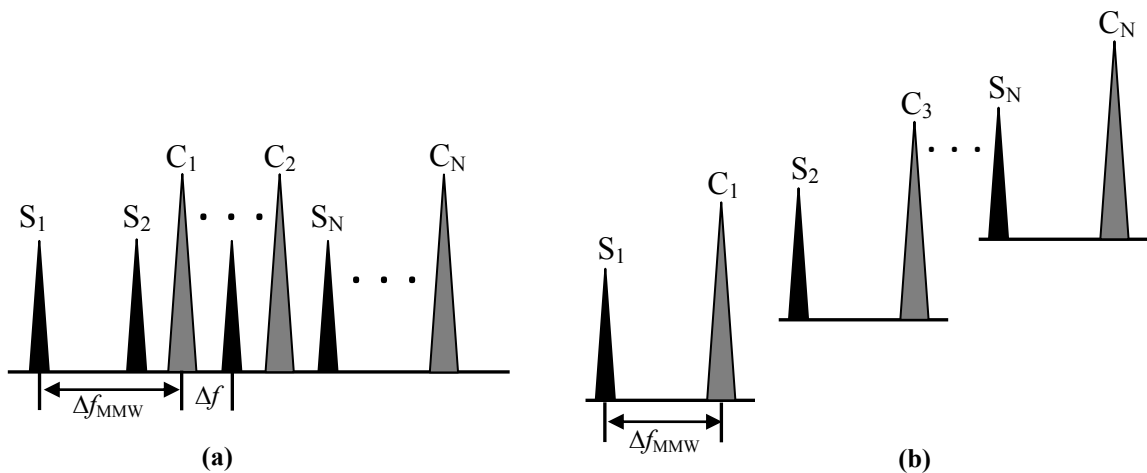


Fig. 4.3 Optical Spectra of MMW (a) Multiplexed (b) Demultiplexed channels in DWDM

Incorporating this technique gives the capability to transmit channels with as low as 25GHz channel spacing. As shown in Fig. 4.3 the optically modulated single sideband with carrier channels and channel separation less than the drive frequency of  $2\Delta f$  and  $3\Delta f$ , respectively are multiplexed using DWDM-CWI.

As a result, the free spectral-bands available between the optical carriers and the modulated sidebands of the optical millimeter-wave channels are taken by the neighboring DWDM channels. The optical carriers  $C_1, C_2, \dots, C_N$  and their sidebands  $S_1, S_2, \dots, S_N$  in OSSB+C modulation format are interleaved in such a way that the channel spacing, regardless of carrier or sideband, becomes  $\Delta f$ . The right selection of the channel spacing enables the DWDM system to interleave many optical millimeter-wave channels, generated by different millimeter-wave ways of generation in different frequency bands (M. Bakaul, et al. 2005).

#### **4.1.2 The Characteristics of Investigated Wavelength-Interleave Multiplexer**

In this section, the performance of the WI-MUX is theoretically investigated. The investigated WI-MUX consists of a  $(2N+2) \times (2N+2)$  AWG with a channel bandwidth,  $\leq \Delta f$  and a channel spacing,  $\Delta f$ , equal to the adjacent channel spacing of the desired WI scheme. Therefore, the performance of the WI-MUX is largely dependent on proper selection of suitable AWG in order to get a result as in Fig.4.3.

Furthermore, to get the best results of multiplexing, it is important to reduce the carrier to side ratio (CSR) for each millimeter-wave signal. To approach this control of CSR without additional hardware, some optical loop-backs are required. Fig 4.4 shows a

schematic diagram for the investigated WI-DWDM that reduces CSR of the interleaved millimeter-wave signals (M. Bakaul, et al. 2006).

For many years, Arrayed Waveguide Gratings have become progressively more useful as tool of wavelength multiplexers and demultiplexers MUX/DEMUX for DWDM networks. They have demonstrated to show capability of MUX/DEMUX a large number of channels efficiently with low losses. Basically, AWG consists of two slab waveguide star couplers which are directly connected by a dispersive waveguide array. Through the first star coupler, light will be coupled into the array. The array has been designed with an assumption that an integer multiple of the space between the multiplexed channels should be equal to the space between the array arms of the AWG (Amersfoort 1998).

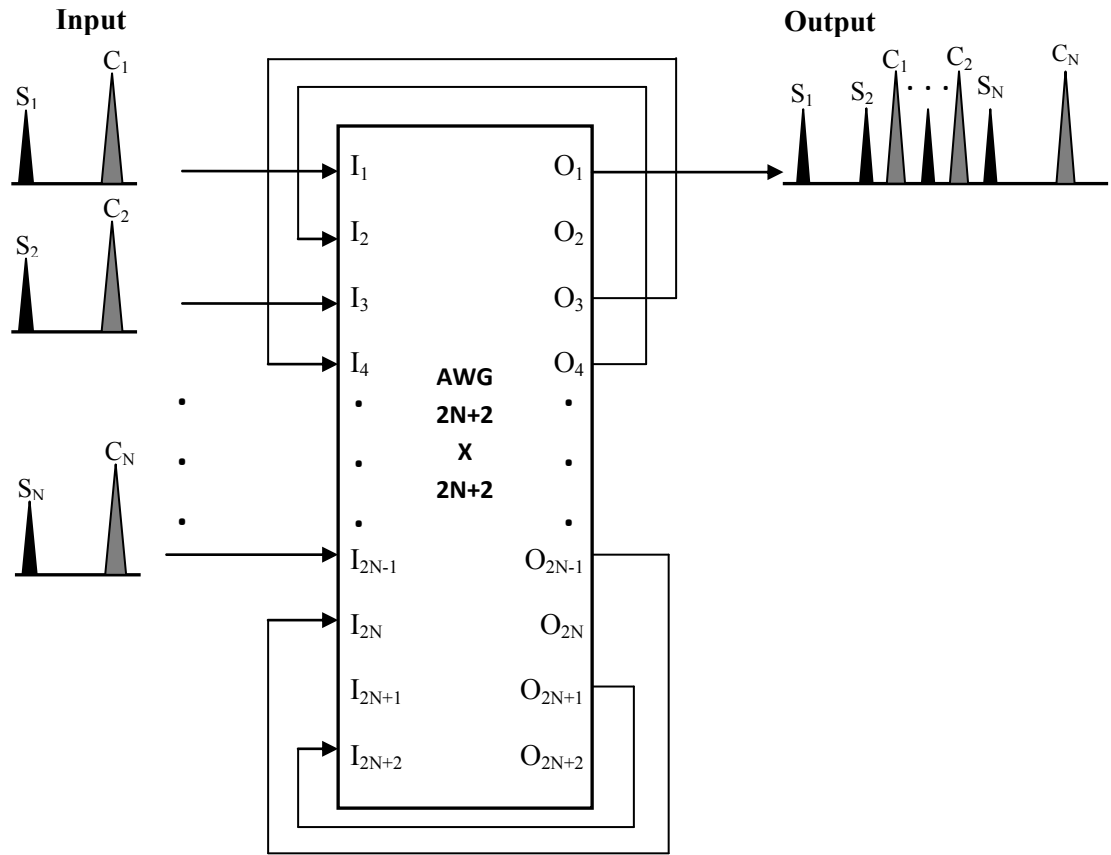


Fig. 4.4 WI-MUX for optical millimeter-wave signals in a DWDM system

Moreover, AWG can be compatible with many components either active or passive to build more complicated network systems such as optical cross connect, optical add-drop multiplexer (OADM), DWDM channel monitor, dynamic gain equalizer, etc.. AWG has a property of being cyclic or periodic which give it the capability to deal with multiple periodic frequencies and pass them through the same route with a separation between them called free spectral range (FSR). In other definition for the FSR, it is the number of AWG inputs or outputs multiplied by the frequency separation between them. For instance, an AWG has characteristics of 8 x 8 inputs and frequency separation of  $\Delta f = 25$  GHz. The FSR is equal to  $8 \times 25 = 200$  GHz (M. Bakaul, et al. 2006). Table 4.1 shows all possible inputs/outputs matrix of  $(2N+2) \times (2N+2)$  of an AWG.

		AWG Outputs										
		O <sub>1</sub>	O <sub>2</sub>	O <sub>3</sub>	...	O <sub>N-1</sub>	O <sub>N</sub>	O <sub>N+1</sub>	...	O <sub>2N</sub>	O <sub>2N+1</sub>	O <sub>2N+2</sub>
AWG Inputs	I <sub>1</sub>	$\lambda_1$	$\lambda_2$	$\lambda_3$		$\lambda_{N-1}$	$\lambda_N$	$\lambda_{N+1}$		$\lambda_{2N}$	$\lambda_{2N+1}$	$\lambda_{2N+2}$
	I <sub>2</sub>	$\lambda_2$	$\lambda_3$	$\lambda_4$		$\lambda_N$	$\lambda_{N+1}$	$\lambda_{N+2}$		$\lambda_{2N+1}$	$\lambda_{2N+2}$	$\lambda_1$
	I <sub>3</sub>	$\lambda_3$	$\lambda_4$	$\lambda_5$		$\lambda_{N+1}$	$\lambda_{N+2}$	$\lambda_{N+3}$		$\lambda_{2N+2}$	$\lambda_1$	$\lambda_2$
	⋮											
	I <sub>N-1</sub>	$\lambda$	$\lambda_N$	$\lambda_{2N+1}$		$\lambda_{2N-3}$	$\lambda_{2N-2}$	$\lambda_{2N-1}$		$\lambda_{N-4}$	$\lambda_{N-3}$	$\lambda_{N-2}$
	I <sub>N</sub>	$\lambda$	$\lambda_{N+1}$	$\lambda_{2N+2}$		$\lambda_{2N-2}$	$\lambda_{2N-1}$	$\lambda_{2N}$		$\lambda_{N-3}$	$\lambda_{N-2}$	$\lambda_{N-1}$
	I <sub>N+1</sub>	$\lambda$	$\lambda_{N+2}$	$\lambda_{2N+3}$		$\lambda_{2N-1}$	$\lambda_{2N}$	$\lambda_{2N+1}$		$\lambda_{N-2}$	$\lambda_{N-1}$	$\lambda_N$
	⋮											
	I <sub>2N</sub>	$\lambda_{2N}$	$\lambda_{2N+1}$	$\lambda_{2N+2}$		$\lambda_{N-4}$	$\lambda_{N-3}$	$\lambda_{N-2}$		$\lambda_{2N-3}$	$\lambda_{2N-2}$	$\lambda_{2N-1}$
	I <sub>2N+1</sub>	$\lambda_{2N+1}$	$\lambda_{2N+2}$	$\lambda_1$		$\lambda_{N-3}$	$\lambda_{N-2}$	$\lambda_{N-1}$		$\lambda_{2N-2}$	$\lambda_{2N-1}$	$\lambda_{2N}$
	I <sub>2N+2</sub>	$\lambda_{2N+2}$	$\lambda_1$	$\lambda_2$		$\lambda_{N-2}$	$\lambda_{N-1}$	$\lambda_N$		$\lambda_{2N-1}$	$\lambda_{2N}$	$\lambda_{2N+1}$

**Table 4.1 Inputs/Outputs matrix of AWG**

In addition to the FSR, many other features can affect the capabilities of an AWG such as: insertion loss, optical crosstalk, pass-band shape.

#### **i. Insertion Loss**

The main cause for insertion loss in the AWG is the inefficient coupling at the input or output edges between the free propagation regions (FPRs) and the arrayed waveguides

(AWs). As smaller separations of the arrayed waveguides increase the coupling efficiency, insertion loss is largely determined by the separation of the arrayed waveguides at these edges. Therefore, smaller separation coupling between the arrayed waveguides is important to recognize. Not only coupling is the reason for insertion loss, but also there are other reasons such as the material loss, scattering due to fabrication errors, and waveguide roughness that is defocusing of the spot on the output plane due to phase errors.

### **ii. Passband Shape**

Preferably, the passband shape of an AWG for a WDM channel should have a flat top with no more than a 1 dB deviation, and over 70% of the channel separation. A sharp passband results in a very little error in laser frequency and AWG wavelength tolerance. In most situations it is required that the passband is flattened so that the device produces a similar output for small changes in laser wavelength. The technique is to modify the intensity side view at the object focal plane to give the object spot a flat top with steep sides. When the wavelength is changed slightly, the overlap integral between the signals and the mode of output waveguide is not significantly changed, and this produces a flat top for the passband (Suzuki 1997).

### **iii. Optical Crosstalk**

In an AWG, many reasons for the phenomena of crosstalk are possible. Optical crosstalk can occur by the overlap of the concentrated spot in the output with the neighboring output waveguides. The issue of inter-channel crosstalk increases by increasing the beam spot size which is a result of an anomaly design and fabrication of the arrayed waveguides. In addition, the crosstalk is also result of complex multimodal

light propagation effects in the arrayed waveguides that negatively affects the signal components (phase and amplitude) propagations at the output of the arrayed waveguides. In order to accomplish a crosstalk free AWG, the sources of inter-channel crosstalk need to be controlled and managed. The controlling of inter-channel crosstalk of the AWG through fabrication process is not very simple, and often lead to a tradeoff between the crosstalk and the other desirable characteristics.

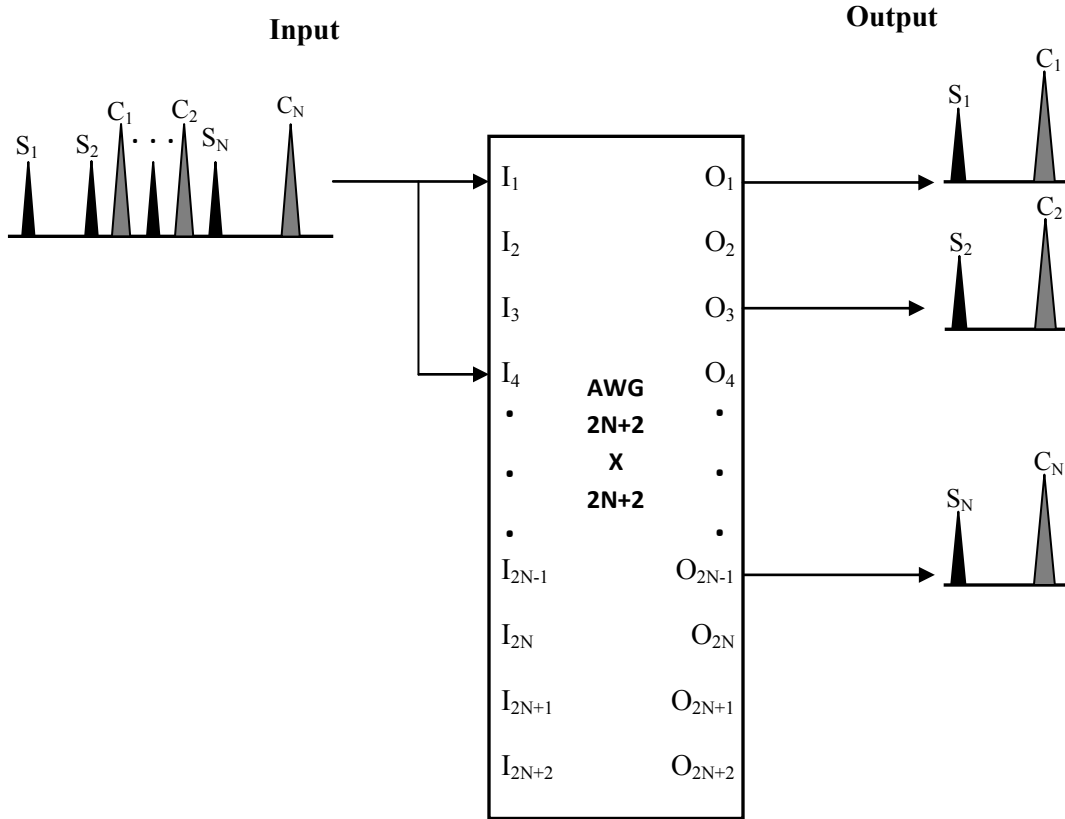
#### **4.1.3 Wavelength Interleaved Demultiplexing of WI-DWDM Signals**

In the past, many demultiplexing techniques based on modified AWGs were proposed; however, they are still complicated because they depend on wavelength-selective pre- and post- processing techniques. However, the investigated WI-DEMUX in this paper has eliminated that processes of wavelength-selective pre- and post-, and that what make it simpler than others.

Fig 4.5 shows the investigated WI-DEMUX and its inputs/outputs. This WI-DEMUX has characteristics of  $(2N+2) \times (2N+2)$ , channel spacing of  $\Delta f$  which is equal to that channel spacing of DWDM, and channel bandwidth less than  $\Delta f$ . Table 3.1 shows in this case too, the real behavior of the arrayed waveguide allocating the inputs/outputs when it is used as demultiplexer (M. Bakaul, et al. 2006).

As mentioned before, the channel spacing  $\Delta f$  is less than the millimeter-wave signal  $(N \cdot \Delta f)$ . Where;  $N$  is the number of interleaved signals. Therefore, the optical single sideband signal with carrier has a frequency of  $(N \cdot \Delta f)$ . For demultiplexing and before entering the AWG, the WI-DWDM signals are distributed on the inputs numbers 1 and  $(N+1)$  by a 3dB coupler. These inputs are specified based on the above information of the

channel separation and the millimeter-wave frequency adopted in the WI-DWDM signals.



**Fig. 4.5 WI-DEMUX for optical millimeter-wave signals in a DWDM system**

For instance, if DWDM system is transmitting 3 OSSB millimeter-wave signals in one channel, with channel spacing equal to  $1/3$  of the millimeter-wave signals' frequency. Thus,  $N = 1$ , and the WI-DWDM signals should be distributed to the inputs 1 and 4. From table 4.1, AWG's input number 1 will allow the signals sides to be at the odd numbered outputs 1, 2, and 3 respectively. Moreover, the input number 4 will enable the optical carriers to be distributed to the same odd numbered outputs 1, 2, and 3. Filtering the output signals of the ports 1, 2, and 3, the demultiplexing process will be successfully done.



## 4.2 Simulation and Results for WDM

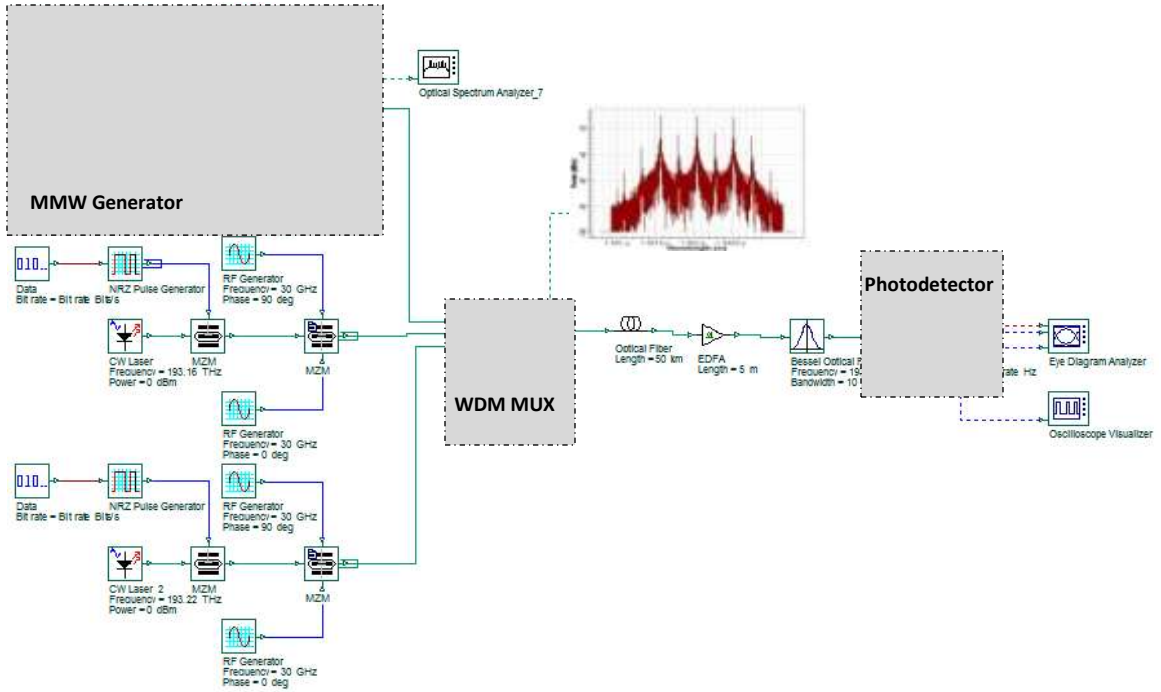
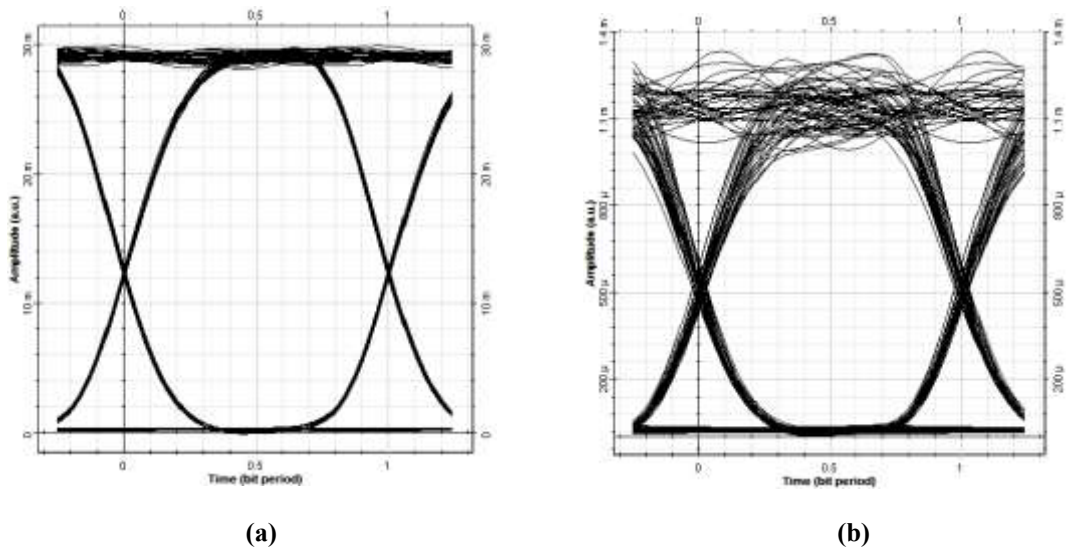


Fig. 4.6 WDM system uses OSSB technique for MMW generation

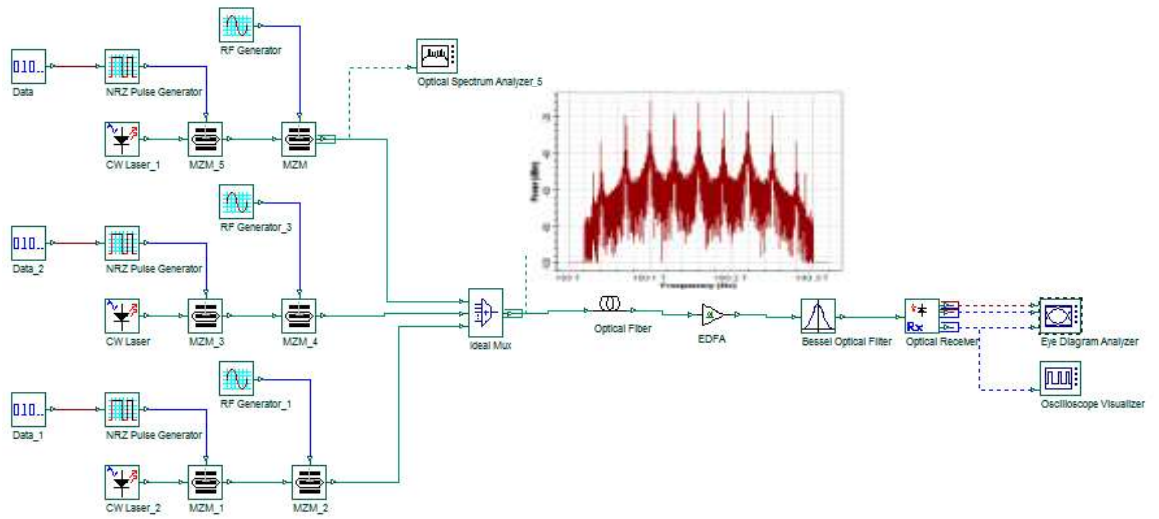


(a)

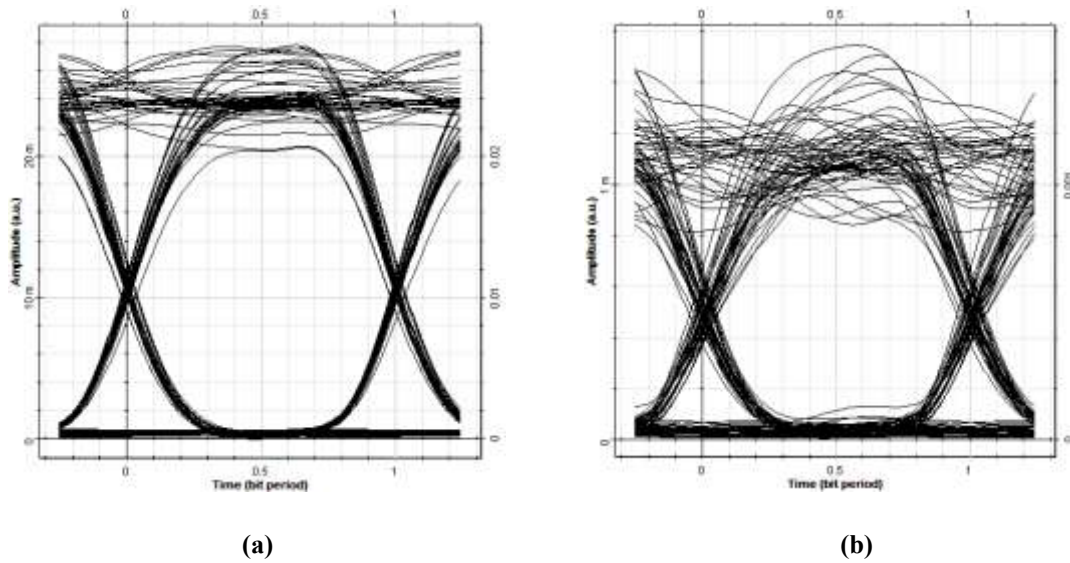
(b)

Fig. 4.7 Eye diagrams of MUX/DEMUX SSB signals after

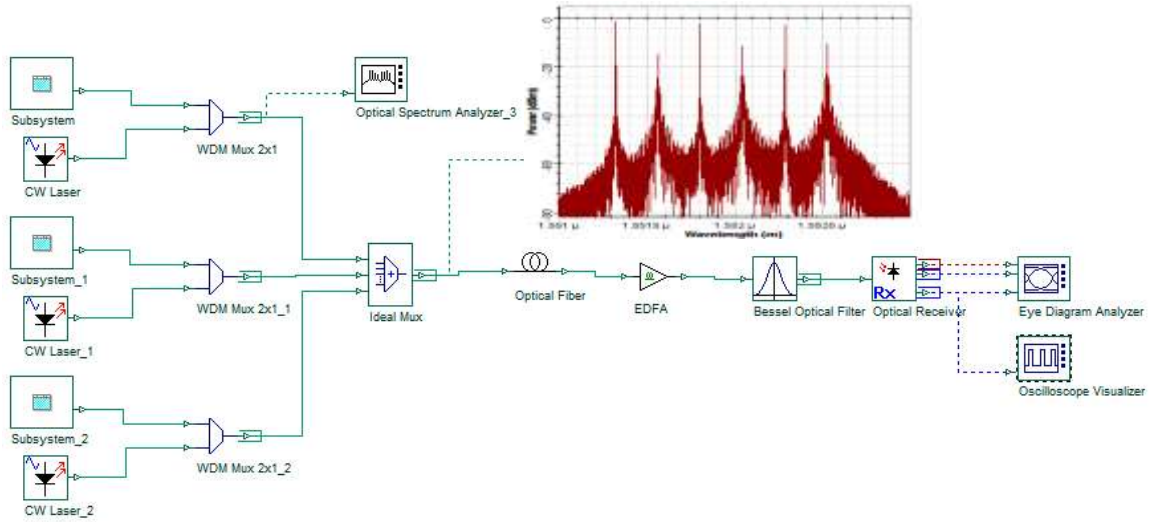
(a) 50 km of fiber link and (b) 600 m of FSO link



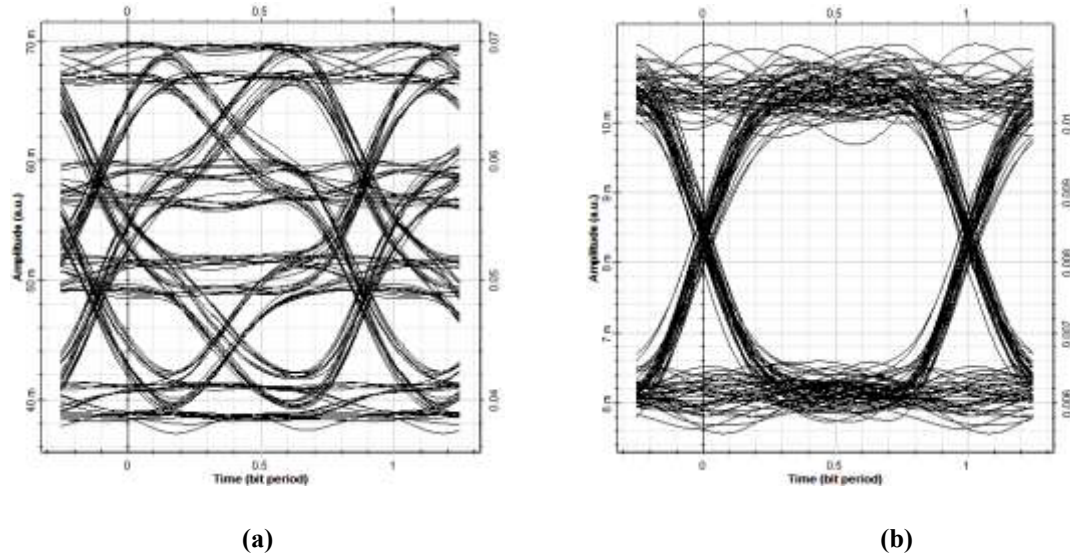
**Fig. 4.8 WDM system uses ODSB technique for MMW generation**



**Fig. 4.9 Eye diagrams of MUX/DEMUX DSB signals after  
(a) 50 km of fiber link and (b) 600 m of FSO link**



**Fig. 4.10 WDM system uses RHD technique for MMW generation**



**Fig. 4.11 Eye diagrams of MUX/DEMUX RHD signals after**

**(a) 50 km of fiber link and (b) 600 m of FSO link**

The WDM systems showed above in figures 4.7, 4.8, and 4.10, representing multiplexing techniques for OSSB, ODSB, and RHD techniques of generation. In order to make a comparison between there techniques of generation in the aspect of multiplexing, the applied frequencies, attenuation of the free space channel, dispersion of

the fiber link, distance between transmitters and receivers, and bit rates are the same in all the systems.

From the results shown above we can demonstrate that the WDM depends not only on the efficiency of used multiplexer and channel of transmission, but also on the used technique of MMW generation. For instance, eye diagrams shown in fig. 4.7, show that the technique of OSSB generation is perfect for transmitting its signals through fiber links after multiplexing. However, this signal saturated when it was transmitted through free space. Even though OSSB MMW is saturated, it still has the best results when it compared to the other two techniques of photonic millimeter-wave generation as shown in the eye diagrams in figures 4.9 and 4.11.

## [ CHAPTER 5 ]

### 5. Conclusion and Future Work

#### 5.1 Conclusion

This thesis concerns of many photonic based techniques for millimeter-wave signals. As fiber/wireless access networks for the bands of millimeter-waves has an efficient features to offer wide bandwidth and higher bit rates, many techniques related to this area are investigated. Aspects of millimeter-wave technology have been studied such as generation or up-conversion, transceivers, multiplexing, and transmission links. Besides the theoretical study of each aspect, simulations and results have been presented in this thesis. Three ways of optical millimeter-wave signals were simulated and compared to each other depending on the link type and distance. Each way of generation showed its advantages and disadvantages different from the other two ways. That means, choosing a specific way of optical millimeter-wave generation for any application, should not be done before testing the strengths and weaknesses of each one in the environment of that application.

Moreover, a huge number of users are expected to use a system offering wide bandwidth. This is where techniques of WDM become important to efficiently exchange data between those users. In addition, the technique of wavelength interleaved WI-DWDM based on AWG is a promising technology to build costly effective and highly efficient fiber networks. The investigated WI-DWDM technique has the advantage of

reducing the bandwidth required from each single fiber. For more testing to the discussed techniques of MMW generation, they were applied to a WDM system and then transmitted through fiber and wireless links. As a result, the technique of OSSB offered competitive results when it compare to ODSB and RHD technologies.

## **5.2 Future Work**

Orthogonal frequency division multiplexing (OFDM) is adopted extensively in broadband wireless and wired communication systems because it is an efficient solution to intersymbol interference (ISI) caused by multipath delay spread (Jansen, Morita and Tanaka 2007). OFDM is designed to transmit many carriers at the same time. This makes OFDM is the promising technique for radio-over-fiber signals transmission as data rates increase as explained in chapter 1. This is quite similar to frequency division multiplexing (FDM) or wavelength division multiplexing (DWM) with the exception of the requirement of orthogonality between the sub-carriers. Moreover, as phase variation with frequency can be maintained at inexpensive costs in the digital domain of the system, OFDM makes it uncomplicated for the transmitters and receivers as it transfers the signals from analog to digital domain (Chuang, et al. 2008, Perahia and Stacey 2008).

An extensive work is required to make some developments to this technology in order to employ it in optical fiber/wireless communications. OFDM can eliminate the effect of chromatic dispersion at the fiber links. The integration of OFDM and ROF technologies is naturally appropriate for optical and wireless systems to extend the distance of transmission over both wireless and fiber links. Even though these important advantages and applications of OFDM already exist, it just has been considered for photonic based communication networks.

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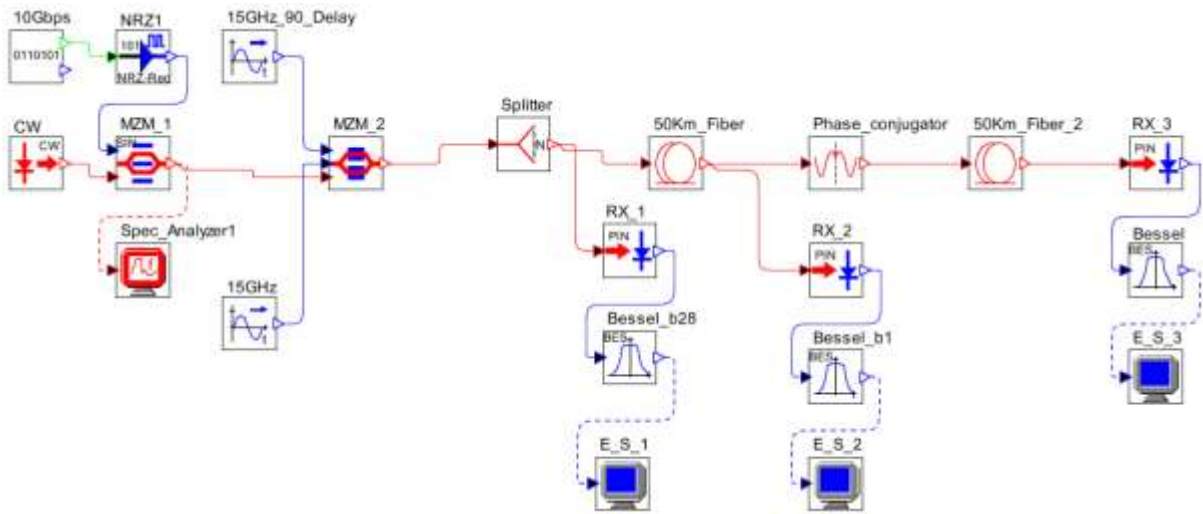
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# Appendix A

## Main Items Properties of Dispersion Compensation Simulation



Parameter	Value	Units	Range
Center emission frequency	193.41449	THz	[ 193.28949, 193.539...
Center emission wavelength	1550.00000026	nm	[ 1548.99891, 1551.0...
Source Status	1		[ 0, 1 ]
CW Power	0.0	dBm	[ -3000, 3000 ]
CW Power	1.0	mW	( 0, Inf )
FWHM Linewidth	10.0	MHz	[ 0, Inf )
-20 dBm Linewidth	99.4987437107	MHz	[ 0, Inf )
Initial Phase	"Deterministic"		
Deterministic Initial Phase	0.0	rad	[ 0, 6.28319 ]
Noise Type	"Ideal"		
Relaxation Oscillation peak Frequency	5.0	MHz	( 0, Inf )
Relaxation Oscillation Peak Overshoot	7.0	dB	( 0, Inf )

Parameter	Value	Units	Range
Excess loss	3.0	dB	[ 0, Inf )
Maximum Transmissivity Offset voltage: Von	2.5	V	
Extinction Ratio Type	"Ideal"		
Extinction Ratio	20.0	dB	[ 0, Inf )
Chirp Factor	0.0		
V pi	5.0	V	( 0, Inf )
Electrical Filtering with SII(f/Bw)/pf Law	"No"		
-3 dB bandwidth	10.0	GHz	( 0, 110.73662 )
First filter notch	= 22.57609	GHz	

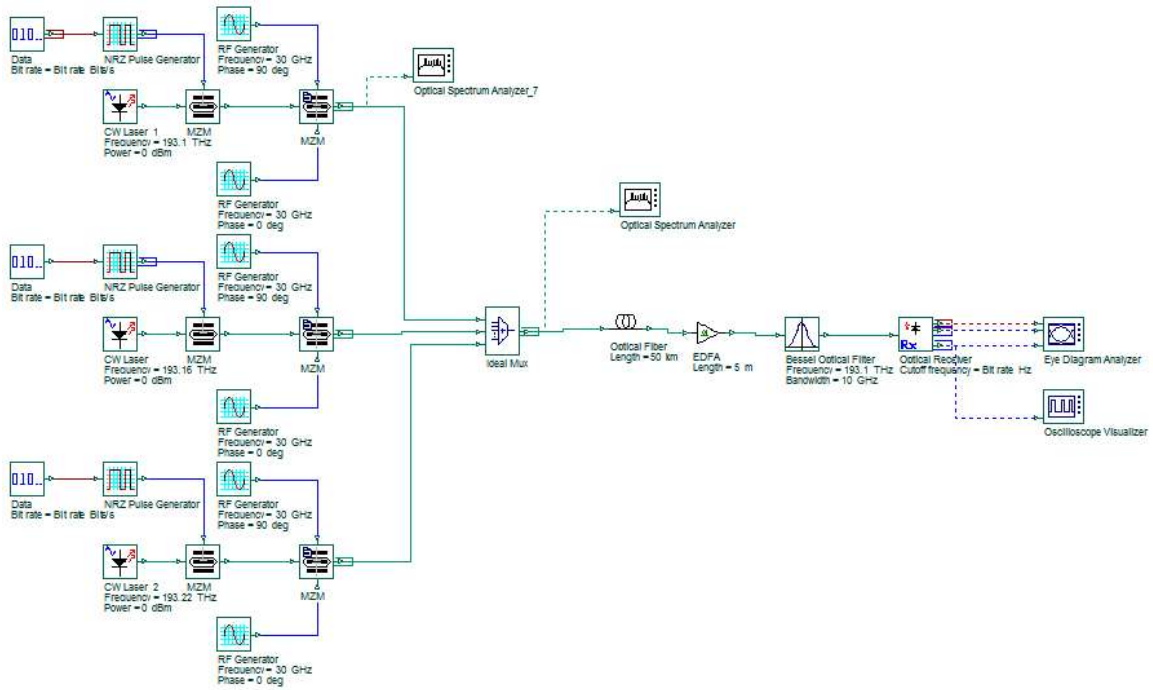
Parameter	Value	Units	Range
Bit rate	10.0	Gbit/s	( 0, Inf )
Corresponding Simulated Bit-Rate	= 10.0	Gbit/s	
Baud rate	= 10.0	GBaud/s	
Samples per bit	= 25		
Sequence	"Random"		
Custom Sequence Filename	""		
Pseudo Random Sequence Mode	"Automatic"		
Pseudo-Random Sequence Degree	7		[ 5, 28 ]
Generating Polynomial Type	"Deterministic"		
Polynomial Number	1		[ 1, 18 ]

Parameter	Value	Units	Range
Reference Frequency	193.41449	THz	( 0, Inf )
Reference Wavelength	1550.00000026	nm	( 0, Inf )
Quantum Efficiency	0.7		( 0, 1 ]
Responsivity (at reference frequency)	0.87510440132	A/W	( 0, Inf )
Single-Pole Electrical Filtering	"Off"		
-3dB Bandwidth	20.0	GHz	( 0, 100 )
Quantum noise	"Off"		
Dark Current	1.0E-4	nA	[ 0, Inf )

Bessel_b28			
Parameter	Value	Units	Range
Type	"Lowpass" <input type="button" value="v"/>		
Center Frequency	30.0	GHz	( 0, 50 )
Number of Poles	5		[ 1, 10 ]
-3dB Bandwidth	10.0	GHz	( 0, 50 )
Amplitude plot	"No" <input type="button" value="v"/>		

50Km_Fiber			
Parameter	Value	Units	Range
Dispersion from file	"No" <input type="button" value="v"/>		
Reference Frequency for Dispersion	193.41449	THz	( 0, Inf )
Reference Wavelength for Dispersion	1550.00000026	nm	( 0, Inf )
Dispersion at the reference frequency	-20.4071711988	ps <sup>2</sup> /km	
Dispersion at the reference frequency	16.0	ps <sup>2</sup> /km	
Dispersion derivative at the reference frequency	2.62376319743E-7	ps <sup>3</sup> /km	
Dispersion derivative at the reference frequency	-0.02065	ps <sup>3</sup> /km	
Dispersion second derivative at the reference frequency	0.0	ps <sup>4</sup> /km	
Dispersion third derivative at the reference frequency	0.0	ps <sup>5</sup> /km	
Zero-Dispersion Frequency	= 1.2379e+07	THz	
Zero-Dispersion Wavelength	= 0.02402	nm	
Dispersion File Name	-		
Dispersion File Format	"beta2_vs_frequency"		

## Main Items Properties of WDM System Using SSB of MMW Generation



**Layout 1 Parameters**

Label:

**Simulation** | Signals | Spatial effects | Noise | Signal tracing

Name	Value	Units	Mode
Simulation window	Set bit rate		Normal
Reference bit rate	<input checked="" type="checkbox"/>		Normal
Bit rate	2500000000	Bits/s	Normal
Time window	5.12e-008	s	Normal
Sample rate	160000000000	Hz	Normal
Sequence length	128	Bits	Normal
Samples per bit	64		Normal
Number of samples	8192		Normal

**CW Laser\_1 Properties**

Label:  Cost\$:

**Main** | Polarization | Simulation | Noise | Random numbers

Disp	Name	Value	Units	Mode
<input checked="" type="checkbox"/>	Frequency	193.1	THz	Normal
<input checked="" type="checkbox"/>	Power	1	mW	Normal
<input type="checkbox"/>	Linewidth	10	MHz	Normal
<input type="checkbox"/>	Initial phase	0	deg	Normal



**FSO Channel Properties**

Label:  Cost\$:

**Main** | Simulation

Disp	Name	Value	Units	Mode
<input checked="" type="checkbox"/>	Range	600	m	Normal
<input checked="" type="checkbox"/>	Attenuation	25	dB/km	Normal
<input type="checkbox"/>	Geometrical loss	<input checked="" type="checkbox"/>		Normal
<input type="checkbox"/>	Transmitter aperture diam	5	cm	Normal
<input type="checkbox"/>	Receiver aperture diamete	20	cm	Normal
<input type="checkbox"/>	Beam divergence	2	mrad	Normal
<input type="checkbox"/>	Transmitter loss	0	dB	Normal
<input type="checkbox"/>	Receiver loss	0	dB	Normal
<input type="checkbox"/>	Additional losses	0	dB	Normal
<input type="checkbox"/>	Propagation delay	0	ps/km	Normal

**Optical Fiber Properties**

Label:  Cost\$:

**Main** | Disp... | PMD | Nonl... | Num... | Gr... | Simu... | Noise | Rand...

Disp	Name	Value	Units	Mode
<input type="checkbox"/>	User defined reference wa	<input checked="" type="checkbox"/>		Normal
<input type="checkbox"/>	Reference wavelength	1550	nm	Normal
<input checked="" type="checkbox"/>	Length	50	km	Normal
<input type="checkbox"/>	Attenuation effect	<input checked="" type="checkbox"/>		Normal
<input type="checkbox"/>	Attenuation data type	Constant		Normal
<input type="checkbox"/>	Attenuation	0.2	dB/km	Normal
<input type="checkbox"/>	Attenuation vs. wavelengt	Attenuation.dat	...	Normal

**Optical Fiber Properties**

Label:  Cost\$:

**Main** | **Disp...** | PMD | Nonl... | Num... | Gr... | Simu... | Noise | Rand...

Disp	Name	Value	Units	Mode
<input type="checkbox"/>	Group velocity dispersion	<input checked="" type="checkbox"/>		Normal
<input type="checkbox"/>	Third-order dispersion	<input checked="" type="checkbox"/>		Normal
<input type="checkbox"/>	Dispersion data type	Constant		Normal
<input type="checkbox"/>	Frequency domain parame	<input type="checkbox"/>		Normal
<input type="checkbox"/>	Dispersion	16.75	ps/nm/km	Normal
<input type="checkbox"/>	Dispersion slope	0.075	ps/nm <sup>2</sup> /k	Normal
<input type="checkbox"/>	Beta 2	-20	ps <sup>2</sup> /km	Normal
<input type="checkbox"/>	Beta 3	0	ps <sup>3</sup> /km	Normal
<input type="checkbox"/>	Dispersion file format	Dispersion vs. wavelength		Normal
<input type="checkbox"/>	Dispersion file name	Dispersion.dat	...	Normal