

INVESTIGATION ON RADIO OVER FIBER NETWORKS
USING
VARIOUS MODULATION SCHEMES

A Dissertation Submitted in partial fulfilment of the requirements for the award of

the degree of

Master of Engineering

in

Electronics and Communication Engineering

Submitted by

Ashima Rana

Roll No. : 801461006

Under the guidance of

Dr. R.S. Kaler

Senior Professor and Deputy Director

Thapar University, Patiala



ELECTRONICS AND COMMUNICATION ENGINEERING
DEPARTMENT

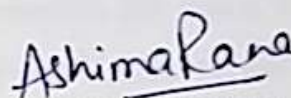
THAPAR UNIVERSITY

(Established under the section 3 of UGC Act, 1956)

PATIALA – 147004 (PUNJAB)

CERTIFICATE

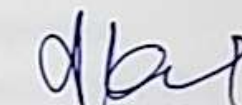
I, Ashima Rana, hereby declare that the work which is being presented in the dissertation entitled "**Investigation on radio over fiber networks using various modulation schemes**" by me in partial fulfillment of the requirement for the award of degree of M.E. in Electronics and Communication submitted in Electronics and Communication Engineering Department of Thapar University, Patiala, is an authentic record of my own work carried out under the supervision of **Dr. R. S. Kaler**, Senior Professor, ECED.


ASHIMA RANA

Date: July 11, 2016

ROLL No. 801461006

It is certified that the above statement made by the student is correct to the best of my knowledge and belief.

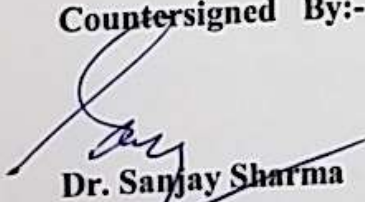

Dr. R.S. Kaler

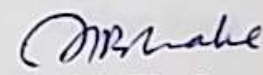
Date: July 11, 2016

Senior Professor & Deputy Director

Thapar University

Countersigned By:-


Dr. Sanjay Sharma
Professor & Head
ECED, Thapar University

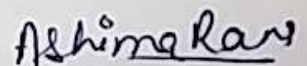

Dr. S.S. Bhatia
Dean of Academic Affairs
Thapar University

ACKNOWLEDGEMENT

To discover, analyze and to present something new is to venture on an untrodden path towards and unexplored destination is an arduous adventure unless one gets a true torch bearer to show the way. I would have never succeeded in completing my task without the cooperation, encouragement and help provided to me by various people. Words are often too less to reveals one's deep regards. I take this opportunity to express my profound sense of gratitude and respect to all those who helped me through the duration of this thesis. I acknowledge with gratitude and humility my indebtedness to **Dr. R. S. Kaler, Senior Professor**, Electronics and Communication Engineering Department, Thapar University, Patiala, under whose guidance I had the privilege to complete this thesis. I wish to express my deep gratitude towards him for providing individual guidance and support throughout the dissertation work.

I convey my sincere thanks to **Head of the Department, Dr. Sanjay Sharma** as well as **PG Coordinator, Dr. Amit Kumar Kohli, Associate Professor**, Electronics and Communication Engineering Department, entire faculty and staff of Electronics and Communication Engineering Department for their encouragement and cooperation.

My greatest thanks are to all who wished me success especially my parents. Above all I render my gratitude to the almighty GOD who bestowed self-confidence, ability and strength in me to complete this work for not letting me down at the time of crisis and showing me the silver lining in the dark clouds. I do not find enough words with which I can express my feelings of thanks to my dear friends for their help, inspiration and moral support which went a long way in successful competition of the present study.


Ashima Rana

Roll No. 801461006

ABSTRACT

Radio over fiber is a potential solution to meet up with the growing internet bandwidth demand. It is a spectacular combination of both optical and wireless communication. A radio over fiber system supports convergent network architecture, which by exploiting the benefits of both optical and wireless technologies, provides multiple services to both mobile and fixed users. The applications that require bandwidth up to 1Gbps for operation such as, WiMAN and WiMax are well supported by radio over fiber network. The execution of radio over fiber network can be further enhanced by using several techniques such as, wavelength division multiplexing, time division multiplexing, orthogonal frequency division multiplexing, optical code-division multiplex access, wavelength reuse scheme, etc.

The objective of this dissertation is to analyze the performance of radio over fiber system when integrated with various modulation schemes. Firstly, a bidirectional radio over fiber wavelength division multiplexing passive optical network is proposed using subcarrier multiplexing/amplitude shift keying technique. A narrow wavelength spacing of 0.4nm is maintained between the subsequent channels to enhance the capacity of the system. The proposed system offers acceptable values of Q-factor and bit error rate for both the uplink and downlink signals up to a transmission distance of 50km. Secondly, a cost-effective full duplex radio over fiber passive optical network is proposed based on wavelength remodulation using fiber Bragg grating. Simulation of the proposed system demonstrates 1Gbps uplink and 1Gbps downlink signals sharing the same continuous wave laser source located at the remote central station. The system exhibit smooth execution up to a transmission distance of 100km and henceforth, is capable of supporting long haul transmissions. Thirdly, the effects of four wave mixing (FWM) is mitigated up to 30dBm in a wavelength division multiplexing radio over fiber network by using hybrid four wave mixing suppression modules. Thus, in this dissertation the execution of radio over fiber network is investigated and is further improved by integrating radio over fiber with various modulation schemes.

TABLE OF CONTENTS

CONTENTS	PAGE No.
CERTIFICATE	i
ACKNOWLEDGMENT	ii
ABSTRACT	iii
CONTENTS	iv
LIST OF FIGURES	vii
LIST OF TABLES	x
LIST OF ABBREVIATIONS	xi
Chapter 1 INTRODUCTION	1
1.1 Introduction to Optical Fiber Communication	1
1.2 Need of Radio Over Fiber Technique	1
1.3 Overview on Radio Over Fiber	2
1.3.1 Benefits of Radio over Fiber	3
1.3.2 Limitations of Radio over Fiber	4
1.4 Classification of Radio Over Fiber Technique	4
1.5 Designing of Radio Over Fiber Link	7
1.6 Integration of Radio Over Fiber with Wavelength Division Multiplexing Technique	7
1.7 Remodulation in Radio Over Fiber	8
1.7.1 Remodulation in WDM-PON using Reflective Semiconductor Optical Amplifier	9
	iv

1.7.2 Remodulation in RoF-PON using Fiber Bragg Grating	10
1.8 Non-linearities in radio over fiber	11
1.9 Four Wave Mixing in Radio Over Fiber	13
1.10 Methodology	14
1.11 Gaps in Previous Work	15
1.12 Objective of Dissertation	15
1.13 Organization of Dissertation	16
Chapter 2 LITERATURE SURVEY	17
Chapter 3 WAVELENGTH DIVISION MULTIPLEXING RADIO OVER FIBER NETWORK USING SUBCARRIER MULTIPLEXING/AMPLITUDE SHIFT KEYING	29
3.1 Introduction	29
3.2 Theory and Simulation Setup	30
3.3 Results and Discussion	33
Chapter 4 WAVELENGTH REMODULATION IN RADIO OVER FIBER NETWORK USING FIBER BRAGG GRATING	39
4.1 Introduction	39
4.2 Theory and Simulation Setup	41
4.3 Results and Discussion	43
Chapter 5 SUPPRESSION OF FOUR WAVE MIXING EFFECTS IN RADIO OVER FIBER SYSTEM	49
5.1 Introduction	49
5.2 Theory and Simulation Setup	50
5.3 Results and Discussion	52

Chapter 6 CONCLUSION AND FUTURE SCOPE	57
6.1 Conclusion	57
6.1 Future Scope	58
REFERENCES	59
LIST OF PUBLICATIONS	67

LIST OF FIGURES

No.	TITLE	PAGE No.
1.1	Topology of RoF Network	2
1.2	a) Intensity modulation-direct detection technique for directly modulated RF signal	5
	b) Intensity modulation-direct detection technique using external modulator	5
1.3	Remote heterodyne detection by using two lasers	6
1.4	Remote heterodyne detection by using single laser	6
1.5	Wavelength division multiplexing system	8
1.6	Remodulation using reflective semiconductor optical amplifier	9
1.7	Optical pre-amplified receiver	10
1.8	Remodulation using fiber Bragg grating	11
1.9	Nonlinear effects occurring in optical fiber	12
1.10	a) New frequency components arising due to FWM when there are two input wavelengths ω_1 and ω_2	13
	b) New frequency components arising due to FWM when there are three input wavelengths ω_1 , ω_2 and ω_3	14
3.1	Block diagram of proposed RoF WDM-PON system	31
3.2	Internal structure of transmitter	32
3.3	Optical spectrum after multiplexing	33
3.4	a) Variation of Q-factor as a function of fiber length for different input powers, -2dBm, 2dBm and 6dBm	34
	b) Variation of BER as a function of fiber length for different input powers, -2dBm, 2dBm and 6dBm	35
3.5	a) Variation of Q-factor with input power at different optical	35

	fiber lengths, 10km, 20km and 30km	
	b) Variation of BER with input power at different optical fiber lengths, 10km, 20km and 30km	36
3.6	a) Eye diagram for downstream signal when fiber length is 5km	36
	b) Eye diagram for downstream signal when fiber length is 10km	36
	c) Eye diagram for downstream signal when fiber length is 50km	37
3.7	a) Eye Diagram for Upstream signal when fiber length is 5km	37
	b) Eye Diagram for Upstream signal when fiber length is 10km	37
	c) Eye Diagram for Upstream signal when fiber length is 50km	38
4.1	Block diagram of the proposed RoF network	41
4.2	Internal structure of wavelength remodulation block	42
4.3	a) Optical spectrum of signal after modulation by MZM	44
	b) Optical spectrum of downlink transmission	44
	c) Optical spectrum of wavelength reflected by FBG1 for uplink transmission1	44
	d) Optical spectrum of wavelength reflected by FBG2 for uplink transmission2	44
4.4	Variation of BER with OSNR for the downstream and the two upstream signals	45
4.5	a) Variation of received power with fiber length for different values of EDFA gain, 5dBm, 10dBm and 20dBm for downstream signal	45
	b) Variation of received power with fiber length for different values of EDFA gain, 5dBm, 10dBm and 20dBm for upstream signal 2 remodulated by using FBG filter 2	46
4.6	Variation of output power against the input power for the downstream and the two upstream signals	46
4.7	a) Eye diagrams with and without dispersion compensation for	47

	downstream transmission	
	b) Eye diagrams with and without dispersion compensation for upstream transmission remodulated by using FBG filter1	47
	c) Eye diagrams with and without dispersion compensation for upstream transmission 2 remodulated by using FBG filter2.	48
5.1	Block diagram of the proposed WDM-RoF system	51
5.2	a) FWM mitigation hybrid modules - FBG+OPC hybrid module	52
	b) FWM mitigation hybrid modules - DCF+OPC hybrid module	52
5.3	a) Optical spectrum of multiplexed signal without any suppression	53
	b) Optical spectrum of multiplexed signal with FWM suppressed by FBG+OPC module	53
	c) Optical spectrum of multiplexed signal with FWM suppressed by DCF+OPC module	53
5.4	Variation of overall FWM power at the output of two hybrid modules against the channel input power.	54
5.5	Variation of suppressed FWM power from the two hybrid modules against channel input power.	55
5.6	a) Eye diagrams of received signal without any suppression	56
	b) Eye diagrams of received signal with FWM suppressed by FBG+OPC module	56
	c) Eye diagrams of received signal with FWM suppressed by DCF+OPC module	56

LIST OF TABLES

No.	TITLE	PAGE No.
2.1	Summary of literature survey	23

LIST OF ABBREVIATIONS

RoF	Radio over Fiber
BS	Base Station
CS	Central Station
SMF	Single-Mode optical Fiber
RF	Radio Frequency
MMF	Multi-Mode optical Fiber
WDM	Wavelength Division Multiplexing
PON	Passive Optical Network
RSOA	Reflective Semiconductor Optical Amplifier
FBG	Fiber Bragg Grating
TDM	Time Division Multiplexing
DPSK	Differential Phase Shift Keying
AWG	Arrayed Waveguide Grating
EDFA	Erbium-Doped Fiber Amplifier
PD	Photodiode
PRBS	Pseudo Random Bit Sequence
MZM	Mach-Zehnder Modulator
SPM	Self-Phase Modulation
XPM	Cross-Phase Modulation

FWM	Four Wave Mixing
SRS	Stimulated Raman Scattering
SBS	Stimulated Brillouin Scattering
SCM	Subcarrier Multiplexing
ASK	Amplitude Shift Keying
Q-factor	Quality-factor
OFDM	Orthogonal Frequency Division Multiplexing
OCDMA	Optical Code-Division Multiplex Access
OOK	On-Off Keying
GPON	Gigabit Passive Optical Network
OSNR	Optical-Signal-to-Noise Ratio
DI	Delayed Interferometer
VOA	Variable Optical Attenuator
EVM	Error Vector Magnitude
OPC	Optical Phase Conjugator
IM-DD	Intensity Modulation-Direct Detection
RHD	Remote Heterodyne Detection
RAU	Remote Antenna Units
DCF	Dispersion Compensating Fiber
DF-HNLF	Dispersion Flattened High Nonlinear Fiber
EPON	Ethernet Passive Optical Network
BER	Bit Error Rate
POF	Plastic Optical Fiber

CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION TO OPTICAL FIBER COMUNICATION

The global internet protocol traffic is growing at a massive pace and it is expected to cross the zettabyte threshold by the end of 2016. This growing demand for high data rate communication system has heralded optical fiber communication system as the potential solution. Optical fiber communication involves transmission of data from one place to other using pulses of light that are sent through an optical fiber. An electromagnetic carrier wave is formed by light which is modulated to carry information. Optical communication was first developed in the 1970s and since then it has not only revolutionized the telecommunications industry but also played a crucial role in the initiation of the Information Age [1]. The main benefit provided by optical communication is extremely broad bandwidth which is associated with an optical carrier. The optical carrier frequency (~ 100 THz) is greater than the microwave carrier frequency (~ 1 GHz) by five orders of magnitude. Since, the modulation bandwidth is limited usually to a small fraction of carrier frequency in digital systems, it roughly translates to 100,000 times more capacity for an optical fiber communication system.

1.2 NEED OF RADIO OVER FIBER TECHNIQUE

In initial phase of telecommunication, services like GPRS and GSM agreed with low information rates. But, currently, the users demand services that are capable of providing them with a faster transmission, anytime anywhere and flexible solutions. Also, the rapidly growing number of users will limit the available bandwidth. One possible solution is to reduce the cell size for accommodating more number of clients. This is known as micro-cells or pico-cells concept. Another method involves utilization of new operational bands because there is already congestion in the unlicensed ISM frequency bands. Currently, several designers are preferring millimeter-wave as the new operational

band [3]. It lies in 40 to 90GHz optical frequency region and offers higher bandwidth. But, some other problems will arise when these methods are implemented. More base stations (BSs) would be needed to cover the entire service area if size of cell is reduced. On the other hand, increasing the frequency will require more equipments, maintenance and installation costs. Radio over Fiber (RoF) concept is developed for eliminating these issues. RoF is a spectacular incorporation of optical and wireless networks leading to high information rate, high capacity and mobility solution [4].

1.3 OVERVIEW ON RADIO OVER FIBER

The concept of RoF involves modulation of light by a radio signal followed by transmission through optical fiber in order to support wireless applications. In conventional optical systems, transmission of digital signal occurs. Fundamentally, it is an analog transmission system because it involves distribution of radio signals, directly on radio carrier frequency which are transmitted between control unit and BS [5]. However, the information signal can be digital. RoF network comprises of a transmitter and a receiver which are joined by an optical fiber. At transmitter, the optical laser source is modulated by an electrical signal. The resulting signal is in optical domain which is further transmitted through the optical fiber. At receiver, photodetector converts back the information signal into electrical form. Figure 1.1 depicts the framework of RoF network.

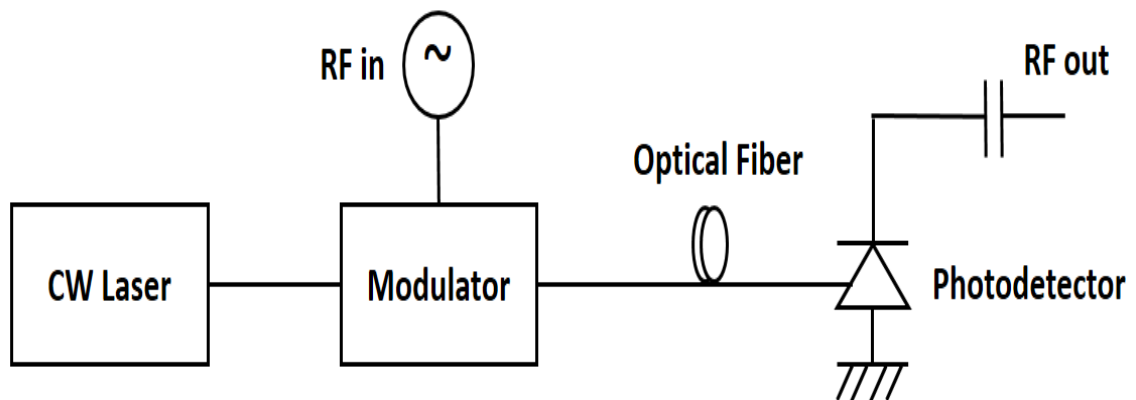


Figure 1.1 Topology of RoF network

1.3.1 BENEFITS OF RADIO OVER FIBER

RoF is an incorporation of both optical and wireless domains. So, it exploits the advantages of both the techniques. Some of the benefits are described below [6-8]:

- Enormous bandwidth and high data rate: The radio signals are preferably transmitted over fiber because it offers huge bandwidth, up to THz. High bandwidth also supports high speed for processing the signals. This may be more difficult to implement electronically.
- Low attenuation: Signals transmitting through optical fiber suffer much less attenuation than through other media (such as metal cables). The signal travel further when optical fiber is used, reducing the need of repeaters.
- Low complexity: RoF uses the concept of BS. BS only comprises of an optical-to-electrical converter, amplifiers and an antenna. This implies that the signal generation circuitry and resource management is shifted to a centralized location which is shared among several BSs, thus simplifying the network.
- Dynamical allocation of resources: The resources are controlled at the central station (CS). Thus, resources like bandwidth will be allocated dynamically according to priority and demand.
- Lower cost: The expensive and complex equipments utilized for processing the signal are placed at CS. Simpler, lighter and smaller remote antenna units are kept at BSs. Thus, the system can be easily installed and maintained resulting in reduction of system cost.
- Security: RoF does not suffer from radio frequency interference because signal transmission occurs in lightwave form. It provides security to the signals that are transmitted through the fiber.
- Future-proof: Fiber optics is developed to support data rate in Gbps. Thus, they are capable of handling the data rate required in future high speed networks. RoF technique is also bit-rate and protocol transparent.

1.3.2 LIMITATIONS OF RADIO OVER FIBER

RoF technique offers a number of advantages as discussed earlier. Apart from them, there are also certain limitations in this concept. Some of them are listed below:

- **Nonlinearities:** RoF suffers from a number of nonlinear effects. This is a result of the nonlinear condition of devices (such as laser) that are used in communication link [9]. This puts a limit on the noise figure and dynamic range that are very important parameters of radio signal transmission.
- **Single-mode fiber limitations:** Chromatic dispersion in single-mode optical fiber (SMF) puts a limit on the length of fiber link [10]. This might also cause de-correlation which increases the radio frequency (RF) carrier phase noise.
- **Multi-mode fiber limitations:** In multi-mode optical fiber (MMF), modal dispersion puts a limit on the total available bandwidth and the transmission distance [11].

1.4 CLASSIFICATION OF RADIO OVER FIBER TECHNIQUE

There are various optical techniques to generate and transport radio signals through optical fiber. In terms of modulation/demodulation format, it is classified into two categories that are, intensity modulation-direct detection and remote heterodyne detection [12].

- **Intensity Modulation-Direct Detection (IM-DD):** It involves modulation of light source intensity directly with RF signal. DD is performed by photodetector for recovering the RF signal. Modulation of laser can occur by two methods. In first method, direct modulation of laser occurs using RF signal for driving the laser bias current. This has been depicted in figure 1.2(a). Other method involves operation of laser in continuous wave followed by modulation of light intensity by external modulator (for example, Mach Zehnder modulator) as shown in figure 1.2(b) [13]. The photocurrent obtained at the PIN photodiode replicates the

modulating RF signal whose connections are made with external modulator or with laser placed at transmitter.

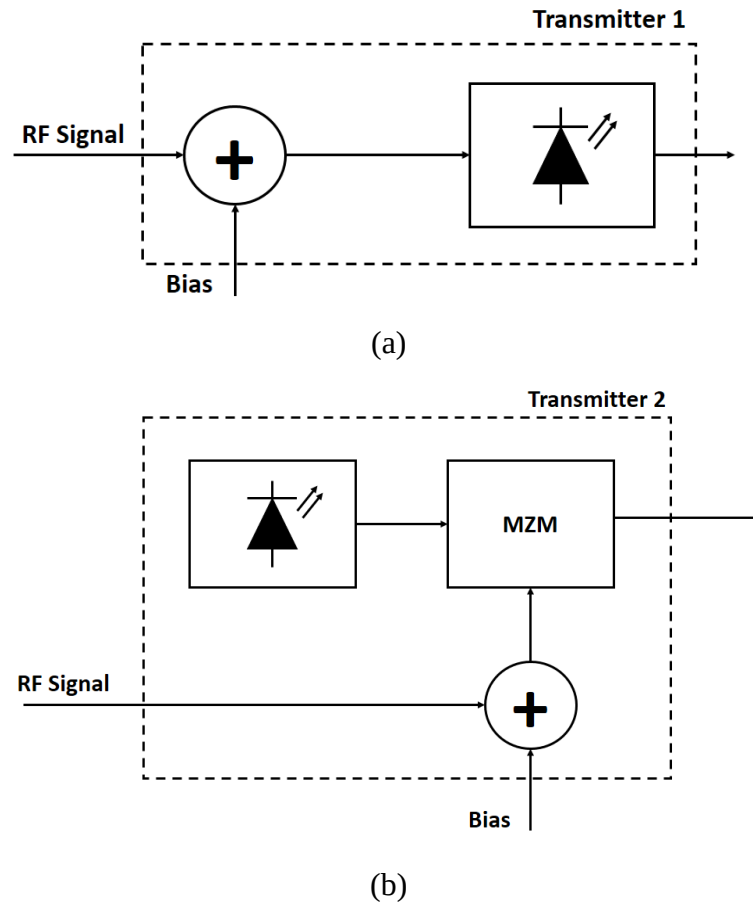


Figure 1.2 Intensity modulation-direct detection technique (a) directly modulated RF signal (b) using external modulator

- **Remote Heterodyne Detection (RHD):** It is necessary for a system to have good transmission and reception performance according to the network terms when very high frequency signals are transmitted through the optical fiber link. The involved processes should be linear. For achieving this purpose, optical heterodyning is used for the remote generation of modulated microwave signal. Two laser diodes having narrow spectral linewidth are utilized, where the spacing of central optical and microwave frequencies are equal as shown in figure 1.3. Out of the two lasers, one involves intensity-modulation of information and other involves emission of CW light. Combination of light from the two lasers occurs followed by transmission via the optical fiber. At receiver, radio signal appears by

using optical heterodyning in photodiode which is further amplitude-modulated with the information signal.

Figure 1.4 shows that if a single laser is used then the Mach Zehnder Interferometer modulator (MZI) will be biased at its inflexion point of modulation characteristic. Sinusoidal signal drives the MZI and is at half the desired frequency of microwave signal. Thus, at the MZI output, a two-tone optical signal appears whose tone spacing and microwave frequency are equal accompanied by suppression of optical carrier. In the case of intensity-modulation of laser with the information signal, self-heterodyning in photodiode produces the modulated radio signal at receiver end.

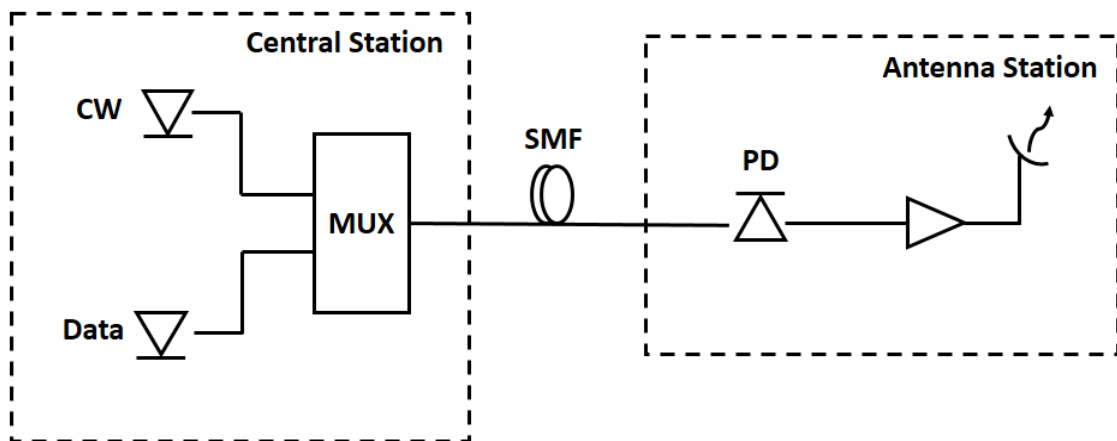


Figure 1.3 Remote heterodyne detection by using two lasers

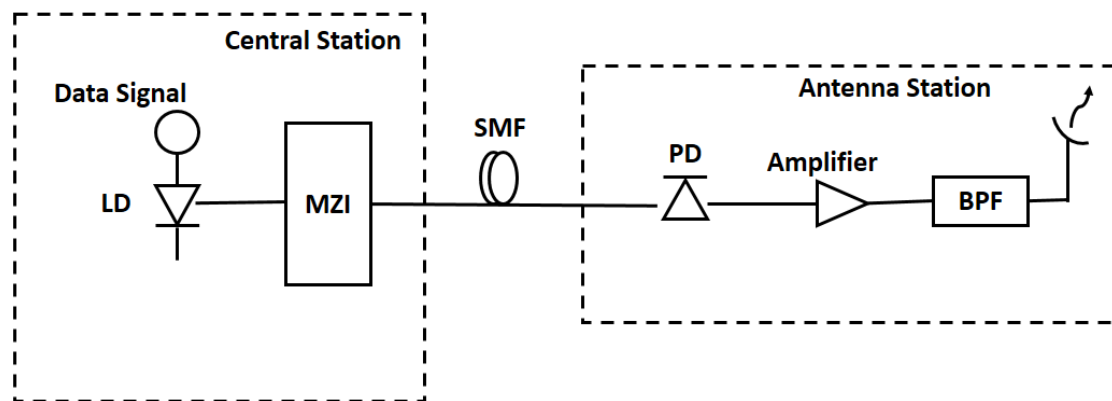


Figure 1.4 Remote heterodyne detection by using single laser

1.5 DESIGNING OF RADIO OVER FIBER LINK

Various factors are needed to be taken into account while designing a RoF link for real-world system. Some of them are listed below [14-16]:

- Carrier frequency: It decides the type of optoelectronic components that are incorporated in the network. Also, a higher bandwidth is supported by higher frequency but it increases dispersion in the optical fiber link.
- Radio channel bandwidth: This factor relies on the allocated number of clients and the carrier frequency.
- Number of channels: The number of channels for a remote station is decided by the stability requirements and the maximum allowable transmitted noise.
- Modulation format: Simple modulation formats are easier to design and are cost-effective but they lack in spectral efficiency. Thus, complex modulation schemes that can accommodate a large number of clients will prove economical in long run when high traffic growth is predicted.
- Cost: It is another important factor that has to be considered while deploying the practical systems. It relies on long term and short term profits.
- Distance: This factor decides the length of optical fiber link, operating power of laser diode and hence the data rate.

1.6 INTEGRATION OF RADIO OVER FIBER WITH WAVELENGTH DIVISION MULTIPLEXING TECHNIQUE

In optical fiber communication, wavelength division multiplexing (WDM) refers to a technique that combines several optical carrier signals on a single optical fiber link by using different wavelengths of light source [17]. It has been shown in figure 1.5. Thus, a different frequency is allocated to each communication channel followed by multiplexing and transmission on a single fiber. The wavelengths are separated spatially to different receiver locations at the destination. For this purpose, a WDM network uses a multiplexer

to combine all the signals together at transmitter and a demultiplexer to separate them apart at receiver [18].

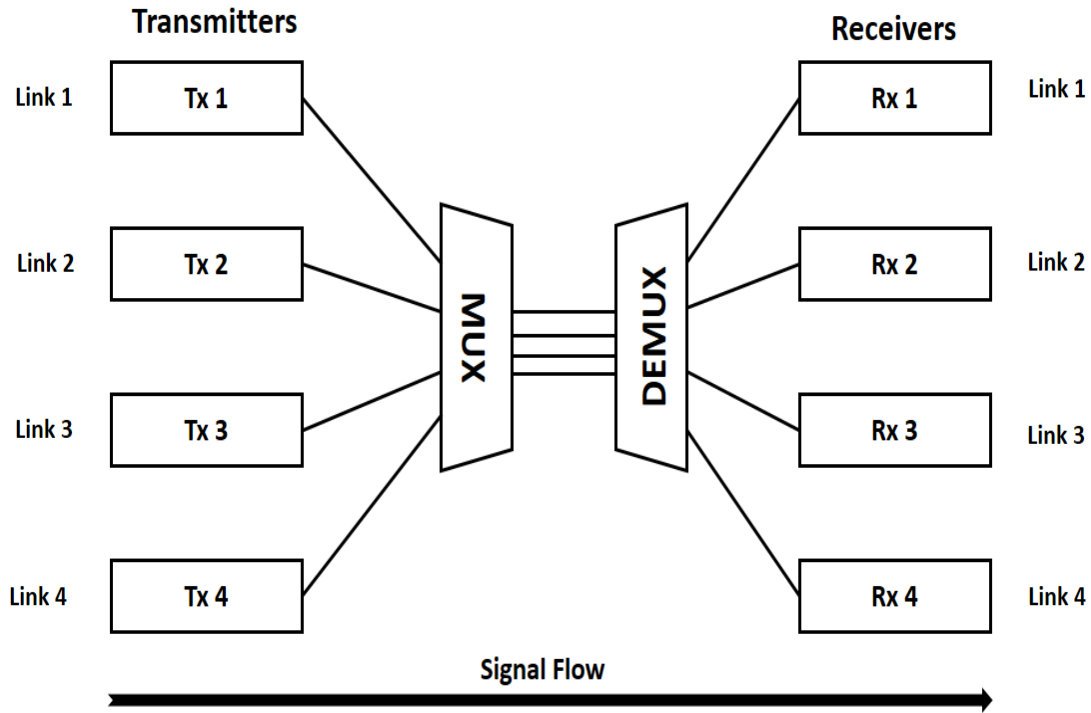


Figure 1.5 Wavelength division multiplexing system

WDM passive optical network (PON) offers several advantages including an increase in coverage range, effective bandwidth utilization of optical fiber, transparency and upgradability [19]. WDM systems are a potential solution for emerging applications, like medical imaging and supercomputer visualization, that need to support low error rate, minimal propagation delay and high information transmission rate to a huge number of clients. Integration of WDM-PON with RoF leads to significant increase in the coverage area and overall capacity of the current optical networks. This has eradicated the need to design and install two separate networks [20-21].

1.7 REMODULATION IN RADIO OVER FIBER

A RoF based network utilizes the huge bandwidth offered by optical fiber and shifts the network complexity to CS. A CS is linked to several base stations (BSs) through an optical fiber link. A great challenge in producing a cost-effective RoF-WDM PON is the

requirement for a transmitter at each BS with a dedicated wavelength. This will not only overload the total cost of system but also reduce the total available wavelengths in the network. To reduce the system cost, a centralized source of light was introduced at the CS; hence the BS remodulates the received downstream signal and utilizes the same as the upstream data carrier. This means that each BS uses a single wavelength which increases the network capacity and also simplifies network management.

In optical fiber micro cellular system, entire operational area is covered by several BSs. So, it is beneficiary if the cost of BS can be reduced [22]. To achieve this purpose, the downstream signal is remodulated using several available components such as reflective semiconductor optical amplifier (RSOA), fiber Bragg grating (FBG) etc.

1.7.1 REMODULATION IN WDM-PON USING REFLECTIVE SEMICONDUCTOR OPTICAL AMPLIFIER

Figure 1.6 shows the architecture implementing remodulation scheme in WDM integrated with time division multiplexing (TDM) PON. A CW laser is used and is encoded by differential phase shift keying (DPSK) data. This is accomplished by using a phase modulator. The downlink signal is transmitted over a SMF of length 10km through a pair of arrayed waveguide grating (AWG) and a distribution/drop fiber of 10km length.

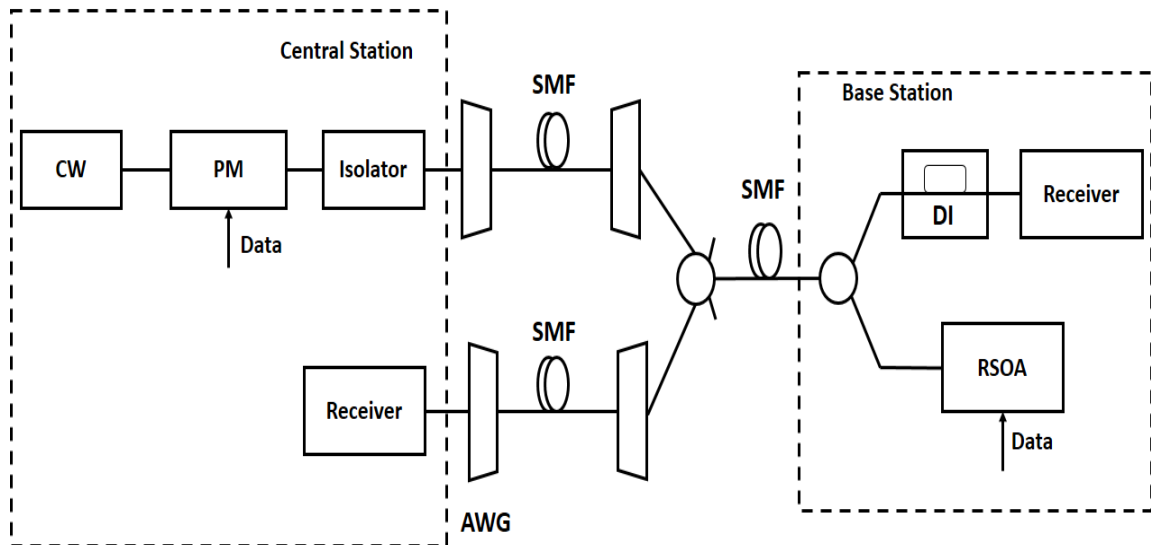


Figure 1.6 Remodulation using reflective semiconductor optical amplifier

At BS, a portion of optical power is delivered to a receiver which is optically pre-amplified. A 1-bit delayed interferometer (DI) is utilized for the demodulation of constant intensity DPSK downstream signal. The receiver comprises a variable optical attenuator (VOA) which is followed by erbium-doped fiber amplifier (EDFA) and PIN photodiode (PD), as depicted in figure 1.7. The other portion of downlink signal is then launched into RSOA for remodulation. The uplink signal is further transmitted to CS receiver using same distribution/drop fiber (which was used for downstream signal transmission) and the lower path of SMF [23].

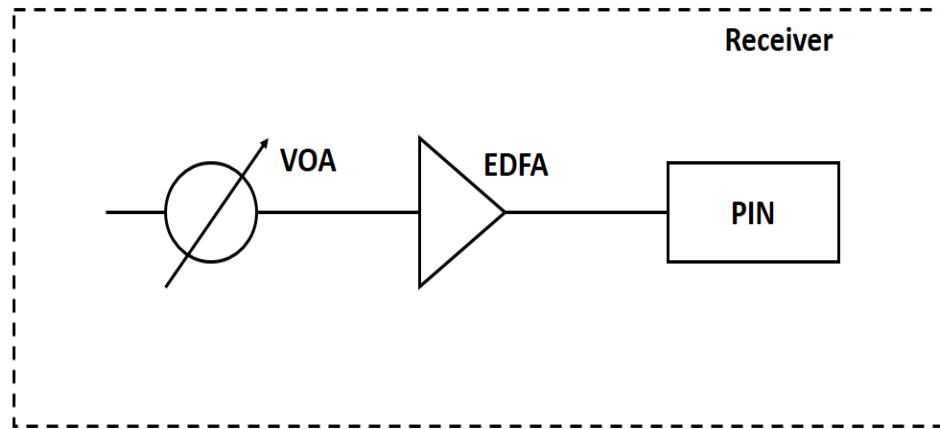


Figure 1.7 Optical pre-amplified receiver

1.7.2 REMODULATION IN RoF-PON USING FIBER BRAGG GRATING

The architecture showing the remodulation of downstream signal by using a FBG in the RoF network has been depicted in figure 1.8. A pseudo random bit sequence (PRBS) generator (having bit rate of 1Gbps) is utilized to initiate a Gaussian pulse generator for generation of baseband signal. The base band signal undergoes RF modulation and is filtered by utilizing a band pass filter. The further optical modulation of the RF signal is performed using a CW laser through a Mach-Zehnder Modulator (MZM). Transmission of resulting downlink signal occurs through a SMF.

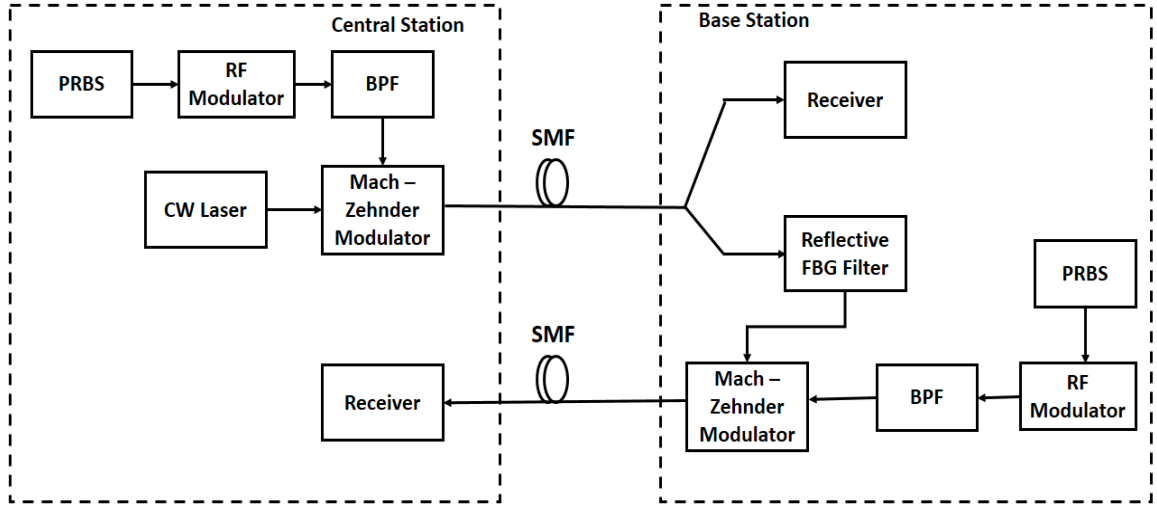


Figure 1.8 Remodulation using fiber Bragg grating

At BS, one portion of the received signal is demodulated by applying to a series of photodetector, band pass filter (BPF) and RF demodulator. Other portion is applied to FBG filter for the purpose of reusing the downstream wavelength for upstream transmission. FBG filter offers the benefit of reusing the downstream wavelength without requiring any additional light source. A FBG has a periodic structure and is built in a small section of fiber link to reflect specific wavelengths of light [24]. Thus, a FBG can be utilized as wavelength-specific reflector allowing all the wavelengths to pass through except the one which satisfies the Bragg law. Bragg's law is defined as [25]:

$$\Lambda = \frac{\lambda_B}{2n_{eff}}$$

where Λ represents period of grating, λ_B signifies the reflected wavelength and $n_{eff} = 1.46$ mm represents fiber core's effective group refractive index.

1.8 NON-LINEARITIES IN RADIO OVER FIBER

Normally when light waves are transmitted through RoF, they have slight interactions with each other and do not change while passing through the optical fiber link. However, there are exceptional cases in which the light waves interact with the material

transmitting them and generate nonlinear effects [26]. The two reasons behind the occurrence of the nonlinear effects are:

- Intensity dependence of the refractive index of medium: Dependence of power on refractive index causes Kerr-effect. This nonlinearity is categorized into three different effects based on input signal form. These categories are self-phase modulation (SPM) and cross-phase modulation (XPM) and FWM.
- Inelastic-scattering phenomenon: This phenomenon induces stimulated effects at high power level which are stimulated Raman scattering (SRS) and stimulated Brillouin scattering (SBS). Exponential increase in the scattered light intensity occurs when incident power crosses a certain critical value. Raman and Brillouin scattering differ in the way that in SRS, the generated phonons (optical) are incoherent and there is no generation of macroscopic wave while in SBS, the phonons (acoustic) are coherent leading to the generation of a macroscopic acoustic wave in optical fiber [27].

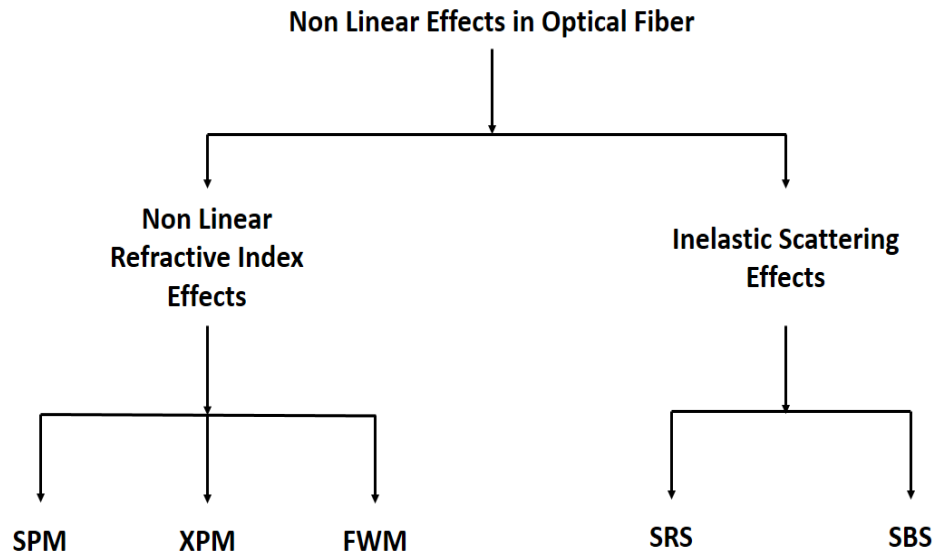


Figure 1.9 Nonlinear effects occurring in optical fiber

All nonlinear effects, except SPM and XPM, provide extra gain to one channel on the expense of other channels i.e. the power of one channel is increased causing depletion of power of other channels. SPM and XPM only cause spectral broadening. The

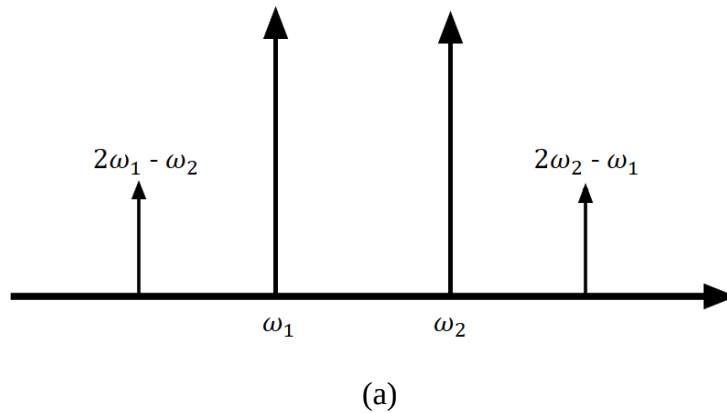
spectral broadening results in increased dispersion [28-29]. The categorization of nonlinearities occurring in optical fiber has been shown in figure 1.9.

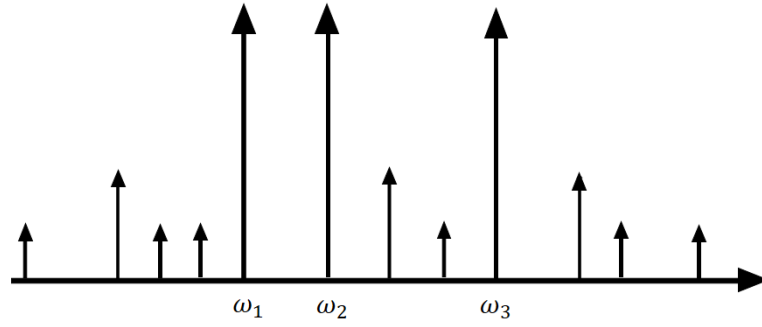
1.9 FOUR WAVE MIXING IN RADIO OVER FIBER

FWM is one of the nonlinear effects arising because of the power dependence of refractive index in optical fiber link. It is an effect of optical Kerr nonlinearity. It occurs in WDM networks where the wavelength spacing between the channels is very close to each other [30]. Channel spacing and fiber dispersion are the two important factors on which FWM depends on. As the spacing between the channels is decreased, FWM effects increase. Also, decrease in dispersion leads to increase in FWM effects [31]. The cross products that are generated interfere with original wavelengths which leads to mixing. In addition to this, these interfering signals lay exactly on the original wavelengths causing problems while separating them apart. For N input wavelengths, the number of mixing products (M) are given by [32]:

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

For instance, consider a system consisting of three wavelengths and experiencing FWM distortion. This system involves the generation of nine cross products. Figure 1.10 shows two or more original wavelengths. Additional products are generated but these generated products do not lay over the original wavelengths [33].





(b)

Figure 1.10 New frequency components arising due to FWM when there are (a) two input wavelengths ω_1 and ω_2 (b) three input wavelengths ω_1 , ω_2 and ω_3 .

1.10 METHODOLOGY

Optical communication through RoF network has been implemented using Optisystem and OptSim. These softwares are briefly described below:

- **OptiSystem:** OptiSystem is a powerful and innovative software design tool enabling users to design, test and simulate almost each kind of optical link located in transmission layer of optical networks broad spectrum. This spectrum of optical networks varies from local area network and metropolitan area network to ultra-long-haul network. OptiSystem enables users to design, test and simulate:
 - Transmitter, receiver, channel and amplifier design
 - WDM/TDM or CATV system development
 - Calculation of bit error rate and penalties of network using different receive models
 - SONET/SDH ring design
 - Amplified System bit error rate and link budget calculations
- **OptSim:** This software consists of most commonly used components required for engineering of the electro-optical systems and particular emphasis is laid on digital CATV and WDM systems. Innovative optical approaches such as dispersion managed soliton and quasi-return-to-zero systems are also supported

by the software. OptSim exchanges signals by utilizing documented OptSim signal format during simulation. It is a stand-alone product which comes with an on-line HTML help and Windows-like user interface. The users do not require expensive frameworks or additional tools for realizing full power of OptSim. This software is extremely easy to use and allows even the non-experts to carry out complex simulations in minutes.

1.11 GAPS IN PREVIOUS WORK

After thorough research on this topic on the basis of literature survey, some gaps are observed in the study. Some of them are listed below:

- Previously proposed architectures involved transmission of signal at a short distance and suffered from the shortcoming where the number of channels were to be reduced in order to increase the fiber length.
- Some networks required larger channel spacing, such as 0.8nm to operate or needed extra optical carriers in order to accomplish full duplex criterion.
- In previous works, authors used components such as fiber Bragg grating, dispersion compensating fiber, optical phase conjugator or rectangle filter to reduce the four wave mixing effects and were able to achieve the suppression till 20dBm in radio over fiber networks.

1.12 OBJECTIVE OF DISSERTATION

The main objectives that are covered in this dissertation for analysing and improving the performance of RoF network are discussed below:

- To improve the performance of wavelength division multiplexing radio over fiber passive optical network using subcarrier multiplexing/amplitude shift keying in terms of bit error rate and quality factor.
- To develop a cost effective radio over fiber passive optical network based on wavelength remodulation using fiber Bragg grating.
- To estimate and suppress the four wave mixing effects in wavelength division multiplexing radio over fiber network.

1.13 ORGANIZATION OF DISSERTATION

Chapter 1 gives the introduction about RoF and discusses various concepts and techniques that can be integrated with it.

Chapter 2 briefly describes the literature survey done for understanding the concepts of radio over fiber and to state the main objectives of thesis. The work done by different authors is studied comprehensively to analyze the various techniques used in integration with radio over fiber scheme. And therefore, gaps are observed in their work with aim to improve the networks further.

Chapter 3 of the thesis focuses on investigation of RoF WDM-PON using subcarrier multiplexing/amplitude shift keying (SCM/ASK) technique. A narrow spacing of 0.4nm is maintained between the channels which offers the benefit of supporting a high data rate and huge number of clients. The performance of system is analyzed by investigating the variations in quality factor and bit error rate when fiber length and channel input power changes.

Chapter 4 demonstrates a full duplex RoF-PON based on wavelength remodulation using fiber Bragg grating. This framework supports long haul transmissions and eliminates the requirement of using a separate source of light at the BS. It results in simplifying the design of BS and reducing the overall system cost. Also, the overall dispersion of the fiber link is compensated by using FBG and dispersion compensating fiber (DCF).

Chapter 5 deals with the estimation and mitigation of FWM in WDM-RoF system using hybrid modules. These modules improve the execution of the network by suppressing the FWM power up to 30dBm.

Chapter 6 includes the Conclusion and Future scope of the work presented in this dissertation.

RoF is acquiring a huge interest because it is considered as a potential solution to meet up the growing internet bandwidth demand. RoF is an amalgamation of both optical and wireless technologies offering the benefits of high information rate and increased mobility. Many authors have done research on the integration of RoF with several technologies such as, WDM, TDM, orthogonal frequency division multiplexing (OFDM), optical code-division multiplex access (OCDMA), wavelength reuse scheme, etc. Some authors analyzed the effects of nonlinearities in a RoF system and proposed various methods to suppress them.

The literature survey discussed below describes the contributions made by various authors in the field of optical communication:

S. Singh [34]

Author evaluated the enactment of bi-directional PON and compared in triple play service scenario for different bit rates. The data, video and voice signals were combined for the realization of triple-play service. This architecture was examined for the symmetrical data traffic transmitted as downlink and uplink signals and the performance was estimated in terms of eye height and quality factor (Q-factor). The proposed system was examined for 128 users and the corresponding eye height and Q-factor was estimated at diverse transmission distances with diverse number of users. The results of Q-factor showed that the system had acceptable performance for upstream and downstream transmission at a data rate of 10Gbps.

M. Bi et al. [35]

The authors proposed a stacked WDM-OFDM-PON system that could transmit downstream OFDM signals of 10Gbps per wavelength and also on-off keying (OOK) signals for upstream transmission up to a distance of 100 km without using any repeater.

The authors used electronic controlled liquid tunable optical filter that was specially designed for simultaneously selection of downstream signals and also processing of upstream signal chirp. The experimental results showed that a 35.6dB power budget was obtained for transmission over a fiber length of 25km for supporting 1:512 splitting ratios. An optical power budget of 34.4dB was also achieved for transmission over a distance of 100km without using a repeater.

A. O. Aldhaibania et al. [36]

The authors presented a 2.5Gbps gigabit PON (GPON) downstream link using the RoF technology in GPON system architecture. TDM GPON and WDM GPON were integrated into a single PON which reduced the system cost and increased the data rate. The radio signals were propagated along a standard SMF of length 25km. The proposed framework supported 32 and 64 clients. Performance of the proposed system was analyzed based on optical signal-to-noise ratio (OSNR), received power, error vector magnitude, constellation diagram and eye diagram. As the distance was increased, the value of EVM also increased, reaching to 30.3% at 50 km. However, the OSNR and received power were reduced to 35dBm and -24dbm respectively when the distance was increased to 50km.

G. Kaur et al. [37]

The authors analyzed mitigation of FWM power in hybrid network topologies. The topologies were in the form of ring and bus. They investigated a method centered on optical phase conjugator (OPC) to mitigate the FWM power. The performance of system was evaluated using the parameters of Q-factor, eye diagram and induced FWM power. The results showed that the FWM power was suppressed over 40dBm using OPC module.

G. Cheng et al. [38]

The authors proposed and demonstrated a novel RoF network implementing optical interleaver and external modulator to produce dual octupling-frequency millimeter waves used for two BSs. The remodulation scheme was used to generate the uplink connection. The system was cost effective because additional laser source was not utilized for

generating the two upstream signals and sharing the same laser source located at the central office. The results showed that when the uplink and downlink signals were transmitted over a SMF of length 60km, they suffer from a power penalty which was less than 0.6dB.

C. W. Chow et al. [39]

The authors demonstrated a migration scheme to WDM-PON from TDM-PON using DPSK scheme for downlink and ASK (wavelength-shifted) for uplink signal. An optical filter was installed at base station to choose the appropriate downlink wavelength in the network and demodulate the downlink signal simultaneously. Experimental results depicted that the remodulated wavelength shifted ASK uplink provided successful transmission of signal under 32 and up to 64 splits.

X. Jin-Ling et al. [40]

The authors proposed a novel RoF network based on frequency quadrupling and double-sideband modulation to reduce the cost of system both at the CS and the BS. The optical millimeter-wave's repetitive frequency was made four times the local oscillator signal frequency by biasing the intensity modulator properly. The theory evaluation showed that the information signals after transmitting over fiber could be made resistant to the walk-off of signals, signal fading and the code time shift.

S. Mitathaa et al. [41]

The authors proposed a novel design Terahertz frequency for RoF networks integrated with dense WDM scheme. Proposed framework supported enhanced signal security and channel capacity. The wavelength enhancement in optical communication was also reviewed. The proposed system could be incorporated with the current networks in both terabit wireless and wired systems.

F. I. El-Nahal [42]

The author proposed a novel bidirectional RoF network transmitting 10Gbps DPSK downlink at central office and using ON-OFF keying remodulation scheme at BS for uplink. The proposed system utilized the same optical carrier for both downlink and uplink and so no additional source of light was required at the base station. Thus, the

wavelength utilization efficiency was improved and the overall cost of the system was reduced. The simulation results showed that system supported transmission over a distance of 50 km without dispersion compensation.

J. M. Kang et al. [43]

The authors presented a WDM/SCM PON utilizing the same wavelength for downlink and uplink signals. The proposed system utilized RSOA for modulation. A 622Mbps downstream utilizing distributed feedback laser source with DD and 100Mbps upstream utilizing RSOA for modulation with 900MHz SCM signal. The desired received power for 622Mbps downstream signal was -23dBm and for 100Mbps upstream signal was -14dBm after 10km transmission. Power penalty for baseband signal low-pass filtering was 2dB.

M. Matsuura et al. [44]

The authors demonstrated experimentally bidirectional RoF utilizing a 100m double-clad fiber. The double-clad fiber was used for remote antenna units (RAUs) which were optically powered. It had a multimode inner cladding and a single mode core for a RoF link. The inner cladding was utilized for delivering optical power to RAU while the single mode core was used for simultaneous uplink and downlink transmissions of optical RoF information signals. The main aim of the approach was to eliminate the necessity of utilizing external power supplies, like public power lines or batteries power at the RAUs which were powered optically.

A. Emsia et al. [45]

The authors described a new reach extension technique that increased bandwidth and reduced deployment costs by increasing the number of users in the system. Differential (quadrature) phase-shift keying signals were analyzed in the system. Hybrid TDM/WDM transmission up to 40Gbps upstream and 120Gbps downstream were demonstrated experimentally. The access budget of 33.4 dB was achieved on every WDM channel at 10Gbps when DPSK was used with a per wavelength splitting ratio of 1:512. Also, power budget of 40dB was obtained in case of DQPSK with a per wavelength splitting ratio of 1024. The proposed system also eradicated nonlinear impairments appearing in dense WDM transmission.

G. Kaur et al. [46]

The authors investigated the implementation of FBG, DCF and OPC. Further, these configurations were compared with conventional schemes. The effect of hybrid modules was studied on FWM in a WDM framework supporting information rate of 10Gbps and consisting of 16 channels. The proposed schemes improved the performance of system by mitigating the FWM up to 40dBm.

F. Brendel et al. [47]

Authors investigated the influence of chromatic dispersion on SMF centered around mode locked laser sources. The simulation results were experimentally validated for a 60 GHz radio carrier delivering laser, and also for a 400 m long length which represented the length of a realistic link for in-house distribution. In addition to this, the effect of chromatic dispersion was demonstrated on signal quality for wireless local area network transmission which employed direct and external link modulation.

R. Yadav [48]

The author described possible architectural approaches for an access network which was converged and based on PON for supporting business and residential services. This framework would enable the network providers to efficiently use the investment made in fiber for deploying premises centered around PON. This would be done by supporting those business services which are higher value on the same infrastructure with the additional benefit of minimal incremental cost. This system reduced the cost of supporting business services and increased revenue opportunities by extending the availability of business service.

T. Liu et al. [49]

The authors conducted an experiment to present an efficient multi wavelength generation having small wavelength spacing which was centered around FWM. Dispersion flattened high nonlinear fiber (DF-HNLF) was employed along with double-pass configuration to enable an efficient multi wavelength generation. This multi wavelength generation had a 3 dB bandwidth approximately equal to 11 nm with 0.1nm spacing in wavelength. A standard SMF of length 500m, a high nonlinear fiber of length 500m and a DF-HNLF of length 500m were inserted in cavity to analyze the impact of nonlinearity and dispersion.

H. Bai et al. [50]

The authors designed a switching node. This Switch structure was developed using tunable wavelength converter technique and was introduced in hybrid WDM/TDM PON. Experimental results depicted that the system performance was improved by using switch node in terms of packet loss rate and bandwidth-utilization rate. The results showed that 64 optical network units $\times$ 16 wavelengths mode operated fairly supported by shortest average packet delay and minimum packet loss.

B. Kaur et al. [51]

The authors analyzed the execution of WDM ethernet PON (EPON) with RoF optical link using FBG and DCF to compensate the FWM and dispersion. For compensating FWM and dispersion, two FBGs were used at a wavelength of 1550.11nm and 1552.5nm and also a DCF with dispersion value of -50 ps/nm/km was used. By using FBG and DCF, the system was improved by 77.67%. Q factor, bit error rate (BER) and eye diagrams were the three parameters used for analyzing the execution of the framework.

D. D. Patel et al. [52]

The authors analyzed the impact of FWM, XPM and SRS on WDM optical communication network. The proposed WDM system consisted of 16 channels. The results showed that when the number of input channels and the input power were increased, the nonlinearities like XPM also increased. Some novel techniques were described to mitigate the effects of nonlinearities. To compensate the FWM effects rectangular optical filter was utilized and to mitigate the XPM effects a method based on FBG was used.

H. U. Manzoor et al. [53]

The authors introduced a method using alternative circular polarizers to alter the input pulses polarization in left and right polarized pulses prior to multiplexing leading to reduction in FWM. Circular polarizers reduced the products of FWM without degrading the original pulses. Also, FWM could be completely eliminated by utilizing circular polarizers and by adjusting the network parameters like decrementing data rate, increasing the fiber length and increasing channel spacing.

Table 2.1 summarizes the contribution made by the various authors in the field of radio over fiber and optical communication.

Table 2.1 Summary of literature survey.

S. No.	AUTHORS	YEAR	WORK DONE	RESULTS
1.	S. Singh	2014	Evaluated the enactment of bi-directional PON and compared in triple play service scenario for different bit rates	Acceptable performance of framework for upstream and downstream transmission at a data rate of 10Gbps and serving 128 users.
2.	M. Bi et al.	2014	Proposed a stacked WDM-OFDM-PON system that could transmit downlink OFDM signals of 10Gbps per wavelength and uplink on-off keying signals transmitting up to 100km	35.6dB and 34.4dB power budget was obtained for transmission over 25km and 100km distance respectively.
3.	A. O. Aldhaibania et al.	2013	Presented a 2.5Gbps gigabit PON (GPON) downstream link using the RoF technology in GPON system architecture.	As the distance was increased, the value of EVM also increased, reaching to 30.3% at 50 km. However, the OSNR and received power were reduced.

4.	G. Kaur et al.	2015	Analyzed mitigation of FWM power in hybrid network topologies by using OPC. The topologies were in the form of ring and bus.	FWM power was suppressed over 40dBm using optical phase conjugator module.
5.	G. Cheng et al.	2014	Proposed and demonstrated a novel RoF network implementing optical interleaver and external modulator to produce dual octupling-frequency mm waves.	The uplink and downlink signals suffered from a power penalty which was less than 0.6dB when they were transmitted over 60km long SMF.
6.	C. W. Chow et al.	2013	Demonstrated a migration scheme to WDM-PON from TDM-PON using DPSK scheme for downlink and ASK (wavelength-shifted) for uplink signal.	The remodulated wavelength shifted ASK uplink provided successful transmission of signal under 32 and up to 64 splits.
7.	X. Jin-Ling et al.	2010	Proposed a novel RoF network based on frequency quadrupling and double-sideband modulation to reduce the cost of system both at the CS and the BS.	Information signals were made resistant to walk-off of signals, signal fading and the code time shift.

8.	S. Mitathaa et al.	2012	Proposed a novel design Terahertz frequency for RoF networks integrated with dense WDM scheme. The wavelength enhancement in optical communication was also reviewed.	Enhanced signal security and channel capacity.
9.	F. I. El-Nahal	2013	Proposed a novel bidirectional RoF network transmitting 10Gbps DPSK downlink at central office and using ON–OFF keying remodulation scheme at base station for uplink.	System supported transmission over a distance of 50 km without dispersion compensation.
10	J. M. Kang et al.	2006	Presented a WDM/SCM PON sharing the same wavelength for downlink and uplink signals. The proposed system utilized RSOA for modulation.	Power penalty for baseband signal low-pass filtering was 2dB.
11	M. Matsuura et al.	2015	Demonstrated experimentally bidirectional RoF utilizing a 100m double-clad fiber (DCF). The DCF was used for remote antenna units (RAUs) which were optically powered.	Eliminated the necessity of external power supplies, like public power lines or batteries, at RAUs so that they were powered optically

12	A. Emsia et al.	2014	Described a new reach extension technique that increased bandwidth and reduced deployment costs by increasing the number of users in the system.	Access budget of 33.4 dB and 40dB were achieved on every WDM channel at 10Gbps when DPSK and DQPSK schemes were respectively used.
13	G. Kaur et al.	2014	Investigated the implementation of FBG, DCF and OPC to mitigate the FWM power in a WDM framework.	Reduced the FWM up to 40dBm.
14	F. Brendel et al.	2011	Investigated the influence of chromatic dispersion on SMF centered around mode locked laser sources.	In a framework utilizing mode locked laser in 60 GHz band, the EVM and band power had acceptable values when length was altered more than 50 m from its maximum value.

15	R. Yadav	2012	Described possible architectural approaches for an access network which was converged and based on PON for supporting business and residential services.	Reduced the cost of supporting business services and increased revenue opportunities by extending the availability of business service.
16	T. Liu et al.	2016	Conducted an experiment to present an efficient multi wavelength generation having small wavelength spacing which was centered around FWM.	The framework performance was improved by 200% in terms of output spectrum 3dB uniformity when DF-HNLF was utilized instead of HNLF.
17	H. Bai et al.	2013	Designed a switch node using tunable wavelength converter technique which was introduced in hybrid WDM/TDM PON.	64 optical network units $\times$ 16 wavelengths mode operated well with shortest average packet delay and minimum packet loss.
18	B. Kaur et al.	2013	Analyzed the execution of WDM EPON with RoF optical link using FBG and DCF to compensate the FWM and dispersion.	Using FBG and DCF, the system execution was improved by 77.67%.

19	D. D. Patel et al.	2014	Analyzed the impact of FWM, XPM and SRS on WDM optical communication network. The proposed WDM system consisted of 16 channels.	Rectangular optical filter and FBG mitigated the FWM and XPM effects respectively.
20	H. U. Manzoor et al.	2015	Introduced a method using alternative circular polarizers to alter the input pulses polarization in left and right polarized pulses prior to multiplexing leading to reduction in FWM.	Eliminated FWM completely by utilizing circular polarizers and by adjusting the network parameters.

WAVELENGTH DIVISION MULTIPLEXING RADIO OVER FIBER NETWORK USING SUBCARRIER MULTIPLEXING/AMPLITUDE SHIFT KEYING

The idea of RoF is integrated with WDM-PON in order to exploit the benefits of high data rate and increased mobility. In this chapter, a full duplex RoF WDM-PON system is proposed using SCM/ASK strategy. The proposed system is based on signal remodulation using bidirectional reflective filter and thus, sharing the same wavelength for uplink and downlink. Simulation of the system demonstrates 1Gbps uplink and 1Gbps downlink data stream for 17 channels. A narrow spacing of 0.4nm is maintained between the channels to enhance the capacity of the system. The performance of system is determined by investigating the variations in Q-factor and BER when fiber length and channel input power changes.

3.1 INTRODUCTION

The global internet protocol traffic is growing at an enormous pace and is expected to increase three folds over the next five years. To support this kind of growth, there is a need to design future proof network that can support large bandwidth and high data rate in a cost effective way. If the proposed network can converge wireless and wired services together, then high data rate can also be incorporated with increased mobility [54]. RoF is the technique that combines both the optical (wired) and microwave (wireless) networks. A RoF network involves transmission of RFs over an optical fiber link in order to support several wireless applications.

PON is already being deployed in several countries over the globe to meet the growing internet bandwidth demand. WDM-PON offers several advantages including an increase in coverage range, effective bandwidth utilization of optical fiber, transparency and upgradability [19]. WDM-PON is an efficient and cost-effective option for future high

speed access networks. Integration of WDM-PON with RoF leads to significant increase in the coverage area and overall capacity of the current optical networks. This has eradicated the need to design and install two separate networks [20-21]. Many researchers have already addressed the same problem and made progress to provide a solution. Singh et al. [55] proposed a WDM-RoF system transmitting 1Gbps downlink and uplink information stream over a length of 25km with the aim to acquire an adequate Q-factor. Pradeep et al. [56] proposed an architecture for wired as well as wireless system capable of delivering a 2.5Gbps downlink and 1Gbps uplink signal. Aldhaibani et al. [36] exhibited a 2.5Gbps GPON downlink signal using RoF technique in GPON system propagating over a 25km optical fiber link. Won et al. [57] showed the synchronous transmission of a 1.25Gbps wired and 1.25Gbps wireless information stream over a WDM-RoF access system. M. Arief et al. [58] proposed a blend of SCM and WDM model to provide vast transmission capacity and high information rate in cellular communication particularly between CS and BS.

Previously proposed architectures involved transmission of signal at a short distance and suffered from the shortcoming where the number of channels were to be reduced in order to increase the fiber length. Other schemes required larger channel spacing, such as 0.8nm to operate or needed extra optical carriers in order to accomplish full duplex criterion.

This chapter focuses on the transmission of downlink and uplink data streams over a range of optical fiber length by using wavelength reuse scheme. The channel spacing is maintained at 0.4nm and the input power is varied in order to analyze the execution of WDM-RoF network.

3.2 THEORY AND SIMULATION SETUP

The block diagram of the proposed WDM-RoF system is shown in figure 3.1. The transmitter comprises of 17 channels and all channels on the transmitting side have their own operating wavelength (for channel 1 ~ 1552.52 nm with a linewidth of 10 MHz). Accordingly, a wavelength spacing of 0.4 nm is maintained between subsequent channels for smooth and low loss transmission. The narrow separation also helps to support huge

number of clients and accomplish a high information rate. Input power of each channel is changed from -15dBm to 15dBm with a step of 5dBm. The WDM multiplexer (with a bandwidth of 10GHz) combines the signal coming from each input channel and transmits over the optical fiber link via a bidirectional circulator. The length of optical fiber is varied from 5km to 50km with a step of 5km. EDFAs are used in optical communication links to enhance the power of signal on all the channels simultaneously. EDFAs operate in the wavelength window of 1550nm and demand dispersion management. For this reason, we use a DCF for decreasing the overall dispersion of the fiber link.

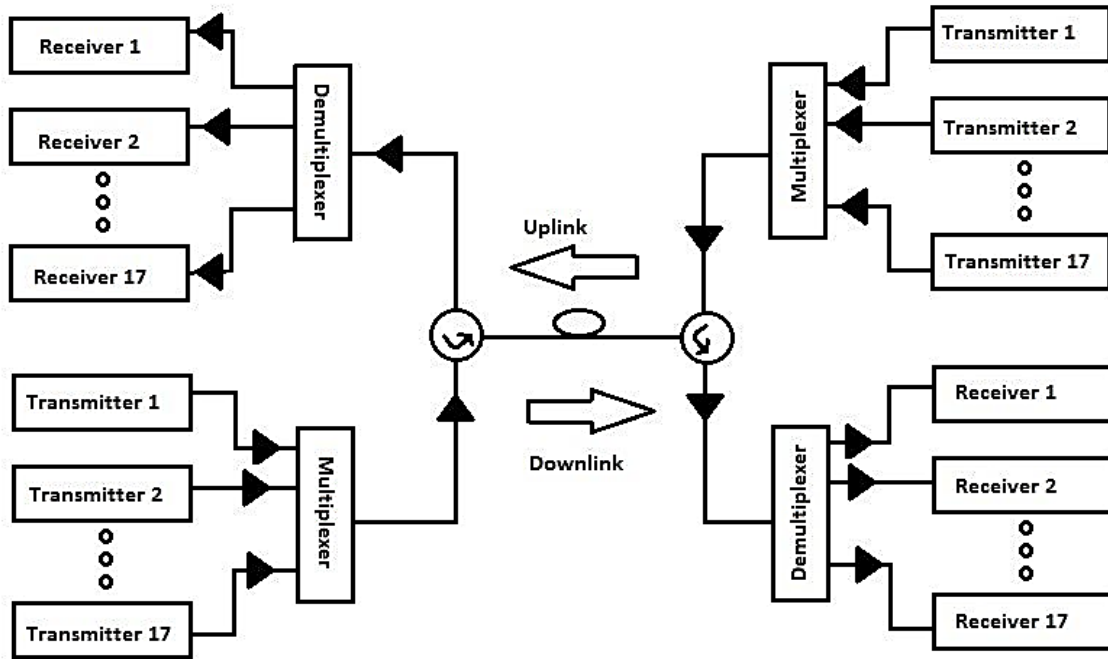


Figure 3.1 Block diagram of proposed RoF WDM-PON system

On the transmitter side, a Gaussian pulse generator converts the binary data delivered by pseudo-random bit generator into return-to-zero super Gaussian electrical pulses and thus, the baseband signal is generated. The information rate for reenactment of both the downlink and uplink signal is set to 1Gbps. All other parameters are suitably adjusted to obtain an acceptable value of Q-factor. An electrical amplitude modulator having carrier frequency of 1.7GHz is used to convert the baseband signal frequency to the frequency of

RF clock. The RF signal is applied to 90° hybrid coupler after SCM carrier generator as shown in figure 3.2. Further, the outputs of hybrid coupler are connected to dual port dual drive LiNb MZM. MZM is utilized for the transformation of microwave signal into optical signal. MZM has four ports out of which three are used as input port and one as output port. Subsequently, Port 1 of MZM is driven by the amplitude modulator and Port 2 by 1Gbps baseband signal. The optical signal obtained on the output port of MZM is further transmitted over the optical fiber link.

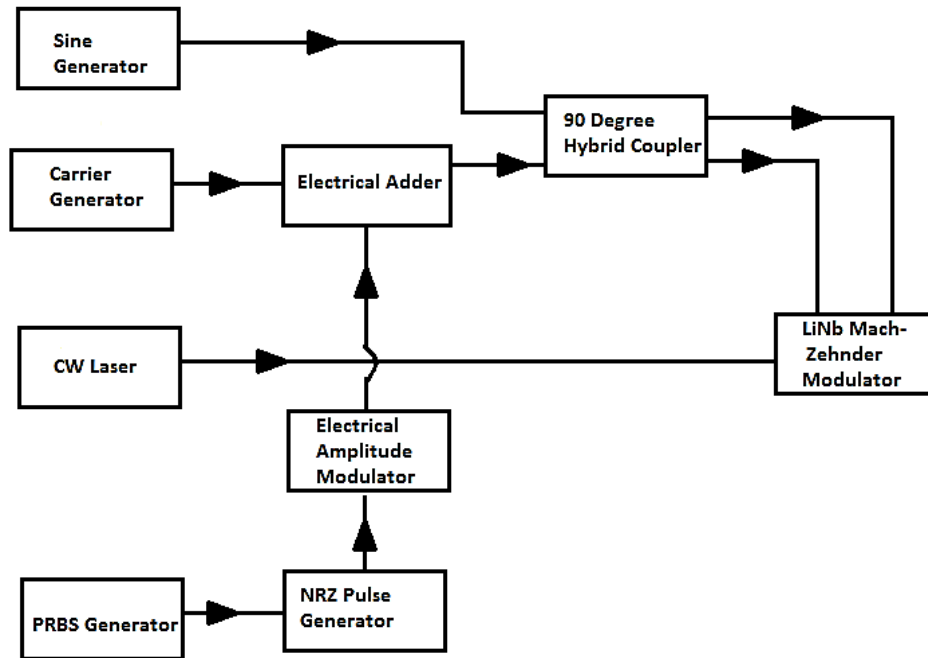


Figure 3.2 Internal structure of transmitter.

On the receiver side, a bidirectional circulator is used to avoid optical interferences occurring between downlink and uplink signal. A WDM demultiplexer (with a bandwidth of 16 GHz) demultiplexes the received signal and then further distributes to the respective receivers. The main component used here is a bidirectional reflective filter for the purpose of wavelength reuse. This filter allows a portion of signal to pass through and reflects the remaining information carrying signal for demodulation. The reflected signal is demodulated by a PIN diode which is followed by a BPF.

The portion of received signal passed through bidirectional reflective filter is modulated by amplitude modulator which is driven by 1Gbps baseband signal. WDM multiplexer

(with a bandwidth of 70GHz) multiplexes the signal coming from each channel which is sent again to the transmitter side as uplink signal. On the transmitter side, the uplink signal is demultiplexed by WDM demultiplexer (with a bandwidth of 55GHz) and is further demodulated by passing through a PIN diode and Bessel filter.

3.3 RESULTS AND DISCUSSION

The proposed WDM-RoF network is positively simulated and analyzed using OptiSystem 7.0, a commercial optical system simulator. Figure 3.3 shows the optical spectrum after getting multiplexed by WDM multiplexer. The spectrum is observed by using optical spectrum analyzer at the output of WDM multiplexer.

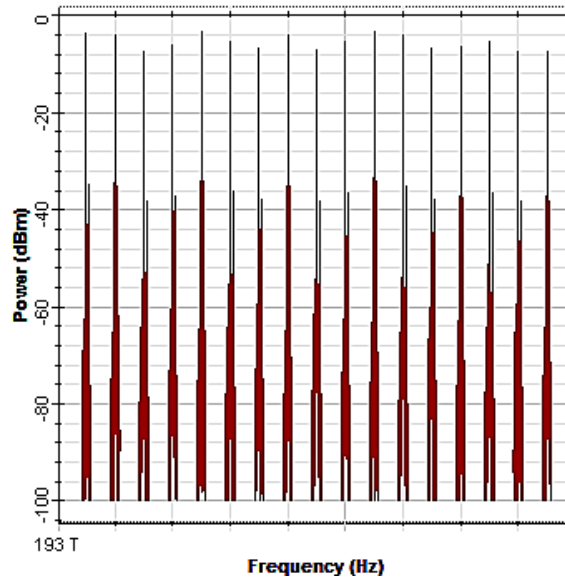
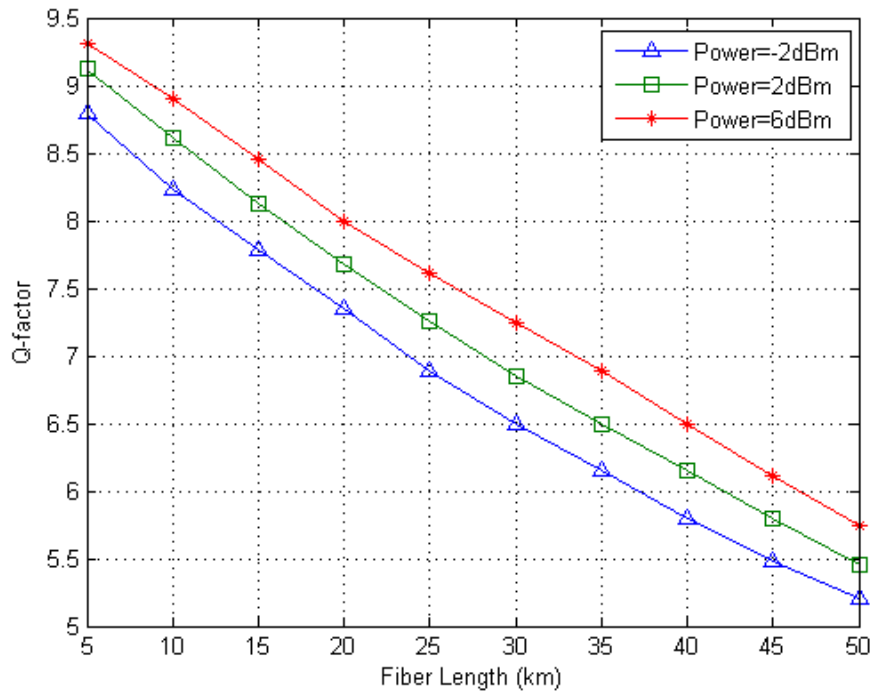


Figure 3.3 Optical spectrum after multiplexing

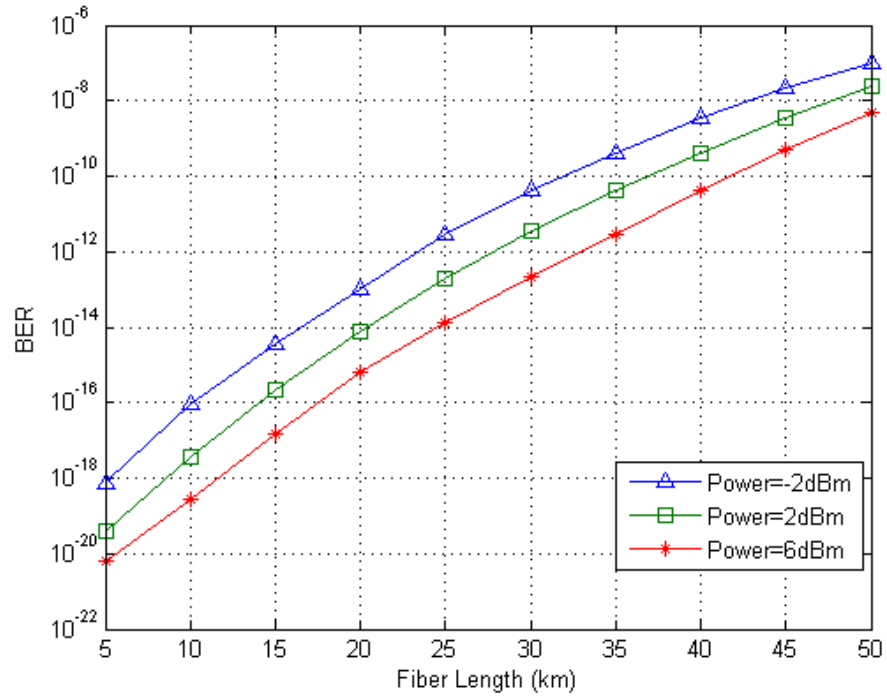
Figure 3.4 graphically shows the variation of Q-factor and BER against the length of optical fiber at different input powers (such as -2dBm, 2dBm and 6dBm). From the results, it is noticed that as the length of fiber is incremented, the Q-factor decrements as depicted in figure 3.4(a). This is attributed to attenuation and dispersion losses which increase with the fiber length. In the simulation setup, when the input power is increased from -2dBm to 2dBm and 6dBm, the value of Q-factor also increases from 8.79 to 9.12 and 9.31 respectively when the length of fiber is set to 5km. From figure 3.4 (b), it is

observed that the BER increases as the length of fiber is increased from 5km to 50 km. This variation of BER with fiber length has been recorded at three different values of input power. For instance, in the proposed system, the BER decreases from 3.6262×10^{-15} to 2.14651×10^{-16} and 1.4565×10^{-17} when the input power is increased from -2dBm to 2dBm and 6dBm respectively, when the length of fiber is kept fixed at 15km.

Figure 3.5 demonstrates the variation of Q-factor and BER against channel input power at three diverse lengths of optical fiber. The input power is changed from - 15dBm to 15dBm with a step of 5dBm and the estimations of Q-factor are taken. In figure 3.5(a), it is noticed that as the Q-factor increases with the input power. It is because as the input power of channel is increased, the inter-channel distortion and other nonlinearities are avoided. The proposed setup provides acceptable values of Q-factor such as 8.91, 7.71 and 6.04 over a fiber length of 10km, 20km and 30km respectively with a fixed input power of 5dBm. From figure 3.5 (b), it is observed that BER decreases with the increase in channel input power. Three lines in figure 3.5(b) show the variation of BER with input power for different fiber lengths (10km, 20km and 30km). For example, the BER comes out to be 6.9629×10^{-20} , 1.8206×10^{-15} and 5.7036×10^{-10} for a fiber length of 10km, 20km and 30km respectively with the value of input power fixed at 10dBm.

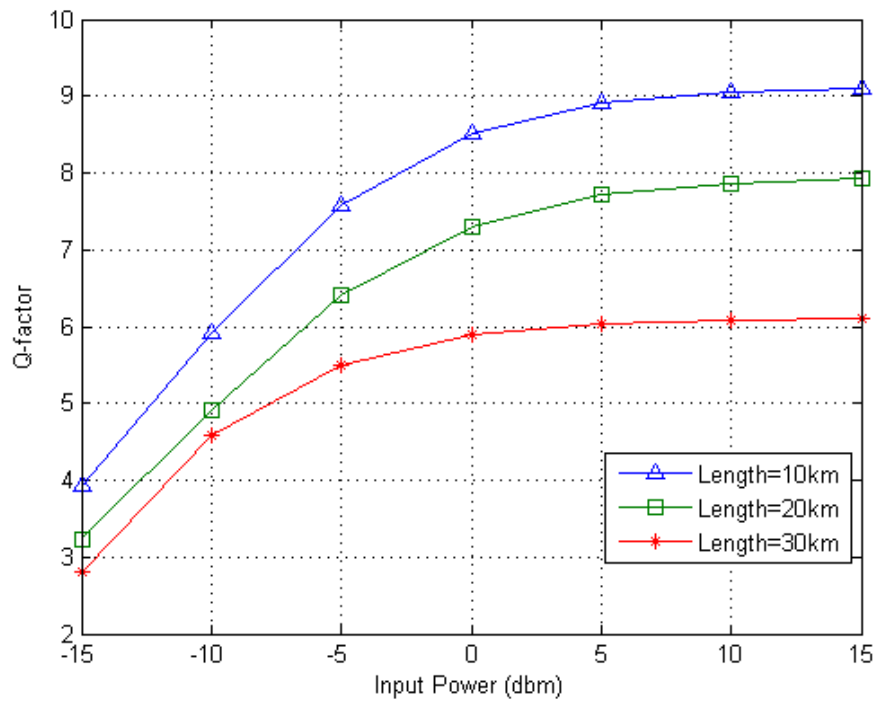


(a)

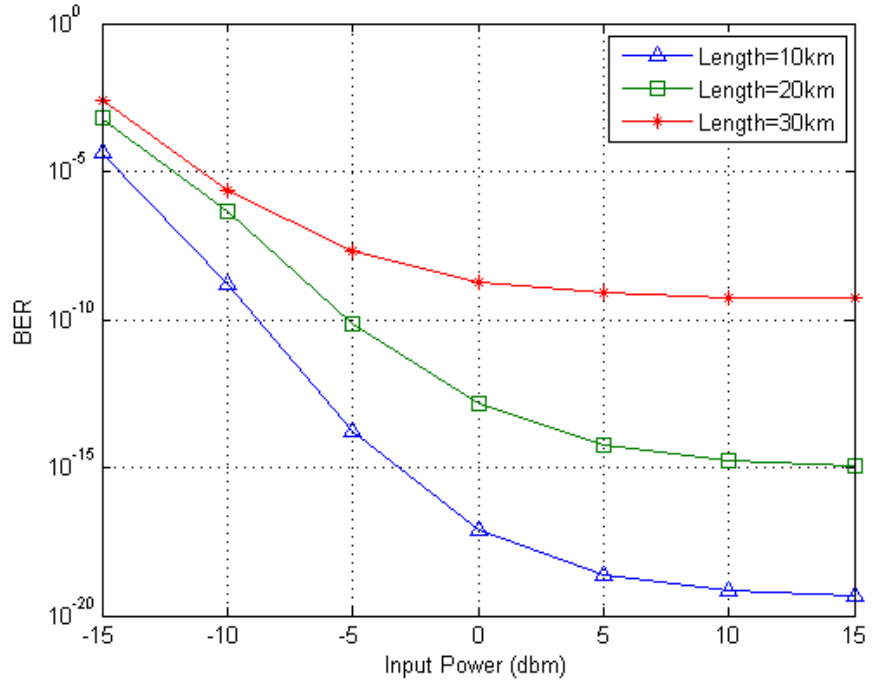


(b)

Figure 3.4 Variation of Q-factor and BER as a function of fiber length for different input powers, -2dBm, 2dBm and 6dBm (a) Q- factor (b) BER



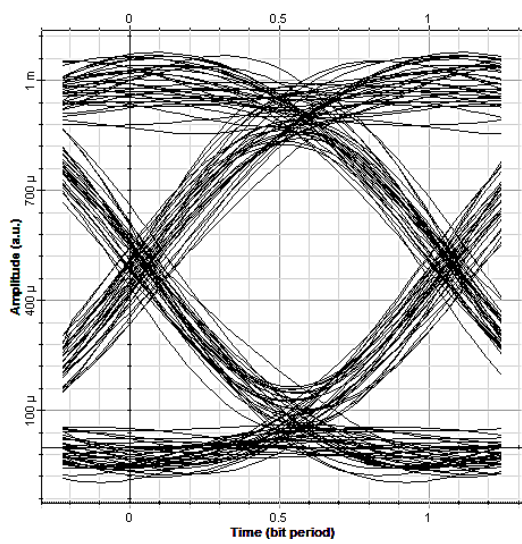
(a)



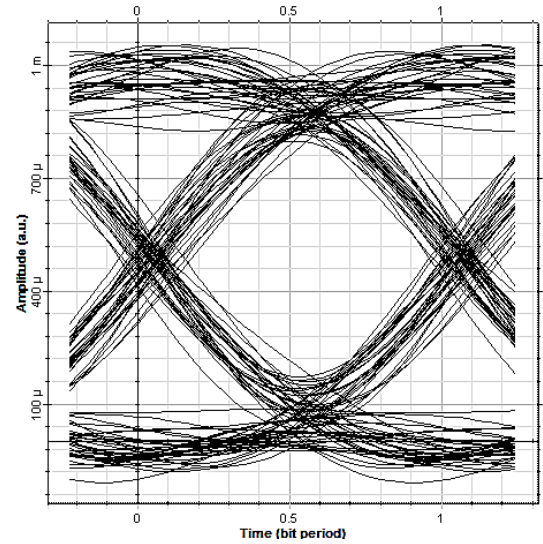
(b)

Figure 3.5 Variation of Q-factor and BER with input power at different optical fiber lengths, 10km, 20km and 30km (a) Q-factor (b) BER.

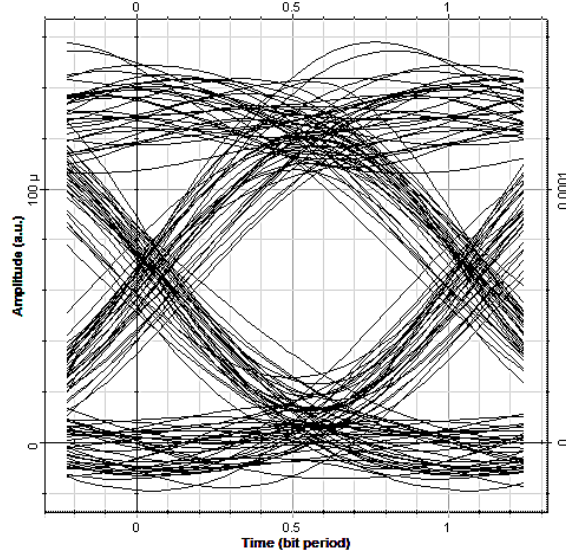
Figure 3.6 depicts the eye diagrams for downlink signal at three distinct optical fiber lengths, 5km, 10km and 50 km. An eye diagram shows the signal quality during high speed digital signal transmission.



(a)



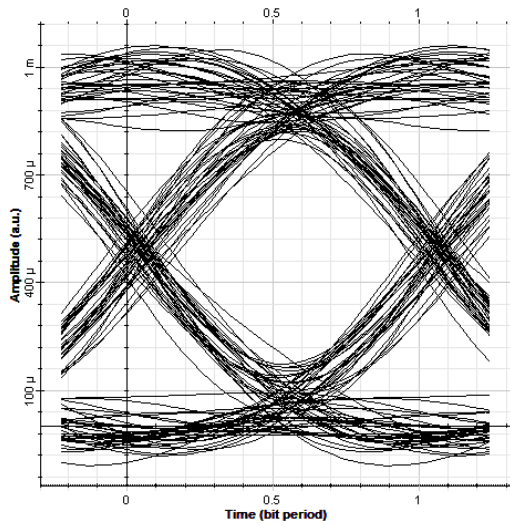
(b)



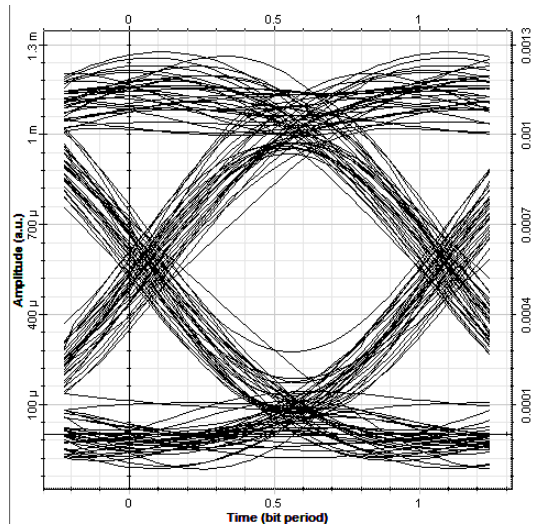
(c)

Figure 3.6 Eye diagram for downstream signal when (a) fiber length is 5km (b) fiber length is 10km and (c) fiber length is 50 km

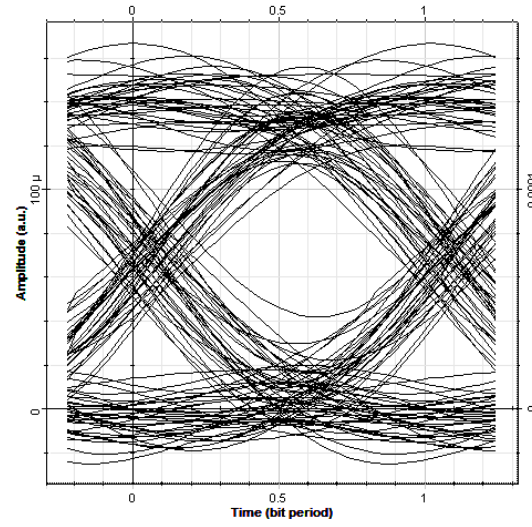
Figure 3.7 shows the eye diagrams for uplink signal at a fiber length of 5km, 10km and 50 km. A system performance can be measured effortlessly with the assistance of an eye diagram. The eye opening in each figure clearly indicates that the system has smooth execution up to a transmission distance of 50km.



(a)



(b)



(c)

Figure 3.7 Eye diagram for upstream signal when (a) fiber length is 5km (b) fiber length is 10km and (c) fiber length is 50km

WAVELENGTH REMODULATION IN RADIO OVER FIBER NETWORK USING FIBER BRAGG GRATING

RoF is an amalgamation of both optical and wireless technologies offering the benefits of high information rate and increased mobility. In this chapter, a full duplex RoF PON is proposed based on wavelength remodulation using FBG. Simulation of the proposed system demonstrates 1Gbps uplink and 1Gbps downlink signals sharing the same CW laser source located at the remote CS. The performance of system is investigated in terms of BER, OSNR, received optical power and eye diagrams of the transmitted signals. The results show that the network performance is improved by decreasing the overall dispersion of the fiber link using FBG and DCF. The system exhibit smooth execution up to a transmission distance of 100km and henceforth, is capable of supporting long haul transmissions.

4.1 INTRODUCTION

The global internet protocol traffic is growing at an enormous pace and it is expected to cross the zettabyte threshold by the end of 2016. So, it's high time to develop a technology that can support the rapidly growing internet bandwidth demand. One of the possible solutions for providing broadband capacity and transmission stability is PON. The PON based wired networks are globally accepted as optical network solutions for allocating rationally high bandwidth to the users [39]. But the major drawback is that wired networks lack flexibility needed for moving connections. Wireless networks offer flexibility and portability to the users but fall short in bandwidth issue [59]. So there is a need to develop a convergent network architecture, which by exploiting the advantages of wired and wireless technologies, provides multiple services to both mobile and fixed users. RoF is the spectacular combination of both wired and wireless communication.

The concept of RoF involves modulation of light by a radio signal followed by transmission over an optical fiber in order to support wireless access. A RoF based

network utilizes the huge bandwidth offered by optical fiber and shifts the network complexity to CS. A CS is linked to several BSs through an optical fiber link [60]. The processing of microwave signal (modulation, coding and routing) occurs at the CS, after which the signal is shifted from microwave domain to optical domain and distributed to the BSs through an optical fiber. At the BS, only amplification and optoelectronic conversion of signal is performed. Thus, RoF technique offers the advantage of using simple BSs along with centralized control of processing functions of radio signals. This centralized control provides the additional benefits of dynamic allocation of resources, equipment sharing and simplified system operation.

Many researchers have already addressed the same problem and made progress to provide a solution. Seena et al. [25] proposed a RoF system centered around remodulation using FBG and delivering an information rate of 1Gbps per cell. The system was capable of supporting transmission up to a distance of 50km. Singh et al. [55] proposed a WDM-RoF system transmitting 1Gbps downlink and uplink information streams over a length of 25km with the aim to acquire an adequate quality factor. Coelho et al. [61] studied the performance of orthogonal frequency division multiplexed signal in a frequency-interleaved WDM-RoF network using FBG for optical channel selection. Nahal [42] proposed a full-duplex RoF framework transmitting a DPSK signal and using on-off keying modulation format for the remodulation of downlink carrier which is transmitted as upstream signal.

Previously proposed frameworks were suitable for short haul signal transmission where the number of channels needed a reduction in order to increase the transmission distance, which as a result, decreases the capacity of the system. Other schemes required extra optical carriers in order to accomplish the full duplex criterion and were relatively expensive to implement practically.

In this chapter, a full-duplex RoF framework is proposed and a wavelength reuse scheme is used to increase the number of users. This framework supports long haul transmissions and eliminates the requirement of using a separate source of light at the BS. It results in simplifying the structure of BS and reducing the overall system cost.

4.2 THEORY AND SIMULATION SETUP

The block diagram of proposed framework is shown in figure 4.1. At the CS, a CW laser with an operating frequency of 193.1THz and linewidth of 0.1MHz is used. The input power of channel is set to 0dBm. A PRBS generator (with a bit rate of 1Gbps) is used to initiate a Gaussian pulse generator in order to generate a 1Gbps baseband signal. The pulse generator provides an electrical network which is simple and low speed. An amplitude modulator is used for radio frequency modulation which translates the frequency of baseband signal into the frequency of RF clock. In RF domain, ASK scheme is utilized. The RF signal is connected to 90° hybrid coupler after its combination with SCM generator. In order to convert the modulated RF signal into optical domain, a dual drive dual port LiNb MZM is utilized. The two input ports of MZM are connected to the output ports of 90° hybrid coupler and third input port is connected to CW laser for optical modulation. In order to convert the modulated RF signal into optical domain, a dual drive dual port LiNb MZM is utilized. The two input ports of MZM are connected to the output ports of 90° hybrid coupler and third input port is connected to CW laser for optical modulation.

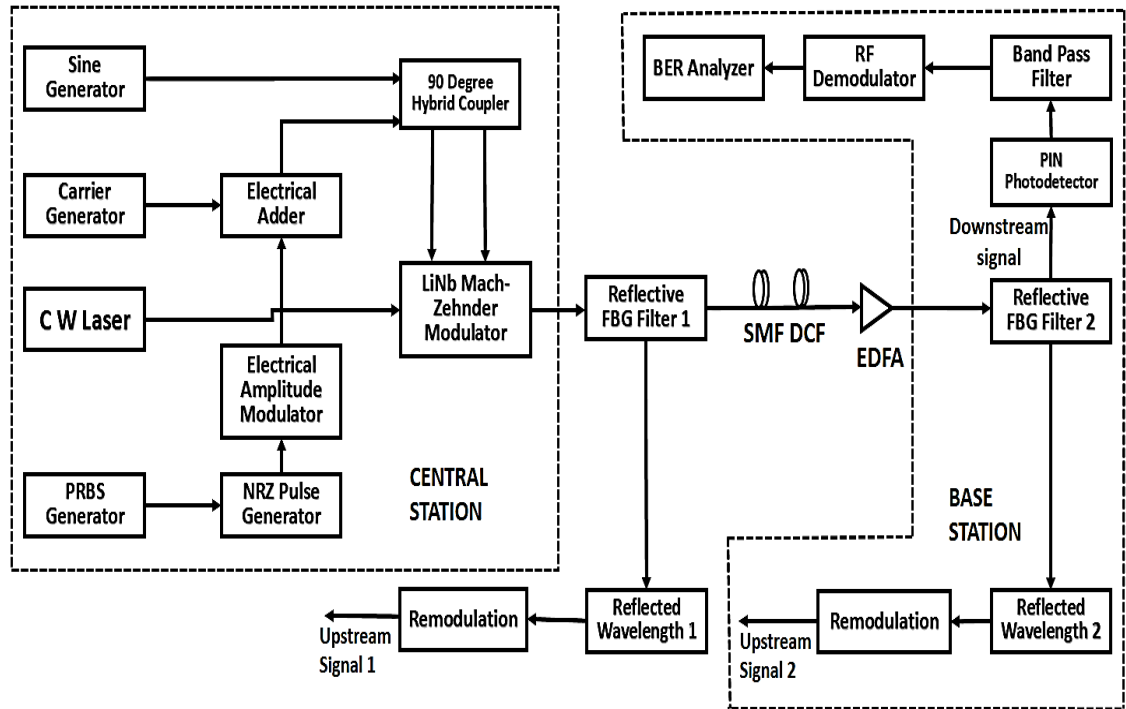


Figure 4.1 Block diagram of the proposed RoF network

The operating speed of MZM limits the extremely high information rate and thus, a trade-off is maintained between extremely high information rate and cost of installation. The

output signal from MZM is connected to a power splitter which splits the power of the optical signal into two portions. One portion is transmitted over a SMF followed by DCF and the other portion is fed to FBG filter. FBG filter reflects a particular optical wavelength for upstream transmission and transmits all others of the downstream signal. At the BS, a power splitter is utilized. It splits the power of received signal. One portion of the received signal is demodulated by applying to a series of PIN diode, band pass filter and RF demodulator. Other portion is applied to FBG filter for the purpose of reusing the downstream wavelength for upstream transmission.

FBG filter offers the benefit of reusing the downstream wavelength without requiring any additional light source. This simplifies the design of the network and also reduces the system cost. A grating is a crucial component in WDM systems in order to combine and separate individual wavelengths. A FBG has a periodic structure and is built in a small section of fiber link to reflect specific wavelengths of light. Thus, a FBG can be utilized as wavelength-specific reflector allowing all the wavelengths to pass through except the one which satisfies the Bragg law.

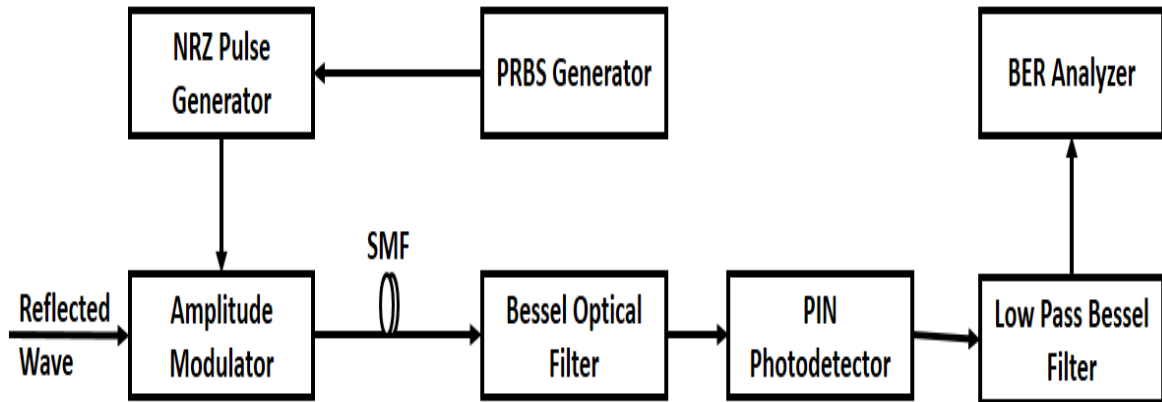


Figure 4.2 Internal structure of wavelength remodulation block

Figure 4.2 shows the internal structure of remodulation. The wavelength reflected by the FBG filter is applied to an amplitude modulator which is driven by a 1Gbps baseband signal. Thus, the downstream signal is remodulated twice and is transmitted through a

SMF as the upstream signal. At receiver, the upstream signal is demodulated by passing through a PIN diode and Bessel filter and is investigated by using a BER analyzer.

4.3 RESULTS AND DISCUSSIONS

Figure 4.3(a), (b), (c) and (d) show the optical spectrum of the transmitted signals. Figure 4.3(a) represents the optical spectrum of the modulated signal at the output of MZM. Figure 4.3(b) shows the optical spectrum of downlink signal after transmitting over the SMF. Figure 4.3(c) and 4.3(d) represent the optical spectrum of the wavelengths reflected by FBG filter1 and FBG filter2 respectively which are further remodulated and sent as uplink signals. From the results, it can be concluded that an acceptable output power is achieved for both uplink and downlink data streams.

Figure 4.4 shows the BER of the system as a function of OSNR for downstream and both upstream transmissions. It is observed that the BER decreases as the value of OSNR increases in each signal transmission. The downlink signal shows less BER than that of the uplink signals because in downlink transmission, a CW laser and MZM is used for the optical modulation of RF modulated signal while remodulation is used for both the uplink transmissions. The results depict that the system shows good performance for both upstream and downstream transmissions in terms of BER and OSNR.

Figure 4.5(a) and (b) show the variation of received optical power with respect to length of fiber (used for downstream transmission) for three different values of EDFA gain, 5dBm, 10dBm and 20dBm. The length of fiber is changed from 10km to 100km with a step of 10km. Figure 4.5(a) represents the variation of optical power for downstream signal received at the BS with the length of fiber. A decrement in the received power is observed with the increment in fiber length, which happens due to increase in the attenuation losses with fiber length. So, EDFAs are utilized in communication links to compensate for these losses. With the increase in gain of EDFA from 5dBm to 10dBm and 20dBm, the received optical power also increases. Figure 4.5(b) depicts a graph of received power against fiber length plotted for upstream signal 2 which remodulates the downstream signal reflected by FBG filter 2 (used at the BS). It is observed that the

power of the received upstream signal decreases with the fiber length. But acceptable values of output power are achieved in each transmission up to a fiber length of 100km.

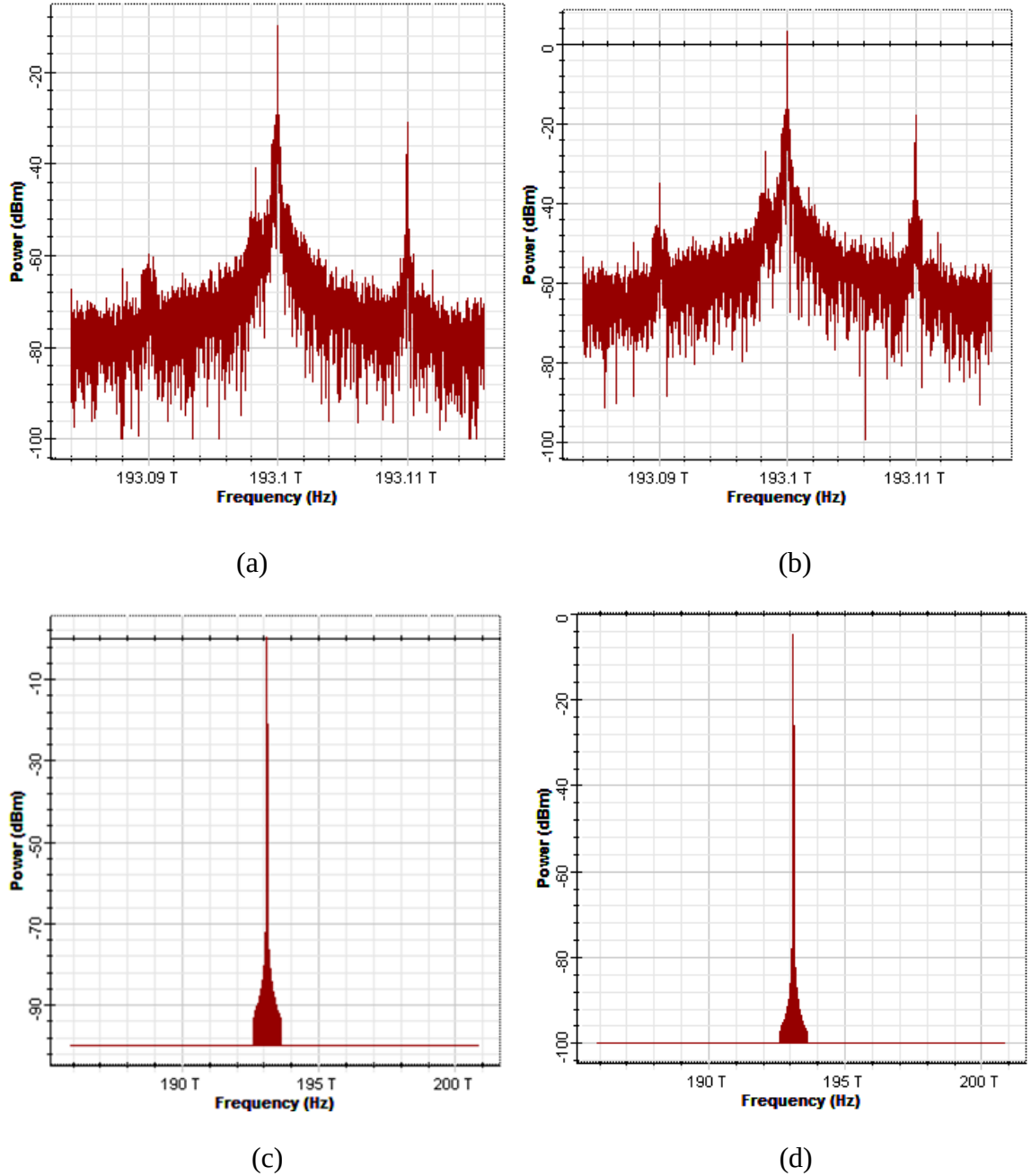


Figure 4.3 Optical spectrum of (a) signal after modulation by MZM (b) downlink transmission (c) wavelength reflected by FBG1for uplink transmission1 (d) wavelength reflected by FBG2 for uplink transmission2

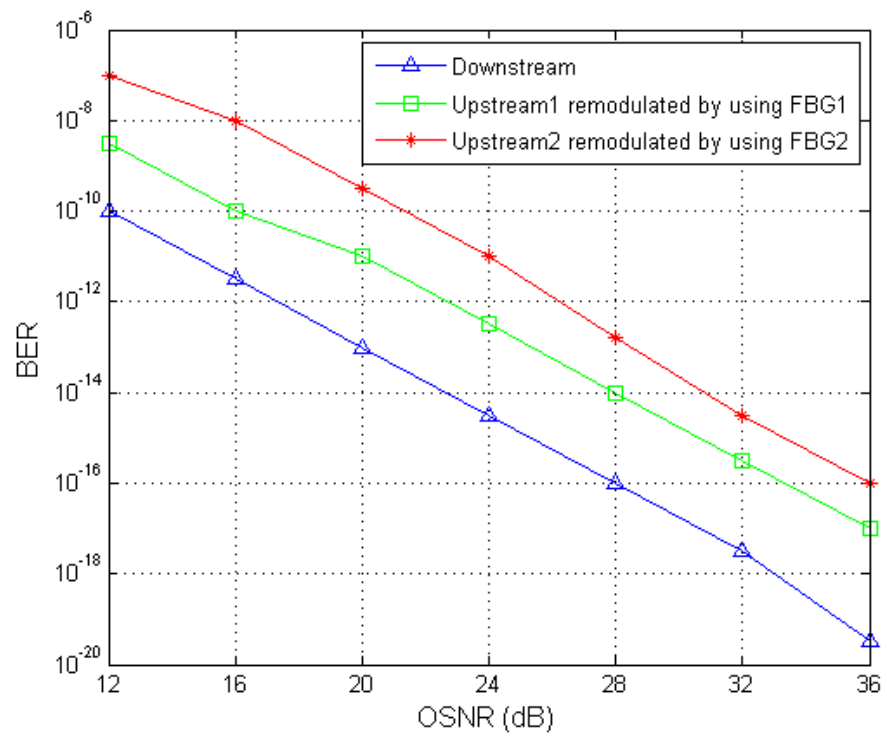
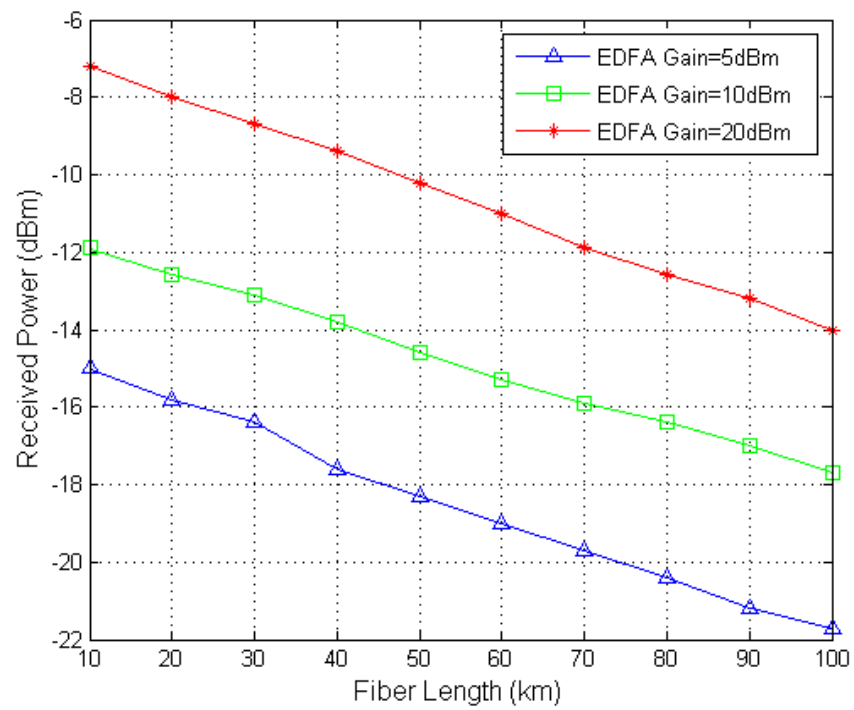
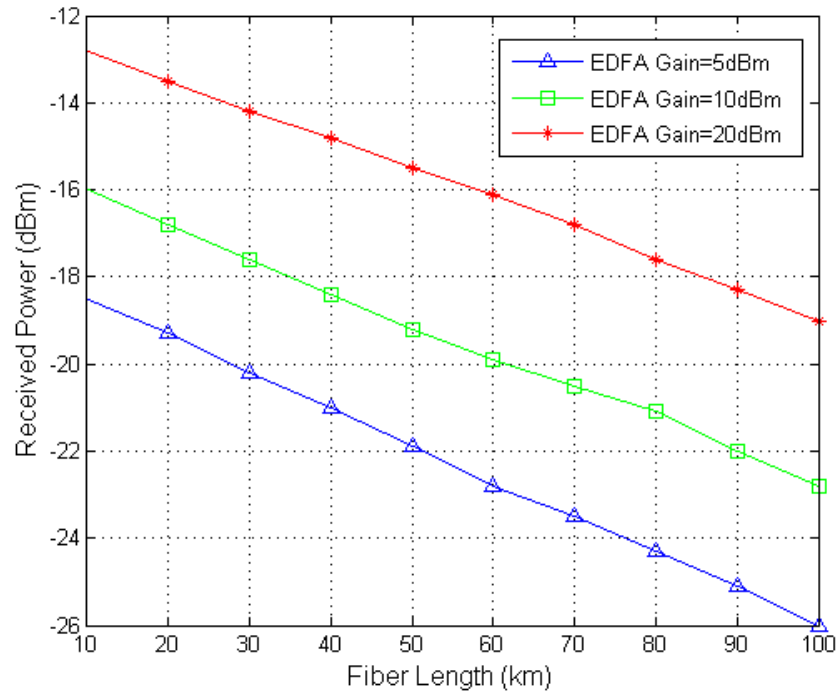


Figure 4.4 Variation of BER with OSNR for the downstream and the two upstream signals.



(a)



(b)

Figure 4.5 Variation of received power with fiber length for different values of EDFA gain, 5dBm, 10dBm and 20dBm for (a) downstream signal (b) upstream signal 2 remodulated by using FBG filter 2.

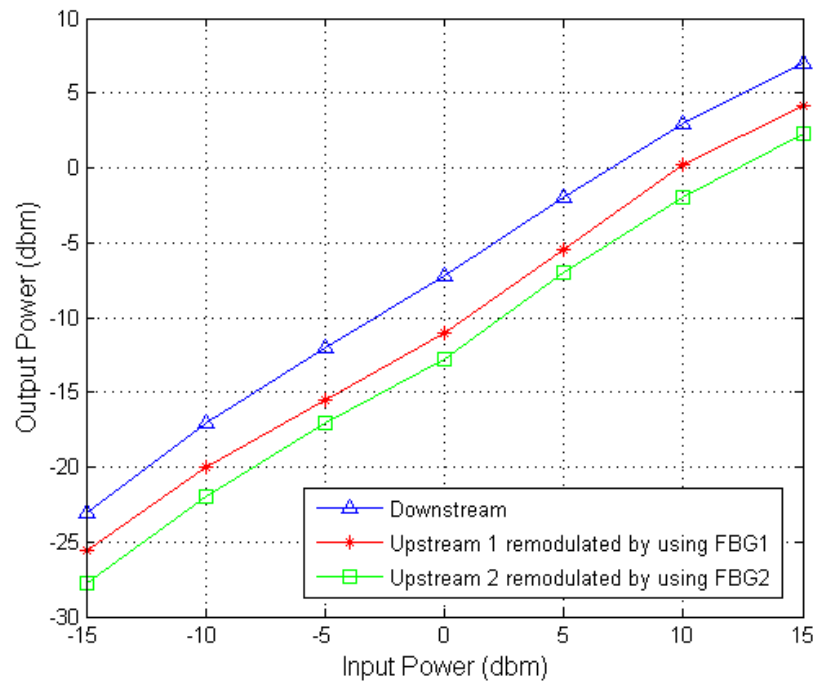
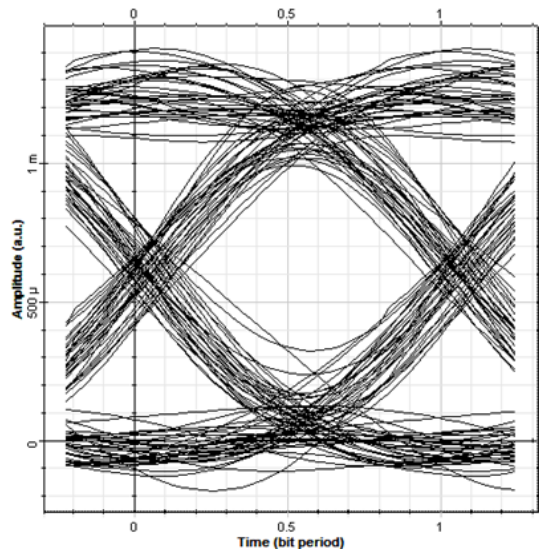
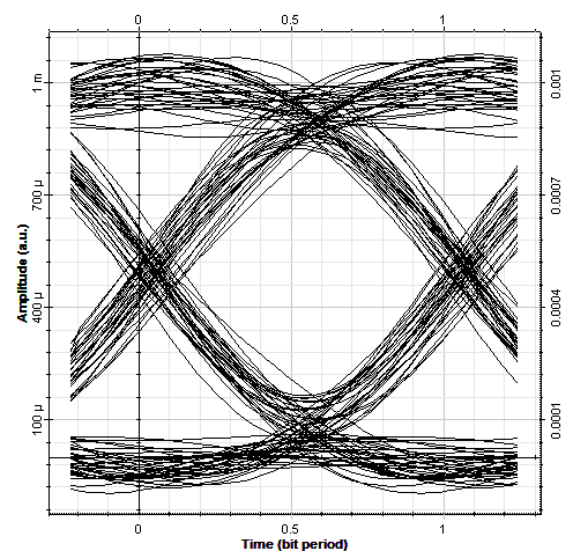


Figure 4.6 Variation of output power against the input power for the downstream and the two upstream signals.

Figure 4.6 depicts the variation of output (received) power as a function of input power for the downstream and the two upstream signals. It is noticed that the output power increases with the input power for each transmission. For better clarification, eye diagrams are taken for the proposed system. Figure 4.7(a), (b) and (c) show the eye diagrams for downlink and uplink signals with and without dispersion compensation provided by FBG and DCF. From the eye opening in each figure it is noticed that the quality of signal improves after dispersion compensation.

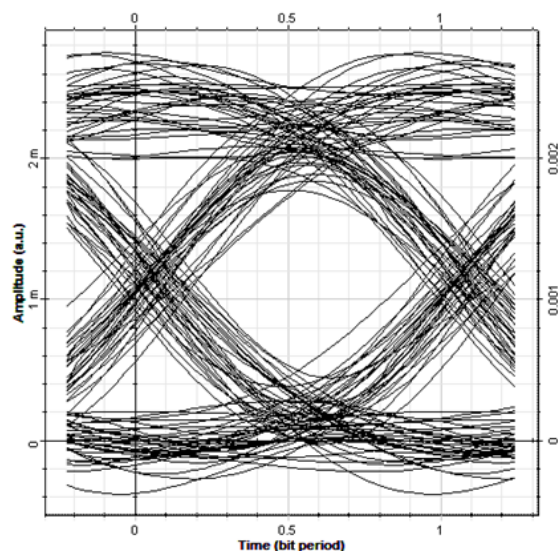


Without dispersion compensation

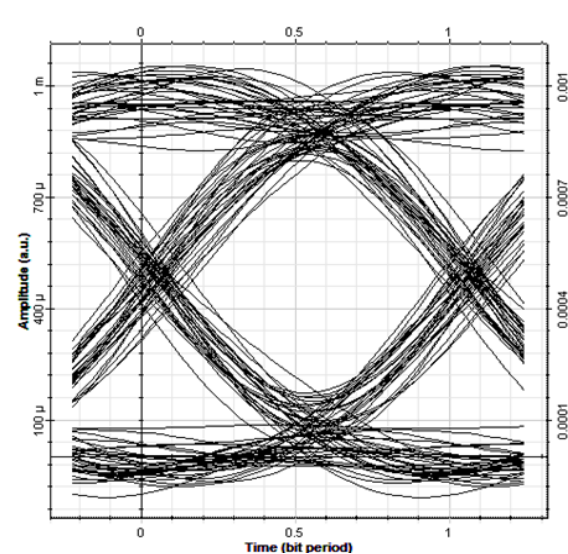


(a)

With compensation

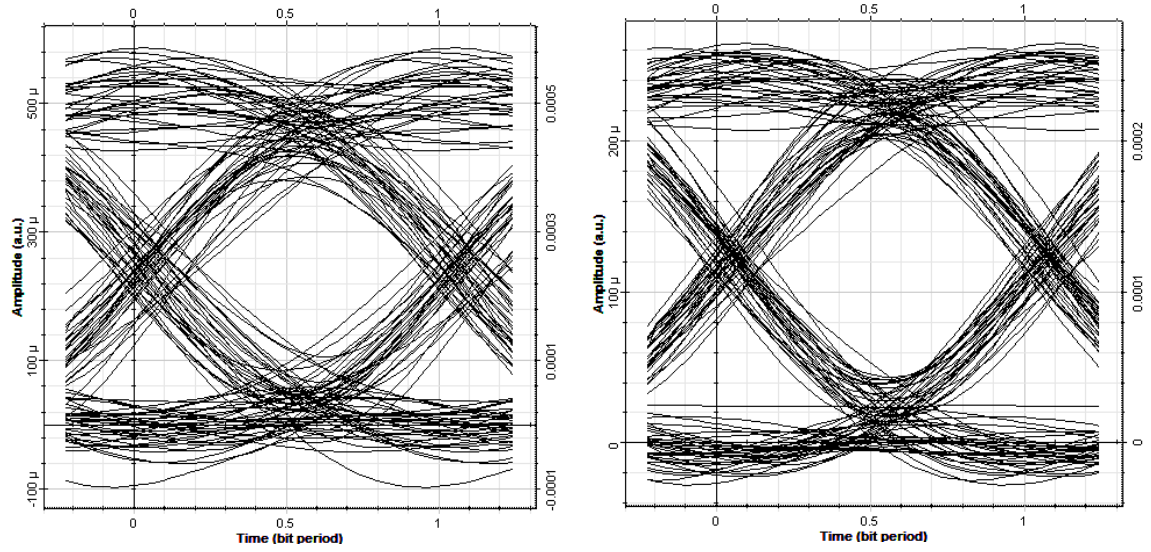


Without dispersion compensation



(b)

With compensation



Without dispersion compensation (c) With compensation

Figure 4.7 Eye diagrams with and without dispersion compensation for (a) downstream transmission (b) upstream transmission remodulated by using FBG filter1 (c) upstream transmission 2 remodulated by using FBG filter2.

SUPPRESSION OF FOUR WAVE MIXING EFFECTS IN RADIO OVER FIBER SYSTEM

In this chapter, hybrid FWM suppression modules are proposed to reduce the effects of FWM in WDM-RoF network. The two hybrid modules comprise of OPC, FBG and DCF. These modules improve the execution of the WDM-RoF framework by suppressing the FWM power up to 30dBm. The overall FWM power is estimated and is found to vary with channel input power. The results depict that the FWM power varies from -70dBm to -47.5dBm in FBG plus OPC module and from -73.6dBm to -49.8dBm in DCF plus OPC module. The FBG plus OPC module provides a suppression of FWM power up to 27.3dBm while the FBG plus OPC module suppresses up to 30dBm. Thus, DCF plus OPC module has greater efficiency for mitigating FWM effects than the FBG plus OPC module.

5.1 INTRODUCTION

RoF is a spectacular incorporation of both wired and wireless technologies offering the benefits of high information rate and increased mobility. The concept of RoF involves transmission of RFs over an optical fiber link in order to support several wireless applications. The modulation of the broadband microwave information signals on an optical carrier occurs at the central station which are then transferred to remote locations via an optical fiber link [62]. Normally when light waves are transmitted through RoF, they have slight interactions with each other and do not change while passing through the optical fiber link. However, there are exceptional cases in which the light waves interact with the material transmitting them and generate nonlinear effects [26]. The two reasons behind the nonlinearities are, intensity dependence of the refractive index of medium and inelastic-scattering phenomenon.

FWM is one of the nonlinear effects occurring due to the power dependence of refractive index in optical fiber link. FWM occurs in an optical fiber when two or more light waves

of variable wavelengths are launched in a WDM system [63]. This not only leads to the shifting of the phase of signals coming from the channels but also generation of new cross products. These generated cross products cause interference with the original wavelengths and results in mixing.

Several methods are available to suppress the undesirable effects of FWM. OPC, FBG, DCF and rectangle filter are some of the components that are used in a WDM system to mitigate the FWM effects. Many researchers have already addressed the same problem and made progress to provide a solution. Selvamani et al. [64] mitigated the FWM effects by putting an OPC in the middle of optical fiber. The FWM was reduced by 0.3–0.8dBm which is insignificant according to current requirements. Kaur et al. [37] analyzed the FWM power mitigation in hybrid topology by utilizing an OPC. The hybrid network topology consisted of bus and ring topologies. Jain et al. [65] analyzed the performance of WDM system using several external modulation schemes and optical filter under the FWM effects. Sharma et al. [66] stated the improved analysis for XPM and SPM induced crosstalk by changing the walk off parameters with the aim to reduce the induced crosstalk.

In previous works, authors have used a single component (FBG, DCF, OPC or rectangle filter) to reduce the FWM effects and were able to achieve the suppression till 20dBm. The authors mainly concentrated on FWM mitigation in systems based on WDM technique. In this chapter, the FWM effects are investigated in a system in which WDM is integrated with RoF technology. The previously stated investigations are extended by further suppression of FWM power using hybrid technologies. FBG plus OPC and DCF plus OPC are the two hybrid modules whose performance is compared for different channel input power.

5.2 THEORY AND SIMULATION SETUP

In the proposed WDM-RoF framework, two signals with wavelength of 1551.72nm and 1552.52nm (with a spacing of 0.8nm) are transmitted as shown in figure 5.1. The transmitter consists of CW laser whose power is varied from -15dBm to 15dBm with a step of 5dBm. The output of CW laser is modulated by a phase modulator using a sine

generator with a frequency of 10 GHz. The sine generator is used to transmit modulated radio signals. The phase modulator translates the microwave signal into optical signal. The two signals are combined by a WDM multiplexer and transmitted over a SMF of length 15km followed by the hybrid modules. At the receiver side, a WDM demultiplexer demultiplexes the received signal and then further distributes to the respective receivers. The received signal is demodulated by passing through a PIN diode and Bessel filter and is investigated by using a BER analyzer.

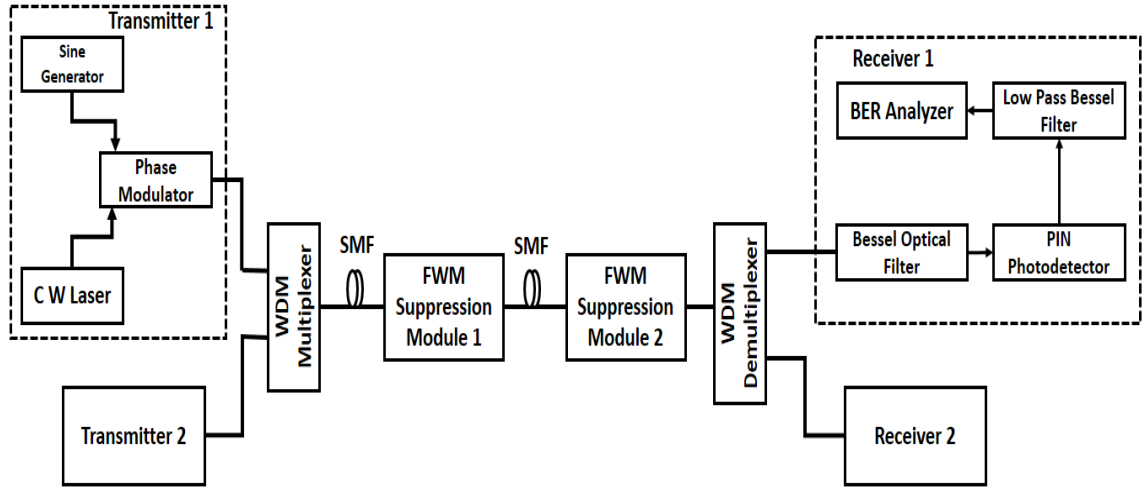


Figure 5.1 Block diagram of the proposed WDM-RoF system

Figure 5.2(a) and (b) depict the two different FWM suppression hybrid modules comprising of OPC, FBG and DCF. FBG+OPC forms the hybrid module in which FBG is placed after the SMF and is followed by an OPC as shown in figure 5.2(a). The first OPC (OPC1 used in FWM suppression module 1) is placed in the middle of two spans of SMF. OPC1 optically conjugates the phase of optical signal in the middle of transmission link so that the impairments occurring before conjugation (in the first fiber span of SMF) can be cancelled by the impairments occurring after conjugation (in the second span of SMF). The other OPC placed at the output of second SMF span recovers the original signal from the reversed one. The other component used is FBG. A FBG is utilized as wavelength-specific reflector allowing all the wavelengths to pass through except the one which satisfies the Bragg law.

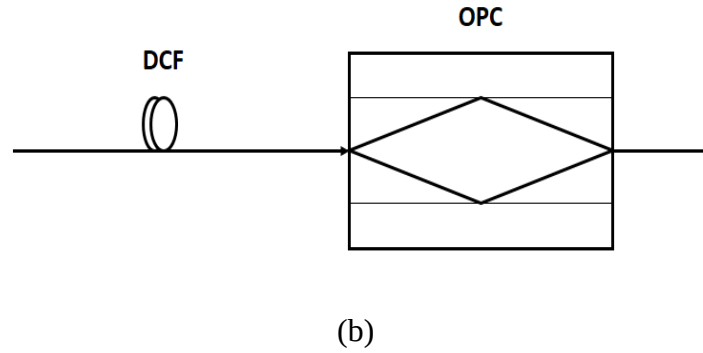
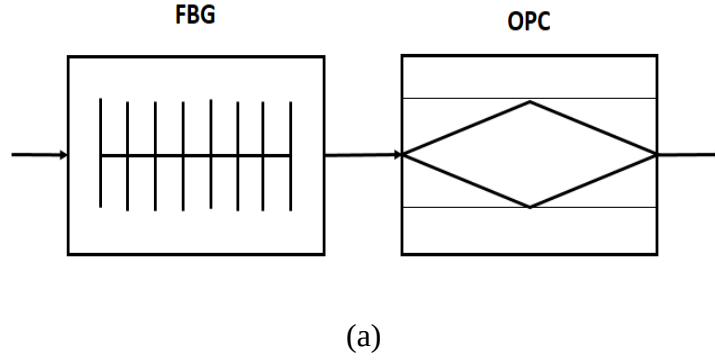


Figure 5.2 FWM mitigation hybrid modules (a) FBG+OPC hybrid module (b) DCF+OPC hybrid module

Figure 5.2(b) shows the hybrid module involving DCF+OPC. The FWM effects are suppressed twice by DCF which is followed by the OPC. OPC1 is placed between two fiber spans consisting of SMF and DCF. FWM occurs in those WDM networks where dispersion is very small. So, those components are utilized which deliberately add dispersion in WDM networks. DCF compensates this purposely introduced dispersion in optical fiber link which leads to reduction in FWM.

5.3 RESULTS AND DISCUSSIONS

Figure 5.3(a), (b) and (c) show the optical spectrum of the multiplexed signal. The optical spectrum of signal without any FWM suppression is shown in figure 5.3(a). The FWM power in this case is -47.5dBm. Figure 5.3(b) and 5.3(c) depict the optical spectrum of signal after suppressing the FWM effects using FBG+OPC and DCF+OPC hybrid modules respectively. It is observed that the FWM power is suppressed from -47.5dBm to -56dBm in FBG+OPC module and from -47.5dBm to -60dBm in DCF+OPC module.

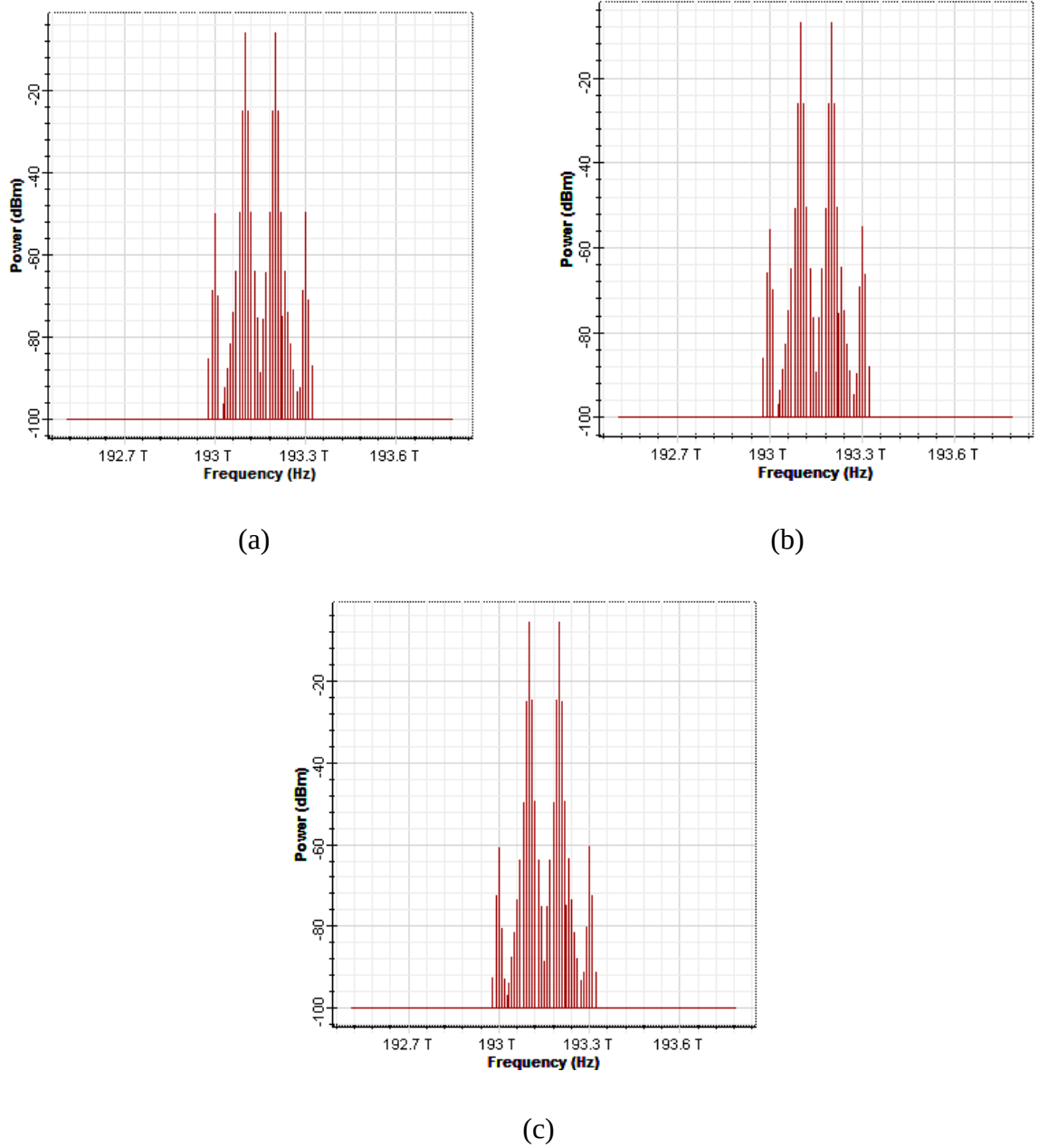


Figure 5.3 Optical spectrum of multiplexed signal (a) without any suppression (b) with FWM suppressed by FBG+OPC module (c) with FWM suppressed by DCF+OPC module

Figure 5.4 depicts the variation of overall FWM power as a function of channel input power. The FWM power is measured after the second fiber span when different hybrid modules are used. It is noticed that when the input power is increased from -15dBm to 15dBm, the FWM power also increases in both the configurations. This confirms that FWM depends directly on the power level of signal source. The DCF+OPC module

results in lower values of FWM power as compared to the FBG+OPC module. For instance, the value of FWM power is -55.2dBm and -58.3dBm in case of FBG+OPC and DCF+OPC modules respectively when the input power is fixed at 5dBm.

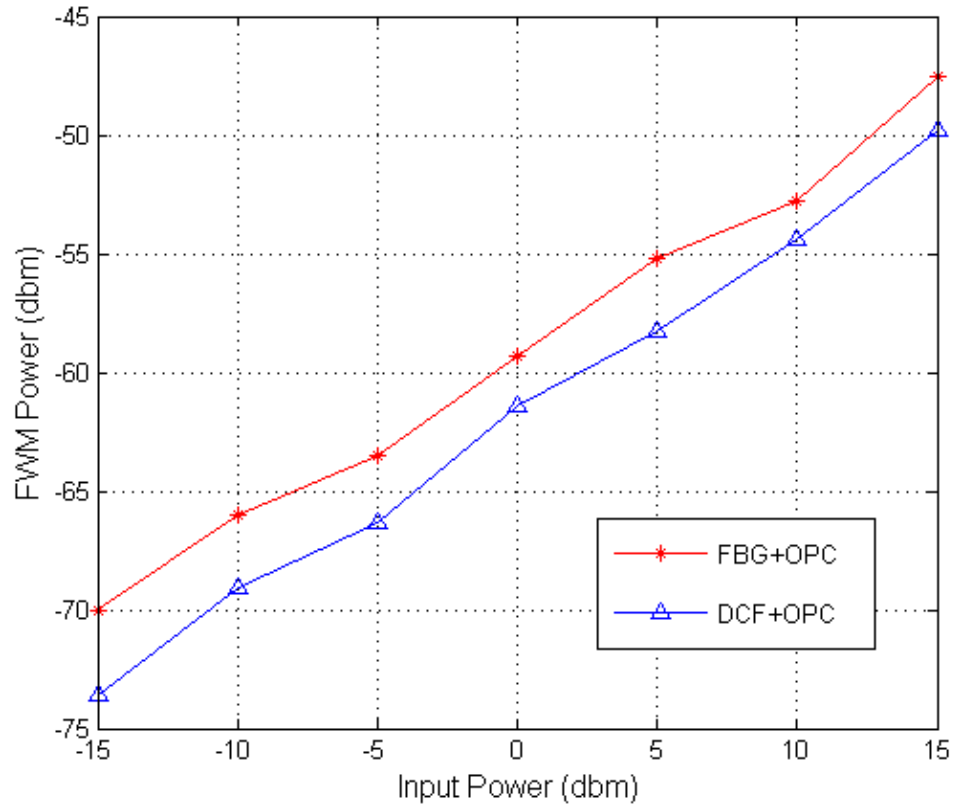


Figure 5.4 Variation of overall FWM power at the output of two hybrid modules against the channel input power.

In order to calculate the FWM power suppressed by the hybrid modules, the signal power is first analyzed after the first SMF (P1) and then after the OPC2 (P2). The final suppression of FWM power is calculated as: $(P1 - P2) - 3 \text{ dB}$, where 3 dB refers to attenuation which is a product of SMF length and its losses. Figure 5.5 shows the variation of suppressed FWM power with the channel input power for both the configurations. The results show that FWM power suppressed by the DCF + OPC module is larger as compared to the FBG + OPC module. In this setup, the suppressed FWM power is 22.9dBm and 24.5dBm in case of FBG+OPC and DCF+OPC modules respectively when the input power is set to -10dBm.

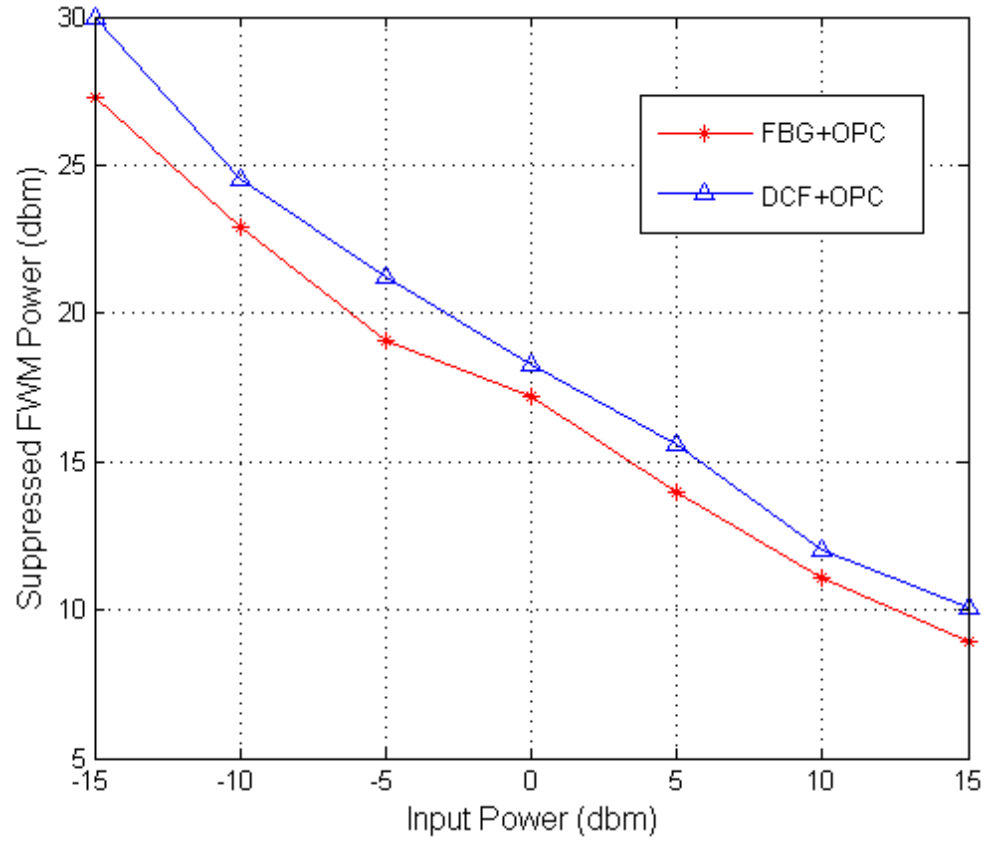
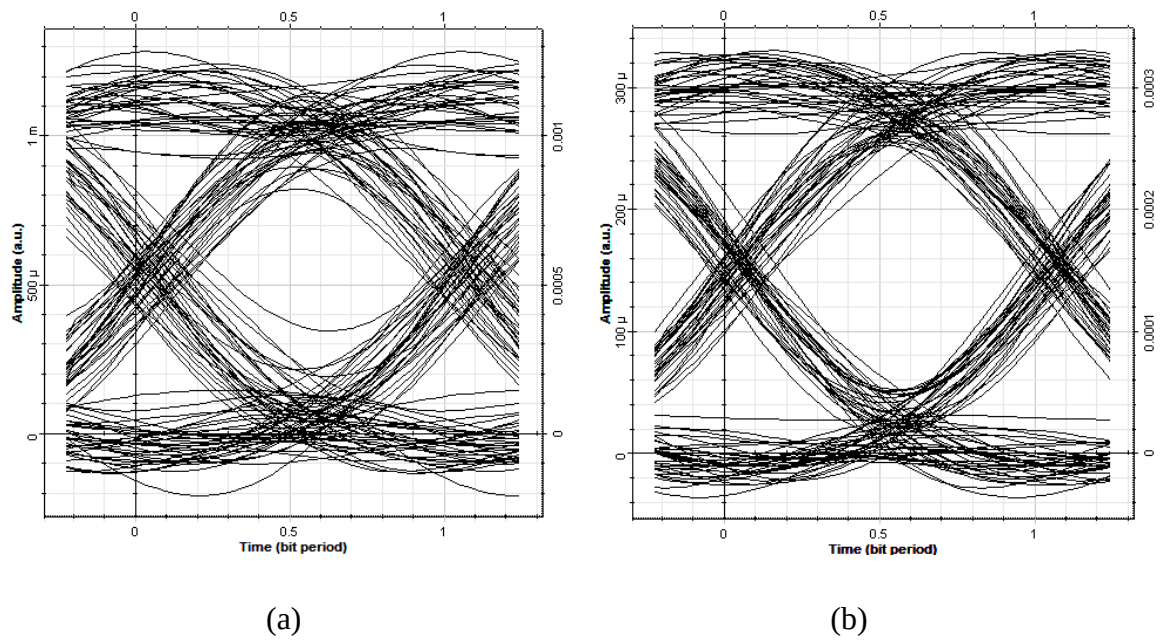
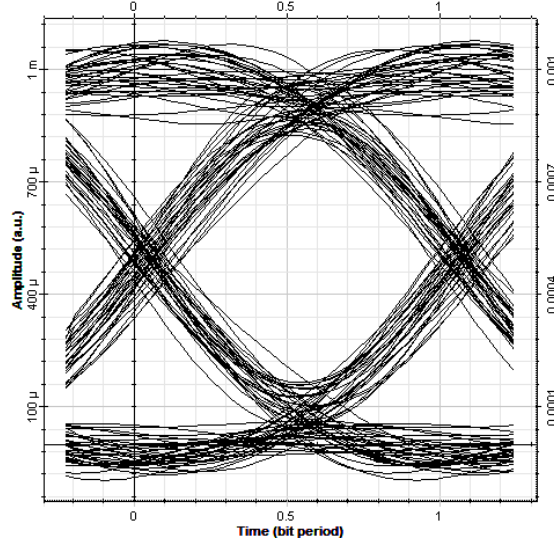


Figure 5.5 Variation of suppressed FWM power from the two hybrid modules against channel input power.





(c)

Figure 5.6 Eye diagrams of received signal (a) without any suppression (b) with FWM suppressed by FBG+OPC module (c) with FWM suppressed by DCF+OPC module.

Figure 5.6(a), (b) and (c) depict the eye diagrams of the received signal. Figure 5.6(a) shows the eye diagram of signal when no suppression module is used. Figure 5.6(b) and figure 5.6(c) show the eye diagrams when FBG+OPC and DCF+OPC hybrid modules are used respectively. An eye diagram indicates the signal quality during high speed digital signal transmission. The closure of an eye diagram depicts distortion in the signal waveform due to noise and intersymbol interference. The eye opening in figure 5.6(b) and (c) clearly shows that network performance is improved by using the hybrid modules.

CONCLUSION AND FUTURE SCOPE

6.1 CONCLUSION

The results and conclusions drawn from the research work done in this dissertation are summarized below:

1. In the first part, a bidirectional RoF WDM-PON using SCM/ASK strategy is proposed and investigated. The proposed system consists of 17 channels with a spacing of 0.4nm between subsequent channels. The narrow channel spacing offers the benefit of supporting a high data rate and huge number of clients. The execution of system is investigated on the basis of two critical parameters, Q-factor and BER. The results show that the proposed system offers acceptable values of Q-factor and BER for both the uplink and downlink signals up to a transmission distance of 50km. To summarize, the WDM-RoF network provides a reliable communication for a large number of users in order to meet up with the growing demand of internet bandwidth.
2. In the second part, a full duplex RoF PON based on remodulation using FBG is proposed. The same wavelength has been reused twice without using an additional source of light. This results in simplifying the design of BS and reducing the cost of the overall system. The system cost can further be reduced by increasing the number of users in the network. The execution of the system is improved by reducing the overall dispersion of the fiber link using FBG and DCF. The system shows acceptable values of BER and received power up to a transmission distance of 100km. Thus, the proposed system can be used for long distance transmissions. To summarize, RoF PON is an efficient and cost effective solution in order to meet up with the rapidly growing internet bandwidth demand.
3. In the third part, the effect of FWM suppression hybrid modules on the execution of WDM-RoF system is investigated. These hybrid modules improve the

performance of the system by mitigating the FWM power up to 30dBm. The overall FWM power and the suppressed FWM power are calculated for the two hybrid modules (DCF+OPC and FBG+OPC) and their variation is studied at different channel input power. The results show that the overall FWM power varies from -73.6dBm to -49.8dBm in case of DCF+OPC module and from -70dBm to -47.5dBm in case of FBG+OPC module. The DCF+OPC module suppresses the FWM power up to 30dBm while the FBG+OPC module suppresses it up to 27.3dBm. Thus, DCF+OPC module is more efficient in mitigating the undesirable effects of FWM than the FBG+OPC module.

6.2 FUTURE SCOPE

Several avenues for further optimization of this work became evident, during the course of this study. The considerable topics are summarized below:

1. The WDM-RoF network discussed in chapter 3 uses a silicon based fiber. However, nowadays plastic optical fiber (POF) is gaining a lot of research interest because of its attractive physical properties such as, resilience to both bending and shock, a higher flexibility, inexpensive and easy to handle. An extension to the work presented in this dissertation will be to analyze the use of POF in the proposed architecture.
2. The RoF-PON discussed in chapter 4 implements the remodulation scheme in a system consisting of a single transmission channel. The number of channels in the network can be increased by incorporating the WDM technique. This will result in enhanced number of users which will further reduce the overall system cost.
3. The effects of FWM in a RoF network that are suppressed in chapter 5 can be further reduced by using other suppression components. Apart from this, a RoF network suffers from a number of other nonlinearities too, such as SPM, XPM, SRS, etc. These nonlinearities can also be compensated for improving the system performance.

REFERENCES

- [1] G.P. Agrawal, *Fiber-Optic Communication Systems*, 3rd Ed. India: Wiley, 2007.
- [2] M.S. Kumar, *Fundamentals of Optical Fibre Communication*, 2nd Ed. India: PHI Learning Pvt. Ltd., 2014.
- [3] X. S. Qiu, Z. M. Tuo and Z. Yan, *Millimeter Wave Technology in Wireless PAN, LAN and MAN*, CRC Press, 2008.
- [4] D. Novak, R.B. Waterhouse, A. Nirmalathas, C. Lim, P.A. Gamage, T.R. Clark, M.L. Dennis and J.A. Nanzer, "Radio-Over-Fiber Technologies for Emerging Wireless Systems," *IEEE Journal of Quantum Electronics*, vol. 52, no. 1, pp. 1-11, 2016.
- [5] V. Sarup and A. Gupta, "A Study of various Trends and Enabling Technologies in Radio over Fiber (RoF) Systems," *Optik-International Journal for Light and Electron Optics*, vol. 126, no. 20, pp. 2606-2611, 2015.
- [6] M. Vidmar, "Optical-fiber communications: Components and systems," *INFORMACIJE MIDEM*, vol. 31, no. 4, pp. 246-251, 2001.
- [7] A. Nirmalathas, P.A. Gamage, C. Lim, D. Novak and R. Waterhouse, "Digitized radio-over-fiber technologies for converged optical wireless access network," *Journal of Lightwave Technology*, vol. 28, no. 16, pp. 2366-2375, 2010.
- [8] V. Sharma, A. Singh and A.K. Sharma, "Challenges to radio over fiber (RoF) technology and its mitigation schemes—A review," *Optik-International Journal for Light and Electron Optics*, vol. 123, no. 4, pp. 338-342, 2012.
- [9] C. Lim, A. Nirmalathas, K.L. Lee, D. Novak and R. Waterhouse, "Intermodulation distortion improvement for fiber-radio applications incorporating OSSB+C modulation in an optical integrated-access environment," *Journal of lightwave technology*, vol. 25, no. 6, pp. 1602-1612, 2007.
- [10] U. Gliese, S. Norskov and T.N. Nielsen, "Chromatic dispersion in fiber-optic microwave and millimeter-wave links," *IEEE Transactions on microwave theory and techniques*, vol. 44, no. 10, pp. 1716-1724, 1996.

- [11] E. Alon, V. Stojanovic, J.M. Kahn, S. Boyd and M. Horowitz, "Equalization of modal dispersion in multimode fiber using spatial light modulators," In *IEEE Global Telecommunications Conference*, vol. 2, pp. 1023-1029, 2004.
- [12] A.M. Zin, M.S. Bongsu, S.M. Idrus and N. Zulkifli, "An overview of radio-over-fiber network technology," In *IEEE International Conference On Photonics*, pp. 1-3, 2010.
- [13] C.T. Lin, J. Chen, P.C. Peng, C.F. Peng, W.R. Peng, B.S. Chiou and S. Chi, "Hybrid optical access network integrating fiber-to-the-home and radio-over-fiber systems," *IEEE Photonics Technology Letters*, vol. 19, no. 8, pp. 610-612, 2007.
- [14] R. Kaur and K.S. Bhatia, "Effect of modulation formats in hybrid amplified radio over fiber systems," *J. Opt. Commun.*, vol. 34, no. 4, pp. 365-369, 2013.
- [15] D. Visani, G. Tartarini, P. Faccin and L. Tarlazzi, "Cost-effective radio over fiber system for multi service wireless signal," *Optics Communications*, vol. 284, no. 12, pp. 2751-2754, 2011.
- [16] K.I. Kitayama, A. Maruta and Y. Yoshida, "Digital coherent technology for optical fiber and radio-over-fiber transmission systems," *Journal of Lightwave Technology*, vol. 32, no. 20, pp. 3411-3420, 2014.
- [17] N. Zhang and H. Bao, "Research on WDM optical transport network with GMPLS technology," In *Second IEEE International Conference on Computer Science and Information Technology*, pp. 323-326, 2009.
- [18] S.Y. Kim, S.H. Lee, S.S. Lee and J.S. Lee, "Upgrading WDM networks using ultradense WDM channel groups," *IEEE Photonics Technology Letters*, vol. 16 no. 8, pp. 1966-1968, 2004.
- [19] K. Lee, S. Do Lim, Y.M. Jhon, C.H. Kim, P. Ghelfi, A.T. Nguyen, L. Poti, and S.B. Lee, "Broadcasting in colorless WDM-PON using spectrum-sliced wavelength conversion," *Optical Fiber Technology*, vol. 18, no. 2, pp. 112-116, 2012.
- [20] H.S. Kim, T.T. Pham, Y.Y. Won, S.K. Han, "Simultaneous wired and wireless 1.25-Gb/s bidirectional WDM-RoF transmission using multiple optical carrier suppression in FP-LD," *Journal of lightwave technology*, vol. 27, no. 14, pp. 2744-2750, 2009.

- [21] J.M. Kang and S.K. Han, "A novel hybrid WDM/SCM-PON sharing wavelength for up and down-link using reflective semiconductor optical amplifier," *IEEE Photonics Technology Letters*, vol. 18, no. 3, pp.502-504, 2006.
- [22] H.H. Lu, A.S. Patra, W.J Ho, P.C. Lai and M.H. Shiu, "A full-duplex radio-over-fiber transport system based on FP laser diode with OBPF and optical circulator with fiber Bragg grating," *IEEE Photonics Technology Letters*, vol. 19, no. 20, pp. 1652-1654, 2007.
- [23] C. H Wang, F.Y. Shih, C. W. Chow, C. H. Yeh, and S. Chi, "Using downstream DPSK signal for upstream OOK signal remodulation with RSOA in hybrid WDM-TDM passive optical networks," In *National Fiber Optic Engineers Conference*, Optical Society of America, 2009.
- [24] K.O. Hill and G. Meltz, "Fiber Bragg grating technology fundamentals and overview," *Journal of lightwave technology*, vol. 15, no. 8, pp. 1263-1276, 1997.
- [25] R. Seena, R. Pradeep and N. Vijayakumar, "A full duplex radio over fiber system using fiber Bragg grating filter," In *First IEEE International Conference on Computational Systems and Communications*, pp. 139-143, 2014.
- [26] A. Panda and D.P. Mishra, "Nonlinear Effect of Four Wave Mixing for WDM in Radio-over-Fiber Systems," *Journal of Electronics and Communication Engineering Research*, vol. 2, no. 4, pp. 01-06, 2014.
- [27] J. Toulouse, "Optical nonlinearities in fibers: review, recent examples, and systems applications," *Journal of Lightwave Technology*, vol. 23, no. 11, pp. 3625-3641, 2005.
- [28] Sawetanshumala, S. Jana, and S. Konar, "Propagation of a mixture of modes of a laser beam in a medium with saturable nonlinearity," *Journal of Electromagnetic Waves and Applications*, vol. 20, no. 1, pp. 65–77, 2006.
- [29] B. Mandal and A. R. Chowdhary, "Spatial soliton scattering in a quasi phase matched quadratic media in presence of cubic nonlinearity," *Journal of Electromagnetic Waves and Applications*, vol. 21, no. 1, pp. 123–135, 2007.
- [30] Monika, A. Wason and R. S. Kaler, "Investigation of four wave mixing effect with different number of input channels at various channel spacing," *Optik-*

- International Journal for Light and Electron Optics*, vol. 124, no. 20, pp. 4227-4230, 2013.
- [31] M. Noshad and A. Rostami, "FWM minimization in WDM optical communication systems using the asymmetrical dispersion-managed fibers," *Optik-International Journal for Light and Electron Optics*, vol. 123, no. 9, pp. 758-760, 2012.
 - [32] B. Patnaik and P. K. Sahu, "Optimization of four wave mixing effect in Radio-over-fiber for a 32-Channel 40-GBps DWDM System," In *International Symposium on Electronic System Design*, pp. 119-124, 2010.
 - [33] M.S. Uddin, S.M.R. Ullah and M.M. Hasan, "Effect of four wave mixing nonlinearity in wavelength division multiplexing radio over fiber," In *IEEE International Conference on Electrical Engineering and Information & Communication Technology*, pp. 1-6, 2014.
 - [34] S. Singh, "Performance evaluation of bi-directional passive optical networks in the scenario of triple play service," *Optik-International Journal for Light and Electron Optics*, vol. 125, no. 19, pp. 5837-5841, 2014.
 - [35] M. Bi, S. Xiao, H. He, J. Li, L. Liu and W. Hu, "Power Budget Improved Symmetric 40-Gb/s Long Reach Stacked WDM-OFDM-PON System Based on Single Tunable Optical Filter," *IEEE Photonics Journal*, vol. 6, no. 2, pp. 1-8, 2014.
 - [36] A.O. Aldhaibani, S. Yaakob, R.Q. Shaddad, S.M. Idrus, M.Z.A. Kadir and A.B. Mohammad, "2.5 Gb/s hybrid WDM/TDM PON using radio over fiber technique," *Optik-International Journal for Light and Electron Optics*, vol. 124, no. 18, pp. 3678-3681, 2013.
 - [37] G. Kaur, M.S. Patterh and R. Kaur, "Four wave mixing power suppression in hybrid network topology using optical phase conjugation module," *Optik-International Journal for Light and Electron Optics*, vol. 126, no. 3, pp. 347-349, 2015.
 - [38] G. Cheng, B. Guo, S. Liu and W. Fang, "A novel full-duplex radio-over-fiber system based on dual octupling-frequency for 82GHz W-band radio frequency

- and wavelength reuse for uplink connection,” *Optik-International Journal for Light and Electron Optics*, vol. 125, no. 15, pp. 4072-4076, 2014.
- [39] C.W. Chow and C. H. Yeh, "Using downstream DPSK and upstream wavelength-shifted ASK for rayleigh backscattering mitigation in TDM-PON to WDM-PON migration scheme," *IEEE Photonics Journal*, vol. 5, no. 2, pp. 7900407-7900407, 2013
 - [40] J.L. Xie, X.G. Huang and J. Tao, "A full-duplex radio-over-fiber system based on a novel double-sideband modulation and frequency quadrupling," *Optics Communications*, vol. 283, no. 6, pp. 874-878, 2010.
 - [41] S. Mitatha, R. Putthacharoen and P.P. Yupapin, “THz frequency bands generation for Radio-over-Fiber systems,” *Optik-International Journal for Light and Electron Optics*, vol. 123, no. 11, pp. 974-977, 2012.
 - [42] F.I. El-Nahal, “A bidirectional radio-over-fiber system using differential phase-shift keying signals for downstream and remodulated OOK for upstream,” *Optik-International Journal for Light and Electron Optics*, vol. 124, no. 20, pp. 4682-4684, 2013.
 - [43] J.M. Kang and S.K. Han, “A novel hybrid WDM/SCM-PON sharing wavelength for up-and down-link using reflective semiconductor optical amplifier,” *IEEE Photonics Technology Letters*, vol. 18, no. 3, pp. 502-504, 2006.
 - [44] M. Matsuura and J. Sato, "Bidirectional radio-over-fiber systems using double-clad fibers for optically powered remote antenna units," *IEEE Photonics Journal*, vol. 7, no. 1, pp. 1-9, 2015.
 - [45] A. Emsia, Q.T. Le, M. Malekizandi, D. Briggmann, I.B. Djordjevic and F. Kuppers, "WDM–TDM NG-PON Power Budget Extension by Utilizing SOA in the Remote Node," *IEEE Photonics Journal*, vol. 6, no. 2, pp. 1-10, 2014.
 - [46] G. Kaur and M. S. Patterh, "Suppression of four wave mixing in wavelength division multiplexed system with hybrid modules," *Optik-International Journal for Light and Electron Optics*, vol. 125, no. 15, pp. 3894-3896, 2014.
 - [47] F. Brendel, J. Poette, B. Cabon, T. Zwick, F. van Dijk, F. Lelarge and A. Accard, "Chromatic dispersion in 60 GHz radio-over-fiber networks based on mode-

- locked lasers," *Journal of Lightwave Technology*, vol. 29, no. 24, pp. 3810-3816, 2011.
- [48] R. Yadav, "Passive-optical-network (PON) based converged access network [Invited]," *Journal of Optical Communications and Networking*, vol. 4, no. 11, pp. B124-B130, 2012.
 - [49] T. Liu, D. Jia, T. Yang, Z. Wang and Ying Liu, "Experimental validation of FWM efficiency improvement in multichannel fiber laser by using DF-HNLF," *Optics Communications*, vol. 367, pp. 12-16, 2016.
 - [50] H. Bai and Yang Wang, "Tunable wavelength converters based switching structure for WDM-TDM hybrid PON," *Optik-International Journal for Light and Electron Optics*, vol. 124, no. 22, pp. 5388-5390, 2013.
 - [51] B. Kaur, A.K. Sharma and V. Kapoor, "Performance Analysis of WDM RoF-EPON Link with and without DCF and FBG," *Optics and Photonics Journal*, vol. 3, pp. 163-168, 2013.
 - [52] D.D. Patel and R.B. Patel, "Chromatic Dispersion Compensation for 16×10 Gbps WDM Optical Communication System with Non Linearity," *International Journal of Emerging Trends in Electrical and Electronics*, vol. 10, no. 3, pp. 29-32, 2014.
 - [53] H.U. Manzoor, A.U. Salfi, T. Mehmood and T. Manzoor, "Reduction of Four Wave Mixing by employing circular polarizers in DWDM optical networks," In *12th International Bhurban Conference on Applied Sciences and Technology*, pp. 637-640, 2015.
 - [54] J.S. Malhotra, M. Kumar, A.K. Sharma and A. Kumar, "Performance evaluation of 16 channel DWDM radio-over-fiber link," *Optik-International Journal for Light and Electron Optics*, vol. 124, no. 20, pp. 4120-4122, 2013.
 - [55] H. Singh, M.L. Singh and R. Singh, "A novel full duplex 16Gbps SCM/ASK radio over fiber WDM-PON sharing wavelength for up-and down-link using bidirectional reflective filter," *Optik-International Journal for Light and Electron Optics*, vol. 125, no. 14, pp. 3473-3475, 2014.

- [56] R. Pradeep, G.S. Karthikeya, M. Jeevan and N. Vijayakumar, "A novel architecture for full duplex WDM radio over fiber system converged with wired network using dual drive MZM and light remodulation using RSOA," In *Ninth IEEE International Conference On Wireless And Optical Communications Networks, Indore, India*, pp. 1-5, 2012.
- [57] Y.Y. Won, H.S. Kim, Y.H. Son and S.K. Han, "Full colorless WDM-radio over fiber access network supporting simultaneous transmission of millimeter-wave band and baseband gigabit signals by sideband routing," *Journal of Lightwave Technology*, vol. 28, no. 16, pp. 2213-2218, 2010.
- [58] M. Arief, S.M. Idrus and S. Alifah, "The SCM/WDM system model for radio over fiber communication link," In *IEEE International RF and Microwave Conference, Kuala Lumpur, Malaysia*, pp. 344-347, 2008.
- [59] K. Iniewski, *Internet Networks: Wired, Wireless, and Optical Technologies. Devices, Circuits, and Systems*, CRC Press, 2009.
- [60] H. Wen, L. Chen, C. Huang and S. Wen, "A full-duplex radio-over-fiber system using direct modulation laser to generate optical millimeter-wave and wavelength reuse for uplink connection," *Optics Communications*, vol. 281, no. 8, pp. 2083-2088, 2008.
- [61] D. Coelho and H.M. Salgado, "OFDM signals in WDM radio-over-fiber networks with fiber Bragg grating selection," In *Eleventh IEEE International Conference on Transparent Optical Networks*, pp. 1-4, 2009.
- [62] S. Jain and A.B. Therese, "Four wave mixing nonlinearity effect in WDM Radio over fiber system," *International Journal of Scientific Engineering and Technology*, vol. 4, no. 3, pp. 154-158, 2015.
- [63] S. Singh, "Investigation of wavelength division multiplexing ring network topology to enhance the system capacity," *Optik-International Journal for Light and Electron Optics*, vol. 125, no. 21, pp. 6527-6529, 2014.
- [64] A. Selvamani and T. Sabapathi, "Suppression of four wave mixing by optical phase conjugation in DWDM fiber optic link," In *IEEE International Conference on Recent Advancements in Electrical, Electronic and Control Engineering*, pp. 95-99, 2011.

- [65] S. Jain and A.B. Therese, "Reduction of Four Wave Mixing Nonlinearity Effect in WDM Radio over Fiber Systems," *Indian Journal of Science and Technology*, vol. 8, no. 19, 2015.
- [66] A.K. Sharma and S.K. Arya, "Improved analysis for SRS and XPM-induced crosstalk in SCM-WDM transmission link in the presence of HOD," *Optik-International Journal for Light and Electron Optics*, vol. 120, no. 15, pp. 773-781, 2009.

LIST OF PUBLICATIONS

- [1] Ashima Rana, R.S. Kaler, Gurpreet Kaur, "Investigation of Radio over Fiber Wavelength Division Multiplexed Passive Optical Network using Subcarrier Multiplexing/Amplitude Shift Keying Technique," Communicated to National Academy of Sciences.
- [2] Ashima Rana, R.S. Kaler, Gurpreet Kaur, "Wavelength Remodulation and Dispersion Compensation for Full duplex Radio over Fiber System using Fiber Bragg Grating," Communicated to Optical Engineering, SPIE.
- [3] Ashima Rana, R.S. Kaler, Gurpreet Kaur, "Estimation and mitigation of four wave mixing in wavelength division multiplexing radio over fiber system using hybrid modules," Communicated to Optica Applicata.

ORIGINALITY REPORT

10%

SIMILARITY INDEX

5%

INTERNET SOURCES

8%

PUBLICATIONS

2%

STUDENT PAPERS

PRIMARY SOURCES

1

A. M. Zin. "An overview of radio-over-fiber network technology", International Conference On Photonics 2010, 07/2010

Publication

1%

2

Kaur, Gurpreet, and M.S. Patterh. "Suppression of four wave mixing in wavelength division multiplexed system with hybrid modules", Optik - International Journal for Light and Electron Optics, 2014.

Publication

1%

3

Singh, Harpreet, Maninder Lal Singh, and Rajandeep Singh. "A novel full duplex 16Gbps SCM/ASK radio over fiber WDM-PON sharing wavelength for up- and down-link using bidirectional reflective filter", Optik - International Journal for Light and Electron Optics, 2014.

Publication

1%

4

Seena, R, R Pradeep, and N Vijayakumar. "A full duplex radio over fiber system using fiber Bragg grating filter", 2014 First International

<1%