Four Wave Mixing Suppression using Optical Phase Conjugation and Band Pass filter

A Thesis submitted in partial fulfillment of the requirement for the Award of the Degree of

MASTER OF TECHNOLOGY
VLSI Design

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DECLARATION

I, **Hitesh Kumar Gupta** hereby declare that the work presented in this thesis entitled "**Four Wave Mixing Suppression using Optical Phase Conjugation and Band Pass filter"** in partial fulfillment of the requirement for the award of Degree of**Master of Technology (VLSI Design**) submitted at**Department ofElectronics and Communication Engineering**, Thapar Institute of Engineering & Technology (Deemed to be University), Patiala is an authentic record of work carried out under supervision of **Dr. Hardeep Singh(Associate** Professor)&**Dr. Gaganpreet Kaur** (Assistant Professor) **Electronics and Communication Engineering, Thapar Institute of Engineering & Technology**) from **2019 to 2022**. The matter presented in this has not been submitted either in part or full to any other university or institute for the award of any other degree.

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ABSTRACT

Microcellular systems are getting attention due to ever-increasing data and capacity demands in wireless services. Utmost advantage of microcellular systems is the potential to support high speed because of the many small cells for frequency utilization. However, aforementioned advantages come at the cost of huge investment for installing multiple Base stations (BSs). One the most expensive factor for high cost is the complex channel control in the spectral delivery in BSs and the handoffs. In order to eradicate this limitation, operations performed at BSs should replace and done at the Control Station. Radio over Fiber (RoF) systems supporting high frequency millimetre waves are emerged as a great choice for Fifth generation (5G) broadband communication. Nonlinear and scattering effects are distance and performance limiting and introduce spectrum broadening, pulse broadening and signal modulation. Wavelength division multiplexed (WDM) system are maximum prone to the Four wave mixing (FWM) performance deteriorating effects and interferences in the intended wavelengths and their power can be lowered by taking wide channel spacings, lower power levels, and optical fiber lower effective area. However, mode efficient technique to suppress the FWM effects is required.

In this research work, a RoF system has been proposed with the integration of WDM over 100 km single mode fiber with FWM suppression. Optical phase conjugation (OPC) and Band pass optical filter (BPF) based joint technique has been employed to suppress the FWM idlers. The results of proposed WDM-RoF system has been evaluated at different input parameters such as input power, WDM channel spacings and number of channels in terms of output power, FWM, Q factor and Bit error rate (BER). A detailed comparison of Dispersion compensation fiber (DCF)-BPF and proposed OPC-BPF is performed and results revealed that due to midlink spectrum inversion in OPC-BPF, it has improved performance with enhanced FWM suppression and can support high input powers.

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CHAPTER 1

INTRODUCTION

1.1 Introduction

By the end of 2023, the amount of internet protocol traffic predicted worldwide will have surpassed one zettabyte. Optical fibre communication systems have been lauded as a viable remedy for the rising demand for high data rate communication systems. Using light pulses that are conveyed across an optical fibre, optical fibre communication entails sending data from one location to another. Light, which has been manipulated to convey information, creates an electromagnetic carrier wave. Since its invention in the 1970s, optical communication has transformed the telecommunications sector and been a key factor in the advent of the information age [1]. Extremely large bandwidth, which is connected to an optical carrier, is the major advantage of optical communication. The microwave carrier frequency (1 GHz) is five orders of magnitude lower than the optical carrier frequency (100 THz). An optical fibre communication system has around 100,000 times more capacity since the modulation bandwidth in digital systems is typically constrained to a tiny portion of the carrier frequency. Block diagram of optical fiber system is illustrated in Figure 1.1.

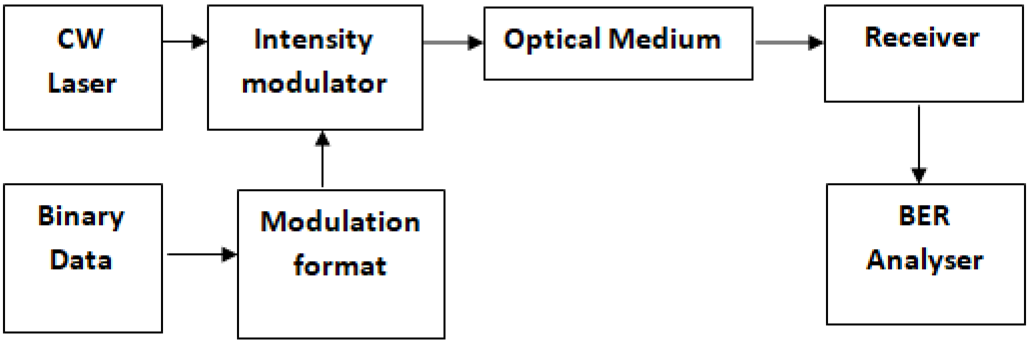


Figure 1.1 Representation of fiber optic communication [2]

1.2 Need of Radio over Fiber

Future communication systems will require ultra-wide bandwidth, extremely low latency, and higher potential to meet these demands. This will allow scientists and researchers to concentrate on standards beyond the Fourth Generation (4G) spectrum range, i.e. Fifth Generation (5G) technology. Multimedia applications such as augmented reality (AR), live streaming, high resolution online gaming, ultra high definition television (UHDTV), and virtual reality have increased the data demands by 8 times. Some of the applications that would encounter a pace in their technical growth in 5G include self-driving cars, smart homes and cities, machine learning, and online gaming.

To provide high-speed data services using competent wireless communication technology, the service provider must make efficient use of the electromagnetic spectrum that is currently available. The associated apps undergo a paradigm shift while moving from 4G to 5G cellular operations, and this offers up new opportunities for these applications. The requirements of the aforementioned systems can be met by both a huge number of tiny cells and an extremely wide window of a spectrum. Long term evolution (LTE) advanced (LTE-Advanced) technology, which comprises of Pico, micro, and macro cellular architecture, is now used to provide cellular communications with speeds greater than 1 Gbps. Mm waves are one of the main options for long-distance, high-speed data transfer, however the current microwave band is experiencing significant traffic and is becoming congested. Therefore, the use of optical fibre communication can be used to transmit radio signals or millimeter waves over greater distances at high data speeds.

RoF and mm wave communication can be integrated to create 5G base stations that are affordable and devoid of complexity. Services like GPRS and GSM were in agreement with low information rates throughout the early stages of telecommunication. However, customers today seek services that can offer them faster transmission, anytime, everywhere access, and adaptable solutions. The bandwidth that is available will also be limited by the quickly expanding user base. Reducing cell size to accommodate more clients is one potential option. This is referred to as the micro- or Pico-cells notion. Because the unlicensed ISM frequency channels are already congested, another approach involves using new operational bands. Millimeter-wave is the new operational band that many designers favour right now [3]. It offers a higher bandwidth and is located in the optical frequency range of 40 to 90GHz. However, using these techniques will lead to some additional issues. If the size of the cell is decreased, more base stations (BSs) will be required to cover the full service area. On the other side, raising the frequency will cost more in terms of equipment, upkeep, and installation. To solve these problems, the Radio over Fiber (RoF) concept was created. RoF is an amazing integration of optical and wireless networks that provides a solution with a high information rate, large capacity, and mobility. Optical fiber is a desirable choice for communication because of its near-ideal qualities [4].

1.3 Overview of Radio over Fiber Systems

In the late 1980s, the idea of radio over fibre (RoF) technology was developed and later subcarrier multiplexing flourished quickly in cable TV. During the same period, the advancement of wireless fidelity (WiFi) with cellular communication attracted attention and brought about a paradigm shift in wireless communication. Massive wireless bandwidth needs have significantly strained the lower microwave window, which has resulted in the advent of millimetre waves (Mm waves). Due of license-free operations, the 60 GHz band has attracted a lot of attention during the past two decades compared to other Mm frequency bands including the V band, W band, and D band.In contrast to competing wireless communication, which suffers from significant transmission attenuation, RoF's initial goal was to provide the most effective method for distributing Mm wave communications over fibre optic networks in order to address spectrum bottlenecks in the lower microwave frequency range. RoF's single core infrastructure allows wired and wireless connections and makes the most of optical fibre and wireless technology. Consolidating wireless and optical fibre networks simplifies control, administration, and relaying tasks, which will lower operational and capital costs significantly. Despite the benefits of Mm wave transmission in RoF, there are certain drawbacks and careful design planning is required.With the hope that Mm wave free space communications would be a cutting-edge broadband technology for wireless, RoF development first concentrated on the generation and transmission of Mm wave signals in the optoelectronic framework [5] [6].Mm wave transmission over greater distances is difficult, hence several studies have been done to increase the link length by addressing the shortcomings. To the best of our knowledge, spectral efficient modulations, suppressing the carrier to make the spectrum narrow, transmitting the carrier spectrum by suppressing its sidebands, wavelength interleaving, using dispersion compensation fibre, Fiber Bragg Gratings, and optical phase conjugation are the best approaches to overcome pulse broadening effects and transmission problems in mm waves. The use of wavelength division multiplexing (WDM) in optical communication networks increased data throughput and pushed the design toward larger bandwidth, better security, bidirectional transmission, flexibility, and ease of use. Researchers focused on the integration of radio signals in WDM-PON systems throughout the 2000s, when passive optical networks (PON) and WDM were at the height of their popularity for optical metro networks. The RoF block diagram for the WDM-PON system is shown in Figure 1.2. As wireless transmission demand continued to soar in the 2010s, improvements in RoF toward ultra-high speed networks were anticipated to offer smooth free space transmission [7] [8].

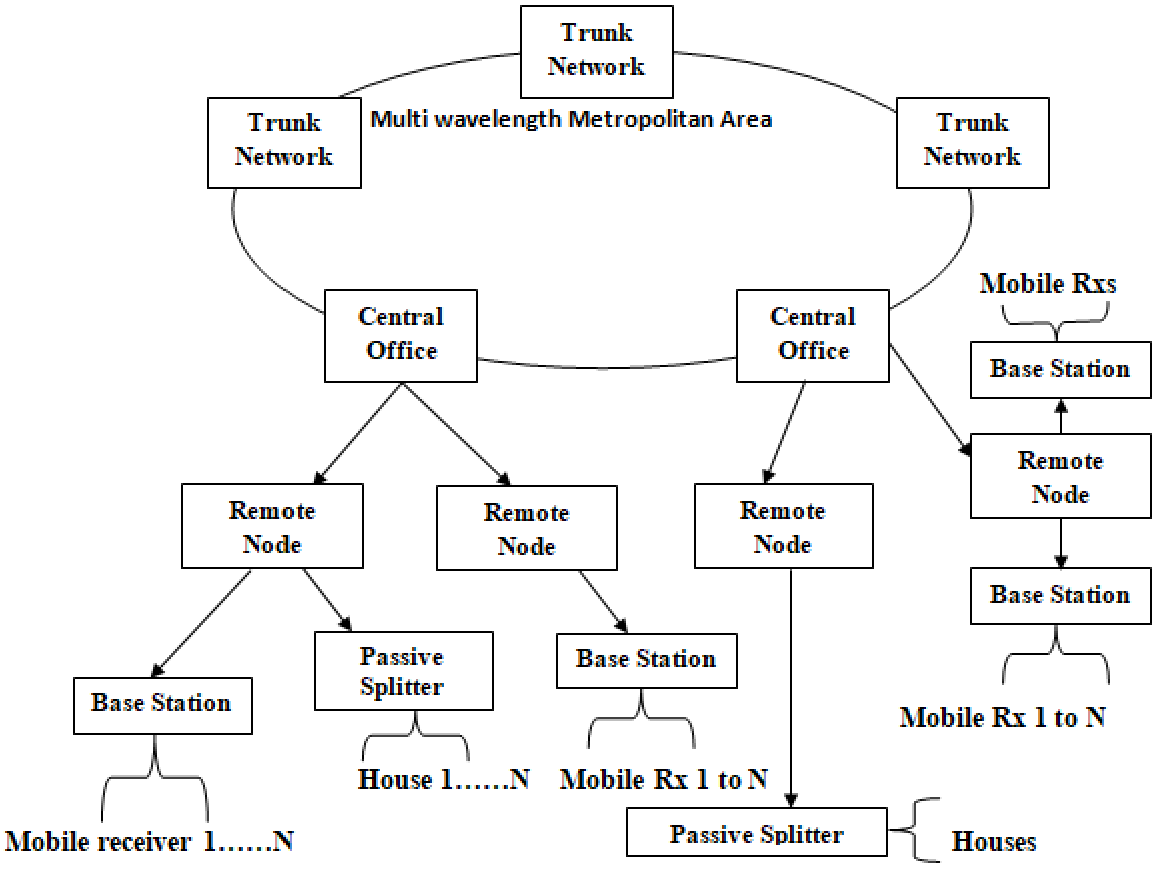


Figure 1.2 Hybrid WDM-PON and RoF wireless access [63]

RoF systems may achieve >100 Gbps speed thanks to multi input, multi output and polarization multiplexing based multi-level modulation. With the inclusion of analogue transport in 5G, RoF is seen as a good alternative to Common Public Radio Interface (CPRI), which is thought to have scaling issues in mobile communication [9] [10].In order to accommodate wireless applications, the RoF idea entails modulating light with a radio signal before transmitting it through an optical fibre. Digital signal transmission takes place in traditional optical systems. Because radio signals are distributed directly on radio carrier frequency and transmitted between the control unit and the BS, it is fundamentally an analogue transmission system. The information signal, however, can be digital. A transmitter and a receiver are part of a RoF network, and an optical fibre connects them. At the transmitter, an electrical signal modulates the optical laser source. The generated optical signal is then sent through the optical cable for further transmission [11].The information signal is converted back into electrical form by the photo detector at the receiver. The RoF network's framework is shown in Figure 1.3.

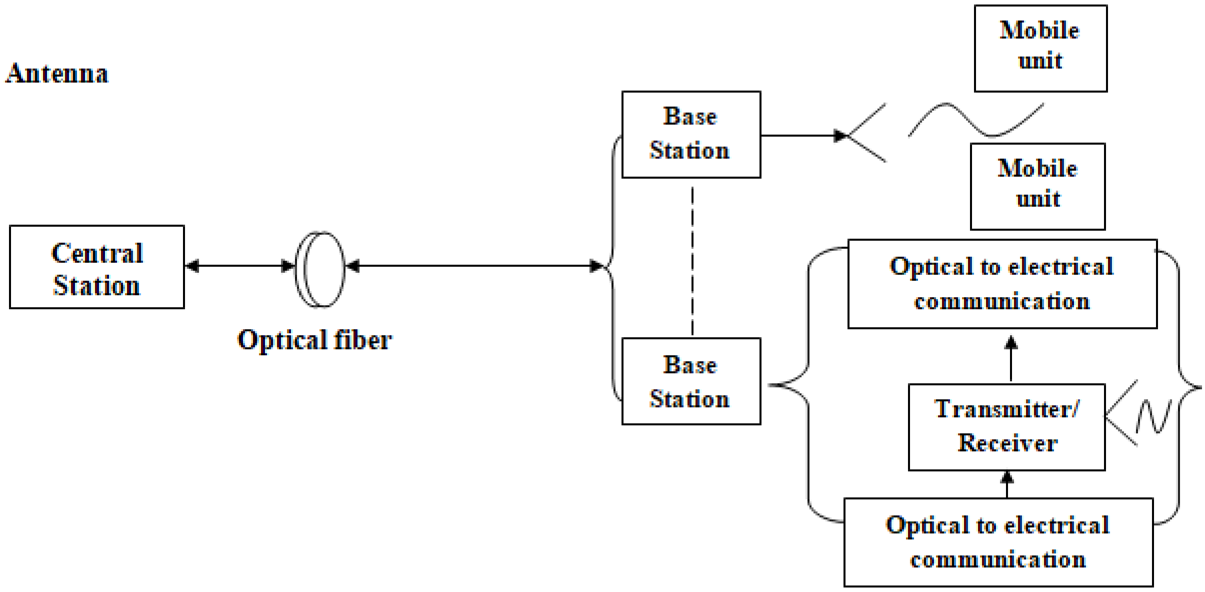


Figure 1.3Representation of RoF systems [63]

1.4 Working of RoF Systems

Radio signals in RoF system modulates over optical laser signals through intensity modulator or through direct modulation. Intensity modulators that are widely used in optical communication systems are Mach zehndar modulator (MZM) and is maximum efficient out of Electro-absorption modulator (EAM), phase modulator (PM) etc. Frequency is generated by laser source and output performance of radio signals directly depends on the input power. There are major two types of radio communication over fiber such as (1) Intermediate frequency RoF systems (IoF) and (2) Radio frequency over fiber (RoF).High frequencies (>10 GHz) are superimposed on the optical carrier and therefore eliminate the requirement of up/down conversions at BS and it results into lower cost and simpler operations. On the other hand, in case of IoF, less than 10 GHz frequency signals used and need up/down conversion making system expensive and complex. RoF takes benefits of both wireless and wired transmissions and also provides enhanced cellular communication, greater power efficiency, wide bandwidth and lesser signal attenuations [12] [13].

1.5 Advantages of Radio over Fiber

Both the optical and wireless domains are combined in RoF. Therefore, it makes use of both methodologies' advantages. The following is a list of some advantages [14] [15].

- **Huge bandwidth and high data rate:** Fiber is used for the transmission of radio signals because it provides bandwidth that can reach THz. High speed signal processing is supported by high bandwidth. Electronic implementation of this might be more challenging.

- **Low attenuation:** Compared to other media, optical fibre transmits signals with substantially less attenuation (such as metal cables). When optical fibre is utilized, the signal may go farther, which eliminates the need for repeaters.

- **Low complexity:** RoF makes use of the BS idea. The only components of BS are an antenna, amplifiers, and an optical-to-electrical converter. This suggests that the network is made simpler by moving the signal production circuitry and resource management to a single site that is shared by numerous BSs.

- **Dynamic resource allocation:** The central station is in charge of managing the resources (CS). As a result, bandwidth will be dynamically allotted based on demand and priority.

- **Lower cost:** The sophisticated and expensive technology needed to process the signal is located at CS. The BSs maintain simpler, lighter, and smaller remote antenna devices. As a result, the system's cost can be decreased because it is simple to install and maintain.

- **Security:** Since signals are transmitted as light waves rather than radio waves, RoF is immune to radio frequency interference. The signals that are transferred through the fibre are secure thanks to it.

Fiber optics is created to support data rates in Gbps, making them future-proof. They can therefore handle the data rate needed in upcoming high-speed networks. The RoF approach is transparent to both bit rates and protocols.

1.6 Limitations of Radio over Fiber

As was already said, the RoF approach has several benefits. In addition to them, this notion has several restrictions [16] [17]. A few of them are listed below:

- Nonlinearities: There are several nonlinear effects that RoF experiences. This is a result of the nonlinear nature of the equipment employed in communication links, including lasers.

The noise figure and dynamic range, which are crucial elements of radio signal transmission, are constrained as a result.

• Chromatic dispersion in single-mode optical fibre (SMF) limits the length of the fibre link. This is a restriction of single-mode fibre. De-correlation may result from this, which raises the radio frequency (RF) carrier phase noise.
• Limitations of multi-mode fibre: In multi-mode optical fibre (MMF), modal dispersion imposes a restriction on the total amount of available bandwidth and the transmission range.

1.7 Classifications of Radio over Fiber systems/Mm Wave Generation

For 5G services to handle rising data traffic for indoor/outdoor communications, a transition from lower frequencies to high frequency waves like 30 GHz to 300 GHz (Mm waves) is necessary. High frequency signals (Mm waves) and the following performance-degrading conditions, such as weather disturbances, diffractions, and high path loss, cause collisions more frequently in wireless communication. One of the main problems with this communication is the small size of the cells. Because micro, mini, or Pico cells are so small, several BS are required to cover a few meters of distance, which increases the frequency reuse and raises the price of the system. But in RoF, central office data processing and cost-effective connectivity over fibre architecture are done while also minimizing latency. Therefore, a millimeter wave-based RoF establishing the merger of wired and wireless communication is the most realistic option for providing the variety of capabilities required for 5G networks [18] 19] [20].The Features of Mm waves are listed below:

- Less crowded band for the communication is Mm wave band
- Speed of data transfer is very fast because of higher frequencies
- Low latency
- Due to RoF, operations are economical
- MIMO system can increase spectral efficiency
- Better connectivity due to small cells

One of the major challenges is the development and transmission of Mm wave-based RoF systems, which will be employed in 5G applications. High frequency Mm waves can be produced in both the electrical and optical domains. The photonic generating techniques of Mm wave signals with RoF propagation are of interest and are examined in the following sections, with important developments especially in recent years being presented. This is because electrical generation is a challenging and problematic operation. Figure 1.4 illustrates various methods for creating Mm waves. To create and transmit radio signals over optical fibre, a variety of optical techniques are available. It is divided into two groups in terms of modulation/demodulation format: intensity modulation-direct detection and remote heterodyne detection

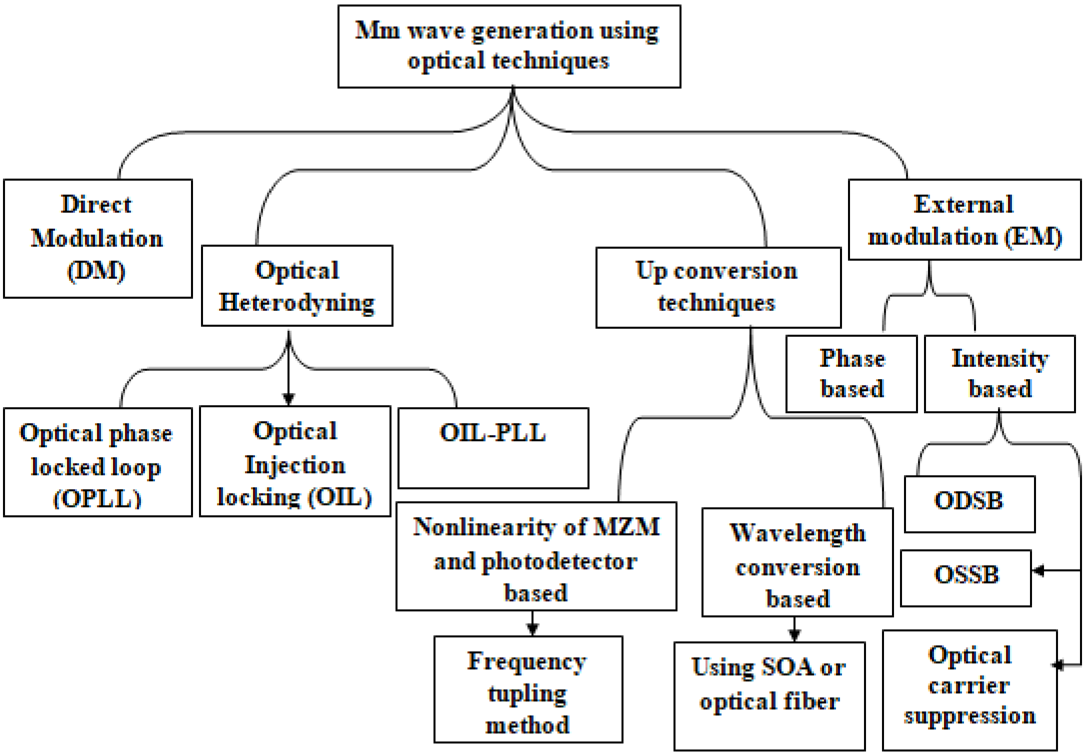


Figure 1.4 Different Mm wave generation techniques in optical domain [63]

1.7.1 Generation of RoF Signals using Direct Modulation (DM)

A standard, affordable method of directly modulating the laser signal, Figure 1.5 shows the block diagram of the direct creation of Mm waves through DM. Because the laser's bandwidth is limited to 40 GHz, DM can only deliver low frequency, which is also plagued by nonlinear harmonics, frequency chirping, undesired noise, and unsteady output. By using an external modulator for high frequency production, the aforementioned issue can be solved [21].

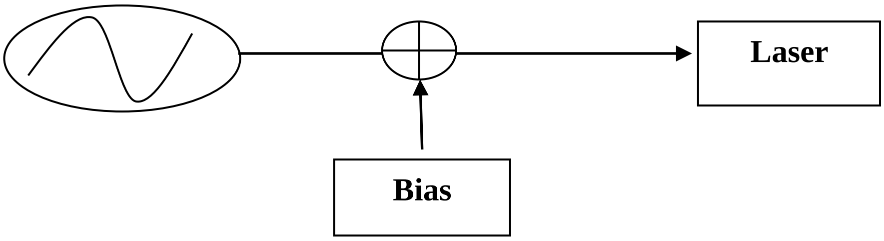


Figure 1.5 Block diagram of direct intensity modulation Mm wave generation [64]

1.7.2Generation of RoF Signals using External Modulation (EM)

Figure 1.6 depicts the creation of Mm waves using an external modulator, such as an electro absorption modulator (EAM) or a Mach Zehndar modulator (MZM), along with a modulated laser signal. The primary idea behind frequency creation is that higher order harmonics are produced as a result of modulator nonlinearities. The power of the harmonics is influenced by the bias voltage and index of modulation, and the local oscillator drive voltage modifies the frequency amplitude. By producing higher frequencies and reducing the need for a large amount of bandwidth, the system's cost can be decreased [22]. Two types of EM are described below: phase modulations and external intensity modulations.

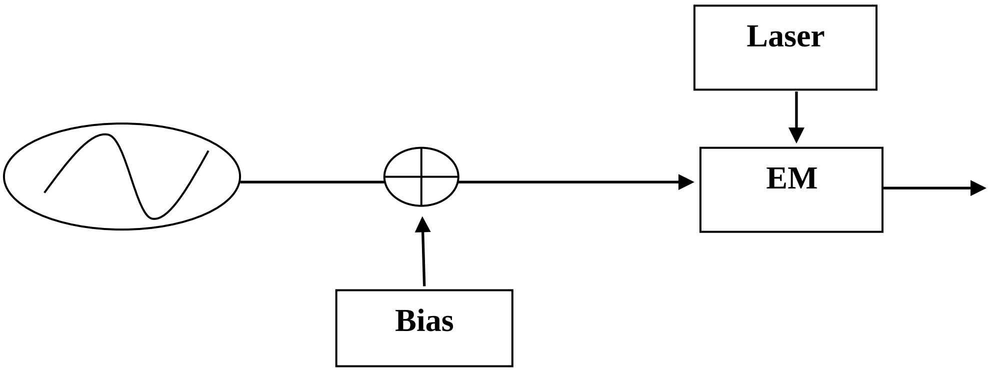


Figure 1.6 Block diagram of direct intensity modulation Mm wave generation [64]

(a) Generation of Mm waves using external phase modulation

In external phase modulation, the carrier signal's phase is altered by phase modulators to match that of the light signal. The advantage of phase modulators over MZM is that they don't need direct current biasing, which solves the problem of bias drifting and provides a stable output. A technique for creating tunable millimeter wave signals at 126, 90, and 54 GHz has been devised by researchers. This method, based on the spectrum slicing of the phase modulator, used the "Fabry Perot" filter to reduce sidebands. The complication that the tunable filter brought can be eliminated by using a fixed optical filter.

(b) Generation of Mm waves using external intensity modulation

External Intensity Modulation, which may be accomplished using EAM or MZM, modifies the square of the amplitude, or the signal's intensity, in accordance with the baseband signal. MZM requires higher driving force and is more challenging to integrate with the source of optical laser than an EAM. With this technology, complex circuitry is not required, but a large bandwidth and long-distance transmission are still possible without the necessity of an amplifier. Despite being straightforward, this method suffers from fibre dispersion effects, a significant insertion loss, and distortion brought on by inherent modulator nonlinearity [23]. Three distinct variations of this technique—Optical Single Sideband, Optical Double Sideband, and Optical Carrier Suppression Modulation—are produced when either EAM or MZM are added. These versions are discussed in the following subsections.

(i) Optical single sideband modulation

The carrier and sideband that make up the optical single sideband signal are separated in frequency from the RF signal. This type of modulation is produced by removing one of the sidebands from an ODSB signal using FBGs filters. A dual drive MZM with a quadraturebias and a phase shift of /2 can likewise be used to create this form of modulation. Gain-switched lasers modulated with Single Sideband Sub Carrier Multiplexed quadrature Phase Shift Keying modulation, which uses a self-heterodyne technique and Wavelength Selective Switch (WSS) for filtering comb lines of SSMF across 25 kilometers, have been used to illustrate a 60 GHz RoF system. To enable error-free transfer, it made use of the Dispersion Compensation Module (DCM) [24].

(ii) Optical double sideband modulation

An optical double sideband is defined as having the optical carrier frequency f_c as its centre and one upper sideband and one lower sideband.The frequency of the modulating RF signal is equal to the gap between one of the sidebands and the carrier frequency in an optical double sideband. Direct modulation of a laser or the use of external modulators like the single or dual drive EAM or MZM may be used to produce it. To assure the development of a millimeter wave signal devoid of any frequency chirps when using a dual-drive MZM, a phase difference between the RF signals equal to is necessary. However, a phase shift between the spectral components occurs when this signal is transmitted by fibre because of the effect of fibre chromatic dispersion. Equalizers or dispersion compensating fibres, as well as dispersion resistant techniques like carrier signal suppression (OCS) or one sideband suppression, can be utilized to eliminate these undesired results (SSB) [25].

(iii) Optical carrier suppression modulation

Two sidebands with frequency $f_c \pm f_{rf}$ Hz, where “f_{rf}” is the modulating signal frequency, make up an optical carrier suppression (OCS) modulated signal. The biasing of MZM at $V_\pi \pm$

$m2V_\pi$ results in an optical carrier suppression signal having frequency equal to f_{rf} Hz.This modulation technique has been found to have the lowest spectral occupancy, the highest receiver sensitivity, the highest spectrum efficiency, the least amount of RF signal bandwidth required, and the least amount of amplifier and optical modulator power required at long range[26].

Table 1.1Various MZM Biasing points

Bias Point	Bias Voltage
MITP	V_π
MP	$2V_\pi$
QP	$\frac{V_\pi}{2}$

The three biassing points used for MZM are the Minimum Point (MITP), Maximum Point (MP), and Quadrature Point (QP), which are all shown in Table 1.1 along with the corresponding voltages. The researchers found that the quadrature point produces both odd and even order harmonics, while the lowest point produces odd order harmonics and the maximum point produces even order harmonics. To tame the optical sidebands, MZMs are biassed at the minimum or maximum transfer function point (MTP). However, this causes bias drifting, which impairs system resilience and necessitates the use of control circuitry to address the problem, raising the complexity and cost of the scheme. This issue can be resolved by using Phase Modulators in place of MZM [27].

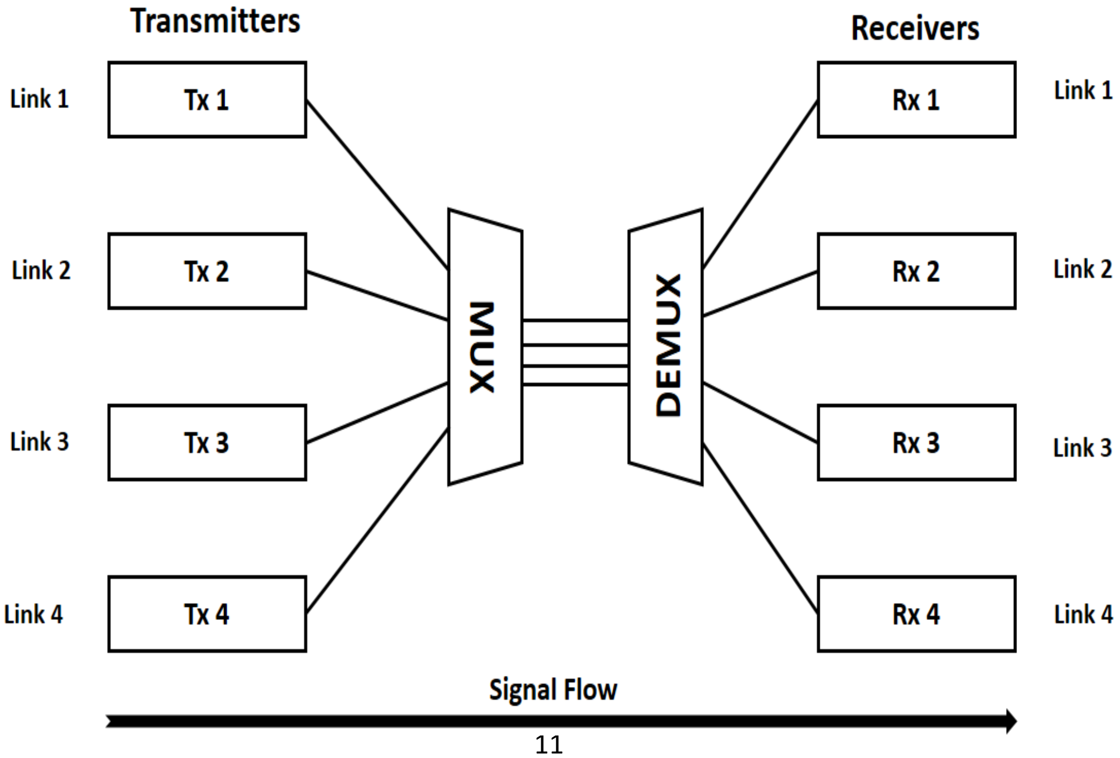


Figure 1.7 Wavelength division multiplexing system [65]

1.8WDM-RoF Systems

With regard to optical fibre communication, wavelength division multiplexing (WDM) is a method that uses several light source wavelengths to aggregate numerous optical carrier signals on a single optical fibre link. Figure 1.7 illustrates it. As a result, each communication channel is given a different frequency, which is then multiplexed and sent through a single fibre. At the destination, the wavelengths are spatially split to different receiver sites. A WDM network does this by using a multiplexer to combine all the signals at the transmitter and a de-multiplexer to de-multiplex them at the receiver. Increased coverage area, efficient bandwidth use of optical fibre, transparency, and upgradeability are only a few benefits of WDM passive optical networks (PON) [28]. Emerging applications that require low error rates, little propagation delay, and high information transfer rates to a large number of clients, such medical imaging and supercomputer visualization, may find a solution in WDM systems. The coverage area and overall capacity of the current optical networks are significantly increased by the integration of WDM-PON with RoF. Due to this, it is no longer necessary to build and install two distinct networks [29].

1.9 Nonlinear Effects in RoF

Light waves typically interact slightly when they are sent through a RoF, but they do not change as they move across an optical fibre link. There are, however, rare instances where the light waves interact with the medium through which they are transmitted and produce nonlinear effects [30]. The emergence of the nonlinear effects has two causes, which are:

- Medium refractive index dependence on intensity: Kerr effect is caused by power dependence on refractive index. Depending on the shape of the input signal, this nonlinearity can have one of three possible effects. These subcategories include FWM, cross-phase modulation (XPM), and self-phase modulation (SPM).
- This phenomenon causes stimulated effects such as stimulated Raman scattering (SRS) and stimulated Brillouin scattering at high power levels (SBS). When incident power exceeds a specific critical amount, then intensity of the dispersed light increases exponentially. Raman and Brillouin scattering are distinct from one another because in SRS, the generated phonons (optical) are incoherent and no macroscopic wave is generated,

whereas in SBS, the generated phonons (acoustic) are coherent and an acoustic wave is generated in an optical fibre.

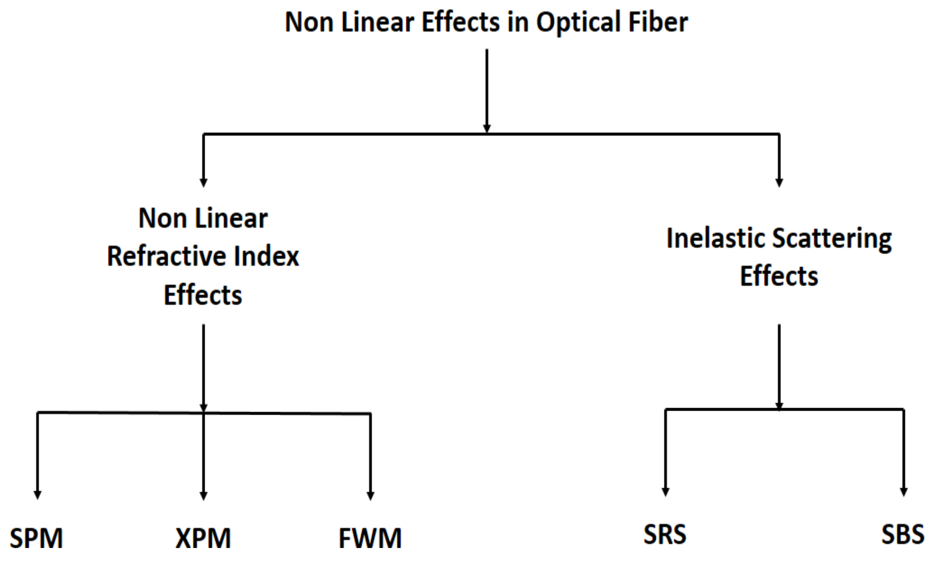


Figure 1.8 Nonlinear effects occurring in optical fiber [66]

With the exception of SPM and XPM, all nonlinear effects give one channel greater gain at the expense of other channels, i.e., one channel's power is enhanced at the expense of another channel's power. Only spectral broadening results from SPM and XPM. Increased dispersion is the outcome of the spectral widening. Figure 1.8 illustrates the classification of nonlinearities that occur in optical fibre.

1.9.1 Four wave mixing

One of the nonlinear effects brought on by the optical fibre link's power-dependent refractive index is FWM. The result of optical Kerr nonlinearity, in other words when the wavelength separation between the channels in a WDM network is very small, it happens [30]. The two key elements on which FWM depends are channel space and fibre dispersion. FWM effects increase as the distance between the channels is shrunk. Additionally, FWM effects grow as dispersion decreases. The resulting cross products interfere with the original wavelengths, causing mixing. Additionally, these interfering signals coincide with the original wavelengths, making it difficult to distinguish between them [31]. For N input wavelengths, the number of mixing products (M) are given by [67]:

$$M = \frac{N^3 - N^2}{2} \tag{1.1}$$

Consider a system with three wavelengths that is experiencing FWM distortion, for instance. Nine cross products will be produced as a result of this system. Two or more original wavelengths are displayed in Figure 1.9. Additional products are produced, although they do not overlap the original wavelengths.

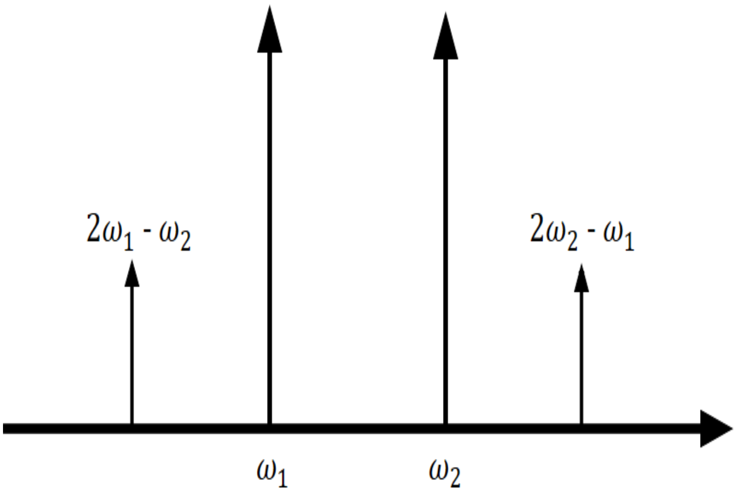
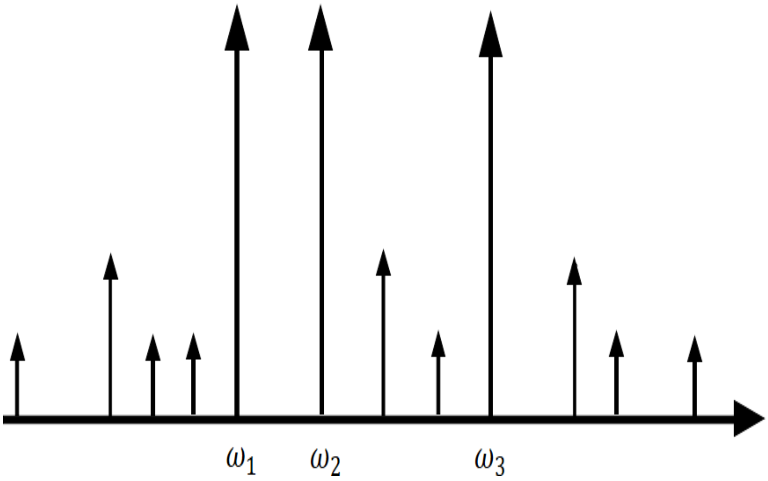


Figure 1.9(a) New frequency components arising due to FWM when there are two input wavelengths ω1 and ω2



(b)

Figure 1.9 (b) New frequency components arising due to FWM when there are three input wavelengths ω1, ω2 and ω3[67]

1.10 Motivation

Nowadays, expeditious growth in internet services such as online gaming, video conferencing, high definition video transmission, etc. has led to a prominent increase in high speed data demands. Microcellular systems are getting attention due to ever-increasing data and capacity demands in wireless services. Utmost advantage of microcellular systems is the potential to support high speed because of the many small cells for frequency utilization.

However, aforementioned advantages come at the cost of huge investment for installing multiple Base stations (BSs). One the most expensive factor for high cost is the complex channel control in the spectral delivery in BSs and the handoffs. In order to eradicate this limitation, operations performed at BSs should replace and done at the Control Station. RoF technology incorporating fiber optical has emerged as a competent technique to cater high speed data. Optical fiber is promising medium for the transmission of radio frequency (RF) signals due to absence of electro-magnetic interferences (EMI), low attenuation, and ability to support high speed. As a result, RoF systems can provide prolonged reaches, better signal transmission in wireless networks and moreover provide improved mobility. RoF systems can be integrated with multiple wavelengths to increase capacity and termed as Wavelength Division Multiplexing (WDM). Integration of RoF systems with WDM offer transparency, flexibility, and high speed but also suffer from nonlinear effects such as FWM, SPM, and XPM.Non-linear and scattering effects are distance and performance limiting and introduce spectrum broadening, pulse broadening and signal modulation. WDM systems have higher nonlinear effects but provide constructive results in RoF systems due to accumulated effects. FWM generated wavelengths causes interferences in the intended wavelengths and their power can be lowered by taking wide channel spacings, lower power levels, and optical fiber lower effective area. OPC has competence to reverse the phase of the input signal and used in middle of the link to suppress FWM. Numerous studies have been reported to suppress the effects of FWMhowever optimal technique is required to mitigate the FWM power [32-34].

CHAPTER 2

LITERATURE REVIEW

N. Kathpal et al. (2020) proposed a RoF system with the integration of WDM over 100 km SMF with FWM suppression. DCF and Band pass optical filter (BPF) based joint technique was employed to suppress the FWM idlers. The results of WDM-RoF system was evaluated at different input parameters such as input power, WDM channel spacings and number of channels in terms of output power, FWM, Q factor and BER. Results revealed that with the use of DCF and BPF, FWM power was suppressed efficiently in 8 channel WDM-RoF system [35].

M.L. Meena et al. (2019) proposed two alternative pulse width broadening compensation strategies to compensate for the pulse width widening in a dense WDM system with eight channels. Pulse width widening causes distance limitation in optical communication systems. Diverse modules were investigated for pulse width broadening compensation, including linear chirped FBG profiles and DCFs, and these modules were tested and assessed. A dense WDM system with return to zero modulation was used, while EDFA was used for amplification. A 150-kilometer SMF and a 45-millimeter FBG were included in the system. In the system, DCF lengths of 30 km were used, and the Opti system version 7 was examined. Power, length, and attenuation were all different performance factors. The chirped FBG performed best in the planned work, according to the results [36].

A. Wilson et al. (2018) demonstrated a linearization approach for RoF connections that lowers nonlinear distortion and improves receiver sensitivity. The design also addressed the RoF system without considerably increasing the system's cost or complexity. Regardless of the RF carrier employed, the suggested approach was capable of suppressing both second- and third-order aberrations. It was also demonstrated that it outperformed typical RoF systems in terms of BER and receiver sensitivity. Improved receiver sensitivity and less multi-subcarrier interference are possible thanks to the reduced nonlinear distortions. However, the proposed system employs DSB transmission, which is less spectrally efficient than single sideband (SSB) transmission [38].

A. Nain et al. (2018)studiedthe role of fibre nonlinearities in the functioning of RoF-based 5G networks. It was discovered that different nonlinearities, such as FWM, XPM, and SRS, cause significant crosstalk. Nonlinear crosstalk is observed to vary practically linearly with input optical power and transmission distance, with FWM and XPM generated crosstalk having a greater influence than SRS caused crosstalk. Furthermore, it was determined that FWM generated crosstalk is roughly 35 and 110 dBm greater than XPM and SRS induced crosstalk after transmission over a distance of 30 km. FWM generated crosstalk is 40 dBm greater than XPM caused crosstalk when the input power is 15 mw. In order to decrease nonlinearity in SCM-WDM based RoF networks, a simulation study was conducted.Nonlinearity is investigated using a variety of modulation methods, including Direct Modulation (DM), Mach Zehender Modulation (MZM), and Optical Phase Modulation (OPM). It was discovered that OPM outperforms DM and MZM-based signals and considerably reduces nonlinearity [39].

R. A. Ahmed (2018) proposed a pulse amplitude modulation-based system; researchers developed a system for pulse width widening compensation and investigated three distinct pulse width broadening compensation strategies. The system was tested in pre, post, and symmetrical versions, with a speed of 1 Gbps. In the system, the BER and Q factor for three distinct pulse width broadening compensating units were examined. At various input power levels, such as 0 dBm to 10 dBm, it was discovered that symmetrical configurations functioned best [40].

Y. Quan et al. (2018) since its inception in the 1980s, the exponentially growing information demand has been met by optical communication networks based on the ubiquitous SMF. WDM, polarization multiplexing (PolMux), and multi-level signaling with coherent detection have all improved the situation.The capacity sent over a single SMF has continuously increased. The 110 km real-time 428 Gb/s single mode fiber-based system was examined. Pulse width broadening compensating fiber was employed in both the pre and post configurations in this study. In wavelength division multiplexing systems, a wavelength selective switch is used to compensate for pulse width widening [41].

A. Seal et al. (2017) to enable interior connectivity, an optical fibre was used to connect a central station (CS) to a number of Radio Access Points (RAP). A photodiode, a band pass filter, a power amplifier, and an antenna operating in the 2.4 GHz frequency band made up the indoor RF front end. The RF front end components were modelled using S-parameter measured data from factory data sheets. Indoor Pico cells with a service range of around

100meters and a power capacity of less than 1 Watt (30 dBm) were employed. With the aforementioned arrangement, the system's operational gain was computed [42].

K. Singh et al. (2017) to improve the overall performance of the system, researchers looked at pulse width broadening correction in passive optical communication. To correct for pulse width broadening, DCF and FBG modules were used. At a rate of 10 Gbps, DCF and FBG were employed for Pre, Post, and Symmetrical Compensation. In this operation, a DCF of 24 km was employed to serve 40 channels across a 120 km single mode fiber. The system used a data rate of 10 Gbps per channel, with outcomes measured in terms of BER and Q factor [43].

T. Liu et al. (2016) the authors ran an experiment to demonstrate an effective, FWM-centered multi-wavelength generation with a narrow wavelength spacing. To facilitate effective multi-wavelength generation, dispersion flattened high nonlinear fibre (DF-HNLF) and double-pass configuration were used. With a wavelength spacing of 0.1 nm, this multi-wavelength generation had a 3 dB bandwidth that is roughly comparable to 11 nm. To examine the effects of nonlinearity and dispersion, a conventional SMF of length 500m, a high nonlinear fibre of length 500m, and a DF-HNLF of length 500m were introduced in the cavity [44].

G. Kaur et al. (2015) the authors looked into how FBG, DCF, and OPC were implemented. These arrangements were also contrasted with traditional designs. In a WDM framework with 16 channels and a 10Gbps information throughput, the impact of hybrid modules on FWM was investigated. By reducing the FWM by up to 40dBm, the proposed methods enhanced system performance [45].

M. Matsuura et al. (2015) Using a 100m double-clad fibre, the authors experimentally showed bidirectional RoF. The remote antenna units (RAUs) that were optically powered employed the double-clad fibre. It had a single mode core for a RoF link and a multimode inner cladding. The single mode core was used to simultaneously transmit optical RoF information signals uplink and downlink while the inner cladding was employed to give optical power to RAU. The approach's primary goal was to make it unnecessary for RAUs that were powered optically to use external power sources, such as batteries or public power lines [46].

H. U. Manzoor et al. (2015) The authors described a technique for modifying the polarization of input pulses into left- and right-polarized pulses before multiplexing, which results in a decrease in FWM. Without compromising the quality of the initial pulses, circular polarizers decreased the effects of FWM. Circular polarizers can be used to totally eradicate FWM, and network settings can be changed to decrease data rate, lengthen fibre and widen channel spacing [47].

S. Singh (2014) the implementation of bi-directional PON was assessed by the author and contrasted in a triple play service scenario at various bit rates. To implement the triple-play service, the data, video, and voice streams were integrated. This architecture's performance was evaluated in terms of eye height and quality factor for symmetrical data traffic sent as downlink and uplink signals (Q-factor). The suggested system was tested with 128 users, and for various transmission distances and user counts, the appropriate eye height and Q-factor were estimated. The system performed satisfactorily for upstream and downstream transmission at a data rate of 10Gbps, according to the Q-factor measurements [48].

M. Bi et al. (2014) The authors presented a stacked WDM-OFDM-PON system that could provide upstream on-off keying (OOK) signals up to a distance of 100 km without the use of a repeater and downstream OFDM signals of 10Gbps per wavelength. In order to concurrently pick downstream signals and process upstream signal chirp, the scientists developed an electrical controlled liquid adjustable optical filter. According to the experimental findings, a 35.6dB power budget was achieved for transmission over a 25km fibre in order to accommodate 1:512 splitting ratios. Without the aid of a repeater, transmission over a 100 km distance was also successful with an optical power budget of 34.4dB [49].

G. Cheng et al. (2014) In order to create dual octupling-frequency millimeter waves needed for two BSs, the authors suggested and tested a unique RoF network utilizing optical interleaver and an external modulator. The uplink connection was created using the remodulation approach. The system was cost-effective since only one laser source, located at the central office, was shared for the generation of the two upstream signals. The findings demonstrated that there is a power penalty of less than 0.6dB when the uplink and downlink signals are sent across an SMF of length 60 km [50].

A. Emsia et al. (2014)by growing the system's user base, the authors' novel reach extension technique enhanced bandwidth while lowering implementation costs. The system examined differential (quadrature) phase-shift keying signals. Experimental demonstrations of hybrid TDM/WDM transmission up to 120Gbps downstream and 40Gbps upstream were made. When DPSK was employed with as per wavelength splitting ratio of 1:512, the access budget of 33.4 dB was attained on every WDM channel at 10Gbps. Additionally, DQPSK with as per wavelength splitting ratio of 1024 yielded a power budget of 40dB. Additionally, nonlinear limitations that appeared in dense WDM transmission were eliminated by the suggested approach [51].

G. Kaur et al. (2014) The authors examined FWM power mitigation in hybrid network topologies. The topologies were ring and bus-based. They looked into an approach that relied on an optical phase conjugator (OPC) to reduce the power of the FWM. Utilizing the Q-factor, eye diagram, and induced FWM power factors, the system's performance was assessed. The findings showed that the OPC module successfully suppressed the FWM power by more than 40dBm [52].

D. D. Patel et al. (2014) examined the effect of FWM, XPM, and SRS on a WDM optical communication network. 16 channels made up the proposed WDM system. The findings indicated that the nonlinearities like XPM also grew as the number of input channels and input power increased. To lessen the consequences of nonlinearities, certain innovative strategies were described. Rectangular optical filters were used to counteract the effects of FWM, while a method based on FBG was used to counteract the effects of XPM [53].

A. O. Aldhaibania et al. (2013) The RoF technology in the GPON system architecture was used by the authors to demonstrate a 2.5Gbps gigabit PON (GPON) downstream link. The integration of TDM and WDM GPON into a single PON increased data rate while lowering system cost. The radio transmissions travelled along a standard SMF that was 25 km long. 32 and 64 clients were supported by the proposed framework. Based on the optical signal-to-noise ratio (OSNR), received power, error vector magnitude, constellation diagram, and eye diagram, the suggested system's performance was evaluated. The value of EVM grew along with the distance, peaking at 30.3 percent at 50 km. However, when the distance was increased to 50 km, the OSNR and received power fell to 35 dBm and -24 dbm, respectively [54].

C. W. Chow et al. (2013) by employing DPSK for the downlink and ASK (wavelength-shifted) for the uplink signal, the authors showed how to migrate from TDM-PON to WDM-PON. To select the proper downlink wavelength in the network and simultaneously demodulate the downlink signal, an optical filter was deployed at the base station. According to experimental findings, the re-modulated wavelength-shifted ASK uplink enabled signal transmission under 32 and up to 64 splits [55].

F. I. El-Nahal (2013) A unique bidirectional RoF network with 10Gbps DPSK downlink at the central office and an ON-OFF keying re-modulation method for uplink was proposed by the author. No additional light source was needed at the base station because the proposed method used the same optical carrier for both uplink and downlink. As a result, the system's overall cost was decreased and the efficiency of wavelength usage increased. According to the simulation's findings, the system could enable transmission across a 50 km distance without dispersion compensation [56].

H. Bai et al. (2013) A switching node was created by the authors. The hybrid WDM/TDM PON introduced this switch structure, which was created utilizing tunable wavelength converter technology. In terms of packet loss rate and bandwidth utilization rate, experimental results showed that using switch nodes increased system performance. The findings demonstrated that the 64 optical network units operating in the 16 wavelengths mode performed properly, as evidenced by the least average packet latency and least packet loss [57].

B. Kaur et al. (2013)examined how WDM Ethernet PON (EPON) with a RoF optical link was implemented in order to account for FWM and dispersion. Two FBGs with wavelengths of 1550.11 nm and 1552.5 nm were employed for FWM and dispersion compensation, as well as a DCF with a dispersion value of -50 ps/nm/km. The system was enhanced by 77.67% utilizing FBG and DCF. The framework's performance was examined using three parameters: Q factor, bit error rate (BER), and eye diagrams [58].

R. Yadav (2012) discussed various architectural options for a PON-based, convergent access network that would handle both commercial and residential services. By using this paradigm, network providers would be able to install PON-centered premises while making the most of their fibre investment. Supporting those business services with higher value on the same infrastructure would achieve this with the added benefit of incurring little more expense. By extending the availability of business services, this technology decreased the cost of supporting them and expanded revenue prospects [59].

S. Mitathaa et al. (2012) For RoF networks combined with dense WDM scheme, the authors developed a unique Terahertz frequency architecture. The suggested structure supported increased channel capacity and signal security. It was also discussed how wavelengths have improved optical communication. Both terabit wireless and cable systems that are now in use might be integrated with the proposed system [60].

F. Brendel et al. (2011) the effect of chromatic dispersion on SMF centered around mode locked laser sources was examined by the authors. A 60 GHz radio carrier-delivering laser and a 400 m length that reflected the length of a practical link for in-house distribution were used to empirically validate the simulation results. Additionally, the impact of chromatic dispersion on the signal quality for wireless local area network transmission using external and direct link modulation was illustrated [61].

J. L. Xie et al. (2010)developed a unique RoF network based on frequency quadrupling and double-sideband modulation to lower system costs at both the CS and the BS,. By correctly biasing the intensity modulator, the repeating frequency of the optical millimeter wave was increased to four times that of the local oscillator signal. The theory evaluation revealed that information signals might be made resistant to signal walk-off, signal fading, and code time shift after transmission over fibre [62].

CHAPTER 3

RESEARCH GAPS

3.1 Research Gaps

The growth of data services has necessitated the development of high-speed systems in both wired and wireless communications. To keep up with the substantial next generation applications, super high speed is essential. In the literature, researchers looked at distances, modulations, photo detectors, amplifiers, WDM channels, nonlinearity compensation, filters, and dispersion compensation, among other things. Nonlinearity, on the other hand, is a crucial consideration when developing long-range and high-speed systems. The following are some of the issues that have been raised in the literature:

3.2 Problem Formulation

The following problems in the literature survey are observed:
Dispersion compensation fibre was stated to be utilized to extend the reach of the WDM-RoF system, i.e. for dispersion compensation, although it is known that DCF increases the system's FWM. As a result, regardless of rising nonlinear effects, additional accessible reach extenders can be employed in the system for dispersion adjustment.
In reported work, an optical Bessel filter improved FWM suppression; however, other existing optical filters can also be tried in the RoF system.

3.3 Objectives

1. To study radio over Fiber systems, nonlinear effects and their suppression techniques.
2. To analyze the combined effects of DCF-Band pass filters, FBG-Band pass filters and OPC-Bandpass filters on FWM emergence in RoF systems.
3. To investigate proposed system at different input powers, channel spacings, number of channels and to analyze the results in terms of FWM power, Q factor and BER.

CHAPTER 4

PROPOSED WORK

Implementation of WDM-RoF system is discussed under as:

4.1 Proposed FWM Suppressed WDM-RoF System Using OPC-BPF

RoF systems supporting high frequency millimetre waves are emerged as a great choice for Fifth generation (5G) broadband communication. In this research work, a RoF system has been proposed with the integration of WDM over 100 km single mode fiber with FWM suppression. OPC and Band pass optical filter (BPF) based joint technique has been employed to suppress the FWM idlers. The results of proposed WDM-RoF system has been evaluated at different input parameters such as input power, WDM channel spacings and number of channels in terms of output power, FWM, Q factor and Bit error rate (BER). A detailed comparison of DCF-BPF and proposed OPC-BPF is performed and results revealed that due to mid-link spectrum inversion in OPC-BPF, it has improved performance with enhanced FWM suppression and can support high input powers.

4.2 Principle of FWM and its control

Optical fiber can carry multiple wavelengths at same time but power accumulation of all channels modulates the refractive index of the fiber. Change in refractive index further leads to the change in speed of signals and thus change the phase of the signal. Phase change is the primary reason for the nonlinear effects and in WDM systems, FWM is the most dominant. FWM sidebands products (M) are expressed as [68]:

$$M = \frac{N^3 - N^2}{2} (4.1)$$

Where N are the number of channels and for two channels having wavelengths λ_1 and λ_2, FWM generated sidebands are at λ3and λ_4. Where $\lambda_3 = 2\lambda_1 - \lambda_2$ and $\lambda_4 = 2\lambda_2 - \lambda_1$

Let's assume three wavelengths having power P_1, P_2, P_3 at λ_1, λ_2,λ_3 and their output at the end of optical fiber is [69]

$$P_{FWM} = \eta D_F^2 P_1 P_2 P_3 e^{-\alpha L} L_{eff}^2 \quad (4.2)$$

Where, $L_{eff} = \frac{(1-\exp(-\alpha L))}{\alpha}, \gamma = \frac{2\pi\eta}{\lambda A eff}, \eta = \frac{\alpha^2}{\alpha^2+(\Delta\beta)^2}[1 + \frac{4\exp(-\alpha L) sin^2 \frac{(\Delta\beta L)}{2}}{(1-\exp(-\alpha L)^2},$

$$\beta = \frac{-\lambda^4 \pi}{c} \frac{dD_c}{d\lambda} [(f_1 - f_0) + (f_1 - f_0)]((f_1 - f_3)(f_2 - f_3)$$

Attenuation constant is α, effective core area of fiber Aeff, nonlinear coefficient $\boldsymbol{\gamma}$, length of fiber Leff, FWM efficiency $\boldsymbol{\eta}$, phase matching factor is $\Delta\beta$, dispersion is D_c, zero frequency and 1st frequencies are f_0 and f_1 respectively. f_2 and f_3 are $_{2nd}$ and 3rd frequencies and it is observed that 9 new FWM idlers are obtained as given in equation (1). More the number of WDM channels, more are the FWM idlers. Power of FWM is expressed as [69]

$$\frac{P_{FWM}}{P_0} = (D_F \gamma L_{eff})^2 {P_i}^2 (mW) \quad (4.3)$$

Higher power generates more FWM power as shown in equation (4.3).

Extensive literature studies revealed that FWM reduction is accomplished by using different modulation formats, low input power, wide channel spacings, OPC, dispersion compensation fiber [35] with optical filter etc. However, high suppression of FWM has been required for WDM systems.

4.3 Proposed 8/32 WDM ROF systems Using OPC-BPF

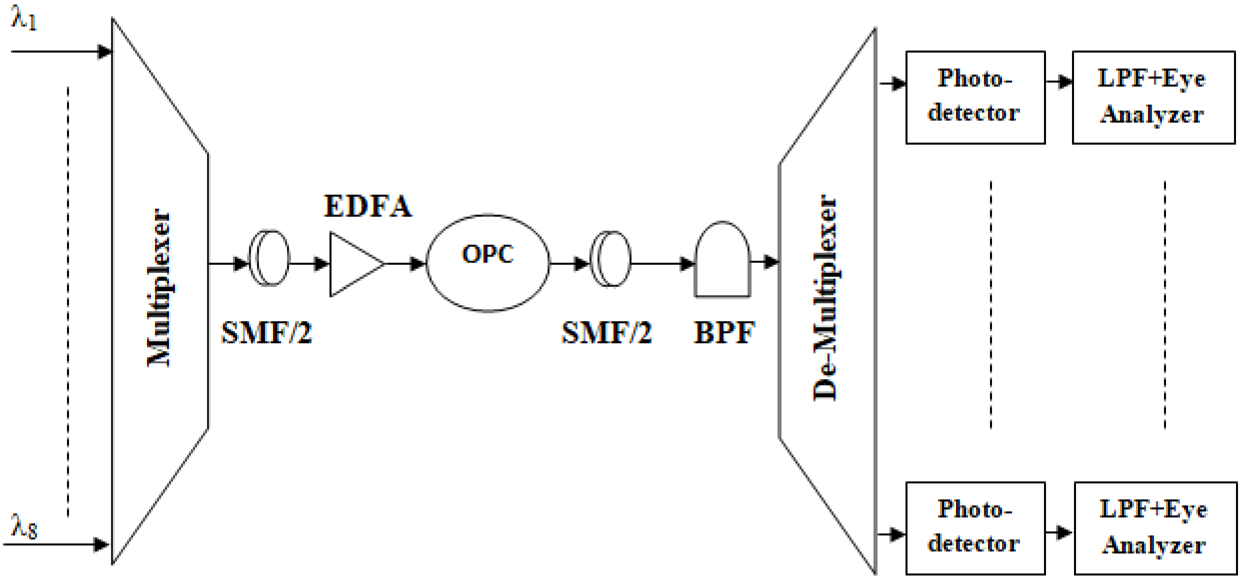


Figure 4.1 Block diagram of represents the proposed WDM-RoF system at 4 Gbps using OPC-BPF for FWM suppression.

Table 4.1 Simulation parameters of proposed WDM-RoF system

Parameters	**Values [50]**
Data Rate	4 Gbps
Sequence length	256 bits
Samples per bit	128
Number of samples	32768
WDM Channels	2, 4, 8
Input Power	-10 to 20 dBm
Channel Spacing	25 to 100 GHz
CW laser line width	10 MHz
MZM extinction ratio	30 dB
SMF Length	100 km
Attenuation and dispersion	0.2 dB and 16.75 ps/nm/km
Effective area	80μm^2
EDFA Gain and Noise Figure	20 dB and 2 dB
PIN responsitivity	1 A/W
Thermal noise	10-^{21} W/Hz
Dark current	10 nA
Low Pass Bessel Filter	0.75* Bit Rate Hz
Insertion Losses LPF	0 dB

In central office, binary data in the form of ones and zeros is generated from pseudo random data generator and followed by electrical pulse shaper such as Non Return to Zero (NRZ). This linecoding has advantage of simple pulse generation and power efficient modulation format. RF signal at 40 GHz is superimposed on the NRZ data pulse and further electrical to optical conversion is performed with high carrier laser at conventional band (C-Band) and Mach-zehndar modulator (MZM). Eight wavelengths starting from 193.1 THz to 193.8 THz at -10 dBm to 20 dBm input power with 25 GHz to 100 GHz channel spacing is deployed. Simulation parameters have been presented in Table 4.1.

Further, WDM channels are multiplexed and signal is fed to transmission medium having single mode fiber (SMF) of 100 km. In the proposed system, the total length of the fiber is divided into two halves because of the deployment of OPC (encoded in Matlab) in middle of the link and therefore 50 km SMF and an EDFA is followed by an OPC and then by EDFA+50 km SMF. Gain of EDFA is 20 dB and noise figure 2 dB for both the amplifiers and it utmost of amplifiers is to mitigate the power losses introduced by attenuation and nonlinear effects. OPC suppress the FWM idlers power due to phase reversal properties and therefore nonlinearity generated in the first half of the SMF are compensated by OPC and then in the second half, zero phase change obtained. Bessel optical filter is placed after transmission due to further reduction in FWM. Flat group delay, wave shaping and slow overshoot and cut-off are prominent advantages of band pass filter. FWM suppressed signals are isolated using de-multiplexer and each filtered wavelength passed through photodetector, low pass Bessel filter and BER analyzer in BS.

4.4 Results and Discussions

Investigation of proposed WDM-RoF system at different input parameters has been performed in terms of Q-factor, FWM power and BER for an 8 channel system. Channel spacing between 8 WDM channels has been varied as shown in Table 4.2 and power received, Q factor, and BER output values have been listed. Effects on received power with and without BPF are for DCF [35] and OPC are also compared. There is reduction in the output power in DCF and OPC when BPF is used, and this is because of the filtration of data pulse trains and also filter blocks some unnecessary part of desired signal. Received power in DCF/OPC-BPF systems has been compared at different channel spacings. Results revealed that received power is more in OPC-BPF i.e. 31.02 dB with filter at 25 GHz and reduces to 27.19 dB when BPF has been incorporated as shown if Figure 4.2 (a).

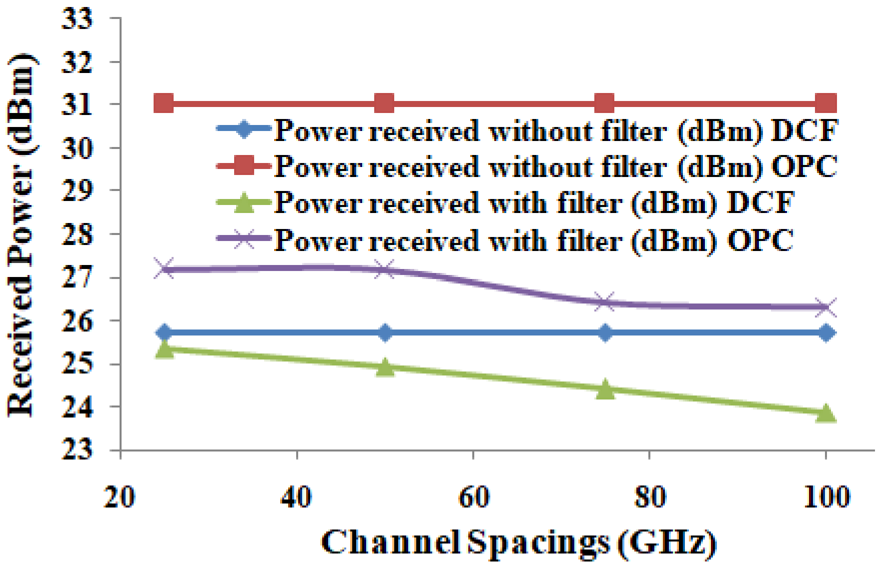
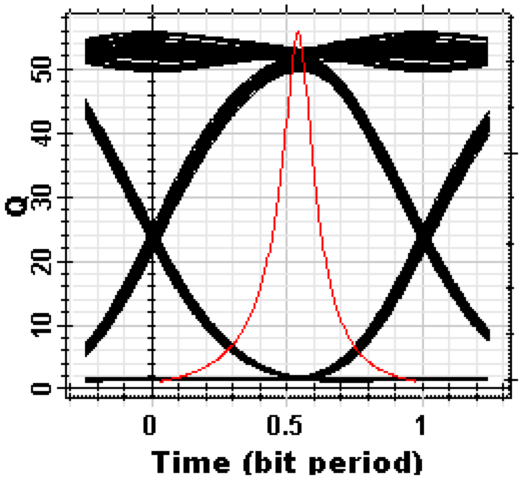
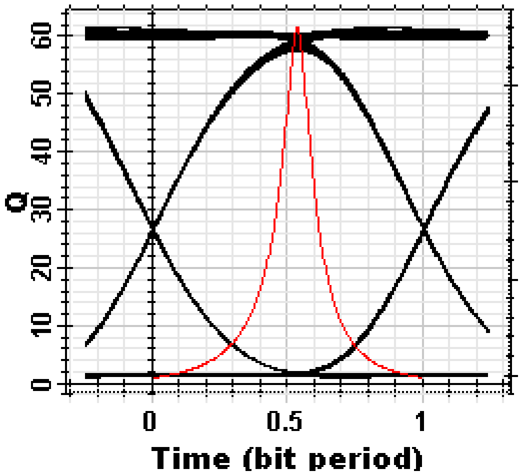


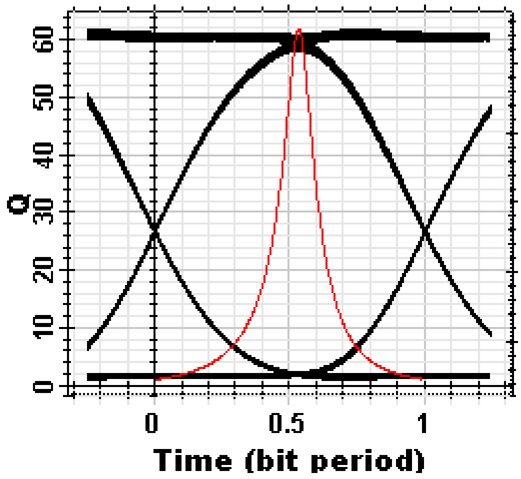
Figure 4.2 (a) Received optical power before and after DCF/OPC-BPF at different channel spacings



4.2(b) Eye diagram at 25 GHz



4.2(c) Eye diagram at 50 GHz



4.2(d) Eye diagram at 75 GHz

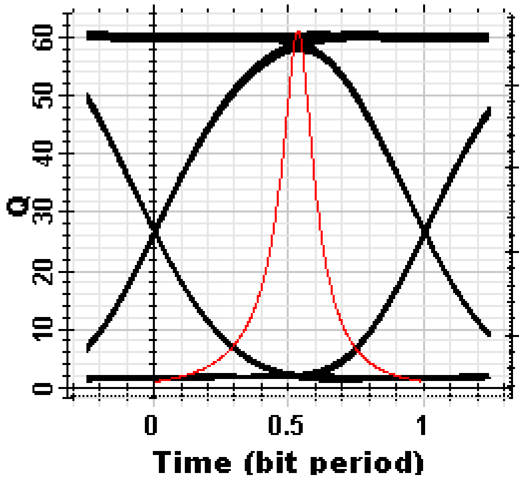


Figure 4.2(e) Eye diagram at100 GHz

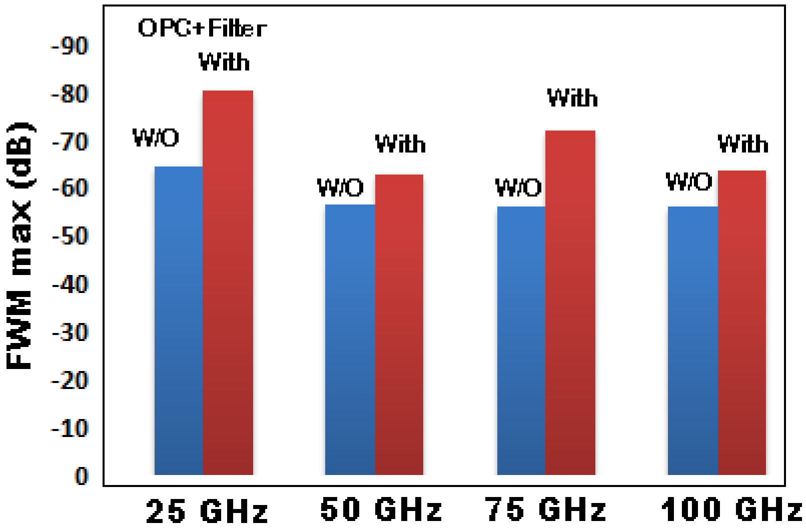


Figure 4.2 (f) Effects on FWM power at different channel spacings with and without OPC+BPF

Q factor at 25 GHz is 55.81 for OPC and 43.17 in case of DCF. Mid-link spectrum inversion with BPF is more competent to reduce FWM and therefore able to provide better Q factor and BER. Eye diagram at 25 GHz for OPC-BPF is presented in Figure 4.2 (b).

Table 4.2 Impact of channel frequency on mitigating FWM effect

Channel Spacings (GHz)	Power received without filter (dBm)		Power received with filter (dBm)		Q factor		BER	
	DCF	OPC	DCF	OPC	DCF	OPC	DCF	OPC
25	25.72	31.02	25.37	27.19	43.17	55.81	0	0
50	25.72	31.02	24.93	27.18	47.05	61.44	0	0
75	25.72	31.02	24.40	26.41	53.15	61.73	0	0
100	25.72	31.02	23.86	26.30	46.83	60.91	0	0

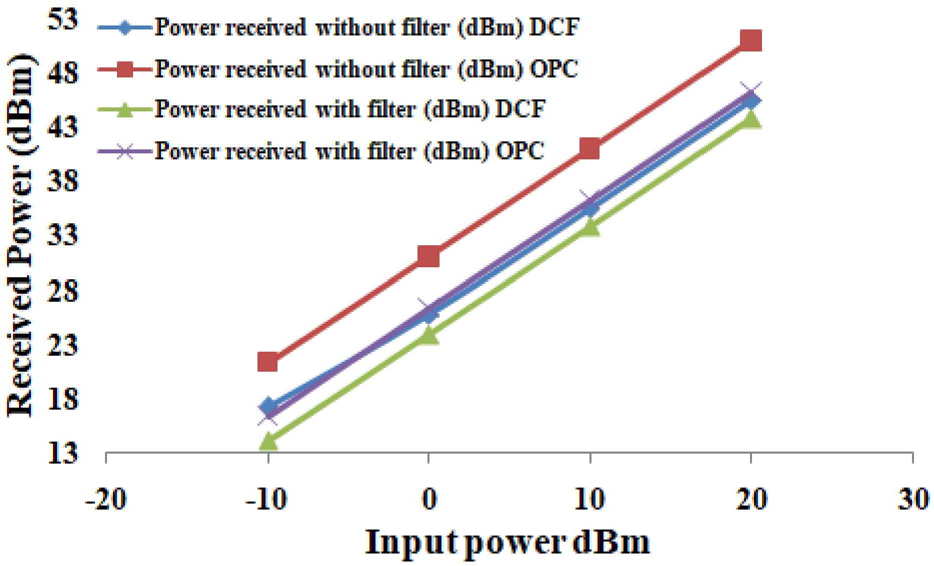
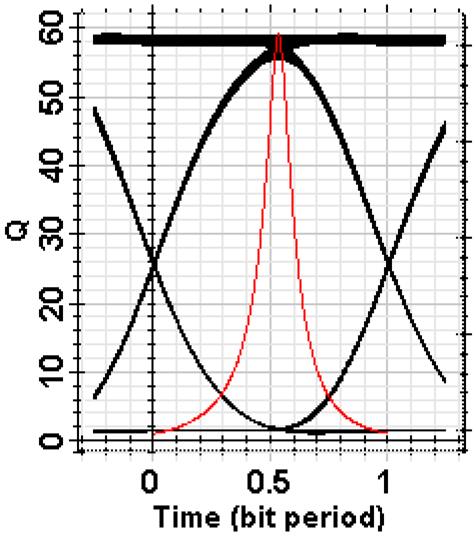


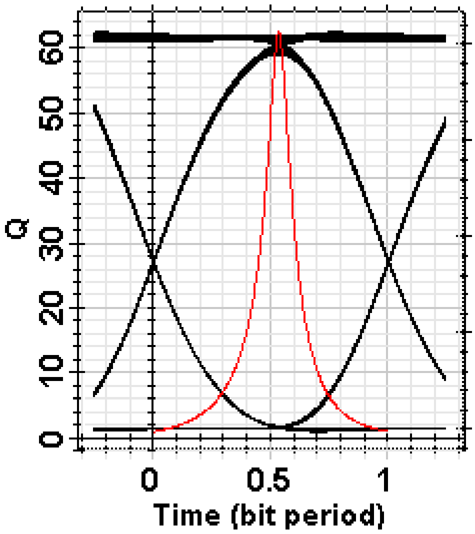
Figure 4.3 (a) Received optical power before and after DCF/OPC-BPF at different input Powers

Further, eye diagrams are also taken at 50 GHz, 75 GHz and 100 GHz and shown in (c), (d) and (e). Effects on FWM power at different channel spacings with and without OPC+BPF is depicted in Figure 4.2 (f) and it is observed that maximum FWM suppression is seen at 25

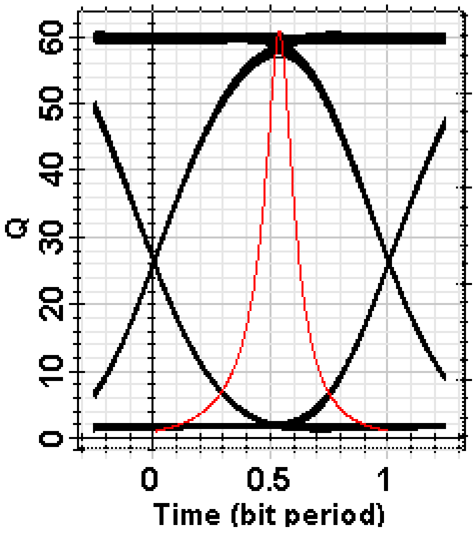
GHz using OPC-BPFEye diagrams at using OPC-BPF for 20 dB, 10 dB, 0 dB and -10 dB input powers are represented in Figure 4.3 (b), (c), (d) and (e).



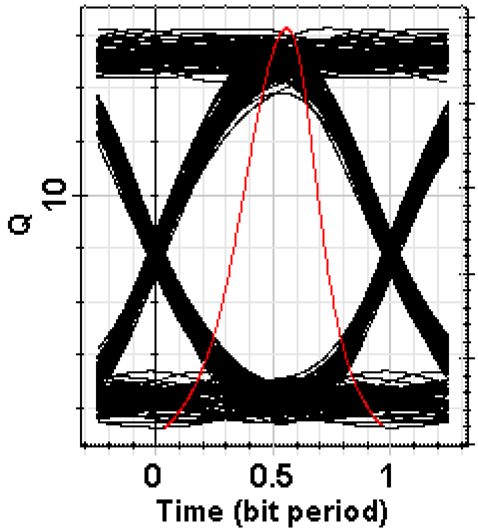
4.3 (b) Eye diagram at using OPC-BPF for 20 dB



4.3 (c) Eye diagram at using OPC-BPF for 10 dB



4.3 (d) Eye diagram at using OPC-BPF for 0 dB



4.3 (e) Eye diagram at using OPC-BPF for -10 dB

Figure 4.3 Eye diagrams at (b) 20 dBm (c) 10 dBm (d) 0 dBm and (e) -10 dBm for OPC-BPF

Lowest FWM is obtained at -10 dB input power and maximum for 20 dB but these values are lower than DCF+BPF as shown in Figure 4.3 (f). Advantage of OPC-BPF is that it has potential to mitigate the effects of FWM even at 20 dB which is not true for DCF-BPF. Maximum suppression is done by OPC-BPF at -10 dBm input power and suppression slightly reduced without BPF.

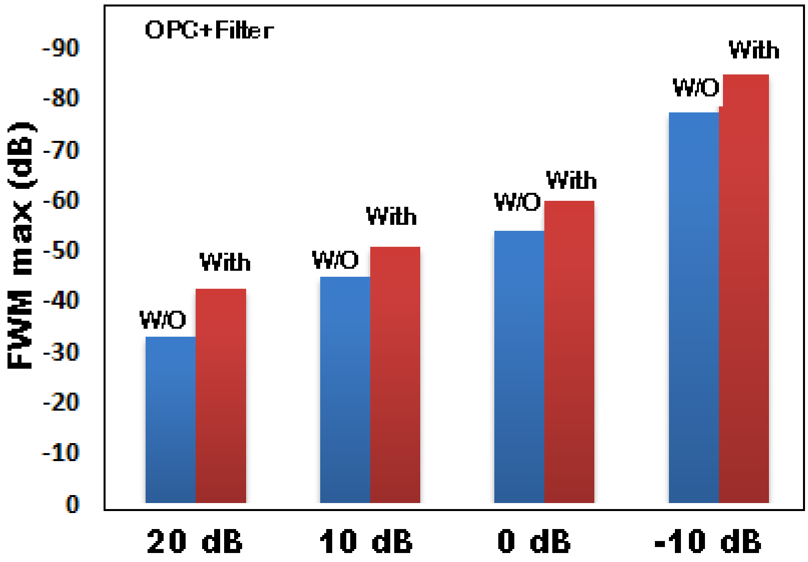


Figure 4.3 (f) Effects of input powers at FWM and compensation with and without BPF in OPC

Table 4.3 Impact of input power on mitigating FWM effect

Input power (dBm)	Power received without filter (dBm)		Power received with filter (dBm)		Q factor		BER	
	DCF	OPC	DCF	OPC	DCF	OPC	DCF	OPC
20	45.52	50.99	43.83	46.30	3.21	59.08	0.0034	0
10	35.54	40.99	33.83	36.30	15.43	62.36	3.08e-45	0
0	25.72	31.02	23.86	26.30	46.83	60.63	0	0
-10	17.17	21.28	14.16	16.32	35.95	16.26	1.54e-283	9.1e-60

Table 4.4 Impact of channels on mitigating FWM effect

WDM channels	Power received without filter (dBm)		Power received with filter (dBm)		Q factor		BER	
	DCF	OPC	DCF	OPC	DCF	OPC	DCF	OPC
2	25.09	25	19.51	23.73	61.44	63.74	0	0
4	22.89	28.30	22.06	25.96	51.95	63.43	0	0
8	25.72	31.02	23.86	26.30	46.83	60.91	0	0

Lastly, channels are varied in WDM system such as 2, 4 and 8 to analyze their effects on FWM. With the increase in WDM channels, more reduced results are obtained in terms of

Received power, Q factor and BER are shown in Table 4.4. Presence of BPF in OPC offers lesser FWM in allWDM channels and minimum FWM is obtained for 2 WDM channels.Optical carrier spectrums with and without BPF for 2, 4, and 8 WDM channels are represented in Figure 5 (a) and (b), Figure 6 (a) and (b), Figure 7 (a) and (b) respectively for OPC. Eye diagrams for aforementioned WDM channels are shown in Figure 5 (c), 6 (c), and 7 (c) respectively for OPC. Q factor of 63.74, 63.43, 60.91 are obtained with OPC-BPF and 61.44, 51.95, 46.83 with DCF-BPF for 2, 4 and 8 WDM channels.

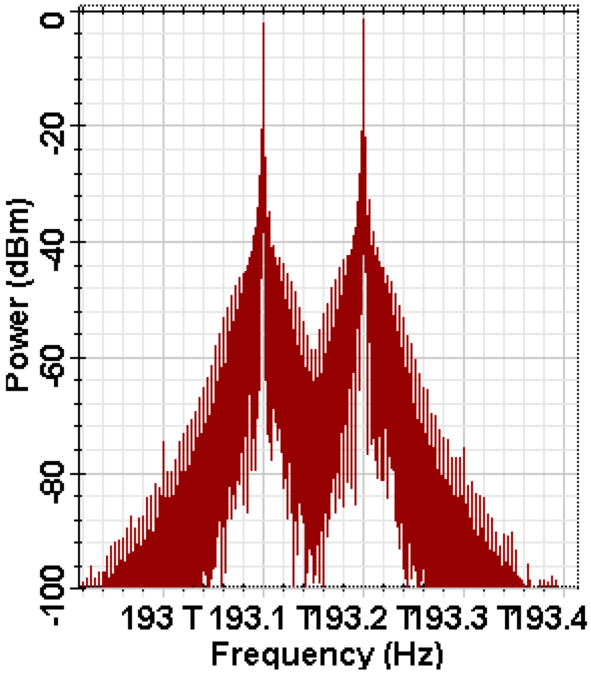


Figure 4.4(a) Optical spectrums for 2 WDM channels before OPC-Bessel filter

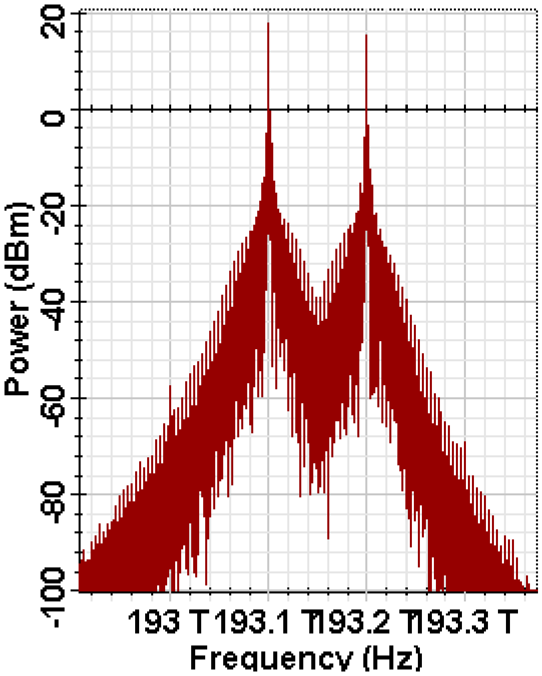


Figure 4.4 (b) Optical spectrums for 2 WDM channels after OPC-Bessel filter

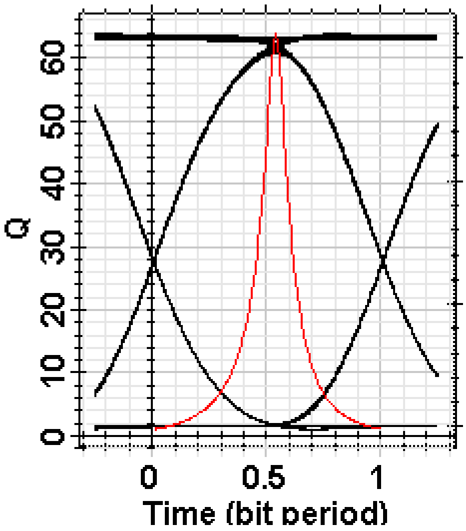


Figure 4.4(c) Eye diagram of Optical spectrums for 2 WDM channels

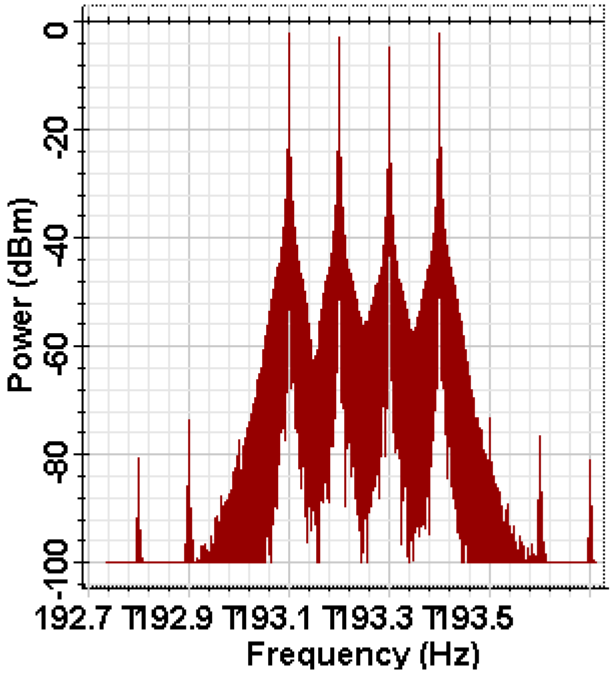


Figure 4.5(a) Optical spectrums for 4 WDM channels before OPC-Bessel filter

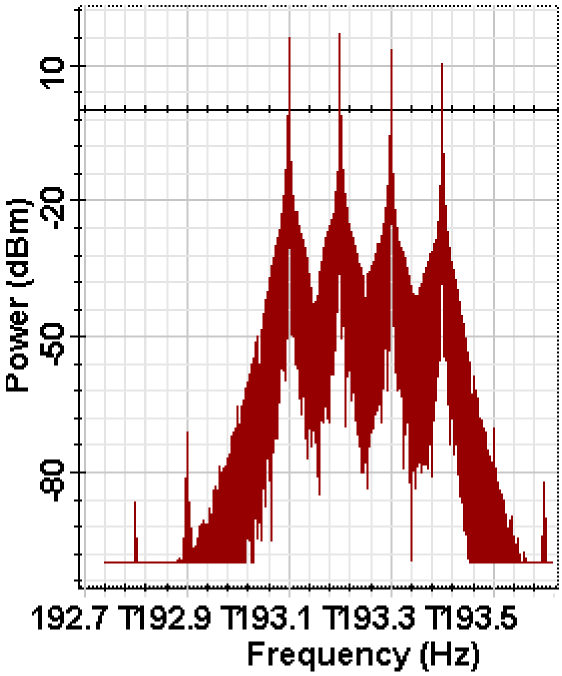


Figure 4.5(b) Optical spectrums for 4 WDM channelsafter OPC-Bessel filter

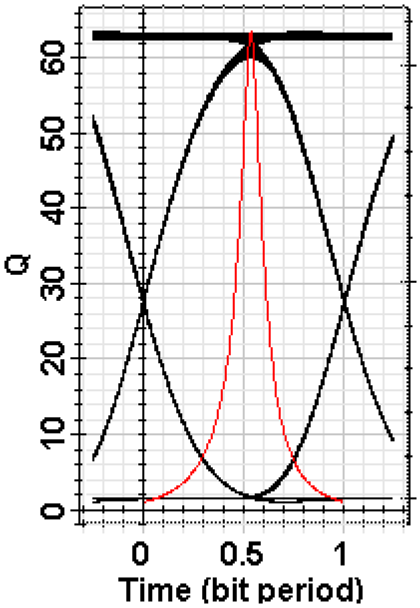


Figure 4.5(c) Eye diagram of Optical spectrums for 4 WDM channels

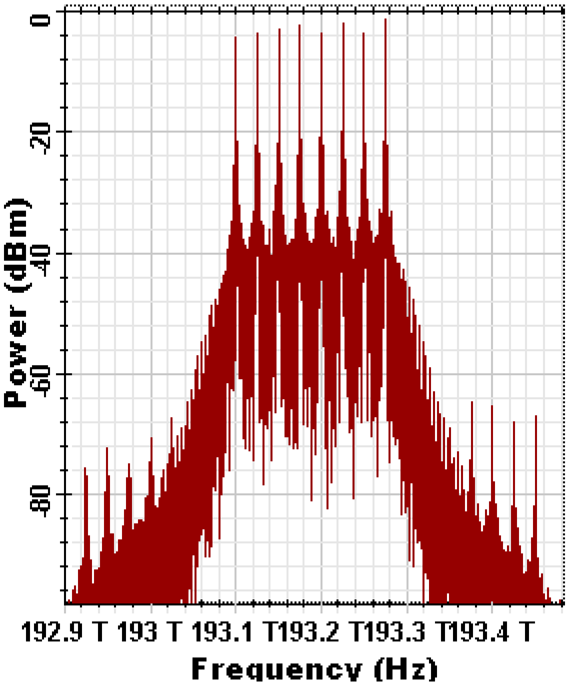


Figure 4.6(a) Optical spectrums for 8 WDM channels before OPC-Bessel filter

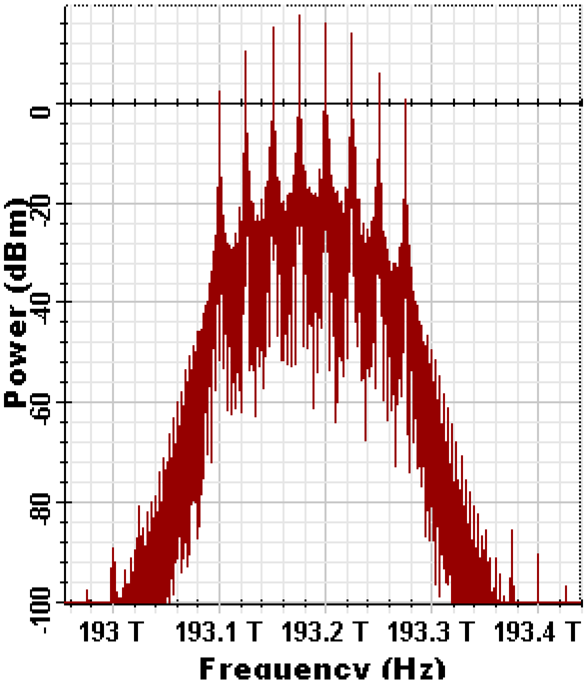


Figure 4.6(b) Optical spectrums for 8 WDM channels after OPC-Bessel filter

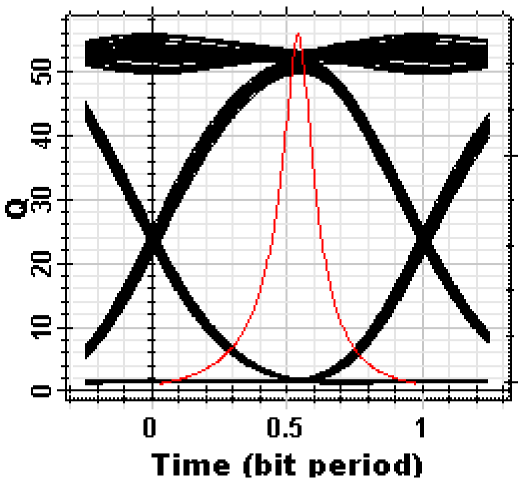


Figure 4.6(c) Eye diagram of Optical spectrums for 8 WDM channels

CHAPTER 5

CONCLUSION AND FUTURE SCOPE

Concluding remarks of results obtained from the detailed investigation of WDM-RoF system are given below

5.1 Conclusion

In this work, a RoF system with the integration of WDM technology is presented and effects of FWM are studied at different input parameters such as input power, WDM channel spacings and number of channels in terms of output power, FWM, Q factor and BER. A detailed comparison of DCF-BPF and proposed OPC-BPF is performed. OPC-BPF is the potential technique to mitigate the effects of FWM even at 20 dB which is not true for DCF-BPF. Maximum suppression is done by OPC-BPF at -10 dBm input power and suppression slightly reduced without BPF. Q factor at 25 GHz is 55.81 for OPC and 43.17 in case of DCF. Q factor of 63.74, 63.43, 60.91 are obtained with OPC-BPF and 61.44, 51.95, 46.83 with DCF-BPF for 2, 4 and 8 WDM channels. Due to mid-link spectrum inversion and joint effects of Bessel filter, proposed system provide lower FWM, greater Q factors and error free BER for 100 km.

5.2 Future Scope

It is expected that multichannel access will become the norm in the near future. This technology is rapidly growing since it allows a bigger number of consumers to share the entire cost. As the number of HDTV channels accessible expands, more bandwidth will undoubtedly be necessary. These days, long-reach systems are essential, and handling nonlinear effects is the only way to do this. The emphasis of the proposed study is on improving the efficiency of FWM suppression in multiple channel systems using OPC-BPF. However, in the not-too-distant future, the following changes will be necessary to expand the capacity and range of optical communication networks.

- NRZ is the modulation formats used in the proposed work. Other bandwidth-efficient multilevel modulations, such as QPSK, QAM, OFDM, dual-polarization based QPSK, QAM, and so on, can perform better.
- The data rate for the proposed work is 10 Gbps, and nonlinear compensation modules are being investigated at this speed. In the near future, this can be investigated at higher data rates to assess the performance of FWM compensation modules.

- The suggested work considers different frequency spacing. In the future, frequency spacing can be lowered to accommodate more channels, and the effect of spacing on FWM can be investigated.
- While EDFA is examined in the proposed work, hybrid optical amplifiers are also a good option for high-capacity WDM systems that can be investigated in the same system.

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