Analysis and Suppression of Intermodulation Distortion Effects in Mach-Zehnder Modulator for Analog Optical Transmission Systems

by

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CANDIDATE'S DECLARATION

It is hereby declared that this thesis or any part of it has not been submitted elsewhere for the award of any degree or diploma.

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Md. Shahidul Islam

To

My beloved Wife, Son and Parents
who encouraged me everyday,
always expressed spirited love and affection

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LIST OF ABBREVIATIONS

AM-SCM	Amplitude Modulation Subcarrier Multiplexing
AM-VSB	Amplitude Modulation Vestigial Side Band
ASE	Amplifier Stimulated Emission
CATV	Cable Television
CNR	Carrier to Noise Ratio
CSO	Composite Second Order
CTB	Composite Triple Beat
DFB	Distributed Feedback
DI	Domain Inversion
DM-DFB	Direct Modulation Distributed Feedback
DPMZM	Dual Parallel Mach-Zehnder Modulator
EA	Electro Absorption
EAM	Electro Absorption Modulator
EMI	Electromagnetic Interference
EMLs	Electro Absorption Modulator Laser
EOM	Electro Optic Modulator
FDM	Frequency Division Multiplexing
FSK	Frequency Shift Keying
IMD	Intermodulation Distortion
IMD3	3^{rd} Order Intermodulation Distortion
IMD5	5^{th} Order Intermodulation Distortion
LAN	Local Area Network
LED	Light Emitting Diode
L-MZ	Linearized Modulator
MARS	Mechanical Anti Reflection Switch

M-QAM	Manchester Quardrature Amplitude Modulation
MQW	Multiple Quantum Well
MZ	Mach Zehnder
MZM	Mach-Zehnder Modulator
NLD	Nonlinear Distortion
NRZ	Non Return Zero
OFS	Optical Frequency Shifter
OMI	Optical Modulation Index
OPC	Optical Phase Conjugation
OPSK	Optical Phase Shift Keying
PSO	Peak Second Order
PMF	Polarization Maintaining Fiber
P-MZ	Predistorted Modulation Scheme
QCSE	Quantum Confined Stark Effect
QAM	Quardrature Amplitude Modulation
QVM	Quasi Velocity Mismatching
RF	Radio Frequency
RIN	Relative Intensity Noise
ROF	Radio Over Fiber
RZ	Return Zero
SCM-WDM	Subcarrier Multiplexing Wavelength Division Multiplexing
SFDR	Spur Free Dynamic Range
TDM	Time Division Multiplexing
TEC	Thermoelectric Cooler
WIB	Wavelength Insensitive Biasing
WDM	Wavelength Division Multiplexing

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ABSTRACT

The Mach-Zehnder (MZ) interferometer has been extensively used as an electro-optic modulator to overcome the limitations of frequency chirping, phase noise and nonlinearity of intensity modulation in analog radio frequency (RF) transmission over optical fiber communication system. The transfer function of MZ modulator is a sine wave function of the input voltage. For this reason, when multiple carrier frequencies pass through it, intermodulation signal products other than the original frequencies are produced and signal distortion is found in the output. In analog transmission, many channels are allocated close to one another and as a result intermodulation distortion (IMD) in a channel causes interference to other channels. The MZ modulators generate two main IMD terms - composite second order (CSO) and composite triple beat (CTB) which severely limit the performance of the analog optical transmission system. In this thesis an attempt is made to suppress IMD effects in conventional MZ modulator (MZM) and dual parallel MZ modulator (DPMZM).

In conventional MZM, an analysis is carried out to derive the expression of CSO and CTB incorporating the parameters like- RF dc bias voltage, input optical phase shift and input signal amplitude etc. It is found that, when the value of optical phase shift is small $(\leq 0.05\pi)$ and dc biasing voltage (V_b) is equal to nV_π (where $n = \pm 1/2, \pm 3/2 \cdots$), the effect of IMD in MZM is minimum. But the performance of the conventional MZM deteriorates in high bandwidth and long haul optical communication system. In such a system DPMZM is used which can handle large amount of power as well as high bandwidth. The performance of DPMZM is also investigated in terms of IMD. Results show that the effect of CSO is minimum, when the DPMZM is operated in quadrature. To reduce CTB effect, the optimum value of power splitting ratio is determined. It is found that when the value of optical power splitting ratio is $\gamma = 0.76$ and electrode length ratio is $\alpha = 1.5$, the effect of CTB is minimum. The findings of this thesis may be used to design a high bandwidth and long haul analog optical transmission system.

CHAPTER 1

INTRODUCTION

1.1 Background

In the past, dating back to the beginning of the human civilization, communication was done through signals, voice or primitive forms of writing and gradually developed to use signaling lamps, flags and other.

As time passed, the need for communication through distances to pass information from one place to another became necessary and the invention of telegraphy brought the world into the electrical-communication. The major revolution that affected the world however was the invention of the telephone in 1876. This event has drastically transformed the development of communication technology. Today's long distance communication has the ability to transmit and receive a large amount of information in a short period of time. Since the development of the first-generation of optical fiber communication systems in the early 80's [1], the optical fiber communication technology has developed fast to achieve higher transmission performance and longer transmission distance to satisfy the increased demand of communication systems. Since the demand on the increasing system performance is expected more noise and distortion free device is needed. The communication capabilities allow not only human to human communication and contact, but also human to machine and machine to machine interaction. Optical fibers can be used to transmit light and thus information over long distances. Fiber-based systems have largely replaced radio transmitter systems for long-haul optical data transmission. They are widely used for telephony, but also for internet traffic, long high-speed local area networks (LANs), cable TV (CATV) and increasingly also for shorter distances. In most cases, silica fibers are used except for very short distances, where plastic optical fibers can be advantageous.

Compared with systems based on electrical cables the approach of optical fiber communications (lightwave communications) has advantages, the most important of which are:

1. The capacity of fibers for data transmission is huge: a single silica fiber can carry hundreds of thousands of telephone channels, utilizing only a small part of the theoretical capacity. In the last 30 years, the progress concerning

transmission capacities of fiber links has been significantly faster than the progress in the speed or storage capacity of computers.

2. The losses for light propagation in fibers are amazingly small: 0.2dB/km for modern single mode silica fibers, so that many tens of kilometers can be bridged without amplifying the signals.
3. A large number of channels can be re-amplified in a single fiber amplifier, if required for very large transmission distances.
4. Due to the huge transmission rate achievable, the cost per transported bit can be extremely low.
5. Compared with electrical cables fiber-optic cables are very lightweight, so that the cost of laying a fiber-optic cable can be lower.
6. Fiber-optic cables are unaffected to problems that arise with electrical cables, such as ground loops or electromagnetic interference (EMI).

The simplest type of fiber-optic communication system is a fiber-optic link providing a point-to-point connection with a single data channel. Such a link essentially contains a transmitter for sending the information optically, a transmission fiber for transmitting the light over some distance and a receiver. The transmission fiber may be equipped with additional components such as fiber amplifiers for regenerating the optical power or dispersion compensators for counteracting the effects of chromatic dispersion and optical modulator for modulating the electrical signal into optical fiber. Within the last 30 years, the transmission capacity of optical fibers has been increased enormously. The rise in available transmission bandwidth per fiber is even significantly faster than the increase in storage capacity of electronic memory chips or in the increase in computation power of microprocessors. The transmission capacity of a fiber depends on the fiber length. The longer a fiber is the more detrimental certain effects such as intermodal or chromatic dispersion and the lower is the achievable transmission rate. For short distances of a few hundred meters or less (e.g. within storage area networks), it is often more convenient to utilize multimode fibers as these are cheaper to install (for example, due to their large core areas, they are easier to splice). Depending on the transmitter technology and fiber length, they achieve data rates between a few hundred Mbps and 10Gbps. Single-mode fibers are typically used for longer distances of a few kilometers or more. Current commercial telecom systems typically transmit 2.5Gbps or 10Gbps per data channel over distances of ten kilometers or more. Future systems may use higher data rates per channel of 40Gbps or even 160Gbps, but currently the required total capacity is usually obtained by transmitting many channels with slightly different wavelengths through fibers, this is called wavelength division multiplexing (WDM). Total data rates can be several terabits per second, sufficient for transmitting many CATV channels simultaneously. Even this capacity does not reach by far the physical limit of an optical fiber. In addition, note that a fiber-optic cable can contain multiple fibers. Fig. 1.1 shows the basic block diagram of CATV system using optical fiber. Here both RF input signal and optical output of laser are combined to external modulator, external modulator modulated this input signal optically and goes to optical medium, for long distance communication optical amplifier are used, finally for receiving purpose photodetector detect this optical signal and convert to electrical signal and distribute to destination. Some key components are used for optical fiber communication systems those are:

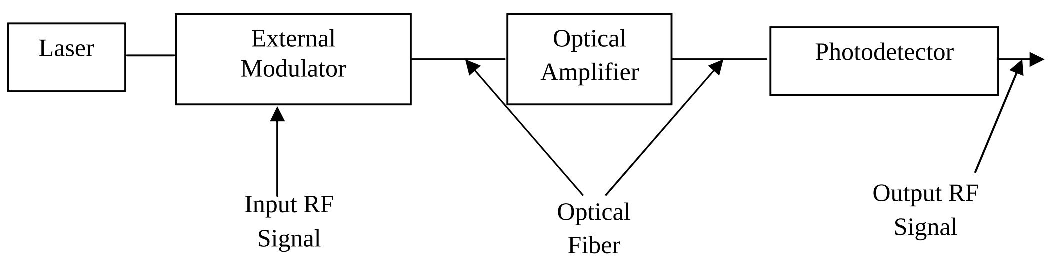


Fig. 1.1: CATV system using optical fiber

1. Optical transmitters, based mostly on semiconductor lasers, fiber lasers and optical modulators.
2. Optical receivers, mostly based on photodiodes.
3. Optical fibers with optimized properties concerning losses, guiding properties, dispersion and nonlinearities.
4. Dispersion-compensating modules.
5. Semiconductor and fiber amplifiers for maintaining sufficient signal powers over long lengths of fibers or as preamplifiers before signal detection.
6. Optical filters and couplers.
7. Devices for signal regeneration (electronic or optical regenerators), clock recovery and etc.

8. Various kinds of electronics for signal processing and monitoring.
9. Computers and software to control the system operation.

To keep up with the performance increasing requirement, new devices and technologies with distortion and noise free are greatly needed by using both electronic and optical technologies together. For multi-channel communication systems various type of techniques are used, such that:

a) Time Division Multiplexing (TDM)
b) Frequency Division Multiplexing (FDM)
c) Wavelength Division Multiplexing (WDM)

Fig. 1.2 shows the technique for combining N independent signals. An information bearing signal on channel i amplitude-modulates a carrier wave that has a frequency f_i, where i=1, 2…, N. An RF power combiner then sums these N amplitude-modulated carriers to yield a composite FDM signal which intensity-modulates a laser diode. Following the optical receiver, a bank of parallel band pass filters separates the combined carriers back into individual channels. The individual signals are recovered from the carriers by standard RF techniques.

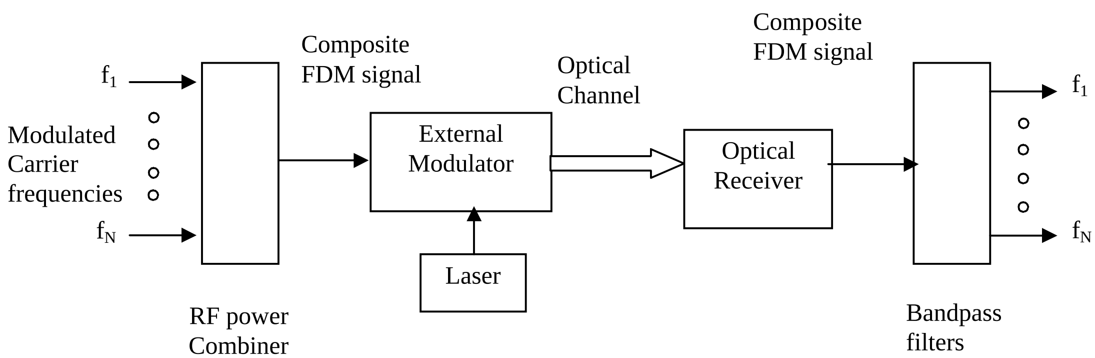


Fig.1.2: Standard technique for FDM of N independent information-bearing signals [2]

When transmitting signals through an optical channel of a hybrid fiber coax (HFC) CATV system, the signals strength reduce and noise and nonlinear distortion products are being added to them. As a sequence carrier to noise ratio (CNR) and intermodulation distortion (IMD) of the channel output decrease and therefore the quality and the accuracy of the transmitted information decrease too. According to the standard minimum value of CNR in the subscriber's contact is -43 dB, which makes necessary this parameter to be maintained more than -52 dB in the optical channel output. The following values are the permissible minimum of the IMD parameter:

a) -54 dB in the subscriber's contact
b) -60 dB in the optical channel output.

Quality of the television and radio programs transmitted through the optical channel as well as the accuracy of the data transmitted is defined by the channel characteristics. The parameters and the working regimes of the components that build it up – laser, optical modulator and amplifiers, photodiode receiver and optical fiber influence significantly upon the optical channel characteristics. On the other hand the working regimes of the channel optical components depend on the parameters of the transmitted optical signal which are defined by the number of the transmitted RF signals, the optical modulation index (OMI) coefficient, the input power of the optical transmitter, the optical power loss in the fiber link and the passive elements.

An optical modulator is a device which can be used for manipulating the property of light – often of an optical beam, e.g. a laser beam. Depending on which property of light is controlled, modulators are called intensity modulators, phase modulators, polarization modulators, spatial light modulators etc. A wide range of optical modulators are used in very different application areas, such as in optical fiber communications, CATV etc. In analog optical communication system two type of modulation technique are used: i) Direct/intensity modulation ii) External modulation. Direct modulation has some number of limitations. The Mach-Zehnder (MZ) interferometer has been extensively used as an electro-optic modulator to overcome the limitations of frequency chirping, phase noise and nonlinearity of intensity/direct modulation in analog radio frequency (RF) transmission over optical fiber communication system [3]. The transfer function of MZ modulator (MZM) is a sine wave function of the input voltage. For this reason, when multiple carrier frequencies pass through it, intermodulation (IM) signal products other than the original frequencies are produced and signal distortion is found in the output. In analog transmission, many channels are allocated close to one another and as a result IMD in a channel causes interference to other channels. The MZM generate two main IMD terms - composite second order (CSO) and composite triple beat (CTB) which severely limit the performance of the analog optical transmission system.

1.2 Review of Previous Works and Observation

The MZM is a nonlinear device which produces IMD effect with its output. For minimizing this effect, over the years a good number of research works have been carried out and different techniques were developed to eliminate or suppress these IMDs. We have discussed some contribution of different authors related to IMD and its suppression in this section.

Brian *et al.* (1987) have characterized IMD and compression properties of an integrated optical modulator at microwave frequencies by measuring the third-order intercept and 1 dB compression points. They have derived the theoretical expressions for the third-order intercept and 1 dB compression points. They also shown both these two depend only on half-wave switch voltage V_{π}. It is clear from their explanation that when the modulator was biased at the quarter wave points, the second order terms would be absent. In the case, where the bias points is shifted away from $\pi/2$, the second order terms rise very fast and quickly dominate the third order terms at low input voltages. These analysis and measurement techniques are general and can be applied to all types of electro-optic modulators [4].

Bodeep *et al.* (1989) have shown optical subcarrier multiplexing to distribute AM-VSB modulated CATV signals with frequencies between 50-550 MHz. Typical specification for CATV trunk system require a peak second-order distortion (PSO) of -60 dB, a third-order distortion or CTB of -65 dB and a carrier to noise ratio (CNR) of -55dB. If sufficiently linear, external modulators may offer a solution to these shortcomings. Second- and third-order distortions were measured as a function of optical OMI for various laser bias currents. In summary, they have completed second- and third-order distortion measurements on various buried hetero-structure DFB lasers and on $LiNbO_3$ external modulator. Optimally biasing the external modulator, the second order distortion can be eliminated but third order distortion is 25 dB greater than that of direct modulation [5].

Gnauck *et al.* (1992) have reported external modulation using a $LiNbO_3$ MZM may be an attractive alternative to direct modulation if sufficient laser power is available to accommodate the modulator insertion loss. CSO distortion products are extremely low when the modulator is biased at the half-transmission point and chirp can be eliminated. CTB distortion products are unacceptably large, but can be reduced by several methods. These include electronic predistortion and feed forward compensation. They have proposed a technique for reduced CTB which is predistortion of the modulator drive signal with a simple diode pair circuit resulted in a reduction of CTB distortion by ~16 dB. [6].

Farwell *et al.* (1993) have experimentally shown the operation of a MZM at an optical bias below the conventional quardrature bias. Theoretical distortion curves as a function of bias have been calculated and experimentally verified. These curves have shown that linear dynamic range is increased as the bias is lowered; so long optical power at the detector can be maintained just below the saturation level or laser noise limit. It has reported that linear dynamic range is increased as bias is lower and finally impact of IMD decreased [7].

William (1995) has shown a serial cascade of a Y branch modulator that construct with two MZM and two directional couplers. In this device a RF drive and appropriate DC biases are applied to each interferometer, but the coupling coefficients in each coupler are considered to be fixed values. This serial cascade approach has several advantages, as pointed out: i) Drive voltages are applied to the interferometer only. ii) Asynchronism in directional couplers can be compensated for by bias adjustment of the interferometers. iii) The improvement in linearity is independent of drive voltage. They have given a solution to the three section serially cascaded MZ device which is the first to eliminate both the third and fifth order Taylor series terms. It results in about 20 dB improvement in third order distortion compared to the two section device. In terms of OMI, the OMI is increased by ~50% for a given level of harmonic distortion [8].

Sabella *et al.* (1996) have considered four different cases for eliminating IMD effects in the transmission system. The first refers to directly modulated DFB lasers (DM-DFB), the other three relate to external modulation using a MZ modulator. In particular these cases refer to conventional MZ modulators (C-MZ), linearized modulators (L-MZ) and a predistorted modulation scheme (P-MZ). Nonlinear distortion (NLD) limits the performance of CATV distribution systems. For reducing the chirping/dispersion effect the predistorted technique appears to be the best solution concerning the transmission performance [9].

Jackson *et al.* (1997) have shown that an increase of CSO distortion with increasing fiber length can occur in analog transmission systems using optically linearized Mach-Zehnder modulators and that the degradation is due to generation of chirp in the modulator. To attain the low levels of CSO two types of solutions have been developed: firstly single-stage MZ transfers function and secondly two-stage MZ transfer function. Using such two-stage modulators with increased linearity can be obtained; with such modulators the RF drive is applied directly to the modulator. The third-order or CTB distortion can be maintained at low levels while using relatively high-optical modulation indexes. A numerical calculation of system CSO is developed which in conjunction with measured performance. An intuitive interpretation of the origin of the chirp is presented and compared with that in single-stage MZ modulators. Finally, a novel two-stage MZ design is proposed and demonstrated in which chirp generated is greatly reduced [10].

Ramos *et al.* (1998) have analyzed compensation for CSO distortion in externally modulated amplitude modulation subcarrier multiplexing (AM-SCM) systems using optical-phase conjugation (OPC). In here a simulation-based study is carried out using a multicarrier intensity modulating signal and a compression with the results obtained in present. The results have revealed significant CSO reductions (>20 dB) over optical spans ranging from 0 to 150 km are achieved by employing a midspan OPC. A realistic random multicarrier simulation-based study has been carried out. A comparison with the phase modulation technique has also been provided showing that the OPC approach is more advantageous than the phase modulation technique as far as the distance independent feature is concerned. The use of OPC compensators is currently limited to modulation formats such as analog FM or digitals OPSK/M-QAM due to the ASE noise generated by OPC [11].

Wilson *et al.* (1999) have reported a technique that commonly used to both MZM and electro-absorption modulator laser (EMLs) and also discusses both fundamental and practical performance limitations. Biasing at the modulation point eliminates the CSO distortion, but the CTB is high at this bias. Predistortion cancels 3rd and 5th –order (IMD3 and IMD5) and ~ 23 dB reductions in CTB is achievable. Compared to MZ transmitters with discrete DFB lasers, EMLs are compact, low cost, require lower drive voltages and need not be compensated for bias drift. Unfortunately, EMLs have not yet been engineered for analog applications, exhibit lower optical output powers and higher relative intensity noise (RIN) than MZ based transmitters. Direct laser modulation can be used to no more than 8 channels due to the chirp-induced CSO. External modulation enables more QAM channels to be carried [12].

Wooten *et al.* (2000) have shown that lithium niobate ($LiNbO_3$) external modulator provide both the required bandwidth and the equally important means for minimizing the effects of dispersion. In analog systems, linearized external modulators can provide very low modulation distortion. In this case bandwidths are limited by the mismatch between the electrical and optical propagation constants as well as by the electrical attenuation of the electrode. $LiNbO_3$ modulators have found widespread use in fiber-optic communication systems, including both chirped and zero-chirp NRZ and RZ digital communication formats. In addition, these integrated-optic devices have prevented to be extremely reliable and device-manufacturing technology has progressed to enable extensive deployment within digital and analog communication systems. As the complexity of fiber-optics transmission systems and networks continues to grow, the capabilities and benefits of $LiNbO_3$ modulators should continue to develop [13].

Abuelma'atti (2001) has analyzed large signal in MZM with variable optical phase shift. The special case of two-tone equal amplitude driving signal has considered. He has shown that IMD performance can be improved if the optical phase shift is in the range $0 < \phi \leq \pi/2$ especially near to $\pi/2$ [14].

Meng *et al.* (2001) have reported most popular linearization technique is to insert an electrical predistortion circuit before the RF input of the modulator such that the totals transfer function is linear. Although dual parallel modulator scheme is attractive as an all-optical method, severe requirements on the optical sources make it. They have shown experimentally an electro-optical predistortion are used for linearization of MZM. The distortion components produced by the distorter are combined with the fundamental signal at the output of the predistorter to drive the primary modulator. The distorter modulator has a higher modulation index and therefore larger distortion. By selecting an optimum of optical power for the distorter, the IMD3 in the primary modulator can be cancelled. This method eliminates the need for a broadband nonlinear electrical element and is limited by the frequency response of the modulator and the associated photodiode detector. They have shown two-tone measurements with and without the predistortion. They found that using the electro-optic predistorter the third order NLD has been suppressed by nearly 20 dB for the 32% modulation index [15].

Dubovitsky *et al.* (2002) have shown photonic systems which use a variable or chirped optical wavelength and a single MZM. It has been analyzed to determine the relation between optical bandwidth and spur free dynamic range. Changes in the carrier wavelength shift the modulator bias from the optimum $\pi/2$ bias point and cause a strong increase in the second order distortion. To prevent spur free dynamic range (SFDR) degradation due to second-order distortion, one therefore must limit the optical bandwidth of the system. The cause of the increased second-order distortion is the change in the bias point of the modulator as the wavelength varies. They proposed a novel wavelength insensitive biasing (WIB) technique that relies on proper combination of interferometer path length imbalance and applied bias trim voltage to reduce the changes in bias point with wavelength. Using the WIB design for a typical polymer based modulator, the second-order distortion can be decreased by 24dB [16].

Lu *et al.* (2003) have reported a technique to achieve long distance transmission. A sophisticated externally modulated transmitter is required to reduce the laser chirp. In a recent study, external light-injection technique has been employed in a hybrid radio-fiber system to improve the bit-error-rate performance. The external light-injection technique, which can greatly enhance the frequency response of the laser diode, is expected to have good performances in analog fiber optical CATV systems. This is attributed to fact that the external light injection will reduce the laser diode threshold current, thus increase the optical output power of the laser diode. The higher the input power launched, the better the CNR performance obtain in the system. Light injection technique not only increases the laser resonance frequency but also reduces the second-order harmonic distortion to carrier ratio and IMD3 to carrier ratio [17].

Abuelma’atti (2007) has analyzed large signal of MZ electro-optic modulators using three tones signal. The special case of two-equal amplitude sinusoids plus a difference-frequency injection is considered in detail. The result have shown even under large signal conditions it is possible, at least in theory to totally eliminate the IMD3 when the amplitudes of the equal-amplitudes input sinusoids and the difference-frequency injection are equal. Since the difference-frequency injection is usually a low frequency component, this would not cause any problem as low frequency electronic circuits can be used for controlling the amplitude and the phase of the difference-frequency injection. Moreover, the results also show that under sufficiently small input sinusoidal amplitudes and with DC biasing, proper selection of the difference-frequency injection can lead to minimum IMD3 performance [18].

Pham *et al.* (2008) have shown that in a traveling-wave electro-optic modulator, the frequency response of the modulation index is restricted by two effects: the velocity of mismatching between the lightwave and modulation microwave and the loss of modulation microwave in the traveling-wave electrodes. They proposed a design to realize the traveling wave electro-optic modulators (EOM) utilizing nonperiodically polarization-reversed structures. Using this proposed design, it is possible to obtain EOMs with arbitrary frequency responses of the magnitude of the modulation index over a specified frequency range. They extended their design method to control frequency responses of both the magnitude and the phase of modulation index in EOMs with nonperiodically polarization-reversed structures utilizing new flatness parameters. This new approach is applicable to the electro-optic modulators for advanced modulation formats, such as duo-binary modulation or broadband single-sideband modulation. This approach is also applicable to design other devices such as broadband optical frequency-shift-keying (FSK) modulator and broadband optical frequency shifter (OFS) [19].

Abuelma'atti (2008) has analyzed a mathematical model for transfer function of MZ interferometers based on the quantum-confined stark effect (QCSE). The model basically a cosine-series function can easily yield closed-form expressions for the amplitudes of the harmonic and IM components of the output when the input is formed of any scenario of large-amplitude multisinusoidal voltages. The results show that harmonics or IM products can be minimized by proper selection of DC biasing. Unfortunately, not all harmonics or IM products even if they are of the same order achieve minima at the same bias voltage. A compromise can be made by selecting a biasing voltage that can achieve a prescribe performance metrics. This can be easily done with the help of a data base that can be generated using the analysis presented in this paper. It is worth mentioning here that the results have obtained show the minimizing of harmonics or IM products can be achieved only within a certain range of the DC biasing voltage [20].

Janner *et al.* (2008) have reported an external $LiNbO_3$ modulator is tilled extremely effective particular for long haul and metro applications. To obtain improved efficiency, improved interaction between microwave and optical fields is required. More recently, domain engineering of z-cut $LiNbO_3$ structures has been proposed to produce large bandwidth and very low voltage modulators in single drive configuration. With respect to previous modulating structures in single domain crystal, the proposed domain inversion (DI) symmetric scheme allows to achieve at the same time maximum efficiency, chirp free and single drive operation all at once. They have reported on micro-structured electro-optic waveguide $LiNbO_3$ modulators which are based on the use of DI in order to enhance the BW/V_π figure of merit. They have experimentally demonstrated the feasibility of a modulator with a switching voltage of ~2V and a bandwidth of 15 GH_z, suitable for inexpensive ultra low-voltage Si-Ge drives [21].

Wang *et al.* (2009) have presented a simple model of a two-stage modulator to improve IMD performance. The splitting ratios of the input optical power and the input RF power are $1:\gamma^2$ and $1:\alpha^2$, respectively and the bias conditions are properly chosen. The outputs of two modulators are coherently combined and IMD3 reduction is realized in optical field. The values of α and γ in their scheme are set differently. Both the primary and secondary modulators are biased at V_π and the phase shift between the two modulators is set to 180^0. In order to optimize the values of α and γ for the unbalanced DPMZM, they undertake two tone analysis. They perform numerical calculations by MATLAB to find the optimal setting of γ in order to achieve the desired performance of IMD3 reduction. In their analysis, they shown that the parameters α and γ of the Dual Parallel Mach-Zehnder modulator (DPMZM) were $\alpha = 1.75$ and $\gamma = 5.3$. A DPMZM is designed and it is proved to be an effective way to realize IMD3 reduction [22].

From the above literatures review, we found that signal products other than the original frequencies are produced due to the IMD of external modulator. The CSO and CTB are controlled by varying the bias voltage or optical phase shift independently. No work reported yet to control the IMD by varying both bias voltage and phase shift simultaneously. In order to study the impact of signal distortion caused by IMDs of MZM, a model has been developed to suppress the detrimental effects of IMDs in MZM for analog optical transmission systems. All even order distortion can be controlled by proper selection of bias voltage and optical phase shift. Using the proposed model that by varying bias voltage and phase shift both second and third order distortions are suppressed. For long haul and large bandwidth applications conventional MZM performance deteriorates sharply, in case DPMZM is used. An analytical model of DPMZM is also developed. Both conventional MZ-modulator and DPMZ-modulators output characteristic are expressed as a cosine function and mathematical model based on Bessel functions has been used to describe both type of modulator. The dependence of the IMD/C parameter on the modulation index is studied for N-channel CATV systems applying both conventional modulator and DPMZM. Using this output expression optical channel implementing DPMZM instead of a conventional one are compared and the possibilities to improve by the RF signal dynamic range are analyzed. In this research, distortions caused by IMD have carried out using standard parameters of electro-optics modulator. Matlab software package is used to evaluate the effects of IMD by varying different parameters like OMI, channel number for the aforementioned modulator.

1.3 Research Aims

The goal of this research is to analyze and mitigate the detrimental effects of IMD products generated by MZM in analog optical transmission system. To meet the goal, the following objectives have been identified:

a) To develop analytical models of MZM and DPMZM for analog optical transmission systems.

b) To find the optimal input optical power splitting ratio and electrode length ratio for DPMZM.

c) To observe the effect of IMD at various OMI and channel numbers for CATV system using the developed models for both modulators.

d) To compare the performance of MZM and DPMZM in terms of CSO/CTB suppression.

e) To compare the evaluated results with already published works.

1.4 Outline of the Thesis

This thesis is divided in five chapters. At the beginning of **Chapter 1** historical background of optical fiber and analog communication system is presented. Then an elaborate record of previous works on the effect of IMD in MZM and DPMZM are described.

Chapter 2 provides a general discussion about analog optical transmission and optical modulation such as direct modulation and various types of external modulation and also about IMD and CNR.

Chapter 3 includes theoretical analysis of conventional MZM and DPMZM.

Chapter 4 includes results and discussion of this thesis works. The results are discussed considering different system parameters (OMI, CSO to carrier in dB and CTB to carrier in dB, CNR in dB) for two different types of external modulators.

Chapter 5 concludes this thesis. Recommendations for future research are presented in this chapter.

CHAPTER 2

ANALOG OPTICAL TRANSMISSION AND OPTICAL MODULATION

2.1 Introduction of Analog Optical Transmission Systems

Analog signal transmission uses electrical impulses that vary continuously with respect to the variation of physical signal. When we use a phone, the variations in our voice are transformed by a microphone into similar variations in an electrical signal and carried down the line to the exchange. On the other hand, a method of storing, processing and transmitting information through the use of discrete electronic or optical pulses that represent the binary digits 0 and 1 is called digital transmission. There are many advantages in digital system, such as less expensive, more reliable, easy to manipulate and flexible. But digital system has some disadvantages, such as sampling error, digital communications require greater bandwidth than analog to transmit the same information. So the analog system required less bandwidth than digital system and more accurate than digital system.

Although we can interpret digital signals, we do better with analog signals. Music and speech as well as most other sound are analog. We interpret analog audio signals almost instantly and without even thinking about it. Without analog signals, most of our listening activities are for nothing. Let's take sound to the electronics form. Electronically, a digital signal requires that we convert our analog signal to a digital one in an audio-to-digital converter (A/D) and we have to convert it back at the other end. We can do all this, but it takes extra stages and effort to make it happen. Certainly it's the only way we can move all the signals we have to move, like with cell phone traffic but voice traffic starts and ends as analog signals. From above discussion we say that, although digital system are better than analog but some type of technology should be use analog system such as CATV, AM and FM radio. Although digital system is adventurous than analog system, but if we convert all analog system into digital systems it is expensive and pricey. So, now a day analog systems are popular and used for communication. Required transmission bandwidth of communication system are increasing day by day for various causes so it is necessity to transmit all of the data would be optically.

2.1.1 CATV System

The abbreviation CATV is often used to mean Cable TV. It originally stood for Community Antenna Television. In the areas where over-the-air reception is limited by distance from transmitters, CATV is used. In most CATV systems, off-air signals are not available or are very weak because of the terrain or the distance of the receiver from television transmitters.

In the year 1990's, CATV systems were not intended to be general-purpose communications mechanisms. Their primary and often only purpose was the transportation of a variety of entertainment television signals to subscribers. Thus, they needed to be one-way transmission paths from a central location, called a head-end to each subscriber's home, delivering essentially the same signals to each subscriber. The signals are intended for use with the consumer-electronics equipment that subscribers already own. This equipment is built to operate on the current U.S. television technical standard called National Television Systems Committee (NTSC) after the organization that created it in 1941's. This black-and-white television standard was modified in 1953 to provide compatible color information to color television receivers and again in 1984 to add compatible stereo sound. The original purpose for CATV was to deliver broadcast signals in areas where they were not received in an acceptable manner with an antenna.

CATV is a system of providing television to consumers via radio frequency signals transmitted to televisions through fixed optical fibers or coaxial cables as opposed to the over-the-air method used in traditional television broadcasting (via radio waves) in which a television antenna is required. TV broadcast frequency plan by NTSC are given in Table 2.1 which is mention below.

Among the primary telecommunications network architectures in use today, modern CATV designs provide supreme capability and capacity afforded by the HFC architecture. The underlying foundation of HFC networks is the optical fiber deployed primarily in the trunk/transport and distribution portions of the plant. By eliminating RF trunk amplifiers, increasing transmission and eliminating interference ingress, optical fiber has allowed CATV networks to transform into the pipes which now carry the full spectrum of voice, video and data services. Definitely, standard single-mode fiber has been the workhorse and possibly the key element in HFC design. In early stage of HFC deployment, the benefits of transitioning from copper to optical fiber for CATV transport purpose were clear with some of those advantages stated above. Significant development was required in the optical transmission field to realize the large and powerful HFC networks of today. Optical transmission was typically viewed as sufficient where copper trunks were replaced with fiber and the technology was relatively mature and economically feasible.

Table 2.1: Range of operating frequencies and channel in CATV system

Bandwidth (MHz)	**Operating Frequencies (RF Range in MHz)**	**Number of Channels**
170	50-220	12-22
220	50-270	30
280	50-330	40
350	50-400	52
400	50-450	60
500	50-550	80
700	50-750	110
950	50-1000	150

2.2 Optical Modulation

Optical modulators are one of the key devices for realizing of high-performance optical analog transmission system. An optical modulator generates desired intensity, color and then passing light by changing optical parameters such as the transmission factor, refractive index, reflection factor, degree of deflection and coherency of light in the optical system according to the modulating signal.

In recent years, huge volumes of data in communications have been transmitted through optical fiber and optical communication instruments so that it becomes essential to popularize widespread optical communication networks using optical fibers. In the optical communication networks, high-speed semiconductor lasers are used as key devices therefore semiconductor optical modulators are also used for modulating input light beams generated by the semiconductor lasers. Much of the optical transmission system in place utilizes optical fibers. Optical fiber transmission has played a key role in increasing the bandwidth of transmission systems. Optical fiber offers much higher bandwidths than copper cable and is less susceptible to various types of electromagnetic interferences and other undesirable effects. Modulation of an optical signal results in optical harmonics of the modulation frequency about the carrier frequency. The optical carrier signal is modulated by an RF information signal or many information signals on respective sub-carriers.

In optical fiber communication systems, data is transmitted as light energy over optical fibers. The data is modulated on an optical light beam with an optical modulator. Optical modulators modulate the amplitude or the phase of the optical light beam. A semiconductor optical modulator used for signal modulation typically functions to regulate an intensity of incident light. In this manner, analog signals which are subjected to intensity modulation (IM) are simply differentiated as ones having intensity higher than a predetermined reference level and ones having intensity lower than the predetermined reference level. Optical modulators are typically based on

1. Direct or Intensity modulation.
2. External modulation.

2.2.1 Direct or Intensity Modulation

Direct detection is the simplest technique to use for an electro-optic conversion circuit employed in an optical communications system. Direct optical modulators modulate the optical wave as it is generated at the source. In direct modulation, a current that activates a semiconductor laser is turned on and off directly by the data signal to control the emission and extinction of the laser beam. When a laser is turned on and off directly, however, the light signal experiences a fluctuation in wavelength (chirping) owing to the properties of the semiconductor.

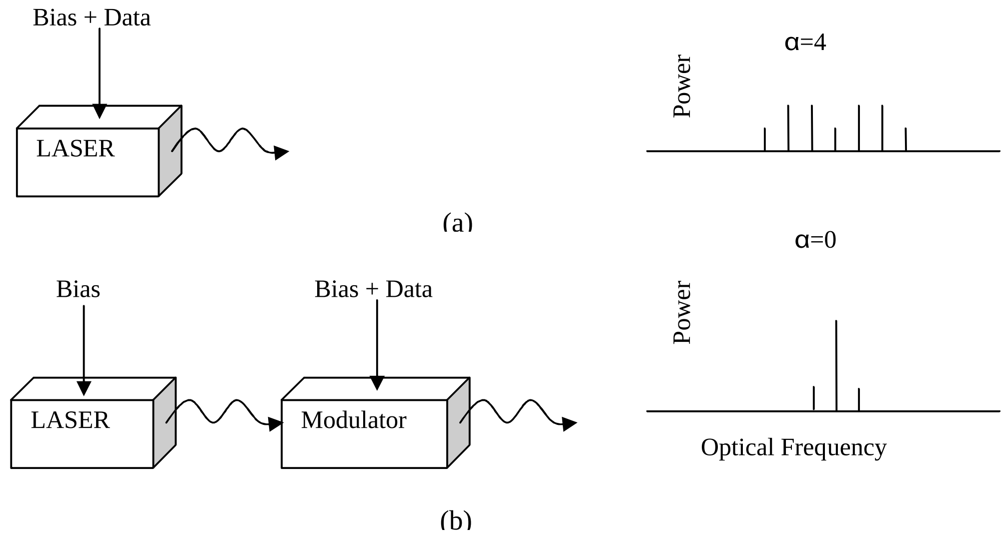


Fig. 2.1: Comparison of transmission spectra for (a) Direct and (b) External modulation

Fig. 2.1 shows the comparison between direct and external modulator. In Fig. 2.1 (a) RF signal are modulated internally into laser and produce output light with chirped. But in Fig. 2.1 (b) laser output goes to another device called external modulator and RF signal combined with light into external modulator that's produced light output with no chirp. When chirping is caused by direct modulation, propagation velocity fluctuates, waveforms are distorted during propagation through optical fiber and it becomes difficult to perform long-distance transmission and transmission at high speed. With direct modulation, the optical source is turned on and off at intervals. The direct modulation method can be realized with a simple system configuration.

2.2.2 External Modulation

Due to the limitation of direct modulation, external modulation can be used for solving this limitation. For communications involving ultrahigh speeds and long distances, modulation is usually carried out using an external modulator.

External optical modulators modulate the optical wave after it has been generated by an optical source. External modulation is used for high transmission speeds of 2.5Gbps to 10Gbps. In external modulation, a laser diode emits light continuously and the emitted light is turned on and off by using an external modulator. With external modulation, the optical source is operated continuously and its output light is modulated using an optical external modulator. Optical external modulators are superior to direct modulation in many ways. For example, optical external modulators are suitable for many high-speed applications and do not typically affect the wavelengths carrying the data signal as much as direct modulation. Optical external modulators are often based on electro-optic, magneto-optic, acousto-optic, and/or electric field absorption type effects, thus providing additional design flexibility. Fig. 2.2 shows the block diagram of external modulator, here modulating is done into another device called external device. The laser output and RF signal combined into external modulator and external modulator produced the output light.

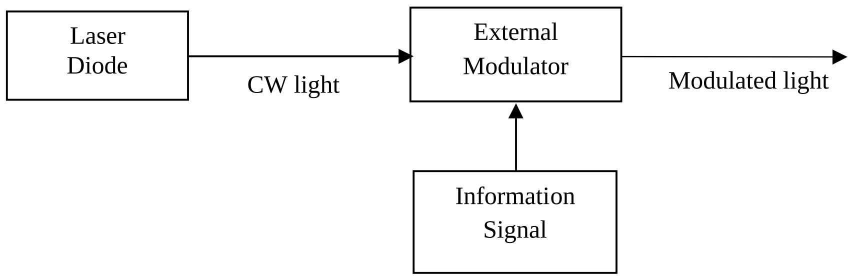


Fig. 2.2: Block diagram of external modulator

Some types of external modulators are available in market such as:

a) Electro-absorption Modulator (EAM)
b) Electro-mechanical Optical Modulator
c) Electro-optic Modulator (EOM)

2.2.2.1 Electro-absorption Modulator (EAM)

An electro-absorption modulator (EAM) is used as an optical modulator with the external modulation system. The EAM is an optical modulator that utilizes the electroabsorption (EA) effect that the optical absorption coefficient of a substance varies depending on the electric field applied to it. The EA type modulator utilizes a mechanism such that if a modulation signal voltage is applied to light propagated through a waveguide; the resulting electric field causes an EA coefficient in a medium to change, thereby intercepting the light. EAM can be roughly divided into two types: that is, an EAM using a single thick light-absorption layer and an EAM employing a multiple quantum well (MQW) structure formed by means of stacking thin quantum well layers, each quantum well layer being capable of forming exciting at room temperature.

The absorption edge is shifted toward the longer wavelength direction by applying an electric field to the modulator so that the absorption coefficient is changed, thus modulating a light intensity. An MQW structure comprises a stack of thin layers of narrow bandgap semiconductor material alternating with layers of wide bandgap semiconductor material so that each layer of narrow bandgap material is sandwiched between two layers of wide bandgap material. The alternating structure forms a series of quantum wells located in the narrow bandgap layers that are capable of confining conduction band electrons and valence band holes. Fig. 2.3 shows that the Thermoelectric Cooler (TEC) & Thermistor are used for temperature control. The former type of EAM effects extinction by utilization of variation in an absorption spectrum due to the Franz-Keldysh effect and the latter type of EAM effects extinction by utilization of variation in absorption spectrum due to the Stark effect. The EA optical intensity modulator can remarkably reduce the waveform chirping phenomenon as compared with the direct modulation system by the semiconductor laser diode, however, the waveform chirping amount cannot be zero.

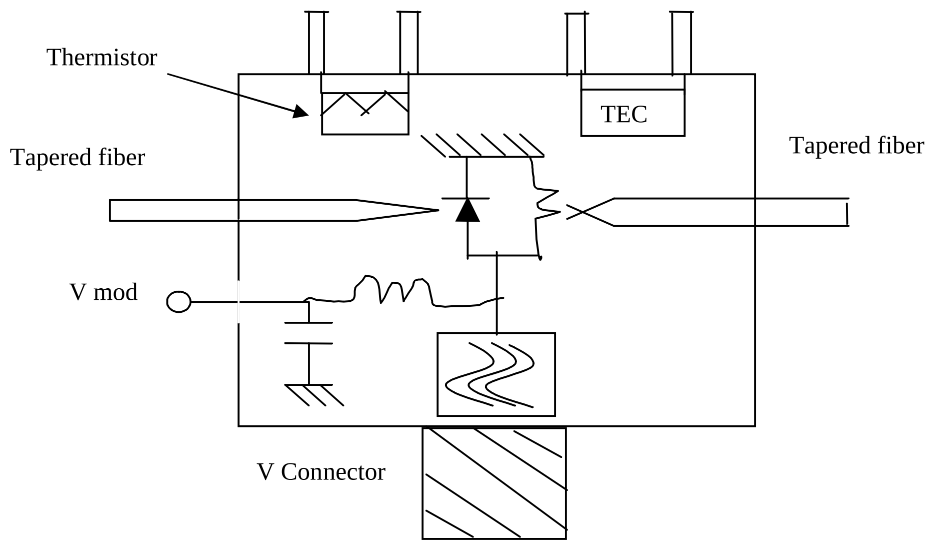


Fig. 2.3: A Structure of EAM

Among RF optical modulators, an EA optical modulator with a MQW is a device having a high-frequency operating speed, low-power consumption and a capability to be integrated with other devices. For these reasons, the EA optical modulator attracts attention in the optical transmission technology for the ROF link. In an electroabsorption type optical modulator, the amount of carriers comprised of pairs of electrons and holes generated by light absorption increases in accordance with incident light intensity. The electron and hole pairs form an internal electric field so as to cancel an externally applied electric field. The screening effect on the externally applied electric field increases with the intensity level of the incident light and there is a correlation between the intensity level of the incident light and the change in the absorption coefficient.

2.2.2.2 Electro-mechanical Optical Modulator

Electro-mechanical optical modulators, sometimes called mechanical anti reflection switch (MARS) modulators are useful in optical communication systems. An Electro-mechanical optical modulator is basically a Fabry-Perot cavity comprising the air gap between an optical membrane and substrate. Modulation of reflected light is based on voltage-controlled movement of the membrane in relation to the substrate.

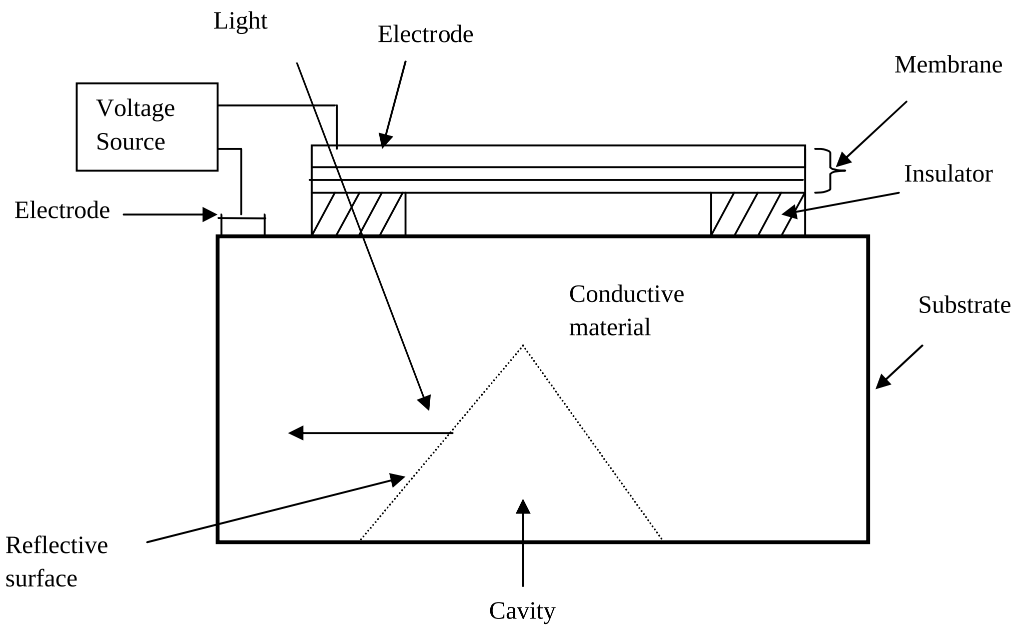


Fig. 2.4: A schematic cross section of electro-mechanical optical modulator

Such devices can provide high contrast reflection modulation at rates in excess of several Mbps. They are particularly useful as optical equalizers, switches for wavelength Add/Drop modules and optical cross-connect mirrors. Optical modulators can generally be categorized into two types depending on their principle of operation. Resonant modulators operate by changing the resonant wavelength to effect switching between the resonant and non-resonant state at a particular wavelength. This change is achieved by altering the optical phase change of the signal as it passes through an active medium. Non-resonant modulators operate by modulating the phase and/or the intensity of the optical signal in the active medium within the modulator. This switching can be achieved by a wide range of physical phenomena e.g. electro-optic, electro-absorption, electro-mechanical or thermal effects.

2.2.2.3 Electro-optic Modulator (EOM)

An electro-optic modulator (EOM) is a device which can be used for controlling the power, phase or polarization of a laser beam with an electrical control signal. It typically contains one or two Pockels cells and possibly additional optical elements such as polarizer. The principle of operation is based on the linear electro-optic effect (also called the Pockels effect), i.e., the modification of the refractive index of a nonlinear crystal by an electric field in proportion to the field strength.

Frequently used nonlinear crystal materials for EOMs are potassium di-deuterium phosphate (KD*P = DKDP), potassium titanyl phosphate (KTP), beta-barium borate (BBO) (the later used for higher average powers and/or higher switching frequencies), also lithium niobate ($LiNbO_3$), lithium tantalate ($LiTaO_3$) and ammonium dihydrogen phosphate ($NH_4H_2PO_4$, ADP). In addition to these inorganic electro-optic materials, there are also special polymers for modulators.

2.3 Mach-Zehnder Modulator

A MZ type modulator is an important device in optical transmission system, optical information processing system and a method of driving the modulator. The MZ interferometric modulator has been extensively investigated and reported in the literature since 1980’s as a potential electro-optic modulator for high digital bit-rate and RF transmission over optical fiber communication systems [23-26]. There are different types of intensity modulators described in the literature based on the linear electro-optic effect, which provides a change in the optical waveguide refractive index proportional to the applied electric field. As a result, a phase change occurs for the incident optical field polarized in the direction of the electrical applied field.

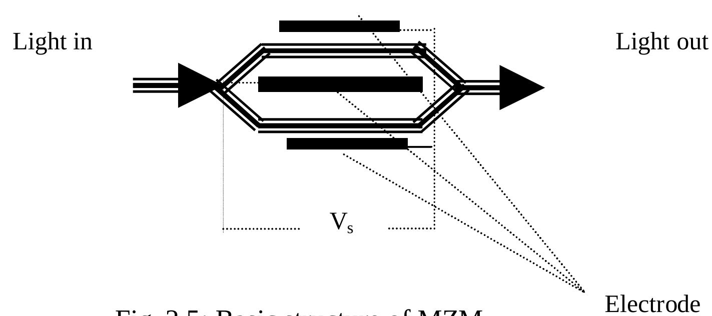
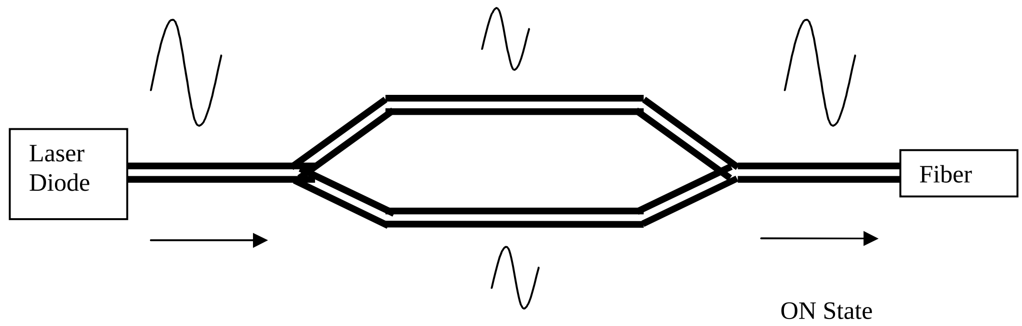
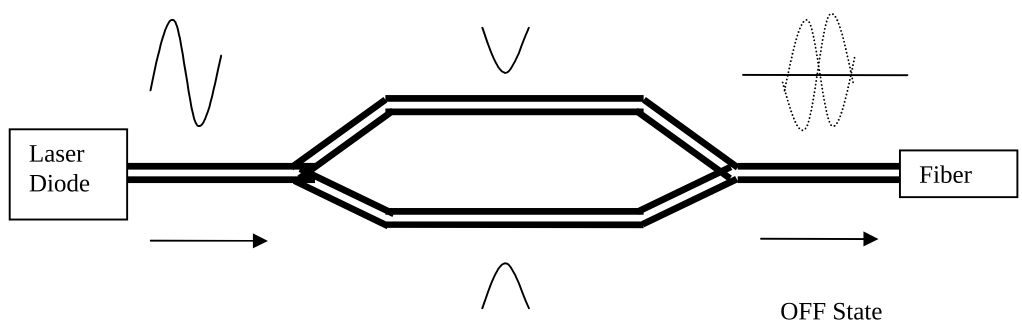


Fig. 2.5: Basic structure of MZM



(a)



(b)

Fig. 2.6: Principle of operation of external MZM. (a) No signal- constructive interference; (b) Signal applied- destructive interference

One of the materials mostly used for EOM is the $LiNbO_3$ crystal with Ti: diffused waveguides. A waveguide phase modulator appropriate to Ti: $LiNbO_3$ is shown in Fig. 2.5. The configuration of Fig. 2.6 is used to induce a phase change in a TE mode for X-cut Y propagating (or Y-cut X propagating) crystals.

The physics of operation has been extensively discussed in the literature [23-24] and it has briefly reviewed here. The guided-wave interferometer shown in Fig. 2.5 modulates the light intensity due to the phase difference that is electro-optically induced between the two arms (in the traveling wave-guide electrode configuration, the phase shift is electro-optically affected in one arm only). The input power I_0 is divided in two halves at the input Y branch (which acts as a 3 dB splitter) and travel along the two arms, having (usually) the same physical and optical length. At the output Y branch the optical fields recombine. If the guided modes are in-phase, they will constructively interfere and excite the lowest order mode of the output wave-guide. If they are exactly 180^0 out of phase, then they recombine to excite the first antisymmetric mode, which is cut off and rapidly attenuated. Since the phase shift in the modulator's arms is affected only for the optical field polarized in the same direction as the exciting electrical field, the MZM is very sensitive to the polarization of the input optical field and usually, a very stable polarized optical source is required and a polarization maintaining fiber (PMF) should be used between the source and the modulator input port.

Assuming an ideal device (no insertion loss), the optical field at the interferometer output is given by [27]:

$$E_0 = \frac{E_i}{2} e^{(j\beta_1 L)} + \frac{E_i}{2} e^{(j\beta_2 L)} \tag{2.1}$$

$$E_o = \frac{E_i}{2} \left[\cos(\beta_1 L) + j\sin(\beta_1 L) + \cos(\beta_2 L) + j\sin(\beta_2 L)\right] \tag{2.2}$$

$$E_0 = \frac{E_i}{2} \left[\left(\cos(\beta_1 L) + \cos(\beta_2 L)\right) + j\left(\sin(\beta_1 L) + \sin(\beta_2 L)\right)\right] \tag{2.3}$$

$$E_0 = \frac{E_i}{2} \left[\left(\cos\frac{(\beta_1+\beta_2)L}{2} \cdot \cos\frac{(\beta_1-\beta_2)L}{2}\right) + j\left(\sin\frac{(\beta_1+\beta_2)L}{2} . \cos\frac{(\beta_1-\beta_2)L}{2}\right)\right] \tag{2.4}$$

$$E_0 = E_i \cos(\Delta\beta L) e^{(j\bar{\beta}L)} \tag{2.5}$$

Where E_0 is the output optical field, E_i is the input optical field, β_1 and β_2 are the propagation constants in arm 1 and 2 of the interferometer, L is the arm's length and

$$\Delta\beta = (\beta_1 - \beta_2)/2 \tag{2.6}$$

$$\bar{\beta} = (\beta_1 + \beta_2)/2 \tag{2.7}$$

The cosine term in equation (2.5) provides the amplitude modulation while the exponential term produces the time dependent phase variation or chirp. It can be seen from equation (2.5) that the phase modulation can be completely compensated if the propagation constants of the two wave-guides (arms) are changing by the same amount and with opposite signs, using two exciting voltage signals with equal amplitude and opposite polarity. In this way one can achieve (theoretically) a zero-chirp modulator. The output intensity of the light as a function of the input intensity is given by [25-26]

$$\frac{I_0}{I_i} = \frac{|E_0|^2}{|E_1|^2} = L_a \cos^2(\Delta\beta L) = L_a \cos^2\left(\frac{\pi V_s}{2V_\pi}\right) \tag{2.8}$$

$$I_0 = \frac{L_a I_i}{2}\left(1 + \cos(\frac{\pi V_s}{V_\pi})\right) \qquad (2.9)$$

Where, L_a is the optical insertion loss of a practical device and V_s is the modulating RF signal voltage, V_π is the voltage required to change the output light intensity I_0 from its maximum value to its minimum value and this parameter is related to the interferometer constants as follows:

$$V_\pi = K\frac{\lambda}{L} \qquad (2.10)$$

Where λ is the optical wave-length (in vacuum) and K is a constant related to geometrical and crystal parameters.

Fig. 2.7 shows that the transfer function of the MZM is expressed as a sine wave-like function of the input voltage. For this reason, signal distortion always found in a MZM output.

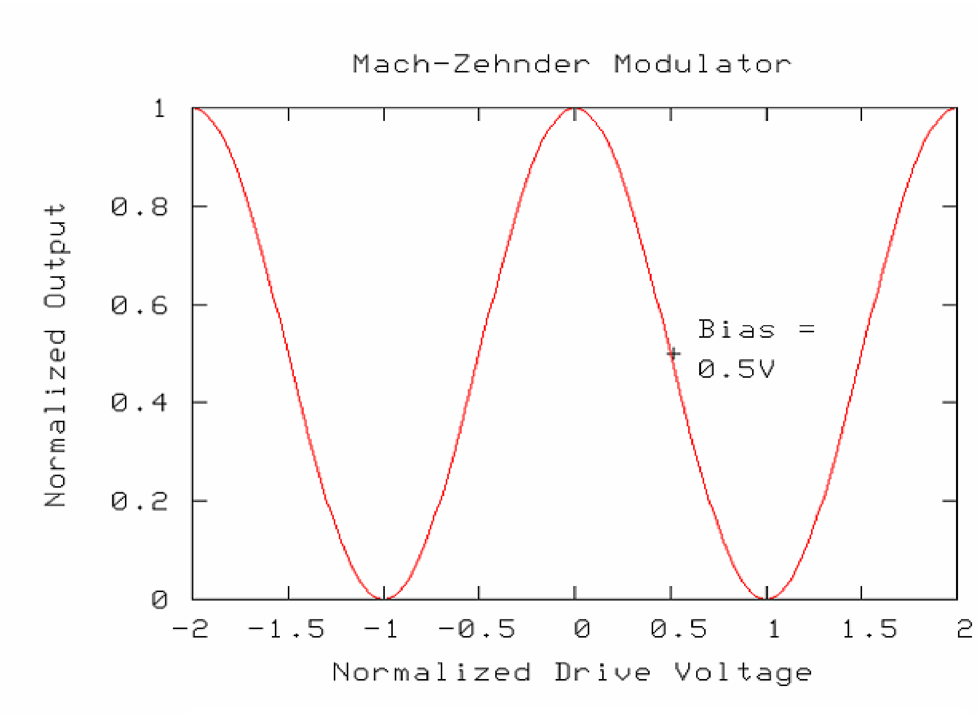


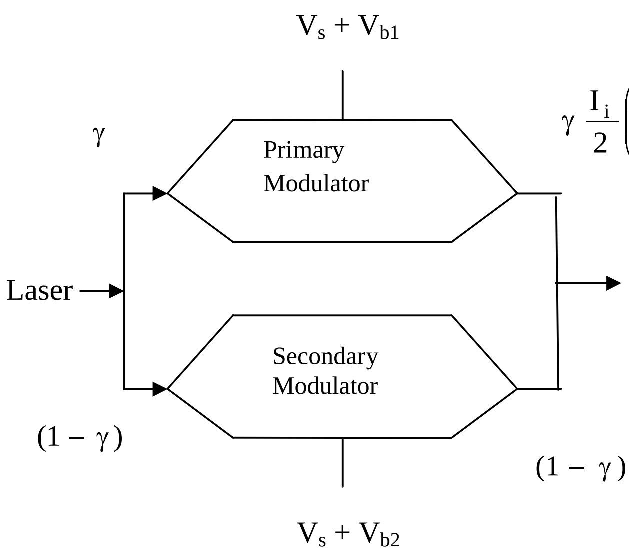
Fig.2.7: Output characteristic of MZ modulator

In other words, when multiple carrier frequencies pass through a nonlinear device such as a conventional MZ modulator, signal products other than the original frequencies are produced. In analog optical transmission many channels are allocated closed to one another. As a result, signal distortion in a channel can cause an interference problem with other channels. These nonlinear terms called IMD.

2.4 Dual Parallel Mach-Zehnder Modulator

The DPMZM is ideally suited for use in metro, long-haul (LH) and ultra long-haul (ULH) optical transport applications. The DPMZM is comprised of two matched in parallel, inside an MZ superstructure. The MZ superstructure also functions as a phase modulator. DPMZM are specifically designed to yield well-behaved and matching electro-optic amplitude and phase responses over high frequency range and to have enhanced extinction ratio. The DPMZM is available with either single mode or PMF.

The basic configuration of optical DPMZM is shown in Fig. 2.8, which is given next page.



$$\gamma \frac{I_i}{2}\left(1 + \cos(\frac{\pi}{V_\pi} V_s + \phi)\right)$$

$$\frac{I_i}{2}\left(1 + \gamma \cos(\frac{\pi}{V_\pi} V_s + \phi) - (1-\gamma)\cos(\frac{\pi\alpha}{V_\pi} V_s + \phi)\right)$$

$$(1-\gamma)\frac{I_i}{2}\left(1 + \cos(\frac{\pi\alpha}{V_\pi} V_s + \phi)\right)$$

Fig. 2.8: Basic structure of dual parallel MZ modulator

In [28-29], by providing less optical power and higher RF drive power to the secondary modulator, the secondary modulator has higher OMI and greater distortion. By providing more optical power to the primary MZM, the third-order distortion products created in the secondary modulator can be made to cancel the distortion products from the primary modulator with a small cancellation of the fundamental signal. In DPMZM single optical source launched into the two modulators and recombined the output signals coherently. A phase modulator is required in one of the two MZM output paths to maintain 180^0 between primary and secondary signals. The transfer function of the DPMZM can be expressed as [28],

$$\frac{I_0}{I_i} = \frac{1}{2}(1+\gamma\cos(\frac{\pi V_s}{V_\pi}+\phi)) + \frac{1}{2}(1-\gamma)(\cos(\frac{\alpha\pi V_s}{V_\pi}+\phi)) \qquad (2.11)$$

Where, γ is the splitting ratio of optical input power and α is electrode length ratio of primary and secondary MZ modulator.

2.5 Light source Linearity and Modulation Index

High-radiance light emitting diodes (LED) and laser diodes are well-suites optical sources for wideband analog applications provided a method is complemented to compensate for any nonlinearities of these devise. In an analog system, the time-varying electric analog signal $S(t)$ is used to modulate directly an optical source about a bias current point I_B , as shown in Fig. 2.9.

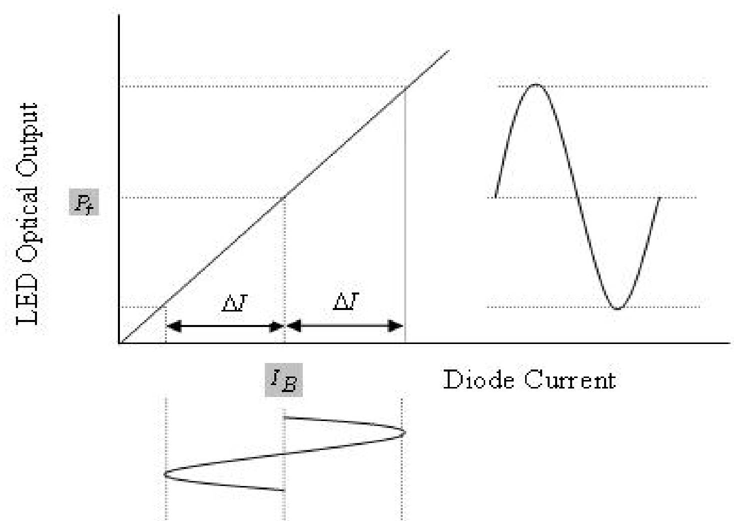


Fig. 2.9(a): Bias point and amplitude modulation range for analog applications of LEDs

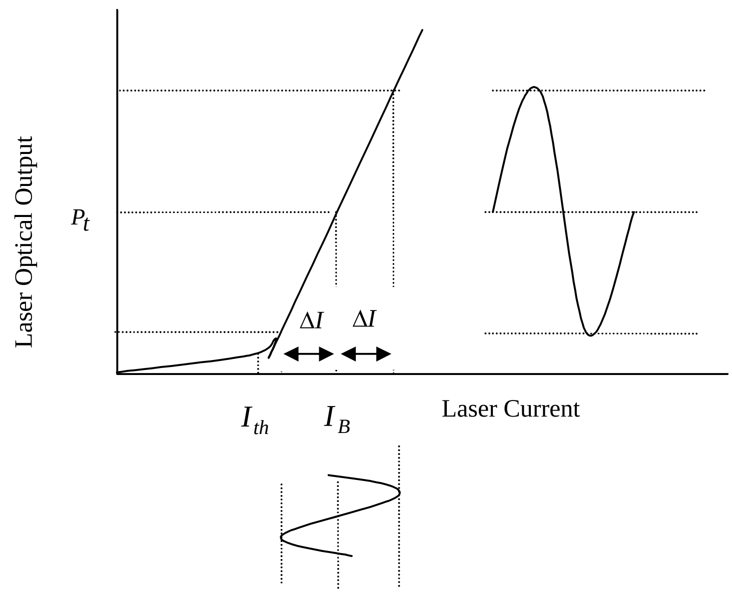


Fig. 2.9(b): Bias point and amplitude modulation range for analog applications of laser

With no signal input, the optical power output is P_t. When the signal $S(t)$ is applied, the optical output power $P(t)$ is

$$P(t) = P_t\left[1 + mS(t)\right] \tag{2.12}$$

Here, m is the modulation index (or modulation depth) defined as

$$m = \frac{\Delta I}{I_B^{'}} \tag{2.13}$$

Where, $I_B^{'} = I_B$ for LEDs and $I_B^{'} = I_B - I_{th}$ for laser diodes, the parameter ΔI is the variation in current about the bias point. To prevent distortions in the output signal, the modulation must be confined to the linear region of the curve for optical output versus drive current. Furthermore, if ΔI is greater than $I_B^{'}$ (i.e., m is greater than 100 percent) the lower portion of the signal gets cut off and severe distortion will result. Typical m values for analog application range are 0.25 to 0.50 [2].

2.6 Harmonics and Intermodulation Distortion

In analog applications, any device nonlinearities will create frequency components in the output signal that were not present in the input signal. Two important nonlinear effects are harmonic and IMD. If the signal input to a nonlinear device is a simple cosine wave $x(t) = A\cos\omega t$, the output will be

$$y(t) = A_0 + A_1\cos\omega t + A_2\cos 2\omega t + A_3\cos 3\omega t + \cdots\cdots \tag{2.14}$$

That is, the output signal will consist of a component at the input frequency ω plus spurious components at zero frequency, at the second harmonic frequency 2ω, at the third harmonic frequency 3ω and so on. This effect is known as harmonic distortion. The amount of nth-order distortion in decibels is given by

$$\text{nth - order harmonic distortion} = 20\log\frac{A_n}{A_1} \tag{2.15}$$

To determine IMD, the modulation signal of a non-linear device is taken to be the sum of two cosine waves $x(t) = A_1\cos\omega_1 t + A_2\cos\omega_2 t$. The output signal will then be of the from

$$y(t) = \sum_{m,n} B_{mn}\cos(m\omega_1 + n\omega_2) \tag{2.16}$$

Where, m and $n = 0,\pm1,\pm2,\pm3,\cdots\cdots$. This signal includes all the harmonics of ω_1 and ω_2 plus cross-product terms such as $\omega_2 - \omega_1$, $\omega_2 + \omega_1$, $\omega_2 - 2\omega_1$, $\omega_2 + 2\omega_1$ and so on. The sum of the difference frequencies gives rise to the IMD. The sum of the absolute values of the coefficients m and n determines the order of the IMD. For example, the second-order IM products are at $\omega_2 \pm \omega_1$ with amplitude B_{11}, the third-order IM products are at $\omega_1 \pm 2\omega_2$ and $2\omega_1 \pm \omega_2$ with amplitude B_{12}, B_{21} and so on.

IMD takes place when more than one carrier interacts with each other in a non-linear system/device like MZM. This interaction produces is unwanted signal or in case of mixers wanted signal. These IMD products can cause serious interference in both in band and out band channels, which results degradation of the transmitted signal. Multi-tone IM takes place when more than two carriers interact with each other in a non-linear system. In Fig. 2.10 and Fig. 2.11 shown that how intermodulated frequency generated.

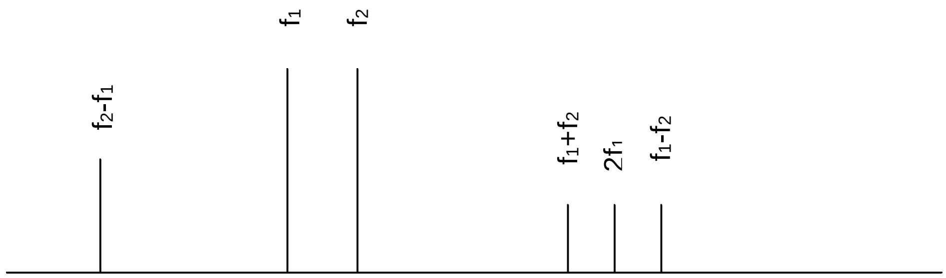
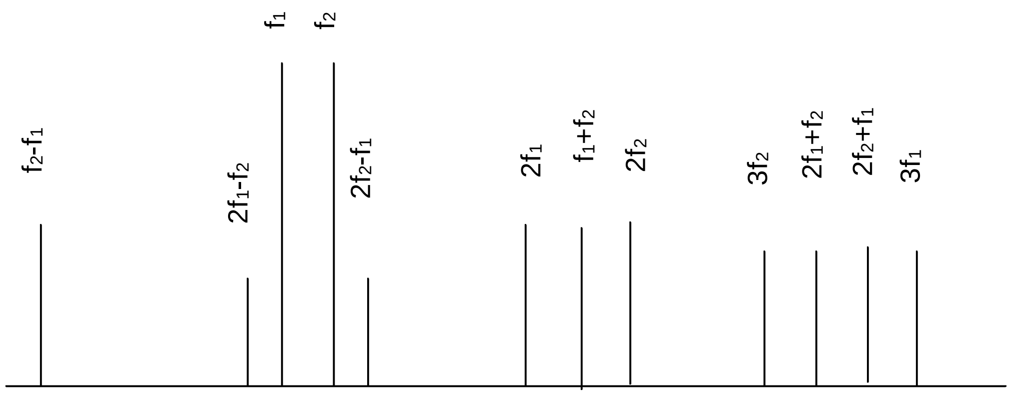


Fig. 2.10: Two tone 2nd order intermodulation products for a device with 1st and 2nd order terms in its transfer function



2nd order: $f_1 \pm f_2$, 2f
3rd order: $f_1 \pm 2f_2$, 3f, $2f_1 \pm f_2$

Fig. 2.11: Two tone 2nd and 3rd order IM products for a device with1st, 2nd and 3rd order terms in its transfer function

In the world of CATV although [30], the term multi-tone IM isn't used and instead the terms CSO and CTB describe the IM performance of CATV equipment when subjected to multiple frequencies. Among the IMD products generally only the 2nd and 3rd orders are considered, since the higher order products are significantly small.

2.6.1 Composite Second Order (CSO)

CSO distortion is a result of one or two carriers experiencing a second order non-linearity. In CATV system CSO define as, it is the ratio of peak carrier power to peak power in composite 2nd order IM tone that expressed in dB. Various type of second order beat are found in a system such as, if f_1 and f_2 are the two fundamental frequencies then following second order are found.

2 f_1: A component with twice the frequencies of f_1.

$2f_2$: A component with twice the frequencies of f_2.

$f_1 + f_2$: The sum of frequency.

$f_2 - f_1$ or $f_1 - f_2$: The difference of frequency.

One second order product is the 2f term. This product is at two times each carrier frequency and therefore there is exactly one beat for each carrier frequency. The products fall 250 KHz above the carriers with the lowest frequency beat being at two times the lowest carrier frequency. This beat is one half (-6 dB) of the magnitude of $(f_1 + f_2)$ and $(f_1 - f_2)$ beats and is usually ignored. The important second order beats are $(f_1 \pm f_2)$ or $(f_2 \pm f_1)$. There are two useful expressions that can be used to find the number of second order beats on any channel. To calculated the number of second order beats that fall below the carrier use the following formula [31]. Equal carrier spacing is assumed. Frequencies are in MHz range.

$$\text{Number of beats (below carrier)} = (N-1)(1-((f-d)(f_h - f_L))$$

$$\text{For } (0 < f < (f_h - f_L))$$

Where, N= Numbers of carriers.

f= Frequency of measurement channel.

f_h= Frequency of highest frequency channel.

f_L= Frequency of lowest frequency channel.

d= Frequency separation of each channel.

To calculated the number of second order beats that fall above the carrier use the following formula [31].

$$\text{Number of beats (above carrier)} = (N-1)((f-f_L+d)/2(f_h-f_L))$$

For $(2f_L < f < (f_h + f_L))$ and another terms are as defined above.

In multi-channel system, the number of CSO terms increase linearly as the number of channels increase. Fig. 2.12 shows the CSO $(f_1 \pm f_2)$ IM product terms for 78-channel system where the terms $(f_1 - f_2)$ are clearly seen to be dominant at the lower end of the multi-channel spectrum while at the upper edges the type $(f_1 + f_2)$ that dominates. In this case the number of second-order IM products that fall right on the first CATV channel is N_{cso}=69. Fig.2.13 shows the CSO IM product terms for 58-channel system. In this case the number of second-order IM products that fall right on the first CATV channel is N_{cso}=65. From Fig. 2.12 and Fig. 2.13 it shows that if the number of CATV channel increase in a system then number of CSO terms also increase.

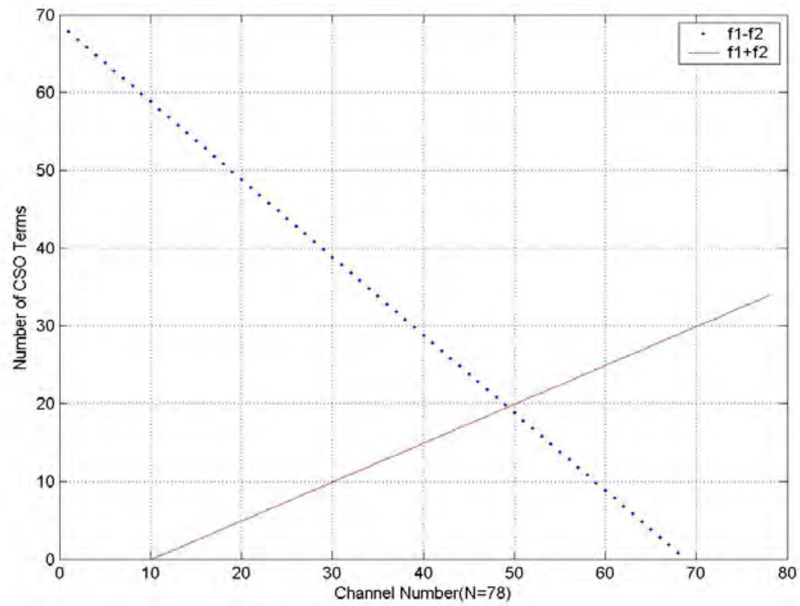


Fig. 2.12: Number of CSO terms vs. channel number (N=78)

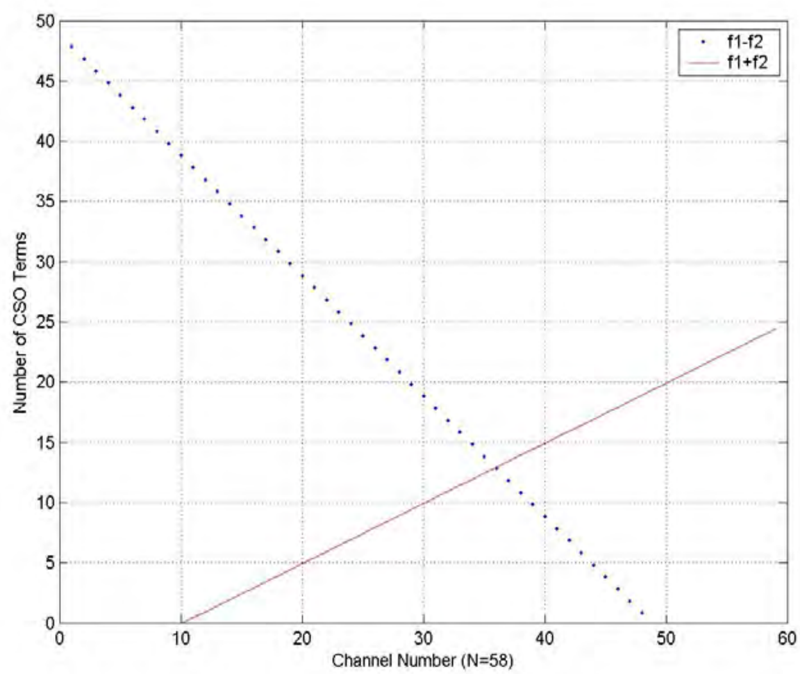


Fig. 2.13: Number of CSO terms vs. channel number (N=58)

2.6.2 Composite Triple Beat (CTB)

CTB distortion is also known as Composite Triple Beat and by few other unmentionable names such that third order distortion or composite third order. Third order distortion products are the result of one or more carriers experiencing a third order non-linearity. In CATV system CTB defines as, a composite third order or CTB distortion of the desired signals caused by third order curvature of non-linear transfer characteristic in system equipment. It is the ratio of the peak carrier power to peak power in composite 3rd order IM tone that expressed in dB.

The strongest and most important third order products are the result of three frequencies [31]. These can be expressed as:

$A \pm B \pm C$ Where, A<B<C

It is valuable to further categorize these products as:

$A + B + C$, $A + B - C$, $A - B + C$, $A - B - C$ where A<B<C

One distortion product generated by the third order non-linearity is 3A, three times any frequency. There are of course N of these products where N=number of carriers. These products are 15.6 dB weaker than the ABC products. These products do not fall near a carrier and usually are ignored.

A second third order distortion product that falls near the carrier is the $(2A - B)$ product where $A \neq B$. This product is one half (-6dB) of the magnitude of the ABC product and they are fewer in number. In a system with 20 channels the contribution of the $(2A - B)$ distortion product is less then 0.1 dB and its contribution decreases with increasing number of channels.

There is a third product generated that is a result of the offset channels 4 and 5. These generate products that are 750 KHz offset from the carriers. These products are the same level as the ABC products, but are few in number and are usually ignored.

A fourth product is the A+B+C term. This product is also the same level as the other ABC products but also does not fall near a carrier but rather 500 KHz above a carrier. Most of these products fall above the band. These products are also usually ignored.

It does now appear at the most important third order products. These distortion products are important because they fall near the carriers, they are the strongest products and there are many more of them. The expressions for the important third order beats becomes

$A + B - C$, $A - B + C$, $A - B - C$ where A<B<C

With our choice of terms it has negative frequencies which are just as real as positive frequencies. The reason for our choice is that unless we are careful we can count some beats twice. If the beat products are positive or negative there is no problem but in some cases, $A + B - C$ for example, the beats go from positive to negative frequency. Here the positive frequencies fall on channels but the reflected negative frequencies do not. Extra care must be used to avoid errors in evaluating the number of beats.

For the case of equally spaced carriers, a simple expression can be used to estimate the number of third order beats on any channel [31].

$$\text{Number of beats} = ((N-1)^2/4 + (N-M)(M-1)/2) - (N/2)$$

Where, N = total number of channels and M = number of the channel being measured

For N>>1, we may use N-1=N and N/2=0

$$\text{Number of beats} = N^2/4 + (N-M)(M-1)/2$$

In the middle of the band this expression simplifies to:

$$\text{Number of beats (mid band)} = 3N^2/8$$

At the edges of the band the expression simplifies to:

$$\text{Number of beats (band edge)} = N^2/4$$

It is interesting to note that the number of beats at the band edge is 2/3 of the number of beats in the middle of the band. This ratio is independent of the number of channels. From Fig. 2.14 middle of the band the number of CTB terms is high (at N= 38, N_{ctb}=2180) and Fig. 2.15 middle of the band the number of CTB term is also high (at N=28, N_{ctb}=1190). So from Fig. 2.14 and Fig. 2.15, it is shown that if the number of CATV channel increase in a system then CTB terms also increase.

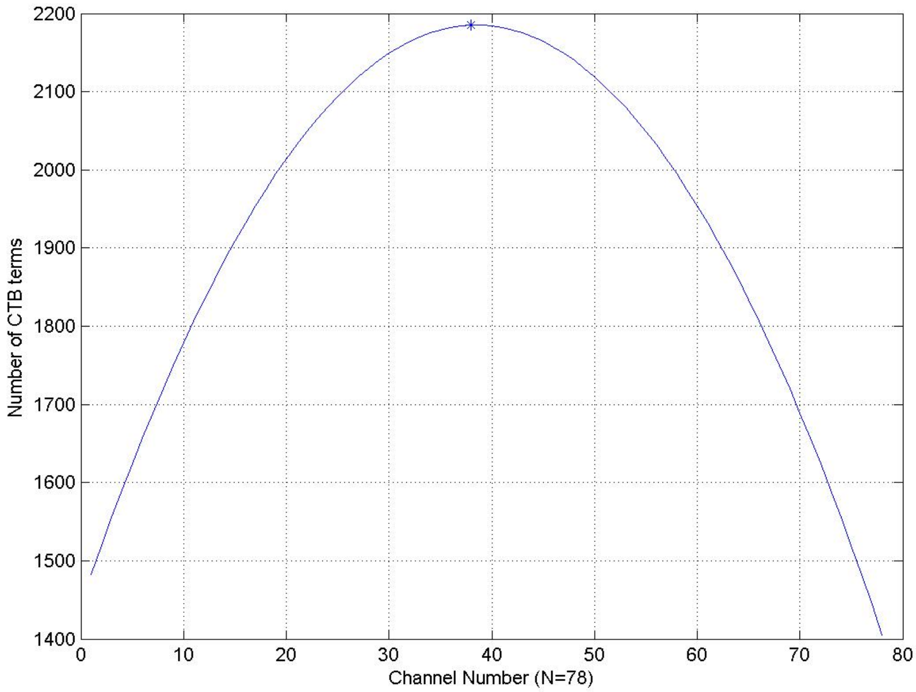


Fig. 2.14: Number of CTB terms vs. channel number (N=78)

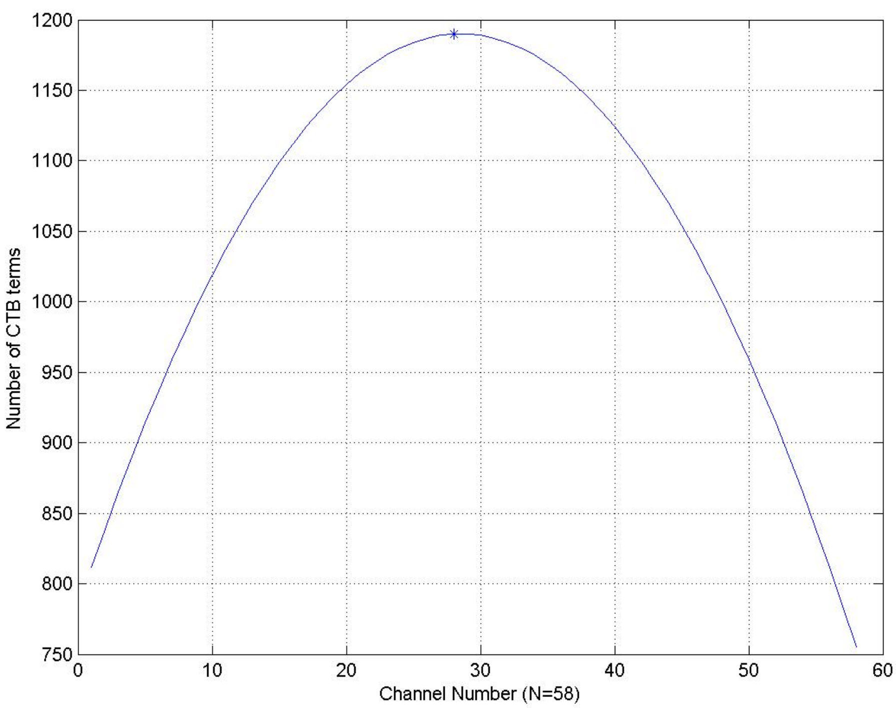


Fig. 2.15: Number of CTB terms vs. channel number (N=58)

2.6.3 Technical Standard Values for CATV

If it is analyzed the performance of CATV systems, it should consider the CNR which is expressed as the ratio of the signal power to the total noise power, also calculates the IMD such that CSO and CTB.

In [32], the Federal Communication Commission (FCC) requires CNR>43 dB and distortions such as CSO and CTB>51 dB under FCC specification section 76.605(a). In this thesis, the target values for CNR and IMD is shown in Table 2.2.

Table 2.2: Signal quality target values

Parameter	FCC Requirement	Typical Value	Thesis Target Value
CNR	>43 dB [Section 76.605 (a) (7)]	48±2 dB	50 dB
CSO	>51 dB [Section 76.605 (a) (8)]	-53±2 dB	-60 dB
CTB	>51 dB [Section 76.605 (a) (8)]	-53±2 dB	-60 dB

2.7 Carrier to Noise Ratio (CNR)

In analog communication, the carrier-to-noise ratio, often written CNR or C/N, is the carrier-to-noise ratio of a modulated signal. The CNR is the measure between the average received modulated carrier power C and the average received noise power N after the receiver filters.

High CNR provide good quality of reception; C and N may be measured in watts or in volts squared.

$$\mathrm{CNR} = \frac{C}{N} = \left(\frac{V_{\mathrm{carrierRMS}}}{V_{\mathrm{noiseRMS}}}\right)^2 \tag{2.17}$$

Where, $V_{\mathrm{carrierRMS}}$ and V_{noiseRMS} are the root mean square voltage levels in volts of the carrier signal and noise respectively. Engineers often specify the CNR in decibels (dB) between the power in the carrier of the desired signal and the total received noise power, according to the following:

$$\mathrm{CNR(dB)} = 10\log_{10}\frac{C}{N} = 20\log_{10}\frac{V_{\mathrm{carrierRMS}}}{V_{\mathrm{noiseRMS}}} \tag{2.18}$$

The CNR is given an indication of the quality of a communications channel. There are various types of dominant noise that impair the detected signal in analog transmission systems. These are: (i) Thermal noise; (ii) Shot noise from photo-diode; (iii) Relative Intensity Noise (RIN) within laser; (iv) Clipping noise from the nonlinear distortion results of the laser output and (v) IMD from the nonlinear distortion of MZM.

If CNR_i represents the carrier-to-noise ratio related to a particular signal contaminant then for N signal-impairment factors the total CNR is given by [2]:

$$\frac{1}{CNR} = \sum_{i=1}^{N} \frac{1}{CNR_i} \tag{2.19}$$

CHAPTER 3

THEORETICAL ANALYSIS

3.1 IMD analysis of Mach-Zehnder Modulator (MZM)

A MZM use a simple drive circuit for modulating the input voltage. The modulator includes two waveguides with respective MQW structures. Well layers of the MQW structures of the two optical waveguides have different thicknesses or are made from different materials so the phase of light propagating through one waveguide advances and through the other waveguide is delayed in response to the same applied voltage. The phase-changed light signals are combined as an output light signal that is intensity modulated. The MZM output-intensity/input-voltage characteristic can be expressed as is given by [16],

$$I_{out} = \frac{I_i}{2} L_a \left(1 + \cos(\frac{\pi V_s}{V_\pi} + \phi) \right) \quad (3.1)$$

where L_a the optical insertion loss of a practical device and V_s is the modulating RF signal voltage, V_π is the voltage required to change the output light intensity from its maximum values to its minimum values, I_{out} is the output light intensity and I_i is the input light intensity, ϕ is a static phase shift of the two arms of the modulator.

In [27], the modulating signal V_s is a sinusoidal voltage with angular frequency ω_i and amplitude A is superimposed on a dc voltage V_b, thus we can write

$$V_s = A \sum_{i=1}^{N} \sin \omega_i t + V_b \quad (3.2)$$

Where N is the total number of channels. Putting the value of equation (3.2) into equation (3.1):

$$I_{out} = \frac{I_i}{2} L_a \left(1 + \cos(\frac{\pi}{V_\pi} (A \sum_{i=1}^{N} \sin \omega_i t + V_b) + \phi) \right) \quad (3.3a)$$

$$I_{out} = \frac{I_i}{2} L_a \left(1 + \cos(\frac{\pi A}{V_\pi} \sum_{i=1}^{N} \sin \omega_i t + (\frac{\pi}{V_\pi} V_b + \phi)) \right) \quad (3.3b)$$

Assuming, $(\frac{\pi}{V_\pi} V_b + \phi) = \theta$, Now equation (3.3b) can be written as:

$$I_{out} = \frac{I_i}{2} L_a \left(1 + \cos(\frac{\pi A}{V_\pi} \sum_{i=1}^{N} \sin \omega_i t + \theta) \right) \quad (3.4)$$

Trigonometric identities and Bessel function are given below:

$$\sin(x + y) = \sin x.\cos y + \cos x.\sin y \quad (3.5)$$

$$\cos(x + y) = \cos x.\cos y - \sin x.\sin y \quad (3.6)$$

$$\sin(x.\sin y) = 2\sum_{i=1}^{\infty} J_{2i-1}(x)\sin(2i-1)y \quad (3.7)$$

$$\cos(x.\sin y) = J_0(x) + 2\sum_{i=1}^{\infty} J_{2i}(x)\cos.2i.y \quad (3.8)$$

Using the trigonometric identities equation (3.4) becomes,

$$I_{out} = \frac{I_i}{2} L_a \left(1 + \cos(\frac{\pi A}{V_\pi} \sum_{i=1}^{N} \sin \omega_i t). \cos \theta - \sin(\frac{\pi A}{V_\pi} \sum_{i=1}^{N} \sin \omega_i t). \sin \theta \right) \quad (3.9)$$

Derivation of the amplitude of higher order IM using the Bessel function:

$$I_{out} = \frac{I_i}{2} L_a \left(\begin{array}{l} 1 + \cos \theta J_o(\frac{\pi A}{V_\pi}) + 2 \cos \theta \sum\limits_{\substack{\text{possible} \\ \text{condition} \\ \text{of } \alpha_i}} (\prod\limits_{i=1}^{N} J_{\alpha_i}(\frac{\pi A}{V_\pi}) \cos(\sum\limits_{i=1}^{N} \alpha_i \omega_i)t) \\ - 2 \sin \theta \sum\limits_{\substack{\text{possible} \\ \text{condition} \\ \text{of } \gamma_i}} (\prod\limits_{i=1}^{N} J_{\gamma_i}(\frac{\pi A}{V_\pi}) \sin(\sum\limits_{i=1}^{N} \gamma_i \omega_i)t) \end{array} \right) \quad (3.10)$$

$$\text{For, } \sum_{i=1}^{N} |\alpha_i| = \text{even integer } \& \sum_{i=1}^{N} |\gamma_i| = \text{odd integer only,} \quad (3.11)$$

Where, α_i and γ_i are positive, negative integer or zeros. From equation (3.11), the output dc component can be expressed as:

$$I_{dc} = \frac{I_i L_a}{2} (1 + \cos\theta J_0(\frac{\pi A}{V_\pi})) \quad (3.12)$$

The specific k-th channel can be found by setting the index $n_i = 1$ and the remaining indices become zero. For example, the amplitude of output carrier at k-th channel with ω_i, where $i = 1 : N$ is

$$I_{k-th} = I_i L_a \left[J_1(\frac{\pi A}{V_\pi})[J_0(\frac{\pi A}{V_\pi})]^{N-1} \right] \sin\theta \tag{3.13}$$

The amplitude of an output CSO can be expressed by setting the index $n_i = n_j = 1$ and remaining indices become zeros.

$$I_2 = I_i L_a \left[J_1[(\frac{\pi A}{V_\pi})]^2 [J_0(\frac{\pi A}{V_\pi})]^{N-2} \right] \cos\theta \tag{3.14}$$

The amplitude of an output CTB can be expressed by setting the index, $n = n_j = n_k = 1$ and remaining indices become zeros.

$$I_3 = I_i L_a \left[J_1[(\frac{\pi A}{V_\pi})]^3 [J_0(\frac{\pi A}{V_\pi})]^{N-3} \right] \sin\theta \tag{3.15}$$

Using equation (3.12)-(3.15), the OMI, the relative third order IMD or CTB and the relative second order distortion or CSO can be expressed as

$$OMI = \frac{I_{k-th}}{I_{dc}} = \frac{2\left[J_1(\frac{\pi A}{V_\pi})[J_0(\frac{\pi A}{V_\pi})]^{N-1} \right] \sin\theta}{(1 - \cos\theta J_0(\frac{\pi A}{V_\pi}))} \tag{3.16}$$

$$\frac{CSO}{C} = \frac{I_2}{I_{k-th}} = \frac{\left[J_1[(\frac{\pi A}{V_\pi})]^2 [J_0(\frac{\pi A}{V_\pi})]^{N-2} \right] \cos\theta}{\left[J_1(\frac{\pi A}{V_\pi})[J_0(\frac{\pi A}{V_\pi})]^{N-1} \right] \sin\theta} \tag{3.17}$$

$$\frac{CTB}{C} = \frac{I_3}{I_{k-th}} = \frac{\left[J_1[(\frac{\pi A}{V_\pi})]^3 [J_0(\frac{\pi A}{V_\pi})]^{N-3} \right]}{\left[J_1(\frac{\pi A}{V_\pi})[J_0(\frac{\pi A}{V_\pi})]^{N-1} \right]} \tag{3.18}$$

From equation (3.16)-(3.18), it appears that CTB is independent of optical phase shift ϕ and RF dc bias voltage V_b and CSO is dependent on both optical phase shift ϕ and RF dc bias voltage V_b. So we can control CSO if we control the RF dc bias voltage V_b with certain value of optical phase shift properly.

For sufficiently small value of amplitude A such that $(\pi A/V_\pi) << 1$, the Bessel functions can be approximated by $J_0(z) \cong 1, J_n(z) \cong (z/2)^n/n!$ and equation (3.16)-(3.18) can be written as:

$$OMI = \frac{\pi A}{V_\pi}\frac{\sin\theta}{1-\cos\theta} \tag{3.19}$$

$$\frac{CSO}{C} = \frac{1}{2}\frac{\pi A}{V_\pi}\frac{\cos\theta}{\sin\theta} \tag{3.20}$$

$$\frac{CTB}{C} = \frac{1}{4}\left(\frac{\pi A}{V_\pi}\right)^2 \tag{3.21}$$

From the above equations (3.19) – (3.21), the relationship between OMI, CSO/C and CTB/C can be expressed as:

$$\frac{CSO}{C} = \frac{1}{2}\frac{\cos\theta}{1+\cos\theta}OMI \tag{3.22}$$

$$\frac{CTB}{C} = \frac{1}{4}\left(\frac{1-\cos\theta}{\sin\theta}\right)^2 (OMI)^2 \tag{3.23}$$

3.2 IMD analysis of Dual Parallel Mach-Zehnder Modulator (DPMZM)

A DPMZM is a device that has recently been gaining popularity in the communications field for increasing the distance of transmission of an optical signal and for increasing the bit rates, both of which are in high demand. The working function for the MZM drifts when the temperature and other working conditions change. A bias-control circuit is therefore necessary in order to lock the working point to the drifting working function of the MZM. From equation (2.11) the transfer function of the DPMZM can be expressed as,

$$\frac{I_0}{I_{in}} = \frac{1}{2}\left((1+\gamma\cos(\frac{\pi V_s}{V_\pi}+\phi)) + \frac{1}{2}(1-\gamma)(\cos(\frac{\alpha\pi V_s}{V_\pi}+\phi))\right) \tag{3.24}$$

Where, γ is the splitting ratio of optical input power and α is electrode length ratio of primary and secondary MZM, V_s is the modulating RF signal voltage, V_π is the voltage required to change the output light intensity from its maximum values to its minimum values, I_{out} is the output light intensity and I_i is the input light intensity, ϕ is a static phase shift of the two arms of the modulator.

In [27], the modulating signal V_s is a sinusoidal voltage with angular frequency ω_i and amplitude A is superimposed on a dc voltage V_b thus it can write:

$$V_s = A\sum_{i=1}^{N}\sin\omega_i t + V_b \tag{3.25}$$

Where, N is the total number of channel. Putting the value of equation (3.25) into equation (3.24), it becomes:

$$I_{out} = \frac{I_i}{2}\left[1+\gamma\cos(\frac{\pi A}{V_\pi}(\sum_{i=1}^{N}\sin\omega_i t + V_b)+\phi)\right]+$$

$$\frac{I_i}{2}\left[(1-\gamma)(\cos(\frac{\alpha\pi A}{V_\pi}(\sum_{i=1}^{N}\sin\omega_i t + V_b)+\phi))\right] \tag{3.26}$$

$$I_{out} = \frac{I_i}{2}\left[1+\gamma\cos(\frac{\pi A}{V_\pi}\sum_{i=1}^{N}\sin\omega_i t + (\frac{\pi V_b}{V_\pi}+\phi))\right]+$$

$$\frac{I_i}{2}\left[(1-\gamma)(\cos(\frac{\alpha\pi A}{V_\pi}\sum_{i=1}^{N}\sin\omega_i t + (\frac{\pi V_b}{V_\pi}+\phi))\right] \tag{3.27}$$

Assuming, $(\frac{\pi V_b}{V\pi}+\phi)=\theta$, equation (3.27) can be written as:

$$I_{out} = \frac{I_i}{2}\left[(1+\gamma\cos(\frac{\pi V}{V_\pi}\sum_{i=1}^{N}\sin\omega_i t + \theta))\right]+$$

$$\frac{I_i}{2}(1-\gamma)(\cos(\frac{\alpha\pi V}{V_\pi}\sum_{i=1}^{N}\sin\omega_i t + \theta)) \tag{3.28}$$

Trigonometric identities and Bessel function are given below:

$$\cos(x+y) = \cos x.\cos y + \sin x \sin y \tag{3.29}$$

$$\sin(x.\sin y) = 2\sum_{i=1}^{\infty} J_{2i-1}(x)\sin(2i-1)y \tag{3.30}$$

$$\cos(x.\sin y) = J_0(x) + 2\sum_{i=1}^{N} J_{2i}(x)\cos 2iy \tag{3.31}$$

Where, $J_{2i-1}(x)$ is the ordinary Bessel function of the first kind and of order (2i-l).

$$I_{out} = \frac{I_i}{2}\left(1+\gamma[\cos(\frac{\pi A}{V_\pi}\sum_{i=1}^{N}\sin\omega_i t).\cos\theta+\sin(\frac{\pi A}{V_\pi}\sum\sin\omega_i t)\sin\theta)]\right)$$

$$+\frac{I_i}{2}\left((1-\gamma)[\cos(\frac{\alpha\pi A}{V_\pi}\sum_{i=1}^{N}\sin\omega_i t)\cos\theta+\sin(\frac{\alpha\pi A}{V_\pi}\sum_{i=1}^{N}\sin\omega_i t)\sin\theta]\right) \quad (3.32)$$

The expression can be simplified by assuming the modulation index per channel small and by making the approximations $m=\frac{\pi A}{V_\pi}$.Using trigonometric and Bessel expression:

$$I_{out} = \frac{I_i}{2}\left[\begin{array}{l}\left(\begin{array}{l}(1+\gamma(\cos\theta\left(J_0(m)^N+2\sum_{\chi_i}(\prod_{i=1}^{N}(J_{\chi_i}(m)\cos(\sum_{i=1}^{N}\omega_i t)))\right)+\\ 2\sin\theta.\sum_{\lambda_i}(\prod_{i=1}^{N}(J_{\lambda_i}(m)\sin(\sum_{i=1}^{N}\omega_i t))))\end{array}\right)\\ +(1-\gamma)\\ \left(\begin{array}{l}(1+\cos\theta\left(J_0(\alpha m)^N+2\sum_{\chi_i}(\prod_{i=1}^{N}(J_{\chi_i}(\alpha m)\cos(\sum_{i=1}^{N}\omega_i t)))\right)\\ +2\sin\theta.\sum_{\lambda_i}(\prod_{i=1}^{N}(J_{\lambda_i}(\alpha m)\sin(\sum_{i=1}^{N}\omega_i t)))\end{array}\right)\end{array}\right]$$

... (3.33)

$$\sum_{\chi_i} = \text{even integer only} \ \sum_{\lambda_i} = \text{odd integer only} \quad (3.34)$$

Using equation (3.33), it is easy to show that the amplitude of the fundamental output carrier with frequency ω_i, where $i=1,2,....,N$ can be expressed as:

$$\frac{I_{fund}}{I_i} = \left[\gamma J_1(m)J_o(m)^{N-1} - (1-\gamma)J_1(\alpha m)J_0(\alpha m)^{N-1}\right]\sin\theta \quad (3.35)$$

The amplitude of an output even order component with $\omega_i = \omega_j = 1$ and remaining indices become zero.

$$CSO = \frac{I_{2nd}}{I_i}$$

$$= \left[\gamma J_1(m)^2 J_o(m)^{N-2} - (1-\gamma)J_1(\alpha m)^2 J_0(\alpha m)^{N-2}\right]\cos\theta \quad (3.36)$$

The amplitude of an output odd order component with $\omega_i = \omega_j = \omega_k = 1$ and remaining indices become zero.

$$\text{CTB} = \frac{I_{3rd}}{I_i}$$

$$= \left[\gamma J_1(m)^3 J_o(m)^{N-3} - (1-\gamma) J_1(\alpha m)^3 J_0(\alpha m)^{N-3}\right] \sin\theta \qquad (3.37)$$

It is obvious that when $V_b = 0.5V_\pi$ and $\phi = 0$ thus θ become 90^0 then CSO product in the modulator output become cancelled. So it is enough to calculate the C/CTB ratio in the central RF channel in order to estimate IMD. On the basis of the relations obtained for the fundamental output signal and power of the CTB products the following formula for the C/CTB ratio can be obtained:

$$\frac{C}{CTB} = \left[\frac{\gamma J_1(m) J_0(m)^{N-1} - (1-\gamma) J_1(\alpha m) J_0(\alpha m)^{N-1}}{\gamma J_1(m)^3 J_0(m)^{N-3} - (1-\gamma) J_1(\alpha m)^3 J_0(\alpha m)^{N-3}}\right]^2 N_{ctb} \qquad (3.38)$$

In worse case, let assume that CTB product become 1. So parameter α and γ can be optimized using equation (3.37). For calculating CTB let, CTB=0 and it is found the following relation between α and γ:

$$0 = \gamma J_1(m)^3 J_0(m)^{N-3} - (1-\gamma) J_1(\alpha m)^3 J_0(\alpha m)^{N-3} \qquad (3.39)$$

$$\gamma = \frac{J_1(\alpha m)^3 J_0(\alpha m)^{N-3}}{J_1(m)^3 J_0(m)^{N-3} + J_1(\alpha m)^3 J_0(\alpha m)^{N-3}} \qquad (3.40)$$

The expression can be simplified by assuming that the modulation index/channel is small and by making the approximations:

$\frac{J_1(\alpha m)}{J_0(\alpha m)} = \alpha \frac{m}{2}$ and $J_0(\alpha m)^N = \exp(-\alpha^2 m^2 N/4) \approx 1$ where m is extremely small.

From equation (3.40), we easily find the optimize value of optical input power spiting ratio γ and α is the electrode length ratio of primary and secondary modulator and OMI to minimize third order IM product or CTB.

3.3 CNR analysis on Analog Optical Transmission System

For analog optical links in which only a signal information channel is transmitted, the important signal impairments include laser intensity noise fluctuations, laser clipping and photo-detector noise. When multiple information channels operating at different carrier frequencies that sent simultaneously over the same fiber, then harmonic and IMD arise. There are various types of dominant noise that impair the detected signal in analog transmission systems. These are: (i) Thermal noise (ii) Shot noise from photo-diode (iii) Relative Intensity Noise (RIN) within laser (iv) Clipping noise from the nonlinear distortion results of the laser output and (v) IMD from the nonlinear distortion of MZM. So, it has discussed that terms briefly:

Thermal Noise: Thermal noise is generated in resistive elements of the link including the photo-diode and the modulator. Its mean square current value is given by [2]:

$$\left\langle I_{th}^2 \right\rangle = \frac{4.K.T.B}{R} \tag{3.41}$$

Where K is Boltzmann's constant, T is the absolute temperature, B is the signal bandwidth and R is the load resistance value.

Shot Noise: Shot noise is generated when an optical signal is incident on the photo-detector and is given by [2]:

$$\left\langle I_{sh}^2 \right\rangle = 2.q.(I + I_d).B \tag{3.42}$$

Where q is the electronic charge, I is the mean optically generated current and I_d is the photo-detector dark current.

Relative Intensity Noise (RIN): Relative Intensity Noise is generated by spontaneous emission within the laser source and is dependent on material, structural and modulation parameters. The contribution of the source RIN to the noise current at the detector for a CW laser is given by [2]:

$$\left\langle I_{RIN}^2 \right\rangle = I^2.RIN.B \tag{3.43}$$

Clipping: When transporting multiple signals in analog transmission system the modulated composite input signal is only weakly clipped by laser so that the desirable CNR and low CTB/CSO values are obtained. Clipping sets the fundamental limitation on how much the laser can be clipped for composite input signal. Clipping is given by [33]:

$$\text{Clipping}^{-1} = \left[\sqrt{2\pi}\, \frac{(1+6\mu^2)}{\mu^3}\, e^{\frac{1}{2\mu^2}} \right]^{-1}, \qquad \mu = m\sqrt{\frac{N}{2}} \tag{3.44}$$

Where N is the number of channels and m is the OMI per channel.

Intermodulation Distortion: As mentioned in Section 2.6, the transfer function of the MZM is expressed as a sine wave-like function of the input voltage. For this reason, signal distortion is always found in a MZM output. Two nonlinear terms are generated by MZM are: CSO and CTB.

The CTB is given by: $$\frac{CTB}{C} = \left(\frac{m}{2}\right)^4 .N_{CTB} \tag{3.45}$$

The CSO is given by: $$\frac{CSO}{C} = \left(\frac{m}{2}\right)^2 .N_{CSO} \tag{3.46}$$

Where, N_{CTB} is the products count of third-order IMD and N_{CSO} is the products of second-order IMD in a particular channel.

Using equation (2.19), assuming that all of these noise sources are uncorrelated, and the total CNR for the analog transmission system can be expressed by:

$$CNR_{total}^{-1} = CNR_{RIN}^{-1} + CNR_{thermal}^{-1} + CNR_{shot}^{-1} + CNR_{Clipping}^{-1} + CNR_{CTB}^{-1} + CNR_{CSO}^{-1} \tag{3.47}$$

Using equation (3.41) to (3.46) equation (3.47) becomes

$$CNR_{total}^{-1} = \left[\frac{m^2 I_p^2}{2RIN.I_p^2 B}\right]^{-1} + \left[\frac{m^2 I_p^2}{\frac{8KTB}{R}}\right]^{-1} + \left[\frac{m^2 I_p^2}{4qI_p B}\right]^{-1} + \left[\frac{\sqrt{2\pi}\left(1+6\mu^2\right)e^{\frac{1}{2\mu^2}}}{\mu^3}\right]^{-1} + \left[\frac{16}{m^4.N_{CTB}}\right]^{-1} + \left[\frac{4}{m^2.N_{CSO}}\right]^{-1} \tag{3.48}$$

CHAPTER 4

RESULTS AND DISCUSSIONS

According to the theoretical analysis presented in chapter 3, performance results of a conventional MZM and DPMZM are presented in the following section. The analysis is carried out in terms of CSO and CTB vs. OMI that encounter the effect of CSO and CTB simultaneously. The results have evaluated for both conventional MZM and DPMZM.

4.1 Effect of Bias Voltage on MZ-Modulator

In MZM bias voltage is an important variable, it can control CSO distortion using proper selection of bias voltage. Fig. 4.1 shows the plots of CSO/C & CTB/C vs. RF dc biasing voltage with an OMI (i.e. OMI=0.04). It is observed that biasing voltage has no impact on CTB at all, which is a constant value at -34 dB.

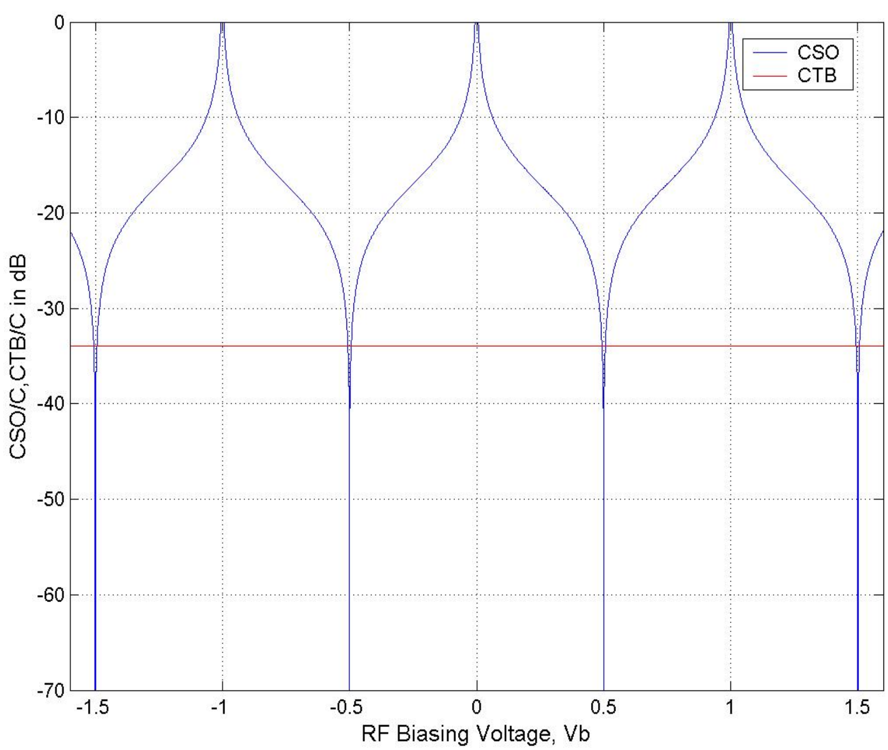


Fig. 4.1: CSO/C, CTB/C vs. applied RF biasing voltage with OMI (OMI=4%)

Here biasing voltage has significant impact on CSO. In Fig. 4.1, it is found that when the applied dc voltage is biased at nV_π, (where $n = \pm 1/2, \pm 3/2 \ldots$), known as Q-point, the best CSO/C distortion ratio is obtained. It is also noticed that when the biasing voltage is offset slightly from the Q-point, the CSO/C increases sharply; i.e. if biasing voltage is maintained within one of the multiple values of n then the effects of CSO can be eliminated totally. For example; if $n = 0.5$ then $V_b = 0.5V_\pi$, putting this value in equation (3.20) θ becomes 90^0. So, $\cos\theta$ and $\sin\theta$ become 0 and 1 respectively. Therefore, CSO term becomes eliminated.

4.2 Effect of Optical Phase Shift on MZM

In MZM optical phase shift is also an important variable on the basic principle of operation; optical signal can be divided into two arms using phase differences. So it can control IMD effect using proper values of optical phase shift. In Fig. 4.2 and Fig. 4.3 the effect of optical phase shift with respect to CSO and CTB are shown.

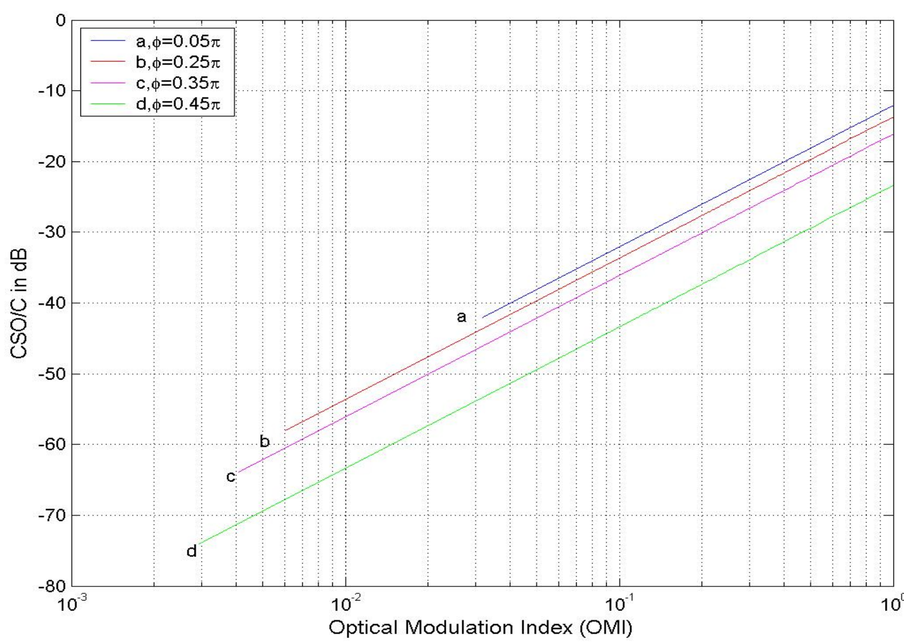


Fig. 4.2: Variations of CSO/C with OMI for different values of ϕ and $V_b = 0$.

The plots of CSO/C vs. OMI for different values of optical phase shift ϕ and dc bias voltage $(V_b = 0)$ is shown in Fig. 4.2. From Fig. 4.2, it has appeared that CSO/C increases linearly with OMI. In this plot, for large value of ϕ (such as, $\phi = 0.45\pi$), CSO performance improves. So, it can be summarized that if only optical phase shift is controlled then at large phase shift (such as, $\phi = 0.45\pi$) CSO distortion becomes industry standard value (given Table 2.2) for CATV system.

The plots of CTB/C vs. OMI for different values of optical phase shift ϕ and dc bias voltage $(V_b = 0)$ is shown in Fig. 4.3. From Fig. 4.3, it is noted that for anyone value of optical phase shift (ϕ) CTB/C becomes minimum. It is found that CTB increases linearly with OMI. It appears that for relatively small values of OMI, CTB increases at a rate 38 dB/decade.

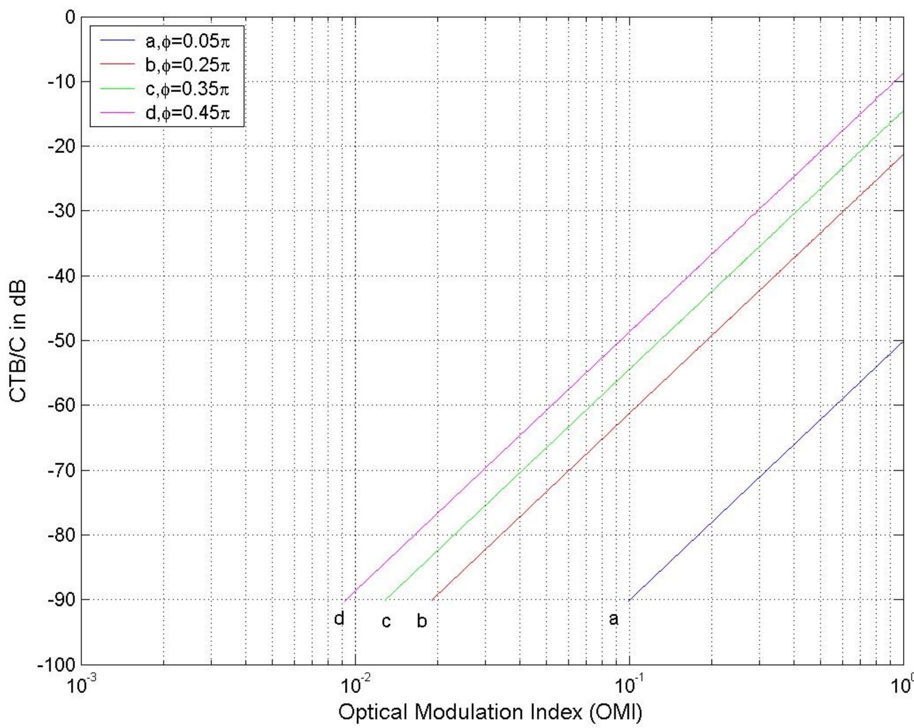


Fig. 4.3: Variations of CTB/C with OMI for different values of ϕ and $v_b = 0$.

4.3 Combine Effect of Optical Phase Shift and Biasing Voltage on MZM

All of the previous works are analyzed on MZM on the basis of biasing voltage or optical phase shift separately but the main contribution is to, the IMD effect of MZM using bias voltage and optical phase shift at same platform. The analytical results showed in next the figure. Fig. 4.4 and Fig. 4.5 show the variations of CSO/C and CTB/C with respect to OMI for different values of optical phase shift (ϕ) and biasing voltage $V_b = nV_\pi$ (where n= ±1/2, ±3/2 etc). From Fig .4.4, it is appeared that for small value of ϕ (i.e., $\phi = 0.05\pi$), the amount of CSO/C become small and the values of OMI also become small. If only the optical phase shift is controlled then effect of CSO/C decreases at relatively small optical phase shift.

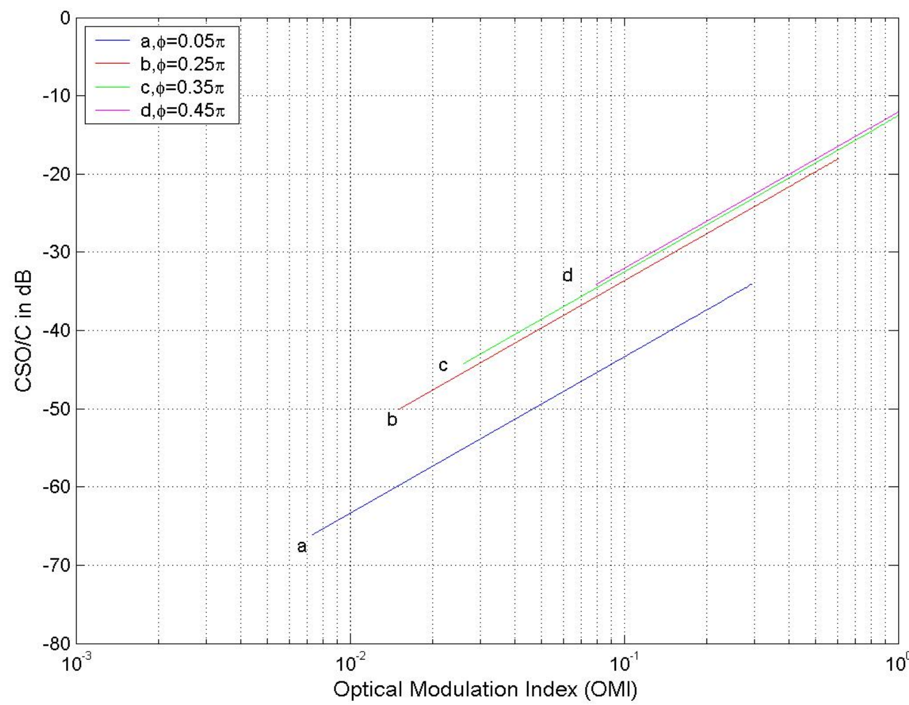


Fig. 4.4: Variations of the CSO with OMI for different values of ϕ and $V_b = nV_\pi$

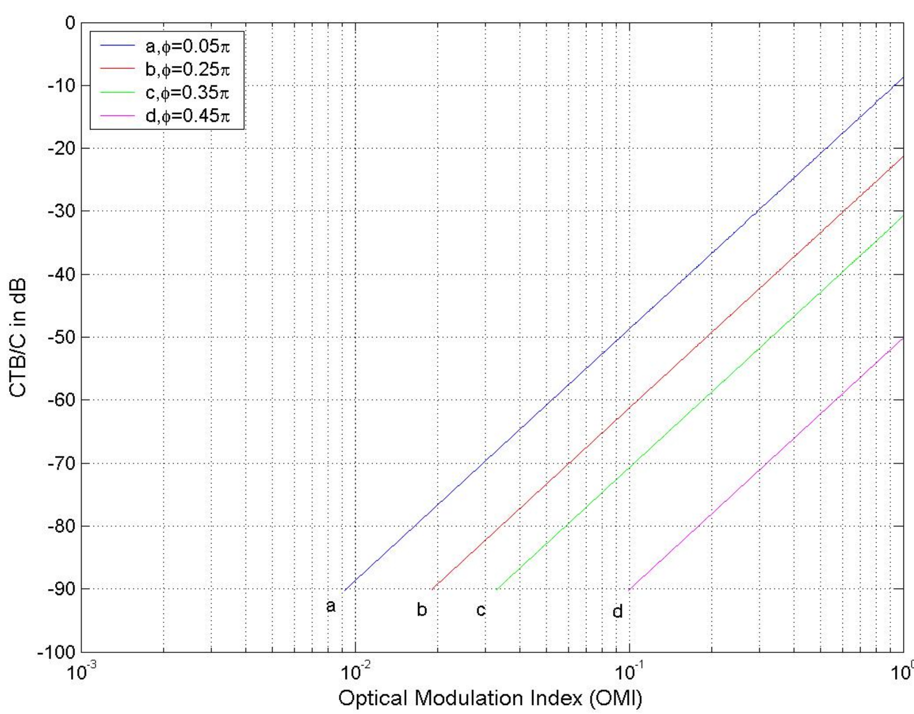


Fig. 4.5: Variations of the CTB with OMI for different values of ϕ and $V_b = nV_\pi$

From Fig. 4.5, it is appeared that any value of optical phase shift (ϕ) CTB/C still remains in industry standard values (given Table 2.2). From Fig. 4.4 and Fig. 4.5, it is noted that at small phase shift (i.e., $\phi = 0.05\pi$) both CSO and CTB distortion have industry standard values. It is also found that if the applied RF voltage with dc bias can be kept at bias voltage $V_b = nV_\pi$ (where $n = \pm 1/2, \pm 3/2 \ldots$) and optical phase shift ($\phi = 0.05\pi$) the effect of CSO and CTB is decreased. Therefore, the research work operates MZM at small phase shift ($\phi = 0.05\pi$) with combination of biasing voltage ($V_b = 0.5V_\pi$) to minimize CTB and CSO.

4.4 Comparison of CSO and CTB with Previous Works

From the plots, it is found that at small optical phase shift CSO becomes significantly small when both phase shift and biasing voltage are varies. But if only controlled optical phase shift then CSO performance is not minimum at this phase shift [14]. This situation is depicted in Fig. 4.6.

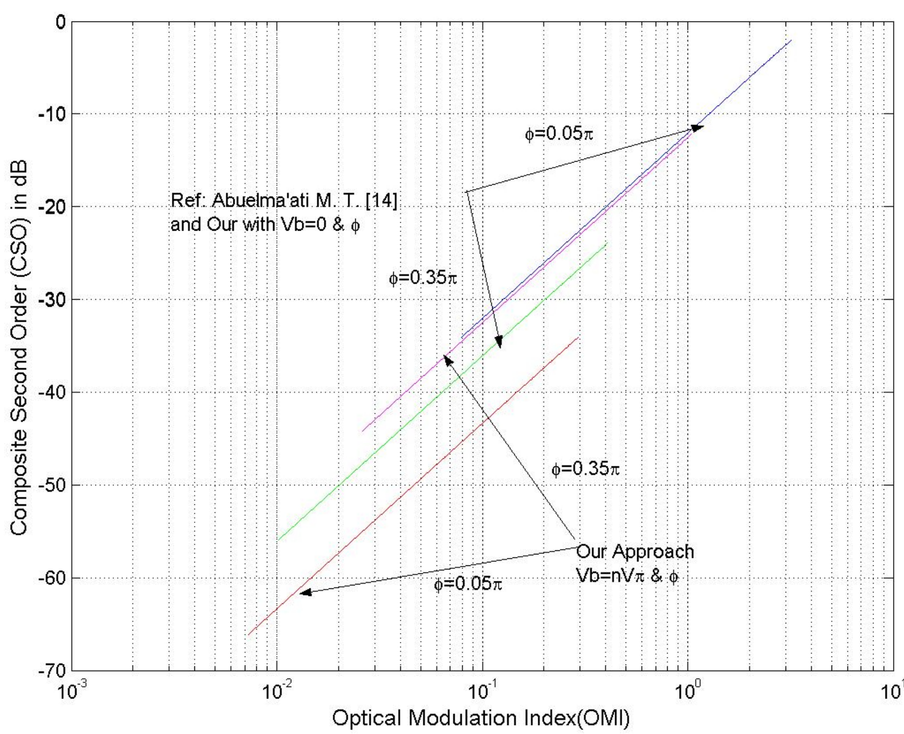


Fig. 4.6: Comparison graph of CSO vs. OMI with published works

In this case of CSO, it is found that at small optical phase shift (i.e. $\phi = 0.05\pi$), the value of CSO reaches below threshold for $V_b = nV_\pi$ (where $n = \pm\frac{1}{2}, \pm\frac{3}{2}\cdots$). For example, at optical phase shift ($\phi = 0.05\pi$), the value of CSO becomes -66 dB for $V_b = 0.5V_\pi$. But in [14], it shows that the value of CSO is -34 dB for $V_b = 0$ at the same optical phase shift. Actually, the analysis done here, is perfectly depicted in Fig. 4.7 where at $\phi = 0.05\pi$, the CTB becomes -90 dB at $V_b = 0$ and $V_b = nV_\pi$.

In MZM, when optical phase shift are 180^0, then both half of the modulator are out of phase and cancel each other and produce zero output. On the other hand, when phase shift are 0^0 then both half of the modulator are in-phase and recombine each other. Finally, it produces original output of modulator. So, small phase shift is better for modulator operation.

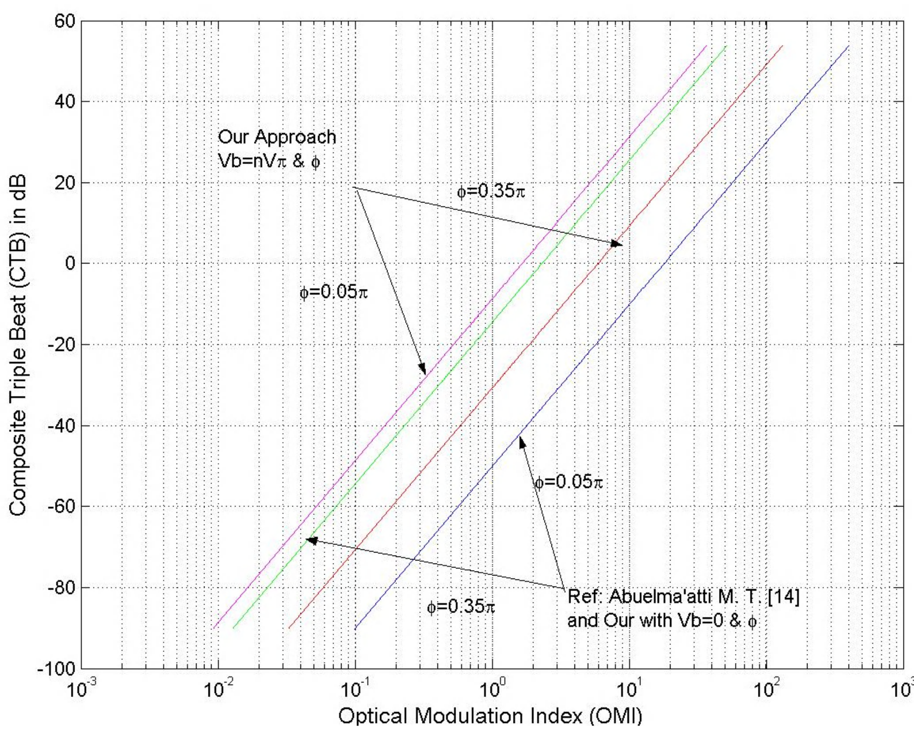


Fig. 4.7: Comparison graph of CTB vs. OMI with published works

The comparisons with previous works are with small phase shift because, at the previous work, for $\phi = 0.05\pi$, the CSO is -34 dB but, at in this work it becomes -66 dB that is more necessary for signal transmission in CATV system. Though in [14], when the phase shift become $\phi = 0.45\pi$ the CSO become -65 dB, but since $\phi = 0.45\pi$ is a high phase shift, the signal tends to zero at output for MZM.

4.5 Results of DPMZM

The DPMZM shown in Fig. 2.8 consists of a primary modulator and a compensative secondary modulator that are connected in parallel optically and electrically. The optical input power splits between primary and secondary modulator in a ratio of $\gamma/(1-\gamma)$. The aim is to find out the optical power splitting ratio γ, to minimize the optical power loss. The compensative secondary modulator electrodes are α times longer than those of the primary modulator electrodes, i.e., the amplitude of the modulating signal is α times smaller which makes the signal distortion. For operating both modulators with in quardrature bias point setting the appropriate value of bias voltage. Thus the phase of the secondary modulator output signal is shifted π radians in relation to primary modulator and the nonlinear distortion products in secondary modulator that will compensate for those in primary modulator.

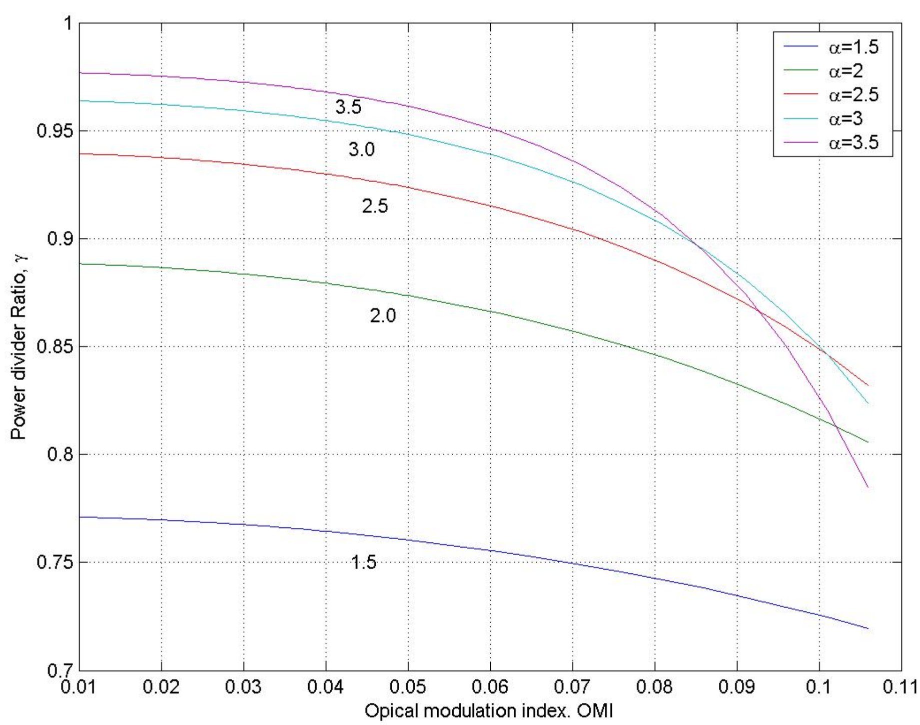


Fig.4.8: DPMZM optical power splitting ratio (γ) versus modulation index (m) under electrode length ratio (α)

Expression of equations (3.35)-(3.40) is used to generate a data-base for IM performance of a DPMZM. The variation limits of the modulation index must be determined. It is well known that increasing OMI improves the CNR, yet it does increase impairment caused by IMD too. Hence optimum operating values of OMI is a balance between noise and distortion. With CATV system range the modulation index is 0.03 to 0.06 for admissible minimum value of the CNR and C/CTB parameters. Fig. 4.8 has shown that the optical power splitting ratio γ is the function of the OMI for five values of α. It is obvious that the smaller the electrode length ratio α, the smaller the optical power loss in the modulator. Besides the fixed value of α, parameter γ is slightly changed with in admissible limits on OMI ($0.03 \le OMI \le 0.06$) which is given in Table 4.1.

Table 4.1: The splitting ratio values versus α.

α \ γ	**1.5**	**2.0**	**2.5**	**3.0**	**3.5**
γ_{max}	0.77	0.88	0.93	0.96	0.97
γ_{min}	0.76	0.87	0.92	0.94	0.95

From Fig. 4.9 to Fig. 4.13, the calculation of CTB performance of the DPMZM with different values of parameters γ and α is depicted.

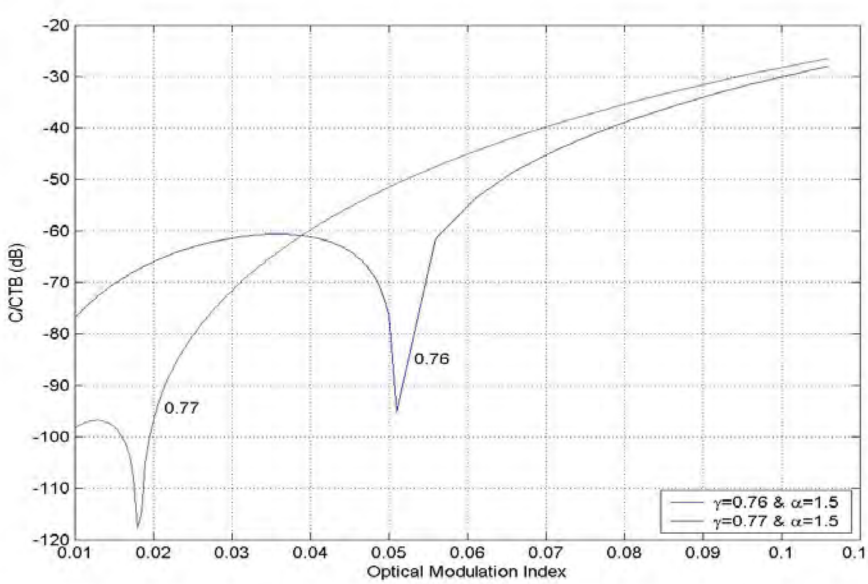


Fig. 4.9: C/CTB performance with $\alpha = 1.5$ and $\gamma = 0.76 \,\&\, 0.77$

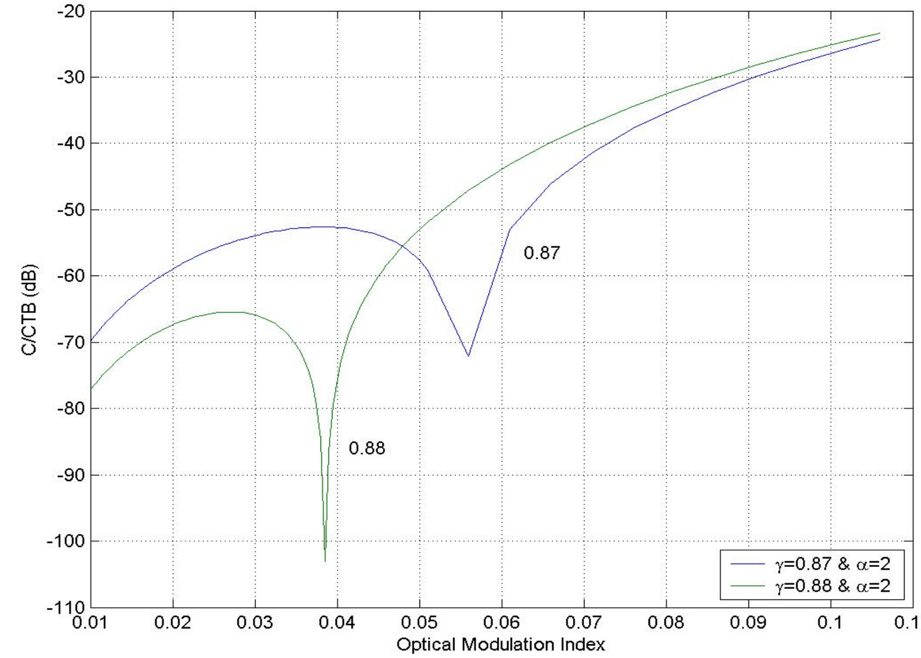


Fig. 4.10: C/CTB performance with $\alpha = 2.0$ and $\gamma = 0.87 \,\&\, 0.88$

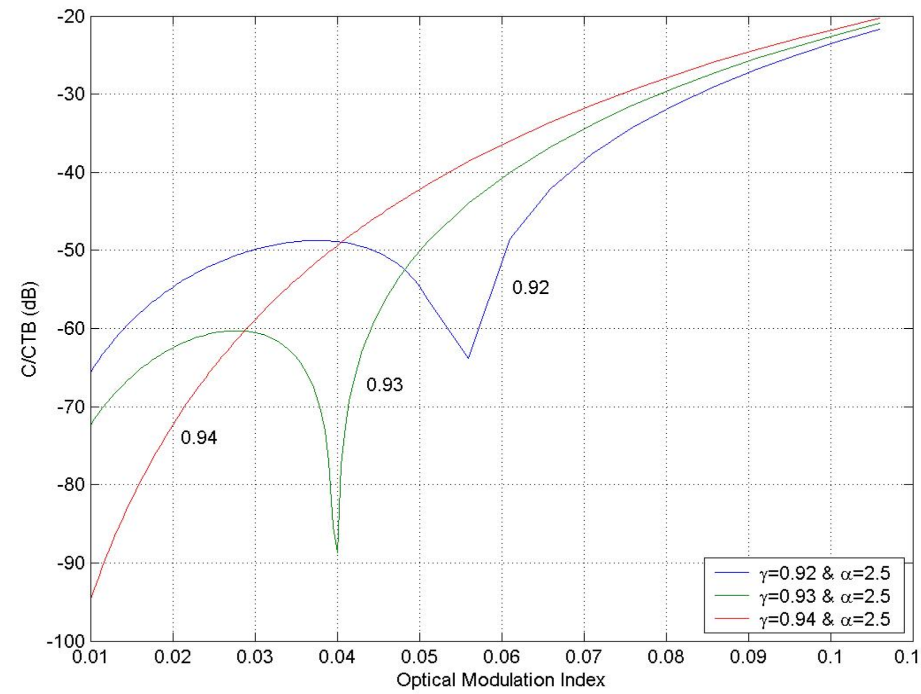


Fig. 4.11: C/CTB performance with $\alpha = 2.5$ and $\gamma = 0.92, 0.93 \,\&\, 0.94$

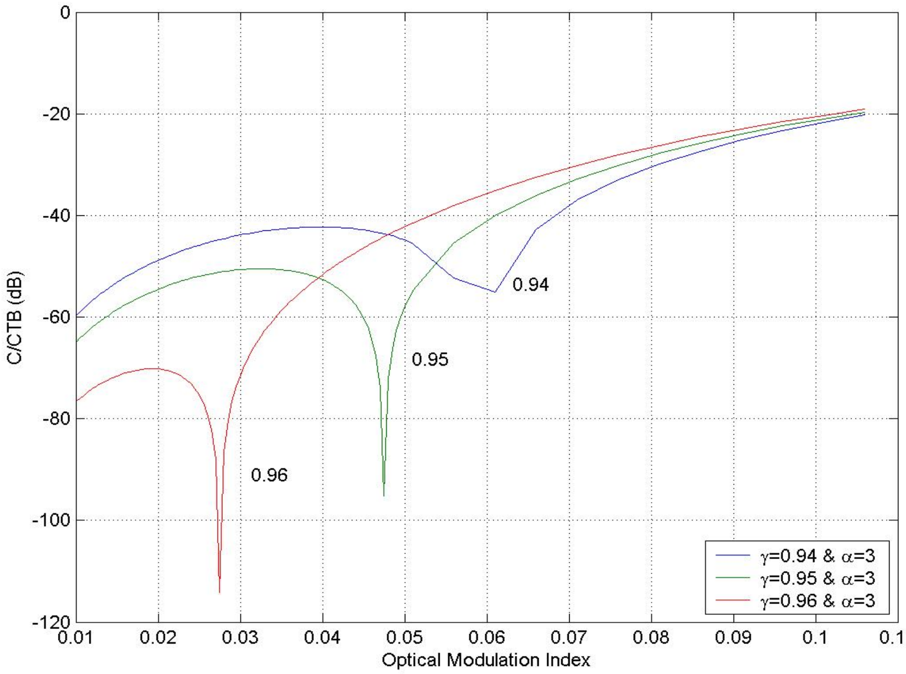


Fig. 4.12: C/CTB performance with $\alpha = 3.0$ and $\gamma = 0.94, 0.95 \,\&\, 0.96$

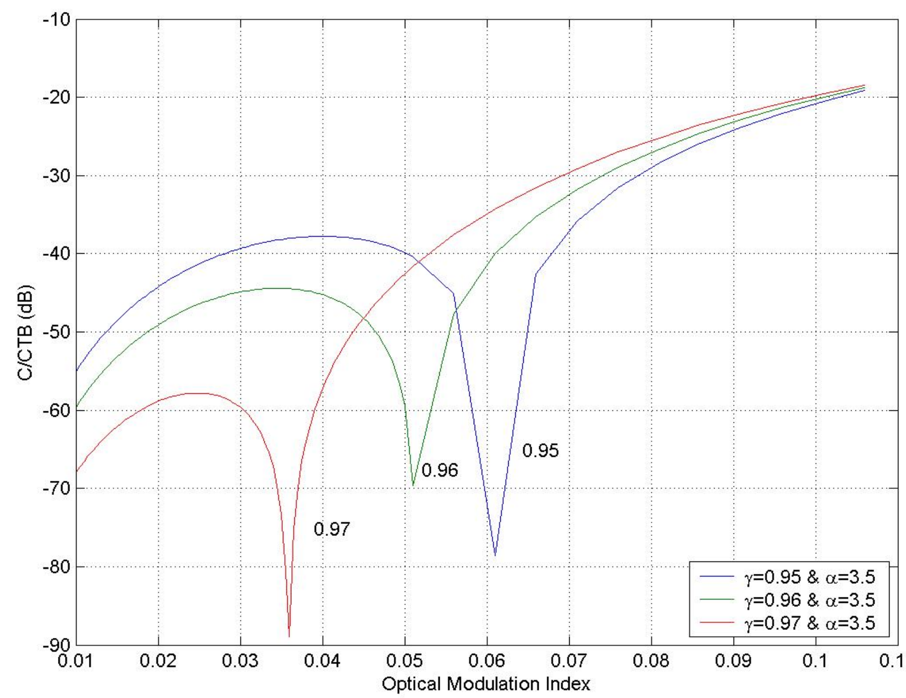


Fig. 4.13: C/CTB performance with $\alpha = 3.5$ and $\gamma = 0.95, 0.96 \,\&\, 0.97$

From the above analysis, it is obtained the DPMZM parameters to meet the C/CTB at -60 dB. As a result, five sets of parameters are selected for reducing the CTB in term of IMD performance. Above analytical results are given in Table 4.2.

Table 4.2: Set of parameters to reduce CTB performance.

Case no	α	γ	**OMI**	**Target value of C/CTB**
I	1.5	0.76	1%-5.6%	C/CTB > 60dB
II	2.0	0.88	1%-4.5%	C/CTB > 60dB
III	2.5	0.93	1%-4.4%	C/CTB > 60dB
IV	3.0	0.96	1%-3.4%	C/CTB > 60dB
V	3.5	0.97	1%-3.9%	C/CTB > 60dB

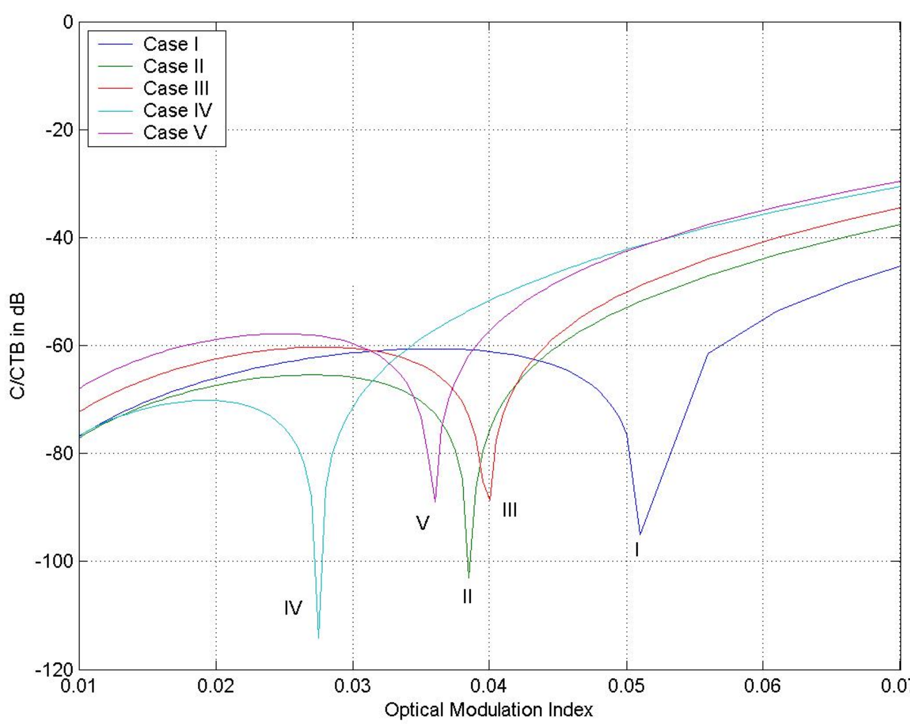


Fig. 4.14: Five cases studies of DPMZM

To determine the optimum values of γ and α, dependence of the modulation index m for different number of transmitted RF channel has been investigated. In Fig. 4.8, obtained results are shown for 78 numbers of channels.

As seen from Fig. 4.8, the requirements for the maximum value of OMI and the minimum value of the optical loss in DPMZM are met simultaneously when α = 1.5 and γ=0.76. Then $C/CTB \geq 60dB$ if $m \leq 0.056$, whereas if large values of γ and α (α=3.5 and γ=0.97) are chosen to minimize the optical power loss then the maximum permissible value of m is 0.039. For considering CNR high modulation index gives good performance over all system. So we have selected $\alpha = 1.5$ and $\gamma = 0.76$ for good performance of CTB.

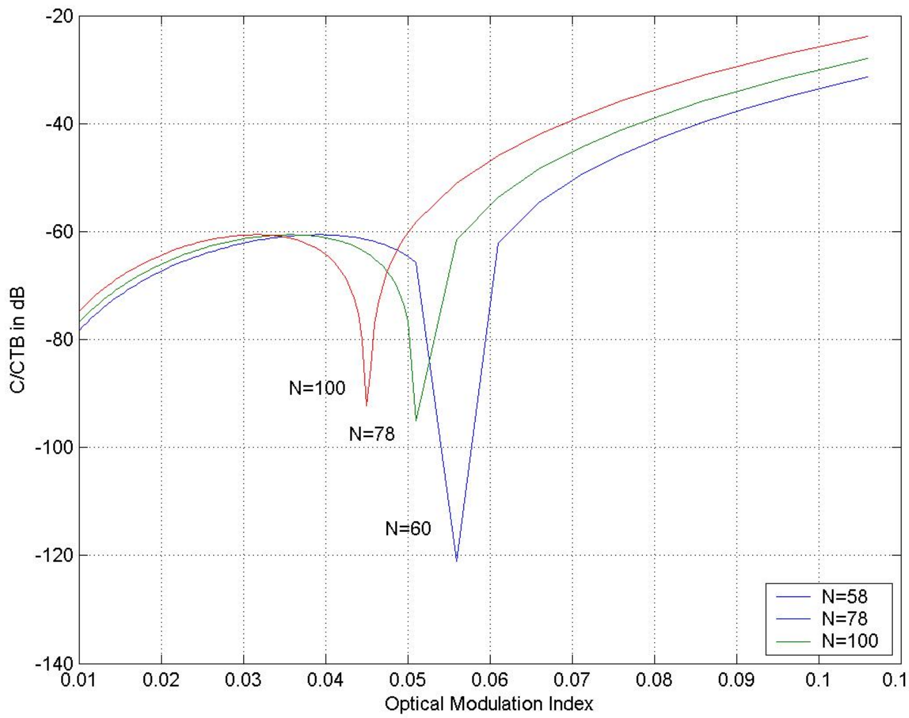


Fig. 4.15: C/CTB vs. OMI for various numbers of channels at α=1.5 and γ=0.76

Fig. 4.15 shows the IMD effect in DPMZM for α=1.5, γ=0.76 and number of channel are varied (number of channel, N=60, 78 and 100). From Fig. 4.15 it noted that if number of channel minimum then C/CTB performance becomes high. So, for the increment of channel number, CTB performance decreases as well as OMI degrades.

4.6 Result of Carrier to Noise Ratio (CNR)

The CNR is commonly used in communications systems to point out the system performance; the best performance of the system is indicated by the maximum CNR. Fig. 4.16 shows channel CNR vs. OMI. One fixation that should be noted from these curves is that CNR is computed by taking into account thermal, shot and RIN noise increase as the signal power increases or the OMI increase. On the other hand, CNR is computed with IMD (such that CSO, CTB) and laser clipping noise decreases at high OMI because these two noise terms become significantly dominant at high OMI.

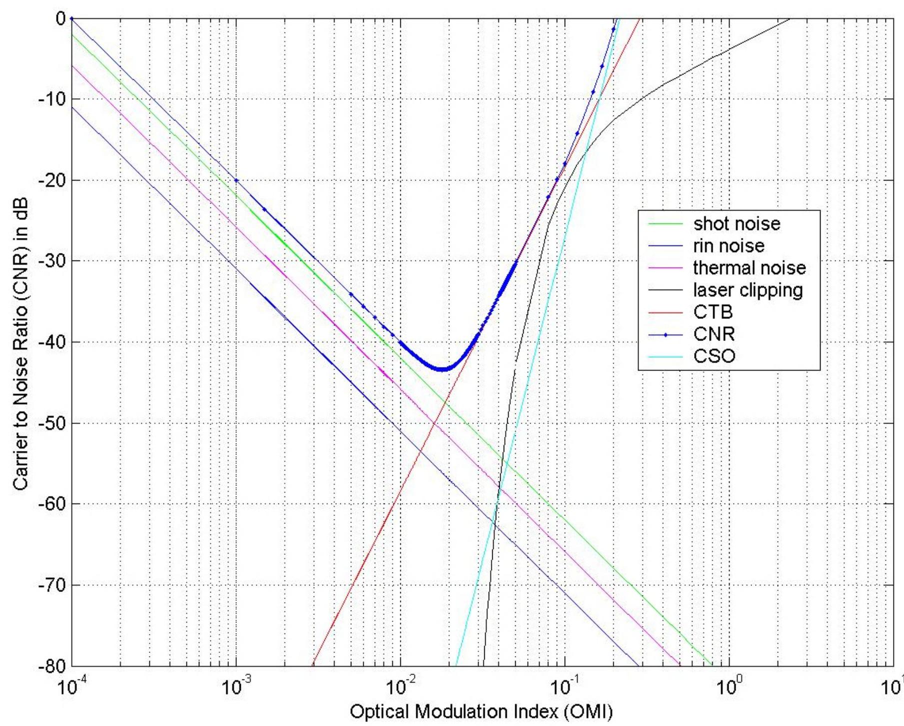


Fig. 4.16: Carrier to noise ratio (CNR) vs. optical modulation index (OMI)

From this analysis, it can be summarized in this way:

- The maximum CNR is 43.5 dB at OMI 1.85% and C/CTB=47 dB.
- If disregarding the CTB noise term for the moment, CNR can be improved to 50dB by increasing the OMI to 3.4 %. However, when OMI increases to 4.4%, clipping noise becomes dominant and the maximum CNR is 53 dB.

CHAPTER 5

CONCLUSION AND FUTURE WORKS

5.1 Conclusion

A detailed theoretical analysis is carried out to evaluate the effect of IMDs (*i.e.*, CSO and CTB) in MZM and DPMZM for analog optical transmission system.

In this thesis, at first we have derived an analytical model for higher order nonlinear distortions that are generated in an analog RF signal in conventional MZM. The developed analytical model helps us to understand how CSO and CTB are generated and can be suppressed within the modulator. It is found that at bias voltage $V_b = nV_\pi$ (where $n = \pm 1/2, \pm 3/2 \ldots$), CSO is totally eliminated and V_b does not have any effect on CTB. Again, at relatively large phase shift ($i.e., \phi = 0.45\pi$) and in presence of bias voltage the CSO and CTB attain minimum value but the output signal power is very low due small value of the modulation index (OMI). We have varied both phase and bias voltage to achieve optimum value of CSO and CTB with relatively high OMI. It is observed that CSO and CTB obtain optimum value when the values of optical phase shift and bias voltage are $\leq 0.05\pi$ and nV_π (where, $n = \pm 1/2, \pm 3/2 \ldots$) respectively.

Though the effects of CSO and CTB can be suppressed significantly in conventional MZM but its performance degrades sharply in high bandwidth and long haul optical communication system. In such situation, the DPMZM is used to handle large amount of power as well as high bandwidth. In order to find out the optimum value of system parameters to cancel CSO and minimize CTB, we have derived analytical model incorporating different system parameters of DPMZM. It is found that if both primary and secondary modulators are operated at quadrature point the CSO is completely eliminated. For minimizing the CTB, we have determined a relationship between optical input power splitting ratio (γ) and electrode length ratio (α). It is observed that the linear modulation characteristic and the minimum loss of the power are achieved when the optical power splitting ratio and electrode length ratio are1.5 and 0.76 respectively.

5.2 Recommendation for Future Work

In this research work, we have analyzed the performance of IMD effects of MZM for CATV transmission systems; these results may be applicable to other similar type of analog transmission systems. Here, we have assumed that the effects of higher order IMD (*i.e*., fourth, fifth etc.) is negligible. Therefore, fifth or even higher order IMD can be considered for future study to reflect the more accurate result. We have observed that the even order distortion (like CSO) produced within a MZM can be cancelled using quadrature bias point, but CSO may also be produced by various phenomena such as chirp, fiber chromatic dispersion and polarization mode dispersion etc, which is not considered in this work. Future research work may be carried out to reduce the combined CSO effect considering other sources. In this thesis, analysis is carried out to evaluate effects of IMD only within the modulator; this work may be extended for an overall transmission system. Experimental validation of the theoretical results and determining the optimum system parameters for reliable system performance may also be carried out.

Appendix – A: Mach-Zehnder Modulator

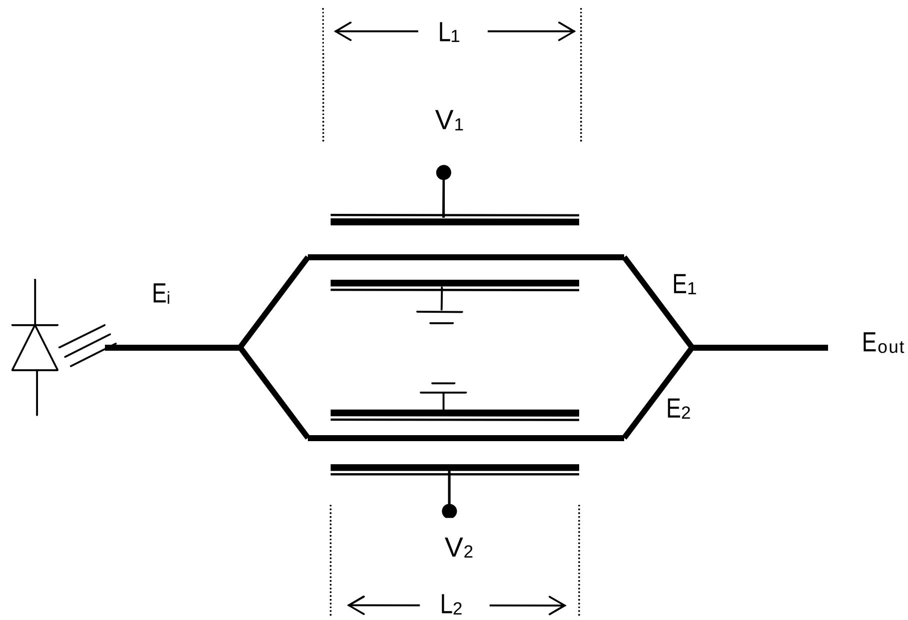


Fig-A.1: Basic structure of MZ-modulator

The E-field in the upper and lower arms of the modulator is given by

$$E_1 = \frac{E_i}{2}\exp(j\beta_1 L_1)$$
$$E_2 = \frac{E_i}{2}\exp(j\beta_2 L_2) \qquad (A.1)$$

Where, $L_1 = L_0 + \frac{h}{2}$ $\quad L_2 = L_0 - \frac{h}{2}$

$$\beta_1 = \beta_0 + \varepsilon V_1 \qquad \beta_2 = \beta_0 - \varepsilon V_2 \qquad (A.2)$$

The output E-field is given by

$$E_0 = \frac{E_i}{2}\left\{\exp^{j\beta_1 L_1} + \exp^{j\beta_2 L_2}\right\} \qquad (A.3)$$

$$E_0 = \frac{E_i}{2}\left[\cos(\beta_1 L_1) + j\sin(\beta_1 L_1) + \cos(\beta_2 L_2) + j\sin(\beta_2 L_2)\right] \qquad (A.4)$$

$$E_0 = \frac{E_i}{2}\left[\cos(\beta_1 L_1) + \cos(\beta_2 L_2) + j\left(\sin(\beta_1 L_1) + \sin(\beta_2 L_2)\right)\right] \qquad (A.5)$$

$$E_0 = E_i\left[\left(\cos\frac{\beta_1 L_1 + \beta_2 L_2}{2}.\cos\frac{\beta_1 L_1 - \beta_2 L_2}{2}\right) + j\left(\sin\frac{\beta_1 L_1 + \beta_2 L_2}{2}.\cos\frac{\beta_1 L_1 - \beta_2 L_2}{2}\right)\right]$$

... (A.6)

$$E_0 = E_i \cos\left(\frac{\beta_1 L_1 - \beta_2 L_2}{2}\right)\exp^{(j\frac{\beta_1 L_1 + \beta_2 L_2}{2})} \quad (A.7)$$

On using the equations (A.2),

$$E_0 = E_i \cos\frac{1}{2}\left\{(\beta_0 + \varepsilon V_1)(L_0 + h/2) - (\beta_0 - \varepsilon V_2)(L_0 - h/2)\right\}\exp^{\frac{j}{2}\left\{(\beta_0+\varepsilon V_1)(L_0+h/2)+(\beta_0-\varepsilon V_2)(L_0-h/2)\right\}}$$

... (A.8)

For balanced operation, it has V_1=V_2=V, hence

$$E_0 = E_i \cos\left[\frac{\beta_0 h}{2} + \varepsilon L_o V\right].\exp^{j\beta_0 L_0 + j\frac{h\varepsilon V}{2}} \quad (A.9)$$

The applied voltage V is in practice sum of a dc bias voltage and the signal voltage, which can be expressed as:

$$V = V_{dc} + V_s \quad (A.10)$$

The dc bias voltage and the differential length h of the arms of the Mach-Zehnder modulator determine the offset of the sinusoidal waveform. Treating the lumped effect of both of these to arise from an effective bias voltage V_{bias}, it become:

$$E_0 = E_i \cos[\varepsilon L_0 (V_s + V_{bias})].\exp^{j\beta_0 L_0 + j\frac{h\varepsilon V}{2}} \quad (A.11)$$

In convention the voltage swing that brings the output of a Mach-Zehnder modulator from full off to full on is denoted by V_π. Using the definition of V_π ignoring the static delay $\exp^{j\beta_0 L_0}$ of the device and bias voltage $V_{bias} = 0$, it become:

$$E_o = E_i \cos\left(\frac{\pi V_s}{2V_\pi}\right)\exp^{j\frac{h\varepsilon V}{2}} \quad (A.12)$$

The cosine terms in equation (A.12) provides the amplitude modulation while the exponential term produces the time dependent phase variation or chirp. The chirp introduced during modulation is determined from the electro-optic parameter ε and the differential length h. In this case it is evident that in general the output field contains both phase (exp) and amplitude (cos) modulation contributions. Also, in [3], we observe that f the two waveguide arms are driven by complementary waveforms then the phase modulation term is identically zero and pure amplitude modulation without chirp is obtained.

The output intensity of the light as a function of the input intensity is given by [24-25]

$$\frac{I_0}{I_i} = \frac{|E_0|^2}{|E_i|^2} = L_a \cos^2(\Delta\beta L) = L_a \cos^2(\frac{\pi V_s}{2V_\pi}) \qquad (A.13)$$

$$I_0 = \frac{L_a I_i}{2}\left(1 + \cos(\frac{\pi V_s}{V_\pi})\right) \qquad (A.14)$$

Where, L_a is the optical insertion loss of a practical device and V_s is the modulating RF signal voltage, V_π is the voltage required to change the output light intensity I_0 from its maximum value to its minimum value.

Appendix – B: Signal Distortion in CATV

Analog CATV systems transmit 80 to 110 channels of video and audio information with in a system bandwidth up to 750 MHz using vestigial sideband amplitude modulation (AM-VSB). Most analog television picture carriers are 6 MHz apart and offset 1.25 MHz upwards form harmonics of 6 MHz. Each channel extends 1.25 MHz below picture carrier to 4.75 MHz above it.

In analog applications, any device nonlinearities will create frequency components in the output signal that were not present in the input signal. Two important nonlinear effects are harmonic and IMD. To understand the effects of this distortion on an analog CATV system, consider the propagation of an N-channel CATV signal through a nonlinear element. The input power, E_i entering the fiber is

$$E_i = \sum_{k=1}^{N} c_k e^{j\omega_k t} + \text{complex conjugate} \tag{B.1}$$

$$= \sum_{k=1}^{N} c_k e^{j\omega_k t} + \sum_{k=1}^{N} c_k^* e^{-j\omega_k t} \tag{B.2}$$

Where, c_k is the power including phase and ω_k is the frequency of the k^{th} CATV channel. When this signal propagates through a nonlinear element with second order distortion, the signal detected at the receiver, E_0 is given by

$$E_0 = aE_i + bE_i^2 \tag{B.3}$$

This can be written explicitly as,

$$E_0 = a(\sum_{k=1}^{N} c_k e^{j\omega_k t} + \sum_{k=1}^{N} c_k^* e^{-j\omega_k t}) + b(\sum_{k=1}^{N} c_k e^{j\omega_k t} + \sum_{k=1}^{N} c_k^* e^{-j\omega_k t})(\sum_{k=1}^{N} c_k e^{j\omega_k t} + \sum_{k=1}^{N} c_k^* e^{-j\omega_k t}) \tag{B.4}$$

The first term is linearly proportional to the input signal. The second terms generates new IM frequencies. Many combinations of different CATV channels lead to the same IM frequency. For example, consider 79, whose visual carrier frequency is at 553.25 MHz. if channel 17 (139.25 MHz) and channels 56 (415.25 MHz) undergo second-order distortion, an IM frequency is produced at the sum of those two frequencies which is 554.5 MHz and is located 1.25 MHz above the visual carrier for channel 79. However, other combinations also lead to this frequency, so second-order distortion at channel 79 is composed of many combinations of frequencies, hence the name composite in composite second-order (CSO) distortion.

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