Investigation of Large Signal Effects on Cascaded Travelling Wave Electro Absorption Modulator (CTWEAM) Performance and Optimization

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Investigation of Large Signal Effects on Cascaded Travelling Wave Electro Absorption Modulator (CTWEAM) Performance and Optimization

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Abstract
In this thesis work large signal model of cascaded travelling wave electroabsorption modulator (CTWEAM) has been studied. The effect of input modulating voltage, input optical power, biasing voltage, and circuit parameters on bandwidth, extinction ratio and overshooting of this modulator carefully investigated. It has been also investigated the sensitivity of the transit time delay and the length ratio of active segment and microstrip line over the total length on the performance of the modulator. As the modulating voltage, input optical power and biasing voltage are increased then the bandwidth, extinction ratio and overshooting are also increased until certain value (except for modulating voltage) after that increasing of input optical power and biasing voltage the bandwidth, extinction ratio and overshooting are decreased. At 1.1 V biasing voltage, 14 mW input optical power and only 0.4 V(p-p) modulating voltage the cascading modulator has 3dB bandwidth, extinction ratio and overshooting 110 GHz, 4 dB and 0.2 dB respectively. It has been shown that at the same biasing voltage and input optical power but at 1 V(p-p) modulating voltage the cascading modulator has 119 GHz 3dB bandwidth, 10.9 dB extinction ratio and 0.47 dB overshooting that could be applicable for telecommunication. It has been seen that the microwave reflection loss is -10 dB at 100 GHz to perform the device on the above mentioned values. It has been shown that the cascading modulator to perform on the above mentioned values, the p-doped mesa structure has changed from rectangular to mushroom shape which has 0.69 Ω-mm, total active segment length is 990 µm where first, second, third and fourth active segment have 11%, 10%, 22% and 56% length over the total active segment length. Since the cascading modulator performance has been studied on large signal model, the results have been obtained from this thesis work would be the crucial for optimum designing and fabrication of the cascading modulator to apply in real life application.
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\textbf{Chapter 4}

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List of Abbreviations

AC: Alternating Current
dB: Decibel
CTWEAM: Cascaded Travelling Wave Electroabsorption Modulator
DC: Direct Current
BCB: Benzocyclobutene
DFB: Distributed Feedback
EAM: Electro-absorption Modulator
FKE: Franz-Keldysh Effect
Gbps: Giga Bit per Second
IMDD: Intensity Modulation Direct Detection
Km: Kilometer
NRZ: Non Return to Zero
OTDM: Optically Time Division Multiplexing
PRBS: Pseudo Random Binary Signal
QCSE: Quantum Confined Stark Effect
TDM: Time Division Multiplexing
TWEAM: Travelling Wave Electroabsorption Modulator
UTP: Unshielded Twisted Pair
VCSEL: Vertical Cavity Surface Emitting Laser
VOIP: Voice Over IP (Internet Protocol)
WDM: Wavelength Division Multiplexing
Introduction

1.1 Motivation

Communication is the way of conveying information from one place to other place. The information is sent from sending side by using transmitter through a communication medium (looks like wire, wireless, optical fiber and etc) and on other hand receiving side receives information by using receiver. People of different countries throughout the world transmit files, text, audio, video and etc between them by using this communication medium. Day by day the numbers of information are increasing dramatically and it is shown in Figure 1.1.

These huge numbers of data should be transfer through communication medium. In the beginning of data transmission people used electronic medium (copper wire). This medium is suitable for short distance communication. But if we want to send these data in long distance then it will suffer high attenuation at high frequency and also it has limited capacity to transmit data. As the distance increased its wiring cost will also increase. For the case of wireless communication, it can transmit long distance with reduce wire cost, users have mobility and easy access to the data transmission and reception. But it has relatively lower bandwidth speed (802.11/n could reach 248 Mbps [2]) compare to wire communication where Cat 6A UTP cable has 10Gbps [3].

Figure 1.1: Cisco VNI global IP traffic forecast [1].
Both medium suffer high losses and attenuation for long distance transmission and reception. This needs of using another kind of communication medium. After invention of laser and optical fiber these problems have been solved. Optical fiber has attenuation 0.2 dB/Km at 1.55\(\mu\)m wavelength [4] which makes it suitable for long distance communication of high frequency electromagnetic wave at low cost. Fiber optic communication has been rapidly growing because of large capacity compared to any kind of the communication medium having low loss, dispersion shifted and compensating fibers, erbium doped fiber amplifier over the 1.55\(\mu\)m window and also Wavelength Division Multiplexing (WDM) technology.

According to the Figure 1.1, the predicted growth rate of data by Cisco in 2010 showed that in 2015 it will be needed more bandwidth to transfer these huge amount of data packets. To meet this demand WDM plays an important role to transfer these data in optical fiber. So, it requires a device called modulator in a transmitting side which can encode the data packets on the optical carrier with high speed and large bandwidth. This can be done by travelling wave electro absorption modulator (TWEAM) [5]. In a European project HECTO has achieved in a field of trail 112 Gbps [6] transmitter with NRZ (non-return to zero coding) coding. It uses simple on-off keying to achieve this record bit rate for transmission and reception. Farther it requires some optimization to use it in Ethernet and as well as in Telecommunication of better efficiency, speed of modulation and large number of supported bandwidth. So, traveling wave electro absorption modulators are getting more attention and also the interest of this study.

1.2 Outline of the Thesis

In this thesis, cascaded travelling wave electroabsorption modulator (CTWEAM) has been studied with large signal model of its performance on different modulating signal, basing voltage, input optical power and also active and passive per unit length. The influence on the performance of passive circuit components has also been studied. The modeling and simulation work have been done by using circuit simulator software called PSPICE. Chapter two discusses the background of the design. Chapter three gives the insight on modeling and simulation of two series coupled segmented TWEAMs as a cascaded TWEAM (CTWEAM) by using its electrical equivalent circuits. Chapter four gives the discussions and explanation of simulated results. Chapter five contains the summary and conclusion of this thesis work.
2.1 Introduction

Optical fiber communication is experiencing a rapid growth, driven by the explosive growth of internet video, gaming, VOIP, and voice traffic. To use the huge bandwidth of the optical fiber, intensity modulation direct detection (IMDD) systems with Time Division Multiplexing (TDM) or Wavelength Division Multiplexing (WDM) are commonly used. Optical fiber communication consists of three basic blocks which are optical transmitter, optical fiber (as transmission medium) and optical receiver. The important part of optical transmitter is light source and the optical modulator which modulates high frequency signals. However, the design part of optical modulator is very complex. Basis of the modulator designing is discussed in simply and briefly in this chapter. Descriptions of different kind of optical modulators with different effects are also discussed.

2.2 Optical Modulators

In optical communication, a transmitter transmits large amount of data at high speed by using light. It converts electrical signals to optical signals requires a light source for which intensity of light output can be modulated. These signals are modulated by using optical modulator before sending into optical fiber. Optical modulator can be divided into two types

(i) Direct Modulation
(ii) External Modulation

2.2.1 Direct Modulation

A semiconductor laser needs threshold current that helps minimum population inversion for lasing. In a semiconductor laser if both the dc threshold current and input ac signal are applied then the output of the laser will vary according to the applied input ac signal. So, this modulation is done by changing the input ac signal around the bias level in a semiconductor laser. It uses simple on-off keying modulation technique. It is cost effective and easier to implement. But it suffers chirping and temperature variation due to modulation [7]. Chirping is the shifting of the carrier frequency. If it happens during transitions from on to off or vice versa
called transient chirping. There is another kind of chirping called adiabatic chirping which is due to the laser frequency is different during on and off times of the modulator [7]. It has very bad effect on the transmission distance of whole communications system due to dispersion [4]. The maximum bandwidth 40 GHz has been achieved using direct modulated VCSEL [8]. The more bit rate is not achieved due to photon life time and also non linear gain [5,7]. The main disadvantages of this modulator are limited bandwidth and chirping which will cause extra broadening effect when transmitting through a dispersive fiber [9,10].

2.2.2 External Modulation

In this case, a laser emits light continuously which is fed to external modulator is used to modulate the light according to the electrical field of modulating signal. This electrical field of the modulating signal controls how to code the output of modulator by using basic phenomena of light interacts with matter either through absorption or polarization which could be later turned intensity or phase modulation [7]. It has better performance than the direct modulation due to low parasitic chirping which will help for long distance transmission. This kind of modulation can be divided into two other types which are given below

(i) Electro-Optical modulator
(ii) Electro-Absorption modulator

2.2.2.1 Electro-Optical modulator

The working principle of this modulator is based on the change of refractive index (phase) due to change of electric field of the modulating signal. If the refractive index changes linear with applied electric field then it is called linear electro-optical effect or Pockels effect, otherwise if it varies quadratic or square of the applied electric signal then it is call quadratic electro-optic effect or Kerr effect. This phase modulation can be converted to intensity modulation by using Mach-Zehnder interferometer setup which is suitable to detect for photo detector [9]. Lithium niobate (LiNbO3) crystal is used in these modulators. But, LiNbO3 is not suitable with InP laser. Electro-optical effect has also been observed in Silicon which is used as modulator for charge carrier modulation [11].
2.2.2.2 Electro-Absorption modulator

The working principle of this modulator is based on the change of material absorption in the presence of applied field of the modulating signal. Usually, this modulator is used in intensity modulation where presence of electric field to high optical absorption and absence of electric field to low optical absorption. This modulator is more suitable than that of electro-optical modulators because of its strong interaction between the optical and electrical field, faster modulation speed, compact in size, easy to integrate with DFB semiconductor laser on a chip [5,7]. It has driving voltage 1-3 V compared to electro-optical modulator where it has driving voltage not less than 3 V [10]. Due to above advantages, electro-absorption modulators are more attracted than others type of modulators [5,9].

2.3 Physics of Electro Absorption Modulator

The p-i-n structure of electro-absorption modulator is similar to photo-detector. But, the difference between them is that the electro-absorption modulator absorbs photons below the band-gap of the semiconductor materials. The absorption layer would be either bulk material or quantum well. The basic physics of electro-absorption could be described by Franz-Keldysh Effect (FKE) for bulk material due to application of an external field and Quantum Confined Stark Effect (QCSE) for quantum well material due to electron and hole wave functions are formed exciton. These two effects are described below

(i) Franz-Keldysh Effect (FKE)
(ii) Quantum Confined Stark Effect (QCSE)

2.3.1 Franz-Keldysh Effect (FKE)

It is a change of absorption in material of a semiconductor when an electric field is applied [10, 12]. This effect occurs in bulk semiconductor materials due to band to band excitation of electron from valence band to conduction band for photon energy less than the band gap. In this case, the band-gap of the semiconductor material is kept slightly greater than the photon energy. When photon strikes on it creates electron-hole pair and the electron is excited to a virtual state close to band-gap. When an electric field is applied to it, the band structure of the material tilts and reduced the band-gap of the material which causes the absorption at that photon energy, electron tunnels into the conduction band with this applied electric field as shown in Figure 2.1. The probability of absorption is increased with the perturbation of wave function of
the applied electric field. By changing the applied electric field we can change the absorption of property of electro-absorption modulator. They used group III-V (like InGaAsP) materials as an absorbing medium.

![Diagram](image)

Figure 2.1: Electro-absorption by Franz-Keldysh Effect [5].

### 2.3.2 Quantum Confined Stark Effect (QCSE)

This effect is occurred when quantum well is used as absorbing materials. A very thin and lower band-gap of quantum well is placed between the two higher band-gap materials. It creates band-gap discontinuity in the valance and conduction band structure which will create potential well in both bands [14]. In this quantum well, electrons and holes are confined due to they have strong columbic attraction between them which helps to form excitons (electrons and holes pairs). These excitons form create exciton resonance since they could not be ionized by applying higher electric field. When a reverse electric field is applied to quantum wells, energy band diagram tilts and reduced the band gap which result in an exciton absorption for photon energy less than the difference between electrons energy in the conduction band well and holes energy in the valence band well (i.e. band to band energy difference) as shown in Figure 2.2. Due to application of reverse electric field, electrons and holes move in opposite direction in the well which reduces the overlap that causes the reduction of the peak absorption as shown in Figure 2.3. In turn, the absorption spectrum shifts to a higher wavelength (red shift). This is called electro-absorption QCSE.
Figure 2.2: Quantum confined stark effect in a quantum well (a) without and (b) with electric field [10].

Figure 2.3: Variation of absorption coefficient spectrum $\alpha(\omega)$ with electric field [15].

The QCSE devices are more polarization and wavelength sensitive than FKE devices. At high frequency performance quantum well devices will suffer escape time for the excited carriers to leave the well [5]. This degrades the performance of device at high frequency. This problem can be solved by proper designing of multiple quantum wells structure. The multiple well QCSE modulators are more attracted then FKE modulators because of they are fast, efficient and required low diving voltage.

2.4 Design of Electro-absorption modulator (EAM)

Electro-absorption modulators are more attracted due to high modulation efficiency, low driving voltage, easy to integrate with laser source and also high speed for fiber optics link design of telecommunication systems [7]. It is not only used for NRZ transmitter, it can be used
as short optical pulse generation, pulse encoding, optical multiplexing and demultiplexing in OTDM and also solution transmission [10]. Group III-V semiconductor materials are mostly used for this type of modulator. It can be designed as

(i) Lumped Modulator
(ii) Travelling Wave Electro-absorption Modulator (TWEAM)

2.4.1 Lumped Modulator

In this design, the electrical signal is applied in center or anywhere along the optical wave guide as shown in figure 2.4. The speed of this device is limited by the total RC time constant. If we want to increase the modulation efficiency then we will have long device structure. In turn, it will increase the internal junction capacitance that will cause the increase of RC time constant which also decreases the bandwidth. Due to this problem, the maximum length for this lumped type EAM has been found 63 µm and maximum bandwidth is 50 GHz [16].

![Figure 2.4: Structure of lumped modulator [10].](image)

2.4.2 Travelling Wave Electro-absorption Modulator (TWEAM)

In this configuration, EAM is designed as transmission line structure. At the end of wave guide the electrical signal is terminated with the matching load otherwise, high frequency signal will reflect back and forth. It will became travelling wave when the $Z_L = Z_0$ as shown in figure 2.5. Travelling wave structure means that the electrical signal and optical signal are co-propagate [10]. Since the capacitance is distributed along the length of the device by proper designing of the transmission line which will cause to increase length of device and also the modulation efficiency without sacrificing bandwidth [16].
The speed of this modulator is limited by microwave attenuation loss in electrode. It occurs due to mismatch between propagation velocity of microwave signal and group velocity of optical signal along the length of the device. The efficiency of the design will decrease if the impedance mismatch between the characteristic impedance of the device (25 Ω) and source resistance (50 Ω). This mismatch reduces the modulation efficiency due to reflection of microwave signals which causes return loss [17]. This problem has been solved by proper designing of device into the segmented TWEAM where the total device is designed into active and passive segment [17] in such a way that the active segment has impedance near about 22 Ω and passive segment has impedance near about 72 Ω where high impedance passive segment try to compensation low impedance active segment to match with 50 Ω source impedance as shown in figure 2.6. This will reduce the return loss of microwave signal and hence improve the modulation efficiency. This will also improve the interaction between the microwave and optical signal, bandwidth and extinction ratio and consequently, it will decrease overshooting and undershooting. Such a design has been found a return loss less than -15 dB and 3dB bandwidth of 90 Gbps [7, 17]. By using this design, it has been showed that it would be suitable for 100 Gbps Ethernet application where device active length is 230 µm, extinction ratio 10 dB, modulating voltage 2v (p-p) and 6.7 db for 2.2 Km fiber [18].
Chapter 2

Background

2.5 Segmented TWEAM

At beginning of the EAM, it was designed with lumped EAM. But it has bandwidth limitation due to the junction capacitance which will raise the RC time constant. This problem has been solved by using travelling wave structure of EAM where the return loss increases due to the mismatch between source impedance and device characteristics impedance. To overcome this problem, segmented TWEAM has been designed by proper design of active and passive segment impedance to match with source impedance [17]. This thesis work is also based on the model of this device. The schematic diagram of the segmented TWEAM which is fabricated in KTH is shown in figure 2.7 and a modification of its mesa structure for this thesis work is shown in figure 2.8 which suitable for Ethernet and as well as Telecommunication system at very low modulating peak to peak (p-p) voltage.

Figure 2.6: Characteristic impedance of active and passive segments [5].

Figure 2.7: (a) Segmented TWEAM [5, 17] and (b) fabricated 100 Gbps DFB TWEAM [6].
To make it easily integrate with laser source, n-type InP substrate is chosen. A n-layer buffer layer will be grown on the top of it. After the 8 layer of multiple quantum wells active section are grown on the buffer layer. The active segment of the modulator contains an intrinsic layer strain compensated InGaAsP/InGaAsP quantum wells where the interaction between light and electrical signal occurs. To reduce the total capacitance of active layer, an intrinsic layer is deposited on top of the quantum wells. For guiding the optical signal in the device, n-type InP is doped with zinc to make it p-type InP which shaped is T-type or Mushroom type, deposited on the top of the intrinsic layer. This mesa structure has lower resistance than the previous mesa structures which will increase the more 3dB bandwidth due to reduction of RC time constant. On the top of the mesa, metal electrode is deposited for carrying high frequency signal. AC (Alternating Current) ground metal planes are deposited on both side of the mesa structure as shown in the figure and in the bottom side of the conducting substrate a metal contact is used for DC (Direct Current). In the passive segment, Benzocyclobutene (BCB) is used to separate the electrode from ground plate which has low capacitance of 30 pF [5] and high impedance. This impedance raises the total impedance close the source impedance and reduces the return loss in the device.
2.6 Statement of Problems

Previous works have been shown that effects of chirping and geometrical parameter such as the width and height of mesa on its performance on extinction ratio, 3db bandwidth, return loss etc by using small and large signal modeling. This thesis work is also based on previous work of geometrical parameters by using large signal modeling with two series couple of segmented TWEAMs as a cascading structure of TWEAM which is called cascaded travelling wave electroabsorption modulator (CTWEAM). The following works are considered to investigate the design

1. What will be the proper cascading design for this device performance?
2. What will be the more robust equivalent model for this cascading structure?
3. What will be the minimum modulating voltage for Ethernet application?
4. What will be the optimum biasing voltage for this application?
5. What will be the optical power for this application?
Modeling and Simulation of Segmented CTWEAM Structure

3.1 Introduction

For modeling the optical modulator, we can consider it as a microwave transmission line which can be divided into active and passive section with its equivalent electrical circuit that would be represented by capacitors, inductors and resistance. The objective of this thesis work is to design a cascaded optical modulator by combine two segmented TWEAM modulators. By using this concept, the cascaded optical modulator is designed and it is discussed in this chapter. Circuit simulation procedure is also discussed at the end of this chapter.

3.2 Circuit Model of Segmented TWEAM

The equivalent electrical circuit of a segmented TWEAM could be divided into following way
(i) Active Segment
(ii) Passive Segment

3.2.1 Active Segment

It is a model of per unit active length of transmission line. The electrical equivalent circuit of the optical modulator for active segment is shown in Figure 3.1. This circuit represents one section of the active segment. Where L is inductance of electrode of transmission line, \( R_{SC} \) is series resistance of the conductor, \( R_C \) is a resistance due to skin effect, \( R_P \) is the resistance of the p-type InP region, \( C_{int} \) is the internal capacitance of the active region, \( C_{ext} \) is external capacitance due to BCB, \( I_{photo} \) is a current source which generates the photocurrent and DELAY is time delay using to account for the transit time delay of photo generated carriers. At high frequency, the skin depth of a conductor is decreased due to the skin effect which increases resistance of the \( R_C \) compared to \( R_{SC} \).
3.2.2 Passive Segment

Similarly, it is also the model of per unit passive length of transmission line. The electrical equivalent circuit of the optical modulator for passive segment is shown in Figure 3.2. This circuit represents one section of the passive segment. Where $L_p$ is the inductance of the microstrip line, $R_{cp}$ is resistance of the microstrip conductor which includes both the skin effect resistance $R_{s}$ and the resistance due to the resistivity of the microstrip line $R_{o}$, $R_{dl}$ is the shunt resistance due to electrical dissipative nature of the BCB, $C_p$ is the capacitance due to dielectric (BCB) between top and bottom of conductors [7].

Figure 3.1: One section electrical equivalent circuit of active transmission segment [7].

Figure 3.2: One section electrical equivalent circuit of passive transmission segment [5, 7].
3.2.3 Extracted value of the components

The values of the components of active and passive segments are given into Table 3.1. These values are extracted by independent tests [17] which are not required to calculate again for this thesis work except the mesa (p-doped region) resistance, \( R_P \). For this thesis work, the value of \( R_P \) resistance is 0.69 Ω mm which is calculated according to its proposed Mushroom (or T) shaped mesa.

Table 3.1: Extracted components value for the active and passive segments of the transmission line [17].

<table>
<thead>
<tr>
<th>Segments</th>
<th>Component</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active</td>
<td>( C_{\text{int}} )</td>
<td>518 fF/mm</td>
</tr>
<tr>
<td></td>
<td>( C_{\text{ext}} )</td>
<td>125 fF/mm</td>
</tr>
<tr>
<td></td>
<td>L</td>
<td>280 pH/mm</td>
</tr>
<tr>
<td></td>
<td>( R_P )</td>
<td>0.69 Ω-mm</td>
</tr>
<tr>
<td></td>
<td>( R_C )</td>
<td>2.05 Ω/(mm( \sqrt{\text{GHz}} ))</td>
</tr>
<tr>
<td>Passive</td>
<td>( C_P )</td>
<td>64 fF/mm</td>
</tr>
<tr>
<td></td>
<td>( L_P )</td>
<td>354 pH/mm</td>
</tr>
<tr>
<td></td>
<td>( R_{\text{dl}} )</td>
<td>4.9 Ω-mm</td>
</tr>
<tr>
<td></td>
<td>( R_{\text{cp}} )</td>
<td>5 Ω/mm + 0.8 Ω/(mm( \sqrt{\text{GHz}} ))</td>
</tr>
</tbody>
</table>

The generated \( I_{\text{photo}} \) current can be calculated by using following equation [7, 19]

\[
I_{\text{photo}} = \frac{e \times (\text{absorbed optical power in the section})}{h w_0}
\]

Where, \( h \) is the Planck’s constant, \( w_0 \) is frequency of the light signal and \( e \) is electron charge.

The transit time delay is a time delay that the electron takes time to travel from one end to other end of the junction [5]. It can be calculated by \( \tau_n = \frac{d}{v_n} = 6.42 \text{ ps} \) [7], where \( \tau_n \) is the transit time, \( v_n = 7 \times 10^6 \text{ cm/s} \) [7, 20], is the velocity of electron and \( d = 0.45 \mu\text{m} \) [17], is the thickness of the intrinsic region.
3.2.4 Relation between the optical absorption and bias voltage

It is necessary to know how the nonlinear relationship between optical absorption and applied bias voltage. It has been observed in previous work [5] which is shown in Figure 3.3 which can be calculated by using the following equation [5]

$$\Delta \alpha = p[E - E_o]^c = p\left[\frac{V - V_o}{h_i}\right]^c$$

Where $\Delta \alpha$ is the change of absorption, $p$ is the proportional constant, $h_i$ is the thickness of the absorption region, $E$ is the electric field, $V$ is applied dc bias voltage, $V_o$ is the low field bias voltage which represents the nonlinear relationship between the optical absorption and the applied voltage and $c$ is the curvature parameter. The curvature parameter, $c$ depends on material properties and its optimum value has been taken 1.8 to fabricate the optical modulator [5]. The extinction ratio is proportional to applied voltage when the driving voltage is kept low. The nonlinear relation between the optical absorption and applied voltage will help to chose suitable extinction ratio at suitable driving voltage which is described in Figure 3.3.

![Figure 3.3](image.png)

Figure 3.3: Relation between applied bias voltage and optical absorption at different curvature parameter $c$ [5].

3.3 Circuit Model of the Segmented CTWEAM

Segmented CTWEAM is designed in such a way, when light signal propagates into the active section then some of the light power is absorbed by this section and modulated according to the applied signal, the rest of signals are transmitted at velocity which depends on the refractive index of the waveguide, when it passes through other section it just passes and has no
absorption and modulation. For this thesis work, two segmented TWEAMs have taken to make a segmented cascaded travelling wave electroabsorption modulator (CTWEAM) which is show in Figure 3.4. It has four active segments and six passive transmission sections. The length of these active and passive transmission (or microstrip) sections are given Table 3.2 and according these lengths of active and passive transmission lines the microscope diagrams are shown in Figure 3.5. The detail electrical equivalent circuit diagram is given in appendix A.

![Microscope photograph of (a) two segmented TWEAMs (b) segmented CTWEAM.](image-url)
Table 3.2: Mask sets [lengths are in µm].

<table>
<thead>
<tr>
<th>Mask</th>
<th>Total active length $L_{a,\text{tot}}$</th>
<th>Micro strips length of First Modulator</th>
<th>Active length of first modulator</th>
<th>Micro strips length of Second Modulator</th>
<th>Active length of Second modulator</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$L_{0t}$</td>
<td>$L_{1t}$</td>
<td>$L_{2t}$</td>
<td>$L_{1a}$</td>
<td>$L_{2a}$</td>
</tr>
<tr>
<td>1A</td>
<td>990</td>
<td>200</td>
<td>270</td>
<td>100</td>
<td>110</td>
</tr>
<tr>
<td>1B</td>
<td>990</td>
<td>100</td>
<td>160</td>
<td>50</td>
<td>560</td>
</tr>
<tr>
<td>1C</td>
<td>980</td>
<td>100</td>
<td>350</td>
<td>50</td>
<td>250</td>
</tr>
</tbody>
</table>

(a)

(b)
Chapter 3

Modeling and Simulation of CTWEAM

Figure 3.5: Microscopic diagram for the CTWEAM (a) 1A (b) 1B and (c) 1C where lengths are in µm.

3.4 Simulation Setup

The objective of this thesis is to design and optimize a segmented CTWEAM in such a way that the device parameters perform effectively throughout the large signal microwave analysis. This modulator is represented by its equivalent circuit using PSPICE circuit simulator. The whole transmission line is divided into many lumped section. Here, each segment is divided into 5 sections and each section is described by its equivalent capacitor, inductor and resistance. Most of analysis is running in transient (or time domain) response for a Pseudo Random Binary Signal (PRBS) source. Some of the analysis is also running in frequency domain (steady-state) for a sine wave generator source. An eye diagram is used to calculate 3dB bandwidth, extinction ratio, jitter, peak overshooting etc. The simulated data are discussed in the chapter four.
Simulation Results and Discussion

The simulated results of the cascaded TWEAM are clearly explained in this chapter. At the beginning of the chapter, it explains the effect of 3db bandwidth, extinction ratio, overshooting and average output power by changing the modulating voltages, biasing voltage and input optical power on cascaded TWEAM. After, it explain all above mention effects for first modulator and next on for second modulator. It is also discussed cascaded modulator performance by varying the device parameters like, active layer capacitance, line inductance and p-region resistances. At end of this chapter, it also explains the cascaded modulator performances by changing its active and passive length. The list of the cases which are discusses in the chapter are given below

1. Effect of modulating signal on the performance of the cascaded modulator, 1st modulator when 2nd modulator is deactivated and 2nd modulator when 1st modulator is deactivated for all the three masks design.
2. Effect of input optical power on the performance of the cascaded modulator for all the three masks design.
3. Effect of basing voltage on the performance of the cascaded modulator for all the three masks design.
4. Effect of circuit parameters on the performance of the cascaded modulator for all the three masks design.
5. Effect of changing the active segment ratio on the performance of the cascaded modulator for all the three masks design.
6. Effect of changing the microstrip length ratio on the performance of the cascaded modulator for all the three masks design.
7. Effect of transit time delay on the performance of the cascaded modulator for all the three masks design.

Figure 4.1 shows the eye diagram for determining extinction ratio, overshooting, undershooting, jitter and also transit time. These parameters are required to explain the extracted data from PSPICE simulation for the performance of CTWEAM.
Figure 4.1: Eye diagram of cascaded TWEAM at 0.4 modulating voltage and 100 Gbps PRBS source.

Extinction ratio: It is the ratio of optical power at $P_{on}$ label to optical power at $P_{off}$ label as shown in Figure 4.1. The modulation efficiency of a modulator is determined by this ratio. It is calculated by

$$\text{Extinction ratio} = 10 \log \left( \frac{P_{on}}{P_{off}} \right)$$

It is measured in dB (Decibel).

Overshooting: It is the ratio of peak amplitude of the optical power, $P_{peak}$ to the optical power level, $P_{on}$ as shown in Figure 4.1. The distortion level is determined by this ratio. It is calculated by

$$\text{Overshooting} = 10 \log \left( \frac{P_{peak}}{P_{on}} \right)$$

It is also measured in dB.

Bandwidth: The bandwidth $\Delta f$ of a RC circuit can be determined by measuring its 10% to 90% rise time called as transit time, $\tau_r$ (in ps) in an eye diagram as shown in Figure 4.1. It is measured in Hz. It is calculated by

$$\Delta f = \frac{0.35}{\tau_r} \quad [4]$$

Jitter: It is also the measure of the distortion in a signal. If the jitter is increased then the opening of the eye is reduced. It is shown in Figure 4.1.
4.1 Effect of Input Signal (Modulating Voltage) on the performance of the Modulator

4.1.1 Effect of Input Signal on 3dB Bandwidth for the device performance

Figure 4.2 shows the effect of varying the modulating signal to the different cascaded modulators. From Figure 4.2 (b) and (c), it is clear that the smaller the total active length of any one modulator in a cascaded modulator which gives higher bandwidth and this result has been also found in previous thesis work [7], as the total active length is increased then the bandwidth is also decreased. When the both modulators of the cascaded modulator are activated and the modulating signal is varied discretely from 0.4 V(p-p) to 1.6 V(p-p), the 3dB bandwidth of modulator 1A is changed from 110 Gbps to 137 Gbps, 1B is changed from 65 Gbps to 85 Gbps and 1C is changed from 100 Gbps to 135 Gbps. It is increased 27 (24% increment), 20 (30% increment) and 35 (35% increment) for 1A, 1B and 1C respectively as shown in Figure 4.2 (a). The simulated data for this Figure is given in Appendix C. When the 1st modulator is activated and 2nd modulator is deactivated in the cascaded modulator and the modulating signal is varied discretely from 0.4 V(p-p) to 1.6 V(p-p) the change of 3dB bandwidth is very small for the modulator 1A, 1B and 1C as shown in Figure 4.2 (b), where the 3dB bandwidth is all time stayed near about in 200 Gbps, 80 Gbps and 115 Gbps for cascaded modulator 1A, 1B and 1C respectively. Similarly, when the 2nd modulator is activated and other modulator is kept off in the cascaded modulator and the modulating signal is varied discretely from 0.4 V(p-p) to 1.6 V(p-p) the change of 3dB bandwidth is also very small for the modulator 1A, 1B and 1C as shown in Figure 4.2 (c). Where the 3dB bandwidth is all time found near about in 85 Gbps, 180 Gbps and 115 Gbps for modulator 1A, 1B and 1C respectively. We get the nonlinear relation between modulating voltage and the 3dB bandwidth of different modulator designs due to the intrinsic nonlinearity of the device performance. In cascaded modulator 1A and 1B design, one modulator active length is 3.7 times higher than the other modulator. So, smaller modulator gives near about 2.5 times higher 3dB bandwidth than the longer active length modulator as shown in Figure 4.2 (b) and (c) respectively. For cascaded modulator 1C, both modulators have same active lengths. In this design, both modulators give the same bandwidth. From above data, it is clear that the cascaded modulator 3dB bandwidth is the resultant 3dB bandwidth which is combining effect of both modulators. Figure 4.3 and 4.4 show the eye diagram and average
output power at modulating voltage 0.4 V(p-p) for all the designs of cascaded modulator. Average output optical is also decreased nonlinearly due to the nonlinearity of modulator.

Figure 4.2: Effect of modulating signal on 3dB bandwidth for (a) both modulators of cascaded modulator are activated, (b) 1st modulator of cascaded modulator is activated and (c) 2nd modulator of cascaded modulator is activated.
Figure 4.3: Eye diagram (at input modulating voltage 0.4 V(p-p)) for (a) both modulators of cascaded modulator are activated, (b) 1st modulator of cascaded modulator is activated and (c) 2nd modulator of cascaded modulator is activated.
Figure 4.4: Average output optical power at different modulating voltages of all cascaded modulators.

4.1.2 Effect of Input Signal on Extinction ratio for the device performance

Figure 4.5 shows the effect of extinction ratio by changing the modulating signal for different designs of cascaded modulator. When the modulating signal is increased linearly the extinction ratio is also increased but non-linearly. This is due to the non-linearity of the device absorption and the junction voltage. As the modulating voltage is increased, the intercept point in the eye diagram is moved downward (as shown in Figure App_B.1, App_B.2 and App_B.3 in Appendix B), which in turn decreases the $P_{off}$ level from its initial level and increases the eye opening with also increases the extinction ratio. Due to the DC coupling biasing, only one level ($P_{off}$ level) in eye diagram changes and other one is near about stay in the same level ($P_{on}$ level).
Figure 4.5: Effect of modulating signal on extinction ratio for (a) both modulators of cascaded modulator are activated, (b) 1st modulator of cascaded modulator is activated and (c) 2nd modulator of cascaded modulator is activated.

4.1.3 Effect of Input Signal on overshooting for the device performance

Figure 4.6 shows the effect of overshooting by changing the modulating signal for different designs of cascaded modulator. When the modulating signal is increased linearly the overshooting is also increased due to the nonlinearity of the device. As the modulating voltage is increased, the peak power, $P_{\text{peak}}$ level in eye diagram is also increased with $P_{\text{on}}$ power level in the
eye diagram is all time kept near about same level (as shown in Figure App_B.1, App_B.2 and App_B.3 in Appendix B), which in turn increases the overshooting also.

Figure 4.6: Effect of modulating signal on overshothing for (a) both modulators of cascaded modulator are activated, (b) 1st modulator of cascaded modulator is activated and (c) 2nd modulator of cascaded modulator is activated.
4.1.4 Effect of reflection factor at different frequency when both modulators activated

Figure 4.7 shows effect of reflection factor ($S_{11}$ parameter) at different frequencies for different designs of CTWEAM modulator. If the total effective complex impedance of the device is put in Smith chart and it is close to center of this chart then the reflection becomes minimum, otherwise it increases as the complex impedance far away from the center. In real life system, below -10 dB reflection factor is normally allowed for data transmission. The total impedance of the modulator 1A, 1B and 1C has been found from small signal analysis, which are 33 $\Omega$, 35 $\Omega$ and 40 $\Omega$ respectively and corresponding frequency versus reflection factor is shown in Figure 4.7. The load impedance of the modulator is 25 $\Omega$. From this graph, 1st modulator of CTWEAM 1A has the reflection -10 dB about 100 GHz, where other two designs suffer more return losses before 50 GHz. But the 2nd modulator of all designed CTWEAMs has below -20 dB reflection factors above 100 GHz. As the return loss in a device is increased more, the modulated signal will be attenuated more in the device before propagating in long haul transmission. From these figures, it is clear that the CTWEAM performance decreases due to one of the major issue of the 1st modulator micro wave return loss.
Chapter 4

Simulation Results and Discussion

4.2 Effect of Input Optical Power on performance of Modulator

4.2.1 Frequency response of the Modulator on different input optical power

Figure 4.8 shows frequency domain (small signal analysis) responses for all the designs of cascaded modulators at different optical powers. In this analysis, we just consider only small part of the signal and it does not contain the nonlinearity effect of the device. When the input optical power increases, the bandwidth of cascaded modulator 1A, 1B and 1C are near about 110 Gbps, 65 Gbps and 90 Gbps respectively. Since, small signal analysis results are less accurate without accounting the non-uniform microwave losses, due to this reason next section describes the large signal analysis (nonlinear model) results.
Figure 4.8: Frequency response (normalized amplitude) of different modulator (a) 1A, (b) 1B and (c) 1C at different input optical power.

4.2.2 Saturation effect of the Modulator on varying input optical power

Figure 4.9 shows the effect of input optical power for different cascaded modulators where other parameters are kept unchanged. When the input optical power changes discretely from 10 mW to 50 mW, the bandwidth of the modulator 1A and 1B increase from 110 Gbps to 130 Gbps and 65 Gbps to 75 Gbps respectively. For the cascaded modulator 1C, the bandwidth decreases from 105 Gbps to 103 Gbps. The increased bandwidth for the modulator 1A and 1B are 20 Gbps (18% increment) and 10 Gbps (15% increment) respectively. The decreased bandwidth for the 1C is 2 Gbps (2% decrement). The active segment of the modulator can be modeled as mesa resistance series connection with a junction capacitor [16]. This junction
capacitor is parallel connected with a shunt resistor which is equal to change in junction voltage divide by change in photogenerated current [16]. At low frequency, the capacitor is open circuit and the total voltage drops between these two resistors, which in turn does not decrease the RC time constant that helps to increase bandwidth. But, at high frequency the mesa resistance and the shunt resistance are parallel with the junction capacitor which helps to decrease the total RC time constant that causes to increase bandwidth. As the optical power increases below saturated optical power, the bandwidth is increased due to increase of photogenerated current which causes large voltage drop in the p-doped resistance and decreases the voltage drop across the junction capacitor. Which in turn to reduce the shunt resistance and also the RC time constant that helps to increase the bandwidth at high optical input power.

The photogenerated current nonlinearly depends on input optical power, junction voltage [19]. The increased of photo generated current due to increase of optical power which changes some of the RC property of the modulator to LC property. This results in increased of bandwidth at higher optical power [19]. The LC property of a modulator has resonance effect. At resonance, microwave signals (forward and backward) interfere constructively which causes the increased of modulating voltage magnitude. As the input optical power increases, the resonance effect moves to a new higher frequencies which increases the bandwidth from one optical power to higher optical power.

All the designed three cascaded modulators have same total active length, but they have different active segment length. 1st modulator of cascaded modulator 1A has short total active length, 210 µm where 2nd modulator has biggest total active length 780 µm. Smaller total active length of the modulator gives higher bandwidth compared to higher total active length as shown in Figure 4.2 (b) and (c) respectively [7]. For modulator 1B the relative active segment lengths are reversed compared to modulator 1A. The resultant bandwidth of a cascaded modulator is due to combine effect of two segmented TWEAMs (i.e. combine of 1st and 2nd modulator). Both modulator 1A and 1B bandwidth are increased due to above reasons. Modulator 1A has higher bandwidth among all design since it has -10 dB low return loss at about 100 GHz frequency (as shown in Figure 4.7 (a)) that supports our real life system and its 1st modulator total active length is shorter among the three designs, modulator 1B has lowest bandwidth since its 1st modulator total active length is the largest among all the three cascaded modulators and also it suffer return loss (as shown in Figure 4.7 (b)). But, the bandwidth of modulator 1C decreases
very little at high input optical power due to saturation effect of photogenerated current which is caused by screening effect [19] and also it suffers higher return loss after near about 50 GHz (as shown in Figure 4.7 (c)), among all the three designed cascaded modulators, where both (1st and 2nd) modulators of cascaded modulator 1C have equal total active length, 445 µm.

As the input optical power increase from 10 mW to 50 mW, the extinction ratio of modulator 1A, 1B and 1C are increased very small from 3.9 dB to 4.3 dB (increment of 0.4 dB), 4.1 dB to 5.2 dB (increment of 1.1 dB) and 4.0 dB to 5.0 dB (increment of 1 dB) respectively. This is due to all the cascaded modulators have same total active length and as input optical power is increased the photogenerated current increases nonlinearly which increases the extinction ratio as shown in Figure 4.9 (b).

Similarly, as the input optical power increased from 10 mW to 50 mW then the overshooting of the three modulators 1A, 1B and 1C increased from 0.2 dB to 0.7 dB (increment of 0.5 dB which is less than 1dB that is acceptable for real life application), 0.0 dB to 0.2 dB (increment of 0.2 dB) and 0.6 dB to 1.2 dB (increment of 0.6 dB) respectively as shown in Figure 4.9 (c). This is because of nonlinearly photogenerated current and also nonlinear behavior of device performance which turns to increase the overshooting.

At low optical power the average output optical power of all the three designed cascaded modulators are near about -1dBm as shown in Figure 2.9 (d). This is because of low photogenerated current which has small significant effects on the nonlinear device performance for its average output optical power. As the input optical power increased to 50 mW then the modulator 1A and 1C have an average output optical power 1.80 dBm and 1.60 dBm respectively. But, the modulator 1B has an average output power -1.20 dBm. At 100 GHz, the reflection factor of modulator 1A, 1B and 1C are -10 dB, -6 dB and -3 dB as shown in Figure 4.7. The average output power of modulator 1B decreased more compared to other because of microwave signal return loss and also its 1st modulator total active length. The total active segment length of 1st modulator in cascaded modulator 1B has highest length among all the designed, as the total active length is increased more which in turn absorbs more photogenerated current and reduces the average output optical power (as shown in Figure App_B.6). The effect of the input optical power on the eye diagrams are shown in Figure App_B.4 and App_B.5 for the input optical power 14 mW and 40 mW respectively.
Chapter 4  

Simulation Results and Discussion

(a) 3dB bandwidth response of different designs at different input optical powers

(b) Extinction ratio of different designs at different input optical powers

(c) Overshooting of different designs at different input optical powers
Chapter 4  Simulation Results and Discussion

4.3 Effect of biasing voltage on the performance of modulator

4.3.1 Effect of biasing voltage on Bandwidth of modulator

Figure 4.10 shows the effect of biasing voltage on bandwidth of different cascaded modulators at constant modulating voltage 0.4 V (p-p). As the biasing voltage increases, the bandwidth of all cascaded modulators increases as shown in Table 4.1. When the biasing voltage increases from 0.5 V to 2.5 V, the bandwidth of cascaded modulator 1A, 1B and 1C increase for input optical power 10 mW and 30 mW are 15 GHz (15% increment) and 25 GHz (26% increment), 15 GHz (25% increment) and 20 GHz (33% increment) and 5 GHz (5% increment) and 20 GHz (22% increment) respectively. If the biasing voltage is increasing then electron and hole wave functions are moving in opposite direction which causes to increase the absorption and also the absorption spectrum. As the biasing voltage is increased, the voltage drop across mesa p-doped resistor is also increased by the photogenerated current acts as a reduced value of the shunt resistor that is parallel with the junction capacitor [16]. This turns to reduce the RC time constant to increase the bandwidth. It is seen in Table 4.1, at high power (30 mW compared to 10 mW) the bandwidth of cascaded modulator 1A and 1C are increased due to increase of photogenerated current as described previous section. Similarly, the bandwidth of cascaded modulator 1B decreases with increasing power is also described.
Table 4.1: Effect of biasing voltage on bandwidth of different modulators.

<table>
<thead>
<tr>
<th>Biasing voltage (V)</th>
<th><strong>Modulator 1A</strong></th>
<th><strong>Modulator 1B</strong></th>
<th><strong>Modulator 1C</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3dB Bandwidth (GHz)</td>
<td>3dB Bandwidth (GHz)</td>
<td>3dB Bandwidth (GHz)</td>
</tr>
<tr>
<td>At optical power 10 mW</td>
<td>100</td>
<td>60</td>
<td>100</td>
</tr>
<tr>
<td>At optical power 30 mW</td>
<td>95</td>
<td>50</td>
<td>90</td>
</tr>
<tr>
<td>At optical power 10 mW</td>
<td>115</td>
<td>75</td>
<td>120</td>
</tr>
<tr>
<td>At optical power 30 mW</td>
<td>120</td>
<td>70</td>
<td>110</td>
</tr>
</tbody>
</table>

(a) Frequency response of device 1A for different optical input power

(b) Frequency response of device 1B for different optical input power
Figure 4.10: Frequency response of different modulators (a) 1A, (b) 1B and (c) 1C at different input optical power.

### 4.3.2 Effect of biasing voltage on Extinction Ratio of modulator

Figure 4.11 shows the effect of biasing voltage on extinction ratio of different cascaded modulators at constant modulating voltage 0.4 V (p-p) and input optical power 14 mW. As the biasing voltage increases, the extinction ratio of all cascaded modulators increases as shown in Table 4.2. It is seen from the Table 4.2, when the biasing voltage increases from 0.5 V to 2.5 V, the extinction ratio of cascaded modulator 1A, 1B and 1C increase for input optical power 10 mW and 30 mW are 2.4 dB (80% increment) and 1.5 dB (38% increment), 2.1 dB (65% increment) and 1.8 dB (40% increment) and 2.4 dB (80% increment) and 1.9 dB (50% increment) respectively. The nonlinear relationship between junction voltage and the optical power helps to more absorption. Which in turns, at same modulating voltage there is high voltage across junction that causes the absorption during ‘On’ time of the modulating signal is very high compared to absorption during ‘Off’ time of the modulating signal. So, the ratio of ‘On’ and ‘Off’ time becomes high which causes the increment of the extinction ratio for increasing biasing voltage. The extinction ratio of a modulator depends on biasing point, driving voltage, junction voltage and also optical power as shown in Figure 4.11. Due to nonlinear relationship of optical power and junction voltage, we all time fix the biasing voltage and optical power to operate the modulator at a particular extinction ration. The extinction ratio of all the
three cascaded modulator is higher at high optical power than that of low optical power due to increase of photogenerated current.

Table 4.2: Effect of biasing voltage on extinction ratio of different modulators.

<table>
<thead>
<tr>
<th>Biasing voltage (V)</th>
<th>Modulator 1A</th>
<th>Modulator 1B</th>
<th>Modulator 1C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Extinction ratio (dB)</td>
<td>Extinction ratio (dB)</td>
<td>Extinction ratio (dB)</td>
</tr>
<tr>
<td>At optical power 10 mW</td>
<td>3.0</td>
<td>3.2</td>
<td>3.0</td>
</tr>
<tr>
<td>At optical power 30 mW</td>
<td>3.9</td>
<td>4.4</td>
<td>3.8</td>
</tr>
<tr>
<td>0.5</td>
<td>5.4</td>
<td>5.3</td>
<td>5.4</td>
</tr>
<tr>
<td>2.5</td>
<td>5.4</td>
<td>6.2</td>
<td>5.7</td>
</tr>
</tbody>
</table>

(a) Extinction ratio of device 1A for different input optical power

(b) Extinction ratio of device 1B for different input optical power
4.3.3 Effect of biasing voltage on Overshooting of modulator

Figure 4.12 shows the effect of biasing voltage on overshooting of different cascaded modulators at constant modulating voltage 0.4 V (p-p). As the biasing voltage increases, the overshooting of cascaded modulator 1A and 1C increases as shown in Table 4.3. When the biasing voltage increases from 0.5 V to 2.5 V, the overshooting of the cascaded modulator 1A and 1C increases for input optical power 10 mW and 30 mW are 0.2 dB and 0.4 dB and 0.4 dB and 0.5 dB respectively. The increment of overshooting of modulator 1A and 1C is similar reason as the extinction ratio increment which is described previous section. But, there is no overshooting at variation of biasing voltage for the cascaded modulator 1B. This is due to the total active length of 1st modulator of cascaded modulator 1B which has largest total active segment length among all the 1st modulator of all cascaded modulators. This large active length causes the high optical loss.

After examination effect of biasing voltages, we can say that it is tradeoffs between bandwidth, extinction ratio and overshooting. From above results, biasing voltage between 1.0 V and 1.5 V are suitable for selecting optimum value of bandwidth, extinction ratio and overshooting to operate the cascaded modulator.
Table 4.3: Effect of biasing voltage on overshooting of different modulators.

<table>
<thead>
<tr>
<th>Biasing Voltage (V)</th>
<th>Modulator 1A</th>
<th>Modulator 1B</th>
<th>Modulator 1C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Overshooting (dB)</td>
<td>Overshooting (dB)</td>
<td>Overshooting (dB)</td>
</tr>
<tr>
<td>At optical power 10 mW</td>
<td>0.1</td>
<td>0.0</td>
<td>0.4</td>
</tr>
<tr>
<td>At optical power 30 mW</td>
<td>0.0</td>
<td>0.0</td>
<td>0.8</td>
</tr>
<tr>
<td>0.5</td>
<td>0.0</td>
<td>0.0</td>
<td>1.0</td>
</tr>
<tr>
<td>2.5</td>
<td>0.3</td>
<td>0.4</td>
<td>1.0</td>
</tr>
</tbody>
</table>

(a) Overshooting of device 1A for different input optical power

(b) Overshooting of device 1B for different input optical power
4.4 Effect of circuit parameters on the performance of modulator

4.4.1 Effect of per unit length internal capacitance ($C_{\text{int}}$)

Figure 4.13 shows the effect of per unit length of internal capacitance on device performances of all the cascaded modulators at constant modulating voltage, 0.4 V(p-p) and input optical power, 14 mW. As the internal capacitance decreases, the bandwidth and overshooting of the cascaded modulators 1A, 1B and 1C increase as shown in Table 4.4, where the internal capacitance, $C_{\text{int}}$ decreases from 550 fF/mm to 250 fF/mm of cascaded modulator 1A, 1B and 1C, the bandwidth increases 75 GHz (71% increment), 50 GHz (83% increment) and 55 GHz (55% increment) respectively with decrement of 55% internal capacitance. As the capacitance decreases which in turn also decreases the RC time constant that helps to increase the bandwidth. The increment of bandwidth has a disadvantage which increases the overshooting to distort the signal as shown in Figure 4.13 (c). The overshooting of modulator 1A, 1B and 1C increases 0.7 dB, 0.7 dB and 0.5 dB respectively with decreases of capacitance from 550 fF/mm to 250 fF/mm. The extinction ratio of all the cascaded modulators has remain in the same level as the internal capacitance changes, which depends on modulating voltage, biasing voltage and input optical power that are described in previous sections. The internal capacitance from 400 fF/mm to 550 fF/mm has a good bandwidth and also acceptable overshooting which is less than 1dB for the device performance in real life application.
Table 4.4: Effect of internal capacitance on bandwidth and overshooting of different modulators.

<table>
<thead>
<tr>
<th>Capacitance (fF/mm)</th>
<th>Modulator 1A</th>
<th>Modulator 1B</th>
<th>Modulator 1C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bandwidth (GHz)</td>
<td>Overshooting (dB)</td>
<td>Bandwidth (GHz)</td>
<td>Overshooting (dB)</td>
</tr>
<tr>
<td>550</td>
<td>105</td>
<td>0.1</td>
<td>60</td>
</tr>
<tr>
<td>250</td>
<td>180</td>
<td>0.8</td>
<td>110</td>
</tr>
</tbody>
</table>

(a) 3dB bandwidth response for different designs

(b) Response of extinction ratio for different designs
Figure 4.13: Effect of per unit internal capacitance on (a) Bandwidth, (b) Extinction Ration and (c) Overshooting.

4.4.2 Effect of per unit length p-doped region resistance ($R_p$)

Figure 4.14 shows the effect of per unit length resistance of p-doped region (mesa) on device performances of all the cascaded modulators at constant modulating voltage, 0.4 V(p-p) and input optical power, 14 mW. It is seen from Table 4.5, the bandwidth of cascaded modulator 1A, 1B and 1C increases 20 GHz (21% increment), 5 GHz (8% increment) and 15 GHz (16% increment) respectively when mesa resistance decreases from 1.4 $\Omega$-mm to 0.6 $\Omega$-mm. The bandwidth is increased with decreasing of mesa resistance which is also the similar reason of decreasing internal capacitance i.e. the decreased of RC time constant. This also suffers the increment of overshooting to distort the signal as like as increment of internal capacitance which is shown in Figure 4.14 (c). The overshooting of modulator 1A and 1C increases 0.1 dB and 0.2 dB respectively with decreasing of mesa resistance from 1.4 $\Omega$-mm to 0.6 $\Omega$-mm. The overshooting of cascaded modulator 1B is 0.00 dB due to optical loss. There is no changed in effect on extinction ratio if the mesa resistance changes as shown in Figure 4.14 (b). The changed of internal capacitance has big effect of changing bandwidth and overshooting compared to changed of mesa resistance. But, it is easier to change the mesa resistance than of internal capacitance. The mesa resistance from 0.6 $\Omega$-mm to 0.8 $\Omega$-mm is suitable to operate the cascaded modulator at 110 GHz 3dB.
Table 4.5: Effect of mesa resistance on bandwidth and overshooting of different modulators.

<table>
<thead>
<tr>
<th>Resistance (Ω-mm)</th>
<th>Modulator 1A</th>
<th>Modulator 1B</th>
<th>Modulator 1C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Bandwidth (GHz)</td>
<td>Overshooting (dB)</td>
<td>Bandwidth (GHz)</td>
</tr>
<tr>
<td>1.4</td>
<td>95</td>
<td>0.1</td>
<td>60</td>
</tr>
<tr>
<td>0.6</td>
<td>115</td>
<td>0.2</td>
<td>65</td>
</tr>
</tbody>
</table>

(a) Response of 3dB bandwidth for different designs

(b) Response of extinction ratio for different designs
4.4.3 Effect of per unit length inductance of passive transmission line ($L_p$)

Figure 4.15 shows the effect of per unit length inductance of passive transmission line (microstrip) on device performances of all the cascaded modulators at constant modulating voltage, 0.4 V(p-p) and input optical power, 14 mW. As the per unit length inductance of microstrip increases, the bandwidth and overshooting of all the cascaded modulators increase as shown in Table 4.6. The bandwidth of cascaded modulator 1A, 1B and 1C increases 5 GHz (5% increment), 6 GHz (10% increment) and 10 GHz (10% increment) respectively with increasing microstrip inductance from 250 pH/mm to 450 pH/mm. As the microstrip inductance increases, which causes more voltage drops of modulating signal across it and reduces the total voltage drop across junction capacitor. This reduces the shunt resistance across the junction capacitor to decrease the RC time constant. This is why the bandwidth increases with increasing of microstrip inductance. As the inductance of microstrip increases from 250 pH/mm to 450 pH/mm then the overshooting of cascaded modulator 1A, 1B and 1C increases 0.2 dB, 0.3 dB and 0.2 dB respectively as shown in Figure 4.15 (c). This is tradeoff between bandwidth and overshooting for nonlinear device operation. The microstrip inductance from 300 pH/mm to 400 pH/mm has good bandwidth and also acceptable overshooting which is below 1 dB. The extinction ratio does not change too much with varying microstrip inductance which is also described in previous section.
Table 4.6: Effect of per unit length inductance of passive transmission line (microstrip) on bandwidth and overshooting of different modulators.

<table>
<thead>
<tr>
<th>Inductance (pH/mm)</th>
<th>Modulator 1A</th>
<th>Modulator 1B</th>
<th>Modulator 1C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Bandwidth (GHz)</td>
<td>Overshooting (dB)</td>
<td>Bandwidth (GHz)</td>
</tr>
<tr>
<td>250</td>
<td>105</td>
<td>0.2</td>
<td>64</td>
</tr>
<tr>
<td>450</td>
<td>110</td>
<td>0.4</td>
<td>70</td>
</tr>
</tbody>
</table>

(a) Response of 3dB bandwidth for different designs

(b) Response of extinction ratio for different designs
4.4.4 Effect of other equivalent circuit parameters ($C_{\text{ext}}$, $R_c$, $R_{\text{ot}}$ and $R_{\text{ft}}$)

The other equivalent circuit parameters like, per unit length external capacitance ($C_{\text{ext}}$) of passive transmission line, skin effect resistor $R_c$ of electrode and the microstrip resistor $R_{cp}$ is the combine resistance includes both the resistance due to the resistivity of the microstrip line $R_{\text{ot}}$ and the skin effect resistance $R_{ft}$ are varied to observe their effect on bandwidth as shown in appendix B (Figure App_B.7, Figure App_B.8, Figure App_B.9 and Figure App_B.10 respectively). The variation of these external parameters has no significant effect on device performance. Therefore, these parameters are less attractive to consider them for device performance and optimization.

4.5 Effect of changing active segment length ratio on the performance of cascaded modulator

Cascaded modulator consists of two segmented TWEAMs. A segmented TWEAM consists of two active (first (1a) and second (2a)) segments and three passive (first (0t), second (1t) and third (2t) microstrip or) passive transmission lines as shown in Figure 4.16. The length of first active (1a) segment of 1st modulator of a cascaded modulator varies where total length of active (sum of first and second) segment of 1st modulator and also the total active length of 2nd modulator of that cascaded modulator are all time keeping unchanged as shown in Table 4.7. In this case of investigation, we all time keeps (equal or at least 50 $\mu$m) the length of second (1t) passive (or microstrip) transmission line of 2nd modulator greater than the length of second
active segment (2a) of 1st modulator. If this microstrip length is less than the second active segment length of 1st modulator then the cascaded modulator design will be violated.

\[
Ratio \ R_1 \ (\%) = \frac{\text{length of first active segment of 1st modulator}}{\text{total active segment length of 1st modulator}} \times 100 \%
\]

Table 4.7: Calculation of active segment length ratio for first active segment length of 1st modulator of cascaded modulator 1B.

<table>
<thead>
<tr>
<th>Ratio (%)</th>
<th>Total active length of 2nd modulator (µm)</th>
<th>Total active length of 1st modulator (µm)</th>
<th>Active length of first (1a) segment of 1st modulator (µm)</th>
<th>Active length of second (2a) segment of 1st modulator (µm)</th>
<th>Length of second segment (1t) microstrip line of 2nd modulator (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>210</td>
<td>780</td>
<td>080</td>
<td>700</td>
<td>750</td>
</tr>
<tr>
<td>23</td>
<td>210</td>
<td>780</td>
<td>180</td>
<td>600</td>
<td>650</td>
</tr>
<tr>
<td>38</td>
<td>210</td>
<td>780</td>
<td>300</td>
<td>480</td>
<td>530</td>
</tr>
<tr>
<td>53</td>
<td>210</td>
<td>780</td>
<td>420</td>
<td>360</td>
<td>410</td>
</tr>
<tr>
<td>69</td>
<td>210</td>
<td>780</td>
<td>540</td>
<td>240</td>
<td>290</td>
</tr>
<tr>
<td>87</td>
<td>210</td>
<td>780</td>
<td>680</td>
<td>100</td>
<td>150</td>
</tr>
</tbody>
</table>

Similarly, the length of second active (2a) segment of 2nd modulator of a cascaded modulator varies where total length of active (sum of first and second) segment of 2nd modulator and also the total active segment length of 1st modulator of that cascaded modulator are all time keeping same as shown in Table 4.8. In this case of investigation, we all time keeps (equal or at least 50 µm) the length of second microstrip (1t) transmission line of 1st modulator greater than the length of first active (1a) segment of the 2nd modulator otherwise the cascaded designed will be violated.

\[
Ratio \ R_2 \ (\%) = \frac{\text{length of second active segment of 2nd modulator}}{\text{total active segment of 2nd modulator}} \times 100 \%
\]
Figure 4.16: Cascaded modulator 1B.

Table 4.8: Calculation of active segment length ratio for second active segment length of 2nd modulator of cascaded modulator 1B.

<table>
<thead>
<tr>
<th>Ratio (%)</th>
<th>Total active length of 1st modulator (µm)</th>
<th>Total active length of 2nd modulator (µm)</th>
<th>Active length of 2nd segment (2a) of 2nd modulator (µm)</th>
<th>Active length of 1st segment (1a) of 2nd modulator (µm)</th>
<th>Length of 2nd segment (1t) microstrip line of 1st modulator (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>14</td>
<td>780</td>
<td>210</td>
<td>030</td>
<td>180</td>
<td>230</td>
</tr>
<tr>
<td>28</td>
<td>780</td>
<td>210</td>
<td>060</td>
<td>150</td>
<td>200</td>
</tr>
<tr>
<td>42</td>
<td>780</td>
<td>210</td>
<td>090</td>
<td>120</td>
<td>170</td>
</tr>
<tr>
<td>57</td>
<td>780</td>
<td>210</td>
<td>120</td>
<td>090</td>
<td>140</td>
</tr>
<tr>
<td>71</td>
<td>780</td>
<td>210</td>
<td>150</td>
<td>060</td>
<td>110</td>
</tr>
<tr>
<td>85</td>
<td>780</td>
<td>210</td>
<td>180</td>
<td>030</td>
<td>080</td>
</tr>
</tbody>
</table>

4.5.1 Effect of changing the length ratio of first active (1a) segment of 1st modulator

Figure 4.17 shows the effect of length ratio, R1 of first active segment of 1st modulator on device performances of all the cascaded modulators. Table 4.9 shows the effect of this length ratio for all cascaded modulators. When the length ratio, R1 of cascaded modulator 1A varies from 10% to 50% then the bandwidth increases 15 GHz (15% increment). But, the bandwidth is decreased 5 GHz (4% decrement) as the length ratio increases up to 90% from 50%. The length ratio, R1 of cascaded modulator 1C increases from 10% to 32% then the bandwidth increases 10 GHz (10% increment) and it decreases 15 GHz (14% decrement) as the length ratio increases.
from 32% to 80%. This is due to improve the total effective impedance of the active segment section that reduces the microwave reflection loss to increase the bandwidth [17]. The bandwidth decreases as length ratio increment because of the total effective impedance of that active segment section which causes more microwave return loss. Similarly, why the bandwidth of cascaded modulator 1B increases upto length ratio 23% and beyond this length ratio the bandwidth is decreased. Cascaded modulator 1B has the smallest bandwidth among all the cascaded modulators because of its longest 1st modulator active segment length which causes the significant effect of velocity mismatch between optical signal and microwave signal.

Table 4.9: Effect of first active length ratio of 1st modulator on device performance for different designs.

<table>
<thead>
<tr>
<th>Ratio R1 (%)</th>
<th>Modulator 1A</th>
<th>Modulator 1B</th>
<th>Modulator 1C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>BW (GHz)</td>
<td>ER (dB)</td>
<td>Over Shoot (dB)</td>
</tr>
<tr>
<td>10</td>
<td>95</td>
<td>4.1</td>
<td>0.1</td>
</tr>
<tr>
<td>30</td>
<td>105</td>
<td>4.1</td>
<td>0.1</td>
</tr>
<tr>
<td>50</td>
<td>110</td>
<td>4.0</td>
<td>0.2</td>
</tr>
<tr>
<td>70</td>
<td>110</td>
<td>4.0</td>
<td>0.2</td>
</tr>
<tr>
<td>90</td>
<td>105</td>
<td>4.0</td>
<td>0.3</td>
</tr>
<tr>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

The extinction ration of cascaded modulator 1B and 1C are increased as the length ratio increases, this is due to absorb more optical power in this active segment before the modulating voltage starts attenuation in the direction of propagation [7]. But the extinction ratio of cascaded modulator 1A decreases little bit due to absorb less optical power as this length ratio increases.

The overshooting of all the cascaded modulator 1A, 1B and 1C increases as the active length ratio increases beyond 50%, 23% and 50% respectively, because of its total effective complex impedance. This causes more return loss which turn to increase overshooting to distort the signal. The ratio, R1 values between 25% and 40% gives the optimum values of bandwidth, extinction ratio and also overshooting for the operation of cascaded modulator. So, it is tradeoff of between these parameters to optimal perform of the device.
Figure 4.17: Variation of (a) Bandwidth, (b) Extinction Ratio and (c) Overshooting by changing in percentage (%) of first active segment of 1st modulator for different designs.
4.5.2 Effect of changing the length ratio of second active segment of 2nd modulator

Figure 4.18 shows the effect of length ratio, R2 of second active (2a) segment of 2nd modulator on device performances of all the cascaded modulators. Table 4.10 shows the effect of this length ratio for all cascaded modulators. When the length ratio, R2 of cascaded modulator 1A varies from 10% to 70% then the bandwidth remains at about same value. But, the bandwidth is decreased 15 GHz (14% decrement) as the length ratio increases up to 90% from 70%. The length ratio, R2 of cascaded modulator 1C increases from 10% to 40% then the bandwidth increases 5 GHz (5% increment) and it decreases 10 GHz (9% decrement) as the length ratio increases from 40% to 80%. This is due to improve the total effective complex impedance which is described in the previous section. The bandwidth decreases as length ratio increment which is also described in the previous section. When the one active segment length ratio increases then the other active segment length becomes small since we all time keep the same total active length for a segmented modulator. This is why until a particular length ratio the bandwidth increases because of its effective impedance which reduces the microwave return loss, beyond this length ratio the return loss increases and decreases the bandwidth. The bandwidth of cascaded modulator 1B decreases upto length ratio 85% because of its effective impedance which is described.

Table 4.10: Effect of second active length ratio of 2nd modulator on device performance for different designs.

<table>
<thead>
<tr>
<th></th>
<th>Modulator 1A</th>
<th></th>
<th>Modulator 1B</th>
<th></th>
<th>Modulator 1C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ratio</td>
<td>BW (GHz)</td>
<td>ER (dB)</td>
<td>Over Shoot</td>
<td>Ratio</td>
<td>BW (GHz)</td>
</tr>
<tr>
<td>R2 (%)</td>
<td></td>
<td></td>
<td>(dB)</td>
<td>R2 (%)</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>110</td>
<td>4.1</td>
<td>0.4</td>
<td>14</td>
<td>75</td>
</tr>
<tr>
<td>32</td>
<td>110</td>
<td>4.1</td>
<td>0.4</td>
<td>28</td>
<td>70</td>
</tr>
<tr>
<td>48</td>
<td>110</td>
<td>4.1</td>
<td>0.4</td>
<td>42</td>
<td>65</td>
</tr>
<tr>
<td>70</td>
<td>110</td>
<td>4.0</td>
<td>0.2</td>
<td>57</td>
<td>65</td>
</tr>
<tr>
<td>90</td>
<td>95</td>
<td>4.0</td>
<td>0.0</td>
<td>71</td>
<td>65</td>
</tr>
<tr>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>85</td>
<td>60</td>
</tr>
</tbody>
</table>

The extinction ratio and overshooting of cascaded modulator 1A, 1B and 1C are decreased as the active segment length ratio increases, this is due to low absorption of optical power in this active segment and also microwave return loss.
Figure 4.18: Variation of (a) Bandwidth, (b) Extinction Ratio and (c) Overshooting by changing in percentage (%) of 2nd active segment of 2nd modulator for different designs.
4.6 Effect of changing length ratio of First, Second, Third and Fourth of active segment length as of total active segment length for all cascaded modulators

Here, we have all time kept the total active length of all the cascaded modulators equal (990 µm) and changed only one active segment length while other three active segment lengths are remaining equal as shown in Figure 4.19 and the ratios are shown in Table 4.11. So, we change one of four active segment lengths and others are remaining equal length due to get maximum bandwidth at each design [7]. The ratio, \( R_i \) (\( i=1, 2, 3, 4 \)) in percentage, is the ith active segment length over the total active segment length. In this case of investigation, we all time keep (equal or at least 50 µm) the length of second microstrip (1t) line of 1st modulator greater than the length of first active segment (1a) of 2nd modulator and similarly, the length (equal or at least 50 µm) of second microstrip (1t) line of 2nd modulator greater than the length of second active (2a) segment of the 1st modulator otherwise the cascaded designed will be violated. All these variables have been varied independently and their effects on the bandwidth, extinction ratio and overshooting of the cascaded modulators are investigated.

The difference between this and previous section active segment length ratio is that, here the total active segment length of 1st and 2nd modulator of a cascaded modulator are not kept equal length (compared with the original design of all cascaded modulators as shown in Table 3.2), but in previous section we change the active segment length ratio (only first active segment length of 1st modulator or second active segment length of 2nd modulator) but we all time keep the total length of 1st and 2nd modulator of all the cascaded modulators equal as shown in Table 4.7 and 4.8 (only for cascaded modulator 1B).

\[
R_1 (%) = \frac{\text{length of first active segment of 1st modulator}}{\text{total active segment length}} \times 100%
\]
\[
R_2 (%) = \frac{\text{length of second active segment of 1st modulator}}{\text{total active segment length}} \times 100%
\]
\[
R_3 (%) = \frac{\text{length of first active segment of 2nd modulator}}{\text{total active segment length}} \times 100%
\]
\[
R_4 (%) = \frac{\text{length of second active segment of 2nd modulator}}{\text{total active segment length}} \times 100%
\]
Table 4.11: Calculation of active segment length ratio for all the cascaded modulators (length in µm).

<table>
<thead>
<tr>
<th>Ratio (%)</th>
<th>(L_{a,tot})</th>
<th>Micro strips length of 1st Modulator</th>
<th>Active segment length of 1st modulator</th>
<th>Micro strips length of 2nd Modulator</th>
<th>Active length of 2nd modulator</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>(L_{0t})</td>
<td>(L_{1t})</td>
<td>(L_{2t})</td>
<td>(L_{1a})</td>
</tr>
<tr>
<td>06</td>
<td>990</td>
<td>200</td>
<td>350</td>
<td>100</td>
<td>60</td>
</tr>
<tr>
<td>10</td>
<td>990</td>
<td>200</td>
<td>350</td>
<td>100</td>
<td>99</td>
</tr>
<tr>
<td>20</td>
<td>990</td>
<td>200</td>
<td>350</td>
<td>100</td>
<td>198</td>
</tr>
<tr>
<td>30</td>
<td>990</td>
<td>200</td>
<td>350</td>
<td>100</td>
<td>297</td>
</tr>
<tr>
<td>40</td>
<td>990</td>
<td>200</td>
<td>350</td>
<td>100</td>
<td>396</td>
</tr>
<tr>
<td>50</td>
<td>990</td>
<td>200</td>
<td>350</td>
<td>100</td>
<td>495</td>
</tr>
<tr>
<td>70</td>
<td>990</td>
<td>350</td>
<td>350</td>
<td>100</td>
<td>693</td>
</tr>
<tr>
<td>80</td>
<td>990</td>
<td>350</td>
<td>350</td>
<td>100</td>
<td>792</td>
</tr>
</tbody>
</table>

Figure 4.19: Cascaded modulator 1B for active segment length ratio.

4.6.1 Effect of changing length ratio of first active segment of cascaded modulator

Figure 4.20 shows the effect of active segment length ratio, \(R_1\) on device performances of all the cascaded modulators. Table 4.12 shows the effect of this length ratio for all cascaded modulators. It is seen from the Table 4.12, when the length ratio, \(R_1\) of cascaded modulator 1A varies from 6% to 10% then the bandwidth and overshooting are increased to 110 GHz and 0.6
dB respectively. If the ratio R1 increases until 40% from 10% then bandwidth decreases 35 GHz (31% decrement) and overshooting increases 0.7 dB. Similarly, when the ratio R1 of cascaded modulator 1B increases from 06% to 20% then bandwidth and overshooting are increased to 15 GHz (15% increment) and 0.2 dB (40% increment), as the ratio R1 becomes 70% the bandwidth and overshooting decrease to 45 GHz (40% decrement) and 0.7 dB respectively, for cascaded modulator 1C the bandwidth and overshooting increase 10 GHz (10% increment) and 0.1 dB (25% increment) as the ratio R1 increases from 06% to 10% and the bandwidth and overshooting decrease 51.58 GHz (47.17% decrement) and 0.52 dB. The extinction ratio increases not too much of all cascaded modulators as the ratio R1 increases as shown in Figure 4.20 and also in Table 4.12. Why the bandwidth, overshooting and extinction ratio of all cascaded modulator increase with increasing R1 ratio until certain ratio after that bandwidth and overshooting decrease are also described in the previous section.

Table 4.12: Effect of first active length ratio, R1 of all cascaded modulators.

<table>
<thead>
<tr>
<th>Ratio R1 (%)</th>
<th>Modulator 1A</th>
<th>Modulator 1B</th>
<th>Modulator 1C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ratio R1 (%)</td>
<td>BW (GHz)</td>
<td>ER (dB)</td>
</tr>
<tr>
<td>06</td>
<td>06</td>
<td>105</td>
<td>4.1</td>
</tr>
<tr>
<td>10</td>
<td>10</td>
<td>110</td>
<td>4.1</td>
</tr>
<tr>
<td>20</td>
<td>20</td>
<td>100</td>
<td>4.1</td>
</tr>
<tr>
<td>30</td>
<td>30</td>
<td>90</td>
<td>4.11</td>
</tr>
<tr>
<td>40</td>
<td>40</td>
<td>75</td>
<td>4.2</td>
</tr>
<tr>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

![Graph showing the effect of 3dB bandwidth of different designs at different first active length ratio](a)
Figure 4.20: Variation of (a) Bandwidth, (b) Extinction Ratio and (c) Overshooting by changing in percentage (%) of first active segment of different designs.

4.6.2 Effect of changing length ratio of second active segment of cascaded modulator

Figure 4.21 shows the effect of active segment length ratio, R2 on device performances of all the cascaded modulators. Table 4.13 shows the effect of this length ratio for all cascaded modulators. It is seen from the Table 4.13, when the length ratio, R2 of cascaded modulator 1A, 1B and 1C varies from 6% to 20%, the bandwidth increases 5 GHz (5% increment), 5 GHz (5% increment) and 5 GHz (5% increment) respectively, the bandwidth decreases 5 GHz (5% decrement), 10 GHz (9% decrement) and 5 GHz (5% decrement) respectively as the ratio R2 increases up to 30% from 20%. There is no effect on extinction ratio as the increment of ratio R2 and it stays all time in a constant level. But, the overshooting of all the cascaded modulators 1A,
1B and 1C decreases 0.1 dB, 0.1 dB and 0.2 dB respectively as the increment of 24% second segment active length ratio, R2.

Table 4.13: Effect of second active length ratio, R2 of all cascaded modulators.

<table>
<thead>
<tr>
<th>Ratio R2 (%)</th>
<th>Modulator 1A</th>
<th></th>
<th>Modulator 1B</th>
<th></th>
<th>Modulator 1C</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>BW (GHz)</td>
<td>ER (dB)</td>
<td>Over Shoot (dB)</td>
<td></td>
<td>BW (GHz)</td>
<td>ER (dB)</td>
</tr>
<tr>
<td>06</td>
<td>90</td>
<td>4.1</td>
<td>0.8</td>
<td></td>
<td>06</td>
<td>105</td>
</tr>
<tr>
<td>10</td>
<td>95</td>
<td>4.1</td>
<td>0.8</td>
<td></td>
<td>10</td>
<td>105</td>
</tr>
<tr>
<td>20</td>
<td>95</td>
<td>4.1</td>
<td>0.7</td>
<td></td>
<td>20</td>
<td>110</td>
</tr>
<tr>
<td>30</td>
<td>90</td>
<td>4.1</td>
<td>0.7</td>
<td></td>
<td>30</td>
<td>100</td>
</tr>
</tbody>
</table>
Figure 4.21: Variation of (a) Bandwidth, (b) Extinction Ratio and (c) Overshooting by changing in percentage (%) of second Active segment of the device for different designs.

4.6.3 Effect of changing length ratio of third active segment of cascaded modulator

Figure 4.22 and Table 4.14 show the effect of active segment length ratio, R3 on device performances of all the cascaded modulators. It is seen form the Table 4.14, when the length ratio, R3 of cascaded modulator 1A, 1B and 1C varies from 6% to 30%, the bandwidth increases 35 GHz (53% increment), 35 GHz (43% increment) and 30 GHz (42% increment) respectively. There is no effect on extinction ratio as the increment of ratio R3 and it stays all time same level. But, the overshooting of all the cascaded modulators 1A, 1B and 1C increases 0.4 dB, 0.5 dB and 0.4 dB respectively as the increment of 24% third segment active length ratio, R3.

Table 4.14: Effect of third active length ratio, R3 of all cascaded modulators.

<table>
<thead>
<tr>
<th>Ratio R3 (%)</th>
<th>BW (GHz)</th>
<th>ER (dB)</th>
<th>Overshoot (dB)</th>
<th>Ratio R3 (%)</th>
<th>BW (GHz)</th>
<th>ER (dB)</th>
<th>Overshoot (dB)</th>
<th>Ratio R3 (%)</th>
<th>BW (GHz)</th>
<th>ER (dB)</th>
<th>Overshoot (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>06</td>
<td>65</td>
<td>4.1</td>
<td>0.4</td>
<td>06</td>
<td>80</td>
<td>4.1</td>
<td>0.3</td>
<td>06</td>
<td>70</td>
<td>4.1</td>
<td>0.3</td>
</tr>
<tr>
<td>10</td>
<td>70</td>
<td>4.1</td>
<td>0.4</td>
<td>10</td>
<td>95</td>
<td>4.1</td>
<td>0.4</td>
<td>10</td>
<td>80</td>
<td>4.1</td>
<td>0.4</td>
</tr>
<tr>
<td>20</td>
<td>90</td>
<td>4.1</td>
<td>0.6</td>
<td>20</td>
<td>110</td>
<td>4.1</td>
<td>0.6</td>
<td>20</td>
<td>100</td>
<td>4.1</td>
<td>0.6</td>
</tr>
<tr>
<td>30</td>
<td>100</td>
<td>4.1</td>
<td>0.8</td>
<td>30</td>
<td>115</td>
<td>4.1</td>
<td>0.8</td>
<td>30</td>
<td>110</td>
<td>4.1</td>
<td>0.7</td>
</tr>
</tbody>
</table>
Figure 4.22: Variation of (a) Bandwidth, (b) Extinction Ratio and (c) Overshooting by changing in percentage (%) of third active segment of the device for different designs.
4.6.4 Effect of changing length ratio of fourth active segment of cascaded modulator

Figure 4.23 and Table 4.15 show the effect of active segment length ratio, R4 on device performances of all the cascaded modulators. It is seen from the Table 4.15, when the length ratio, R4 of cascaded modulator 1A and 1C varies from 6% to 50%, the bandwidth increases 15 GHz (17% increment) and 15 GHz (15% increment) respectively, the bandwidth decreases 20 GHz (20% decrement) and 40 GHz (36% decrement) respectively as the ratio R4 increased upto 70% from 50%. For cascaded modulator 1B the bandwidth increases 10 GHz (10% increment) until 40% increment of ratio R4, after that increasing more active segment ratio R4 upto 70%, the bandwidth decreases 40 GHz (36% decrement). The extinction ratio and overshooting of cascaded modulator 1A, 1B and 1C decrease 0.2 dB and 0.8 dB, 0.3 dB and 0.8 dB and 0.3 dB and 0.7 dB respectively.

After above investigation of all four active segment length ratios of cascaded modulators, if the ratio R1 more increases then the bandwidth decreases more and also increases the signal distortion. Ratio, R2 has no effect on extinction ratio, very little effect on changing the bandwidth but it has big effect on overshooting. If the ratio R3 changes then the bandwidth and overshooting increase more than 30%. Ratio R4 has also big effect of changing the bandwidth, extinction ratio and also overshooting. By selecting suitable active length ratio of R1, R3 and R4 we can tune the device for optimum performance.

Table 4.15: Effect of fourth active length ratio, R4 of all cascaded modulators.

| Ratio R4 (%) | Modulator 1A | | | Modulator 1B | | | Modulator 1C | | |
|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|
|              | BW (GHz)    | ER (dB)      | Over Shoot (dB) | Ratio R4 (%) | BW (GHz)    | ER (dB)      | Over Shoot (dB) | Ratio R4 (%) | BW (GHz)    | ER (dB)      | Over Shoot (dB) |
| 06           | 85          | 4.2          | 0.8           | 06           | 100         | 4.3          | 0.8           | 06           | 95          | 4.3          | 0.7           |
| 10           | 85          | 4.2          | 0.8           | 10           | 105         | 4.2          | 0.8           | 10           | 95          | 4.2          | 0.7           |
| 20           | 90          | 4.1          | 0.8           | 20           | 110         | 4.1          | 0.7           | 20           | 100         | 4.1          | 0.7           |
| 30           | 95          | 4.1          | 0.8           | -            | -           | -            | -             | 30           | 105         | 4.0          | 0.6           |
| 40           | 100         | 4.0          | 0.6           | 40           | 110         | 4.0          | 0.6           | 40           | 105         | 4.0          | 0.5           |
| 50           | 100         | 4.0          | 0.4           | 50           | 105         | 4.0          | 0.4           | 50           | 110         | 4.0          | 0.3           |
| 70           | 80          | 4.0          | 0.0           | 70           | 70          | 4.0          | 0.0           | 70           | 70          | 4.0          | 0.0           |
Figure 4.23: Variation of (a) Bandwidth, (b) Extinction Ration and (c) Overshooting by changing in percentage (%) of fourth active segment of the device for different designs.
4.7 Effect of changing microstrip line length ratio on the performance of cascaded modulator

4.7.1 Effect of changing microstrip line length ratio of 1st modulator of cascaded modulator

We have varied one of three passive transmission line (microstrip) lengths of 1st modulator by keeping total passive transmission line (microstrip) length of 1st modulator same and also the microstrip length ratio of other two microstrip line lengths of the same modulator have been kept near about same and equal with the corresponding original ratio (as shown in Table 3.2) and also the total microstrip line length of 2nd modulator has been kept as same as in original design. This is because keeping them equal gives maximum bandwidth. The ratio, $R_i$ ($i=1, 2, 3$) in percentage, is the i-th microstrip length of 1st modulator over the total microstrip length of the same modulator. As for example, the microstrip length ratio of first (0t), second (1t) and third (2t), $R_{11}$, $R_{12}$ and $R_{13}$ respectively of 1st modulator are shown in Figure 4.24 and also there calculated ratios (only for cascaded modulator 1A) are shown in Table 4.16, 4.17 and 4.18 respectively. In this case of investigation, we all time keep that the length of second microstrip (1t) line of 1st modulator not less than the length of first active segment (1a) length of 2nd modulator. All these variables have been varied independently and their effects on the bandwidth, extinction ratio and overshoot of the cascaded of cascaded modulator 1A, 1B and 1C are shown in Table 4.19, 4.20 and 4.21 respectively and also there graphs are shown in App_B.11, App_B.12 and App_B.13 respectively.

$$R_{11} (%) = \frac{\text{length of first microstrip (0t) line of 1st modulator}}{\text{total microstrip line length of 1st modulator}} \times 100\%$$

$$R_{12} (%) = \frac{\text{length of second microstrip (1t) line of 1st modulator}}{\text{total microstrip line length of 1st modulator}} \times 100\%$$

$$R_{13} (%) = \frac{\text{length of third microstrip (2t) line of 1st modulator}}{\text{total microstrip line length of 1st modulator}} \times 100\%$$
Figure 4.24: Cascaded modulator 1A for showing microstrip length ratio of 1st modulator.

Table 4.16: Calculation of ratio, R11 of first microstrip (0t) line of 1st modulator of cascaded modulator 1A.

<table>
<thead>
<tr>
<th>Ratio R11 (%)</th>
<th>Total microstrip length (µm)</th>
<th>First microstrip (0t) length (µm)</th>
<th>Second microstrip (1t) length (µm)</th>
<th>Third microstrip (2t) length (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>570</td>
<td>30</td>
<td>400</td>
<td>140</td>
</tr>
<tr>
<td>21</td>
<td>570</td>
<td>120</td>
<td>330</td>
<td>120</td>
</tr>
<tr>
<td>28</td>
<td>570</td>
<td>160</td>
<td>310</td>
<td>110</td>
</tr>
<tr>
<td>38</td>
<td>570</td>
<td>220</td>
<td>260</td>
<td>90</td>
</tr>
<tr>
<td>47</td>
<td>570</td>
<td>270</td>
<td>220</td>
<td>80</td>
</tr>
</tbody>
</table>

Table 4.17: Calculation of ratio, R12 of second microstrip (1t) line of 1st modulator of cascaded modulator 1A.

<table>
<thead>
<tr>
<th>Ratio R12 (%)</th>
<th>Total microstrip length (µm)</th>
<th>First microstrip (0t) length (µm)</th>
<th>Second microstrip (1t) length (µm)</th>
<th>Third microstrip (2t) length (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>38</td>
<td>570</td>
<td>235</td>
<td>220</td>
<td>115</td>
</tr>
<tr>
<td>47</td>
<td>570</td>
<td>200</td>
<td>270</td>
<td>100</td>
</tr>
<tr>
<td>56</td>
<td>570</td>
<td>170</td>
<td>320</td>
<td>80</td>
</tr>
<tr>
<td>64</td>
<td>570</td>
<td>135</td>
<td>370</td>
<td>65</td>
</tr>
<tr>
<td>73</td>
<td>570</td>
<td>100</td>
<td>420</td>
<td>50</td>
</tr>
</tbody>
</table>
Table 4.18: Calculation of ratio, $R_{13}$ of third microstrip (2t) line of 1st modulator of cascaded modulator 1A.

<table>
<thead>
<tr>
<th>Ratio $R_{13}$ (%)</th>
<th>Total microstrip length (µm)</th>
<th>First microstrip (0t) length (µm)</th>
<th>Second microstrip (1t) length (µm)</th>
<th>Third microstrip (2t) length (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>08</td>
<td>570</td>
<td>220</td>
<td>300</td>
<td>50</td>
</tr>
<tr>
<td>15</td>
<td>570</td>
<td>200</td>
<td>280</td>
<td>90</td>
</tr>
<tr>
<td>19</td>
<td>570</td>
<td>195</td>
<td>265</td>
<td>110</td>
</tr>
<tr>
<td>26</td>
<td>570</td>
<td>175</td>
<td>245</td>
<td>150</td>
</tr>
<tr>
<td>33</td>
<td>570</td>
<td>160</td>
<td>220</td>
<td>190</td>
</tr>
</tbody>
</table>

It is seen from Table 4.19, as the ratio $R_{11}$ of all the cascaded modulator increases the bandwidth decreases. This is due to increase of microwave signal loss. This ratio has no significant effect on extinction ratio and overshooting for all the cascaded modulators. But, the ratio $R_{13}$ has reverse effect compared to ratio $R_{11}$. Ratio, $R_{12}$ has no significant effect on bandwidth, extinction ratio and overshooting of all the cascaded modulators.

Table 4.19: Effect of first microstrip length ratio, $R_{11}$ of 1st modulator of all cascaded modulators.

<table>
<thead>
<tr>
<th>Modulator 1A</th>
<th>Modulator 1B</th>
<th>Modulator 1C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ratio $R_{11}$ (%)</td>
<td>BW (GHz)</td>
<td>ER (dB)</td>
</tr>
<tr>
<td>05</td>
<td>110</td>
<td>4.0</td>
</tr>
<tr>
<td>21</td>
<td>110</td>
<td>4.0</td>
</tr>
<tr>
<td>28</td>
<td>115</td>
<td>4.0</td>
</tr>
<tr>
<td>38</td>
<td>107</td>
<td>4.0</td>
</tr>
<tr>
<td>47</td>
<td>105</td>
<td>4.0</td>
</tr>
</tbody>
</table>

Table 4.20: Effect of second microstrip length ratio, $R_{12}$ of 1st modulator of all cascaded modulators.

<table>
<thead>
<tr>
<th>Modulator 1A</th>
<th>Modulator 1B</th>
<th>Modulator 1C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ratio $R_{12}$ (%)</td>
<td>BW (GHz)</td>
<td>ER (dB)</td>
</tr>
<tr>
<td>38</td>
<td>110</td>
<td>4.0</td>
</tr>
<tr>
<td>47</td>
<td>110</td>
<td>4.0</td>
</tr>
<tr>
<td>56</td>
<td>110</td>
<td>4.0</td>
</tr>
<tr>
<td>64</td>
<td>110</td>
<td>4.0</td>
</tr>
<tr>
<td>73</td>
<td>110</td>
<td>4.0</td>
</tr>
</tbody>
</table>
Table 4.21: Effect of third microstrip length ratio, R13 of 1st modulator of all cascaded modulators.

<table>
<thead>
<tr>
<th>Ratio R13 (%)</th>
<th>Modulator 1A</th>
<th>Modulator 1B</th>
<th>Modulator 1C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>BW (GHz)</td>
<td>ER (dB)</td>
<td>Over Shoot (dB)</td>
</tr>
<tr>
<td>08</td>
<td>105</td>
<td>4.0</td>
<td>0.2</td>
</tr>
<tr>
<td>15</td>
<td>110</td>
<td>4.0</td>
<td>0.2</td>
</tr>
<tr>
<td>19</td>
<td>110</td>
<td>4.0</td>
<td>0.2</td>
</tr>
<tr>
<td>26</td>
<td>115</td>
<td>4.0</td>
<td>0.2</td>
</tr>
<tr>
<td>33</td>
<td>120</td>
<td>4.0</td>
<td>0.2</td>
</tr>
</tbody>
</table>

4.7.2 Effect of changing microstrip line length ratio of 2nd modulator of cascaded modulator

Here, we also vary one of three passive transmission line (microstrip) lengths of 2nd modulator by keeping total passive transmission line (microstrip) length of 2nd modulator same and also the microstrip length ratio of other two microstrip line lengths of the same modulator have been kept near about same and equal with the corresponding original ratio (as shown in Table 3.2) and also the total microstrip line length of 1st modulator has been kept as same as in original design. This is because keeping them equal gives maximum bandwidth. The ratio, $R_i$ ($i=1, 2, 3$) in percentage, is the i-th microstrip length of 2nd modulator over the total microstrip length of the same modulator. As for example, the microstrip length ratio of first, second and third, R21, R22 and R23 respectively of 2nd modulator are shown in Figure 4.25 and also there calculated ratios (only for cascaded modulator 1A) are shown in Table 4.22, 4.23 and 4.24 respectively. In this case of investigation, we all time keep that the length of second microstrip line of 2nd modulator not less than the length of second active segment length of 1st modulator. All these variables have been varied independently and their effects on the bandwidth and overshoot of the cascaded modulator 1A, 1B and 1C are shown in Table 4.25, 4.26 and 4.27 respectively and also there graphs are shown in App_B.14, App_B.15 and App_B.16 respectively.

\[
R21 (%) = \frac{\text{length of first microstrip (0t) line of 2nd modulator}}{\text{total microstrip line length of 2nd modulator}} \times 100\%
\]

\[
R22 (%) = \frac{\text{length of second microstrip (1t) line of 2nd modulator}}{\text{total microstrip line length of 2nd modulator}} \times 100\%
\]
\[ R_{23} (%) = \frac{\text{length of third microstrip line (2t) of 2nd modulator}}{\text{total microstrip line length of 2nd modulator}} \times 100\% \]

Figure 4.25: Cascaded modulator 1A for showing microstrip length ratio of 2nd modulator.

Table 4.22: Calculation of ratio, \( R_{21} \) of first microstrip (0t) line of 2nd modulator of cascaded modulator 1A.

<table>
<thead>
<tr>
<th>Ratio ( R_{21} ) (%)</th>
<th>Total microstrip length (µm)</th>
<th>First microstrip (0t) length (µm)</th>
<th>Second microstrip (1t) length (µm)</th>
<th>Third microstrip (2t) length (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>19</td>
<td>310</td>
<td>060</td>
<td>190</td>
<td>60</td>
</tr>
<tr>
<td>29</td>
<td>310</td>
<td>090</td>
<td>170</td>
<td>50</td>
</tr>
<tr>
<td>38</td>
<td>310</td>
<td>120</td>
<td>145</td>
<td>45</td>
</tr>
<tr>
<td>48</td>
<td>310</td>
<td>150</td>
<td>125</td>
<td>35</td>
</tr>
<tr>
<td>58</td>
<td>310</td>
<td>180</td>
<td>100</td>
<td>30</td>
</tr>
</tbody>
</table>

Table 4.23: Calculation of ratio, \( R_{22} \) of second microstrip (1t) line of 2nd modulator of cascaded modulator 1A.

<table>
<thead>
<tr>
<th>Ratio ( R_{22} ) (%)</th>
<th>Total microstrip length (µm)</th>
<th>First microstrip (0t) length (µm)</th>
<th>Second microstrip (1t) length (µm)</th>
<th>Third microstrip (2t) length (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>32</td>
<td>310</td>
<td>140</td>
<td>100</td>
<td>70</td>
</tr>
<tr>
<td>41</td>
<td>310</td>
<td>120</td>
<td>130</td>
<td>60</td>
</tr>
<tr>
<td>51</td>
<td>310</td>
<td>100</td>
<td>160</td>
<td>50</td>
</tr>
<tr>
<td>61</td>
<td>310</td>
<td>080</td>
<td>190</td>
<td>40</td>
</tr>
<tr>
<td>70</td>
<td>310</td>
<td>060</td>
<td>220</td>
<td>30</td>
</tr>
</tbody>
</table>
Table 4.24: Calculation of ratio, R23 of third microstrip (2t) line of 2nd modulator of cascaded modulator 1A.

<table>
<thead>
<tr>
<th>Ratio R23 (%)</th>
<th>Total microstrip length (µm)</th>
<th>First microstrip length (µm)</th>
<th>Second microstrip length (µm)</th>
<th>Third microstrip length (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>09</td>
<td>310</td>
<td>105</td>
<td>175</td>
<td>030</td>
</tr>
<tr>
<td>19</td>
<td>310</td>
<td>095</td>
<td>155</td>
<td>060</td>
</tr>
<tr>
<td>29</td>
<td>310</td>
<td>080</td>
<td>140</td>
<td>090</td>
</tr>
<tr>
<td>38</td>
<td>310</td>
<td>070</td>
<td>120</td>
<td>120</td>
</tr>
<tr>
<td>48</td>
<td>310</td>
<td>060</td>
<td>100</td>
<td>150</td>
</tr>
</tbody>
</table>

It is seen from Table 4.25, as the ratio R21, of the cascaded modulator 1C increases the bandwidth also increases, of the cascaded modulator 1A and 1B increases then the bandwidth is also increased upto certain ratio (39%) then it starts to decrease. Why the bandwidth increases or decreases has also been described in previous section. The bandwidth, of cascaded modulator 1A and 1C decreases as the ratio R22 increases, of cascaded modulator 1B remains in the same level as this ratio changes as shown in Table 4.26. The ratio, R23 has no significant effect on bandwidth as shown in Table 4.27. It is seen from Table 4.25 to 4.27, the ratio R21, R22 and R23 have no significant effect on extinction ratio and overshooting for all the cascaded modulators. After investigation of all the six microstrip ratios, the ratio R11, R13 and R22 has significant effect on bandwidth, extinction ratio and overshooting. By choosing suitable above mentioned microstrip ratios, we can tune the cascaded modulator for best performance.

Table 4.25: Effect of first microstrip length ratio, R21 of 2nd modulator of all cascaded modulators.

<table>
<thead>
<tr>
<th>Ratio R21 (%)</th>
<th>Modulator 1A</th>
<th>Modulator 1B</th>
<th>Modulator 1C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>BW (GHz)</td>
<td>ER (dB)</td>
<td>Over Shoot (dB)</td>
</tr>
<tr>
<td>19</td>
<td>110</td>
<td>4.0</td>
<td>0.2</td>
</tr>
<tr>
<td>29</td>
<td>110</td>
<td>4.0</td>
<td>0.2</td>
</tr>
<tr>
<td>38</td>
<td>110</td>
<td>4.0</td>
<td>0.1</td>
</tr>
<tr>
<td>48</td>
<td>110</td>
<td>4.0</td>
<td>0.1</td>
</tr>
<tr>
<td>58</td>
<td>110</td>
<td>4.0</td>
<td>0.1</td>
</tr>
</tbody>
</table>
Table 4.26: Effect of second microstrip length ratio, R22 of 2nd modulator of all cascaded modulators.

<table>
<thead>
<tr>
<th>Ratio R22 (%)</th>
<th>BW (GHz)</th>
<th>ER (dB)</th>
<th>Over Shoot (dB)</th>
<th>Ratio R22 (%)</th>
<th>BW (GHz)</th>
<th>ER (dB)</th>
<th>Over Shoot (dB)</th>
<th>Ratio R22 (%)</th>
<th>BW (GHz)</th>
<th>ER (dB)</th>
<th>Over Shoot (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>32</td>
<td>110</td>
<td>4.0</td>
<td>0.2</td>
<td>38</td>
<td>70</td>
<td>4.2</td>
<td>0.0</td>
<td>49</td>
<td>110</td>
<td>4.0</td>
<td>0.6</td>
</tr>
<tr>
<td>41</td>
<td>110</td>
<td>4.0</td>
<td>0.2</td>
<td>47</td>
<td>65</td>
<td>4.2</td>
<td>0.0</td>
<td>56</td>
<td>110</td>
<td>4.0</td>
<td>0.6</td>
</tr>
<tr>
<td>51</td>
<td>110</td>
<td>4.0</td>
<td>0.2</td>
<td>56</td>
<td>65</td>
<td>4.2</td>
<td>0.0</td>
<td>64</td>
<td>105</td>
<td>4.1</td>
<td>0.6</td>
</tr>
<tr>
<td>61</td>
<td>110</td>
<td>4.0</td>
<td>0.2</td>
<td>64</td>
<td>65</td>
<td>4.2</td>
<td>0.0</td>
<td>72</td>
<td>100</td>
<td>4.1</td>
<td>0.6</td>
</tr>
<tr>
<td>70</td>
<td>105</td>
<td>4.0</td>
<td>0.2</td>
<td>73</td>
<td>65</td>
<td>4.2</td>
<td>0.0</td>
<td>80</td>
<td>95</td>
<td>4.1</td>
<td>0.6</td>
</tr>
</tbody>
</table>

Table 4.27: Effect of third microstrip length ratio, R23 of 2nd modulator of all cascaded modulators.

<table>
<thead>
<tr>
<th>Ratio R23 (%)</th>
<th>BW (GHz)</th>
<th>ER (dB)</th>
<th>Over Shoot (dB)</th>
<th>Ratio R23 (%)</th>
<th>BW (GHz)</th>
<th>ER (dB)</th>
<th>Over Shoot (dB)</th>
<th>Ratio R23 (%)</th>
<th>BW (GHz)</th>
<th>ER (dB)</th>
<th>Over Shoot (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>09</td>
<td>110</td>
<td>4.0</td>
<td>0.2</td>
<td>08</td>
<td>70</td>
<td>4.2</td>
<td>0.0</td>
<td>10</td>
<td>100</td>
<td>4.1</td>
<td>0.6</td>
</tr>
<tr>
<td>19</td>
<td>110</td>
<td>4.0</td>
<td>0.2</td>
<td>15</td>
<td>70</td>
<td>4.2</td>
<td>0.0</td>
<td>18</td>
<td>105</td>
<td>4.1</td>
<td>0.6</td>
</tr>
<tr>
<td>29</td>
<td>110</td>
<td>4.1</td>
<td>0.2</td>
<td>19</td>
<td>65</td>
<td>4.2</td>
<td>0.0</td>
<td>24</td>
<td>105</td>
<td>4.1</td>
<td>0.6</td>
</tr>
<tr>
<td>38</td>
<td>110</td>
<td>4.0</td>
<td>0.2</td>
<td>26</td>
<td>65</td>
<td>4.2</td>
<td>0.0</td>
<td>30</td>
<td>105</td>
<td>4.1</td>
<td>0.6</td>
</tr>
<tr>
<td>48</td>
<td>110</td>
<td>4.1</td>
<td>0.2</td>
<td>33</td>
<td>65</td>
<td>4.3</td>
<td>0.0</td>
<td>37</td>
<td>105</td>
<td>4.1</td>
<td>0.6</td>
</tr>
</tbody>
</table>

4.8 Effect of transit time delay on the performance of cascaded modulator

Figure 2.26 shows the effect of approximate variation of transit time delay on jitter for different type of cascaded modulators. This delay is caused by finite velocity of charge carriers in the intrinsic region of a modulator which turns to delay on photogenerate current. This acts as a timing jitter in the eye diagram as shown in Figure 2.27 which reduces the eye opening that falls the detector in a big error to detect on or zero from the transmitting signal. As the input optical power increases, the bandwidth increases (it has been discussed in the previous section) and the jitter also increases for all cascaded modulators. The transit time delay has no effect on low power like 1 mW due to few photogenerated current, but for the input optical power 30 mW, it has large amount of photogenerated current and it is delayed by transit time, has large jitter in the eye diagram. From Figure 2.26, it is seen that the input optical power between 10 mW to 20 mW would be suitable for the cascaded modulator operation. From Figure 4.26, the timing jitter is less than 400 fs for all input optical power.
Figure 4.26: Effect of approximate variation of transit time delay on jitter for cascaded modulator (a) 1A (b) 1B and (c) 1C at different input optical power.
(a) Eye diagram of cascaded modulator 1A at input power = 10 mW and t = 10 ps.

(b) Eye diagram of cascaded modulator 1A at input power = 30 mW and t = 30 ps.

(c) Eye diagram of cascaded modulator 1B at input power = 1 mW and t = 10 ps.
Chapter 4

**Simulation Results and Discussion**

(d) Eye diagram of cascaded modulator 1B at input power = 30mW and t = 20 ps.

(e) Eye diagram of cascaded modulator 1C at input power = 1mW and t = 30 ps.

(e) Eye diagram of cascaded modulator 1C at input power = 30 mW and t = 30 ps.

Figure 4.27: Effect of approximate variation of transit time delay on eye diagram for cascaded modulators.
Summary and Conclusion

5.1 Conclusion
In this thesis work, a cascaded modulator has been designed by using two segmented travelling wave electroabsorption modulators. This modulator has been studied by large signal model. The effect of input signal (modulating) voltage, input optical power, biasing voltage, circuit parameters, active segment ratio, microstrip line ratio and transit time delay have been studied on response of bandwidth, extinction ratio and overshooting.

It has been found that the cascaded modulator 1A has 3dB bandwidth, extinction ratio and overshooting at modulating voltage 0.4 V(p-p) and 1 V(p-p) are 110 Gbps and 120 Gbps, 4.0 dB and 11 dB and 0.2 dB and 0.5 dB respectively which can be used for real life application in Ethernet and Telecommunication system. Other two designs have less bandwidth but have suffered with overshooting problem.

The effect of input optical power on device performance has a significant effect. As the input optical power increased the bandwidth, extinction ratio and overshooting are also increased due large photogenerated current. But, bandwidth of the cascaded modulator 1B decreases due to saturation effect of photogenerated current. Between 10 mW to 20 mW input optical power, the device has optimum performance due to tradeoff between bandwidth, extinction ratio and overshooting. It has been seen that the biasing voltage has a significant effect on the device performance. As the biasing voltage increases the bandwidth, overshooting and extinction ratio are also increased. Bandwidth is increased due to increase of phototgenereated current which drops more voltage in p-doped region acts to reduce the shunt resistor that is parallel with the junction capacitor. Extinction ratio increases due to nonlinear relationship between absorption and applied voltage. It has been seen that the biasing voltage between 1 V and 1.5 V are suitable for optimum performance of the cascaded modulator at 0.4 V(p-p) modulating voltage and 14 mW input optical power.

The sensitivity of the cascaded modulator performance can be changed by varying the circuit parameters of the cascaded modulator. It has been seen that the bandwidth of the cascaded modulator depends on the internal capacitance (\(C_{\text{int}}\)), mesa resistance (\(R_P\)) and also the inductance (\(L_P\)) of passive transmission line. To increase the bandwidth, the internal capacitance and mesa resistance should be decreased and \(L_P\) should be increased. This will also increase the
overshooting to distort the signal. It has been found that the internal capacitance, mesa resistance and passive transmission line inductance between 400 fF/mm and 450 fF/mm, 0.6 Ω-mm and 0.8 Ω-mm and 300 pH/mm and 400 pH/mm have suitable value to optimum performance of the device without too much sacrificing bandwidth and signal distortion.

It has been also found that the active segment length ratio (R1, R2, R3 and R4) over the total active segment length has big effect on device performance. Ratio R1 increases more than 15% then the bandwidth starts to decrease but the overshooting increases until 40%. Ratio, R2 has no effect on extinction ratio, very little effect on changing the bandwidth but it has big effect on overshooting. The bandwidth and overshooting are increase as the ratio, R3 increases. As it is increase up to 30% then the overshooting increased more than 100% compared to 30% increment of bandwidth. Ratio, R4 has also significant effect of changing the bandwidth, extinction ratio and also overshooting as it is increased. By selecting suitable active length ratio of R3 and R4 between 50% to 70% and 20% to 30% respectively the device could be tuned for optimum performance.

It has been found that the effect of microstrip length ratio over the total microstrip length of 1st or 2nd modulators of a cascaded modulator. These ratios change the total effective complex impedance of the cascaded modulator which causes the microwave return loss. Ratio, R12, R21 and R23 have no significant effect on device performance. But, carefully section of microstrip length ratio R11 (5% to 22%), R13 (15% to 30%) of 1st modulator, and R22 (20% to 40%) of 2nd modulator of a cascaded modulator could be tuned the device for optimum performance. It has been seen that the transit time delay of photogenerated carrier causes increasing of timing jitter to distort the signal. This effect is effective for high input power. At, 14 mW input optical power jitter is less than 100 fs. After carefully investigations of all the designing parameters, we have designed three types of cascaded modulators and their performances are shown in Table 5.1.
Table 5.1: Performances of all the cascaded modulators

<table>
<thead>
<tr>
<th>CTWEAM</th>
<th>Modulating Voltage = 0.4 V (p-p)</th>
<th>Modulating Voltage = 1 V (p-p)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>BW (GHz)</td>
<td>ER (dB)</td>
</tr>
<tr>
<td>1A</td>
<td>110</td>
<td>4.0</td>
</tr>
<tr>
<td>1B</td>
<td>65.91</td>
<td>4.3</td>
</tr>
<tr>
<td>1C</td>
<td>101.16</td>
<td>4.1</td>
</tr>
</tbody>
</table>

From the above table, it is seen that cascaded modulator 1A is the best design among all the cascaded modulators because of it has best tradeoff between bandwidth, extinction ratio and overshooting to perform it for real life application. All the results that have been obtained from this thesis work could be used to design and fabrication of a cascaded modulator for real life application in Ethernet and telecommunication system.

5.2 Future Work

By using cascaded concept, more segmented TWEAM could be added to make it as a mixer. It is also possible to make it as a wave shaper circuit, NRZ to RZ and also TWEAM as a detector.
The electrical equivalent circuits for whole modulators and its different parts are given below.

Figure App_A.1: Schematics of equivalent circuit of cascading TWEAM.
Figure App_B.2: Parameters value of the modulator.
Figure App_A.3: Schematics of equivalent circuit of passive micro strip line of cascading TWEAM.
Figure App_A.4: Schematics of equivalent circuit of active segment of cascading TWEAM.
Figure App_B.1: Eye diagram at input modulating voltage (a) 0.4 V(p-p), (b) 1 V(p-p) and (c) 2 V(p-p) for cascading modulator 1A.
Figure App_B.2: Eye diagram at input modulating voltage (a) 0.4 V(p-p), (b) 1 V(p-p) and (c) 1.6 V(p-p) for cascading modulator 1B.
Figure App_B.3: Eye diagram at input modulating voltage (a) 0.4 V(p-p), (b) 1 V(p-p) and (c) 1.6 V(p-p) for cascading modulator 1C.
Figure App_B.4: Eye diagram at input optical power, 14 mW of cascading modulator (a) 1A, (b) 1B and (c) 1C.
Figure App_B.5: Eye diagram at input optical power, 40 mW of cascading modulator (a) 1A, (b) 1B and (c) 1C.
Figure App_B.6: Eye diagram at input optical power (a) 20 mW, (b) 50 mW and (c) 70 mW for 1st modulator of cascading modulator 1B.
Figure App_B.7: Variation of per unit length external capacitance $C_{\text{ext}}$ on bandwidth.

Figure App_B.8: Variation of per unit length skin effect resistor $R_C$ of electrode on bandwidth.
Figure App_B.9: Variation of microstrip line resistor $R_{ot}$ on bandwidth.

Figure App_B.10: Variation of skin effect resistor $R_{ot}$ of microstrip on bandwidth.
Effect of changing first microstrip length ratio of 1st modulator for all cascading modulators

Figure App_B.11: Variation of (a) Bandwidth, (b) Extinction Ration and (c) Overshooting by changing in percentage (%) of first microstrip line length of 1st modulator for different designs.
Effect of changing second microstrip length ratio of 1st modulator for all cascading modulators

Figure App_B.12: Variation of (a) Bandwidth, (b) Extinction Ration and (c) Overshooting by changing in percentage (%) of second microstrip line length of 1st modulator for different designs.
Effect of changing third microstrip length ratio of 1st modulator for all cascading modulators

Figure App_B.13: Variation of (a) Bandwidth, (b) Extinction Ration and (c) Overshooting by changing in percentage (%) of third microstrip transmission line length of 1st modulator for different designs.
Effect of changing first microstrip length ratio of 2nd modulator for all cascading modulators

Figure App_B.14: Variation of (a) Bandwidth, (b) Extinction Ration and (c) Overshooting by changing in percentage (%) of first microstrip line length of 2nd modulator for different designs.
Effect of changing second microstrip length ratio of 2nd modulator for all cascading modulators

Figure App_B.15: Variation of (a) Bandwidth, (b) Extinction Ration and (c) Overshooting by changing in percentage (%) of second microstrip line length of 2nd modulator for different designs.
Appendix B

Results of Simulated

Effect of changing third microstrip length ratio of 2nd modulator for all cascading modulators

Figure App_B.16: Variation of (a) Bandwidth, (b) Extinction Ratio and (c) Overshooting by changing in percentage (%) of third microstrip line length of 2nd modulator for different designs.
### Simulated Data

The simulated data for the cascading modulators are given below

Table 1a: Effect of modulating voltage on the performance of the cascading modulator 1A (when both modulators are activated)

<table>
<thead>
<tr>
<th>Input modulating Voltage Vin (V (p-p))</th>
<th>VOIP (mW)</th>
<th>Poff (mW)</th>
<th>Pon (mW)</th>
<th>Ppeak (mW)</th>
<th>Pdown (mW)</th>
<th>Jitter (ps)</th>
<th>Tr (ps)</th>
<th>BW (GHz)</th>
<th>Extinction ratio 10log(Pon/Poff) (dB)</th>
<th>Overshooting 10log(Ppeak/Pon) (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.0</td>
<td>14</td>
<td>0.005</td>
<td>1.50</td>
<td>1.82</td>
<td>0.00</td>
<td>0.07</td>
<td>2.34</td>
<td>149.57</td>
<td>24.77</td>
<td>0.83</td>
</tr>
<tr>
<td>1.8</td>
<td>14</td>
<td>0.011</td>
<td>1.50</td>
<td>1.78</td>
<td>0.00</td>
<td>0.07</td>
<td>2.43</td>
<td>144.03</td>
<td>21.35</td>
<td>0.74</td>
</tr>
<tr>
<td>1.6</td>
<td>14</td>
<td>0.021</td>
<td>1.50</td>
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Table 1b: Effect of modulating voltage on the performance of the cascading modulator 1B (when both modulators are activated)

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<th>Pon (mW)</th>
<th>Ppeak (mW)</th>
<th>Pdown (mW)</th>
<th>Jitter (ps)</th>
<th>Tr (ps)</th>
<th>BW (GHz)</th>
<th>Extinction ratio 10log(Pon/Poff) (dB)</th>
<th>Overshooting 10log(Ppeak/Pon) (dB)</th>
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Table 1c: Effect of modulating voltage on the performance of the cascading modulator 1C (when both modulators are activated)

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References

15. R. Sankaralingam. Electroabsorption Modulators.

