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Design Considerations for Electro-Optic Absorption Modulators In Optical Fiber Transmission Systems

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***Abstract*- Electro optic absorption modulator provides high speed external optical modulation at multi Gbit/s. The device operates across 1550 nm near infrared transmission bands with low dispersion penalty. Electro-optic absorption modulator devices offer low drive voltage solution to optical modulation requirements. Modulator optimum length, output power, modulation current, insertion loss, contrast ratio, modulation depth, power length product, modulator switching speed, bit error rate, energy/bit, modulator transmission are the design considerations in this study.**

***Keywords*- Output power, Low insertion loss, Fiber transmission systems, Modulation depth, and Low dispersion penalty.**

I. INTRODUCTION

Semiconductor modulators mainly used as electro-absorption (EA) modulators are one of the important devices playing a role as key components of this new age. EA modulators integrated with distributed feedback (DFB) lasers have been developed and applied to commercial uses for metropolitan high bit rate and long haul optical transmission systems [1, 2]. Moreover, in optical time division multiplexed (OTDM) systems based on high speed optical switching (over 100 Gb/s), EA modulators are indispensable, and much interest has been focused on them [3]. Electro-absorption modulators (EAMs) have been widely used in fiber optic communication systems for their small size, low driving voltage, low chirp, and high bandwidth. In addition, due to matching of material systems, EAMs can be easily integrated with other optical components, such as semiconductor lasers, semiconductor optical amplifiers, and attenuators [4]. Since many material properties, such as band gap, refractive index, and thermal conductivity, change with temperature, internal heating must be considered in the design of an EAM. This is especially important for high power operation, because large heating can damage the device. The input power tolerance of InGaAsP EAMs have been investigated experimentally in terms of breakdown phenomena, and it was shown that optical power for breakdown depended on bias voltage and operating wavelength [5].

The realization of fiber integrated all-optical modulators has high importance in the field of optics communication that is seeking for fast, cheap and integrated ways to perform modulation of information carried over the 1300 nm and 1550 nm wavelength [6]. All optical modulation is realized when a transmission of a certain light beam is controlled by the presence of another light beam. This type of modulation may achieve higher modulation rates by avoiding hardware performing conversion into electronic domain and then back to photons. Avoiding such hardware makes the modulation process faster, less noisy and less cumbersome. Since a direct modification of the absorption coefficient cannot perform a direct significant modulation and the desire is to use silicon for integrated photonics applications [7].

The paper is organized in the following sections. Section II has explained the basic device structure and its dimensions has been discussed in more details. Section III has explained the mathematical device model equations. Section IV has presented the simulation results and performance evaluation of GaAs electro-absorption modulators. Finally, section V has presented the summary of comparison between SiGe (experimental results) and GaAs electro-absorption modulators (presented theoretical results).

II. BASIC DEVICE STRUCTURE

A simple electro-absorption modulator that is formed out of a single waveguide that is with appropriate length in order to modulate light with the integrated Schottky diodes into the waveguide, which allows control of the free carrier density in the waveguide. Schottky diodes have the advantage over traditional PN junction diodes of being majority carrier devices that operate with low turn on voltage. The device has squared shape which its length L_m and intrinsic layer thickness is d as show in Fig. 1.

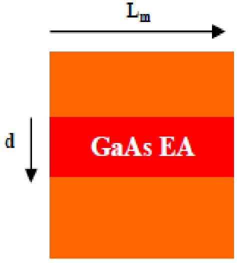

Fig. 1. GaAs EA modulator with square shape.

Fig. 2. Basic schematic View of GaAs Electro-absorption modulator.

The device structure consists of a waveguide on a thin rib having a P type doping of 10^{15} cm^{-3}, with two 10^{18} cm^{-3} P type doped regions on the sides of the waveguide. The device consists of two 110 nm wide copper metal contacts on top gate of the waveguide, and two ohmic contacts connected to the heavily doped regions away from the waveguide as seen in Fig. 2.

III. DEVICE MODELING

If the absorption spectrum to be a Lorentzian function rather than calculate the exact absorption spectrum by using the Schrödinger equation. The absorption coefficient depends on the wavelength and the drive voltage due to the quantum-confined Stark effect [8, 9]:

$$\alpha(\lambda, V) = \frac{\alpha_P(V)\,(0.5\Delta\lambda(V))^2}{(\lambda - \lambda_P(V))^2 + (0.5\Delta\lambda(V))^2} \tag{1}$$

Where $\alpha_p(V)$, and $\lambda_P(V)$ are the peak absorption coefficient and wavelength with the peak absorption coefficient respectively which are given by:

$$\alpha_P(V) = \alpha_0(1 + V/24) \tag{2}$$

$$\lambda_P(V) = \lambda_{P0} - 4x10^{-9}V \tag{3}$$

And $\Delta\lambda(V)$ stands for the spectral broadening which can be given by:

$$\Delta\lambda(V) = \left[(10 - 1.28\,V^3)x10^{-9}\right] \tag{4}$$

The input resistance can be further reduced using multiple vias with a tradeoff of more insertion loss:

$$R = \rho\ L/A \tag{5}$$

Where ρ is the resistivity, L is the contact length (50 μm) and A is the contact area (110 nm x 50 nm). The transient time response of the device and modulator switching speed (MSS) can be calculated as follows [10]:

$$\tau = R\ C \tag{6}$$

$$MSS = \frac{1}{2\pi RC} \tag{7}$$

Where C is the device capacitance which can be given by the mathematical relation [11]:

$$C = \frac{2\pi\,\varepsilon_0\ \varepsilon_r\ c\ L_m}{\lambda\ d} \tag{8}$$

Where d is the modulator intrinsic layer thickness. The relation between power length product and switching speed for electro-absorption materials can be estimated based on MATLAB curve fitting program [12, 13]:

$$PLP = 2.54\,MSS - 1.65\,MSS^2 + 1.0654\,MSS^3 \tag{9}$$

The relative refractive index difference Δn can be estimated by the following formula:

$$\Delta n = \frac{0.5\ n_{eff}^3\ r_{41} V}{L_m} \tag{10}$$

Where n_{eff} is the effective refractive index which can be given by the following formula [14]:

$$n_{eff} = n - \lambda\frac{dn}{d\lambda} \tag{11}$$

For GaAs electro-absorption modulator, n is the refractive index required to characterize the temperature and operating wavelength with the Sellmeier equation is under the form of [15]:

$$n = \sqrt{A_1 + \frac{A_2}{\lambda^2 - A_3} - A_4\lambda^2} \tag{12}$$

The set of parameters is recast and dimensionally adjusted as: A_1= 8.906, A_2=2.3501, $A_3=a_3T^2$; a_3= $(0.25286/T_0)^2$, and $A_4=a_4$ $(1.921+ 0.257x10^{-4}T)$; a_4=0.03454. Therefore the first differentiation of above empirical equation with respect to operating optical signal wavelength, λ that gives:

$$\frac{dn}{d\lambda} = -(\lambda/n)\left[\frac{A_2}{(\lambda^2 - A_3)^2} + A_4\right] \tag{13}$$

The modulator phase shift, Δφ can be expressed by the mathematical relation [16];

$$\Delta\varphi = \frac{2\pi\,\Delta n\ L_m}{\lambda} \tag{14}$$

Therefore the optimum length for GaAs electro-optic absorption modulator can be given by [17]:

$$L_{opt.} = \frac{1}{\Delta\alpha(\lambda, V)}\ln\left(\frac{\Delta\alpha(\lambda, V)}{\alpha_0} + 1\right) \tag{15}$$

The optical transmission data were used to calculate the change in the absorption coefficient in the quantum wells Δα due to the applied bias which is given by [18]:

$$\Delta\alpha(\lambda, V) = \frac{1}{d}\ln\left(\frac{\exp(\alpha(\lambda, V)d)}{\exp(\alpha(\lambda, 0)d)}\right) \tag{16}$$

The output signal power as a function of material absorption coefficient, α and input signal power, P_s can be given by [19]:

$$P_0 = P_s\ e^{-\alpha(\lambda, V)L_m} \tag{17}$$

The bit error rate as a function of operating signal wavelength, λ and output signal power, P_0 can be:

$$BER = 0.5\,e^{-\left(\frac{P_0\ \lambda}{h\,c\,B}\right)} \tag{18}$$

Where h is the Planck's constant (h=6.6034x10^{-34} J.sec), c is the speed of light (c=3x10^8 m/sec), and B is the transmission bit rate. Given the material absorption, α and optical confinement of the intrinsic layer, Γ, and assuming unity quantum efficiency, the modulation photocurrent I_{mod} can be calculated for a length L_m of modulator [20]:

$$I_{\text{mod.}} = \frac{q\,P_s\ \lambda\left\lfloor 1 - e^{-\alpha(\lambda, V)\Gamma\,L_m}\right\rfloor}{2\pi\,h\,c} \tag{19}$$

Where q is the electron charge (q=1.6x10^{-19} C). The voltage dependent transmission of electro-absorption modulator can be expressed as [21]:

$$T_m\,(\%) = \exp(-\alpha(\lambda, V)\,L_m) \tag{20}$$

The contrast ratio (CR) can be made as adjusted as possible by increasing the length of the modulator which can be given by:

$$CR = \frac{P_0(V_{on} = 0)}{P_0(V_{off} = V)} = \frac{\exp(-\alpha[\lambda, 0]L_m)}{\exp(-\alpha(\lambda, V)L_m)} \tag{21}$$

Therefore the contrast ratio can be expressed in dB units as the following mathematical formula [22]:

$$CR(dB) = 4.343\,[\alpha(\lambda, V) - \alpha(\lambda, 0)]\,L_m \tag{22}$$

The longer the modulator is, the larger the insertion loss (IL) which is given by the mathematical relation [23]:

$$IL\ (dB) = 10\,\log[1 - \exp(-\alpha(\lambda, 0)\,L_m)] \tag{23}$$

Modulation depth (MD) quantifies how much voltage do we need to modulate the optical signal which is given by:

$$MD\,(dB) = \frac{CR(dB)}{\Delta V} \tag{24}$$

Where ΔV=Ed=V/L_md, where E is the applied electric field, and d the intrinsic layer thickness. The transient energy consumption due to the on/off transitions can be [24]:

$$(E/b)=0.5\left[C\,V_{PP}^{2}+\frac{I_{\text{mod.}}\,V_{PP}+I_{off}\,V_{off}}{B}\right] \qquad (25)$$

Where $V_{PP}=\left|V_{off}-V_{on}\right|$ is the peak to peak modulation voltage, C is the capacitance of the device, and B is the transmission bit rate.

IV. Simulation Results and Performance Analysis

The model has been investigated high performance broadband integrated electro optic absorption modulators in high speed optical fiber communication systems over wide range of the affecting operating parameters as shown in Table 1.

Table 1: Main parameters used in the simulation [3, 6, 9, 16, 22].

Parameter	Definition	Value and unit
T_0	Room temperature	300 K
L_m	Modulator length	10 mm-90 mm
d	Modulator intrinsic layer thickness	1 mm-10 mm
P_s	Input signal power	1000 mW
T	Ambient temperature	320 K-400 K
λ	Operating optical signal wavelength	1550 nm
r_{41}	Electro-optic coefficient	1.4x10^{-10} cm/Volt
V	Applied drive voltage	0 Volt—5 Volt
ε_r	Relative permittivity	1.65
ε_0	Free space permittivity	8.854x10^{-14} F/cm
ρ	Resistivity	2.65x10^{9} Ω.cm
V_{pp}	Peak-to-peak modulation voltage	3 Volt
α_0	Peak absorption coefficient	3x10^{3} cm^{-1}
λ_{P0}	Wavelength with the peak absorption	1.525x10^{-4} cm
Γ	Optical confinement factor	0.075
B	Bit rate	10 Gb/s-100 Gb/s

Based on the model equations analysis, assumed set of the proposed operating parameters, and the set of the series of the Figs. (3-14), the following facts are assured:

i) Fig 3 has assured that modulator switching speed and power length product increase with increasing both intrinsic modulator layer thickness and modulator length or in another word with increasing device dimensions.

ii) As shown in Fig. 4 has demonstrated that modulator phase shift increases with increasing both applied bias voltage and ambient temperatures surrounding the device.

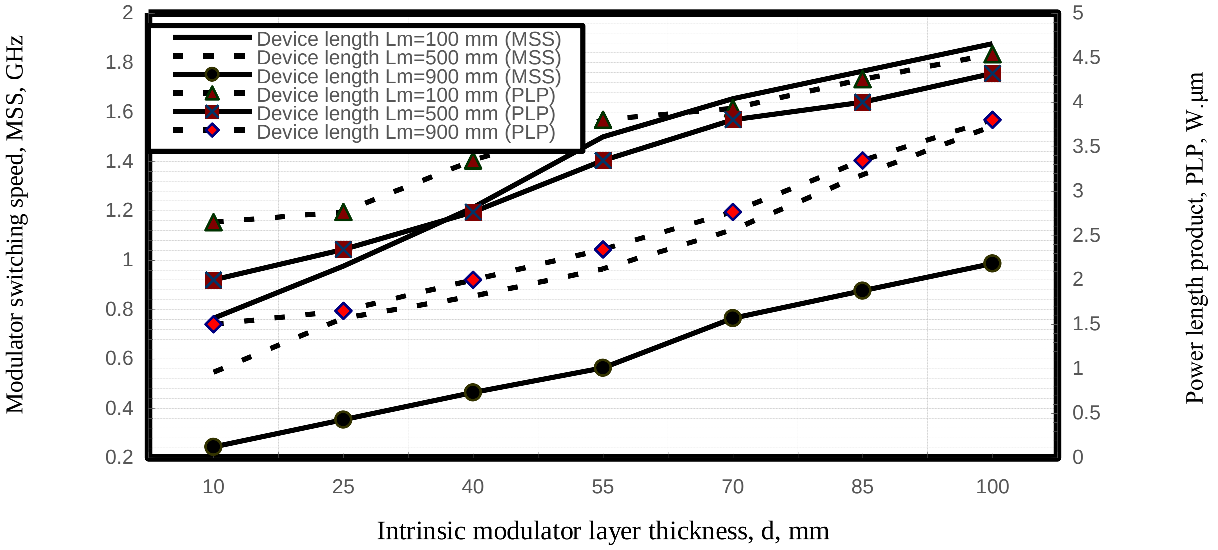

Fig. 3. Modulator switching speed and power length product in relation to modulator intrinsic layer thickness and modulator length at the assumed set of the operating parameters.

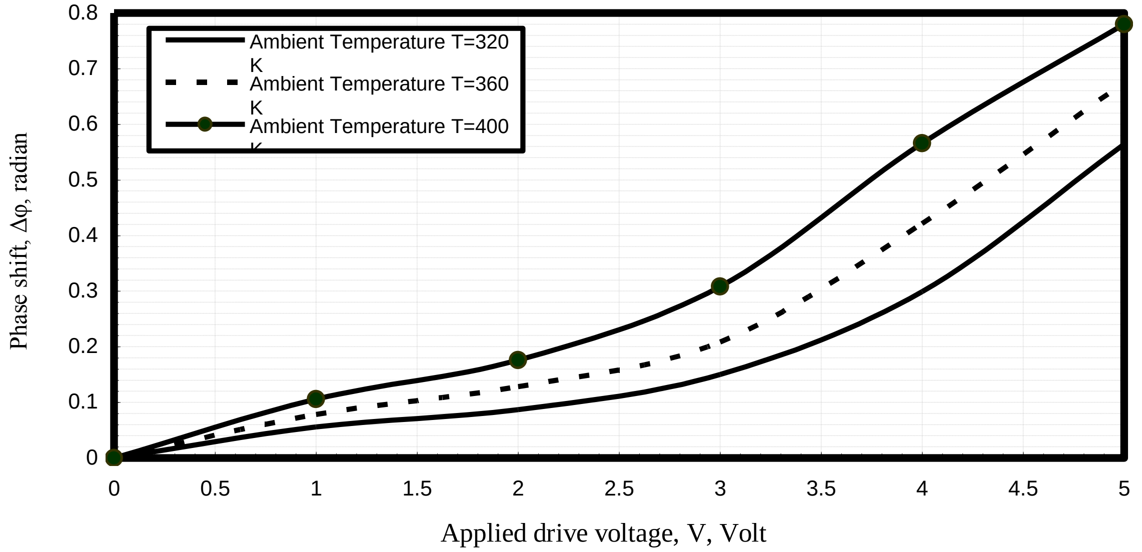

Fig. 4. Variations of phase shift against variations of applied drive voltage and ambient temperature above room temperature at the assumed set of the operating parameters.

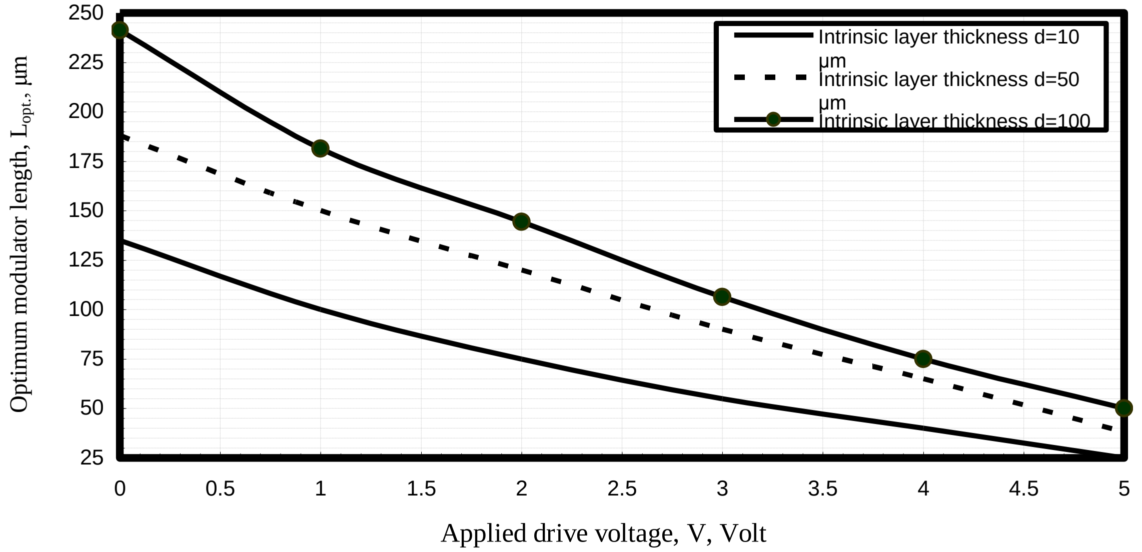

Fig. 5. Optimum modulator length in relation to applied drive voltage and modulator intrinsic layer thickness at the assumed set of the operating parameters.

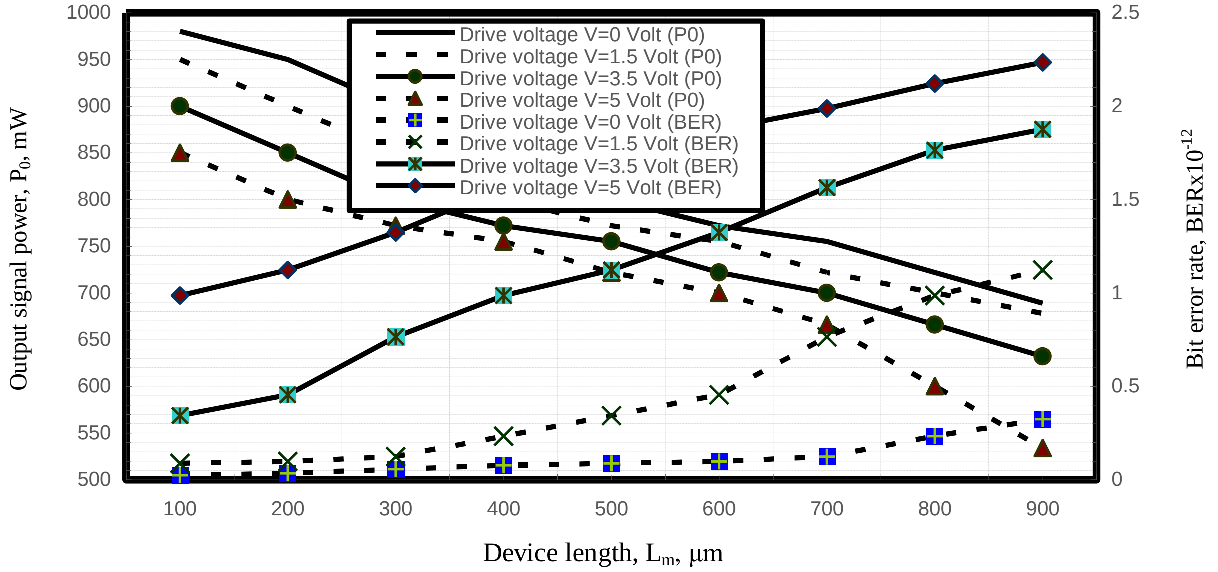

Fig. 6. Output signal power and bit error rate in relation to device length and applied drive voltage at the assumed set of the operating parameters.

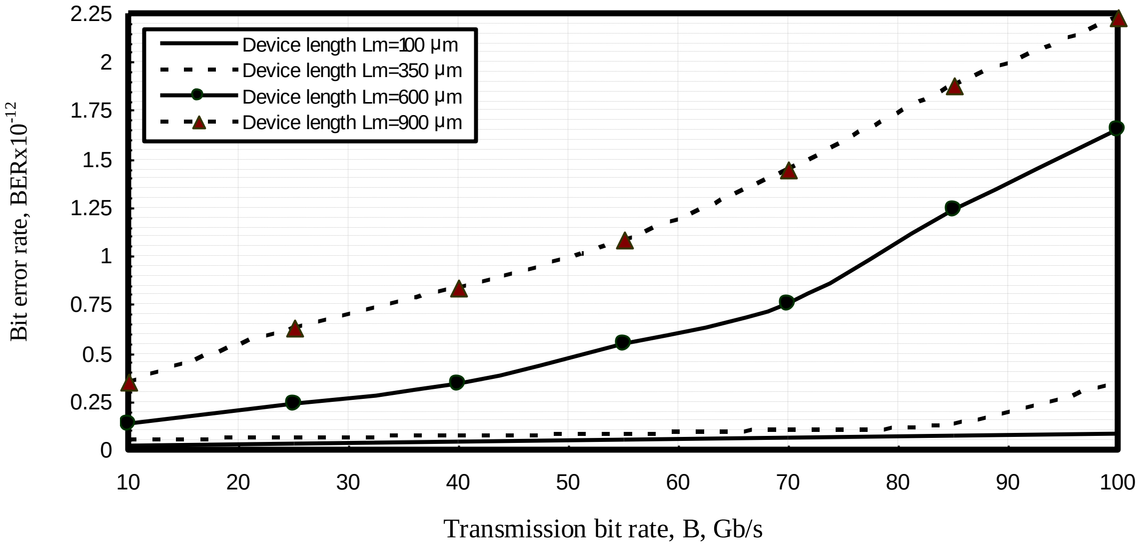

Fig. 7. Variations of bit error rate against variations of transmission bit rate and device length at the assumed set of the operating parameters.

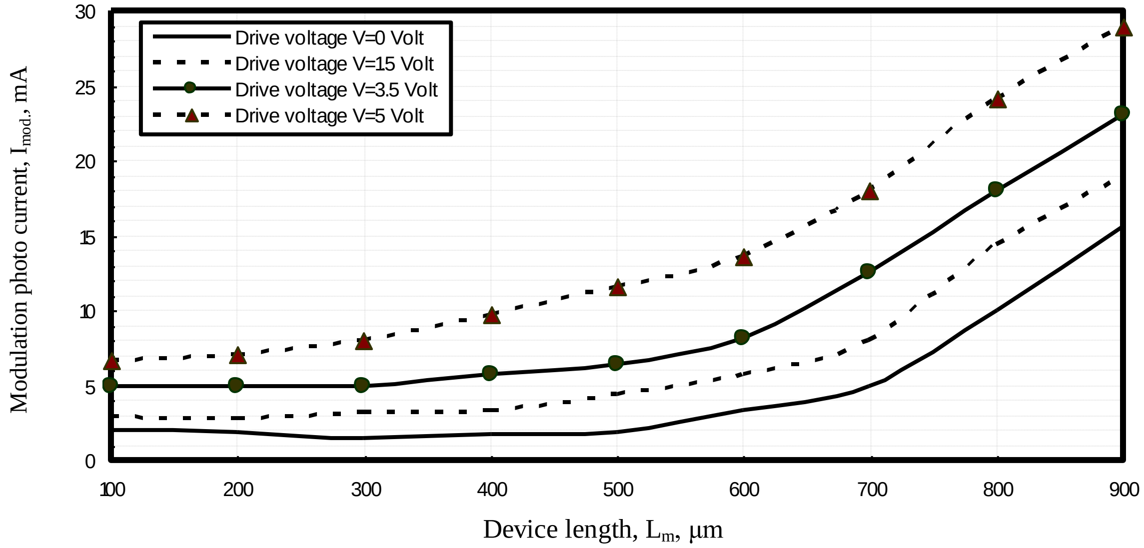

Fig. 8. Variations of modulation photo current against variations of device length and applied drive voltage at the assumed set of the operating parameters.

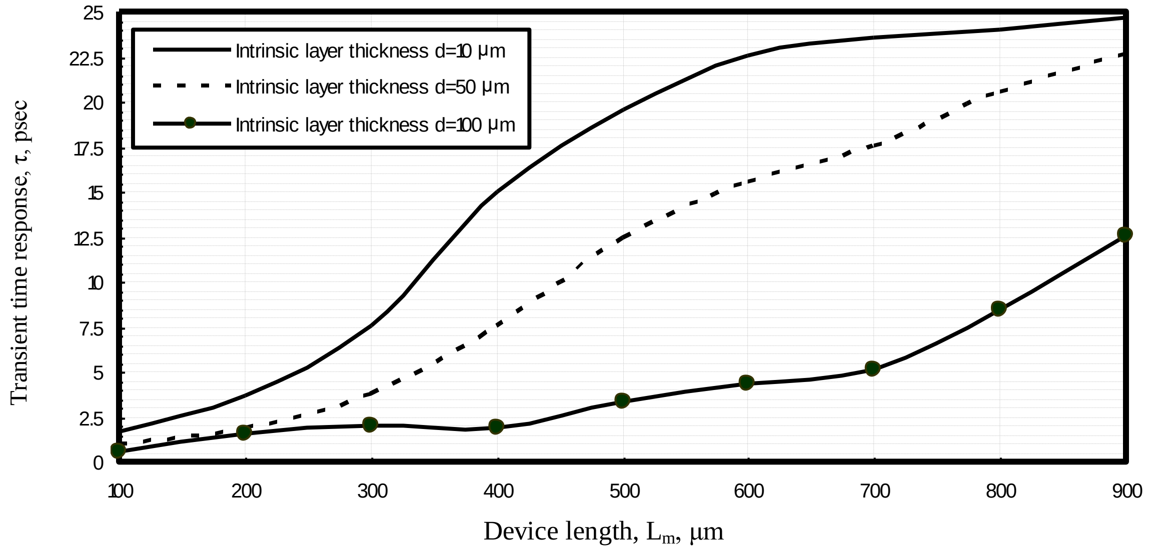

Fig. 9. Variations of transient time response against variations of device length and modulator intrinsic layer thickness at the assumed set of the operating parameters.

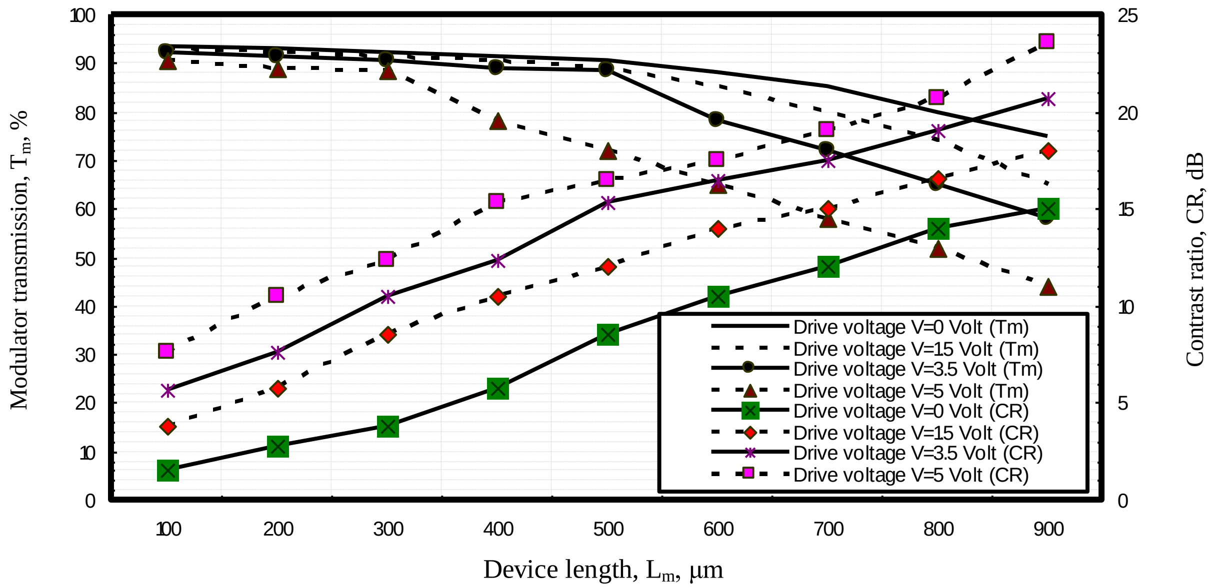

Fig. 10. Variations of modulator transmission and contrast ratio against variations of device length and applied drive voltage at the assumed set of the operating parameters.

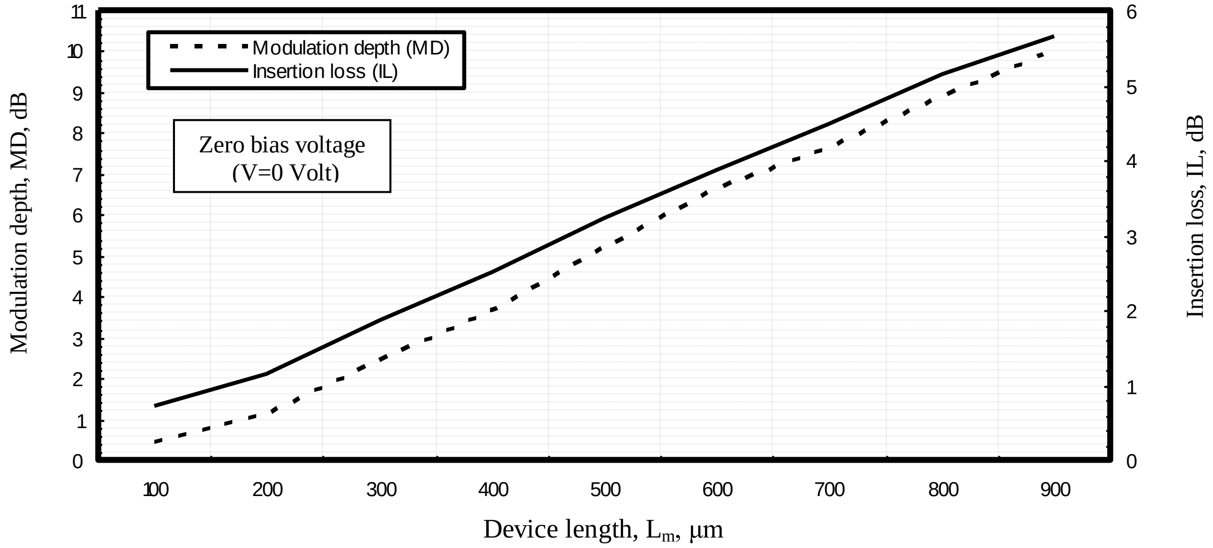

Fig. 11. Variations of modulation depth and insertion loss against variations of device length at the assumed set of the operating parameters

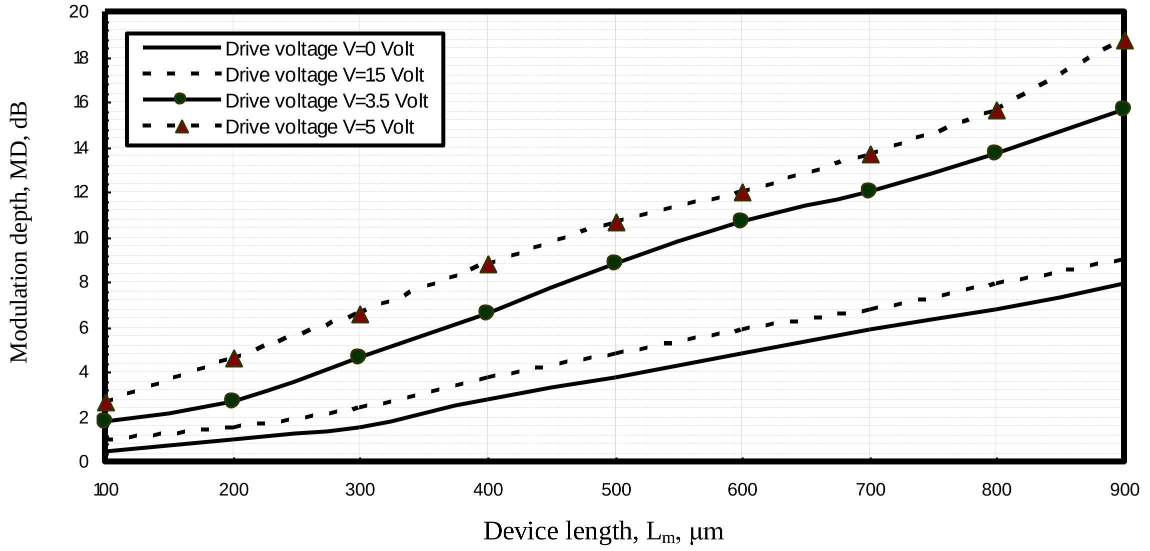

Fig. 12. Variations of modulation depth against variations of device length and applied drive voltage at the assumed set of the operating parameters

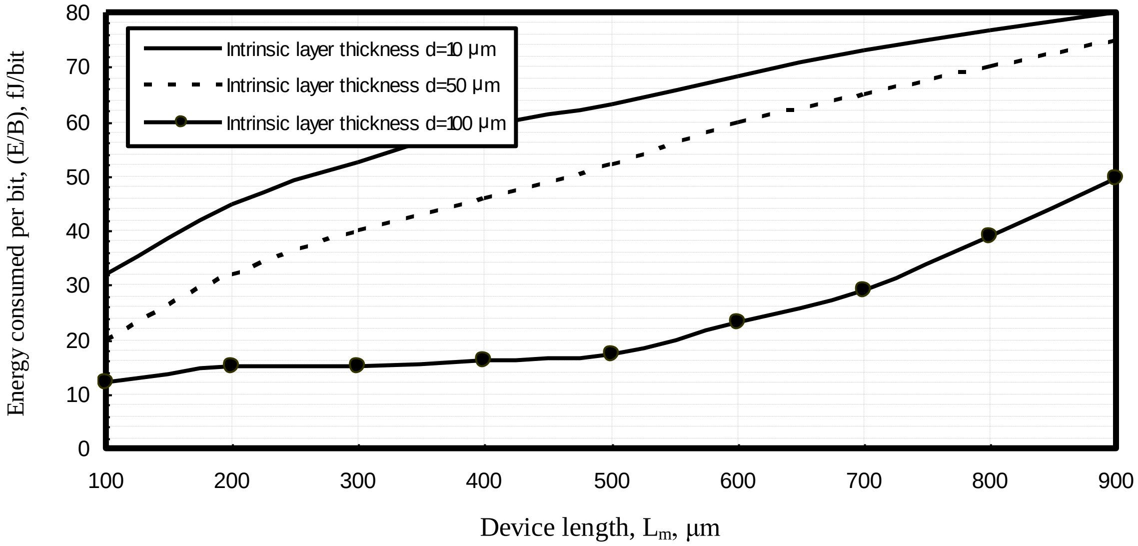

Fig. 13. Variations of energy consumed per bit against variations of device length and modulator layer thickness at the assumed set of the operating parameters

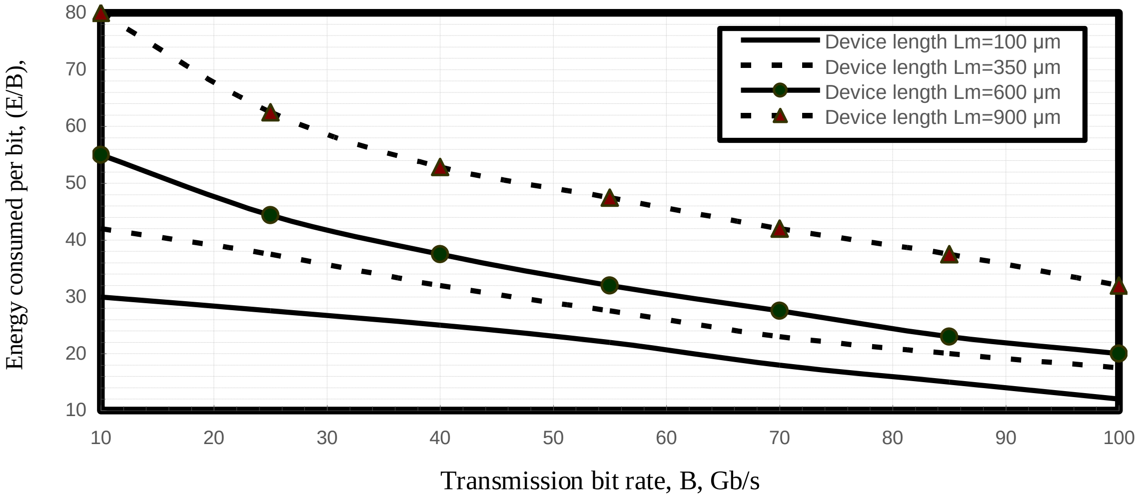

Fig. 14. Variations of energy consumed per bit against variations of transmission bit rate and device length at the assumed set of the operating parameters.

iii) Fig. 5 has indicated that the optimum device length decreases with increasing applied bias voltage and decreasing intrinsic modulator layer thickness.

iv) As shown in Fig. 6 has assured that output signal power decreases with increasing both device length and applied drive voltage. But bit error rate increases with increasing both device length and applied drive voltage.

v) Fig. 7 has demonstrated that bit error rate increases also with increasing both device length and transmission bit rate.

vi) Fig. 8 has indicated that the modulation photo current increases with increasing both device length and applied bias voltage.

vii) As shown in Fig. 9 has indicated that transient time response increases with increasing device length and decreasing intrinsic layer modulator thickness.

viii) Fig. 10 has proved that modulator transmission decreases with increasing both device length and applied drive voltage. But contrast ratio increases with increasing both device length and applied drive voltage.

ix) Fig. 11 has indicated that both modulation depth and insertion loss increase with increasing device length at zero bias voltage.

x) Fig. 12 has proved that modulation depth increases with increasing both device length and applied drive voltage.

xi) As shown in Fig. 13 has demonstrated that the energy consumed per bit increases with increasing device length and decreasing intrinsic layer modulator thickness.

xii) As shown in Fig. 14 has indicated that the energy consumed per bit decreases with increasing transmission bit rate and decreasing device length.

V. CONCLUSIONS

In a summary, the model has been investigated to show the design considerations for electro-absorption modulators over wide range of the affecting parameters. It is theoretically found that the decreased device length, this leads to the increased modulator switching speed and output signal power and the decreased bit error rate and energy consumed per bit. As well as it is found that the increased applied drive voltage, this results in the decreased optimum modulator length and the increased modulation photo current from modulator and contrast ratio and consequently modulation depth. Moreover it is indicated that the increased intrinsic modulator layer thickness, this results in the increased modulator switching speed, and the decreased transient time response. Table 2 has presented the comparison of our theoretical results for GaAs electro-absorption modulator with experimental results for GeSi EA modulator as listed below.

Table 2. Comparison our theoretical results (GaAs EA modulator) with GeSi EA modulator.

Design parameters	GaAs EA modulator (Our theoretical results) V_{PP} to achieve high speed operation at 3 Volt	GeSi EA modulator [17, 18, 24] (Experimental results) V_{PP} to achieve high speed operation at 3 Volt
	Same conditions of operation: intrinsic layer thickness, d=50 µm, device length, L_m=500 µm, and achieved bit rate, B=10 Gb/s	
Speed achieved, MSS, GHz	1.5 GHz	1.2 GHz
Energy per bit, (E/b), fJ/bit	52 fJ/bit	50 fJ/bit
Modulation depth, MD, dB	8.5 dB	8 dB
Insertion loss, IL, dB	4.8 dB	5 dB
Bit error rate, BER	$1.5x10^{-12}$	$1.8x10^{-12}$
Output power, P_0, mW	950 mW	900 mW
Contrast ratio, $R_{on/off}$, dB	15.3 dB	15 dB
Modulator transmission, T_m, %	88 %	85 %
Power length product, PLP, W.cm	3.8 W.µm	3.5 W.µm

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