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Full Length Research Paper

High speed performance of semiconductor electrooptic modulators for multi Gigahertz communication systems operation

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The effects of electrodes geometry and temperature on high frequency radio frequency transmission characteristics are deeply investigated against semiconductor material based electro optic modulator devices such as aluminum gallium arsenide (AlGaAs) and optical waveguide parameters. On the other hand, we have developed the optimization of the electro-optic modulator parameters where the effective index plays an essential role in the evaluation of the bandwidth structure. Therefore, a theoretical analysis of the capacitance, the characteristic impedance and the effective index determine how to increase the bandwidth. The effects of design parameters on the modulating voltage and optical bandwidth are also investigated for different materials based electro-optic modulators by using rigorous transmission modeling techniques. The low-loss wide-bandwidth capability of optoelectronic systems makes them attractive for the transmission and processing of microwave signals, while the development of high capacity optical communication systems has required the use of microwave techniques in optical transmitters and receivers. These two strands have led to the development of the research area of microwave photonics.

Key words: Electrooptic modulator, semiconductor material, optical bandwidth, high transmission performance.

INTRODUCTION

Present communication technology relies on fiber-optic systems which include light sources such as a laser, optical fiber, integrated optical components such as modulators and switches, and optical detectors. The lasers and detectors are fabricated using semiconductor materials, and the integrated optical components are generally fabricated using electrooptic single crystal materials such as lithium niobate ($LiNbO_3$). Among the integrated optical components, the contribution from electrooptic modulators using $LiNbO_3$ waveguide structures has been significant in the last several decades due to their high speed and chirp-free nature (Soref, 2006). The essential requirements for efficient electrooptic modulation are low half-wave (switching) voltage and broad 3-dB bandwidth. The optical modulator is a key component for photonics. Optical fiber communications, microwave photonics, instrumentation, and optical signals processing all require optical modulators. Several different technology platforms can be used for the realization of optical modulators. Of these, $LiNbO_3$ based ferroelectric electrooptic modulators provide the most mature technology. Electro-optic polymers and compound semiconductors are also attractive technologies for optical modulators. High-speed integrated electro-optic modulators and switches are the basic building blocks of modern wideband optical communications systems and represent the future trend in ultra-fast signal processing technology. As a result, a great deal of research effort has been devoted to developing low-loss, efficient and broadband modulators in which the radio frequency signal is used to modulate the optical carrier frequency (Liu et al., 2004). Most of the

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work done in the area of designing electrooptic modulators has been strongly focused on using $LiNbO_3$ (Liao et al., 2005). Interest in research in this field has arisen as lithium niobate devices have a number of advantages over others (Gu et al., 2007), including large electro-optic coefficients, low drive voltage, low bias drift, zero or adjustable frequency chirp, and the facility for broadband modulation with moderate optical and insertion losses and good linearity. However, on the other hand, $LiNbO_3$ devices cannot be integrated with devices fabricated using other material systems such as semiconductors and as a result they are best suited to external modulation applications. However, with the recent developments in semiconductor technology, modulators based on semiconductor materials have been receiving increasing attention. In particular, AlGaAs/GaAs material offers the advantage of technological maturity and potential monolithic integration with other optical and electronic devices in creating better optoelectronic integrated circuits (OEIC). Recently, electrooptic polymer modulators have also emerged as alternatives for optical modulators, particularly for low-cost applications for the next-generation metro and optical access systems**.** Today 2.5 Gb/s and 10 Gb/s modulators are standard commercial products and 40 Gb/s modulators are also being developed for the market after successful prototype demonstrations: however, the continuous demand to increase the data rate further will push their operating frequency well into the millimeter wave range Kim and (Gnauck, 2002).

High-speed optical modulators are essential for dealing with the current explosive growth in network traffic. These modulators are based on two types of physical effect: the electro absorption (EA) effect and the electro-optic (EO) effect. EA modulators have been widely used in recently developed 2.5 and 10 Gb/s optical transmission systems, because they have a small driving voltage of around 2 Volt Tsuzuki et al. (2004), a small size and can be easily integrated with laser sources. However, it is difficult to apply EA modulators to high-bit-rate transmission systems because of their chirp characteristics. EA modulators can only be applied to very-short-reach (VSR) systems at 40 Gb/s (Tsuzuki et al., 2003; 2004). In contrast, the interferometric Mach Zehnder (MZ) modulator provides more flexibility than the EA modulator in terms of chirp controllability. Moreover, MZ modulators are capable of controlling the optical phase. The MZ modulator is the most widely used device employing the EO effect. The optical phase can be controlled by supplying the EO waveguides with a voltage (Tsuzuki et al., 2004). High-bit rate transmission systems require a phase controlled modulation format, such as a carrier-suppressed return-to-zero (CS-RZ) or optical duo binary signal format (Tsuzuki et al., 2005; Cui and Berini, 2006; Shin et al., 2007). These formats are capable of improving the transmission performance because of their dispersion tolerance resulting from the fact that there is less spectral width broadening during modulation.

In the present study, aluminum gallium arsenide (AlGaAs) semiconductor material based electrooptic external modulators have been developed for extensive use in high speed and long distance optical fiber transmission systems. This is because they can offer the advantages of modulation exceeding multi Gb/sec combined with a low driving voltage, and they can eliminate the dynamic laser wavelength chirping which limits the span-rate system product due to their fiber dispersion characteristics. Modulators fabricated on semiconductor substrates such as (AlGaAs) and silicon doped materials are particularly attractive in that there exists the possibility of monolithic integration of these devices with other optoelectronic components.

MODELING ANALYSIS

For $Al_xGa_{(1-x)}As$, the parameters required to characterize the ambient temperature and operating signal wavelength dependence of the refractive-index, where Sellmeier empirical equation is under the form of Ibrahim et al. (2011):

$$n^2 = C_1 + \frac{C_2}{\lambda^2 - C_3} - C_4\lambda^2 \quad (1)$$

The set of the parameters is recast and dimensionally adjusted as the following Tsuzuki et al. (2004; 2005): C_1= 10.906-2.92x, C_2= 0.97501, $C_3=c_3T^2$; c_3= $(0.52886-0.735x/T_o)^2$, for x < 0.36. And $C_4=c_4$ $(0.93721+ 2.0857x10^{-4}T)$; c_4 = 0.002467(1.14x+1). We have taken into account the value of x=0.2, then the first and second differentiation of above empirical equation with respect to operating optical signal wavelength λ gives:

$$\frac{dn}{d\lambda} = -(\lambda/n)\left[\frac{C_2}{(\lambda^2 - C_3)^2} + C_4\right] \quad (2)$$

$$\frac{d^2n}{d\lambda^2} = \frac{-1}{n}\left[\frac{C_2\left(\left(\lambda^2 - C_3^2\right) - 4\lambda^2\right)}{\left(\lambda^2 - C_3^2\right)^3} - C_4\right], \quad (3)$$

The switching voltage V_π or the voltage required to change the output light intensity from its maximum to minimum value can be expressed as the following (Abd El-Naser et al., 2011; Seo and Fetterman, 2006; Abd El-Naser et al., 2009):

$$V_\pi = \frac{\lambda d}{2\Gamma n^3 r_{41} L_m}, \quad (4)$$

Where λ is the operating optical signal wavelength in μm, Γ is the confinement factor, d is the modulator thickness in μm, L_m is the modulator length in μm, and r_{41} is the electrooptic coefficient for used semiconductor material.

Under the perfect velocity matching condition (Allocation and Service Rules, Federal Communications Commission, Washington, DC, 2005; Abd El-Naser et al., 2009), achievable modulation bandwidth f_m is:

$$f_m = \frac{6.84}{\alpha L_m} \ , \ GHz \tag{5}$$

Where α is the power absorption coefficient in dB/μm.

Therefore the device performance index (DPI) can be expressed as the following expression (Abd El-Naser et al., 2009; Tazawa and Steier, 2006):

$$DPI = \frac{f_m}{V_\pi} \ , \ GHz/Volt \tag{6}$$

If a modulating voltage V_m in z-direction is applied, the change in index for the TM polarization is:

$$\Delta n_e = \frac{0.5 V_m n^3 r_{41}}{L_m} \ , \tag{7}$$

Therefore the product of the sensitivity and the bandwidth is not related to the signal quality factor and is given by Abd El-Naser et al. (2009):

$$SBP = \frac{0.65 n^2 \Gamma r_{41} c}{d\lambda} \ , \tag{8}$$

Where r_{41} is the electro optic coefficient for aluminum gallium arsenide material based EO modulator devices.

The total system rise time is the square root of the sum of the squares of the transmitter, optical fiber connection, and receiver rise times. That is given by Xu, et al. (2005):

$$\tau_s = \sqrt{\tau_t^2 + \tau_{mat.}^2 + \tau_r^2} \ , \tag{9}$$

The material dispersion time of the single mode fiber $\tau_{mat.}$ is given by the following equation:

$$\tau_{mat.} = -\left(\frac{L_m . \Delta\lambda . \lambda}{c}\right) . \left(\frac{d^2 n}{d\lambda^2}\right) \ , \tag{10}$$

In addition to providing sufficient power to the receiver, the system must also satisfy the bandwidth requirements imposed by the rate at which data are transmitted. A convenient method of accounting for the bandwidth is to combine the rise times of the various system components and compare the result with the rise time needed for the given data rate and pulse coding scheme. The system rise time is given in terms of the data rate for non return to zero pulse code by the expression (Abd El-Naser and Ahmed, 2009):

$$B_R\,(NRZ) = \frac{0.7}{\tau_s} , \tag{11}$$

Then the bandwidth length product within electrooptic modulator device is given by Abd El-Naser et al. (2009; 2011):

$$P_R(NRZ) = B_R . L_m \ , \ \text{Gbit.μm/sec} \tag{12}$$

The bandwidth for single mode operation within electrooptic modulator length L_m is given by:

$$B.W_{sig.} = \frac{0.44}{\tau_s \ . \ L_m} \ , \ \text{GHz} \tag{13}$$

The signal to noise ratio (SNR) is a measure of signal quality at the receiver end, it is given by Michalak et al. (2006):

$$SNR = \frac{(G P_0 \rho)^2 R_L}{4kT\, B.W_{sig.} + 2e R_L\, B.W_{sig.}\, G^n (I_D + \rho P_0)} \ , \tag{14}$$

$$(SNR)_{dB} = 10 \log SNR \ , \tag{15}$$

Where P_0 is the received or output optical power, ρ is the detector's unamplified responsivity, G is the detector gain if an avalanche photodiode (APD) is used, n accounts for the excess noise of the APD (usually between 2 and 3), $B.W_{sig.}$ is the signal bandwidth at the receiver, k is Boltzmann's constant (k = 1.38 x 10^{-23} J/K), e is the magnitude of the charge on an electron (1.6 x 10^{-19} coulomb), T is the ambient temperature in K, I_D is the detector's dark current, and R_L is the resistance of the load resistor that follows the photodetector. The maximum transmission bit rate or capacity according to modified Shannon technique is given by Abd El-Naser et al. (2011):

$$B_{R(SH)} = B.W_{sig.} \log_2 (1 + SNR) \ , \tag{16}$$

Where $B.W_{sig.}$ is the actual bandwidth of the optical signal, and SNR is the signal to noise ratio in absolute value (that is, not in dB). The Shannon Bit rate length product P_{SH} can be given by:

$$P_{SH} = B_{R(SH)} \ . \ L_m \ , \tag{17}$$

SIMULATION RESULTS AND PERFORMANCE ANALYSIS

We have investigated ultra high speed semiconductor electrooptic modulator devices for gigahertz system operation over wide range of the affecting operating parameters as shown in Table 1.

Based on the model equations analysis, assumed set of the operating parameters, and the set of the Figures (1 to 14), the following facts are assured:

i) As shown in the series of Figures (1 to 3), as both modulator length and confinement factor increase, and operating optical signal wavelength decreases, resulting in decreasing of switching voltage.
ii) Figure 4 has assured that as both modulator length and relative refractive index difference increase, this leads to increase in modulating voltage.
iii) Figure 5 has demonstrated that as power absorption coefficient and modulator length increase, this result in decreasing of modulation device bandwidth.

Table 1. Proposed operating parameters for our suggested electrooptic modulator device.

Parameter	Definition	Value and unit
T	Ambient temperature	300 K ≤ T ≤ 330 K
L_m	Modulator length	2 μm ≤ L_m ≤ 5 μm
d	Modulator thickness	0.1 μm ≤ w ≤ 0.5 μm
τ_t	Rise time of the transmitter	0.8 nsec
τ_r	Rise time of the receiver	1 nsec
P_0	Output power	0.1 ≤ P_0, Watt ≤ 0.6
T_0	Room temperature	300 K
λ	Signal operating wavelength	1.3 μm ≤ λ ≤ 1.65 μm
Δλ	Spectral line width of the optical source	0.1 nm
r_{41}	Electoptic coefficient for $Al_xGa_{(1-x)}$ As	18 Pm/volt
L	Inductance	20 μH
C	Capacitance	0.2 pF
R_L	Load resistance	5 kΩ
G	Detector gain	20 dB
α	Power absorption coefficient	0.1–0.5 dB/μm
Δn_e	Effective refractive index difference	0.01 ≤ Δn_e ≤ 0.09
Γ	Confinement factor	0.8 ≤ Γ ≤ 0.95
I_D	Detector dark current	8 nA
ρ	Detector responsivity	0.8 A/Watt
η	Modulator efficiency	90 %
c	Speed of light	3×10^8 m/sec

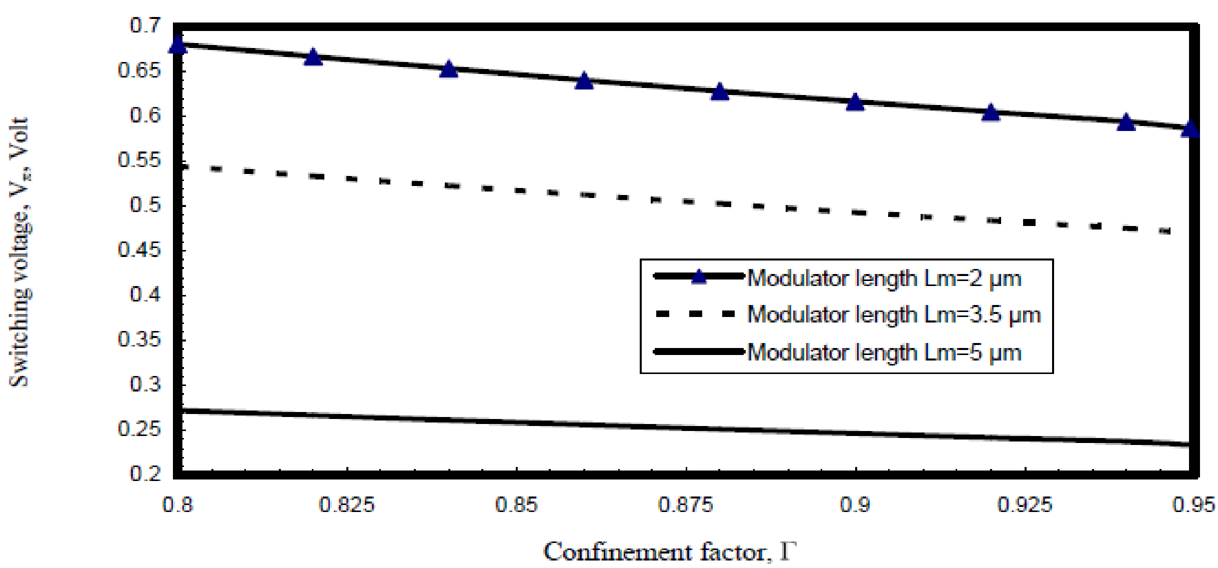

Figure 1. Variations of switching voltage versus confinement factor at the assumed set of parameters.

i) Figures (6 and 7) have indicated that as both operating optical signal wavelength and modulator thickness increase, and confinement factor decreases, this leads to decrease in device performance index.
ii) Figure 8 has assured that as operating optical signal wavelength increases and confinement factor
iii) Decreases, this result in decreasing of device sensitivity bandwidth product.
iv) Figure 9 has proved that as modulator length and optical output power increase, this result in increasing of signal to noise ratio.
v) As shown in Figures (10 and 11) have demonstrated that as modulator length and output power increase, this result in increasing of transmission bit rate length

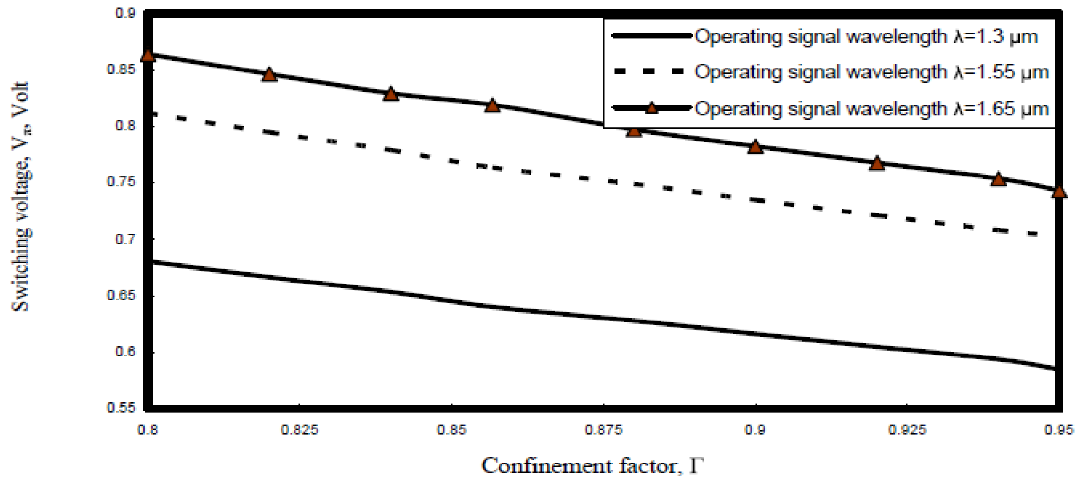

Figure 2. Variations of switching voltage versus confinement factor at the assumed set of parameters.

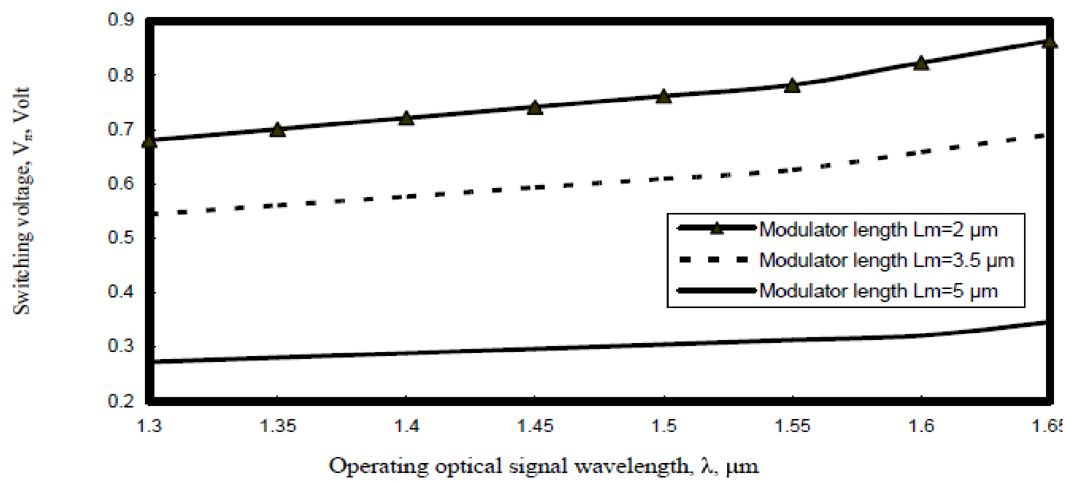

Table 3. Variations of switching voltage versus signal wavelength at the assumed set of parameters.

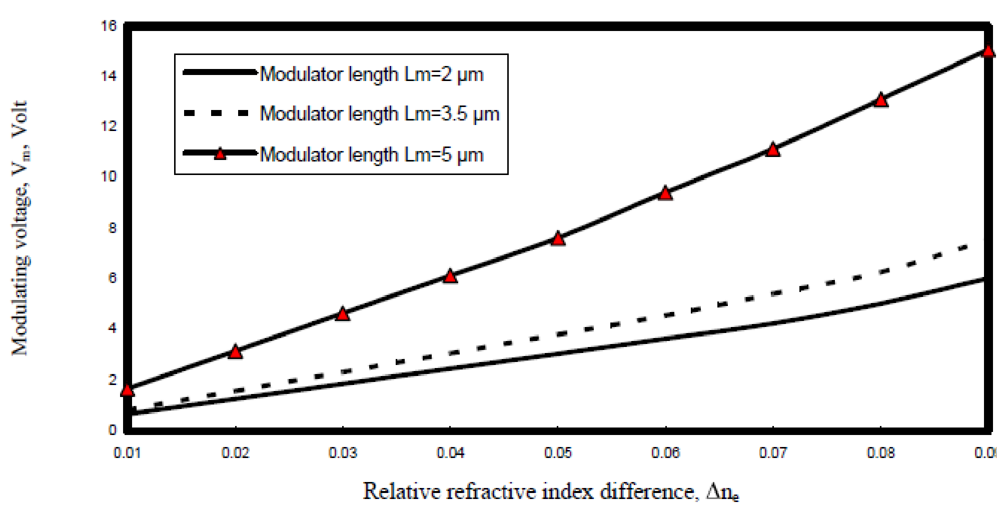

Table 4. Variations of modulating voltage against relative refractive index difference at the assumed set of parameters.

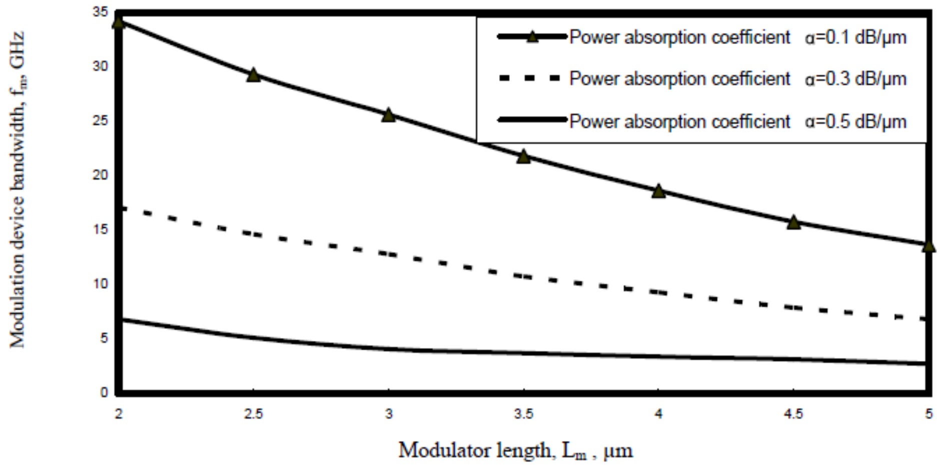

Figure 5. Variations of modulation bandwidth against modulator length at the assumed set of parameters.

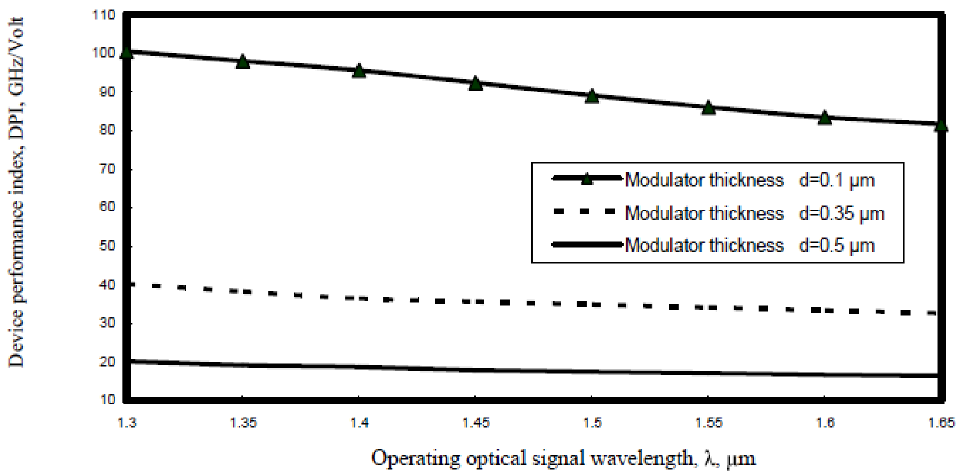

Figure 6. Variations of device performance index against optical signal wavelength at the assumed set of parameters.

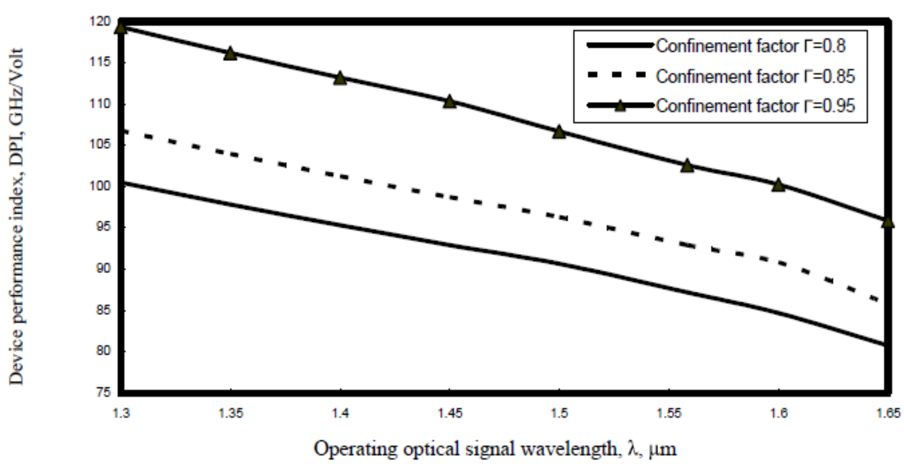

Figure 7. Variations of device performance index optical signal wavelength at the assumed set of parameters.

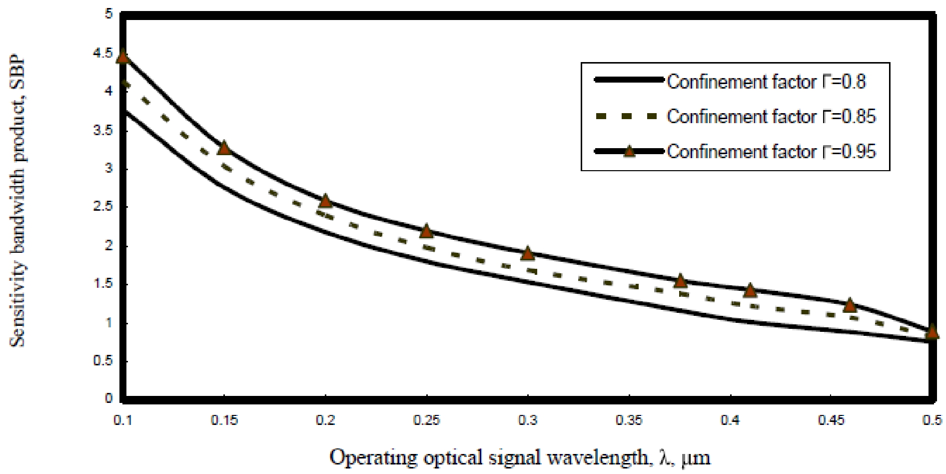

Figure 8. Variations of sensitivity bandwidth product against optical signal wavelength at the assumed set of parameters.

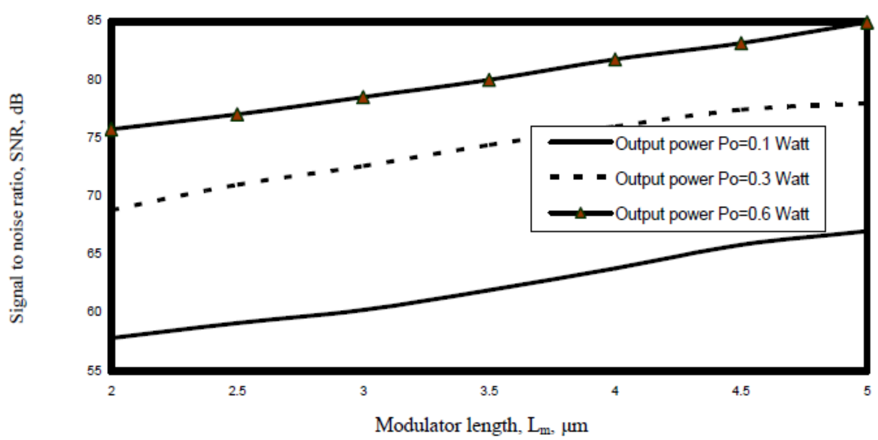

Figure 9. Variations of signal to noise ratio against modulator length at the assumed set of parameters.

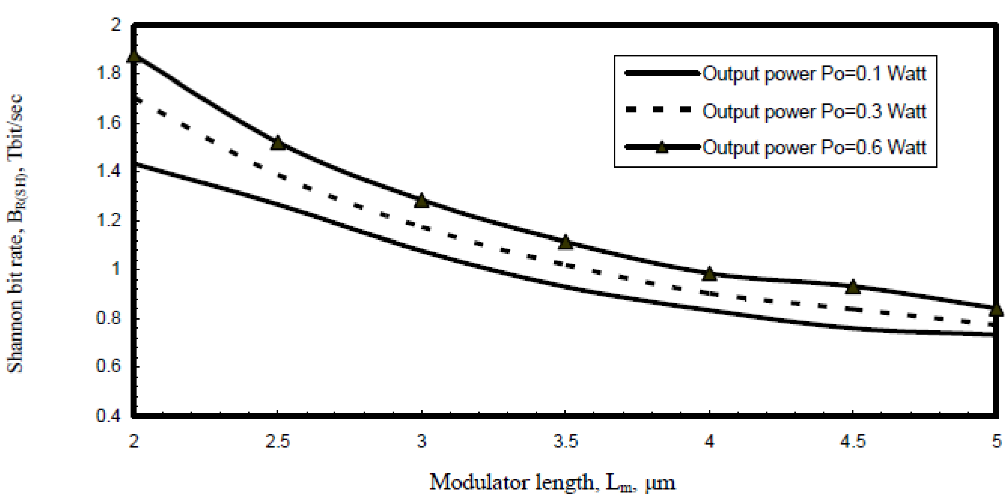

Figure 10. Variations of Shannon transmission bit rate against modulator length at the assumed set of parameters.

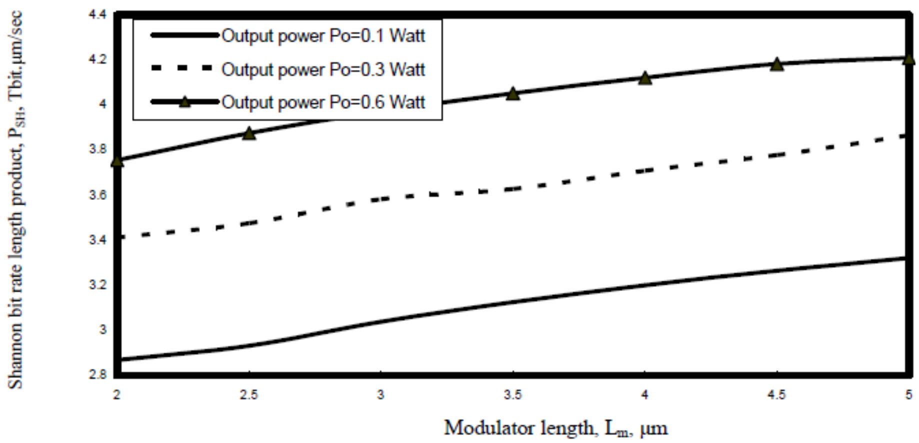

Figure 11. Variations of Shannon bit rate length product against modulator length at the assumed set of parameters.

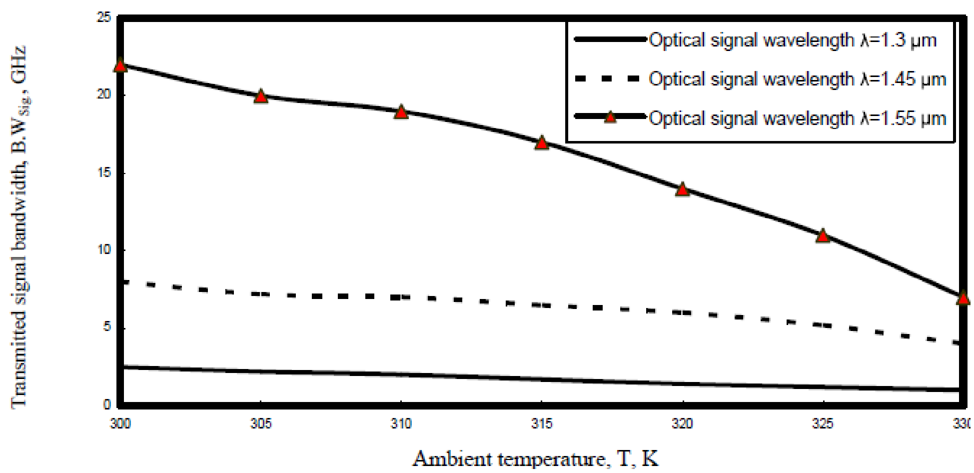

Figure 12. Variations of transmitted signal bandwidth versus ambient temperature at the assumed set of parameters.

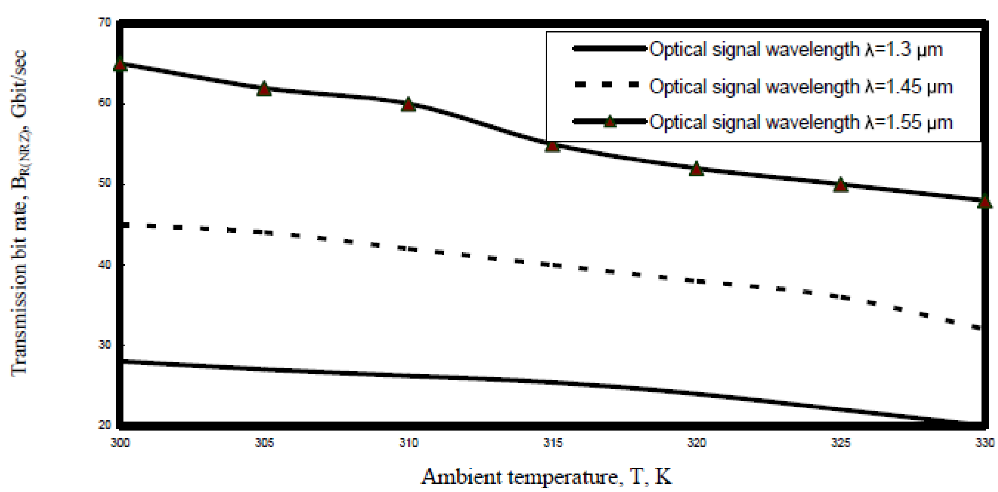

Figure 13. Variations of transmission bit rate versus ambient temperature at the assumed set of parameters.

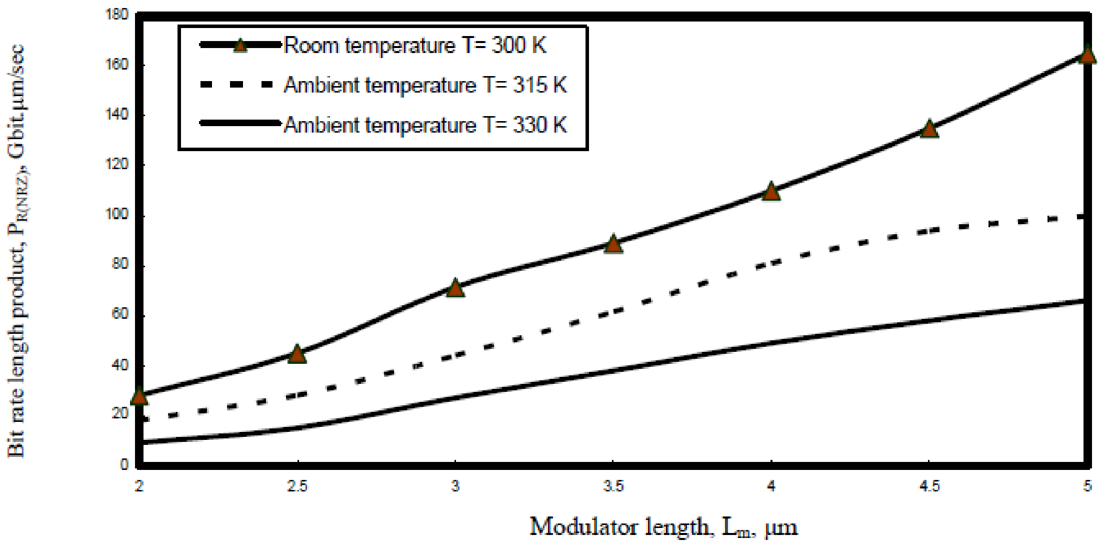

Figure 14. Variations of transmission bit rate length product against modulator length at the assumed set of parameters.

product. As well as modulator length increases, and output power decreases, this leads to decrease in transmission bit rates with Shannon transmission technique.

vi) Figure 12 has indicated that as ambient temperature decreases operating optical signal wavelength increases, this leads to increase in transmitted signal bandwidth.

vii) Figures (13 and 14) have demonstrated that as both modulator length and operating optical signal wavelength increase, and ambient temperature decreases, this result in increasing transmission bit rate length product. As well as both modulator length and ambient temperature increase and operating optical signal wavelength decreases, this result in decreasing of transmission bit rates with non return to zero coding formats.

Conclusions

In summary, we have presented ultra high speed semiconductor electrooptic modulator devices for multi gigahertz operation systems. It is theoretically found that the increased confinement factor and modulator length, and the decreased operating optical signal wavelength, this leads to the decreased switching device voltage. It is evident that the decreased operating optical signal wavelength and modulator thickness, and the increased confinement factor, this results in increasing of device performance index. As well as the increased output received power and modulator length, and the increased operating optical signal wavelength, and the decreased ambient temperature, this results in the increased transmission bit rate length product with using both Shannon transmission technique and NRZ coding formats.

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