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Electrooptic Polymer Modulators Performance Improvement with Pulse Code Modulation Scheme in Modern Optical Communication Networks

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***Abstract*— In the field of photonic modulation and sensing, the primary goal of the device engineer is to achieve the lowest possible switching power (or largest possible sensitivity), with the fastest switching speed, whilst maximizing the optical throughput of the device. To break through the current frequency limitations, adoption of new electrooptic materials and devices is necessary. Electrooptic polymers have high electrooptic activity and consistent frequency response up to at least 200 GHz. Additionally, electrooptic (EO) polymers can be processed to facilitate integration with other materials such as semiconductor light sources and detectors, low voltage drivers, and inorganic and polymeric waveguides. These EO polymer properties, either alone or in combination, lead to optical components or integrated optical devices that can generate, process, and detect optical signals at high frequency with high transmission data rates and broad signal bandwidth. This paper has proposed high speed of polymer electrooptic modulator devices with using pulse code modulation scheme to handle transmitted signal bandwidth, transmission bit rate, and product over wide range of the affecting parameters.**

***Index Terms*— Electrooptic (EO) Polymer, Optical Waveguide, Optical Polymers, Integrated Optics and Electrooptic Modulation**

I. INTRODUCTION

THE ability of devices to modulate and sense depends on utilizing various linear and non linear optical effects [1], [2]. A certain subset of these devices is based on electrical control of optical material properties, where the application of an electric voltage changes the refractive index and/or optical absorption of the material. Pockels effect, observed in certain crystals and in electro-optic polymers, gives rise to a linear change in refractive index with applied electric field. This effect is extremely useful and the principle on which the microwave receivers and field sensors in this work are based. Recent advances in polymer electro-optic materials have increased Pockels effect by an order of magnitude, and thus have allowed engineers to develop modulators and sensors with the lowest switching powers and fastest switching speeds to date [3, 4].

Low driving voltage and high-speed electro-optic (EO) modulators are of great interest due to their wide variety of applications including broadband communication, RF photonic links, millimeter wave imaging, and phased-array radars. In order to attain optical modulation at low driving voltages, a strong mode concentration and a tight mode overlap between optical and radio-frequency (RF) modes in the nonlinear EO material are required. Typically, to maintain a single mode operation in optical domain, the optical mode size is on an order of wavelength, that is [5], [6] 2μm at telecommunication region. As a result, to match with the optical mode, the RF guiding structure essentially has to reduce a factor of three orders of magnitude. Conventional traveling wave EO modulators are usually driven by RF transmission lines, such as coplanar waveguides (CPWs) and microstrip lines [7], [8]. These electrode designs provide not only high speed operation but also a strong overlap between optical and RF modes. While the device operates at very high frequency, that is, over 20 GHz, the RF wave propagation attenuation attributed from both conduction loss and dielectric loss becomes the key issue that prevents the device from operating over a wide bandwidth. Physically, a small mode size provides a strong RF field concentration, or a small mode volume, however, leads to a significant increase in propagation loss. As a result, an optimal design of RF electrode design including signal electrode and gap between signal and ground is required to minimize the overall RF propagation loss [9]. Polymer electrooptic devices have been extensively studied and explored during the last few years. They have intrinsic advantages over conventional materials such as high speed operation, compatibility with other materials and substrates, and the ability to make complex configurations and arrays. On the other hand, there have been problems with thermal stability, power handling, and drift. These problems are currently the subject of intense research and must be solved before commercial devices become available [10], [11].

In the present work, the need for increased capacity and speed in transporting and processing information is driving the development of advanced optical components for applications in broadband communication, high speed computing, and national security. In general, advanced optical components should operate at high frequency with broad bandwidth, consume less power and be integratable with other optical components. A key aspect of any optical component is the translation of an electrical signal into an optical signal. One way to accomplish this electrical to optical translation is by exploiting the electrooptic effect, which changes the refractive index of a material in response to an applied electric field. We have deeply investigated electrooptic modulator device to estimate rise time, transmitted signal bandwidth, transmitted data rats and transmission bit rate length product, and switching voltage with using pulse code modulation scheme. The reliability of high speed polymer electrooptic (EO) modulators is the most critical milestone for the use of these materials in commercial applications.

II. SCHEMATIC VIEW OF HIGH SPEED TRAVELLING WAVE EO POLYMER MODULATOR

High frequency performance has been obtained with a traveling wave analog high-speed modulator. The modulator was implemented by using a coplanar waveguide (CPW) fabricated directly onto the half-coupler surface followed by the deposition of an electrooptic waveguide, as shown in Fig. 1 [12]. One of the CPW gaps was precisely aligned with the fiber core. The polymer waveguide was deposited between the coplanar electrodes using spin coating deposition. In contrast to the Fabry{Perot device, the electrooptic polymer was contact poled parallel to the surface of the half-coupler. The RF field traveling on the CPW modulates the transmitted light by again altering the phase-matching condition of the waveguides [13].

The maximum modulation frequency demonstrated with this device was 17GHz and was limited by the detector. Based on microwave bandwidth measurements [14], expect a 3dB bandwidth well in excess of 100 GHz. With driving voltage amplitude of 12 V, the modulation efficiency was very low at 0.02%. The small modulation efficiency was due to the short interaction length and low electrooptic coefficient polymer, and it is not an inherent limitation of in-line modulators [15].

III. MODELING DESCRIPTION AND ANALYSIS

The TE–TM phase-difference modulator is realized via the EO polymer and its EO effect, with the applied modulating voltage V_m, the change of the phase difference between the TM and TE modes can be described as [16]:

$$\Delta\phi_{TE-TM} \approx -\frac{2\pi n_e^3 r_{33} \Gamma V_m L_m}{3\lambda d} , \quad (1)$$

Where d is the thickness of the EO polymer modulator in cm, L_m is the modulator length in cm, n_e is approximately the refractive index of the material based EO polymer modulator device, λ is the operating signal wavelength in μm, r_{33} is the electro-optic coefficient, and Γ is confinement factor, and is defined as the overlap integration of the modulating electrical field and the optical mode. Where the effective refractive index n_e of polymer material based electrooptic modulator device can be expressed as [17]:

$$n_e = \sqrt{\frac{B_1\lambda^2}{\lambda^2 - B_2^2} + \frac{B_3\lambda^2}{\lambda^2 - B_4^2} + \frac{B_5\lambda^2}{\lambda^2 - B_6^2}} , \quad (2)$$

The set of parameters of empirical equation coefficients of polymer material are recast as the following [17]: B_1=0.4963, B_2= 0.0718$(T/T_0)^2$, B_3=0.6965, B_4=0.1174 $(T/T_0)^2$, B_5=0.3223, and B_6=9.237 $(T/T_0)^2$. Where T is the ambient temperature, and T_0 is the room temperature. Then the first and second differentiation of Eq. (2) with respect to operating wavelength λ yields the following expressions:

$$\frac{dn_e}{d\lambda} = \frac{-1}{n_e}\left(\frac{B_1B_2^2\lambda}{\left(\lambda^2 - B_2^2\right)^2} + \frac{B_3B_4^2\lambda}{\left(\lambda^2 - B_4^2\right)^2} + \frac{B_5B_6^2\lambda}{\left(\lambda^2 - B_6^2\right)^2}\right) , \quad (3)$$

$$\frac{d^2n_e}{d\lambda^2} = \frac{1}{n_e}\left(\frac{B_1B_2^2\left(3\lambda^2 + B_2^2\right)}{\left(\lambda^2 - B_2^2\right)^3} + \frac{B_3B_4^2\left(3\lambda^2 + B_4^2\right)}{\left(\lambda^2 - B_4^2\right)^3} + \frac{B_5B_6^2\left(3\lambda^2 - B_6^2\right)}{\left(\lambda^2 - B_6^2\right)^3} - \left(\frac{dn_e}{d\lambda}\right)^2\right) , \quad (4)$$

The transmission of a Mach–Zehnder (MZ) EO polymer modulator is given by [18]:

$$T(\lambda) = 0.5\left[1 + \cos\left(\frac{\pi V_m}{V_\pi(\lambda)} + \phi_B(\lambda)\right)\right] , \quad (5)$$

Where the phase bias of EO polymer modulator can be expressed as:

$$\phi_B = \phi_\Delta + \phi_v = \frac{2\pi\,\Delta n_e}{\lambda} + \frac{\pi V_B}{V_\pi} , \quad (6)$$

Where Δn_e is the effective Relative refractive-index change, V_B is the applied bias voltage in Volt, and V_π is the switching voltage or the voltage required to change the output light intensity from its maximum value to its minimum value can be expressed as the following:

$$V_\pi = \frac{\lambda\ d}{2\ \Gamma\ n_e^3(\lambda) r_{33}\ L_m} , \quad (7)$$

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

$$\Delta n_e = \frac{0.5 V_m n_e^3 r_{33}}{L_m} , \quad (8)$$

The sensitivity (S) of the EO polymer modulator can be written as [19-21]:

$$S = \frac{0.65\ Q\Gamma r_{33} n_e^2}{d} , \quad (9)$$

Where Q is the quality factor of the EO modulator device. The higher Q device will have higher sensitivity, as expected. The bandwidth of the modulator is inversely proportional to the Q. However, the product of the sensitivity and the bandwidth is not related to the Q and is given by [22, 23]:

$$SBP = \frac{0.65 n_e^2 \Gamma r_{33} c}{d\lambda} , \quad (10)$$

The quality factor of the EO modulator device Q can be expressed as the following [24, 25]:

$$Q = \sqrt{m_1} - \sqrt{m_0} , \quad (11)$$

Where $m_0=m_{b0}+m_d$ is the average number of electrons representing the 'zero' symbol, $m_1=m_{b1}+m_d$ is the average number of electrons representing the 'one' symbol, $m_d=i_d T_s/q$ is the average number of electrons correspond the dark current i_d during the switching time T_s. Where $m_{b0}=\lambda\eta P_0 T_s/hc$, $m_{b1}= \lambda\eta P_1 T_s/hc$. Where η is the efficiency of EO modulator device, h is the Plank's constant (6.625×10^{-34} J.Sec), q is the electron charge (1.602×10^{-19} C), P_0 is the optical power representing the 'zero' symbol, and P_1 is the optical power representing the 'one' symbol. The transmitted signal bandwidth for standard single mode for polymer material based electrooptic modulator length L_m is given by [26, 27]:

$$B.W_{sig.} = \frac{0.44}{\Delta\tau\ .\ L_m} , \quad (12)$$

Where Δτ is the total pulse broadening due to total dispersion coefficient in system based EO modulator:

$$\Delta\tau = D_t\,\Delta\lambda\,L_m \ ,\ n\sec/nm.cm \quad (13)$$

Where the total dispersion coefficient in system based EO modulator device is given by:

$$D_t = \left(M_{md} + P\right) , \quad (14)$$

In which both material and profile dispersions were taken into account as M_{md} and P respectively:

$$M_{md} = \left(-\frac{\lambda^3}{c}\left(\frac{dn_e}{d\lambda}\right)^2 - \frac{2\lambda}{c}\left(\frac{d^2 n_e}{d\lambda^2}\right)(N_1 \Delta n_e) C_1 \left(\frac{2\alpha}{\alpha+2}\right)\right)^{0.5} \quad (15)$$

$$P = \left(\left(\frac{N_1 \Delta n_e}{c\lambda}\right)^2 \left(\frac{\alpha - 2 - \varepsilon}{\alpha + 2}\right)^2 \times \frac{2\alpha}{3\alpha + 2}\right)^{1/2} \quad (16)$$

Where N_1 is the group index for the mode which is given by:

$$N_1 = n_e - \lambda \frac{dn_e}{d\lambda} \quad , \quad (17)$$

Where C_1 is a constant related to index exponent and profile dispersion and is given by:

$$C_1 = \frac{\alpha - 2 - \varepsilon}{\alpha + 2} \quad , \quad (18)$$

Where α is the index exponent, and ε is the profile dispersion parameter, and is given by:

$$\varepsilon = -\frac{2n_e}{N_1} \frac{\lambda}{\Delta n_e} \quad , \quad (19)$$

In the pulse code modulation scheme, total transmitted bit rate within EO modulator device can be expressed in terms of transmitted signal bandwidth, and number of quantization levels, M as the following formula [28]:

$$R_T(PCM) = 2\, B.W_{sig.} \log_2 M \quad , \quad (20)$$

Where M is expressed in number of bits as, $M=2^n$, where n is the number of bits in the sample. Previous equation can be expressed in another form as the following formula:

$$R_T(PCM) = 2\, n\, B.W_{sig.} \quad , \quad (21)$$

IV. SIMULATION RESULTS AND PERFORMANCE ANALYSIS

We have investigated the development of electrooptic polymer modulator devices with pulse code modulation scheme for high speed performance operation in modern optical communication networks over wide range of the affecting operating parameters as shown in Table 1.

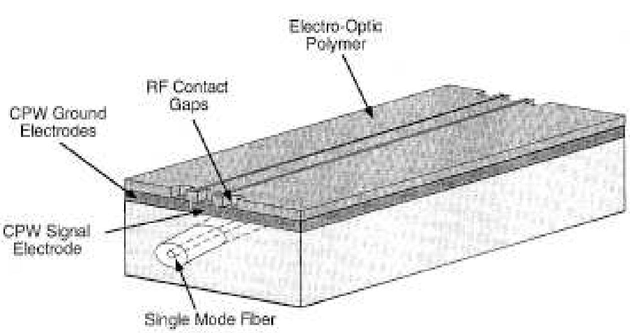

Fig. 1. High-speed traveling wave EO polymer modulator

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

Operating parameter	Symbol	Value
Operating signal wavelength	λ	1.3 μm ≤ λ ≤ 1.55 μm
Spectral width of optical source	$\Delta\lambda$	0.1 nm=10^{-8} cm
Ambient temperature	T	300 K ≤ T ≤ 330 K
Room temperature	T_0	300 K
Modulator length	L_m	0.2 μm ≤ L_m ≤ 1 μm
Speed of light	c	3 x10^{10} cm/sec
Switching time	T_s (on state)	0.5 msec–1 msec
	T_s (off state)	0.1 msec-0.4 msec
Dark current	i_d	0.1 μA–1 μA
Modulator thickness	d	0.02 μm ≤ w ≤ 0.1 μm
Electro-optic coefficient	r_{33}	300 pm/Volt
Bias voltage	V_B	2–10 Volt
Confinement factor	Γ	0.8–0.95
Relative refractive index difference	Δn_e	0.01–0.05
Optical power	P_0=P_1	0.1–0.6 Watt
Quantum Efficiency	η	90 %
Index exponent	α	2
Number of quantization levels	M	16–128

Based on the model equations analysis, assumed set of the operating parameters, and the set of the Figs. (2-20), the following facts are assured as the following results:

i) As shown in Figs. (2, 3) have assured that as ambient temperature decreases, and as modulator thickness, operating optical signal wavelength, and confinement factor increase, this leads to decrease in phase difference between transverse electric and transverse magnetic modes.
ii) Fig. 4 has indicated that as both ambient temperature and modulator length increase, these results in increasing of phase difference between transverse electric and transverse magnetic modes.
iii) Fig. 5 has demonstrated that as both operating optical signal wavelength and ambient temperature increase, this leads to increase in switching voltage.
iv) As shown in Figs. (6, 7) have indicated that as optical signal wavelength increases, and both bias voltage and relative refractive index difference decrease, this results in decreasing in modulator phase bias.
v) Fig. 8 has demonstrated that as ambient temperature increases, and as operating optical signal wavelength decreases, this results in increasing of modulating voltage.
vi) As shown in Fig. 9 has assured that operating optical signal wavelength decreases, and dark current increases, these results in decreasing of modulator signal quality factor.

vii) Figs. (10, 11) have demonstrated that as ambient temperature, and dark current increase, and as operating optical signal wavelength decreases, this results in decreasing of polymer modulator sensitivity.

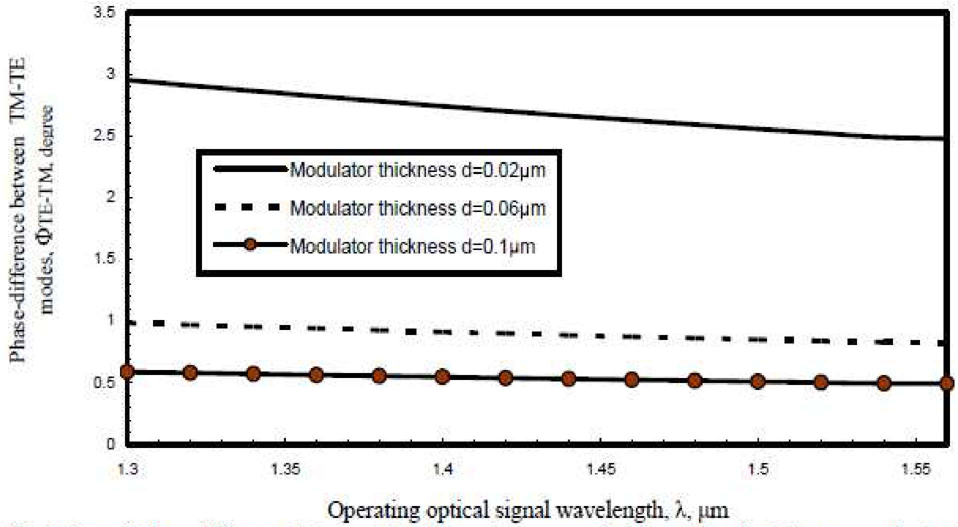

Fig. 2. Variations of phase difference between TM-TE modes versus signal wavelength at the assumed set of parameters.

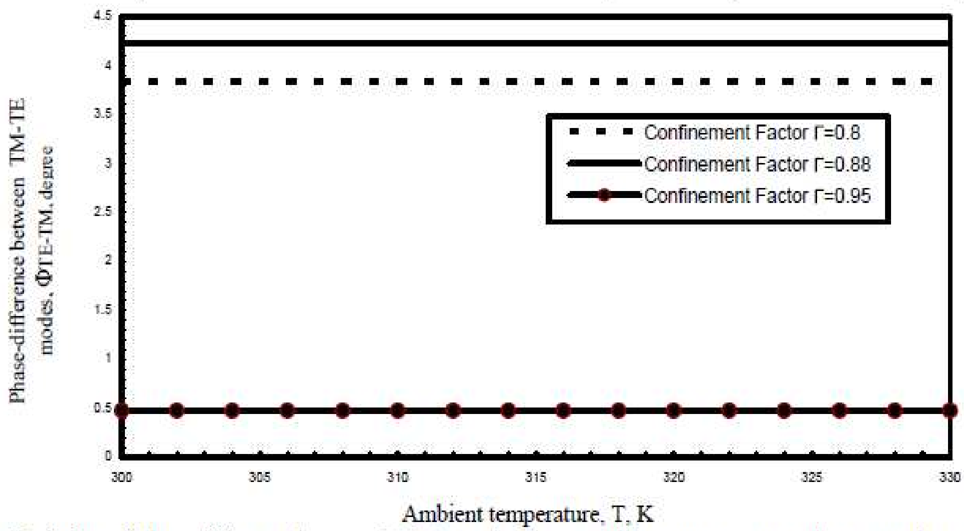

Fig. 3. Variations of phase difference between TM-TE modes versus ambient temperature at the assumed set of parameters.

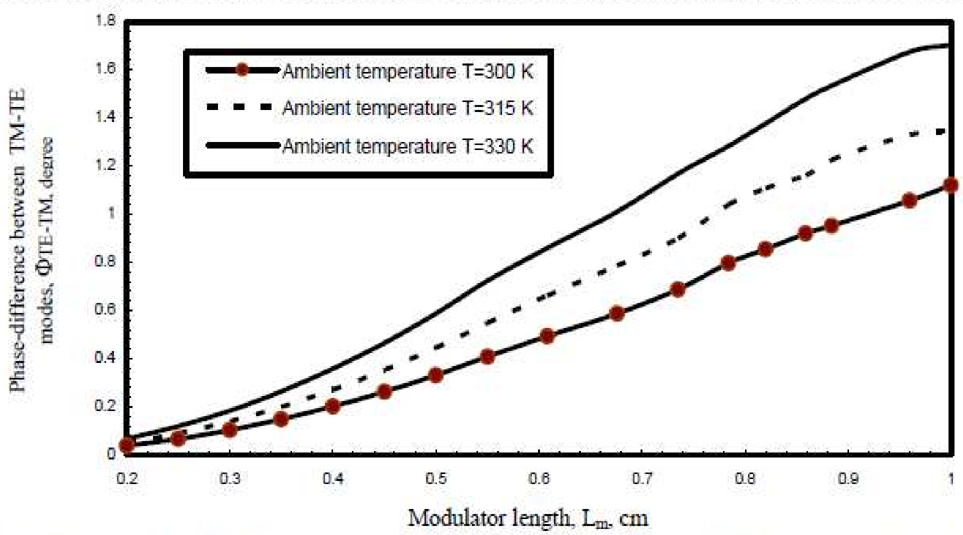

Fig. 4. Variations of phase difference between TM-TE modes against modulator length at the assumed set of parameters.

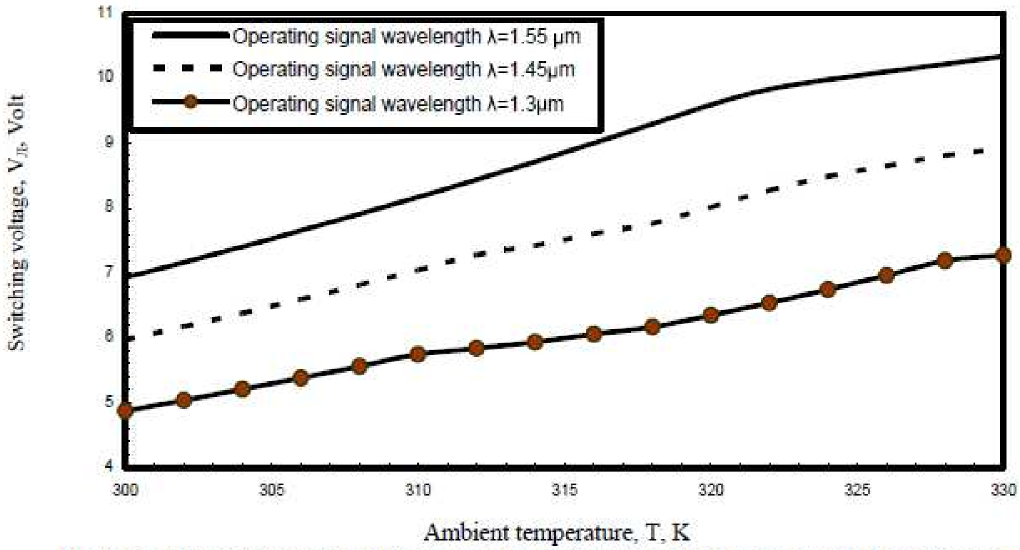

Fig. 5. Variations of switching voltage against ambient temperature at the assumed set of parameters.

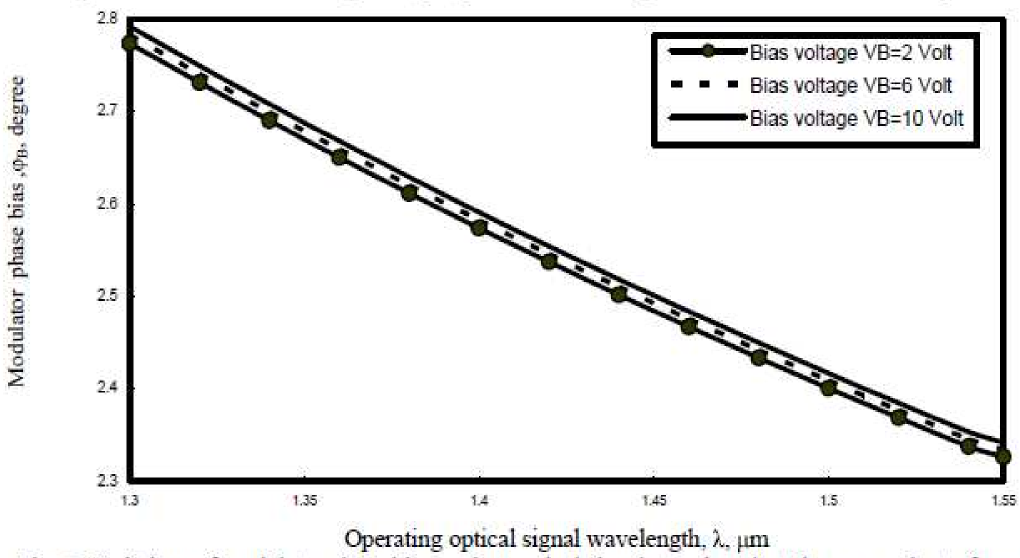

Fig. 6. Variations of modulator phase bias against optical signal wavelength at the assumed set of parameters.

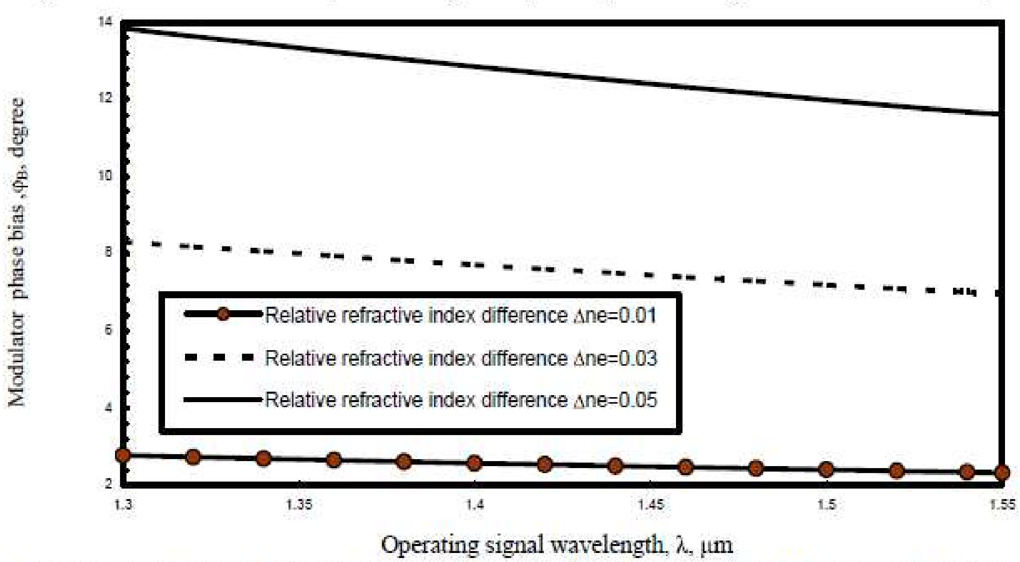

Fig. 7. Variations of modulator phase bias against optical signal wavelength at the assumed set of parameters.

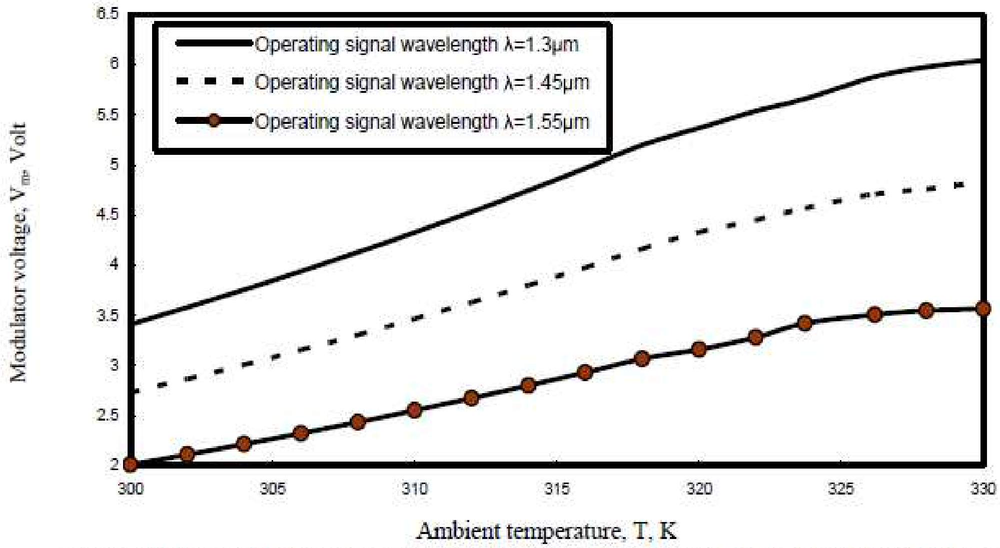

Fig. 8. Variations of modulator voltage against ambient temperature at the assumed set of parameters.

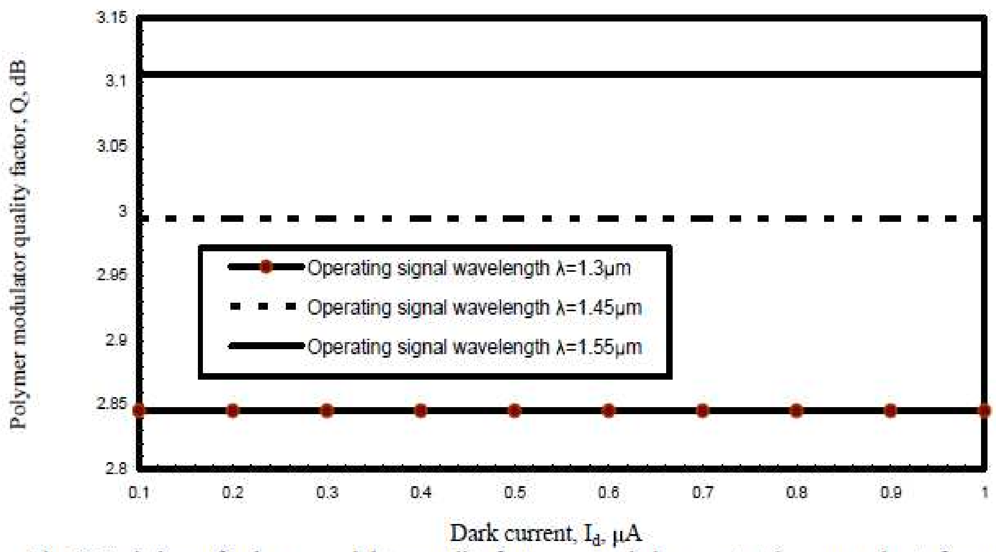

Fig. 9. Variations of polymer modulator quality factor versus dark current at the assumed set of parameters.

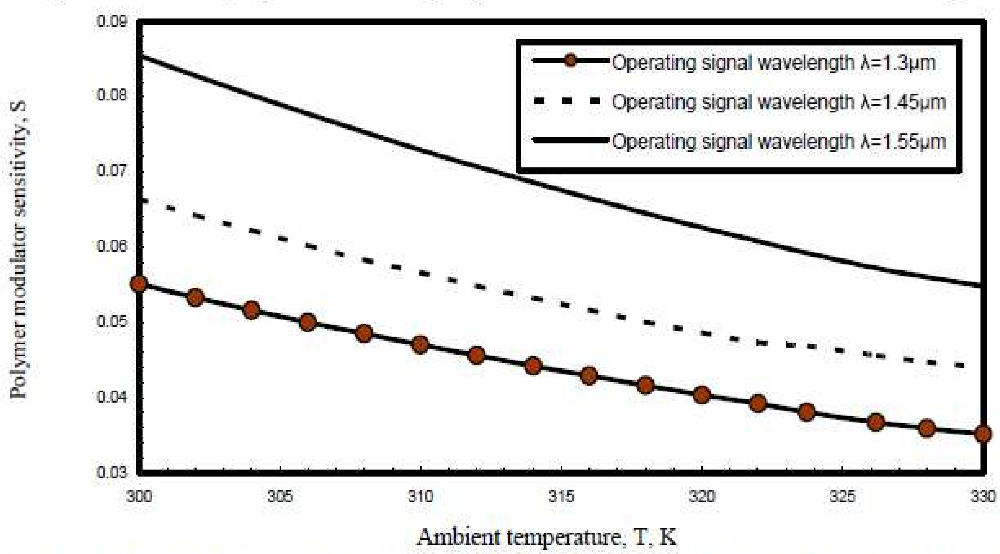

Fig. 10. Variations of polymer modulator sensitivity versus ambient temperature at the assumed set of parameters.

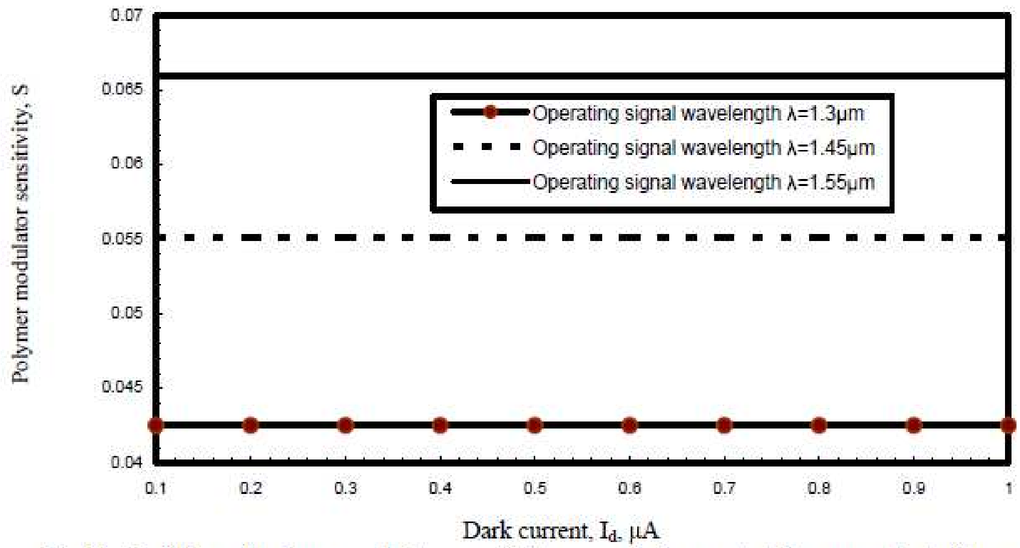

Fig. 11. Variations of polymer modulator sensitivity versus dark current at the assumed set of parameters.

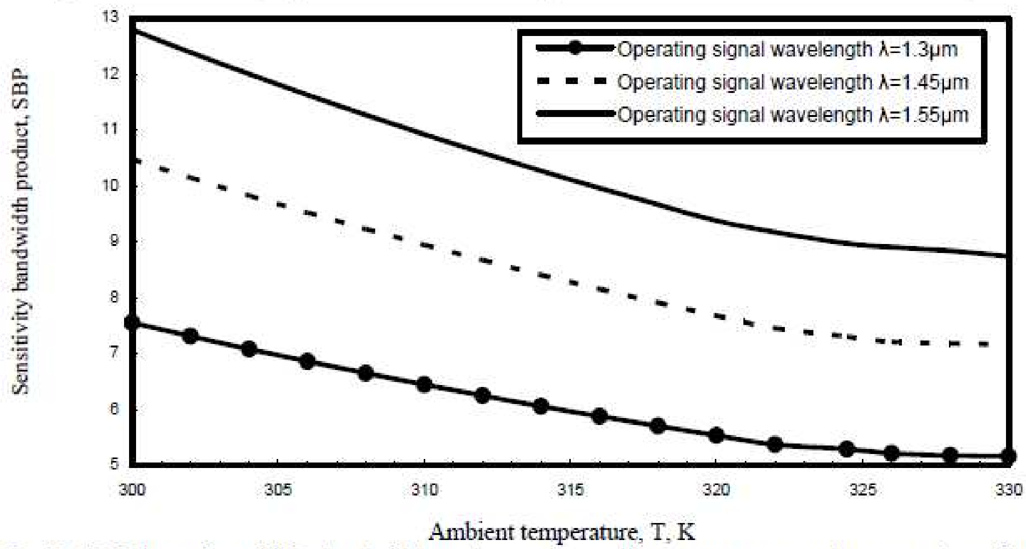

Fig. 12. Variations of sensitivity bandwidth product against ambient temperature at the assumed set of parameters.

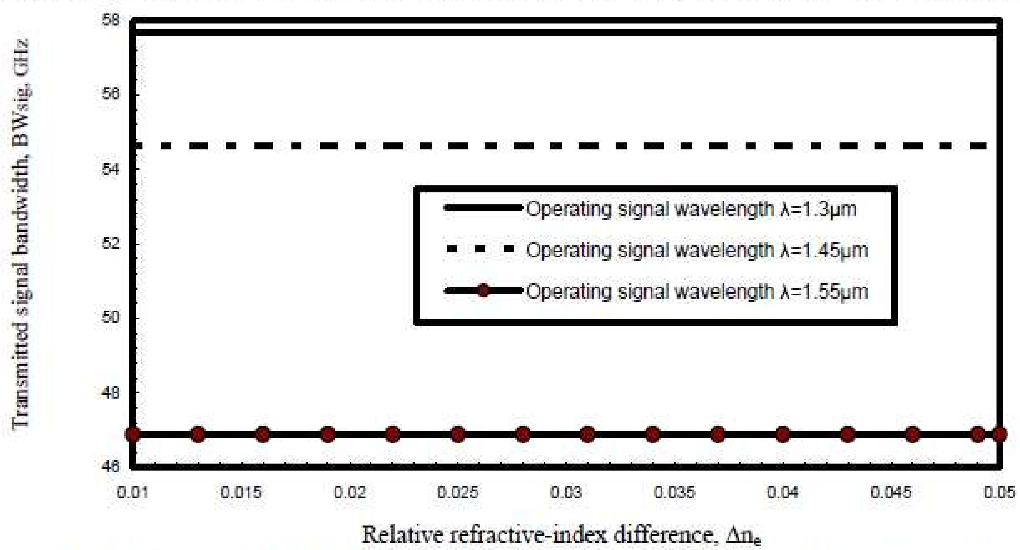

Fig. 13. Variations of signal bandwidth versus relative refractive index difference at the assumed set of parameters.

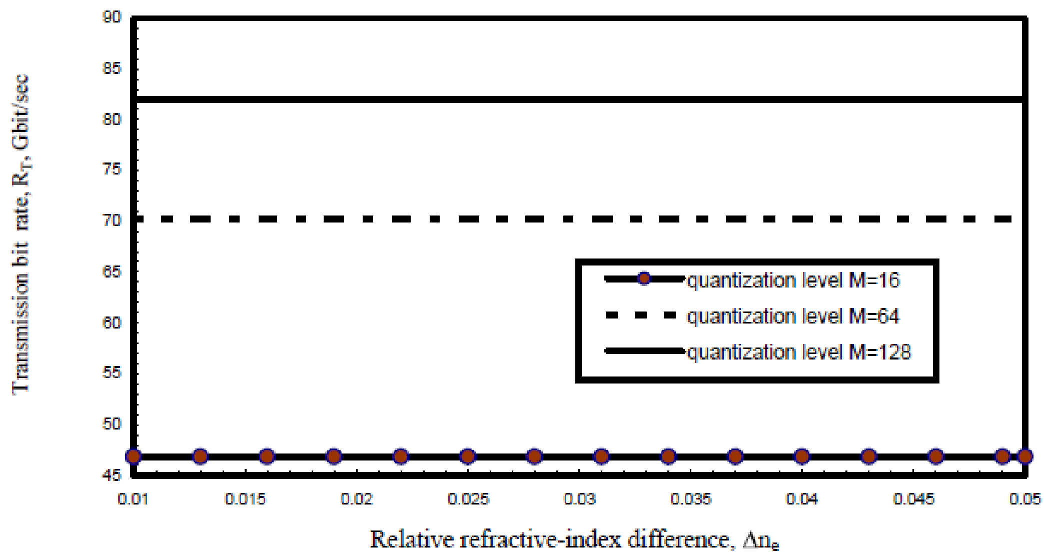

Fig. 14. Variations of bit rate versus relative refractive index difference at the assumed set of parameters.

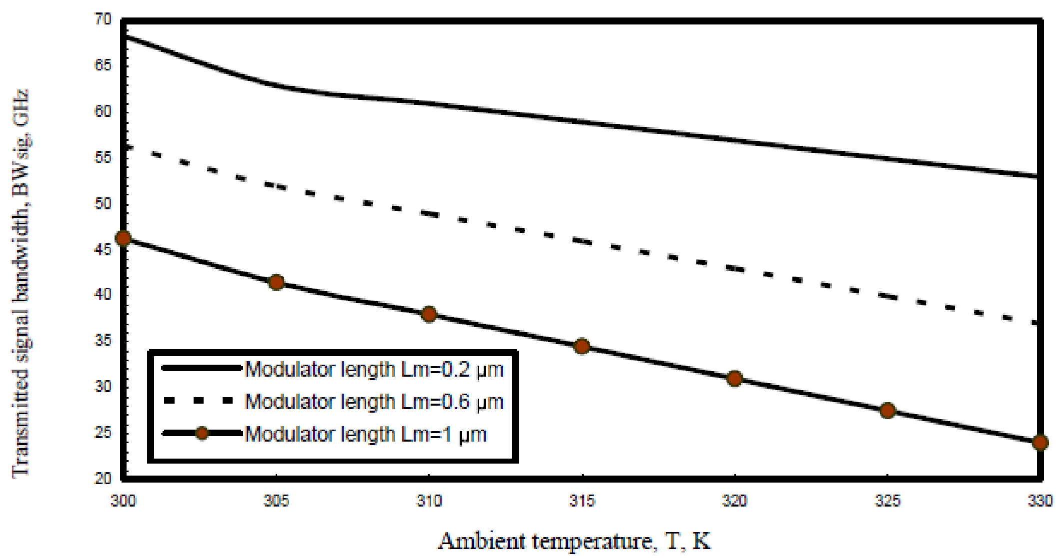

Fig. 15. Variations of signal bandwidth against ambient temperature at the assumed set of parameters.

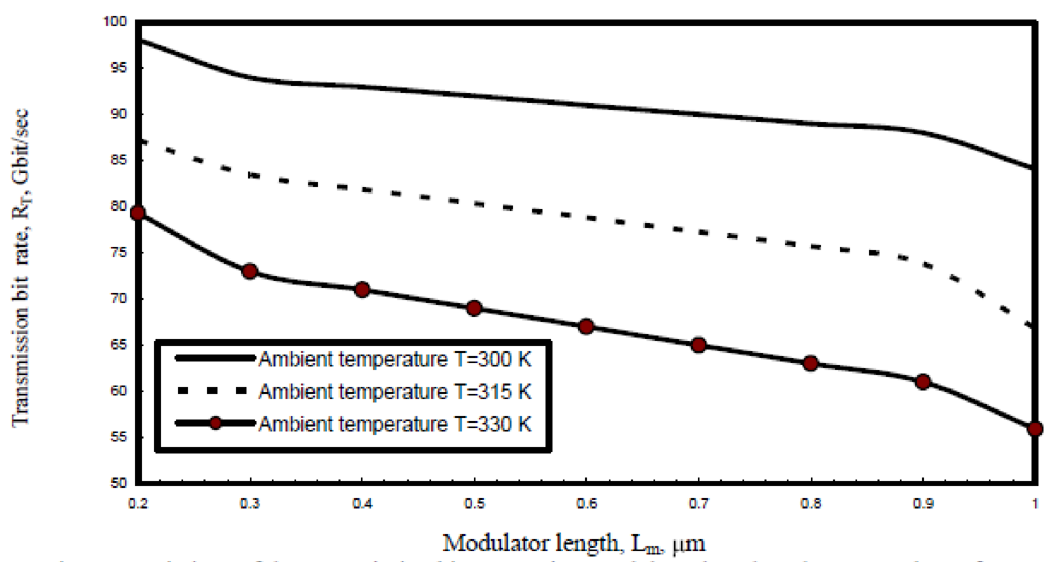

Fig. 16. Variations of the transmission bit rate against modulator length at the assumed set of parameters.

viii) As shown in Fig. 12 has indicated that as ambient temperature increases, and as operating optical signal wavelength decreases, this leads to decrease in sensitivity bandwidth product.

ix) Fig. 13 has assured that as both operating optical signal wavelength and relative refractive index difference decease, this leads to increase in transmitted signal bandwidth.

x) As shown in Fig. 14 has demonstrated that as relative refractive index difference decreases, and number of quantization levels increase, this leads to increase of transmission bit rates.

xi) Figs. (15, 16) have assured that as both modulator length and ambient temperature decrease, these results in increasing of both transmitted signal bandwidth and transmission bit rate.

V. CONCLUSIONS

In a summary, we have presented and developed the polymer electrooptic modulator devices with pulse code modulation scheme for high speed performance operation in modern optical communication networks. It is evident that the decreased modulator length, relative refractive index difference, optical signal wavelength, and ambient temperature, this leads to the increased transmitted signal bandwidth and transmission bit rate. As well as the decreased ambient temperature, dark current, modulator length, and the increased optical signal wavelength, confinement factor, this results in the increasing of modulator sensitivity and modulator sensitivity bandwidth product and then to increase the modulator signal quality factor. It is also theoretically found that the decreased optical signal wavelength and ambient temperature, and the increased modulator length, this leads to the decreased switching voltage. Moreover, the decreased ambient temperature, relative refractive index difference, and modulator length, and the increased optical signal wavelength, this results in the decreased modulating voltage. It is evident that the high speed performance operation of polymer electrooptic modulator devices depend on the variations of the modulator dimensions (modulator length, modulator width and modulator thickness), ambient temperature, operating optical signal wavelength, effective refractive index difference which are considered as the important criteria to make the electroptic modulator devices in high performance operation, upgrading modulator device efficiency and increasing modulator signal quality factor within choosing best operating parameters of these values.

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