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Optical and Electrical Interconnection Networks and its Performance Considerations in Advanced Computing Systems

Ahmed Nabih Zaki Rashed
Electronics and Electrical Communications Engineering Department
Faculty of Electronic Engineering, Menouf 32951, Menoufia University, EGYPT
E-mail: ahmed_733@yahoo.com

Abstract- Parallel and distributed computing systems become more and more powerful and hence place increasingly higher demands on the networks that interconnect their processors or processing nodes. It is believed that the concept of integrated optical interconnect is a potential technological solution to alleviate some of the ever more pressing issues involved in exchanging data between cores in optical communication architectures (inter-line crosstalk, latency, connectivity and power consumption). This study has presented the compete comparison between optical interconnects that bring advantage of high data rate density, i.e. large bandwidth with small physical dimensions, as well as large bandwidth x distance product in compared with electrical interconnections.

Index Terms— Electrical interconnections, Optical interconnections, Computing systems, Integrated electro-optic interconnect.

I. INTRODUCTION

The goal of the interconnection network is to serve as the communications infrastructure for transferring data among the growing massive numbers of processing and memory elements. The performance of advanced computing systems clearly relies upon the efficiency and capabilities of the interconnect. Interconnection networks, unfortunately, have traditionally failed to match the fast progress pace exhibited by microprocessors [1, 2]. Unlike microprocessors, the performance of interconnection networks is not dominated by the transistor gate size, it is rather dependent on the dynamics of signal propagation through electronic transmission lines (e.g., coaxial cables or backplane differential traces). Losses caused by skin effect limit the bandwidth of transmission lines to a few gigahertz and the transmission distance at high data rates to a few meters for cables and less than 1m for backplanes [3, 4]. Careful impedance matching, required to avoid reflections, prohibits the employment of shared busses and dictates the use of point-to-point links, contributing to long network diameters and high latencies in large-scale systems [5-7]. Optical interconnections have the potential of becoming an appealing alternative to electrical interconnections. For long and medium range distances (e.g., local area networks and telecommunication), optical technology (fibers) is the technology of choice, offering better performance and lower costs than electrical wires [8]. There is a trend for optics to replace electronics for shorter distances and larger connectivity applications. Optical interconnections are insensitive to radio wave interference effects, are free from transmission line capacitive loading, do not have geometrical planar constraints, and can be reconfigurable (circuit switched). Due to the difference in speeds of the electronic and optical switching elements and the nature of optical signals.

II. MATHEMATICAL MODEL ANALYSIS

With decreasing device dimensions, we are also seeing further increases in the levels of integration and consequent increases in die size. This lengthens the interconnections from one side of the chip to the other and, therefore, both resistance and capacitance of the interconnects are increased, producing much larger time constant values. Thus the effects of increased propagation delays, signal decay, and clock skew will decrease maximum achievable operating frequency, even though the smaller transistors produce gates with less delay. One solution to this problem has been to make use of multilayer interconnections with thicker [6, 14], wider conductors and thicker separating layers. This will reduce both R and C and also reduce die size. Other measures include the use of cascaded drivers and repeaters to reduce the effects of long interconnects. A further option is to use optical interconnection techniques where a very high level of integration is required for high speed circuits. In order to use such techniques, optical fibers, laser diodes, receivers, and amplifiers must be included in the integrated circuit.

II. 1. ELECTRICAL INTERCONNECTION (EI) PERFORMANCE

The Performance will vary with the materials used, but rough estimations can be made for comparison with metal interconnects. To start our considerations, a model may be set out as in Fig. 2. The propagation delay $T_{p(EI)}$ along a single aluminum electrical interconnect can be calculated from the following approximate equation [15-18].

$$T_{P(EI)} = R_{int.}C_{int.} + 2.3(R_{on}C_{int.} + R_{on}C_L + R_{int.}C_L) \quad (1)$$

Where C_L is the load capacitance, R_{on} is the ON resistance of the transistor, $R_{int.}$ is the resistance of electrical interconnection and $C_{int.}$ is the capacitance of electrical interconnection. The previous equation can be simplified to the following formula:

$$T_{P(EI)} = 2.3(R_{on} + R_{int.})\,C_{int.} \quad (2)$$

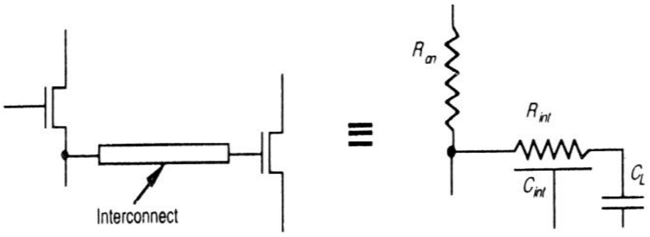

Fig. 2. Model of metal interconnect.

The electrical interconnection resistance can be given by [19, 20]:

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$$R_{\text{int.}} = \rho \frac{L}{HW} \qquad (3)$$

Where ρ is the resistivity of interconnection, L is the interconnection length, H is the interconnection height or thickness, and W is the interconnection width. Based on MATLAB curve fitting program, the fitting relation between material resistivity and ambient temperature (T) can be given by [21-23]:

$$\rho = \rho_0 - 0.00543x10^{-7}\, T + 0.1235x10^{-7}\, T^2 \qquad (4)$$

Where ρ_0 is the material resistivity at room temperature (T_O). In the same way, the interconnection capacitance can be expressed as follows [24]:

$$C_{\text{int.}} = \varepsilon_{ox}\left[\frac{1.15W}{t_{ox}} + 2.28\left(\frac{H}{t_{ox}}\right)^{0.222}\right]L \qquad (5)$$

Where t_{ox} is the thickness of the dielectric oxide, and ε_{ox} is the permittivity of silicon dioxide (SiO_2).

II. 2. Optical interconnection (OI) performance

Optical fibers can be used to replace metal interconnects in critical applications, and Fig. 3 shows this in schematic form. R_{int} and C_{int} may be assumed to be zero, and the time needed for the output driver to transfer a logic state is given by:

$$T_{P(OI)} = 2.3 R_{on} C_L + t_{laser} + t_{\text{int.}} + t_{rec.} \qquad (6)$$

Where C_L is the input capacitance of the laser diode, t_{laser} is the delay time through the laser diode, $t_{int.}$ is the propagation delay along the optical fiber interconnect, and $t_{rec.}$ is the receiver delay time.

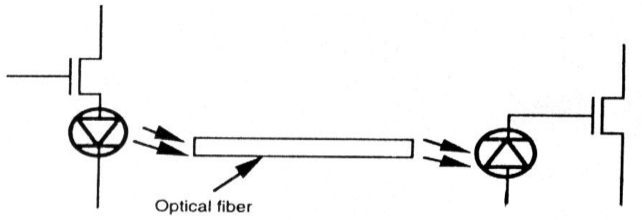

Fig. 3. Electro-optical interconnection.

The propagation delay through optical fiber media can be expressed as the following formula [24, 25]:

$$t_{\text{int.}} = \frac{nL}{c} \qquad (7)$$

Where n is the refractive index for the optic fiber material, L is the interconnection length, and c is the free space speed of light (c = 3 x 108 m/sec). Where the refractive index with its coefficients for different materials based optical fiber interconnection material are listed in Table 1. The set of parameters required to completely characterize the temperature dependence of the refractive index is given below, Sellmeier equation is under the form [26, 27]:

$$n = \sqrt{\frac{A_1\lambda^2}{\lambda^2 - A_2^2} + \frac{A_3\lambda^2}{\lambda^2 - A_4^2} + \frac{A_5\,\lambda^2}{\lambda^2 - A_6^2}}\ , \qquad (8)$$

Where the Sellemeier coefficients for materials based optical interconnections such as polymethyl-methacrylate (PMMA), pure silica, and polystyrene (PS) are listed in Table 1.

Table 1: Sellemeier coefficients for different selected optical interconnection materials [3, 5, 9, 12, 28, 30].

Coefficients	Different materials based optical interconnection		
	PMMA	SiO_2	PS
A_1	0.4963	0.691663	0.08432
A_2	0.6965 (T/T_0)	$(0.0684043^2\,(T/T_0)^2$	12.07654 (T/T_0)
A_3	0.3223	0.4079426	2.06543
A_4	0.718 (T/T_0)	$(0.1162414)^2\,(T/T_0)^2$	0.976542 (T/T_0)
A_5	0.1174	0.8974749	0.007431
A_6	9.237 (T/T_0)	81.876	47.20652 (T/T_0)

The total pulse broadening due to propagation delay in optical interconnection is given by [28-30]:

$$\Delta\tau_{(OI)} = T_{P(OI)}\,\Delta\lambda\, L \qquad (9)$$

Where Δλ is the spectral line width of optical laser diode. Therefore the data transmission bit rate based on non return to zero coding (NRZ) for both OI and EI are given by the following expressions [31-33]:

$$B_{R(OI)} = \frac{0.7}{\Delta\tau_{(OI)}} \qquad (10)$$

$$B_{R(EI)} = \frac{0.7}{T_{P(EI)}} \qquad (11)$$

III. Results and Performance Analysis

In deep sub micrometer VLSI technologies, it has become increasingly difficult for conventional copper based electrical interconnect to satisfy the design requirements of delay, power, bandwidth, and delay uncertainty. One promising candidate to solve this problem is optical interconnect. Based on a practical prediction of optical device development, a comprehensive comparison between optical and electrical interconnects is described in this paper for different technology nodes. Our current study has presented the development of optical interconnects that are primarily attractive for global interconnects, such as data buses and clock distribution networks, since electrical/optical and optical/electrical conversion is required. In our current research, several comparisons have been made between electrical and optical interconnects over wide range of the affecting operating parameters as shown in Table 2.

Table 2: Proposed operating parameters for both electrical and optical interconnections [5, 8, 12, 15, 19, 25].

Operating parameter	**Symbol**	**Value**
Operating signal wavelength	λ	1.3 μm
Room temperature	T_0	300 K
Ambient temperature	T	300 K-340 K
Interconnection length	L	200 μm- 1000 μm
Interconnection width	W	10 μm
Interconnection thickness	H	0.5 μm
Dielectric oxide thickness	t_{ox}	0.8 μm
SiO_2 permittivity	ε_{ox}	$3.4514x10^{-5}$ pF/μm
Resistivity	ρ_0 (Aluminum)	$2.82x10^{-6}$ Ω.cm
	ρ_0 (Copper)	$1.68x10^{-6}$ Ω.cm
	ρ_0 (Nickel)	$6.99x10^{-6}$ Ω.cm
	ρ_0 (Zinc)	$5.9x10^{-6}$ Ω.cm
ON resistance of the transistor	R_{on}	5 KΩ

Laser capacitance or load capacitance	C_L	1 pF
Laser propagation delay	t_{laser}	10 psec
Receiver propagation delay	$t_{rec.}$	10 psec
Spectral line width of optical laser diode	Δλ	0.1 nm

Based on the modeling equations analysis over wide range of the operating parameters, and the series of the Figs. (4-23), the following features are assured:

i) Figs. (4-7) have assured that signal propagation delay through electrical interconnections increases with increasing both interconnection length and ambient temperature for different types of electrical interconnections under study.

ii) Also as shown in Figs. (4-7) have indicated that copper electrical interconnection has presented the lowest signal propagation delay compared to other electrical interconnection under the same operating conditions.

iii) As shown in Figs. (8-11) have assured that data transmission bit rate through electrical interconnections decreases with increasing both interconnection length and ambient temperature for different types of electrical interconnections under study.

iv) As well as shown in Figs. (8-11) have indicated that copper electrical interconnection has presented the highest data transmission bit rate compared to other electrical interconnections under the same operating conditions.

v) As shown in Figs. (12-14) have assured that signal propagation delay through optical interconnections increases with increasing both interconnection length and ambient temperature for different types of optical interconnections under study.

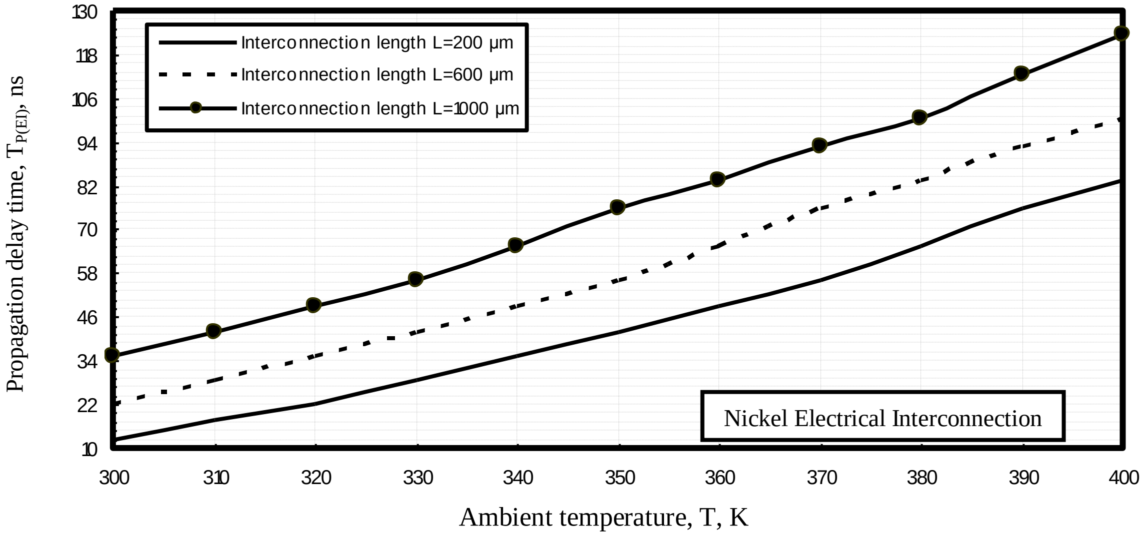

Fig. 4. Nickel electrical interconnection propagation delay in relation to ambient temperature and interconnection length at the assumed set of the operating parameters.

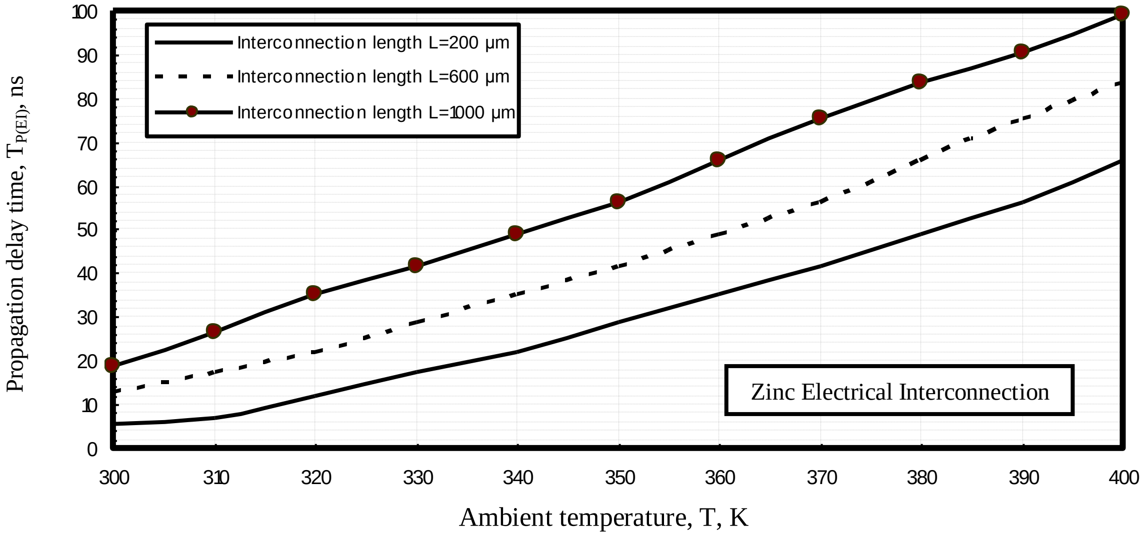

Fig. 5. Zinc electrical interconnection propagation delay in relation to ambient temperature and interconnection length at the assumed set of the operating parameters.

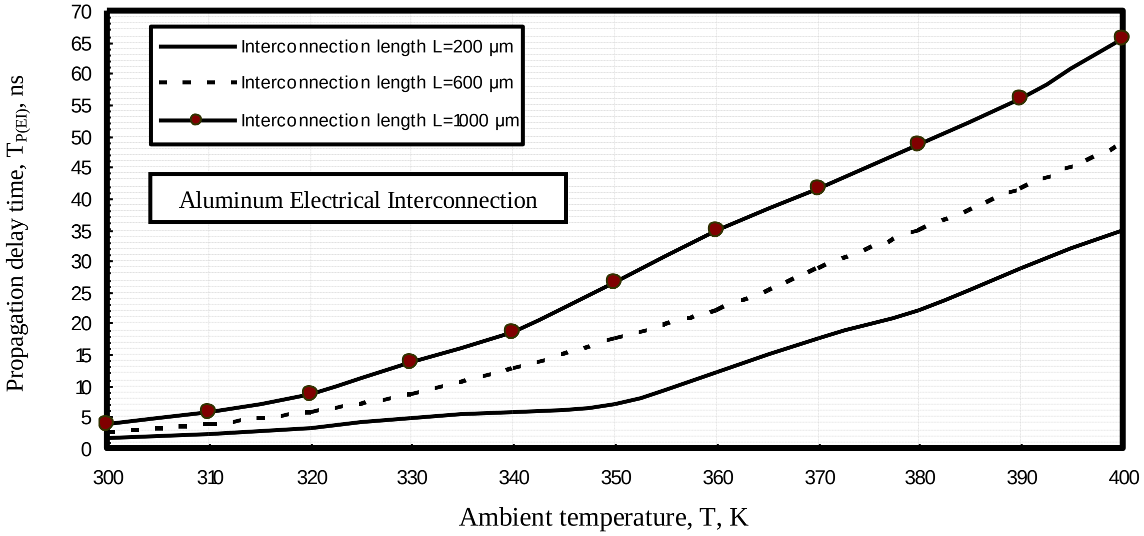

Fig. 6. Aluminum electrical interconnection propagation delay in relation to ambient temperature and interconnection length at the assumed set of the operating parameters.

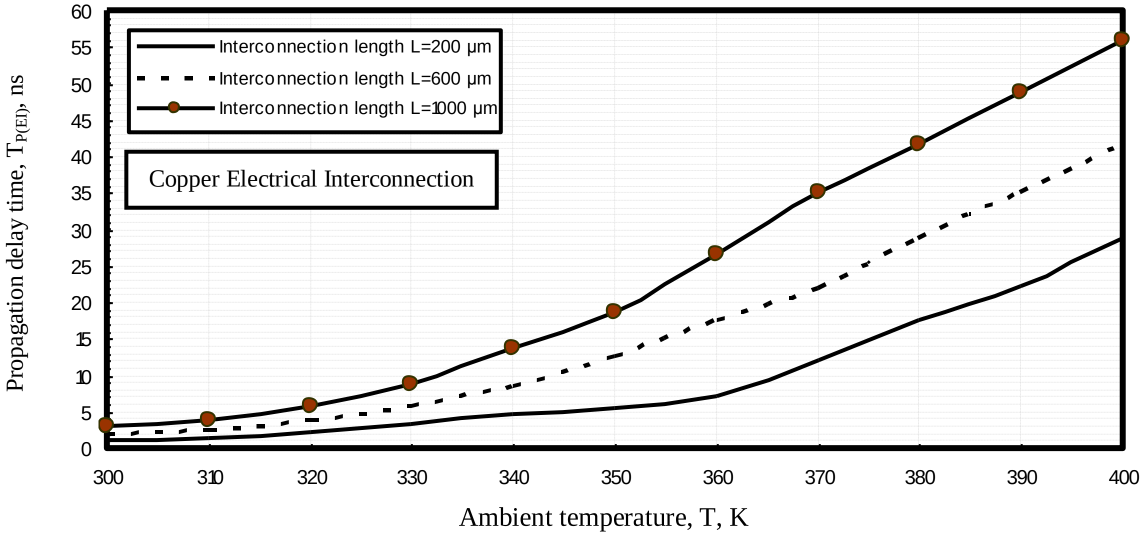

Fig. 7. Copper electrical interconnection propagation delay in relation to ambient temperature and interconnection length at the assumed set of the operating parameters.

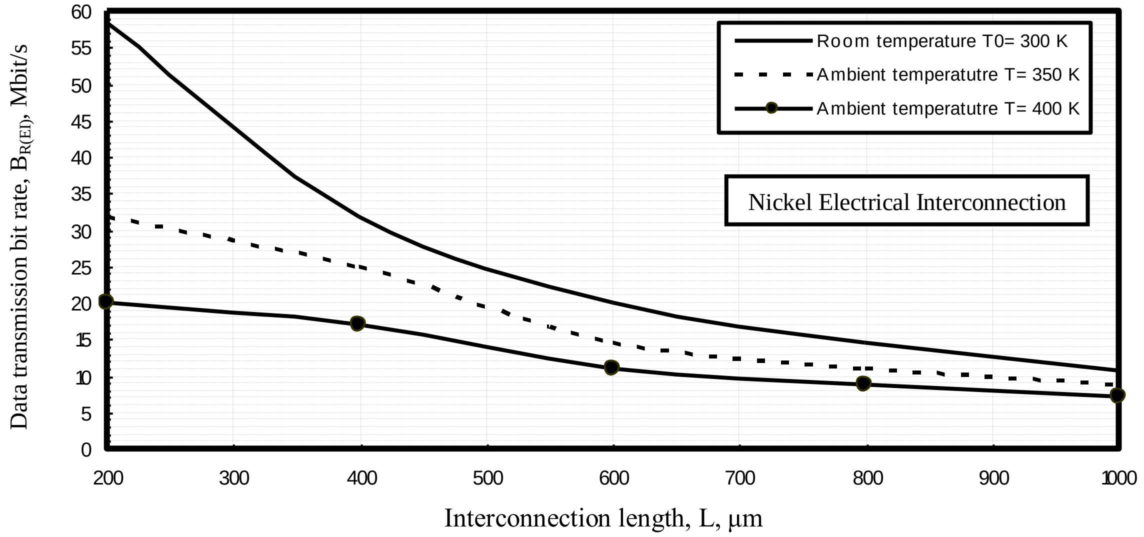

Fig. 8. Nickel electrical interconnection data transmission bit rate in relation to ambient temperature and interconnection length at the assumed set of the operating parameters.

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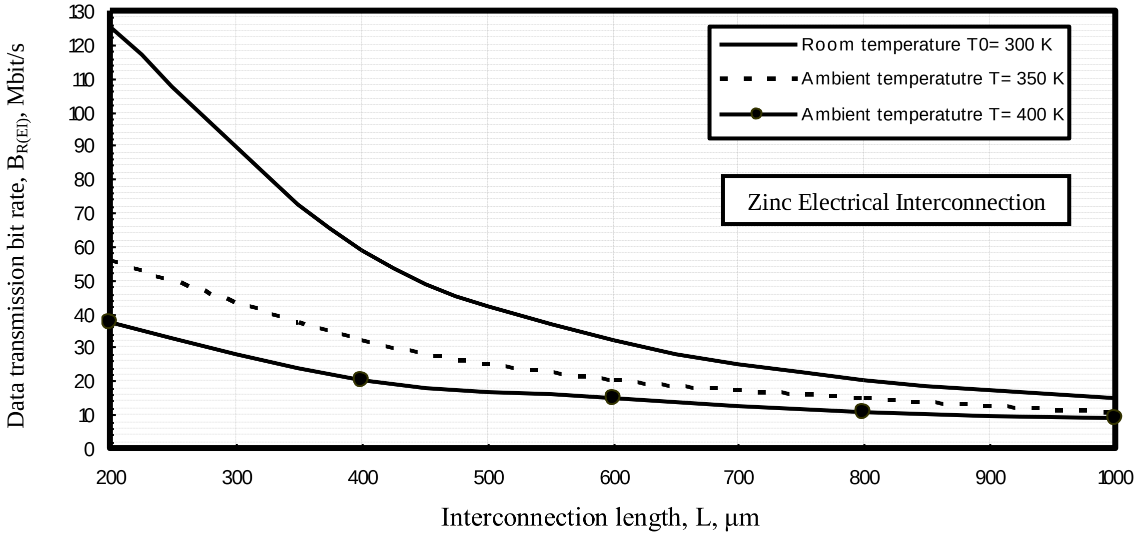

Fig. 9. Zinc electrical interconnection data transmission bit rate in relation to ambient temperature and interconnection length at the assumed set of the operating parameters.

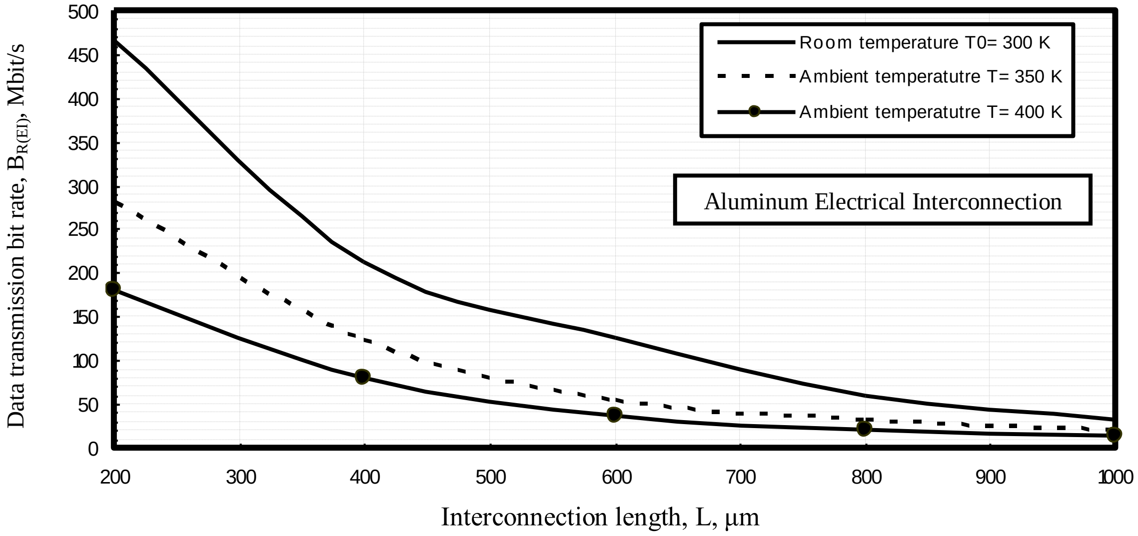

Fig. 10. Aluminum electrical interconnection data transmission bit rate in relation to ambient temperature and interconnection length at the assumed set of the operating parameters.

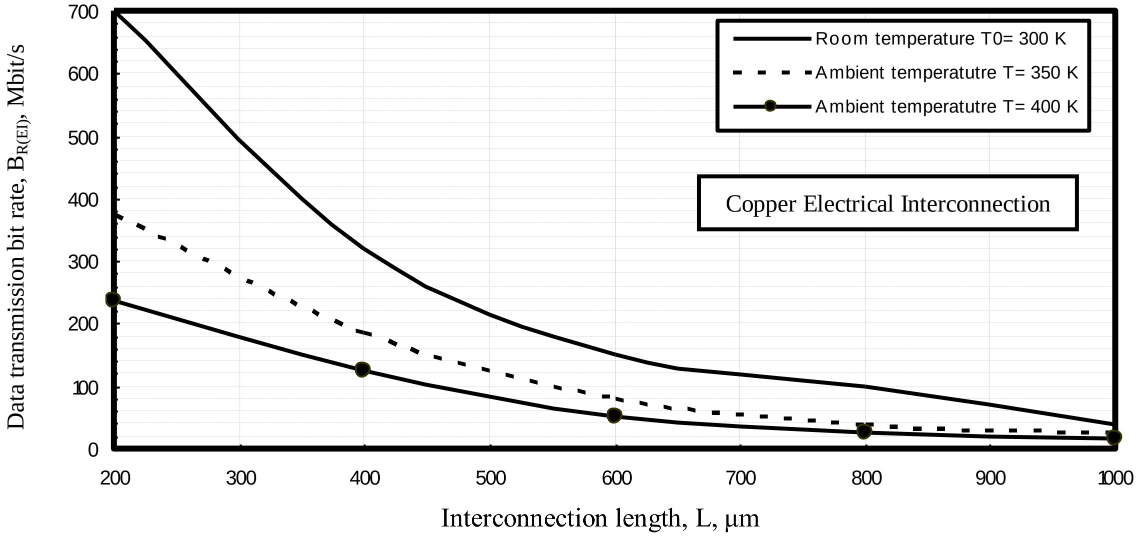

Fig. 11. Copper electrical interconnection data transmission bit rate in relation to ambient temperature and interconnection length at the assumed set of the operating parameters.

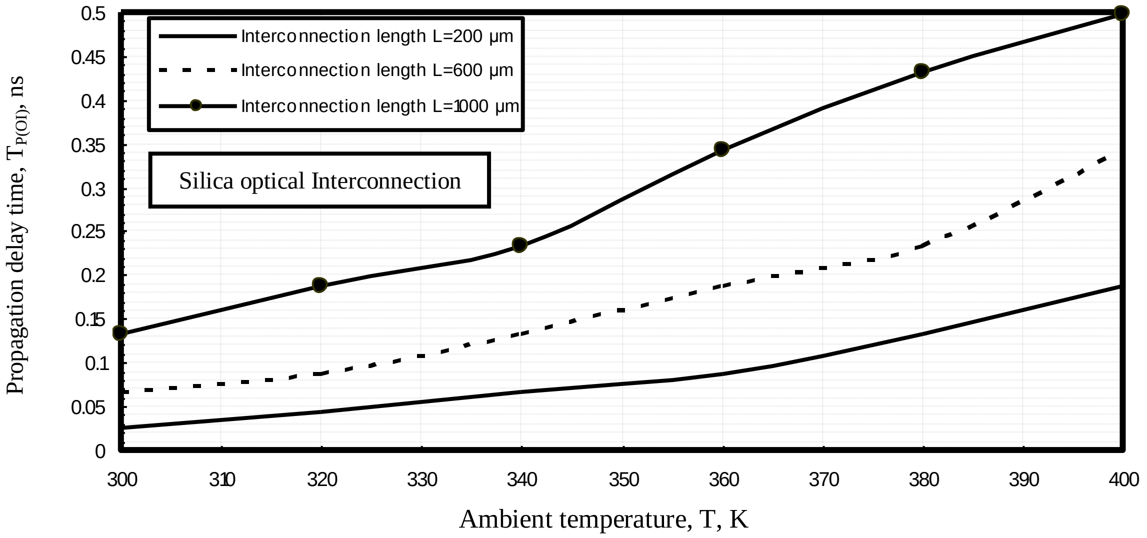

Fig. 12. Silica optical interconnection propagation delay in relation to ambient temperature and interconnection length at the assumed set of the operating parameters.

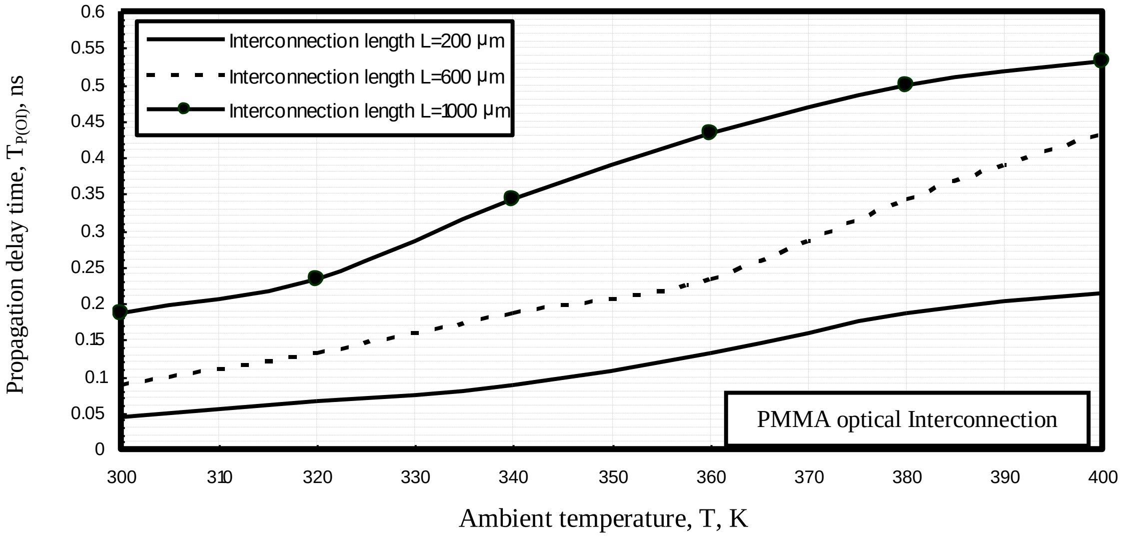

Fig. 13. Polymethyl metha acrylate optical interconnection propagation delay in relation to ambient temperature and interconnection length at the assumed set of the operating parameters.

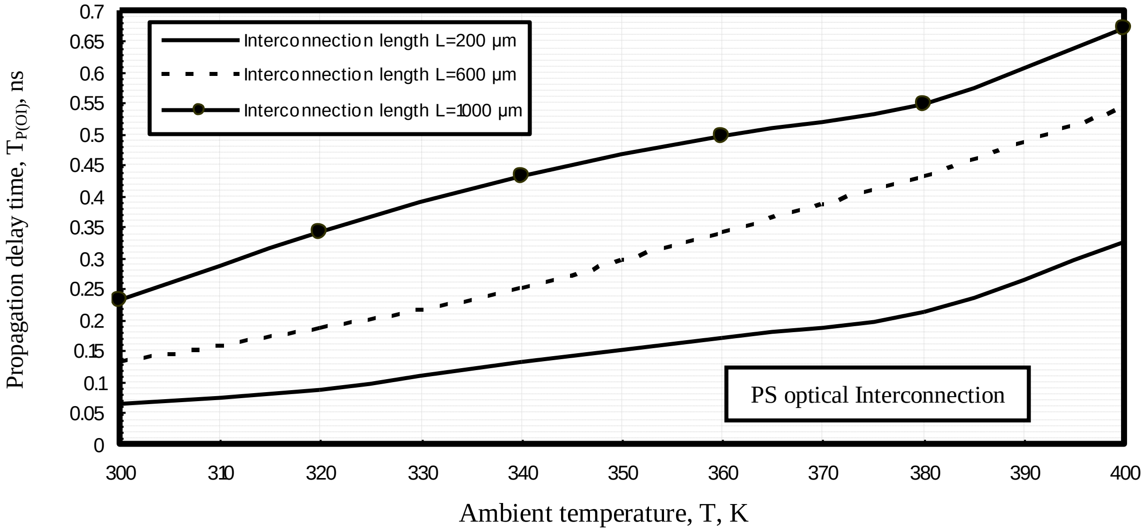

Fig. 14. Polystyrene optical interconnection propagation delay in relation to ambient temperature and interconnection length at the assumed set of the operating parameters.

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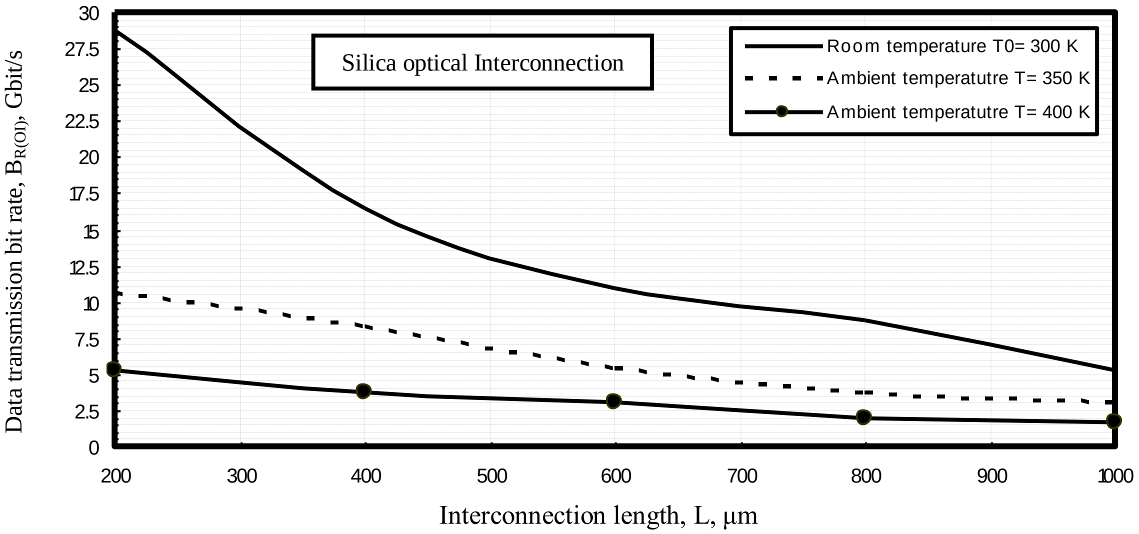

Fig. 15. Silica optical interconnection data transmission bit rate in relation to ambient temperature and interconnection length at the assumed set of the operating parameters.

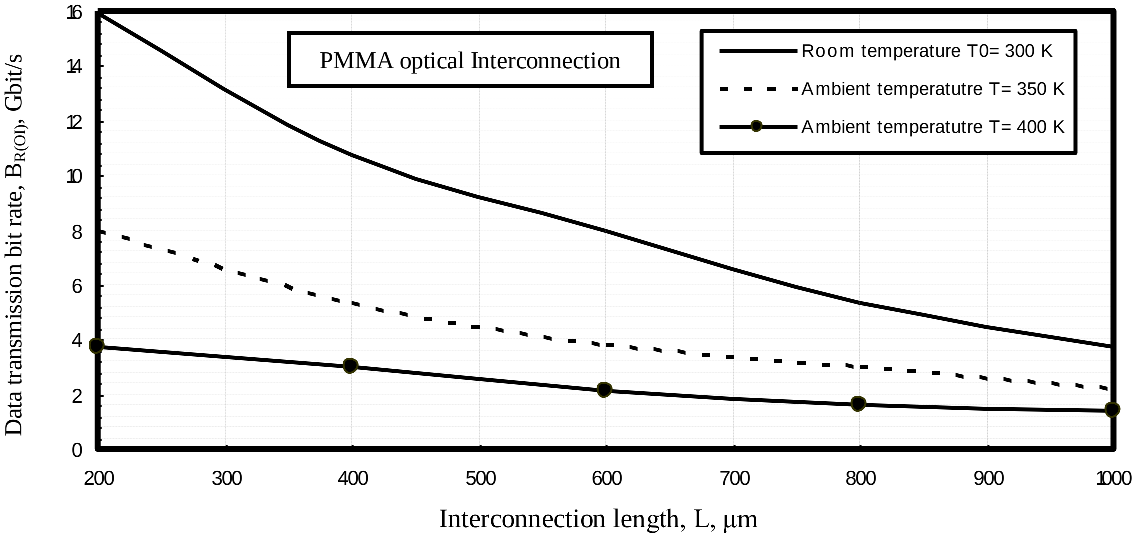

Fig. 16. Polymethyl metha acrylate optical interconnection data transmission bit rate in relation to ambient temperature and interconnection length at the assumed set of the operating parameters.

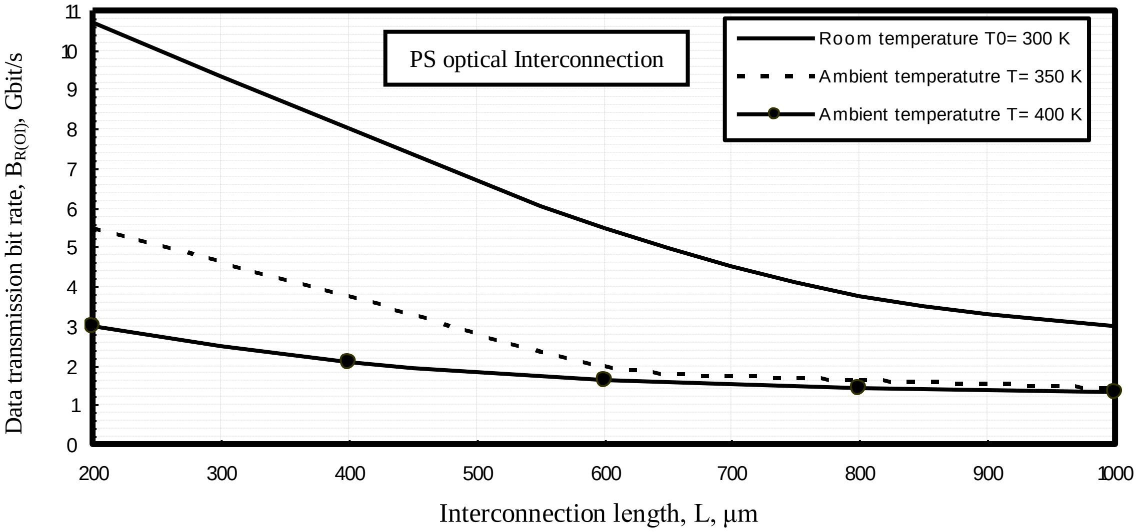

Fig. 17. Polystyrene optical interconnection data transmission bit rate in relation to ambient temperature and interconnection length at the assumed set of the operating parameters.

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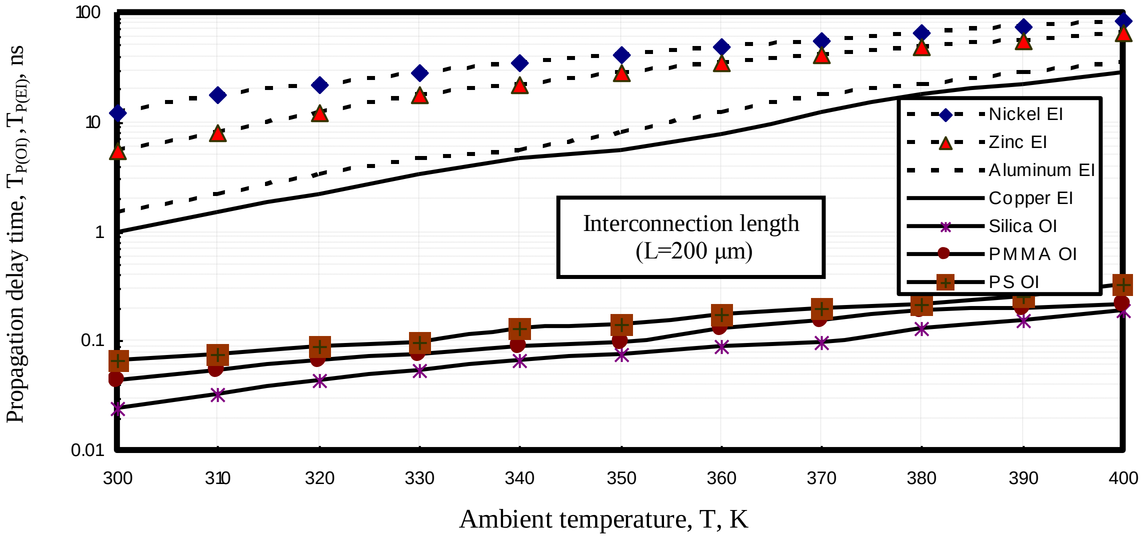

Fig. 18. Electrical and optical interconnection propagation delay in relation to ambient temperature and interconnection length at the assumed set of the operating parameters.

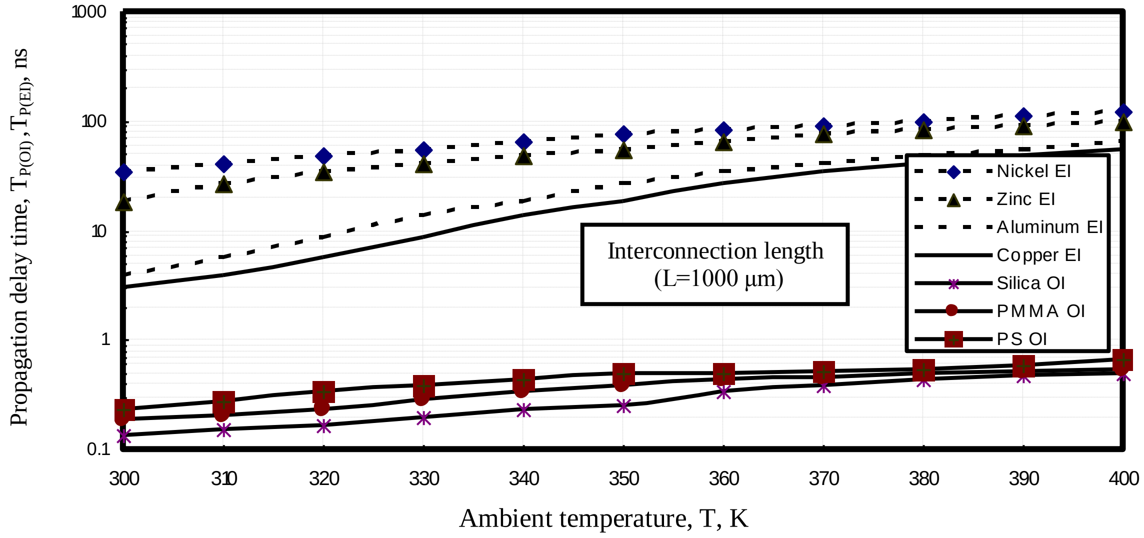

Fig. 19. Electrical and optical interconnection propagation delay in relation to ambient temperature and interconnection length at the assumed set of the operating parameters.

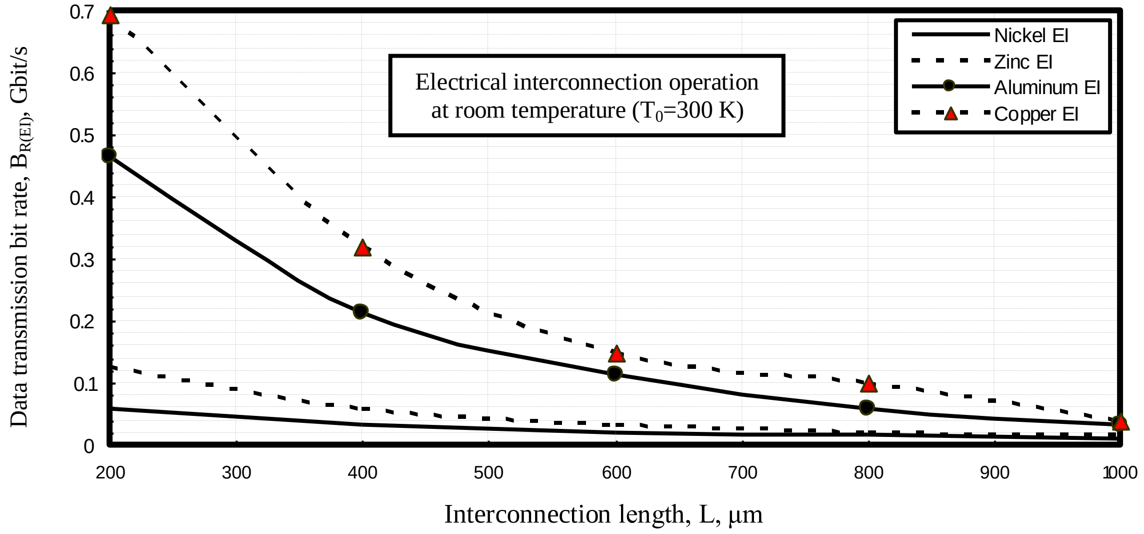

Fig. 20. Variations of data transmission bit rate for electrical interconnection against interconnection length at the assumed set of the operating parameters.

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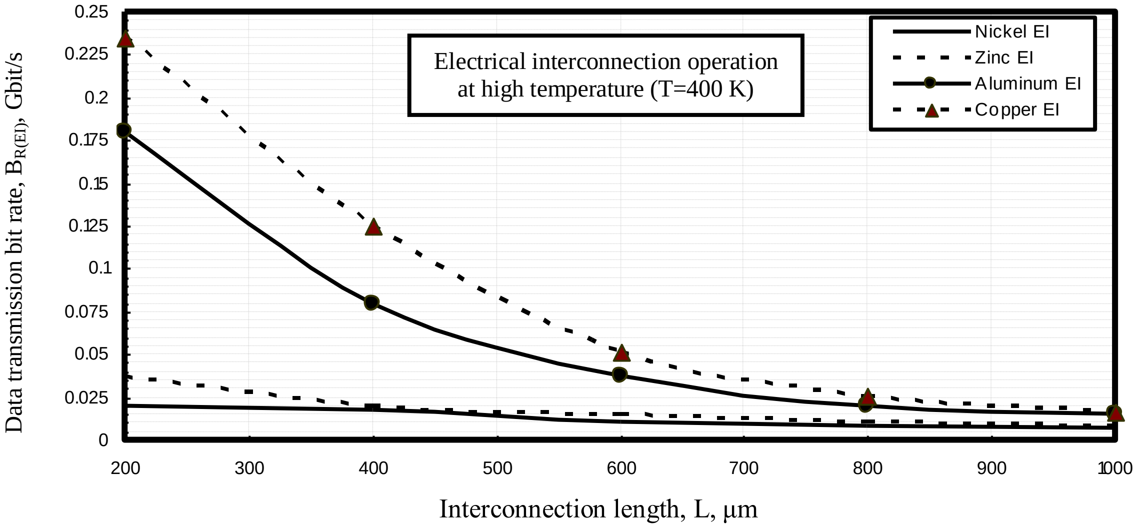

Fig. 21. Variations of data transmission bit rate for electrical interconnection against interconnection length at the assumed set of the operating parameters.

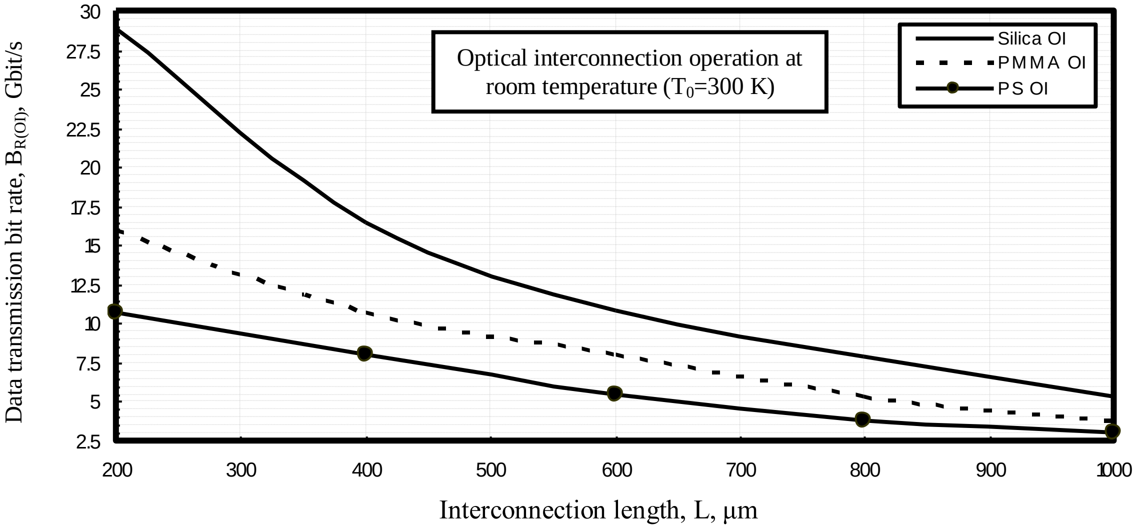

Fig. 22. Variations of data transmission bit rate for optical interconnection against interconnection length at the assumed set of the operating parameters.

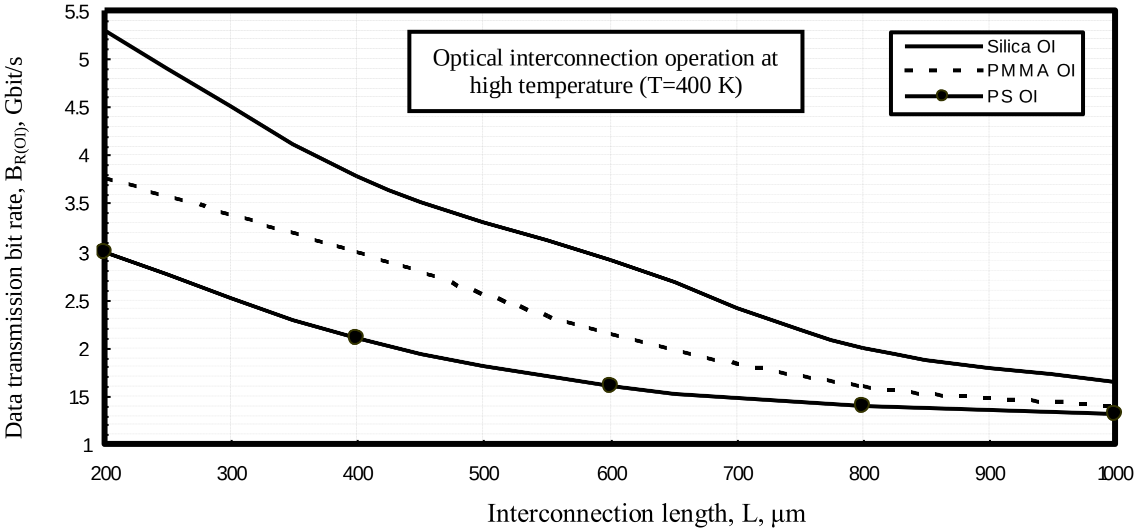

Fig. 23. Variations of data transmission bit rate for optical interconnection against interconnection length at the assumed set of the operating parameters.

vi) Also as shown in Figs. (12-14) have indicated that silica optical interconnection has presented the lowest signal propagation delay compared to other optical interconnection under the same operating conditions.

vii) As shown in Figs. (15-17) have assured that data transmission bit rate through optical interconnections decreases with increasing both interconnection length and ambient temperature for different types of optical interconnections under study.

viii) Also as shown in Figs. (15-17) have indicated that silica optical interconnection has presented the highest data transmission bit rate compared to other optical interconnections under the same operating conditions.

ix) Figs. (18-23) have demonstrated that the bad effects of increasing temperature and interconnection dimensions on both electrical and optical interconnections. Optical interconnections have presented lower signal propagation delay and higher data transmission bit rate compared to electrical interconnection under the same operating considerations.

IV. CONCLUSIONS

Integrated optics are considered as a possible alternative to overcome metallic interconnect limitations that can be the barrier for further gigascale integration predicted by optical interconnection. These expectations are focused on the latency and data transmission bit rates mainly, which should be lower when the optical interconnects are applied. It is theoretically found that the increased interconnection length and surrounding ambient temperatures have dramatically effect on the data transmission bit rates for both electrical and optical interconnections.

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Author's Profile

Dr. Ahmed Nabih Zaki Rashed was born in Menouf city, Menoufia State, Egypt country in 23 July, 1976. Received the B.Sc., M.Sc., and Ph.D. scientific degrees in the Electronics and Electrical Communications Engineering Department from Faculty of Electronic Engineering, Menoufia University in 1999, 2005, and 2010 respectively. Currently, his job carrier is a scientific lecturer in Electronics and Electrical Communications Engineering Department, Faculty of Electronic Engineering, Menoufia university, Menouf. Postal Menouf city code: 32951, EGYPT. His scientific master science thesis has focused on polymer fibers in optical access communication systems. Moreover his scientific Ph. D. thesis has focused on recent applications in linear or nonlinear passive or active in optical networks. His interesting research mainly focuses on transmission capacity, a data rate product and long transmission distances of passive and active optical communication networks, wireless communication, radio over fiber communication systems, and optical network security and management. He has published many high scientific research papers in high quality and technical international journals in the field of advanced communication systems, optoelectronic devices, and passive optical access communication networks. His areas of interest and experience in optical communication systems, advanced optical communication networks, wireless optical access networks, analog communication systems, optical filters and Sensors. As well as he is editorial board member in high academic scientific International research Journals. Moreover he is a reviewer member in high impact scientific research international journals in the field of electronics, electrical communication systems, optoelectronics, information technology and advanced optical communication systems and networks. His personal electronic mail ID (E-mail:ahmed_733@yahoo.com). His published paper under the title **"High reliability optical interconnections for short range applications in high performance optical communication systems"** in Optics and Laser Technology, Elsevier Publisher has achieved most popular download articles in 2013.