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Electrical Interconnections Limits and Optical Interconnections Solutions to Signal Propagation delay for On Chip Data Path

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Abstract: Optical interconnection is a promising solution for high speed interconnects between chips or boards to solve the inherent limits of electrical interconnects in speed, crosstalk, and power dissipation. 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 paper has presented 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. High data rate density enables tight integration of many optical channels with electronic chips.

Keywords: Semiconductor technology, Optical interconnections, optical backplane, On chip, active and passive components.

INTRODUCTION

Increasing interchip communication bandwidth demand has motivated investigation into using optical interconnect architectures over channel limited electrical counterparts. Optical interconnects with negligible frequency dependent loss and high bandwidth [1] provide a viable alternative to achieve dramatic power efficiency improvements at per channel data rates exceeding 10 Gb/s. This has motivated extensive research into optical interconnect technologies suitable for high density integration with CMOS chips. Directly modulated lasers and optical modulators, both electroabsorption and refractive, have been proposed as high bandwidth optical sources, with these different sources displaying tradeoffs in both device and circuit driver efficiency. Vertical-cavity surface-emitting lasers (VCSELs) [2] are an attractive candidate due to their ability to directly emit light with low threshold currents and reasonable slope efficiency values; however, their speed is limited by both electrical parasitics and carrier photon interactions. A device that does not display this carrier speed limitation is the electroabsorption modulator (EAM), based on either the quantum confined Stark effect [3] or the Franz Keldysh effect [4], which is capable of achieving acceptable contrast ratios (CRs) at low drive voltages over tens of nanometers of optical bandwidth. Ring resonator modulators [5], [6] are refractive devices that display very high resonant quality factors and can achieve high CRs with small dimensions and low capacitance; however, their optical bandwidth is typically less than 1 nm. Another refractive device capable of wide optical bandwidth (> 100 nm) is the Mach Zehnder modulator (MZM) [7]; however, this comes at the cost of a large device and high voltage swings. All of the optical modulators also require an external source laser and incur additional coupling losses relative to a VCSEL-based link. Photodetector (PD) efficiency plays a key role in setting the maximum data rate and tolerable channel loss. High speed p-i-n photodiodes [8] are commonly used in optical receivers due to their high responsivity and low capacitance, whereas emerging ultra low capacitance waveguide PDs [9] integrated with CMOS receivers have the potential to dramatically improve optical receiver efficiency.

Requirements for interconnects in computing systems are getting harder to satisfy without employing optical technologies, as the performance keeps growing with the evolution of CMOS technologies as well as system architectures. The emphasis of system designs has been shifting toward reducing power consumption from increasing performance [10]. The total system power, including the power required for cooling as well as for computation, is reaching to or even exceeding the limit of power supply when the system performance is increased. One main advantage of optical compared to electrical interconnects, in addition to the benefit of long-distance transmission at high data rate with optics, is a high data rate density, which provides large bandwidth through a small volume or area. This results in an efficient flow of cooling air through systems as well as tight integration of optical interconnects with electronic chips. As the bandwidth and channel count of interconnects has to be increased for evolving system performance and architecture, these benefits of optical interconnects are crucial [11].

In the present study, different electrical and optical interconnections have been investigated under the same interconnection dimensions and ambient temperature variations. Signal propagation delay and data transmission bit rates are the major interesting design parameters for the evaluation between the electrical and optical interconnections performance.

ON CHIP OPTICAL INTERCONNECTION DATA PATH

Introducing optical interconnects into very large scale integrated (VLSI) architectures requires compatibility with CMOS technology. Due to the absence of an efficient silicon-based laser, only those configurations that utilize an external laser as a light source are considered. A diagram of an optical interconnect system is shown in Fig. 1. A transmitter is used to convert an electrical signal to a light signal, which is composed of a modulator and a driver circuit. The development of a fast and cost efficient CMOS compatible electro-optical modulator is one of the most challenging tasks on the path towards realizing on-chip optical interconnects [12].

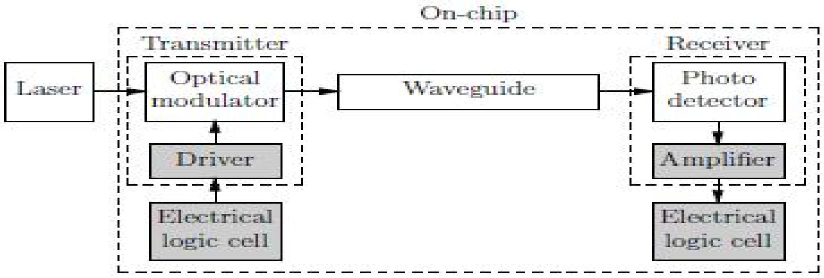


Fig. 1. An on chip optical interconnection data path.

Polymer or silicon-on insulator (SOI) waveguides are used to transmit the optical signal. The optical signal is converted to an electrical signal at the receiver. The receiver has two components: a SiGe metal semiconductor metal (MSM) detector and an amplifier. Models of different components within the optical data path are provided in [13]. Unlike electrical devices, optical devices are not readily scalable due to the light wavelength constraint. The performance and integration ability of optical devices, however, are expected to be further improved by technology innovations and structural optimization.

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.

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].

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

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

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

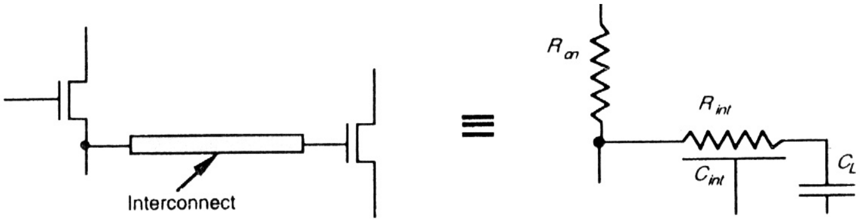


Fig. 2. Model of metal interconnect.

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

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

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]:

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

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]:

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

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

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:

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

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.

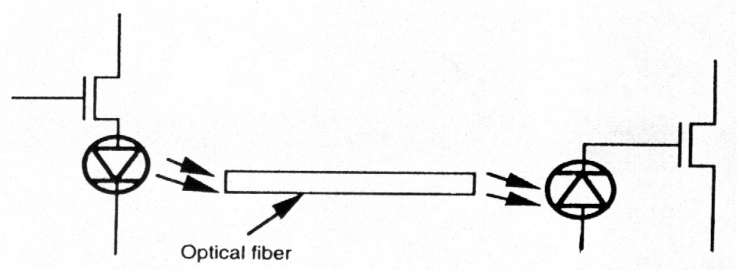


Fig. 3. Electro-optical interconnection.

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

$$t_{int.} = \frac{n\,L}{c} \tag{7}$$

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]:

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

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		
	Polymethylmethacrylate (PMMA)	Silica (SiO_2)	Polystyrene (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]:

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

Where $\Delta\lambda$ 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]:

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

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

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	$\Delta\lambda$	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.

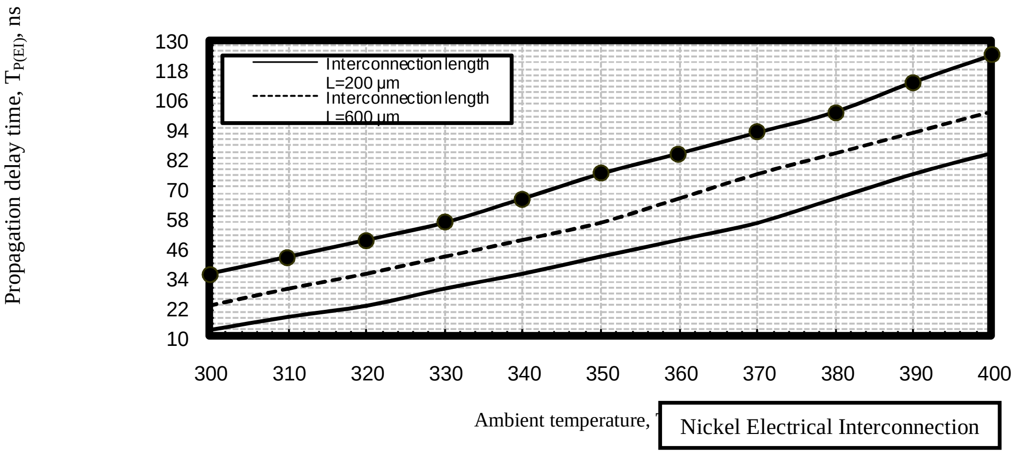


Fig. 4. Nickel electrical interconnection propagation delay in relation to ambient temperature and interconnection length at the assumed set of the operating parameters.

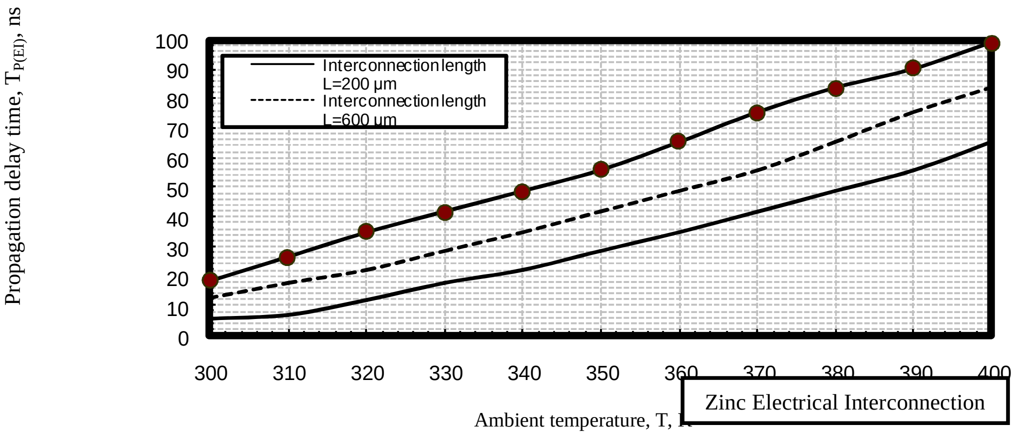


Fig. lectrical interconnection propagation delay in relation to ambient temperature and interconnection length at the assumed set of the operating rameters.

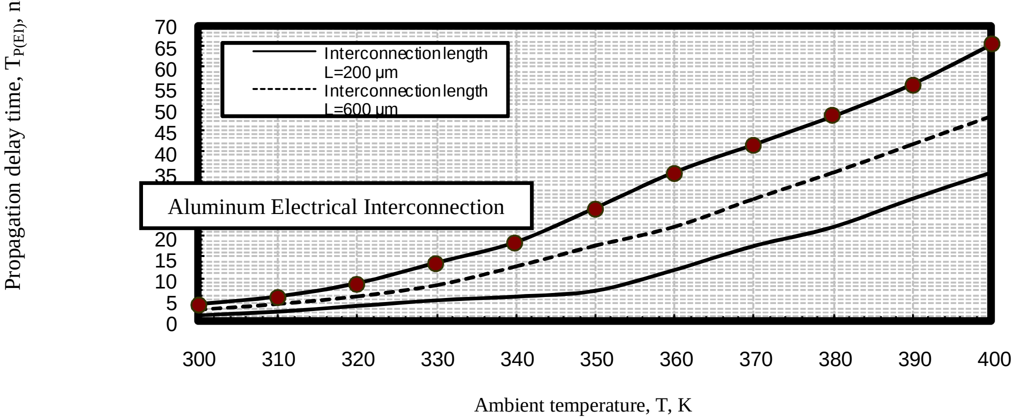


Fig. 6. Aluminum electrical interconnection propagation delay in relation to ambient temperature and interconnection length at the assumed set of the operating rameters.

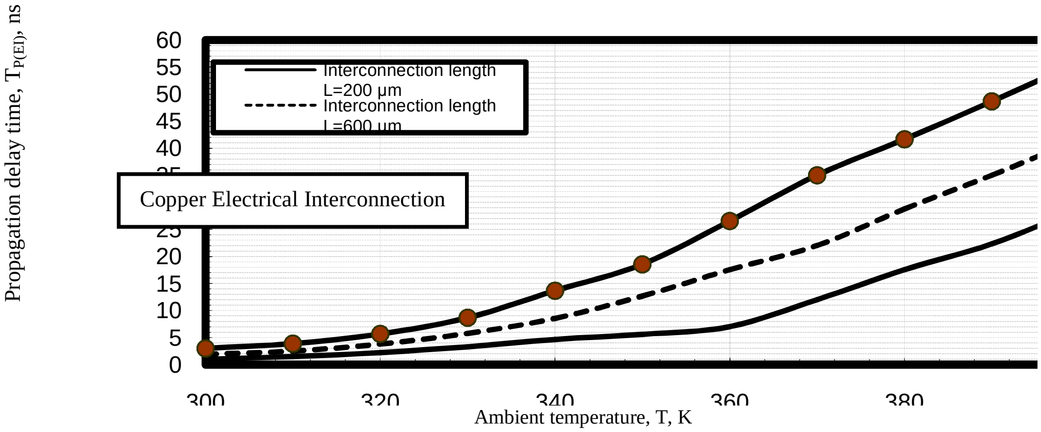


Fig. 7. Copper electrical interconnection propagation delay in relation to ambient temperature and interconnection length at the assumed set of the operating parameters.

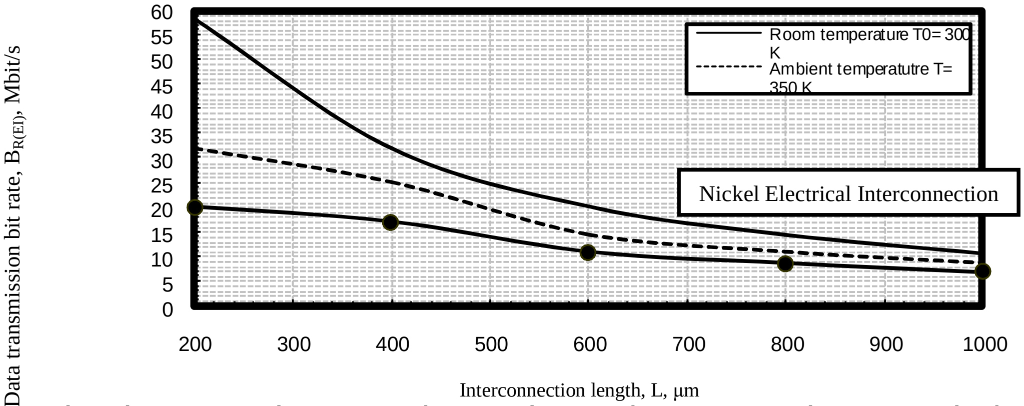


Fig. 8. electrical interconnection data transmission bit rate in relation to ambient temperature and interconnection length at the assumed set of the operating parameters.

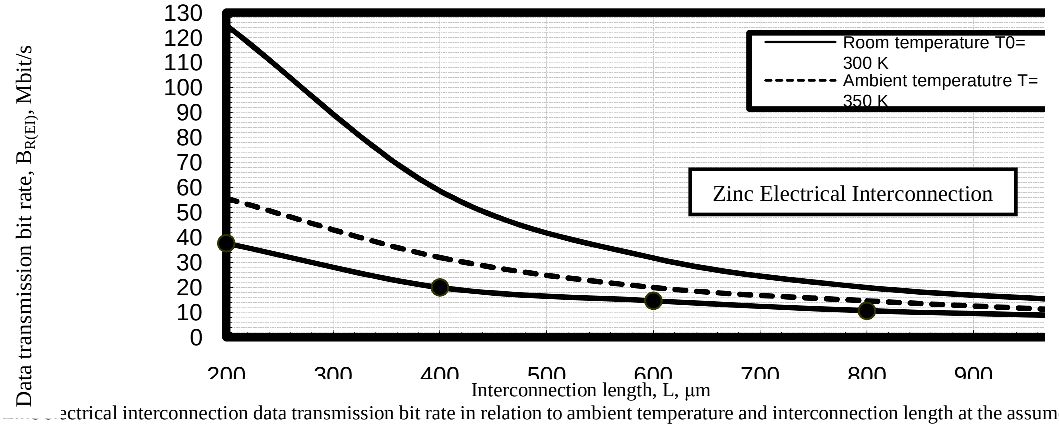


Fig. 9. ectrical interconnection data transmission bit rate in relation to ambient temperature and interconnection length at the assumed set of the operating parameters.

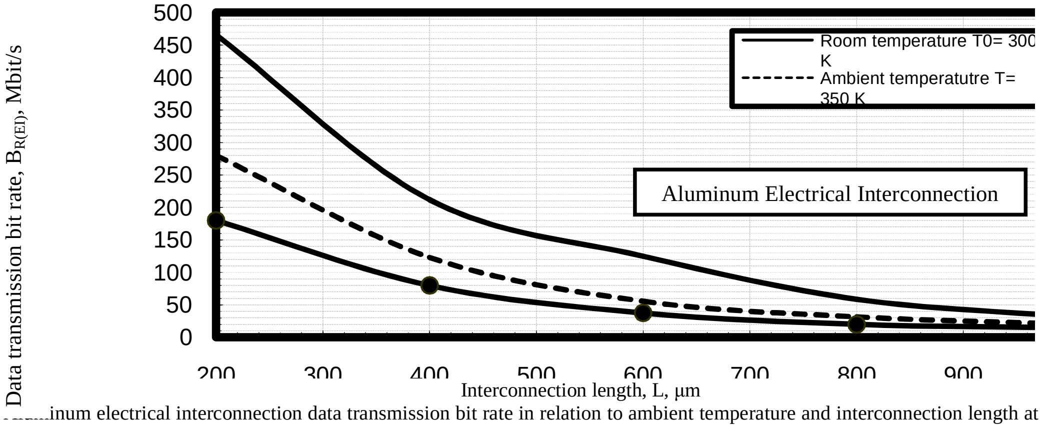


Fig. 1 inum electrical interconnection data transmission bit rate in relation to ambient temperature and interconnection length at the assumed set of the operating parameters.

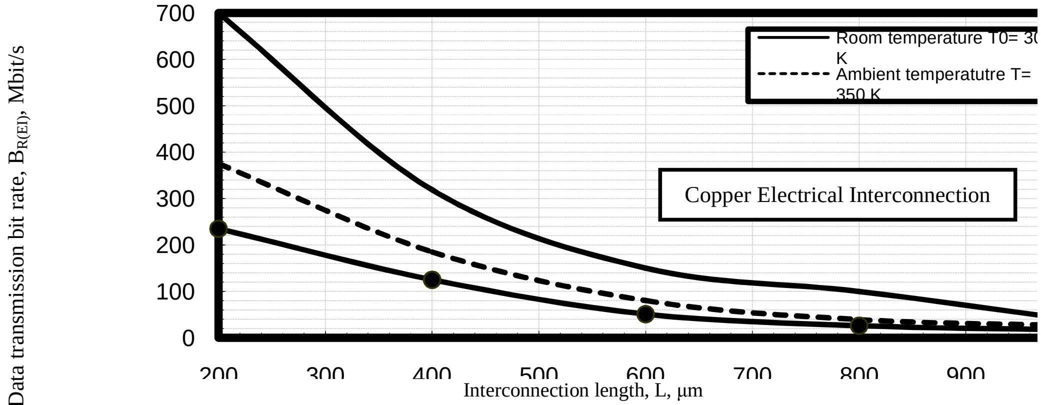


Fig. er electrical interconnection data transmission bit rate in relation to ambient temperature and interconnection length at the assumed set of the erating parameters.

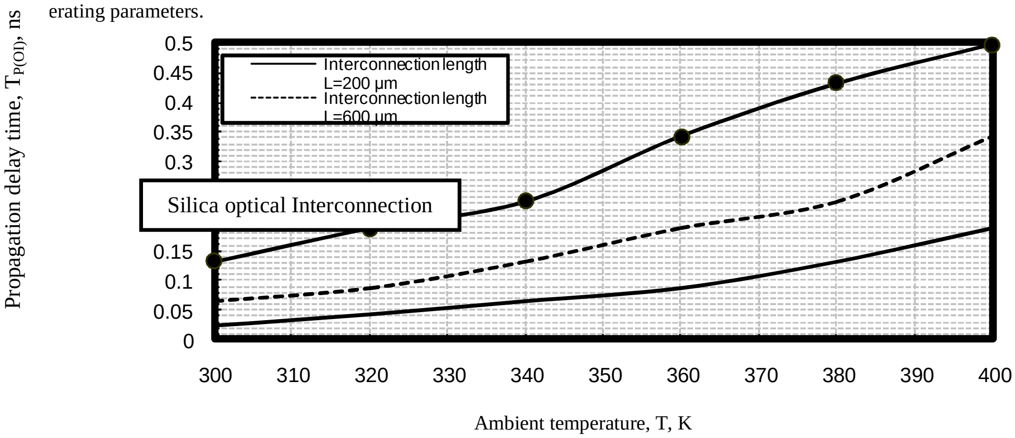


Fig. 12. Silica optical interconnection propagation delay in relation to ambient temperature and interconnection length at the assumed set of the operating parameters.

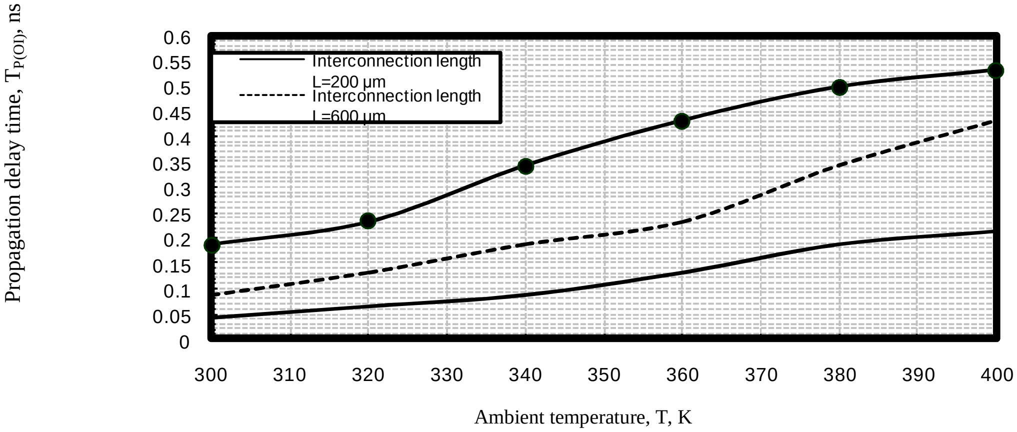


Fig. 13. Polymethyl metha acrylate optical interconnection propagation delay in relation to ambient temperature and interconnection length at the assumed set of the operating parameters.

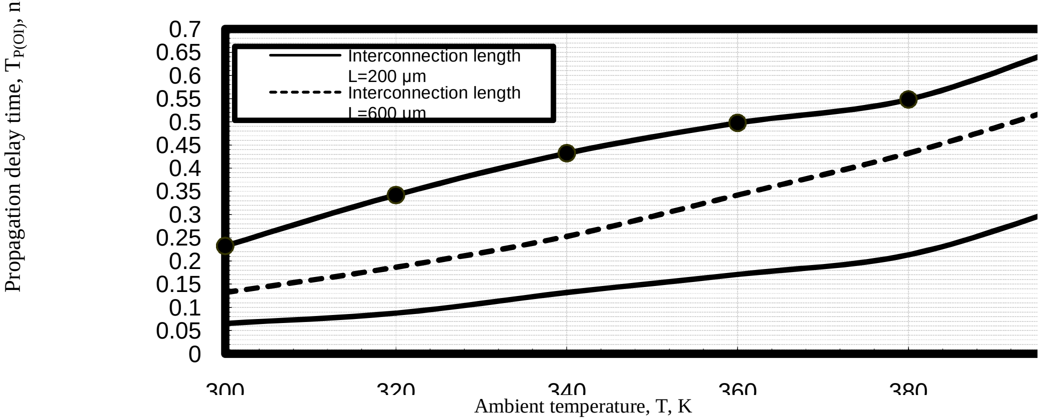


Fig. 14. Polystyrene optical interconnection propagation delay in relation to ambient temperature an med set of the operating parameters.

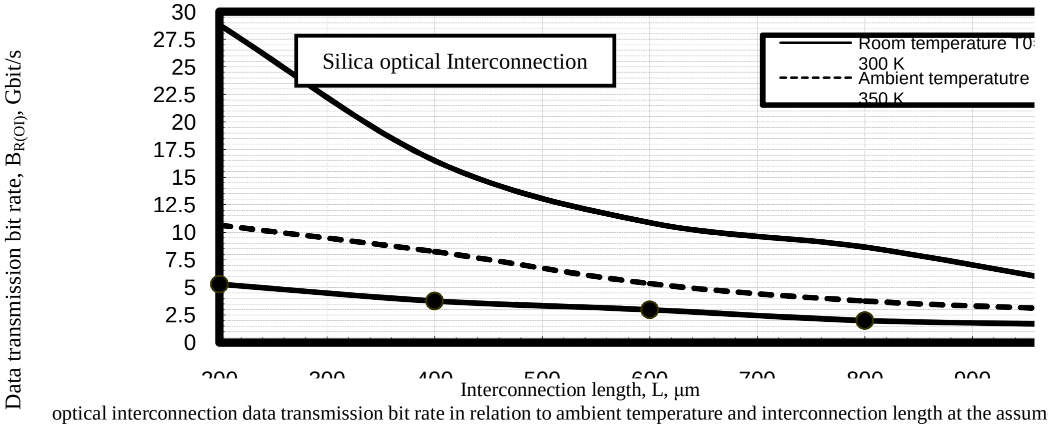
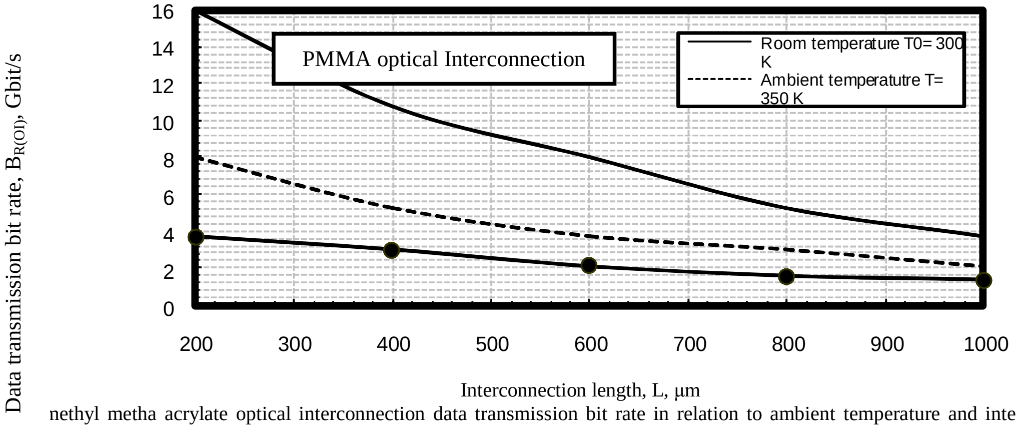


Fig. 1 optical interconnection data transmission bit rate in relation to ambient temperature and interconnection length at the assumed set of the operating parameters.



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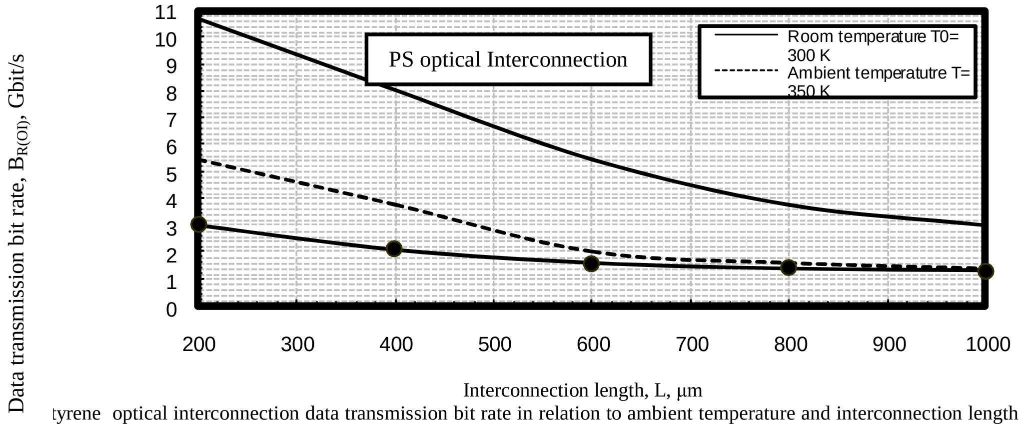

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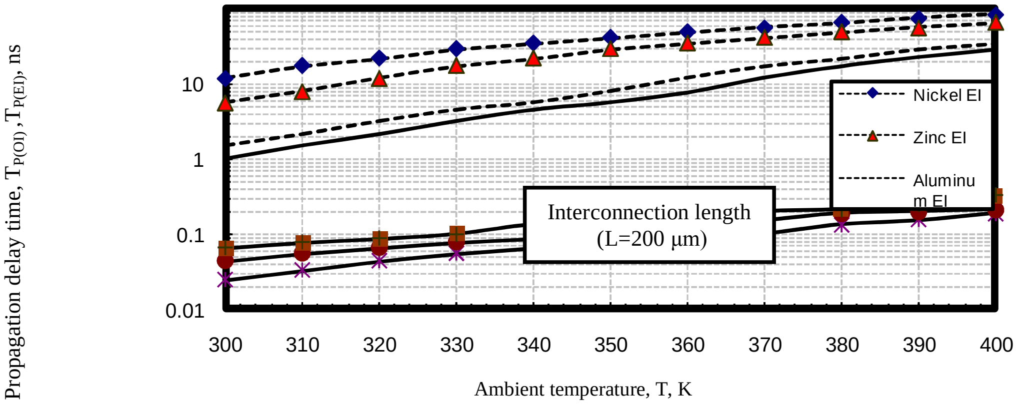


Fig. rical and optical interconnection propagation delay in relation to ambient temperature and interconnection length at the assumed set of the operating parameters.

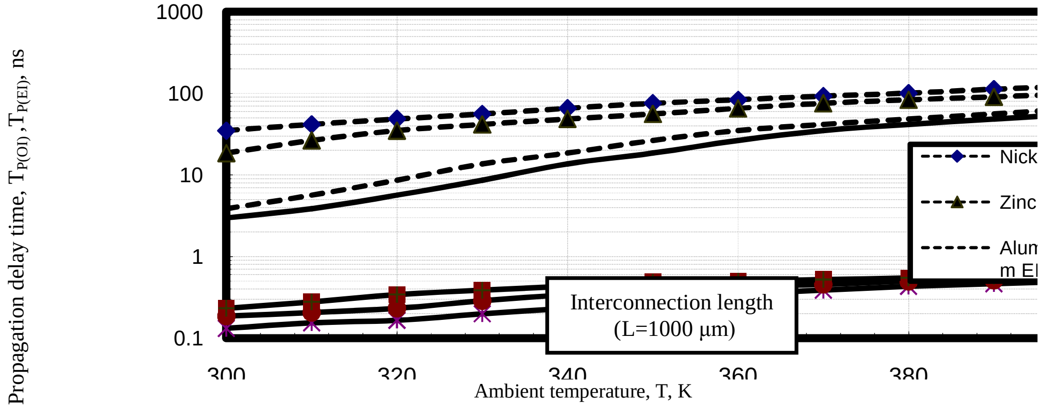
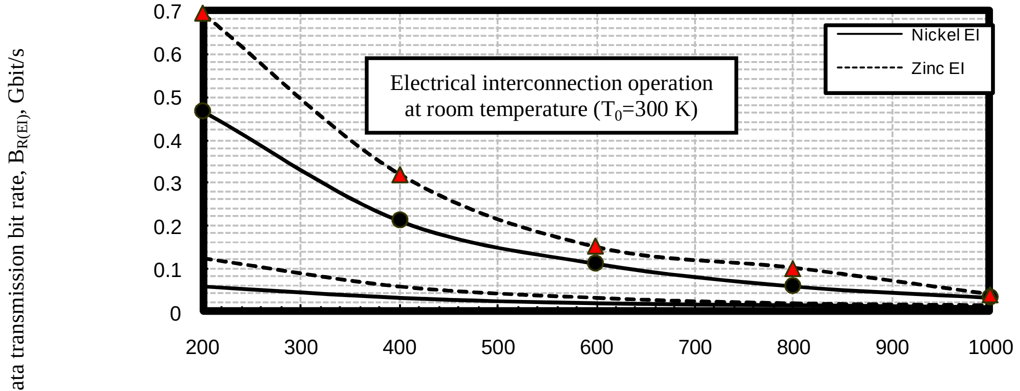


Fig. 1 rical and optical interconnection propagation delay in relation to ambient temperature and interconnection length at the assumed set of the operating parameters.



Interconnection length, L, µm

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

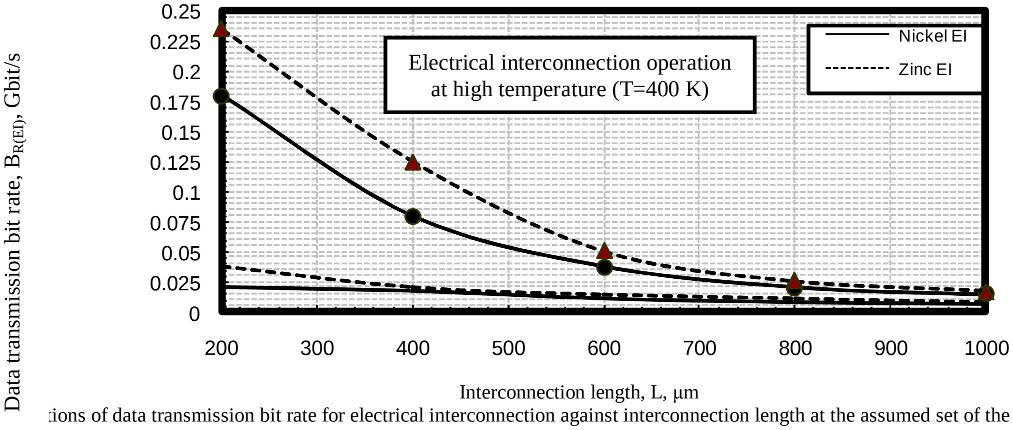


Fig. 2 tions of data transmission bit rate for electrical interconnection against interconnection length at the assumed set of the operating parameters.

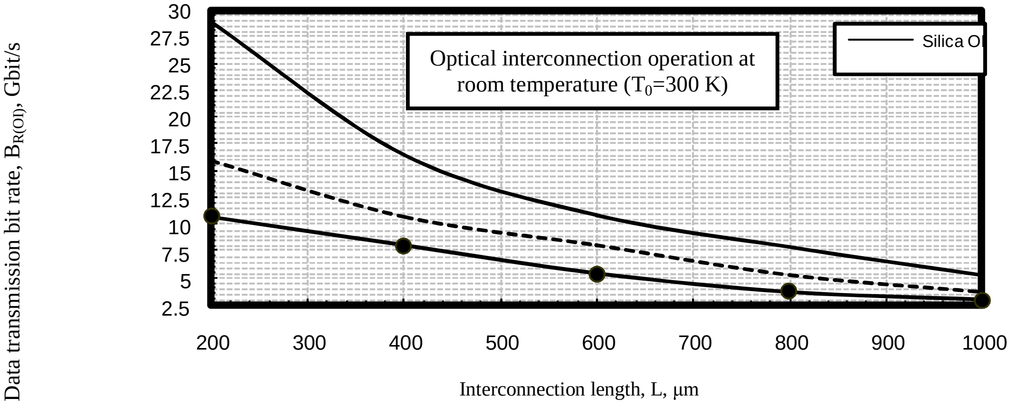


Fig. 2 tions of data transmission bit rate for optical interconnection against interconnection length at the assumed set of the operating parameters.

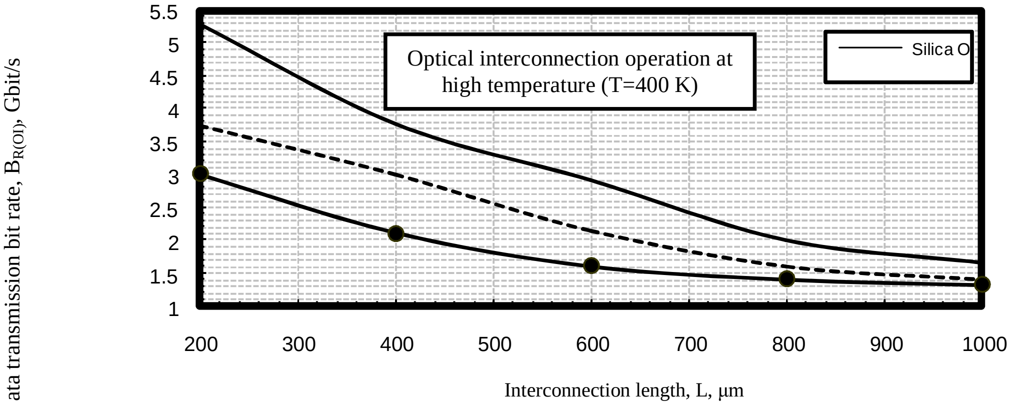


Fig. 2 tions of data transmission bit rate for optical interconnection against interconnection length at the assumed set of the operating parameters.

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.

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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