New Architecture of Optical Interconnect for High-Speed Optical Computerized Data Networks (Nonlinear Response)

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ABSTRACT

Although research into the use of optics in computers has increased in the last and current decades, the fact remains that electronics is still superior to optics in almost every way. Research into the use of optics at this stage mirrors the research into electronics after the 2nd World War. The advantages of using fiber optics over wiring are the same as the argument for using optics over electronics in computers. Even through totally optical computers are now a reality, computers that combine both electronics and optics, electro-optic hybrids, have been in use for some time.

In the present paper, architecture of optical interconnect is built up on the bases of four Vertical-Cavity Surface-Emitting Laser Diodes (VCSELD) and two optical links where thermal effects of both the diodes and the links are included. Nonlinear relations are correlated to investigate the power-current and the voltage-current dependences of the four devices. The good performance (high speed) of the interconnect is deeply and parametrically investigated under wide ranges of the affecting parameters. The high speed performance is processed through three different effects, namely the device 3-dB bandwidth, the link dispersion characteristics, and the transmitted bit rate (soliton). Eight combinations are investigated; each possesses its own characteristics. The best architecture is the one composed of VCSELD that operates at 850 nm and the silica fiber whatever the operating set of causes. The increase of the ambient temperature reduces the high-speed performance of the interconnect.

I. Introduction

Although research into the use of optics in computers has increased in the last and current decades, the fact remains that electronics is still superior to optics in almost every way. The main problems facing the development of the optical computer is related to one of its main benefits. Because photons do not interact with each other like electrons, it is still necessary to include transistors that perform a switch-on or -off on the signal. Until researchers can develop an optical switch that will perform the same functions as a transistor, the development of optical computer will remain a thing of the future [1].

References [2, 3] presented an approach to model the optical interconnect used in networks and advanced high-performance computing systems. The model is generic enough that it can be applied to fiber or free-space technologies, yet precise enough to extract from it salient performance predictions. The developed model was intended as an analysis tool for system builders, and to provide a guide for developing upcoming technologies such as free-space smart pixel-based interconnects [2-4].

The reason of optical interconnects are not widely implemented in modern computing systems is due to computer architecture design and how interconnects are balanced within those constraints. In Section II, we cast a basic model and a parametrical nonlinear analysis of optical interconnections based on two basic sets of elements namely; VCSELDs as sources, and polymer fiber and silica fiber as links. Thermal effects are considered as well as the spectral dependence. Our goal is the maximization of bandwidths of the two basic sets of elements, namely eight structures will be processed.

II. Basic Model, Governing Equations and Analysis

II.1. Optical sources [5]

The first device is an index-guided, vertically-contacted VCSELD. The device has a 100 \( \mu \text{m}^2 \) area and is composed of GaAs-AlAs DBR mirrors, three \( \text{In}_{0.2}\text{Ga}_{0.8}\text{As} \) quantum wells, and \( \text{Al}_{0.2}\text{Ga}_{0.8}\text{As} \) confinement layers. Lateral carrier confinement is provided through an etched mesa design. The second device is an AlGaN-based 683 nm selectively-oxidized VCSELD with a 3 \( \mu \text{m} \times 3 \mu \text{m} \) area. This device consists of compressively-strained InGaAs graded DBR’s. The third device is 863 nm bottom emitting AlGaAs...
VCSEL. This 16 μm diameter device was grown on an AlGaAs n-type DBR, six quantum wells, and a C-doped AlGaAs n-type DBR, six quantum wells, and a C-doped AlGaAs p-type DBR. The final device is the VCSEL a 3.1 μm diameter, thin oxide apertured device composed of an AlGaAs GaAs p-type DBR, three InGaAs quantum wells, and an AlGaAs cavity.

In the present paper, we cast the following more accurate nonlinear relationships than that of [6] to account for voltage-current (V-I) and output power-current (P-I) dependences over the temperature range 290 ≤ T, K ≤ 310 under the forms:

\[ P_o = a + bI + cI^2, \text{mW} \]  
\[ V = \alpha + \beta I + \gamma I^2, \text{V} \]

(1) (2)

We have computed the two sets of the coefficients based on [7,8].

### Table I Coefficients of Eqs. (1) and (2)

<table>
<thead>
<tr>
<th>Device</th>
<th>Weather (°C)</th>
<th>a</th>
<th>b</th>
<th>c</th>
<th>α</th>
<th>β</th>
<th>γ</th>
</tr>
</thead>
<tbody>
<tr>
<td>InGaAs</td>
<td>30</td>
<td>0.05</td>
<td>0.24</td>
<td>-6.064</td>
<td>1.1</td>
<td>0.1760</td>
<td>0.015</td>
</tr>
<tr>
<td>AlGaInP</td>
<td>683</td>
<td>-0.11</td>
<td>0.19</td>
<td>-0.0035</td>
<td>1.9007</td>
<td>0.1300</td>
<td>0.025</td>
</tr>
<tr>
<td>AlGaAs</td>
<td>863</td>
<td>-0.5209</td>
<td>0.19</td>
<td>-6.055</td>
<td>2.2400</td>
<td>0.0600</td>
<td>0.001</td>
</tr>
<tr>
<td>InGaAs</td>
<td>859</td>
<td>9.21</td>
<td>0.28</td>
<td>-6.015</td>
<td>2.1</td>
<td>9.51</td>
<td>0.02</td>
</tr>
</tbody>
</table>

### Table II [5, 7, 8]

Parameters resulting from the fitting of the VCSEL model to experimental data for four devices:

(a) Index-guided InGaAs VCSEL, (b) Selectively oxidized AlGaInP VCSEL, (c) Bottom-emitting AlGaAs VCSEL, and (d) Thin oxide apertured VCSEL

### B. Binary silica fiber link

Following the spirit of [17, 18], in separating the various contributions to the total chromatic dispersion in monomode silica doped fibers of radius R, we have:

\[ D_{\text{tot}} = \Delta \tau / \Delta \lambda = \left( M_{\text{mod}} + M_{\text{sil}} \right) \Delta \lambda \]  

where \( M_{\text{mod}} \) is the material dispersion coefficient, ps/nm.km, \( M_{\text{sil}} \) is the material dispersion coefficient, ps/nm.km, and \( \Delta \lambda \) is the relative refractive index difference. The polymer bandwidth is given by:

\[ BW_p = 0.44 / \left( D_{\text{pol}} \Delta \lambda R \right), \text{THz} \]

(8)

Also, two transmitted bit rates based on the model of [16], the soliton bit rate is computed as:

\[ B_{\text{s}}^2 P_s = 59.6 (\lambda / 1.54)^3 (A_e / 20) (3.2 \times 10^{-20} / n_{\text{sil}}) D_f \Delta \lambda R \]

(9)

where B_s is the soliton bit rates, P_s is power /bit, A_e is the effective area, μm^2 , n_{sil} is nonlinear refractive index coefficient, and D_f is the dispersion coefficient in ps/nm.km

### III. Results and Discussion

Causes of any architecture are in the following set {T, I, R, Δ, R_s} where these causes are, respectively, the ambient temperature, the injected current, the fiber radius, the relative refractive index difference, and the link length.
While effect of any architecture are in the following set $\{f_3\text{-}dB, BW, B_{rs}\}$ where these effects are, respectively, the device 3-dB bandwidth, the link bandwidth, and the transmitted soliton bit rate.

III.1. Variations of the Four Device and Two Links Characteristics

Samples of variations of the four devices characteristics against variations of the affecting parameters are displayed in Fig.1-20, where the following features are clarified: i) Whatever the device is, $f_3\text{-}dB$ and $I_o$ are in positive correlations, ii) Whatever the device is, $f_3\text{-}dB$ and $T_o$ are in negative correlations, iii) The fourth device (thin-oxide-aperture of composed structure, $\lambda = 0.85$ $\mu$m) is the faster device, where it possesses $f_3\text{-}dB$ over the range from 16 GHz up to 35 GHz at room temperature 290 K., iv) The silica bandwidth $BW_f$ is greater than that of polymer fiber for any device ($\lambda = 0.98, 0.683, 0.863,$ and 0.85 $\mu$m), and v) The soliton transmitted bit rates are consequently greater in silica fibers than that of polymer fibers. In general, both $BW_p$ and $B_{rs}$ decrease as $\Delta$ increases.

Variations of both $BW_p$ and $BW_f$ against variations of the link length $R_s$ are given, where both the two bandwidths and link length possess negative correlations. As known before, the soliton bit rates are link length-independent quantities. Finally, an increase in the link radius reduces the transmitted bit rates due to the increase in the effective area.

III.2. Comparison of the Eight Architectures

In the following table, we summarize the maximum possible features of the eight architectures over the total obtained results: The summarized results, in Table III, indicate that: i) The fourth device ($\lambda = 0.85$ $\mu$m) is the faster device, and ii) The link made of silica fiber possesses the largest bandwidth and consequently the maximum possible soliton bit rate. Thus, the architecture made of VCSELD of $\lambda = 0.85$ $\mu$m with the link made of silica is the best architecture.

<table>
<thead>
<tr>
<th>$\lambda$</th>
<th>$T_o$</th>
<th>$R_p$</th>
<th>$\Delta \lambda$</th>
<th>Device</th>
<th>$I_o$</th>
<th>$R_p$</th>
<th>$\Delta \lambda$</th>
<th>Device</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.98 $\mu$m</td>
<td>290 K</td>
<td>750 $\mu$m</td>
<td>0.5E-4 $\mu$m</td>
<td>D1</td>
<td>3.0 mA</td>
<td>5.0 mA</td>
<td>7.0 mA</td>
<td>9.0 mA</td>
</tr>
<tr>
<td>0.683 $\mu$m</td>
<td>290 K</td>
<td>750 $\mu$m</td>
<td>0.5E-4 $\mu$m</td>
<td>D2</td>
<td>1.0 mA</td>
<td>3.0 mA</td>
<td>5.0 mA</td>
<td></td>
</tr>
<tr>
<td>0.863 $\mu$m</td>
<td>290 K</td>
<td>750 $\mu$m</td>
<td>0.5E-4 $\mu$m</td>
<td>D3</td>
<td>5 mA</td>
<td>8 mA</td>
<td>12 mA</td>
<td></td>
</tr>
<tr>
<td>0.85 $\mu$m</td>
<td>290 K</td>
<td>750 $\mu$m</td>
<td>0.5E-4 $\mu$m</td>
<td>D4</td>
<td>1 mA</td>
<td>3 mA</td>
<td>6 mA</td>
<td></td>
</tr>
</tbody>
</table>

Fig.1. Variations of device bandwidth, $F_{3\text{-}dB}$, GHz against Temperature, $T$, K at the assumed set of parameters.

Fig.2. Variations of device bandwidth, $F_{3\text{-}dB}$, GHz against Temperature, $T$, K at the assumed set of parameters.

Fig.3. Variations of device bandwidth, $F_{3\text{-}dB}$, GHz against Temperature, $T$, K at the assumed set of parameters.

Fig.4. Variations of device bandwidth, $F_{3\text{-}dB}$, GHz against Temperature, $T$, K at the assumed set of parameters.
The data shows the following parameters:

- \( \lambda_r = 0.863 \mu m \), \( T_0 = 290 K \), \( R_p = 750 \mu m \), \( D_n = 0.0075 \), \( \Delta \lambda = 0.5 \times 10^{-4} \mu m \) for device D3.

- \( \lambda_r = 0.85 \mu m \), \( T_0 = 290 K \), \( R_p = 750 \mu m \), \( D_n = 0.0075 \), \( \Delta \lambda = 0.5 \times 10^{-4} \mu m \) for device D4.

**Fig. 3.** Variations of device bandwidth, \( F_{3-dB} \), GHz against temperature, \( T \), K at the assumed set of parameters.

**Fig. 4.** Variations of device bandwidth, \( F_{3-dB} \), GHz against temperature, \( T \), K at the assumed set of parameters.

**Fig. 5.** Variations of polymer bandwidth, \( BW_P \), GHz against temperature, K at the assumed set of parameters.

**Fig. 6.** Variations of silica bandwidth, \( BW_F \), GHz against temperature, T, K at the assumed set of parameters.

**Fig. 7.** Variations of soliton bit rate in polymer, \( B_{RSP} \), Gb/s against temperature, T, K, at the assumed set of parameters.

**Fig. 8.** Variations of soliton bit rate in silica, \( B_{Rsf} \), Gb/s against temperature, T, K at the assumed set of parameters.
Fig. 9. Variations of polymer bandwidth, $BW_p$, GHz against Temperature, $K$ at the assumed set of parameters.

Fig. 10. Variations of silica bandwidth, $BW_F$, GHz against temperature, $T$, $K$ at the assumed set of parameters.

Fig. 11. Variations of soliton bit rate in polymer, $BR_{SP}$, Gb/s against temperature, $T$, $K$, at the assumed set of parameters.

Fig. 12. Variations of soliton bit rate in silica, $BR_{SF}$, Gb/s against temperature, $T$, $K$ at the assumed set of parameters.

Fig. 13. Variations of polymer bandwidth, $BW_p$, GHz against Temperature, $K$ at the assumed set of parameters.

Fig. 14. Variations of silica bandwidth, $BW_F$, GHz against temperature, $T$, $K$ at the assumed set of parameters.
Fig. 15. Variations of soliton bit rate in polymer, \( B_{\text{RS}} \), Gb/s against temperature, \( T \), K, at the assumed set of parameters.

Fig. 16. Variations of soliton bit rate in silica, \( B_{\text{RSf}} \), Gb/s against temperature, \( T \), K at the assumed set of parameters.

Fig. 17. Variations of polymer bandwidth, \( B_{\text{WP}} \), GHz against Temperature, K at the assumed set of parameters.

Fig. 18. Variations of silica bandwidth, \( B_{\text{WF}} \), GHz against temperature, \( T \), K at the assumed set of parameters.

Fig. 19. Variations of soliton bit rate in polymer, \( B_{\text{RS}} \), Gb/s against temperature, \( T \), K, at the assumed set of parameters.

Fig. 20. Variations of soliton bit rate in silica, \( B_{\text{RSf}} \), Gb/s against temperature, \( T \), K at the assumed set of parameters.
IV. Conclusions
A special software program is cast to handle the architecture of optical interconnect for high-speed optical data networks. The design is based on four optical VCSEL diodes of different structures and different operating wavelengths \( \lambda \). Also, the design handles two fiber links made of either PMMA polymer or silica fibers. Thus, we have investigated eight different designs, where special emphasis is focused on the following causes and effects shown in Fig. 21.

Caus\es are: i) The injected current \( I \), mA. ii) The ambient temperature \( T \), K. iii) The link radius \( R \) (for polymer) and \( R_1 \) (for silica, \( \mu \)m). iv) The link length, \( R_c \), km., and v) The relative refractive index difference, \( \Delta \).

The effects are: i) The device 3-dB bandwidth, \( f_{3, DB} \), GHz. ii) The links bandwidths, \( B_{WP} \), BW, GHz, and iii) The soliton transmitted bit rate, \( B_{s, TP} \), Bps, Gb/s.

Each device has its own thermal and electrical characteristics, also each of the two links has its thermal and spectral characteristics.

Table III: Comparison of the eight architectures and the link length \( R \)

<table>
<thead>
<tr>
<th>( \lambda ), ( \mu )m</th>
<th>( f_{3, DB} ), GHz</th>
<th>( B_{WP} ), GHz</th>
<th>( B_{s, TP} ), Gb/s</th>
<th>( B_{WP} ), GHz</th>
<th>( B_{s, TP} ), Gb/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.98</td>
<td>6.55</td>
<td>204</td>
<td>0.881</td>
<td>54</td>
<td>0.204</td>
</tr>
<tr>
<td>0.683</td>
<td>6.35</td>
<td>73.5</td>
<td>0.914</td>
<td>21</td>
<td>0.262</td>
</tr>
<tr>
<td>0.863</td>
<td>5.7</td>
<td>144</td>
<td>0.897</td>
<td>40.4</td>
<td>0.227</td>
</tr>
<tr>
<td>0.85</td>
<td>34.9</td>
<td>138</td>
<td>0.898</td>
<td>38.8</td>
<td>0.228</td>
</tr>
</tbody>
</table>

References