Numerical Simulation and Analysis of a Cost Effective Digital Fiber Optic Link

Pavithra R¹ Durga Devi R² Krishna Kumar V³
¹,²,³Department of Electronics & Communication Engineering
¹,²,³Kongunadu College of Engineering and Technology Tamilnadu - India

Abstract—Simulation study of a cost effective digital fiber optic link comprising of an 850nm VCSEL diode source, a multimode fiber and a PIN photodetector based receiver is reported in this paper. The characteristics of the VCSEL source are evaluated under DC and Transient conditions. The link performance is evaluated at 1Gbps, at different link lengths and operating temperatures. For 20 degree celsius ambient temperature, the link output is efficiently detectable up to a length of 600 m. For a fiber length of 600 m, the optical power is observed to be appreciable till a temperature of 40 degree celsius.

Key words: VCSEL Diode, Photodetector, Multimode Fiber

I. INTRODUCTION

Fiber optic links have completely replaced the copper and coaxial transmission mediums, for most of the communication applications. Multimode fiber is preferred for short distance and in building applications. Many office buildings have already been equipped with Multimode fibers. Vertical Cavity Surface Emitting Laser (VCSEL) sources are more cost effective and easily testable compared to other optical sources. Though they exhibit thermal behavior, they have low threshold current, less power consumption along with high output power efficiency. Short-wavelength VCSELs can provide low distortion performance adjacent to that of Fabry–Perot and distributed feedback (DFB) lasers for analog links [1]. The usage of multimode fiber (MMF) in such systems is eye-catching as it continues to be deployed in greater volumes than single-mode fiber, with typical installation lengths of up to 300 m [3]. Further, it has been shown that the MMF may be used for the transmission of RF carriers afar the modal dispersion limited3 dB bandwidth [11], [12].

In this paper, a cost effective digital optical link model is simulated for 1 Gbps applications and its performance is analyzed using MATLAB software. The effect of VCSEL thermal dependence and its impact on link performance is studied.

II. SYSTEM MODELING

The individual components in the optical link are the 850 nm VCSEL diode, the 850 nm multimode graded index fiber and the PIN photodetector. Figure 1 shows a simple system level block diagram of the link.

![Fig. 1: Generic block diagram for digital optical link](image)

A. Modeling VCSEL Diode

The VCSEL diode modelled in this link is a 3.1 micrometer diameter thin-oxide-apertured device which is composed of an Al₀‧₉Ga₀‧₁As-GaAs p-type DBR, three In₀‧₇Ga₀‧₃As-GaAs quantum wells, an Al₀‧₆Ga₀‧₄As cavity, and an AlAs-GaAs -type DBR. The laser model is based on the simple thermal VCSEL model developed by Mena et.al [7]. It is a semi-empirical model established on the standard laser rate equations and a thermally dependent empirical offset current. Linear behavior degrades even under normal device bias and modulation. One of the limitations of a VCSELs performance is its thermal behavior. The effects of self heating on the output characteristics of VCSELs are highly prominent. Hence, an effective model must reproduce this thermal behavior, particularly in terms of the temperature dependent threshold current and output power roll-over. The I-V characteristics of the device under room temperature conditions is modelled by the equation: [7]

$$V = 149.8I + 0.936 \ln \left(1 + \frac{I}{7.918 \times 10^{-5}}\right)$$

(1)

![Fig. 2: Voltage Vs Current Plot of VCSEL diode](image)

The curve shows the behavior of the voltage with respect to the current input in the chosen VCSEL diode model under room temperature. With increase in temperature, the VCSEL gain spectrum broadens and its peak shifts to longer wavelengths. Also, thermal leakage of carriers out of the active region can lead to reduction of injection efficiency, which contributes to thermal roll over.

B. Rate Equations

The rate equations relating N (carrier number), S (Photon number) and T (temperature), in a VCSEL are given as [7]

$$\frac{dN}{dt} = \frac{\eta (1 - I / I_{th})}{q} N \frac{G_r (N - N_e)}{\tau_e} \frac{1 + eS}{1 + eS}$$

(2)

$$\frac{dS}{dt} = - \frac{S}{\tau_s} + \frac{\beta N}{\tau_e} + \frac{G_r (N - N_e)}{1 + eS}$$

(3)

$$T = T_o + (IV - P_o) R_{th} - \tau_{\omega} \frac{dT}{dt}$$

(4)
In this model, the temperature dependence of the device is captured. The power output of a VCSEL above its threshold is given as

\[ P_o = n (T) (1 - I_{th} (N, T)). \]  

(5)

\[ I_{th} (T) \] can be expressed as a constant value \( I_{th0} \) plus an empirical thermal offset current \( I_{thf} (T) \).

\[ I_{th} (T) = I_{th0} + I_{thf} (T). \]  

(6)

\[ I_{thf} (T) = a_0 + a_1 T + a_2 T^2 + a_3 T^3 + a_4 T^4 \]  

(7)

Where the coefficients \( a_0-a_4 \) can be determined during parameter extraction.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Values</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \eta_i )</td>
<td>Injection efficiency</td>
<td>0.821</td>
<td>-</td>
</tr>
<tr>
<td>( \beta )</td>
<td>Spontaneous emission coupling coefficient</td>
<td>2.86e-2</td>
<td>-</td>
</tr>
<tr>
<td>( \tau_n )</td>
<td>Carrier recombination lifetime</td>
<td>1.201</td>
<td>nS</td>
</tr>
<tr>
<td>( K )</td>
<td>Output coupling efficiency</td>
<td>4.166e-8</td>
<td>W</td>
</tr>
<tr>
<td>( G_o )</td>
<td>Gain coefficient</td>
<td>8.486e5</td>
<td>s⁻¹</td>
</tr>
<tr>
<td>( N_o )</td>
<td>Carrier Transparency number</td>
<td>1.286e6</td>
<td>-</td>
</tr>
<tr>
<td>( \tau_p )</td>
<td>Photon lifetime</td>
<td>2.88</td>
<td>pS</td>
</tr>
<tr>
<td>( a_0 )</td>
<td>1st Temperature Coefficient</td>
<td>2.213e-3</td>
<td>A</td>
</tr>
<tr>
<td>( a_1 )</td>
<td>2nd Temperature Coefficient</td>
<td>-1.714e-4</td>
<td>A/K</td>
</tr>
<tr>
<td>( a_2 )</td>
<td>3rd Temperature Coefficient</td>
<td>3.355e-6</td>
<td>A/K2</td>
</tr>
<tr>
<td>( a_3 )</td>
<td>4th Temperature Coefficient</td>
<td>0</td>
<td>A/K3</td>
</tr>
<tr>
<td>( a_4 )</td>
<td>5th Temperature Coefficient</td>
<td>0</td>
<td>A/K4</td>
</tr>
<tr>
<td>( R_{th} )</td>
<td>Thermal Impedance</td>
<td>0.896e3</td>
<td>oC/W</td>
</tr>
<tr>
<td>( T_{th} )</td>
<td>Thermal Time constant</td>
<td>1e-6</td>
<td>S</td>
</tr>
<tr>
<td>( \xi )</td>
<td>Gain compression factor</td>
<td>3.88e-6</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 1: Parameters for the VCSEL [1]

C. Fiber and Detector Modeling

The impulse response of the graded index multimode fiber is generalized as a Gaussian function [13] with respect to the optical power. The function representing the impulse response behavior of the fiber [13],

\[ h_{mmf}(t) = \frac{1}{\sqrt{2\pi}\sigma^2} \exp \left[ -\frac{(t - \tau)^2}{2\sigma^2} \right] \]  

(8)

Where, \( \tau \) is the delay of the channel and \( \sigma \) is the standard deviation of the impulse response which varies linearly with the length of the fiber. The fiber response is obtained by convolution of the optical power output from the VCSEL source with the impulse response function of the fiber.

<table>
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<th>Parameters</th>
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<th>Values</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \alpha )</td>
<td>Attenuation of the fiber</td>
<td>2.5</td>
<td>dB/km</td>
</tr>
<tr>
<td>( D )</td>
<td>Distance of the link</td>
<td>0-1</td>
<td>Km</td>
</tr>
<tr>
<td>( \tau )</td>
<td>Delay due to propagation in fiber</td>
<td>1.5</td>
<td>ns/km</td>
</tr>
<tr>
<td>( \sigma )</td>
<td>Standard deviation of impulse response</td>
<td>0.5</td>
<td>ns/km</td>
</tr>
</tbody>
</table>

Table 2: Multimode Fiber Link Parameters

The fiber performance is limited by its length. For longer fiber lengths the information suffers greater attenuation. The effect of intermodal dispersion also becomes more pronounced with increase in the length of the fiber as observed from its impulse response curve for different lengths of the fiber.

The output from the fiber is obtained through direct detection and optical filtering. The device is modelled as a butterworth low pass filter.

III. RESULT

The characteristics of the individual components- the optical source and the multimode fiber, are analysed in detail before proceeding to the overall testing of the link.

A. VCSEL Static Analysis

The temperature dependent behaviour of the VCSEL diode is reflected in its DC Characteristic curve in Figure 4 where the peak value of the output power calculated in terms of the photon density decreases with increase in ambient temperature.

Fig. 3: Impulse Response of optical fiber for various lengths of the fiber

Fig. 4: Static Analysis- Optical power Vs Current input at (a) 20 degree (b) 30 degree (c) 40 degree C

As the input current increases, output power increases to a particular value and then rolls off. This determines the linear range of operation of laser diode.

B. VCSEL Transient Analysis

At 20 degree Celsius ambient temperature, the optimum bias points for the high level and low level are determined to be 5.5 mA and 0.5 mA respectively. The response of the VCSEL diode is observed for higher ambient temperatures for the same set of bias points.
The characteristics of delay with respect to temperature and the amplitude value after the response settles with respect to temperature in Figure 6 present a more detailed analysis of the chosen optical source.

![Fig. 5: Output power of pulse input at different temperatures](image)

(a) input pulse (b) response at 20 degree C (c) 30 degree C and (d) 40 degree C

From the single pulse response, the VCSEL output is observed to decrease with increase in temperature. Also there is a transient at the output pulse before it settles to the constant value. The response time of the diode is observed to increase with rising temperature. The pulse width is also found to decrease with the increase in ambient temperature. The threshold current in laser sources is found to have exponential relation with the ambient temperature which is given by the equation [4]:

\[ I_{th} = I_0 \exp\left(\frac{T}{T_0}\right) \]  

[9]

Where \( T_0 \) is reference temperature  
\( I_0 \) is normalized current

![Fig. 6: (a) Rise time at different temperatures (b) Output power vs temperature graph](image)

For a data rate of 1 Gbps, beyond the ambient temperature value of 40 degree celsius, the optical power from the VCSEL source drops to zero. From the characteristics amplitude, delay and pulse width of the optical signal with respect to temperature, the best case output is obtained in the temperature range of 10 to 30 degree celsius. Further study is carried out at 20 degree ambient temperature.

C. FIBER Pulse Analysis

The response from the fiber for different lengths of the fiber from 100 m up to 1 Km in steps of 100 m, for a single pulse input of 1 Gbps at the fixed ambient temperature of 20 degree C is shown in Fig 7.

![Fig. 7: Response of fiber at different lengths](image)

As the fiber length increases, it is observed that the peak output power value decreases as the signal is subjected to greater attenuation and the pulse spread increases owing to the dispersion experienced within the fiber.
D. LINK Performance Analysis

To analyze the performance of the link, it is tested with a randomly generated pulse of 1 Gbps data rate sequence for various lengths of the fiber at the fixed ambient temperature of 20 degree C.

The eye diagrams obtained for various lengths of the fiber are in Figure 8.

It is observed that the height of the pulse decreases as the fiber length increases and the pulse spread increases with increase in length of the fiber. This is due to the attenuation and the intermodal dispersion effects of the fiber which becomes more pronounced as length of the fiber increases. The plot of eye height with respect to length of the fiber in Figure 9 shows the declining trend of the eye height parameter.

At the ambient temperature of 20 degree celsius, the power output from the link is appreciable up to a link length of 600 m. Beyond this fiber length, the signal distortion due to attenuation and dispersion effects is very high.

IV. CONCLUSION AND FUTURE WORK

A cost effective Radio over Fiber link for data transmission at low data rates is proposed. The laser diode temperature dependent behavior is modelled and its effects are avoided by choosing the most optimum temperature and bias point for operation of the device. The response of laser is governed by its rate equations. Various parameters used in the rate equations are obtained from experimental study. The fiber is modelled by using a transfer function equation which incorporates both attenuation and dispersion. The variation of attenuation and dispersion effects with the length of the fiber is analyzed and an optimum length is chosen. The photo detector is modelled as a fourth order Butterworth filter. As the photo detector should remove out-of-band noise, it is modelled as a low pass filter. Using higher order filter results in increased complexity and added cost. Hence an order of four is chosen to lessen complexity without much degradation in performance.

A Satellite signal of Digital Video Broadcasting is generated. Hence the future work lies in testing the system with the satellite signal after subjecting it to various path loss models and finding out the maximum number of signals that can be supported by this system with appreciable performance.

REFERENCES


