Electrical package impact on VCSEL-based optical interconnects

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Abstract

A new CAD tool fREEDA® based on state variable approach and universal error concept is presented for modelling and simulating systems where physical domains such as electrical, thermal, and optical interact with each other. A single implementation of device equations in fREEDA® can be used with different analysis types such as transient and harmonic balance, etc. To demonstrate the multi-physics capabilities of fREEDA®, we present a study of the impact of electrical packages on the source module performance in multi-gigabit per second vertical cavity surface emitting laser (VCSEL)-based optical interconnects. The effect of various operating conditions such as bias/drive level and driver configuration are studied. We consider electrical packages such as printed wire board, thin-film and flip-chip in our study. A comparison of VCSELs with stripe lasers is also presented.

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1. Introduction

Ever increasing data traffic within high performance computers requires multi-gigabit per second links between chips, boards and multi-chip modules. At such high data rates electrical interconnects suffer from skin effect, losses, pulse distortion and reflections due to impedance mismatch. The maximum allowable bit-rate for electrical interconnections depends on the aspect ratio of the interconnect. The bit-rate capacity
for a wide range of electrical interconnects is $10^{15} A/l^2$ where $A$ is the cross-sectional area and $l$ is the length of interconnect [1,2]. Electrical interconnects are also plagued by a scaling problem: an electrical interconnect designed to operate in the MHz range may not be suitable in the GHz region. These limitations of electrical interconnects can be overcome by using 3D technologies such as 3D integration of transistors, RF wireless interconnects and optical interconnects [1–3].

Optical interconnects are capable of carrying data at tera-bits per second. Immunity from electromagnetic interference (EMI), low crosstalk noise, low losses and impedance matching through the use of antireflection coatings make them a suitable choice for multi-Gbps links [15]. Optical interconnects also provide voltage isolation between different parts of a system. Recent developments in optoelectronic (OE) component technology, e.g. vertical cavity surface emitting laser (VCSEL), have provided an impetus to the area of optical interconnect research. VCSEL arrays and drivers at 10 Gbps are now readily available from multiple vendors.

Silicon-based drivers are often used to modulate GaAs-based VCSELs. Hybrid integration is therefore the key to realizing high-speed optical interconnects. In hybrid integration, VCSELs grown on III–V compounds are connected to Si-based electronic drivers using various types of packages [7,8]. Studying the impact of these packages on source module performance is therefore important. Design and optimization of such hybrid solutions within a mixed-signal environment requires consideration of linear and nonlinear system response to parasitics that affect the signal integrity. Development of fast solvers for linear and nonlinear analysis of transmission line effects, thermal noise, etc. is therefore needed. A new simulation tool fREEDA®, with multi-physics capabilities, is developed for implementation of advanced modeling and simulations with fast linear and nonlinear solvers. fREEDA® is capable of full-wave EM modeling of on-chip parasitics, optoelectronic and electro-thermal modeling, and digital and analog behavioral modeling [4,5]. In this paper, we demonstrate the multi-physics capabilities of fREEDA® by studying the impact of electrical packages on source module performance in VCSEL-based high-speed optical interconnects under varying operating conditions such as bias/drive level, driver configuration, data rate, etc.

2. Optoelectronic component modeling

The key to optical interconnect design and analysis is the availability of a tool that can be used to simulate the electrical, optical and thermal behavior of OE devices separately and in a system. Existing tools for OE device simulation involve either solving Maxwell equations using for example, the FDTD method that is computationally intensive, or using equivalent circuits [19]. Implementation of device models using an equivalent circuit approach has several drawbacks as described in [6]. Tools that can model devices as a set of algebraic or differential equations provide a global modeling environment and are, therefore, well suited for multi-physics simulations.

The fREEDA® simulator facilitates OE device modeling with sets of differential equations. fREEDA® was originally designed for microwave circuit simulations but over time has evolved into a global multi-physics modeling environment. Based on an object-oriented approach, it uses state variables to represent the physical quantities of interest. Some of the unique features of fREEDA® are automatic differentiation, the concept of local reference nodes, etc. Automatic differentiation allows calculation of derivatives free of truncation error. The local reference node concept is suitable for the analysis of spatially distributed systems as well as for multi-physics simulations where different physical domains such as electrical, optical and thermal are treated simultaneously [4,5]. These features of fREEDA® make it suitable for OE interconnects simulations that involve the interaction of VCSELs, drivers, packages and intermediate optics (such as lenses, gratings, etc.).

We consider two type of laser diodes in our simulations: VCSELs and Stripe lasers. The VCSEL is a low-cost, low-threshold, high-speed optical source. Development of 1D and 2D VCSEL arrays enables implementation of cost-effective high-speed optical interconnects. Stripe
lasers are not as well suited but generally have higher performance with smaller chirp when compared with VCSELs.

2.1. VCSEL model

A VCSEL consists of an optical cavity formed along the device growth direction. The cavity is bounded from the top and bottom by distributed Bragg reflectors (DBR’s) of high reflectivity. These DBRs provide high reflectivity at the emission wavelength [20,21]. VCSELs have a very short cavity length that results in large mode spacing and a single longitudinal mode optical output. DBR mirrors offer a large resistance to current flow and can cause device heating. VCSEL devices therefore exhibit strong thermal dependence that leads to a temperature dependent gain and leakage current to account for thermal effects [12]. The following rate equations were used to model the VCSEL:

\[
\frac{dN_0}{dt} = \frac{\eta I}{q} - \frac{N_0}{\tau_n} - \frac{G(T)(N_0 - N_s)S}{(1 + \epsilon S)} - \frac{I_t}{q},
\]

\[
\frac{dS}{dt} = \frac{S}{\tau_p} + \frac{\beta N_0}{\tau_n} + \frac{G(T)(N_0 - N_s)S}{(1 + \epsilon S)},
\]

where \(N_0\) is the carrier number, \(S\) is the photon number, \(\eta\) is the current injection efficiency, \(\beta\) is the spontaneous emission factor, \(\epsilon\) is the gain saturation factor, \(t\) is the time, \(T\) is the temperature and \(I_t\) is the leakage current. Carrier lifetime and photon lifetime are \(\tau_n\) and \(\tau_p\), respectively. \(G(T)\) and \(N_s(T)\) represent the temperature dependent gain and transparency number, respectively, and are modeled using the empirical relations

\[
G(T) = \frac{G_0(a_{g0} + a_{g1}T + a_{g2}T^2)}{(b_{g0} + b_{g1}T + b_{g2}T^2)}
\]

and

\[
N_s(T) = N_{\text{th}}c_1 + c_{a1}T + c_{a2}T^2,
\]

where \(G_0\) is the gain constant; \(N_{\text{th}}\) is the transparency number constant; \(a_{g0}, a_{g1}, a_{g2}, b_{g0}, b_{g1}\) and \(b_{g2}\) are fitting constants for the gain equation; and \(c_{a0}, c_{a1}\) and \(c_{a2}\) are fitting constants for the transparency number equation.

The instantaneous wavelength of a VCSEL is modeled using the equation proposed in [7]. Here it is modified to include temperature effects:

\[
\lambda(t) = \lambda_0 \left(1 - \frac{\rho(N_0 - N_s)}{n} + \frac{dn}{dT} \frac{(T - T_0)}{n}\right),
\]

and thus the instantaneous wavelength depends on carrier number and temperature. In (5) \(T_0\) is the ambient temperature, \(\rho\) is the refractive index change per unit carrier number change and \(n\) is the refractive index of the medium. Table 1 contains the VCSEL parameters used in our simulations. These parameters are taken from [12] for a thin-oxide aperture VCSEL. Fig. 1 shows the simulated output optical power vs. input current (\(L-I\)) curve for this VCSEL demonstrating the temperature dependent threshold current and thermal rollover that have been observed in experiments [12,13].

The \(L-I\) curves at 20, 30 and 40 °C are shown in Fig. 1. We see that the threshold current at 40 °C is
more than that at 20 °C. We also note that the increased ambient temperature accelerates the optical power rollover. The optical power rollover with an increase in current can be attributed to both the leakage current and temperature dependent gain [12–14]. With an increase in drive current, the device temperature increases causing gain and leakage current to vary with current. This increase in temperature causes gain spectrum broadening and a shift in peak gain wavelength leading to a mismatch between the gain peak and the cavity wavelength. The output optical power therefore reduces due to a reduced gain at the cavity wavelength. Leakage current occurs due to a temperature-induced increase in quasi-fermi levels. This increase in quasi-fermi levels reduces the barrier experienced by carriers in the quantum wells leading to leakage current. Increased temperature exacerbates this effect. Because the quasi-fermi levels depend on temperature and carrier number, leakage current can be modeled using the following empirical relation:

\[
I_l = I_{l0} \exp((-a_0 + a_1N_0 + a_2N_0T - a_3/N_0)/T),
\]

where \(I_{l0}\) is the leakage current constant; and \(a_0, a_1, a_2\) and \(a_3\) are fitting constants. The increase in temperature with current occurs because not all of the electrical power is used in generating photons. The temperature increase with current can be modeled as

\[
T = T_0 + (IV - P)R_{th} - \tau_{th} \frac{dT}{dt},
\]

where \(V\) is the voltage, \(P\) is the optical power, \(R_{th}\) is the thermal resistance of the device and \(\tau_{th}\) is the thermal time constant. In our VCSEL modeling, we have used a thin-oxide aperture VCSEL and its parasitics as given in [12]. The series resistance of VCSEL was taken into account in the expression for voltage, where terminal voltage of VCSEL is modeled using the following expression [12]:

\[
V = IR_s + 0.9366 \log(1 + I/7.918e - 5).
\]

Fig. 2 shows the optical power vs. time for a VCSEL at two different currents (bias0: \(I = 0\); bias1: \(I = 3I_{th}\)). We note that optical power shows ringing which reduces with increase in bias. We also note that increased bias reduces the time between the application of a current pulse and appearance of optical power output (turn-on delay). The ringing in the output power occurs due to the initial energy exchange between the carriers and photons. Wavelength chirp is shown in Fig. 3 for the two different biases. When the laser is turned on there is a sudden increase in the carrier number that leads to a decrease in refractive index. The wavelength in a VCSEL is determined using the condition \(\lambda = 2nL\), where \(n\) is the refractive index and \(L\) is the length of the cavity. This transient variation in refractive index causes the VCSEL wavelength to vary. Once the steady-state is
reached the wavelength becomes constant. Wavelength chirp reduces with the increased bias because reduced current swing induces a small change in refractive index.

2.2. Stripe laser model

Stripe lasers have been modeled extensively [7,10,11] and the type used in our study has a buried heterostructure. This stripe laser is modeled using the rate equations based on Tucker’s equivalent circuit [9,10]:

\[
\frac{dN_0}{dt} = \frac{\eta I}{q} - \frac{N_0}{\tau_n} - \Gamma G_0(N_0 - N_0)(1-\epsilon S)S, \quad (9)
\]

\[
\frac{dS}{dt} = -\frac{S}{\tau_p} + \frac{\Gamma \beta N_0}{\tau_n} + \Gamma G_0(N_0 - N_0)(1-\epsilon S)S. \quad (10)
\]

Wavelength chirp is modeled using (5) as for VCSELs. Fig. 4 shows the optical power vs. current curves for a stripe laser. This stripe laser does not exhibit thermal rollover with increase in current as occurs with a VCSEL. The threshold current for a stripe laser does vary with temperature and is modeled by

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

where \( T \) is the device temperature, \( T_{th} \) is a constant that depends on the device material and \( I_0 \) is the threshold current constant.

The transient output power and wavelength chirp for a stripe laser are shown in Figs. 5 and 6 for two different biases (bias0: \( I = 0 \), bias1: \( I = 3I_{th} \)). The ringing for a stripe laser also reduces with increase in bias. Wavelength chirp of this stripe laser is smaller than obtained with the VCSEL due to the high threshold of the stripe laser. The parameters used for our stripe laser study are given in Table 1.

2.3. Package models

Since our study is concerned with multichannel optical interconnects we consider a 1D array of lasers with a pitch of 250 \( \mu \)m. Interfacing VCSELs...
with Si-based drivers requires the marriage of Si and GaAs technologies. One can achieve this using either monolithic or hybrid integration [22]. Here we consider three hybrid integration methods.

Hybrid integration requires physical packages to interface electrical drivers to the laser array. We consider three different packages for our study: printed wire board (PWB), thin-film (TAB) and flip-chip. Figs. 7–9 show the geometries for these three packages. The PWB has wire bonds on both the driver array side and the VCSEL array side. Transmission line equivalent circuits for the packages are shown in Figs. 10–12. Both PWB and thin-film packages have equivalent circuits that include coupling capacitors and mutual inductances that introduce crosstalk and signal distortion whereas the flip-chip package reduces these parasitics resulting in good signal integrity up to very high data rates. For PWB only wire bonds on the driver side are shown in Fig. 10. Poly(6) element in transmission line equivalent circuits of PWB and TAB packages represent a voltage dependent source being modelled using a polynomial. Physical parameters of all three packages are given in Table 2. The $R$, $L$ and $C$ parameters of the corresponding equivalent circuits are listed in Table 3. We use full-wave electromagnetic simulations to synthesize the transmission line equivalent circuits. Frequency dependent parameters were extracted over a given bandwidth (40 GHz) to obtain a multiport corresponding to the interconnect structure of interest. A netlist was then constructed that represents the same frequency-dependent multiport admittance matrix. The synthesized transmission line equivalent circuits for the packages capture in addition to capacitive coupling between the traces, frequency-dependent inductive coupling as well as the frequency-dependence of the self resistances and self inductances associated with the skin effect in the traces [25]. For the bond wires, the indicated equivalent circuits for the parasitics were extracted assuming that the ground of the PCB or thin-film package is extended under both the driver circuit and laser array die. The indicated equivalent circuits for the bond wires were extracted using the ground plane as the return path.
2.4. Driver models

We consider two driver configurations in our study: Simple drivers and Push-pull drivers as shown in Figs. 13 and 14, respectively. The simple driver represents the lowest complexity and consists of a single transistor; whereas, the push-pull driver is more complex and requires both a signal and its inverted counterpart as input. The push-pull driver dissipates more power compared to the simple driver; however, the simple driver suffers from switching noise that can degrade signal integrity. With multichannel free space optical interconnect (FSOI), switching noise, power dissipation and circuit complexity are major design issues.

Switching noise occurs due to the sharing of power supply and ground lines by different channels. In this section, we combine our driver models with the laser models using the flip-chip package in order to study the impact of switching noise. We consider three adjacent channels in our laser array that keeps the simulation complexity low while demonstrating the inter-channel interaction in source module. To study the impact of switching noise, the input to channels 1 and 3 are delayed by one quarter of a pulse period compared to the middle channel. The input waveforms to all three
channels are shown in Fig. 15. When channels 1 and 3 turn on while channel 2 is already ON, the current demand from the power supply suddenly increases; however, the power supply inductors oppose this increase during the input transition time by inducing a back emf (electromotive force) $LdI/dt$. To make up for this current demand the current is drawn from channel 2. This results in the channel 2 current reduction giving rise to switching noise. We define the switching noise as the magnitude of the dip in the output optical power level of middle channel during the transition of neighboring channels. Fig. 16 shows the output optical power from channel 2 for both VCSEL and stripe lasers at 1 Gps. The stripe laser exhibits more switching noise compared to the VCSEL. This is because the stripe laser diode has a high threshold current that leads to large current swing in order to achieve the same optical power.

![Thin-film package transmission line equivalent.](image1)

![Flip-chip package transmission line equivalent.](image2)

<table>
<thead>
<tr>
<th>Package physical parameters</th>
<th>Printed wire board</th>
<th>Thin-film</th>
<th>Flip-chip</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameter</td>
<td>FR-4</td>
<td>Polymer</td>
<td>SiO$_2$</td>
</tr>
<tr>
<td>Substrate thickness (µm)</td>
<td>75</td>
<td>27.5</td>
<td>1</td>
</tr>
<tr>
<td>Substrate dielectric constant</td>
<td>4.5</td>
<td>3.6</td>
<td></td>
</tr>
<tr>
<td>Conductor thickness (µm)</td>
<td>25</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>Conductor width (µm)</td>
<td>125</td>
<td>45</td>
<td></td>
</tr>
<tr>
<td>Wire bond length (µm)</td>
<td>500</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wire bond diameter (µm)</td>
<td>25</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
ing noise depends on parameters such as the rise
time of the pulse, data rate, bias level and output
power level. Variations of the switching noise with
changes in rise time are shown in Fig. 17 for the
VCSEL and the stripe laser for two different data
rates. Increasing rise time from 0.05 to 0.2 ns at
a fixed data rate of 500 Mbps reduces switching
noise for the stripe laser by 51 percent.

The effect of increasing bias is shown in Fig. 18.
Increasing the bias current reduces switching noise
both for the VCSEL and the stripe laser because
the current swing $I_{\text{high}} - I_{\text{bias}}$ is reduced. The ON
state optical power level was kept fixed at 2.5 mW for both the VCSEL and the stripe laser

### Table 3

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Printed wire board</th>
<th>Thin-film</th>
<th>Flip-chip</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_1$ (Ω)</td>
<td>0.04</td>
<td>0.090</td>
<td>0.2325</td>
</tr>
<tr>
<td>$L_1$ (nH)</td>
<td>0.232</td>
<td>0.271</td>
<td>0.009</td>
</tr>
<tr>
<td>$R_{S1}$ (Ω)</td>
<td>0.111</td>
<td>0.171</td>
<td>–</td>
</tr>
<tr>
<td>$L_{S1}$ (nH)</td>
<td>0.021</td>
<td>0.027</td>
<td>–</td>
</tr>
<tr>
<td>$R_{S2}$ (Ω)</td>
<td>0.394</td>
<td>0.675</td>
<td>–</td>
</tr>
<tr>
<td>$L_{S2}$ (nH)</td>
<td>0.004</td>
<td>0.007</td>
<td>–</td>
</tr>
<tr>
<td>$R_{P1}$ (MΩ)</td>
<td>37.15</td>
<td>0.624</td>
<td>–</td>
</tr>
<tr>
<td>$C_{P1}$ (pF)</td>
<td>0.014</td>
<td>0.108</td>
<td>0.01</td>
</tr>
<tr>
<td>$R_2$ (Ω)</td>
<td>0.016</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>$L_2$ (nH)</td>
<td>0.295</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>$R_{S3}$ (Ω)</td>
<td>0.067</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>$L_{S3}$ (nH)</td>
<td>0.040</td>
<td>–</td>
<td>–</td>
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<tr>
<td>$R_{S4}$ (Ω)</td>
<td>0.293</td>
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<td>–</td>
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<tr>
<td>$L_{S4}$ (nH)</td>
<td>0.003</td>
<td>–</td>
<td>–</td>
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<tr>
<td>$R_{P2}$ (MΩ)</td>
<td>0.71</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>$C_{P2}$ (pF)</td>
<td>0.113</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>$C_{12}$ (pF)</td>
<td>0.498</td>
<td>0.614</td>
<td>–</td>
</tr>
<tr>
<td>$C_{13}$ (pF)</td>
<td>0.108</td>
<td>0.139</td>
<td>–</td>
</tr>
<tr>
<td>$C_{22}$ (pF)</td>
<td>0.002</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>$C_{23}$ (pF)</td>
<td>0.329</td>
<td>–</td>
<td>–</td>
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<tr>
<td>$K_{12}$</td>
<td>0.063</td>
<td>0.023</td>
<td>–</td>
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<tr>
<td>$K_{13}$</td>
<td>0.176</td>
<td>0.005</td>
<td>–</td>
</tr>
<tr>
<td>$K_{22}$</td>
<td>0.066</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>$K_{23}$</td>
<td>0.017</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>
whereas the OFF state optical power was varied from 0 to 1.25 mW in steps of 0.25 mW to vary the bias. The impact of optical power level on switching noise is shown in Fig. 19. Increasing the power level increases the switching noise as increased current is required for increased power output. Switching noise reduction is, therefore, a major concern in the optical interconnect source module.

The $W/L$ ratio for the signal transistors used in our driver circuits is 50/0.5 ($=100:1$). For the bias transistors in the push-pull configuration a $W/L$ ratio of 100/0.5 ($=200:1$) is used. We vary the power supply to achieve the desired current level. More extensive studies on switching noise performance has been performed for backplane optical interconnects [17].

3. Source module study

In this section we combine individual component models (drivers, packages and lasers) to study the performance of the overall source module under various operating conditions. The multi-physics nature of our tool can capture interactions between these components and bring out the impact that hybrid integration has on source module performance. This type of study can help in designing an optimized source module for optical interconnects. We consider three packages in our source module study. The impact of these packages on crosstalk, power dissipation, turn-on delay and chirp is studied. We specify a set of requirements for the source module inter-channel noise (crosstalk + switching noise), turn-on delay and chirp. A source module with an inter-channel noise figure of less than $-10$ dB is desired. The turn-on delay for each laser in the source module is specified to be less than one quarter of the pulse period whereas a wavelength chirp of less than 0.1 nm is desired. We consider two bias levels, two drivers, four data rates and two laser types in our study.
We performed a simulation study of different source module configurations (laser + package + driver combinations) under different operating conditions (bias and data rate).

3.1. Crosstalk

The electromagnetic interactions (EMI) between the channels at high-speeds give rise to crosstalk. These interactions of the channels manifest themselves through the presence of the coupling capacitors and mutual inductors in the transmission line equivalent models of the packages. The coupling capacitors and mutual inductors of both the PWB and thin-film packages, cause a coupling of signals from neighboring channels to the middle channel thus resulting in channel crosstalk. The push-pull driver is used in this crosstalk study so that switching noise is not confused with crosstalk. Crosstalk depends on factors such as the type of package, data rate, current-drive level and bias. The impact of package type on VCSEL crosstalk is demonstrated in Fig. 20. Fig. 21 demonstrates the impact of package type on stripe laser crosstalk. The flip-chip package is seen to generate less crosstalk compared to the other two packages due to its reduced parasitics. The effect of bias is seen to reduce crosstalk as it reduces the net current swing and thus the electromagnetic coupling from neighboring driver circuits. Crosstalk is significantly higher with the stripe laser system relative to the VCSEL system. For flip-chip package, crosstalk introduced by neighboring channels for the stripe laser is 0.8 mW; whereas, crosstalk for the VCSEL is seen to be 0.35 mW.

The impact of data rate on crosstalk for a thin-film package and two different biases is shown in Figs. 22 and 23. We see that increasing the data rate from 500 Mbps to 1 Gbps increases crosstalk from 0.25 to 0.9 mW as the impedance \(1/jC_w\) associated with the capacitive coupling reduces with increasing data rate. This quadratic increase in coupling is expected when the predominant coupling between interconnects is capacitive (or inductive) rather than transmission line coupling. Note that the energy of a pulse and thus of crosstalk is the best measure of signal integrity in high-speed digital interconnect systems as they are designed for first incidence switching. A comparison of flip-chip and thin-film (Tape-Automated Bond) packages is shown in Figs. 24 and 25 for 5 and 10 Gbps demonstrating pulse dispersion and increased crosstalk for the thin-film package; whereas, the flip-chip package still provides good response.
### 3.2. Turn-on delay

Turn-on delay refers to the time lag between the instant that logic begins to go high and the optical output from a laser diode is observed. This turn-on delay can be attributed principally to the existence of a lasing threshold in laser diodes. That is, when the current is applied, the carrier number in the active region increases and reaches the threshold value causing the device to lase. The time taken by the carriers to reach this threshold is responsible for the delay. Turn-on delay depends on factors such as bias, rise time, optical power, data rate and package type. Fig. 26 shows the effect of increasing bias on turn-on delay. We observe that an increase in bias (the quiescent current in bias1 being higher than in bias0) reduces turn-on delay by reducing the time it takes to reach threshold. Turn-on delay for lasers biased below threshold can be estimated using the relation:

\[
\text{Turn-on delay} = \frac{\text{Bias}}{\text{Current}}
\]

![Fig. 21. Crosstalk comparison for various packages using stripe laser. The dashed lines are for bias0 and the solid lines are for bias1.](image1)

![Fig. 22. VCSEL output power for thin-film package at 500 Mbps.](image2)

![Fig. 23. VCSEL output power for thin-film package at 1 Gbps.](image3)
\[ t_{\text{delay}} = \tau_n \ln \left( \frac{I_{\text{on}} - I_{\text{bias}}}{I_{\text{on}} - I_{\text{th}}} \right), \]

where \( \tau_n \) is the carrier lifetime, \( I_{\text{on}} \) is the current injected into the laser and \( I_{\text{bias}} \) is the bias current. Another component that contributes to turn-on delay is electrical delay. Electrical packages play an important role in determining this electrical component of delay. Fig. 27 shows the effect that package type has on turn-on delay. From Fig. 27 we conclude that both the PWB and thin-film packages fail to meet the system specification \((t_{\text{delay}} < \text{Period}/4)\) for turn-on delay for some of the output power levels, when biased below threshold. It is seen that the PWB package introduces more delay compared to thin-film and flip-chip. For 1 mW of output optical power at a data rate of 1 Gbps the delay for PWB, thin-film and flip-chip packages are 0.33, 0.3 and 0.23 ns, respectively, at bias 0. Turn-on delay is seen to reduce with increasing output optical power. This is due to an increased current requirement for high output power that results in large slew rate. This
increase in slew rate occurs because we have fixed the rise time for a given data rate. Fig. 28 shows the effect of data rate on turn-on delay. Delay reduces with increasing data rate due to reduced rise time. We use a rise time of one-tenth of the pulse period or less. A plot comparing delay vs. power for the VCSEL and stripe laser is shown in Fig. 29. The turn-on delay for the push-pull and simple drivers is compared in Fig. 30 at 1 and 2.5 Gbps. The push-pull driver configuration results in more delay than does the simple driver due to the large gate capacitance.

3.3. Power dissipation

Power dissipation is a major concern in optical interconnect system design. The problem is exacerbated by the development of 1D and 2D VCSEL arrays in which a large number of devices are integrated into the same chip. Operating these devices at higher data rate requires more power due to increased package losses at higher data rates. Power dissipation is determined by the wall-plug efficiency of laser diode system. Losses in electrical packages also contribute to power dissipation. Fig. 31 shows the power dissipated for the three
different packages at 2.5 Gbps using the push-pull driver. We see that the PWB packaged device dissipates the most power. To achieve an optical power of 3 mW at bias1, the power dissipated by the PWB, thin-film and flip-chip packages are 3, 2.7 and 2.5 mW, respectively. Power dissipation for the bias1 case is large compared to bias0 as there is always a non-zero off-state current. Fig. 32 shows the power dissipated by various packages using the simple driver under the same operating conditions as in Fig. 31. The power dissipation for the simple driver case reduces with increasing output optical power since turn-on delay reduces as we increase the output power. This behavior was not observed with the push-pull driver as the reduction in turn-on delay with increasing optical power is less significant compared to the situation with the simple driver. Also the push-pull configuration consumes more electrical power compared to the simple driver under the same operating conditions. The impact of data rate on power dissipation for the flip-chip package is shown in Fig. 33. We see that the power dissipation for the push-pull driver increases with an increase in data rate and output optical power. For the simple driver case there is a reduction in power dissipation with increasing output optical power for 1 and 2.5 Gbps because of decrease in turn-on delay. For a data rate of 5 Gbps the power dissipation increases with increasing optical power because the package-induced electrical losses increase.

3.4. Wavelength chirp

Wavelength chirp occurs due to carrier-induced refractive index change. It can be a significant problem in systems having dispersive elements such as gratings. With increasing data rate, chirp-induced degradation ultimately limits the achievable system performance [16,18]. Wavelength chirp depends on package type, bias and data rate. Fig. 34 shows the impact of packages on VCSEL chirp for the simple driver at a data rate of 2.5 Gbps. Wavelength chirp for the PWB package is lower than that of the thin-film and
flip-chip packages due to the low pass filtering induced edge smoothing. As explained earlier, chirp reduces with increasing bias as reduced current swing causes a decrease in refractive index change.

Figs. 35 and 36 demonstrate the effect of data rate on wavelength chirp for the simple and push-pull drivers, respectively. Increasing data rate increases the wavelength chirp as rise-time reduction causes fast switching. A comparison of wavelength chirp for the VCSEL and stripe lasers is shown in Fig. 37. Under the same operating conditions, the stripe laser exhibits smaller chirp compared to the VCSEL. The chirp exhibited by the VCSEL and stripe lasers under the same operating conditions is 0.103 and 0.01 nm, respectively. Chirp results for various packages and data rates show that the system chirp requirement is met for all cases when the laser is biased above threshold.

4. Validation

In this section, we present a validation of simulation results from iREEDA® with both experiments and other experimentally validated CAD
tools such as Spice. In [23,24] fREEDA® (earlier called TRANSIM) results have been validated experimentally and with the Spice CAD tool for monolithic microwave integrated circuits (MMIC) and high-speed electrical interconnects. Fig. 38 shows experimental and simulated $L-I$ curves for single mode VCSEL (Honeywell SV3639) at different temperatures. We extracted the device parameters from $L-I$ and $I-V$ curves. With the extracted parameters we obtain a good match between experiments and fREEDA® results. Our results predict the thermal rollover of VCSEL $L-I$ characteristics at different temperatures. In Fig. 39 we have compared the output optical power from fREEDA® with Spice for flip-chip package at 5 Gbps [7]. The simulations were performed using an array of three lasers and the same input waveforms as in Fig. 15. A comparison of output optical power from fREEDA® with Spice is presented in Figs. 40 and 41 for thin-film package at 1 and 2.5 Gbps, respectively. The match between the results from the two tools is quite good.

5. Conclusion

This performance study is made possible because of the multi-physics nature of the fREEDA® simulation environment. It is seen that fREEDA® provides a mature modeling and simulation tool for OE components such as VCSELs and stripe lasers separately and within a system. For the first time this paper has presented the predicted performance of an optoelectronic system using uncompromised modeling of an optoelectronic system incorporating electromagnetic modeling of packages, electrical modeling, and full optical modeling using a state variable formulation directly related to physical process. This is an alternative to conventional optoelectronic modeling where compromises are required to render optical quantities (photon density, optical power) as

Fig. 39. Comparison of fREEDA and Spice results for flip-chip package at 5 Gbps.

Fig. 40. Comparison of fREEDA and Spice results for thin-film package at 1 Gbps.

Fig. 41. Comparison of fREEDA and Spice results for thin-film package at 2.5 Gbps.
equivalent circuit quantities such as voltage and current. The simulation results for an overall source module (driver + package + laser) study shows that fREEDA® facilitates modeling an understanding of the complex interactions involved in such systems. The results of our source module study are summarized in Table 4. The entries in the table are the laser types that satisfies the system requirements for a given operating condition e.g. An entry with a ‘V’ implies that a VCSEL is required as a light source for meeting the system requirements. These results identify the limitations of different source module configurations.

The good match of fREEDA® results with the experiments and results from Spice in our study and earlier studies [23,24] validates multi-physics capabilities of fREEDA®.

### Table 4
Summary of optoelectronic system modeling results

<table>
<thead>
<tr>
<th>Driver type</th>
<th>Package</th>
<th>Bias0</th>
<th>Bias1</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1 Gbps</td>
<td>2.5 Gbps</td>
</tr>
<tr>
<td>Push-pull</td>
<td>PWB</td>
<td>V/S</td>
<td>–</td>
</tr>
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<td>TAB</td>
<td>V/S</td>
<td>V</td>
</tr>
<tr>
<td></td>
<td>Flip-chip</td>
<td>V/S</td>
<td>V</td>
</tr>
<tr>
<td>Simple</td>
<td>PWB</td>
<td>V/S</td>
<td>–</td>
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<td>V</td>
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<tr>
<td></td>
<td>Flip-chip</td>
<td>V/S</td>
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</tr>
</tbody>
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References