Piecewise Linear Modeling of Vertical Cavity Surface Emitting Lasers

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In this summary, we introduce our technique for component level modeling of non-linear electronic and optoelectronic devices found in optoelectronic systems. By component level, we mean high level models suitable for fast evaluation in system level simulators such as [1]. For illustration, we focus on VCSELs, which have become the optical source of choice for most currently proposed and fabricated optoelectronic links. The methodology is based on solving general linear ODEs with piecewise linear (PWL) models representing non-linear functions [2]. This allows for a computationally efficient simulation of the non-linear system, with the ability to couple both the electrical and optical domains.

A typical L-I and V-I diagram for a VCSEL is shown in Figure 1(a). The dashed curve represents the relation between voltage and current in the device, and the solid curve is the relation between the optical power generated by the VCSEL versus the electrical current. Typically, for first order approximations, the V-I curve is considered to be a linear behavior with an average slope that corresponds to the series resistance for the VCSEL. This is a reasonable assumption for a first order characterization, however, the true form of this relation is non-linear. In fact, the curve becomes highly non-linear as the diameter of the device is reduced below 20 μm in diameter [3]. Consequently, for small devices a better representation should be considered.

Because these curves are frequently generated from experimental data, the model development is based on curve fitting of linear segments over the data, as seen in Figure 1(b). Independent of the methodology used for the fitting, a result of the following form for the V-I curve in three regions of operation will be obtained:

$$I_{VCSELpwl} = \begin{cases} g_2 V - I_2 & V > V_{th2}, \\ g_1 V - I_1 & V_{th1} < V < V_{th2}, \\ 0 & V < V_{th1}, \end{cases} \qquad I_1 = g_1 V_{th1}, \quad I_2 = g_2 V_{th2} - g_1 (V_{th2} - V_{th1})$$

The values of I_1 and I_2 are necessary to maintain continuity in value at the transition points (V_{th1} and V_{th2}) between PWL segments. g_1 and g_2 correspond to the slope of the curve at the transition points, chosen according to the selected fitting procedure criteria. Additionally, a capacitor of value C_v has been added to the PWL models to account for the frequency response of the VCSEL [3][4]. C_b and L_b, shown in Figure 1(c) accounts for the bump bond for the VCSEL. C_v, C_b, and L_b are simply added to the model using their linear representation.

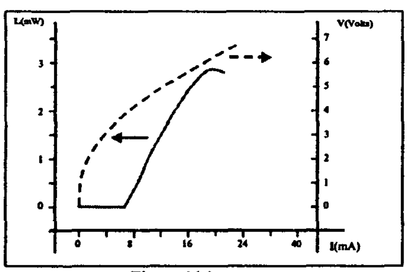

Figure 1(a)

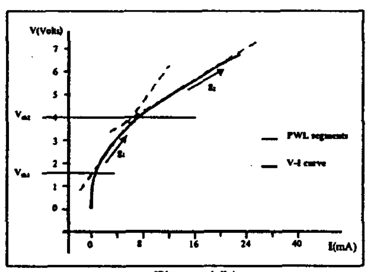

Figure 1(b)

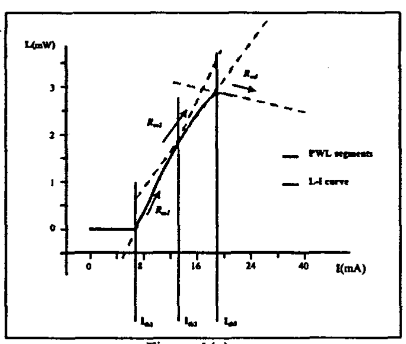

Figure 1(c)

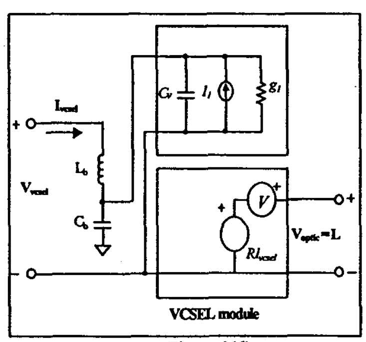

Figure 1(d)

The optical output of a VCSEL device is also a highly non-linear function of current. The current in the laser must overcome a threshold value to allow lasing. After this, the optical power production reaches a maximum value and then decreases with a further increase in electrical current. The reason for this behavior is the loss of efficiency in the laser caused by the increase in temperature as a consequence of the ohmic losses [4]. Ordinarily, the modeling of this device behavior is challenging, since optical power is not an electrical parameter. However, an additional advantage of the PWL methodology is that it is not tied only to the electrical domain. A characterization of the optical power variable is possible, and it can be included into the model as an unknown term to evaluate. As seen in Figure 1(d), the simulator sees the VCSEL device as a two black boxes; one corresponding to the electrical load presented by the VCSEL input port and the second corresponding to the output optical port.

Figure 1(c) shows the VCSEL's L-I curve along with three linear segments to fit the curve and the turn-off region of the VCSEL. These linear functions define four regions delimited by the threshold currents I_{th1}, I_{th2}, and I_{th3}. Notice that the V-I curve was broken in three regions, whereas the VCSEL curve was broken into four. This shows that the PWL method can flexibly allow different orders of linearization for the non-linear elements in the system.

The procedure to develop the L-I expressions is equivalent to the one already used for the V-I characterization. The mathematical definition of the PWL models for the optical behavior of the VCSEL using four regions of operation is given by:

$$V_{optical} = \begin{cases} R_{m3}I - V_3 & I > I_{th3}, \\ R_{m2}I - V_2 & I_{th2} < I < I_{th3}, \\ R_{m1}I - V_1 & I_{th1} < I < I_{th2}, \\ 0 & I < I_{th1}, \end{cases} \qquad \begin{aligned} V_1 &= R_{m1}I_{th1}, \\ V_2 &= R_{m2}I_{th2} - R_{m1}(I_{th2} - I_{th1}), \\ V_3 &= R_{m3}I_{th3} - R_{m2}(I_{th3} - I_{th2}) - R_{m1}(I_{th2} - I_{th1}), \end{aligned}$$

As before, the values of V_1, V_2, and V_3 are necessary for continuity, and the threshold values correspond to the number of points chosen for the curve fitting process. The transfer parameters, R_m, are dependent on the temperature of the VCSEL. The advantage of this characterization is that the designer can directly simulate the effects of electrical conditions in the VCSEL or associated driver against the optical power produced by this device. Additional dependencies can be added to the L-I VCSEL model following this approach (e.g, temperature, diameter of the VCSEL) that allows one to study their effect in complete system simulations.

A *4f* optoelectronic link is simulated and the effects of the VCSEL's temperature and current bias, I_{VCSEL}, on the BER of the link are presented in Figure 2. Generally, the frequency response of the link is dominated by the design of the receiver circuit, however, it is interesting to note that both the VCSEL temperature and bias have a significant effect on system performance, due to their impact on the optical power received through the link. Perhaps most interesting is the fact that increasing bias current does not always correspond to better performance over the whole range of frequencies examined. Note that the curve for 1mA bias offers the best performance below 600MHz, however, the 0.5mA bias (the nominal threshold of the VCSEL), crosses the curve for 1mA, achieving better performance at higher frequencies.

As seen with the inclusion of improved VCSEL models into the optoelectronic link, our PWL modeling methodology allows for high accuracy in an interactive, mixed-signal, multi-domain CAD environment. This modeling allows designers to simulate complete systems, determining the parameters which impact the overall functionality of the system.

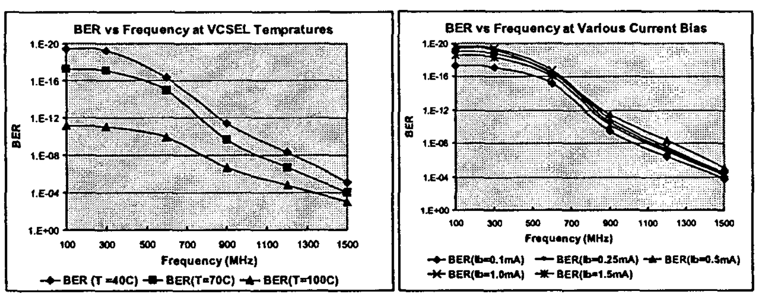

Figure 2

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