# Method for Characterization of Intrinsic and Extrinsic Components of Semiconductor Laser Diode Circuit Model

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*Abstract*—**It is shown that measurements of intensity noise, small-signal modulation response and input reflection coefficients of a semiconductor laser diode can be used to characterize the intrinsic and extrinsic parameters of the laser. These measurements, combined with the analytical expressions presented here enable one to determine the intrinsic 3 dB-modulation bandwidth and the extrinsic parasitic components associated with the laser diode that generally introduce modulation bandwidth limitation.**

## I. Introduction

Accurate determination of the modulation bandwidth of a semiconductor laser diode and its limitations is essential to the high-speed/broadband optical fiber communication applications of the device. In the analysis of its modulation bandwidth it is customary to model the laser diode via the equivalent circuit approach. Typically, such a circuit model comprises of two parts: the intrinsic device that is described by the small-signal rate equations [1], and the external circuit representing the extrinsic chip and package parasitic components of the device. This is shown schematically in Fig. 1. The knowledge of the intrinsic laser diode parameters is important in determining the maximum achievable modulation bandwidth and also to characterize the modulation distortion of the device [2], [3].

A commonly used method to extract the intrinsic laser diode response from the measured extrinsic modulation characteristics is to determine values of parasitic elements by fitting the circuit model to experimentally obtained scattering parameters $S_{11}$ and $S_{21}$ over a broad frequency range [1]. This approach is very laborious however, because of the large number of unknown parameters that must be determined using optimization techniques. (For example, seven unknown parameters for the model shown in Fig. 1 must be found.) In order to simplify this procedure, the implementation of the laser diode intensity noise characteristics to obtain the intrinsic modulation response of the device is proposed here. The intensity noise characteristic of a laser diode is independent of the device's extrinsic elements [4] and it can be measured by the same measuring setup that is typically used to obtain the modulation response of the device. The experimental setup used in our measurements has employed a 30 dB optical isolator and a broadband PIN photodetector in conjunction with a microwave spectrum analyzer as described in [3].

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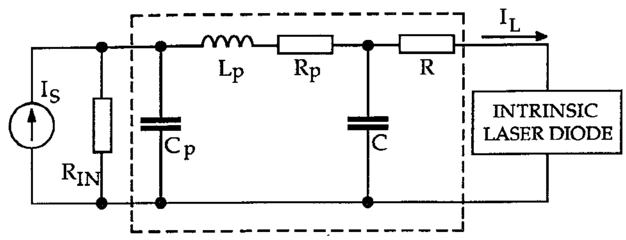


Fig. 1. Equivalent circuit model of semiconductor laser diode where $R$ and $C$ are chip parasitic elements, $R_p$, $C_p$, $L_p$ are package related parasitic elements.

## II. Theory and Experiment

The power density spectrum of the intensity noise $S_I(f)$ of a semiconductor laser diode operated above the threshold is given by [4]:

$$S_I(f) = \left(\frac{I_0 \delta f_{ST}}{\pi}\right) \frac{f^2 + (\gamma/2\pi)^2}{(f^2 - f_p^2)^2 + (\gamma f/2\pi)^2}, \quad (1)$$

where

- $I_0$ is the laser diode photon intensity corresponding to the dc bias current of the device,
- $\delta f_{ST}$ is the Schawlow–Townes linewidth under dc operation
- $\gamma$ is the damping parameter of the intrinsic response and
- $f_p$ is the frequency corresponding to the intrinsic response peak (also called the relaxation oscillation resonance).

Because the value of $\delta f_{ST}$ is often not known, it is convenient to normalize $S_I(f)$ by its peak value $S_I(f_p)$, thus enabling one to determine the unknown $f_p$ and $\gamma$ parameters by fitting (1) to the measured intensity noise response. The magnitude of the intensity modulation response including the extrinsic elements can be expressed as a product of two transfer functions—one corresponding to the intrinsic device and the other to the extrinsic parasitic elements.

The normalized extrinsic modulation response can be writ-

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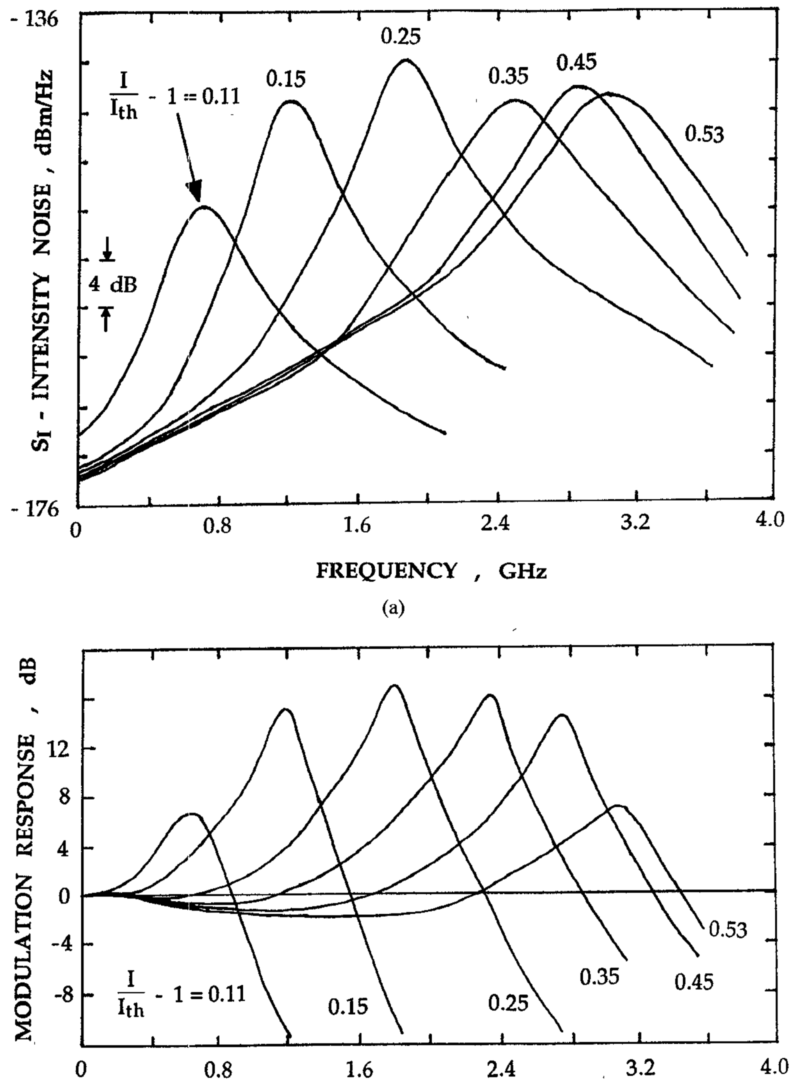


(b)

Fig. 2. (a) Intensity noise characteristics at different bias currents. (b) Extrinsic small-signal intensity modulation responses at different bias currents.

ten as [1]:

$$M(f) = \left|\frac{A_i(f)}{A_i(0)}\right| \frac{f_p^2}{\sqrt{(f^2 - f_p^2)^2 + (\gamma f/2\pi)^2}}, \quad (2)$$

where $|A_i(f)/A_i(0)|$ is the normalized magnitude of the current transfer function of the equivalent circuit comprising of the parasitic components $R$, $R_p$, $C$, $C_p$, and $L_p$.

The $|A_i(f)|$ response can be calculated from (2) since $M(f)$ and the intrinsic modulation response described by the second term in (2) are known from measurements of $S_I(f)$. $|A_i(f)|$ may be related to the equivalent circuit elements by

$$|A_i(f)| = \left|\frac{I_L}{I_S}\right| = \frac{R_{IN}}{\sqrt{(a - bf^2)^2 + f^2(c - df^2)^2}}, \quad (3)$$

where

$$a = R_{IN} + R_p + R; \qquad b = d(f_1 + f_2 + f_3);$$

$$c = (f_2 R_{IN} + f_1 R)/f_1 f_2; \qquad d = R_p/(f_1 f_2 f_3),$$

where

$$f_1 = (2\pi RC)^{-1}, \quad f_2 = (2\pi R_{IN} C_p)^{-1},$$

$$f_3 = R_p/(2\pi L_p), \text{ and } A(0) = R_{IN}/a.$$

The internal resistance of the modulation source $R_{IN}$ is usually known and is typically equal to 50 Ω. By measuring $S_{11}$ of the laser diode, $A_i(f)$ can also be related to the circuit input impedance $y_{IN}$ via:

$$|A_i(f)| = \left|\frac{y_{21}}{R(y_{22} + 1/R)(1/R_{IN} + y_{IN})}\right|, \quad (4)$$

where

$$y_{21} = -(R_p + j\omega L_p)^{-1}, \quad y_{22} = j\omega C - y_{21}, \text{ and}$$

$$\omega = 2\pi f.$$

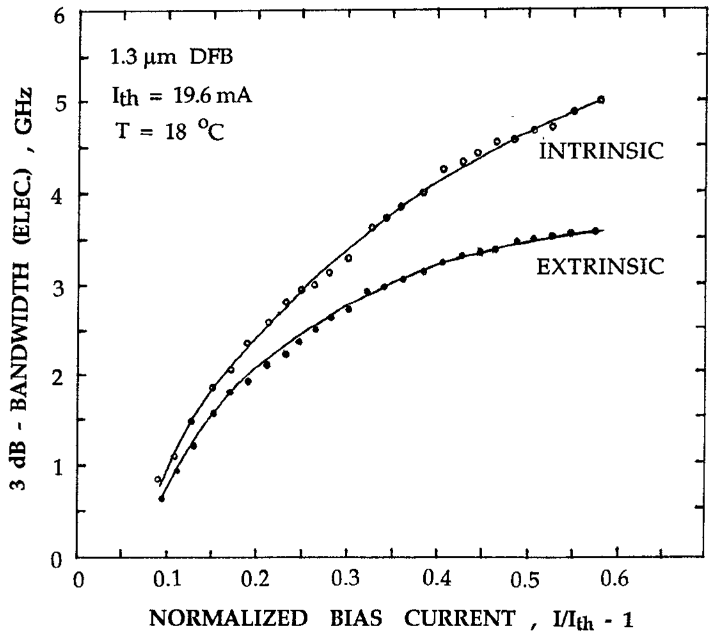


Fig. 3. Intrinsic 3-dB-modulation bandwidth (calculated using intensity-noise measurements) and the extrinsic 3-dB-modulation bandwidth (obtained from $M(f)$ in Fig. 2) characteristics vs. bias current for the 1.3-$\mu$m DFB laser.

Solving (3) and (4) algebraically, one can then determine the unknowns $f_1$, $f_2$, and $f_3$ of the extrinsic circuit and therefore the components $R$, $R_p$, $C$, $C_p$, and $L_p$.

Figs. 2(a) and (b) show typical measured $S_I(f)$ and $M(f)$ responses for a commercial 1.3-$\mu$m DFB laser diode at various bias currents. The intrinsic 3-dB-modulation bandwidth can be calculated from the $S_I(f)$ response parameters by using

$$f_{3\text{dB}}^2 = 0.5\left\{2f_p^2 - (\gamma/2\pi)^2 + \sqrt{\left(2f_p^2 - (\gamma/2\pi)^2\right)^2 + 4f_p^4}\right\}. \quad (5)$$

The intrinsic and extrinsic 3-dB-modulation bandwidth characteristics obtained for the same laser are shown in Fig. 3. It is evident that for the same bias current levels, the extrinsic 3-dB-modulation bandwidth is much narrower than the intrinsic value. Also, the 3-dB-extrinsic modulation bandwidth exhibits saturation with increasing bias current. This limitation can be attributed to the presence of the chip and package parasitic components of the device. The saturation of the intrinsic 3-dB-modulation bandwidth occurs at high frequencies and at much higher bias levels of the device.

The extrinsic chip and package parasitic components of the 1.3-$\mu$m DFB laser have been calculated using the measured $S_I(f)$ and $M(f)$ characteristics and (3) and (4). They are: $R = 3.5\ \Omega$, $R_p = 0.5\ \Omega$, $C = 15\ pF$, $C_p = 0.25\ pF$ and $L_p = 2.5\ nH$. It can be seen from the previous results that the chip-originated RC-time constant introduces a major limitation of the extrinsic 3-dB-modulation bandwidth of the device.

## III. Conclusion

A simple method for the characterization of the intrinsic and extrinsic parameters of a semiconductor laser diode has been described. This method is based on the measurement of intensity noise, small-signal modulation response and input reflection coefficient of the device. The intrinsic 3-dB-modulation bandwidth and the extrinsic parasitic components associated with the device can be readily determined by using analytical expressions developed and presented here. It has been shown that the major limitation of the 3-dB-modulation bandwidth can be attributed to the device chip $RC$-time constant.

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