

Noise Equivalent Circuit of a Semiconductor Laser Diode

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Abstract—The noise equivalent circuit of a semiconductor laser diode is derived from the rate equations including Langevin noise sources. This equivalent circuit allows a straightforward calculation of the noise and modulation characteristics of a laser diode combined with electronic components. The intrinsic junction voltage noise spectrum and the light intensity fluctuation of a current driven laser diode are calculated as a function of bias current and frequency.

I. INTRODUCTION

MODELING of semiconductor laser diodes combined with other electronic components requires an accurate representation of the laser. As a first step, a small-signal electrical circuit of a laser has been developed [1], [2]. The purpose of this work is to extend the model to include noise sources. The extended equivalent circuit allows a straightforward calculation of the modulation and noise characteristics of a laser in dependence of the extrinsic elements, such as the driving source and the parasitic elements.

Intrinsic intensity fluctuations in semiconductor laser diodes are caused by quantum-statistical photon generation and electron-hole recombination within the lasing medium. The intensity noise spectrum for laser light was first calculated by McCumber for a four-level laser system using rate equations with Langevin noise sources [3]. A quantum-mechanical justification of such an approach has been given by Lax [4]. Later, this model was adapted to semiconductor lasers [5], [6]. In early GaAs diode lasers the intrinsic light fluctuations were masked by excess noise due to inadequate transverse mode control, but measurements in stripe contact lasers were nevertheless able to confirm the basic features of the theory, namely large fluctuations at the onset of stimulated emission and a high-frequency noise peak at the resonance frequency of the laser [7].

Recently, it has been verified experimentally [8], [9] that mode stabilized lasers, such as the channeled-substrate planar and the buried heterostructure, operate at the quantum noise limit in excellent agreement with McCumber's noise theory.

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These intrinsic intensity fluctuations are usually very small and the noise performance of an optical communication system is normally determined by the receiver, but in some specific applications the quantum noise may significantly reduce the signal-to-noise ratio [10].

II. INTENSITY NOISE OF A SINGLE-MODE LASER DIODE

The spectral intensity of the quantum fluctuations of the photon and electron population can be found by adding to the familiar rate equations Langevin source terms for electrons $f_N(t)$ and for photons $f_S(t)$, assumed to have shot noise character [3], [5].

$$\frac{dn}{dt} = \frac{i}{q} - \frac{n}{\tau_s} - (E_{CV} - E_{VC})s + f_N \quad (1a)$$

$$\frac{ds}{dt} = (E_{CV} - E_{VC})s + \beta \frac{n}{\tau_s} - \frac{s}{\tau_{ph}} + f_S \quad (1b)$$

n and s are the total number of electrons in the gain medium and photons in the single lasing mode. The pump rate is i/q , τ_s is the spontaneous and τ_{ph} the photon lifetime. $E_{CV}s$ is the downward stimulated rate (stimulated emission) and $E_{VC}s$ is the upward stimulated transition rate (stimulated absorption). The gain g , which is by definition the net stimulated emission, is $g = E_{CV} - E_{VC}$. $\beta n/\tau_s$ is the spontaneous emission coupled into the lasing mode. By setting $\langle f_N \rangle = \langle f_S \rangle = 0$, where $\langle \rangle$ denotes the time average, the equations for the average rates are obtained

$$\frac{i_0}{q} - \frac{n_0}{\tau_s} - g_0 s_0 = 0 \quad (2a)$$

$$- \frac{s_0}{\tau_{ph}} + g_0 s_0 + \beta \frac{n_0}{\tau_s} = 0 \quad (2b)$$

For a given dc pump current i_0 and gain dependence on injected carriers $g(n)$, (2a) and (2b) allow us to calculate the resulting average electron population n_0 , average gain $g_0 = g(n_0)$, and the average number of photons s_0 in the lasing mode.

Following the treatment of McCumber [3], each change in the photon or electron population is associated with a noise impulse of unit integrated intensity. The spectral intensities of the Langevin noise sources f_N and f_S and the cross spectral density are therefore given by the shot noise expression [11], [12] and can be written by inspection of the particle rates entering and leaving the electron and photon reservoir as displayed in Fig. 1.

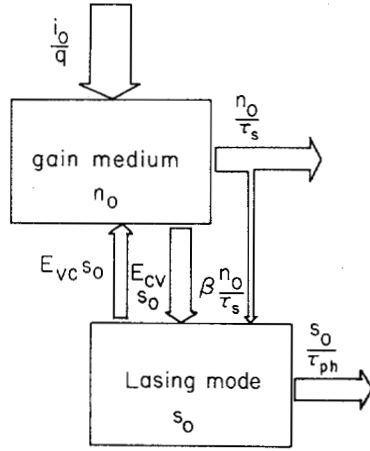


Fig. 1. Model for the shot noise of a semiconductor laser. Each change in the electron (n_0) or photon (s_0) population is associated with a noise impulse of unit integrated intensity.

$$\begin{aligned} \langle F_N^2(f) \rangle &= \sum r_n^+ + \sum r_n^- = E_{VC}s_0 + E_{CV}s_0 + \frac{n_0}{\tau_s} \\ &= \frac{i_0}{q} + 2E_{VC}s_0 \end{aligned} \quad (3a)$$

$$\begin{aligned} \langle F_S^2(f) \rangle &= \sum r_s^+ + \sum r_s^- \\ &= \beta \frac{n_0}{\tau_s} + E_{VC}s_0 + E_{CV}s_0 + \frac{s_0}{\tau_{ph}} \\ &= 2 \frac{s_0}{\tau_{ph}} + 2E_{VC}s_0 \end{aligned} \quad (3b)$$

$$\begin{aligned} \langle F_S(f) F_N(f) \rangle &= - \left[\sum r_{ns} + \sum r_{sn} \right] \\ &= - \left[E_{CV}s_0 + \beta \frac{n_0}{\tau_s} + E_{VC}s_0 \right] \\ &= - \left[\frac{s_0}{\tau_{ph}} + 2E_{VC}s_0 \right] \end{aligned} \quad (3c)$$

where r_n^+ and r_n^- are the rate of entering and leaving the electron reservoir (gain medium) and r_s^+ and r_s^- are the corresponding rates for the photon reservoir (lasing mode). The rates of exchange between electron and photon reservoir are denoted by r_{ns} and r_{sn} . Equation (2a) and (2b) has been used to simplify the expressions in (3). The pump term i_0/q does not enter directly into (3a) in agreement with the collective noise treatment of a semiconductor diode [12]. The reason for the term $E_{VC}s_0$ is that the sum of emission and absorption rates contributes to noise, while only the difference enters into the gain expression.

III. ELECTRICAL EQUIVALENT CIRCUIT

A small-signal analysis of the rate equation (1) gives the following relations for small photon (s_1), electron (n_1), and pump (i_1) variations:

$$\frac{dn_1}{dt} = \frac{i_1}{q} - \left[\frac{1}{\tau_s} + A s_0 \right] n_1 - g_0 s_1 + f_S \quad (4a)$$

$$\frac{ds_1}{dt} = \left[\frac{\beta}{\tau_s} + A s_0 \right] n_1 - \beta \frac{n_0}{s_0 \tau_{ph}} s_1 + f_S. \quad (4b)$$

A is defined as differential gain slope $A = dg/dn$. The small-signal junction voltage v_1 is introduced by the following boundary condition:

$$v_1 = m V_T \frac{n_1}{n_0} \quad V_T = \frac{kT}{q} \quad (5a)$$

$$m = 2 + \frac{n_0}{Vol 2\sqrt{2}} \left[\frac{1}{N_V} + \frac{1}{N_C} \right]. \quad (5b)$$

m in (5b) is given by an approximation of the Fermi-Dirac distribution [13], where N_V and N_C are the effective valence- and conduction-band densities. V_T is the thermal voltage, k is Boltzman's constant, q is the electron charge, and T is the absolute temperature. Anticipating the resulting equivalent electrical circuit of the diode a new variable i_L is introduced.

$$i_L = q g_0 s_1. \quad (6)$$

Now consider the separate problem of the equivalent circuit shown in Fig. 2. The equations describing v_1 and i_L of the equivalent circuit can be written by inspection.

$$\frac{dv_1}{dt} = -\frac{v_1}{RC} + \frac{i_1}{C} - \frac{i_L}{C} + \frac{i_n}{C} \quad (7a)$$

$$\frac{di_L}{dt} = \frac{v_1}{L} - \frac{R_{se}}{L} i_L - \frac{v_n}{L}. \quad (7b)$$

Equations (4a), (4b), (7a), and (7b) are identical in form and by comparing constants and using the definitions (5a), (5b), and (6), one obtains the values of the equivalent electrical circuit as function of n_0 , g_0 , and s_0 given by (2a) and (2b).

$$C = \frac{q}{m V_T} n_0 \quad (8)$$

$$R = \frac{m V_T}{q n_0 [A s_0 + (1/\tau_s)]} \quad (9)$$

$$L = \frac{m V_T}{q n_0 g_0 [A s_0 + (\beta/\tau_s)]} \quad (10)$$

$$R_{se} = \frac{m V_T \beta}{q \tau_s s_0 g_0 [A s_0 + (\beta/\tau_s)]}. \quad (11)$$

C is the usual diffusion capacitance resulting from the storage effect of the injected carriers. R is a modified differential diode resistance which approaches the conventional $m V_T/i_0$ expression in the absence of photons.

In Fig. 3 we plot the elements of the equivalent circuit using (8)–(11) with the following laser parameters. Volume of the active region $Vol = 300 \times 5 \times 0.2 \mu\text{m}^3$, spontaneous lifetime $\tau_s = 3$ ns, photon lifetime $\tau_{ph} = 2$ ps, gain $g_0 = A(n_0 - n_{nom})$, $A = 5 \times 10^{-7} \text{ cm}^3 \cdot \text{s}^{-1}/Vol = 1.7 \times 10^3 \text{ s}^{-1}$, $n_{nom} = 5 \times 10^{17} \text{ cm}^{-3} \times Vol = 1.5 \times 10^8$, and threshold current $i_{th} = q/\tau_s [n_{nom} + (1/A\tau_{ph})] = 24$ mA. The small-signal current in the inductive branch, earlier arbitrarily defined as i_L in (6), is directly proportional to the optical signal.

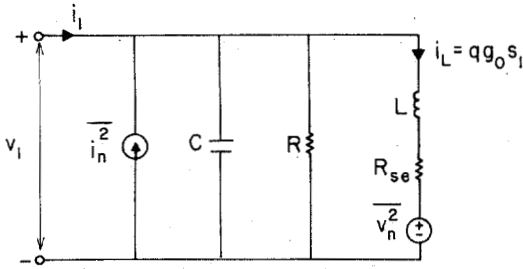


Fig. 2. Small-signal model of a semiconductor laser diode. The input signal is the modulation current i_1 or the modulation voltage v_1 . The optical output signal is directly proportional to i_L . The values of the components R , C , L , and R_{se} are given in Fig. 3. The intrinsic shot noise is modeled by the voltage and current noise sources.

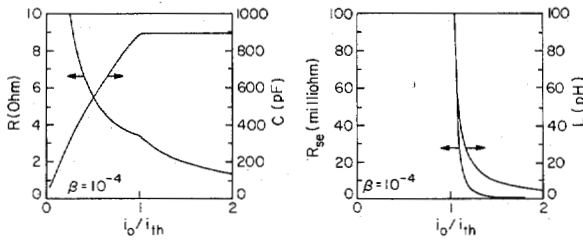


Fig. 3. Values of the elements of the equivalent circuit as a function of the bias point. The parameters of the modeled laser are given in the text.

The spectral intensities S_{ii} and S_{vv} of the current and voltage noise source and the cross spectral intensity S_{iv} do not depend on frequency and are given by comparing the Fourier transforms of (4a), (4b), (7a), and (7b).

$$S_{ii} = \frac{\overline{i_n^2}}{\Delta f} = 2C^2 \left[\frac{mV_T}{n_0} \right]^2 \langle F_N^2(f) \rangle$$

$$= 2qi_0 + 4q^2 E_{VC} s_0 \quad (12a)$$

$$S_{vv} = \frac{\overline{v_n^2}}{\Delta f} = 2L^2 [qg_0]^2 \langle F_S^2(f) \rangle$$

$$= 4 \frac{[mV_T]^2}{[n_0 [As_0 + (\beta/\tau_s)]]^2} \left[\frac{1}{\tau_{ph}} + E_{VC} \right] s_0 \quad (12b)$$

$$S_{iv} = \frac{\overline{i_n v_n}}{\Delta f} = -2LC \frac{mV_T}{n_0} qg_0 \langle F_N(f) F_S(f) \rangle$$

$$= 2 \frac{mV_T q}{n_0 [As_0 + (\beta/\tau_s)]} \left[\frac{1}{\tau_{ph}} + 2E_{VC} \right] s_0. \quad (12c)$$

An additional factor of 2 has been included because we changed from the double-sided to the more common single-sided noise spectrum. The current noise source i_n in parallel with the junction represents mainly the fluctuation in electron population. The first term on the right side of (12a) is the usual shot noise term $2qi_0$ of a nonlasing diode. The second term is resulting from the fact that the noise is determined by the sum of emission and absorption, whereas the net gain corresponds to the difference of the rates.

The fluctuation of the photon population is due mainly to the shot noise of the gain mechanism, that is, due to the voltage noise source v_n . The sources i_n and v_n are partially

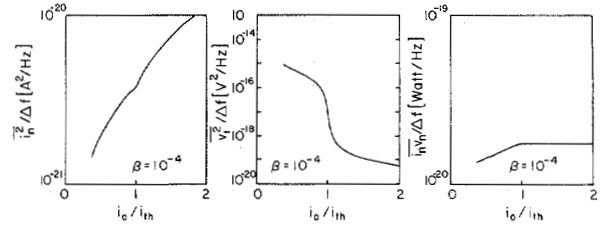


Fig. 4. Spectral intensities of the noise sources of the equivalent circuit as a function of the normalized bias current i_0/i_{th} .

correlated due to the coupled rates and their cross spectral intensity is given by (12c). The spectra of the noise sources $\overline{i_n^2}/\Delta f$, $\overline{v_n^2}/\Delta f$, and $\overline{i_n v_n}/\Delta f$, given by (12a)–(12c) are plotted in Fig. 4 as a function of the pump current, where a simple model has been used to calculate E_{VC} .

IV. AN APPLICATION OF THE FORMALISM

From the intrinsic equivalent circuit and the knowledge of the extrinsic parameters (series resistance, parasitic capacitance, and inductance, the impedance of the modulating source) the noise and modulation characteristics of the laser diode can be calculated. We limit ourselves in the following example to the intrinsic case and current modulation. The following properties of the laser diode are calculated: $Z(\omega)$, the diode impedance, $H(\omega)$, the photon modulation transfer function, $\overline{v_1^2}/\Delta f$, the junction voltage noise spectrum, and $RIN/\Delta f$, the relative intensity noise spectrum.

$$Z(\omega) = \frac{V_1(\omega)}{I_1(\omega)} = \frac{1}{LC} \frac{[R_{se} + j\omega L]}{D} \quad (13a)$$

$$H(\omega) = \frac{S_1(\omega)}{I_1(\omega)} = \frac{1}{LCqg_0 D} \quad (13b)$$

$$\frac{\overline{v_1^2}(\omega)}{\Delta f} = \frac{\overline{i_n^2} [R_{se}^2 + [\omega L]^2] + \overline{v_n^2} + 2\overline{v_n i_n} R_{se}}{[LC]^2 D D^*} \frac{1}{\Delta f} \quad (13c)$$

$$\frac{RIN(\omega)}{\Delta f} = \frac{S_s(\omega)}{s_0^2}$$

$$= \frac{\overline{i_n^2} + \overline{v_n^2} [(1/R^2) + [\omega C]^2] - 2\overline{v_n i_n} (1/R)}{[LC]^2 D D^* [qg_0]^2} \frac{1}{\Delta f} \quad (13d)$$

$$D = -\omega^2 + j\omega \left[\frac{R_{se}}{L} + \frac{1}{RC} \right] + \frac{1}{LC} \left[1 + \frac{R_{se}}{R} \right] \quad (13e)$$

$$S_s(\omega) = 2 \int_{-\infty}^{\infty} \left[\int_{-\infty}^{\infty} s(t)s(t+\tau) dt \right] e^{-j\omega\tau} d\tau \quad \omega \geq 0 \quad (13f)$$

where $S_s(\omega)$ is the photon noise spectrum. Figs. 5 and 6 show the calculated dependence of $\overline{v_1^2}/\Delta f$ and $RIN/\Delta f$ on current and frequency, and display the characteristic noise peak at onset of lasing and the high-frequency resonance. The frequency dependence of $Z(\omega)$ is shown in Fig. 7 for different pump levels.

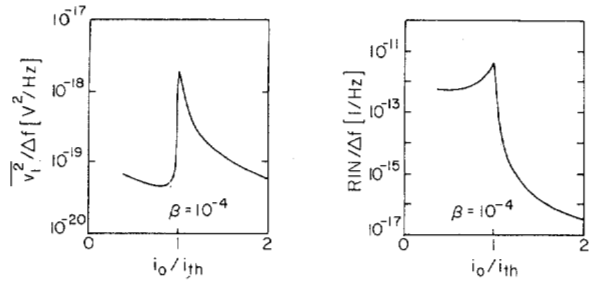


Fig. 5. The junction voltage noise spectrum $\overline{v_1^2}/\Delta f$ of a laser diode driven by a current source at low frequencies as a function of the normalized bias current i_0/i_{th} . RIN/ Δf is the relative intensity noise spectrum. Both noise spectra show a peak at the onset of stimulated emission.

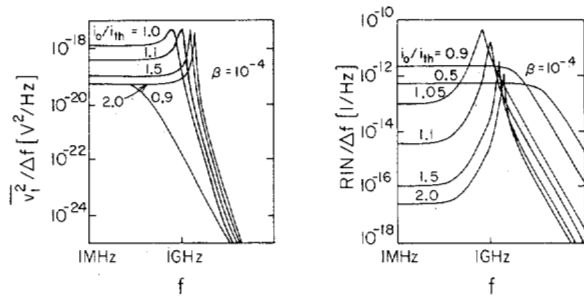


Fig. 6. Frequency dependence of the junction voltage noise spectrum ($\overline{v_1^2}/\Delta f$) and the relative intensity noise spectrum (RIN/ Δf) as a function of the normalized bias current i_0/i_{th} . Both spectra show a resonance at the relaxation frequency of the laser.

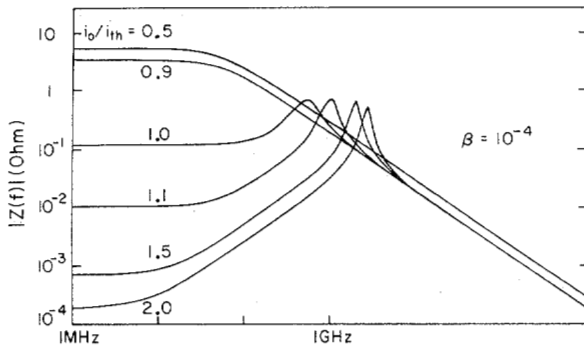


Fig. 7. Frequency dependence of the impedance of a diode laser as function of the normalized bias current i_0/i_{th} .

V. NOISE OF THE MULTILONGITUDINAL MODE LASER

The rate equations for a laser emitting radiation into n longitudinal modes are

$$\frac{dn}{dt} = \frac{i}{q} - \sum_{k=1}^{k=n} g_k s_k - \frac{n}{\tau_s} + f_N \tag{14a}$$

$$\frac{ds_k}{dt} = g_k s_k - \frac{s_k}{\tau_{phk}} + \beta_k \frac{n}{\tau_s} + f_{S_k} \quad k = 1 \dots n. \tag{14b}$$

An analysis analogous to that above yields the equivalent circuit shown in Fig. 8. Each optical mode contributes a parallel branch to the circuit with a current i_{Lk} corresponding to the photons of the signal in the mode k . The capacitance modeling the injected carriers remains unchanged. Taking the

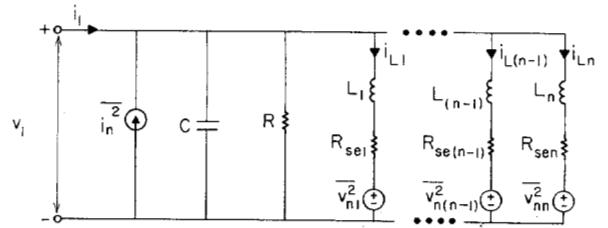


Fig. 8. Noise equivalent circuit of a multilongitudinal semiconductor laser diode. Each optical mode contributes a parallel branch to the circuit with a current i_{Lk} proportional to the photons of the signal in the mode k .

gain of the k th mode as $g_k = g_{0k} + A_k n_{1k}$ the values of the components are

$$R = \frac{mV_T}{qn_0} \frac{1}{\sum_{k=1}^{k=n} A_k s_{0k} + (1/\tau_s)} \tag{15a}$$

$$L_k = \frac{mV_T}{qn_0} \frac{1}{g_{0k} [A_k s_{0k} + (\beta_k/\tau_s)]} \tag{15b}$$

$$R_{se(k)} = \frac{\beta_{n_0} mV_T}{\tau_s s_0 qn_0} \frac{1}{g_{0k} [A_k s_{0k} + (\beta_k/\tau_s)]} \tag{15c}$$

The noise power spectra are:

$$\frac{\overline{i_n^2}}{\Delta f} = 2qi_0 + 4q^2 \sum_{k=1}^{k=n} E_{VCk} s_{0k} \tag{15d}$$

$$\frac{\overline{v_{nk}^2}}{\Delta f} = 4 \frac{[mV_T]^2}{[n_0 [A_k s_{0k} + (\beta_k/\tau_s)]]^2} \left[\frac{1}{\tau_{phk}} + E_{VCk} \right] s_{0k} \tag{15e}$$

$$\frac{\overline{v_{nk} i_n}}{\Delta f} = 2 \frac{mV_T q}{n_0 [A_k s_{0k} + (\beta_k/\tau_s)]} \left[\frac{1}{\tau_{phk}} + 2E_{VCk} \right] s_{0k} \tag{15f}$$

$$\overline{v_{nm} v_{nl}} = 0 \quad m \neq l. \tag{15g}$$

This noise analysis of a multimode laser neglecting the phase relations between the modes is justified if the beat frequencies of the longitudinal modes lie outside the spectrum of interest. The model above predicts that the relative intensity fluctuations of one isolated mode of a multimode laser are several orders of magnitude larger than the relative intensity fluctuations of all the modes together [8]. The intensity fluctuations of different modes are negatively correlated because the different modes are competing for gain from the same electron reservoir. This so-called competition noise may significantly deteriorate the signal-to-noise ratio in communication systems which have mode selective elements, such as material dispersion or interference effects [10].

VI. CONCLUSIONS

The small-signal model of a semiconductor laser has been extended to include the effects of the intrinsic noise by adding a current and a voltage noise sources. The current noise source represents the shot noise of the recombination of the carriers and the voltage noise source the random process of stimulated

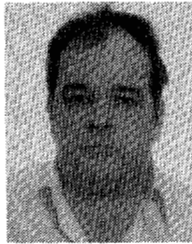
emission. The intensity fluctuation of the light is dominated by the stimulated emission process. The usefulness of the noise equivalent circuit in modeling an electronic circuit with an injection laser as one of its elements is demonstrated by calculating the modulation and noise characteristic of a current driven laser diode. In addition, the model has been generalized to the multimode case.

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