Modulation characteristics of tunable DFB/DBR lasers with one or two passive tuning sections

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Modulation Characteristics of Tunable DFB/DBR Lasers with One or Two Passive Tuning Sections

XING PAN, HENNING OLESEN, AND BJARNE TROMBORG

Abstract—Calculation of the small-signal modulation characteristics of tunable DFB and DBR lasers requires rate equations for the photon number, the phase of the electric field, and the carrier densities. In this paper, we derive the rate equation for the photon number and phase from an optical transmission line model and present examples of the frequency and intensity modulation characteristics of a phase-tunable DFB laser. The modulation responses exhibit the well-known relaxation resonance if either of the drive currents is modulated, but we also demonstrate the possibility of complete removal of the resonance peak together with a perfect cancellation of spurious intensity modulation. The frequency modulation response then assumes a simple low-pass character with a cutoff frequency determined by the carrier lifetime in the passive tuning section. The importance of choosing the proper bias conditions is emphasized.

I. INTRODUCTION

A LARGE variety of tunable multisection DFB and DBR lasers is currently under investigation, and several experimental results have been reported. These lasers typically consist of two to four sections with separate electrodes, and depending on the application, all sections may be active (in the simplest form just a conventional DFB laser with segmented electrodes) [1], one section may act as a saturable absorber in order to achieve bistable operation or optical wavelength conversion [2], or the device may have one active (Fabry-Perot- or DFB-type) and one or two passive sections [3]-[6]. The main advantages of such devices are the capability of fast electronic tuning, a low sensitivity to environmental disturbances, and for the latter type, a large continuous tuning range.

In this paper, we will focus on devices with passive tuning sections. In addition to the advantages mentioned above, these lasers are attractive because of the possibility of getting a high frequency modulation (FM) response, which is uniform in modulation frequency from dc to several hundred megahertz, by modulation of the injection current to one of the passive sections [3]. The carrier density in the passive sections is not clamped as it is in a conventional laser above threshold and is therefore easy to modulate. The cutoff frequency will be determined by the carrier lifetime in the passive section. We have previously analyzed the static tuning properties of DFB and DBR lasers with passive tuning sections [7], [8], and in this paper, which is an extended version of [9], we present the first theoretical study of their modulation characteristics.

II. THEORY

The analysis presented here is an application of our general transmission line theory for compound cavity lasers [10]. It applies to electronically tunable devices with one active and one or two passive control sections. The most important devices in this category are the phase-tunable DFB laser [3] with one passive phase control (PC) section and the three-section tunable DBR laser [4], which has an active Fabry-Perot section and two passive sections, one for phase control and one with a built-in corrugation for frequency control. The passive waveguides are usually made of materials with a higher bandgap than that of the active layer in order to make them transparent (apart from the intrinsic absorption). Hence, there will be only spontaneous and no stimulated recombination in these sections. In the following, we will limit the discussion to the phase-tunable DFB laser, which is shown schematically in Fig. 1, but the modifications for the DBR laser are straightforward.

Initially, we introduce a reference plane at the interface between the active and PC sections. The right and left traveling waves $E^+(w)$ at the reference plane are related by the boundary conditions

$$E^+(w) = r_L(w, N_1) E^-(w) + F_L(w) \quad (1a)$$

$$E^-(w) = r_R(w, N_2) E^+(w) \quad (1b)$$

where $r_L$ and $r_R$ are the effective reflectivities "seen" towards the left and right from the reference plane, $\omega$ is the angular optical frequency, and $N_1$ and $N_2$ are the carrier densities of the active and the PC sections, respectively. $F_L$ is a Langevin noise term, which accounts for the spontaneous emission in the active section [10]. There is no contribution from spontaneous emission in the PC section because of the higher bandgap.

Expressions for $r_L$ and $r_R$ are given in [7, eqs. (4) and (12)]. $r_L$ is derived from the well-known coupled mode...
equations for DFB lasers [11], and if the reflections at the laser-waveguide interface are neglected, \( r_R \) takes the simple form

\[
r_R(\omega, N_2) = r_2 \exp \left\{ -j 2k_2(\omega, N_2) l_2 \right\}
\]

where \( r_2 \) is the facet reflectivity at the end of the PC section, \( k_2(\omega, N_2) \) is the complex wave number, and \( l_2 \) is the length of the PC section. Recent experimental results indicate that the residual reflections at the interfaces can indeed be negligible for butt-jointed devices fabricated by the MOVPE technique [16], [12]. Equation (2) shows that \( r_R \) depends implicitly on \( \omega \) and \( N_2 \) through the complex wave number \( k_2(\omega, N_2) \). Similarly, \( r_L \) depends on \( \omega \) and \( N_1 \) through the complex wave number \( k_1(\omega, N_1) \) for the active section. The expressions for \( k_1 \) and \( k_2 \) are given in Appendix A.

Equations (1a) and (1b) can be combined to give the basic field equation:

\[
\{ r_L(\omega, N_1) r_R(\omega, N_2) - 1 \} E^+(\omega) = F_L(\omega).
\]

The driving term \( F_L(\omega) \) is discussed in detail in [10]. In the present analysis of modulation properties, we shall simply ignore the term and put \( F_L(\omega) = 0 \).

The stationary operation point \((\omega_0, N_{1s}, N_{2s})\) (without noise or modulation) satisfies the oscillation condition

\[
r_L(\omega_0, N_{1s}) r_R(\omega_0, N_{2s}) = 1.
\]

The dominant mode is the particular solution to (4), which has the lowest threshold carrier density \( N_{1s} \). The carrier density \( N_{2s} \) is independently determined by the injection current to the PC section and the condition that the carrier injection rate equals the spontaneous recombination rate [7]. The method for solving (4) is described in [7].

Under dynamic conditions, the frequency and carrier densities are assumed to be close to their stationary values, and we can therefore use a Taylor expansion for \( r_L(\omega, N_1) r_R(\omega, N_2) \) in (3):

\[
r_L(\omega, N_1) r_R(\omega, N_2) - 1 = -j (\tau_{in} + \tau_{ex}) (\omega - \omega_0) + \frac{\partial \ln r_L}{\partial N_1} \Delta N_1 + \frac{\partial \ln r_R}{\partial N_2} \Delta N_2
\]

where \( \Delta N_1 = N_1 - N_{1s} \) and \( \Delta N_2 = N_2 - N_{2s} \). We now define the envelope function

\[
A^+(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} E^+(\omega) e^{j(\omega - \omega_0) t} d\omega
\]

for the right traveling wave at the reference plane [10]. From (3) and (5), the following simple rate equation for \( A^+(t) \) can be derived:

\[
\frac{d}{dt} \ln A^+(t) = \frac{1}{\tau_{in} + \tau_{ex}} \left[ \frac{\partial \ln r_L}{\partial N_1} \Delta N_1(t) + \frac{\partial \ln r_R}{\partial N_2} \Delta N_2(t) \right]
\]

In order to introduce the photon number \( I_{p}(t) \) and the phase \( \phi(t) \) of the electric field [i.e., the envelope function \( A^+(t) \)], we make use of the relation [10]

\[
A^+(t) \propto \sqrt{I_{p}(t)} e^{j\phi(t)}
\]

and obtain the desired rate equation:

\[
\frac{1}{2} \frac{d}{dt} \ln I_{p}(t) + j \frac{d\phi(t)}{dt} = \frac{1}{\tau_{in} + \tau_{ex}} \left[ \frac{\partial \ln r_L}{\partial N_1} \Delta N_1(t) + \frac{\partial \ln r_R}{\partial N_2} \Delta N_2(t) \right]
\]

for the photon number and phase, valid for a short external cavity. A similar equation for a laser with arbitrary external cavity length was given in [10, eq. (22)], but here modulation of the external cavity was not considered.

The rate equations for the carrier densities in the active and PC sections take the usual form:

\[
\frac{d}{dt} N_1(t) = \frac{I_{in}(t)}{e V_1} - R_1(N_1) - G(\omega, N_1) \frac{I_{p}(t)}{V_1}
\]

\[
\frac{d}{dt} N_2(t) = \frac{I_{EC}(t)}{e V_2} - R_2(N_2)
\]

where \( e \) is the electron charge and \( G(\omega, N_1) = v_g g(\omega, N_1) \) is the gain (per unit time) of the active section. \( v_g \) is the group velocity, \( g \) is the gain per unit length (see Ap-
pendix A), and \(V_1, V_2\) and \(I_{iA}(t), I_{PC}(t)\) are the volumes and injection currents for the active and PC sections, respectively. The spontaneous recombination rate per unit volume is represented as

\[
R_i(N_i) = a_i N_i^b + b_i N_i^c + c_i N_i^d, \quad i = 1 \text{ or } 2
\]

where \(a_i, b_i, \) and \(c_i\) are constants. The recombination constant \(c_i\) accounts for Auger recombination.

A small-signal analysis of (10), (11a), and (11b) is given in Appendix B. The result is the following set of modulation responses:

\[
\delta P(\Omega) = 2P \left[ H_i(\Omega) \frac{C_i}{eV_1} \delta I_i(\Omega) + H_d(\Omega) \frac{C_2}{eV_2} \delta I_{PC}(\Omega) \right]
\]

\[
\delta f(\Omega) = \frac{1}{2\pi} \left[ H_i(\Omega) \frac{C_i}{eV_1} \delta I_i(\Omega) + \left\{ C_i H_d(\Omega) + C_2 H_5(\Omega) \right\} \frac{1}{eV_2} \frac{1}{\tau_2} \frac{\delta I_{PC}(\Omega)}{\delta I_{PC}(\Omega)} \right]
\]

\[
\delta N_{i}(\Omega) = \left[ H_d(\Omega) \frac{1}{eV_1} \delta I_i(\Omega) + H_i(\Omega) \frac{1}{eV_2} \delta I_{PC}(\Omega) \right]
\]

\[
\delta N_{v}(\Omega) = \left[ H_d(\Omega) \frac{1}{eV_2} \delta I_{PC}(\Omega) \right]
\]

where \(P\) denotes the output power from the left facet and \(\Omega = 2\pi f_m\) is the angular modulation frequency. The \(C\)-factors and the transfer functions \(H_i, H_d\) are defined in Appendix B. \(\delta P(\Omega)\) and \(\delta f(\Omega)\) represent the intensity modulation (IM) and FM responses for given forms of the two modulation currents \(\delta I_i\) and \(\delta I_{PC}\).

As can be seen from (13a)-(13d), the modulation responses generally contain two contributions, one for each of the modulation currents, except for \(\delta N_{v}(\Omega)\), which depends only on \(\delta I_{PC}(\Omega)\). The complex addition of the two carrier density terms in (10) may lead to interference effects in some frequency intervals, as illustrated in the next section. In particular, (13c) shows that \(N_{i}(\Omega)\) can be modulated via the PC current. This is a result of the photon–carrier interaction in the active section, which leads to the well-known relaxation resonance in a laser above threshold.

The response \(\delta N_{v}(\Omega)\) has a low-pass character with a cutoff frequency of \(1/(2\pi \tau_2)\) and a dc value which is proportional to \(\tau_2\), with \(\tau_2\) being the carrier lifetime in the PC section. This illustrates the role of the carrier lifetime in this type of tunable laser and the characteristic tradeoff between modulation speed and efficiency.

The IM and FM responses can be rewritten in the form

\[
\delta P(\Omega) = 2P C_i H_i(\Omega) \left[ \frac{1}{eV_1} \delta I_i(\Omega) \right] + \frac{j\Omega + (1/\tau_R)}{j\Omega + (1/\tau_{PC})} \frac{C_2}{eV_2} \frac{1}{\tau_2} \delta I_{PC}(\Omega)
\]

\[
\delta f(\Omega) = \frac{\delta f(0)}{1 + j\Omega \tau_2} + \frac{1}{2\pi} \frac{C_i H_i(\Omega)}{eV_1} \frac{1}{\tau_2} \frac{\delta I_i(\Omega)}{\delta I_{PC}(\Omega)} + \frac{j\Omega + (1/\tau_R)}{j\Omega + (1/\tau_{PC})} \frac{C_2}{eV_2} \frac{1}{\tau_2} \frac{\delta I_{PC}(\Omega)}{\delta I_{PC}(\Omega)}
\]

where \(\delta f(0)\) is the FM response at dc [see Appendix B, eq. (B10b)] and \(\tau.text revive
Fig. 2. Frequency shift versus PC current. The points A, B, and C refer to the PC bias currents used in Fig. 3.

### TABLE I

**List of Parameter Values**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
<th>Unit</th>
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<tr>
<td>Active section:</td>
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<tr>
<td>Length of active section</td>
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<td>μm</td>
</tr>
<tr>
<td>Width of active region</td>
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</tr>
<tr>
<td>Thickness of active layer</td>
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</tr>
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<tr>
<td>Group refractive index</td>
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<td></td>
</tr>
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<td>cm⁻¹</td>
</tr>
<tr>
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<td>m²/sec</td>
</tr>
<tr>
<td>Recombination coefficient</td>
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<td>m²/sec</td>
</tr>
<tr>
<td>Confinement factor</td>
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<td></td>
</tr>
<tr>
<td>Gain coefficient</td>
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</tr>
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<td>m⁻³</td>
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</tr>
<tr>
<td>gain peak for Vₐ = V₀</td>
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<td></td>
</tr>
<tr>
<td>Shift of gain peak with carrier</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>density</td>
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<td>m²/sec⁻¹</td>
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</tr>
<tr>
<td>Linewidth enhancement factor</td>
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<tr>
<td>Reference wavelength</td>
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<td>μm</td>
</tr>
<tr>
<td>Reference carrier density</td>
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<td>m⁻³</td>
</tr>
<tr>
<td>Phase control section:</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Length of PC section</td>
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<td>μm</td>
</tr>
<tr>
<td>Width of waveguide layer</td>
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</tr>
<tr>
<td>Thickness of waveguide</td>
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<td>μm</td>
</tr>
<tr>
<td>Refractive index</td>
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</tr>
<tr>
<td>Group refractive index</td>
<td>n₂ₐ₂</td>
<td>3.4</td>
<td></td>
</tr>
<tr>
<td>Internal absorption</td>
<td>α₂₂</td>
<td>17</td>
<td>cm⁻¹</td>
</tr>
<tr>
<td>Recombination coefficient</td>
<td>α₂₂</td>
<td>1.10⁻¹⁵</td>
<td>sec⁻¹</td>
</tr>
<tr>
<td>Recombination coefficient</td>
<td>β₂₂</td>
<td>8.10⁻¹³</td>
<td>m²/sec</td>
</tr>
<tr>
<td>Recombination coefficient</td>
<td>β₂₂</td>
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<td>m²/sec</td>
</tr>
<tr>
<td>Confinement factor</td>
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<td></td>
</tr>
<tr>
<td>Index derivative with respect</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>to carrier density</td>
<td>dₑₛ₍ΔN₎</td>
<td>4.2.10⁻²⁷</td>
<td>m³</td>
</tr>
<tr>
<td>Absorption derivative with</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>respect to carrier density</td>
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<td>1.8.10⁻²¹</td>
<td>m²</td>
</tr>
<tr>
<td>Facet reflectivity</td>
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<td></td>
</tr>
</tbody>
</table>

Fig. 3. FM response versus modulation frequency at three different PC bias currents. (a) Magnitude, (b) Phase. The bias current Iₐ₀ is 30 mA, and the threshold currents at A, B, and C are 17.5, 16.3, and 21.8 mA, respectively [7].

is observed, and intricate "interference" effects occur between the two FM contributions. The phase is 0 at low frequencies (if the static curve has a positive slope) and changes smoothly, except in the vicinity of the resonance peak. The presence of the resonance peak is a new result, which has not been reported experimentally. In the present analysis, we have not included the effect of nonlinear gain (gain compression), which could have some influence on the strength and shape of the resonance peak, but gain compression will not completely eliminate the resonance [14]. The resonance can, however, be shifted to higher frequencies by increasing the bias current to the active section. Below 1 GHz, our calculations are in good agreement with published experiments [3].

Fig. 4(a) and (b) shows the FM and IM responses when the active section is modulated (dotted curves) and when the PC section is modulated (dashed curves). As seen from the figure and predicted by (13a) and (13b), modulation of either of the currents will result in both IM and FM modulation, in all cases with a resonant part centered around the relaxation frequency. For many practical applications, however, it would be desirable to have a pure IM or a pure FM transmitter. For direct detection systems, especially those operating at high bit rates and/or long distances, the FM gives rise to a chirp-induced power penalty, and for coherent transmission systems based on FSK or PSK modulation, the IM is an unwanted effect. In multichannel systems using optical amplifiers, the IM will lead to crosstalk power penalties [15]. We notice that the IM resulting from modulation of the PC section is about an order of magnitude lower than that from the active section, but it still may not be negligible.

As mentioned in the previous section, it is possible to suppress both the IM and the resonant part of the FM response, if both sections are modulated according to (15). For the bias currents Iₐ₀ = 30 mA and Iₐ₀ = 100 mA,
the modulus and phase of the splitting ratio vary with frequency, as shown in Fig. 5. The major part of the current goes to the PC section. Below 1 GHz, the FM response is nearly unchanged by the current modulation of the active section due to the small splitting ratio and the low FM efficiency of the active section. Beyond 1 GHz, the resonant part has been eliminated, resulting in a very simple low-pass behavior, as predicted.

IV. CONCLUSION

In this paper, a theoretical model has been presented for the modulation characteristics of tunable DFB/DBR lasers with passive tuning sections. In the model, two effective reflectivities are used to characterize the active and passive sections. Numerical results have been presented for a phase-tunable DFB laser, but the model has also been applied to two- and three-section DBR lasers. It is shown that the FM characteristics depend critically on the operation point. In order to interpret a measured FM response, it is therefore important to have a measurement of the static frequency tuning characteristics. Generally, the FM efficiency decreases and the modulation bandwidth increases with increasing bias current to the PC section. Our calculations also show the presence of a resonance peak in the FM response when only the PC section is modulated. We have demonstrated that the intensity modulation can be completely suppressed by modulation of both the active and the PC sections with a simple splitting ratio between the currents. The same splitting ratio will eliminate the resonant part of the FM response and result in a low-pass response which is easy to equalize.

APPENDIX A

THE COMPLEX WAVE NUMBERS

The effective reflectivities \( r_a \) and \( r_R \) are functions of the complex wave numbers in the active and passive sections. For the active section, the wave number is represented as

\[
\frac{k_a(\omega, N_i)}{c} = \text{real part} \left( N_{\text{ref}} \right) + j \text{imaginary part} \left( N_{\text{ref}} \right)
\]

where \( n_o(\omega, N_i) \) is the refractive index, \( g(\omega, N_i) \) is the modal gain, and \( \alpha_i \) is the internal loss. The real part is expanded linearly around a reference point \( (\omega_{\text{ref}}, N_{\text{ref}}) \), as explained in [10], and for the gain, we use a parabolic model, which includes the band-filling effect:

\[
g(\omega, N_i) = g_o(N_i - N_0) - g_o(\omega - \omega_p(N_i))^2 (A2a)
\]

\[
\omega_p(N_i) = \omega_p(N_0) + \frac{d\omega_p}{dN} (N_i - N_0). (A2b)
\]
Here, $\omega_p(N_1)$ is the angular optical frequency of the gain peak, $N_0$ is the carrier density at transparency, $g_N$ is the gain coefficient, $g_c$ is the gain curvature, and $\omega_p(N_0)$ is the (extrapolated) angular frequency of the gain peak for $N_1 = N_0$. The effect of nonlinear gain is not included.

The wave number for the PC section is written as [7]

$$k_z(\omega, N_2) = \frac{\omega}{c} \left[ n_2(\omega) + \Delta n(N_2) \right] - j \frac{1}{2} \left[ \alpha_2 + \Delta \alpha_2(N_2) \right]$$  \hspace{1cm} (A3)

where $n_2$ and $\alpha_2$ are the refractive index and the absorption per unit length without current injection and

$$\Delta n_2(N_2) = \Gamma_2 \frac{dn}{dN} N_2 \hspace{1cm} (A4a)$$

$$\Delta \alpha_2(N_2) = \Gamma_2 \frac{d\alpha}{dN} N_2 \hspace{1cm} (A4b)$$

are the changes induced by current injection. $\Gamma_2$ is the confinement factor of the waveguide, and $dn/dN$ and $d\alpha/dN$ are coefficients describing the free-carrier plasma effect and the free-carrier absorption, respectively.

**APPENDIX B**

**SMALL-SIGNAL ANALYSIS**

From (10), (11a) and (11b), the small-signal FM and IM responses can be calculated. In the general case, both currents may be modulated:

$$I_p(t) = I_{p,0} + \delta I_p(t), \hspace{1cm} \text{and} \hspace{1cm} I_{PC}(t) = I_{PC,0} + \delta I_{PC}(t).$$  \hspace{1cm} (B1)

and accordingly, the state variables are written as their stationary values plus a modulation term

$$N_1(t) = N_{1,0} + \delta N_1(t), \hspace{1cm} N_2(t) = N_{2,0} + \delta N_2(t)$$  \hspace{1cm} (B2)

where $\delta f(t)$ is the instantaneous frequency.

By elimination of the stationary values and subsequent Fourier transformation, the following set of equations is obtained:

$$\begin{bmatrix}
  j\Omega & 0 & -2I_{p,s}C_{1r} & -2I_{p,s}C_{2r} \\
  0 & 1 & -C_{1s} & -C_{2s} \\
  G_s/V_1 & 0 & j\Omega + \frac{1}{\tau_R} & 0 \\
  0 & 0 & 0 & j\Omega + \frac{1}{\tau_{12}}
\end{bmatrix} \begin{bmatrix}
  \delta I_p(\Omega) \\
  2\pi\delta f(\Omega) \\
  \delta N_1(\Omega) \\
  \delta N_2(\Omega)
\end{bmatrix} = \begin{bmatrix}
  0 \\
  0 \\
  1/eV_1 \delta L_p(\Omega) \\
  1/eV_2 \delta I_{PC}(\Omega)
\end{bmatrix}. \hspace{1cm} (B3)$$

Here, we have introduced the complex quantities

$$C_1 = \frac{1}{\tau_{in} + \tau_{ex}} \frac{\partial \ln r_t}{\partial N_1} = C_{1r} + jC_{1i} \hspace{1cm} (B4a)$$

$$C_2 = \frac{1}{\tau_{in} + \tau_{ex}} \frac{\partial \ln r_r}{\partial N_2} = C_{2r} + jC_{2i} \hspace{1cm} (B4b)$$

and also $G_s = G(\omega_s, N_{1s})$. The parameters

$$\tau_R = \left[ \frac{dR_1}{dN_1} + \frac{I_{p,s}}{V_1} \right]^{-1} \hspace{1cm} \text{and} \hspace{1cm} \tau_{12} = \left[ \frac{dR_2}{dN_2} \right]^{-1}$$  \hspace{1cm} (B5)

are the relaxation time constant and the carrier lifetime in the PC section, respectively.

The system of equations can now be solved for each of the modulation terms. Instead of the modulation response for the photon number, we may introduce the modulation response $\delta P(\Omega)$ for the output power $P(t)$ from the left facet by noting that [10]

$$P(t) \propto I_p(t). \hspace{1cm} (B6)$$

and hence,

$$\frac{\delta I_p(\Omega)}{I_{p,s}} = \frac{\delta P(\Omega)}{P_s} \hspace{1cm} (B7)$$

where $P_s$ is the stationary value of $P(t)$. By introducing the transfer functions

$$H_1(\Omega) = \frac{1}{-\Omega^2 + j\Omega \frac{1}{\tau_R} + \omega_R^2} \hspace{1cm} (B8a)$$

$$H_2(\Omega) = \frac{j\Omega + (1/\tau_R)}{\left( j\Omega + \frac{1}{\tau_{12}} \right) \left( -\Omega^2 + j\Omega \frac{1}{\tau_R} + \omega_R^2 \right)} \hspace{1cm} (B8b)$$

$$H_3(\Omega) = \frac{j\Omega}{-\Omega^2 + j\Omega \frac{1}{\tau_R} + \omega_R^2} \hspace{1cm} (B8c)$$

$$H_4(\Omega) = \frac{\omega_R^2}{j\Omega + \frac{1}{\tau_{12}} \left( -\Omega^2 + j\Omega \frac{1}{\tau_R} + \omega_R^2 \right)} \hspace{1cm} (B8d)$$

The parameters

$$C_{1r} = \frac{1}{\tau_{in} + \tau_{ex}} \frac{\partial \ln r_t}{\partial N_1} \hspace{1cm} (B4a)$$

$$C_{2r} = \frac{1}{\tau_{in} + \tau_{ex}} \frac{\partial \ln r_r}{\partial N_2} \hspace{1cm} (B4b)$$
\[ H_s(\Omega) = \frac{1}{j\Omega + \frac{1}{\tau_2}} \] (B8e)

this leads to the expressions given in (13a)-(13d). Here, \( \Omega = 2\pi f_0 \) is the angular modulation frequency, and

\[ \omega_0^2 = 2\pi f_0 C_{lr} G' \quad (2\pi f_0^2) \] (B9)

where \( f_0 \) is the relaxation resonance frequency.

The dc values of the modulation responses are given by

\[ \delta P(0) = 2 P_0 \left( \frac{C_{lr}}{\omega_0^2 V_1} \delta I_0 + \frac{\tau_2 C_{lr}}{\tau_2 \omega_0^2 V_2} \delta I_{PC} \right) \] (B10a)

\[ \delta f(0) = \frac{1}{2\pi} \left( C_{2r} - C_{2r} C_{lr} \right) \frac{\tau_2}{V_2} \delta I_{PC} \] (B10b)

\[ \delta N(0) = - \frac{C_{2r}}{C_{lr}} \frac{\tau_2}{V_2} \delta I_{PC} \] (B10c)

\[ \delta N'(0) = \frac{\tau_2}{V_2} \delta I_{PC} \] (B10d)

and are directly related to the slopes of the corresponding static tuning curves (cf. Fig. 2 and [7]).

REFERENCES


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