Enhanced Modulation Bandwidth by Exploiting Photon Resonance in Push-Pull Modulated DFB lasers

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***Abstract*—In this paper, we have proposed a localized dual-mode model to study push-pull modulation responses of DFB lasers. Numerical simulation shows that, with properly designed and controlled photon-photon resonance, an ultra-broad 3dB modulation bandwidth up to 50GHz is achievable.**

I. INTRODUCTION

Cost-effective directly modulated laser (DML) has drawn a lot of interests, but a limiting factor to the 3dB modulation bandwidth (MBW) of the conventional DML, however, is the existence of the relaxation oscillation at relatively low frequency (~10GHz) due to the slow carrier-photon resonance (CPR) [1]. The directly push-pull modulated (PPM) DFB laser has been proposed to reduce the chirp and simultaneously to improve the MBW for about two decades [2]. Theory of the enhanced MBW in the PPM scheme was studied with empirical formulas in [3] and with a spatial interference model in [4]. It was found in these works that the greatly enhanced MBW in the PPM scheme was due to the appearance of the photon-photon resonance (PPR) in a much higher frequency range. However, the PPR peak is usually positioned at a frequency too far away (on the higher end) from the CPR peak and is usually rapidly damped. As a result, a dip appears inside the passband between the CPR and PPR peaks, which cut down the 3dB bandwidth significantly and introduces a huge retreat. Since none of the existing models can link the PPR peak position and damping factor to device design parameters, how to design the device and control its operating condition in favor of its MBW in directly PPM DFB lasers remains as an open problem.

This paper is organized as follow: in part II, we propose a localized dual-mode model that connects the small-signal intensity modulation (IM) response to device parameters in an analytical form; its validity is then checked by comparisons made with the full numerical model in part III; also in this part, we show a design and the associated operating condition of a DFB laser with an ultra-broad 3dB MBW up to 50GHz.

II. THEORY

Conventional directly modulated DFB laser can readily be described by the well-known single mode rate equation model. However, under the PPM scheme, transient multiple mode excitation has to be considered as there is no strict static state in PPM. As such, we must start with the dual mode photon rate equations for DFB laser [5]:

$$\begin{aligned} \frac{dS_1}{dt} &= G_1 S_1 + \frac{\xi_1}{\tau_L}\sqrt{S_1 S_2} + R_{sp1} \\ \frac{dS_2}{dt} &= G_2 S_2 + \frac{\xi_2}{\tau_L}\sqrt{S_1 S_2} + R_{sp2} \end{aligned} , \qquad (1)$$

where τ_L ($=2L/v_g$) is the round-trip time delay of the light propagation inside the laser cavity, the net model gain $G_{1,2}$ is related to the gain coefficient $a_{1,2}$ and photon lifetime $\tau_{p1,p2}$ for the 1st and 2nd mode, respectively, by

$$G_{1,2} = g_{1,2} - \tau_{p1,p2}^{-1} = a_{1,2}(N - N_{tr}) - \tau_{p1,p2}^{-1} , \qquad (2)$$

and the cross-field coefficients $\xi_{1,2}$ are given as

$$\xi_{1,2} = \left\{ 2L\Gamma \int_0^L \mathrm{Re}[g_m(z)\mathbf{w}_{1,2}(z)\bar{\mathbf{\Phi}}_{2,1}(z)]dz \right\} [\cos(\Delta\theta_{21,12}) - \alpha_m \sin(\Delta\theta_{21,21})] , \qquad (3)$$

where g_m, $\bar{\mathbf{\Phi}}$, and $\mathbf{w}$ indicating the material gain, normalized eigen mode and its adjoint mode field distribution [5]. Once the phase difference $\Delta\theta$ between the two modes are slow varying in the time scale of our concern, $\xi_{1,2}$ can be assumed as constants with embedded spatial dependence.

The carrier number rate equation is described by

$$\frac{dN}{dt} = \frac{I}{e} - \frac{N}{\tau_N} - (N - N_{tr})(a_1 S_1 + a_2 S_2) , \qquad (4)$$

where τ_N is the carrier lifetime. By combining equations (1) and (4) , under the small signal assumption, we find:

$$\begin{aligned} \frac{d\Delta s}{dt} &= g_0 \Delta s + \frac{\xi_1 + \xi_2}{2\tau_L}\Delta s + a s_0 \Delta n \\ \frac{d\Delta n}{dt} &= \frac{\Delta i}{e} - \frac{\Delta n}{\tau_N} - a s_0 \Delta n - a n_0 \Delta s \end{aligned} , \qquad (5)$$

where $s_0 \equiv s_{10} + s_{20}$, $a = a_1 \approx a_2$, and

$$g_0 \equiv -R_{sp1} + \left(\tau_{p1}^{-1} - \tau_{p2}^{-1}\right)\frac{\Delta s_2}{\Delta s_1 + \Delta s_2} . \qquad (6)$$

In derivation of equation (5), we have also assumed that the two modes are equally excited and consequently we have

$$\sqrt{\frac{s_{20}}{s_{10}}}\Delta s_1 + \sqrt{\frac{s_{10}}{s_{20}}}\Delta s_2 \approx \Delta s_1 + \Delta s_2 . \qquad (7)$$

Under the PPM scheme, we split the cavity into the left- and right- half. For a cavity with the centre symmetry, due to the parity of the two modes under our consideration, the sign of $\xi_1 + \xi_2$

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changes from left to right for adjacent modes (or interleaved modes with even number of modes in between), and keeps the same for interleaved modes with odd number of modes in between, respectively. In the assumption of the dual adjacent mode excitation, by defining $\Delta s_{L,R}$ as the total photon density Δs in the left- and right- half cavity, respectively, we obtain:

$$\begin{aligned}
\frac{d\Delta s_L}{dt} &= g_0 \Delta s_L + \frac{C}{\tau_L}\Delta s_R + a s_0 \Delta n_L \\
\frac{d\Delta s_R}{dt} &= g_0 \Delta s_R - \frac{C}{\tau_L}\Delta s_L + a s_0 \Delta n_R \\
\frac{d\Delta n_{L,R}}{dt} &= \frac{\Delta i_{L,R}}{e} - \frac{\Delta n_{L,R}}{\tau_N} - a s_0 \Delta n_{L,R} - a n_0 (\Delta s_L + \Delta s_R)
\end{aligned} , \quad (8)$$

where $C=|\xi_1+\xi_2|/2$ can be viewed as the normalization factor of τ_L.

The final expression of the IM response is obtained in the form of

$$H(j\omega) \propto \frac{[(j\omega - g_0 - \omega_{PPR})(j\omega+\gamma) + 2\omega_{CPR}^2]}{(j\omega - g_0)^2 (j\omega+\gamma)^2 + \omega_{CPR}^2 (j\omega - g_0)(j\omega+\gamma) + \omega_{PPR}^2 (j\omega+\gamma)^2}, \quad (9)$$

with

$$\gamma = \frac{1}{\tau_N} + a s_0, \omega_{CRP}^2 \simeq \frac{a s_0}{\tau_p}, \omega_{PRP} = \frac{C}{\tau_L} \quad (10)$$

given explicitly as the damping factor and CPR frequency of the conventional DML, and the PPR frequency of the PPM DFB laser, respectively.

III. Results

To validate the analytical expression, we compared the IM response calculated by (9) with the published data [3] and the result obtained from a full numerical model [6, 7] for a DFB laser with the 2nd-order grating. The analytical model gives sufficiently accurate result as evidenced by Fig. 1.

Following (8), we investigated the impact of parameters γ and $|g_0|$ on the IM response. As shown in Fig. 2, while smaller γ leads to a over-all roll off in the entire frequency range, $|g_0|$ mainly affects the sharpness of PPR with larger $|g_0|$ damping the peak significantly and consequently bringing in a broad and smooth passband.

As discussed in [8], in order to eliminate any possible dip between the CPR and PPR frequencies, the spacing needs to be narrowed to several tens of GHz. A high κL design with strong longitudinal spatial hole burning (LSHB) is then preferred to bring in a smaller C and longer τ_L, hence is helpful to draw the PPR closer to CRP for eliminating the dip.

According to this approach, the 2nd-order grating DFB laser structure [9] is chosen to avoid any possible collapse of the single-mode operation under high κL design. Its parameters are taken from [3] except for an elevated κL(=6) and enhanced emission coefficient that is directly in proportion to κ [9]. Simulation result in Fig. 3 indicates that a flat and much extended 3dB modulation bandwidth up to 50GHz is achievable.

IV. Summary

This paper presents a localized dual-mode model for the description of the IM response of DFB lasers under PPM. The analytical expression is validated through comparisons, followed by the study of the PPR position and peak damping dependence on the device design parameters. By employing the 2nd-order grating DFB structure with enlarged κL=6, a flat 3dB bandwidth up to 50GHz is obtained.

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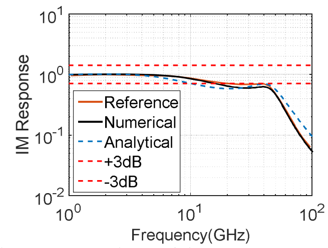

Fig. 1. Comparison of the IM response.

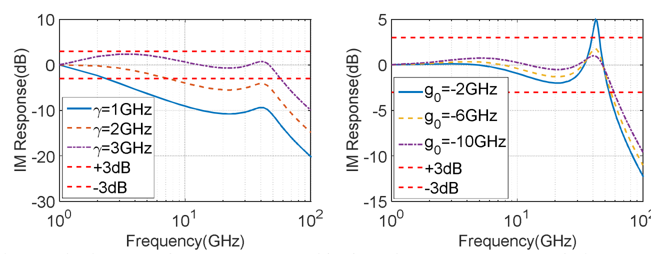

Fig. 2. The impact of parameters γ and |g0| on the IM response. Left: increase γ while keeping g_0=-10GHz, f_{CPR}=10GHz, f_{PPR}=40GHz; Right: increase $|g_0|$ while keeping γ=6GHz, f_{CPR}=10GHz, f_{PPR}=40GHz.

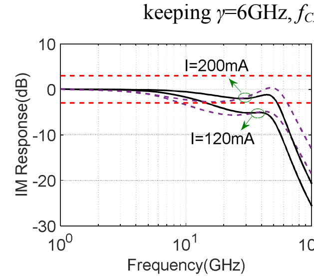

Fig. 3. The IM response of a L=400μm, κ=150 cm^{-1} 2nd-order grating DFB structure calculated numerically (solid) and analytically (dashed) at 120mA (g_0=-20GHz,γ=3.6GHz,f_{CPR}=12GHz, f_{PPR}=50GHz) and 200mA (g_0=-18GHz,γ=6.8GHz,f_{CPR}=17GHz, f_{PPR}=48GHz).