Understanding the photon-photon resonance of DBR lasers using mode expansion method

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***Abstract*—Photon-photon resonance (PPR) in DBR lasers is studied by numerical simulations, which are based on the mode expansion and the rate equations. It is found that the photon number and the mode coupling factor play important roles to understand physical mechanism of the PPR behind.**

I. Introduction

Direct modulated lasers (DMLs) are attractive for short-distance optical communications, such as data centers and 5G wireless. 65-GHz DMLs have been successfully demonstrated with a help of the PPR effect [1].

The PPR effect has been simulated by using the traveling wave model (TWM), and a PPR peak can be clearly observed in the modulation response [2]. However, there is a deeper physical mechanism interrelated with mode dynamics of such special designed multi-section lasers.

Another alternative simulation method is the mode expansion method, which has been well developed for mode dynamics of multi-section lasers [3]. The spatial derivation in the TWM is eliminated by its eigenfunctions and integral operation, and then the rate equations for the complex amplitude of the modes can be obtained. The coupling factors are defined as the integral terms in these rate equations, and are regarded as the driving force of mode dynamics in [4].

In this paper, based on the mode expansion method, we investigate mode dynamics of DBR lasers when the PPR occurs, in terms of the photon number and the mode coupling factor. Simulation results are helpful for understanding physics of the PPR effect behind.

II. Theory of mode dynamics

The cavity of a laser is always open and dissipative. Photons are generated by stimulated emission, lasing out of the mirror, and finally form a stable longitudinal spatial distribution in the cavity. However, this stable field distribution is not a "true mode" but a "quasi mode", which means that different longitudinal modes are not completely orthogonal, and can be coupled with each other.

For a semiconductor laser, the slowly varying amplitudes of forward and backward traveling waves can be denoted as $E^{+}(z,t)$ and $E^{-}(z,t)$, respectively. Assuming there is a main mode 1 and a side mode 2, the envelops of the electric field can be decomposed into:

$$\begin{bmatrix} E^{+}(z,t) \\ E^{-}(z,t) \end{bmatrix} = f_1(t)\begin{bmatrix} \Phi_1^{+}(z) \\ \Phi_1^{-}(z) \end{bmatrix} + f_2(t)\begin{bmatrix} \Phi_2^{+}(z) \\ \Phi_2^{-}(z) \end{bmatrix} \tag{1}$$

where $f_{1,2}(t)$ are the complex amplitude of mode 1 and 2; $\Phi_{1,2}^{+,-}(z)$ are the spatial distribution of mode 1 and 2.

The photon number in the gain section can be expressed as:

$$\begin{aligned} S_a(t) &= \int_0^{L_a}\left[\left|E^{+}(z,t)\right|^2 + \left|E^{-}(z,t)\right|^2\right]\mathrm{d}z \\ &= \left|f_1(t)\right|^2\int_0^{L_a}\left[\left|\Phi_1^{+}(z)\right|^2 + \left|\Phi_1^{-}(z)\right|^2\right]\mathrm{d}z \\ &+ \left|f_2(t)\right|^2\int_0^{L_a}\left[\left|\Phi_2^{+}(z)\right|^2 + \left|\Phi_2^{-}(z)\right|^2\right]\mathrm{d}z \\ &+ 2\,\mathrm{Re}\left\{f_1(t)f_2^{*}(t)\int_0^{L_a}\left[\Phi_1^{+}(z)\Phi_2^{+*}(z) + \Phi_1^{-}(z)\Phi_2^{-*}(z)\right]\mathrm{d}z\right\} \end{aligned} \tag{2}$$

Clearly, on the right-hand side, the first two terms represent the photon number in modes 1 and 2, respectively. It is noteworthy that, the third term, which can be understood as the "extra photon" and due to the non-orthogonality of the longitudinal mode of the open cavity. Here, the integral is only calculated within the gain section ($[0, L_a]$).

Considering dual-mode expansion, following dual-mode rate equations can be derived [4][5]:

$$\frac{df_1}{dt} = \left(i\Omega_1 + K_{11}\right)f_1(t) + K_{12}f_2(t) \tag{3}$$

$$\frac{df_2}{dt} = \left(i\Omega_2 + K_{22}\right)f_2(t) + K_{21}f_1(t) \tag{4}$$

$$\frac{dN_a}{dt} = \frac{I_a}{eV_a} - \frac{N_a(t)}{\tau_N} - \upsilon_g g S_a(t) \tag{5}$$

where the coupling factors K_{nm} (n, m = 1, 2) are defined as:

$$K_{nm} = -\upsilon_g \Delta\beta_a \int_0^{L_a}\left[\Phi_n^{+}(z)\Phi_m^{-}(z) + \Phi_n^{-}(z)\Phi_m^{+}(z)\right]\mathrm{d}z \tag{6}$$

$$\Delta\beta_a = i\frac{1}{2}\left(1 + i\alpha_H\right)\frac{\partial g}{\partial N_a}\left(N_a - N_{th}\right) \tag{7}$$

Equations (3)-(5) are the same as the traditional multi-mode rate equations, if there are only self-coupling factors K_{11} and K_{22}. Here, the cross-coupling factors K_{12} and K_{12} represent the inter-mode coupling, and originated from the non-orthogonality of the two modes. The eigenvalues $\Omega_{1,2}$ and the eigenfunctions $\Phi_{1,2}^{+,-}(z)$ can be solved by the transfer matrix method [4][6].

III. Simulation results

To reveal the mode dynamics behind the PPR effect, a two-section DBR laser is used here for simulation, as shown in Fig. 1(a). In our simulation, the length of the gain section and grating section are selected to be 100 μm and 660 μm, respectively, and the lasing wavelength can be tuned by changing the facet phase ϕ of the gain section.

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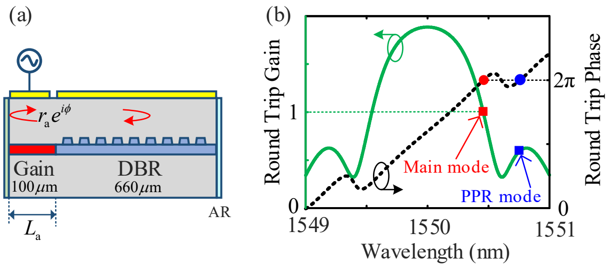

Fig. 1 (a) Schematic of the considered DBR laser. (b) Round-trip gain and round-trip phase at threshold (ϕ = 220°).

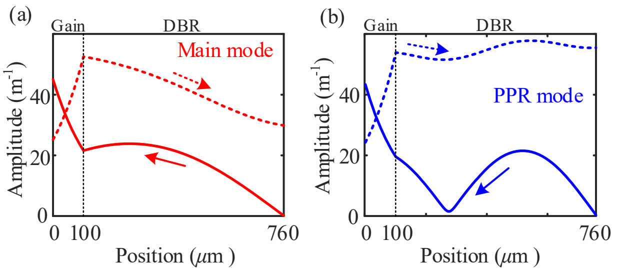

Fig. 2 The spatial distributions of forward and backward traveling waves of (a) main mode and (b) PPR mode (ϕ = 220°).

For a case of ϕ = 220°, the localization of the cavity modes is given in Fig. 1(b), and the spatial distributions of mode 1 (the main mode) and mode 2 (the PPR mode) are displayed in Fig. 2(a) and (b). When the laser is biased above threshold, the spatial distributions of modes are considered unchanged. Therefore, before solving the rate equations (3)-(5), the integral terms in the photon number (2) and coupling factors (6) can be calculated, which determine the mode dynamics at this operation point.

To investigate evolution of the photon number during the PPR, a small frequency sweep signal is added into the gain section, combining with 20 mA DC bias. By solving equations (3)-(5) in time domain, the modulation response is obtained and plotted in Fig. 3. Here, the modulation response is characterized as the difference between the maximum value of the modulated photon number and the stable value of the photon number when only with a DC bias. The response of the total photon number in the gain section is plotted with the black solid line in Fig.3, where a PPR peak at 37 GHz is observed, and the 3dB bandwidth of the DBR laser can reach 45 GHz.

The red dashed line and the blue dot-dashed line in Fig.3 show responses of the photon number in the main mode and the PPR mode, corresponding to the first two terms in (2). As can be seen, at the PPR frequency, even if the response of the PPR side mode is the strongest, it is still 10 dB lower than that of main mode. Seems like that the PPR side mode has a little effect on dynamics of the total photon number. However, we should pay an attention to the third term in (2), which is proportional to $\mathrm{Re}[f_1(t)f_2^*(t)]$. This term means that the main mode amplifies the response of the PPR mode and initiates the PPR effect. This demonstrates the viewpoint in [7] that the PPR mode acts as a catalyst in the DBR laser. Meanwhile, the cross-coupling factors K_{12} and K_{21} are not zero, which is a necessary condition for the PPR mode to have a strong response at the PPR frequency.

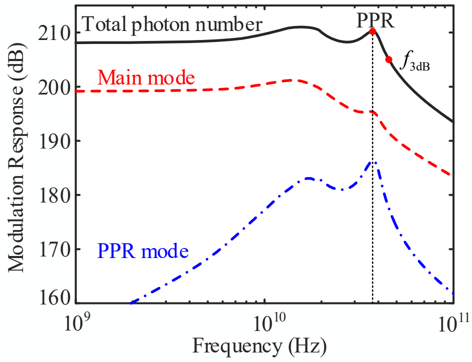

Fig. 3 Modulation responses of the photon number in the main mode, PPR mode, and the total photon number (ϕ = 220°).

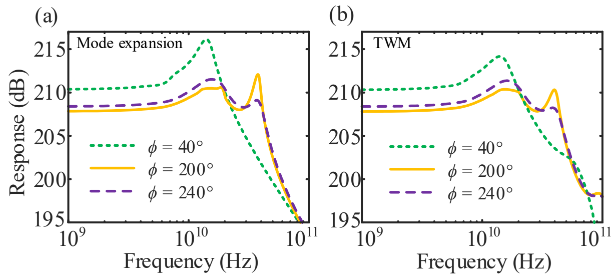

Fig. 4 Modulation responses calculated by (a) mode expansion method, and (b) TWM.

Finally, the small signal responses calculated by the mode expansion rate equations and TWM are compared in Fig. 4 (a) and (b). For different operating points, the results of the mode expansion rate equations and TWM are in good agreement.

IV. Conclution

In summary, the mode dynamics behind the PPR effect of DBR lasers is clarified by solving the mode expansion rate equations, in terms of the photon number and the mode coupling factor. Simulation results show that the photon number and the mode coupling factor together initiate the PPR. Compared with TWM, the mode expansion and the rate equations are helpful with physical connections related to the laser cavity structures.

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