# A simple approach, based on coupled mode theory, to study PhC lasers



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# A simple approach, based on coupled mode theory, to study PhC lasers


**Marco Saldutti[1], Jesper Mork[2], Mariangela Gioannini[1]**

1. *Dipartimento di Elettronica e Telecomunicazioni, Politecnico di Torino, Corso Duca degli Abruzzi 24, Torino, Italy*
2. *DTU Fotonik, Department of Photonics Engineering, Technical University of Denmark, Ørsteds Plads, Building 343, DK-2800 Lyngby, Denmark*


PhC lasers have attracted large interest as efficient light-sources in on-chip and chip-to-chip interconnections. They allow for scaling the active volume while maintaining the high cavity Q-factor, thus exhibiting low threshold current and operating energy [1,2]. Methods for studying these laser cavities are typically based on FDTD simulations, which are often time-consuming and do not allow to catch the most relevant physics of these devices. We propose here an alternative and simple approach to analyze active PhC waveguides and lasers. Our approach is based on coupled-mode theory, which has proved to be an effective tool to study lasers with periodic gain and/or refractive index perturbation, as standard DFB lasers. We apply this method to PhC line-defect waveguides and lasers with a small complex refractive index perturbation (to account for gain and refractive index variation) with respect to a reference, unpumped PhC line-defect waveguide [3]. The optical electric field of the TE-like guided mode is expanded as sum of the forward- and backward-propagating Bloch modes of the passive waveguide; the equation governing the evolution $\psi_{+,-}(z)$ of the Bloch modes along the perturbed waveguide are:

$$\begin{aligned} \partial_z \psi_+ &= i\kappa_{11,q=0}(\omega)\,\psi_+ + i\kappa_{12,q=1}(\omega)\,e^{+2i\delta(\omega)z}\psi_- \\ -\partial_z \psi_- &= i\kappa_{21,q=-1}(\omega)e^{-2i\delta(\omega)z}\psi_+ + i\kappa_{11,q=0}(\omega)\,\psi_- \end{aligned} \qquad (1)$$

where $k_{11,q=0}$ and $k_{12,q=1;21q=-1}$ are the self- and cross- coupling coefficients calculated as in [3]. An example is in Fig. 1 for refractive index perturbation ($\Delta n_s \neq 0$) and positive gain $g_0$. This figure proves that, differently from standard DFB lasers, the cross-coupling coefficient is always comparable to the self-coupling coefficient. This is because of the strong *z*-component of the TE-like electric field of the fundamental guided mode. The coupling coefficients are gain-dependent since gain, not present in the holes, is also a periodic perturbation; $k_{11,q=0}$ and $k_{12,q=1;21q=-1}$ are also frequency-dependent because of the slow-light effect and they significantly increase as frequency approaches the band edge. Therefore, Bloch modes at shorter frequency and/or with higher gain of the active waveguide will go through a stronger distributed feedback effect with respect to longer frequency Bloch modes and/or lower active waveguide gain. Based on this model, we have simulated a laser cavity with the geometry as in Fig. 2a, consisting of a pumped active section, a rear passive mirror with material refractive index smaller than the active section and a front passive buffer with material refractive index equal (Type A) , slightly larger (Type B) or smaller (Type C) than the active region. Based on the model of eq. (1), we have calculated the rear and buffer mirror reflection coefficients ($S_{11}$) (Fig.2a). Threshold condition, found searching for frequency and gain $g_0$ satisfying $r_L(\omega)\cdot r_R(\omega,g_0)=1$, is in Fig.2b as function of the front buffer number of cells. The different trends of the threshold gain with the number of buffer cells can be explained by the interplay, in determining $r_R(\omega,g_0)$, between the distributed feedback in both the active region and the front buffer. In Type C, the latter is dominant (nearly doubled with respect to the active region feedback); therefore, threshold gain diminishes as the front buffer reflection increases (similar to a FP laser with increase of the front mirror reflection). On the contrary, in Type A and Type B the role of distributed feedback in the active region plays a major role and the threshold depends on the interference between the active region distributed feedback and the front buffer back reflection. For this reason, Type B shows an optimum number of cells minimizing threshold gain.

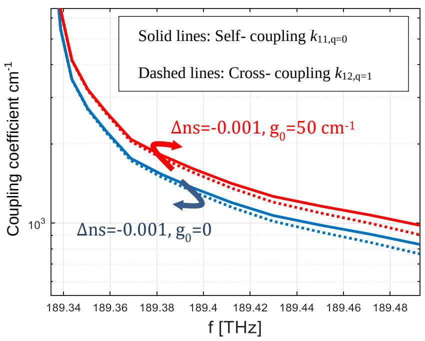


**Fig.1** Self- and cross-coupling coefficients of the PhC waveguide

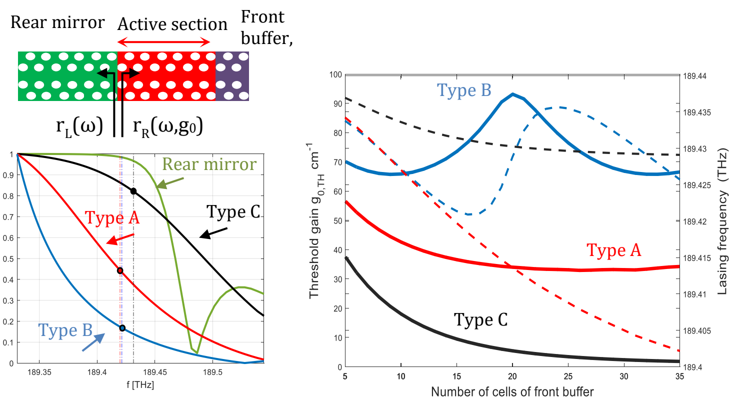


**Fig.2** (a) Rear mirror and front buffer reflection coefficients and (b) corresponding laser threshold gain (solid line) and lasing frequency (dashed line).


[1] S. Matsuo et al., IEEE JSTQE 19, 4900311 (2013).
[2] S. Matsuo et al., Adv. Opt. Photon. 10, (2018).
[3] J. Mørk et al., Phys. Rev. A 92, 053839 (2015).