# Modelling Photonic Crystal Surface Emitting Lasers (PCSELs) with Iterative Weighted Index Method

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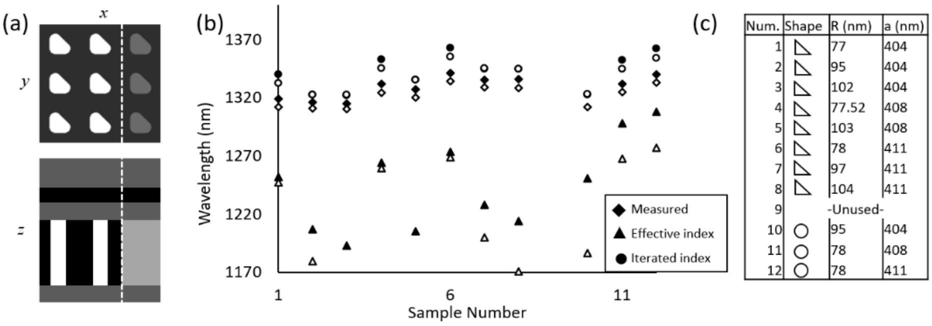
Photonic crystal surface emitting lasers (PCSELs) are a promising type of semiconductor laser, able to maintain single-mode operation over a large area, resulting in a high-power beam with small angular divergence [1].

A PCSEL is a layered device, one layer contains the photonic crystal: a repeating pattern of air holes. The other layers are un-patterned, consisting of optical gain material, substrate, and spaces. The photonic crystal introduces in plane scattering to promote optical feedback and lasing. The pitch, size and shape of the air holes can be engineered to optimize the Q-factor of the lasing mode and maximize the threshold difference between the lasing mode and higher order parasites [2]. Layered devices of this type can only be modelled exactly in 3D. However, effective index methods assume the field in the 3D PCSEL structure is separable and expressed as a product of the 2D in-plane field distribution, $E_{2D}(x,y)$, and vertical 1D field distribution, $E_{1D}(z)$, which avoids computationally expensive 3D simulations, but at the cost of being approximate. Indeed, it is not widely agreed how best to do this approximation: the refractive indices used for the lower dimensional calculations of $E_{1D}$ and $E_{2D}$ are often chosen differently by different authors [3].

This paper derives the error arising from the approximation for a given solution as

$$K = \left(\frac{\omega}{c}\right)^4 \sum_l \sum_r O_l T_r \left| \varepsilon_{l,r} - \bar{\epsilon}_{2D,r} - \bar{\epsilon}_{1D,l} - \left(\frac{\beta c}{\omega}\right)^2 \right|^2, \qquad (1)$$

where $\omega$ is the mode frequency, $c$ is lightspeed, and $\beta$ the propagation constant of the mode in the 1D calculation. The index $l$ labels the layers, while $r$ counts the regions (inside a hole or not). $O_l$ is the integral of $|E_{1D}(z)|^2$ in layer $l$, while $T_r$ is that of $|E_{2D}(x,y)|^2$ in region $r$. $\varepsilon$ is the dielectric constant (taking a value in a given layer and region), while $\bar{\epsilon}_{2D}$ and $\bar{\epsilon}_{1D}$ are the dielectric profiles used to solve for $E_{2D}(x,y)$ and $E_{1D}(z)$ respectively.



| Num. | Shape | R (nm) | a (nm) |
|---|---|---|---|
| 1 | ◺ | 77 | 404 |
| 2 | ◺ | 95 | 404 |
| 3 | ◺ | 102 | 404 |
| 4 | ◺ | 77.52 | 408 |
| 5 | ◺ | 103 | 408 |
| 6 | ◺ | 78 | 411 |
| 7 | ◺ | 97 | 411 |
| 8 | ◺ | 104 | 411 |
| 9 | | -Unused- | |
| 10 | ○ | 95 | 404 |
| 11 | ○ | 78 | 408 |
| 12 | ○ | 78 | 411 |

**Figure 1.** (a) *x*,*y* plane and *z* cut of PCSEL. Left of dashes: slices of 3D structure, right: weighted 2D/1D. (b) Wavelength of modes A (solid) and B (hollow) at Γ-point. (c) idealised hole shape, equivalent radius (R) and pitch (a).

This quantification leads directly to a powerful new approach: to choose the effective indices to minimize the error measure. This optimum solution is found by working iteratively. First, a slab solver is used to obtain the field profile of the lateral (slab) structure. Weighting the slab layers according to the electric field density provides the effective indices of the scatterers and holes of the equivalent 2D PC structure. The density of $|E_{2D}|^2$ is then used to update the effective index of the PC layer in the slab solver. This weighted index approach is iterated until it converges. Fig.1 explores how this Iterative Weighted Index approach compares to traditional effective index methods, and to experimental data collected from real PCSELs. The iterative method is in much closer agreement with the experimental data (see figure), validating the method's application to real devices.

1. K. Hirose, et al., "Watt-class high-power, high-beam-quality photonic-crystal lasers", Nat. Photon, 8, 2014, 406–411.
2. M. Yoshida, et al., "Double-lattice photonic-crystal resonators enabling high brightness semiconductor lasers with symmetric narrow-divergence beams," Nat. Mater, vol. 18, 2, 2019, 121–128.
3. M. Hammer and O. V. Ivanova, "Effective index approximations of photonic crystal slabs: a 2-to-1-d assessment," Opt Quantum Electron, 41, 4, 2009, 16.