Coupled-wave analysis for photonic-crystal surface-emitting lasers (XIV)
– Effect of external reflection on the TE resonant mode –

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Photonic-crystal surface-emitting lasers (PCSELs) can potentially achieve single-mode operation with low beam divergence and high power [1, 2]. It has been known since the 1970s from studies of distributed feedback (DFB) lasers that external reflectors can dramatically alter the performance of lasers with periodic resonant cavity structures [3, 4]. However, the study of this effect in PCSELs is currently lacking. One numerical study was performed by Sakai et al. in 2007 [5], but this study used a two-dimensional coupled-wave model which could not accurately predict the effect of out-of-plane coupling (i.e., surface emission). Furthermore, it did not consider TE modes, which are typically used for lasing in high-power PCSELs. In this work, we present a numerical study of the effect of external reflectors on TE-mode characteristics in PCSELs using a fully three-dimensional model [6, 7].

Figure 1 shows a schematic diagram of external reflection at the left boundary ($x=0$) of a square-lattice PC with side length $L$. At this boundary, right-propagating basic wave $R_s$ is a fraction of left-propagating basic wave $S_x$. Mathematically,

$$R_x = \rho \exp(i\phi) \cdot S_x$$

where $\rho$ and $\phi$ are the reflectivity and total phase, respectively. In a real device, $\rho$ and $\phi$ depend on the refractive index contrast between both sides of the boundary; $\phi$ further depends on the boundary’s position relative to the PC’s holes. A numerical analysis is performed by setting either $\rho$ or $\phi$ to a constant value, then calculating the threshold gain of the cavity’s TE modes as a function of the other.

Such an analysis was performed for a GaAs square-lattice PC with side length $L=70 \mu m$, lattice period 295 nm, and circular air holes with fill factor 0.16. Normalized threshold gain of this PC cavity’s fundamental band-edge TE modes $A_0$ and $B_0$ are shown as functions of reflectivity and phase in Figure 2. In Figure 2(a), $\phi$ is fixed to 0, and threshold gain $\alpha L$ of $A_0$ and $B_0$ peak at around $\rho=0.6$ and $\rho=0.4$, respectively. In Figure 2(b), $\rho$ is fixed to 0.4, and $\alpha L$ of $A_0$ and $B_0$ peak at around $\phi=-\pi/8$ and $\phi=-\pi/4$, respectively. These results serve as design guidelines for minimizing threshold gain or, alternatively, for maximizing the threshold gain margin between modes $A_0$ and $B_0$. A more systematic analysis and detailed physical interpretation will be presented at the conference. This work was partly supported by C-PhoST and JSPS.


Fig. 1 Schematic of reflection at the left ($x=0$) boundary of a square-lattice PC of side length $L$. $S_x$ and $R_x$ are basic waves. $\exp(i\phi)$ is the boundary’s reflection coefficient.

Fig. 2 (a) Normalized threshold gain $\alpha L$ of modes $A_0$ and $B_0$ as a function of reflectivity $\rho$ when phase $\phi=0$. (b) Normalized threshold gain $\alpha L$ of modes $A_0$ and $B_0$ as a function of phase $\phi$ when reflectivity $\rho=0.4$. As indicated in Figure 1, only the left boundary’s reflection is changed; reflection at the other boundaries is zero.