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# フォトニック結晶レーザの結合波理論による解析 (XIV)
# ―ＴＥ共振モードへの外部反射の影響―
# 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 $R_x$ is a fraction of left-propagating basic wave $S_x$. Mathematically,

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

where ρ and ϕ are the reflectivity and total phase, respectively. In a real device, ρ and ϕ depend on the refractive index contrast between both sides of the boundary; ϕ further depends on the boundary's position relative to the PC's holes. A numerical analysis is performed by setting either ρ or ϕ 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 µm, 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), ϕ is fixed to 0, and threshold gain $\alpha L$ of $A_0$ and $B_0$ peak at around ρ=0.6 and ρ=0.4, respectively. In Figure 2(b), ρ is fixed to 0.4, and $\alpha L$ of $A_0$ and $B_0$ peak at around ϕ=-π/8 and ϕ=-π/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.*

*References:* [1] E. Miyai *et al.*, *Nature*, **441,** 946 (2006). [2] K. Hirose *et al.*, *Nature Photon*, **8,** 406 (2014). [3] S. Chinn. IEEE J. Quant. Elec. **QE-9**, 574 (1973). [4] W. Streifer *et al.*, IEEE J. Quant. Elec. **QE-11**, 154 (1975). [5] K. Sakai *et al*. Opt. Express **15**, 3981 (2007). [6] Y. Liang *et al*., Phys. Rev. B **84**, 195119 (2011). [7] Y. Liang *et al*., Opt. Express **20**, 15945 (2012).

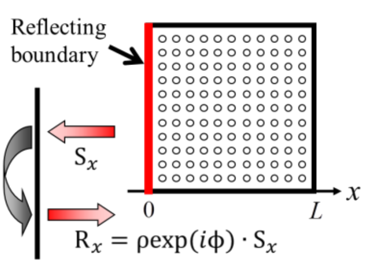


**Fig. 1** Schematic of reflection at the left ($x$=0) boundary of a square-lattice PC of side length $L$. $S_x$ and $R_x$ are basic waves. ρexp($i$ϕ) is the boundary's reflection coefficient.

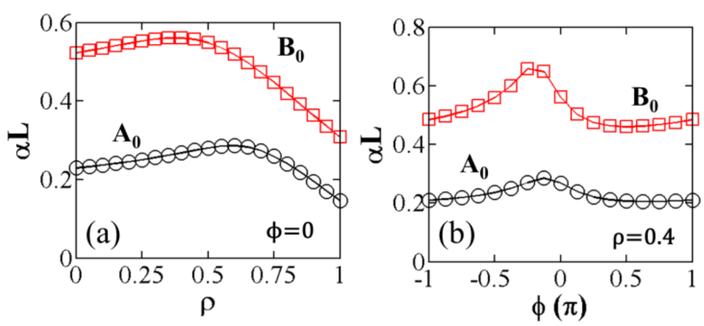


**Fig. 2** (a) Normalized threshold gain $\alpha L$ of modes $A_0$ and $B_0$ as a function of reflectivity ρ when phase ϕ=0. (b) Normalized threshold gain $\alpha L$ of modes $A_0$ and $B_0$ as a function of phase ϕ when reflectivity ρ=0.4. As indicated in Figure 1, only the left boundary's reflection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