フォトニック結晶レーザの結合波理論による解析
―閾値利得に与える複数外部反射の影響―
Coupled-wave analysis for photonic-crystal surface-emitting lasers
– Effect of multiple external reflectors on threshold gain –

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Photonic-crystal surface-emitting lasers (PCSELs) can achieve continuous-wave, single-mode operation with low beam divergence and high power [1, 2]. Until now, analysis of these devices has been limited to structures without boundary reflection [3]. However, boundary reflection might offer a new technique for improving device performance. Previously, the influence of spatially uniform reflection from one side of a photonic crystal (PC) was investigated [4]. From this study, reflection was seen to not only change modal frequencies and gain thresholds, but also create new modes confined between the reflecting boundary and PC. Here, we introduce reflection from multiple boundaries, as well as spatially non-uniform reflection, with the goal of maximizing laser mode stability.

Figure 1 shows a schematic diagram of external reflection at two boundaries of a square-lattice PC with side length L. At the left and top boundaries, respectively, incoming basic waves R_x and S_y are fractions of outgoing basic waves S_x and R_y. Mathematically,

$$R_x(y) = r_x(y)S_x(y) = \rho(y)e^{i\phi}S_x(y)$$
$$S_y(x) = r_y(x)R_y(x) = \rho(x)e^{i\phi}R_y(x)$$

where $\rho(x)$ and $\rho(y)$ are spatially non-uniform reflectivities and ϕ is total phase. In a real device, ρ and ϕ depend on structural properties at the interface between the PC and the surrounding medium. Via appropriate configuration of these two parameters, the threshold gain difference ($\Delta\alpha$) between the PCSEL's fundamental and competing higher-order modes can be widened, leading to stronger single-mode stability and potentially higher-power operation.

Figure 2 shows the dependence of $\Delta\alpha$ on ρ for a square-lattice PC with $L = 70$ µm, lattice period 295 nm, and circular air holes with fill factor 0.16. Three boundary configurations are considered: spatially uniform left boundary (black), spatially uniform left and top boundaries (blue), and spatially non-uniform left and top boundaries as depicted in Figure 1 (green). In each case, reflection at all other boundaries is zero. For each case, ϕ is fixed to the value at which $\Delta\alpha$ is maximized: $-3\pi/8$ (black) and $-\pi/4$ (blue and green). The dashed line indicates $\Delta\alpha$ (= 41.8 cm^{-1}) in absence of boundary reflection. A maximum improvement of 74% ($\Delta\alpha$ = 72.6 cm^{-1}) is obtained when $\rho = 0.45$ for left and top spatially uniform boundaries. For all configurations, $\Delta\alpha$ steeply drops at high ρ due to mode competition involving new modes confined between the reflecting boundaries and PC. Details 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] Y. Liang *et al.*, *Opt. Express* **20**, 15945 (2012). [4] J. Gelleta *et al.*, 18p-C8-8, JSAP Fall 2014.

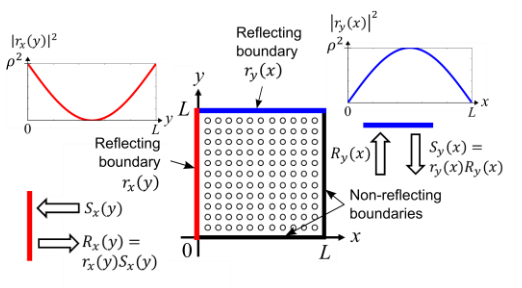

Fig. 1 Exemplary schematic of reflection at the left (x=0) and top (y=L) boundaries of a square-lattice PC of side length L. $S_x(y)$ and $R_y(x)$ are outgoing basic waves. $R_x(y)$ and $S_y(x)$ are incoming basic waves. All basic waves are spatially dependent.

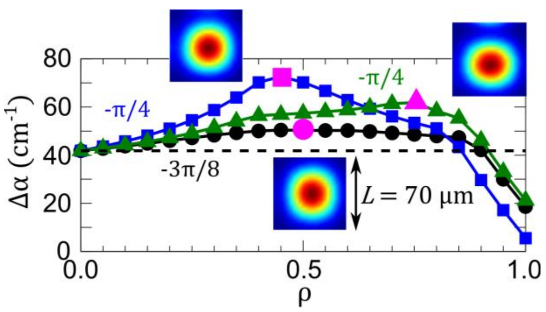

Fig. 2 Threshold gain difference $\Delta\alpha$ versus reflectivity ρ for uniform left boundary (black), uniform top and left boundaries (blue), and non-uniform top and left boundaries (green) when ϕ is fixed to the indicated value. The dashed line is $\Delta\alpha$ when $\rho = 0$ everywhere. The insets are field intensity profiles at the highlighted points.