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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 (XII)
－高次のバンド端モード－
Coupled-wave analysis for photonic-crystal surface-emitting lasers (XII)
–Higher-order band-edge modes–

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Photonic-crystal surface-emitting lasers (PCSELs) can potentially achieve single-mode operation with large cavity area and very high output power [1, 2]. In general, a large device dimension is beneficial for improving output power. However, a long cavity side length usually tends to possess a smaller modal discrimination and results in spatial hole burning (SHB) effect. Previously, we developed an above-threshold coupled-wave theory that incorporates the SHB effect [3]. However, we restricted our analysis to the fundamental band-edge modes. Here, we present modal properties of the higher-order band-edge modes and study their potential influence on the laser mode stability.

Figure 1(a) shows the calculated band structure of a square-lattice PCSEL by assuming a periodic boundary condition [4, 5]. Among the four modes A-D, band-edge modes A and B with lower frequency are most favorable for lasing due to their less radiative nature [4]. Figure 1(b) presents the calculated threshold gain (αL) versus mode frequency (δL) of these two modes (grouped within the blue and red circles) for a finite-size PCSEL with cavity side length L=200 μm (normalized coupling coefficient κL~8.1). In contrast to the infinitely periodic structure where only one band-edge mode A or B exists, a group of multiple resonant states exist for each mode due to the quantized wave vector within a finite-size laser cavity [6]. For example, modes B_0-B_5 shown in the insets of Fig. 1(b) all have the same H-field pattern within a unit cell but different field intensity envelopes. The mode that has only one antinode is called fundamental mode B_0, and modes that have multiple antinodes are called higher-order modes B_1-B_5. Similar denotation also applies to mode A; fundamental mode A_0 is shown in the inset. The mode spacing between modes B_0 and B_1 (0.17 nm) is an order of magnitude narrower than that between the fundamental modes A_0 and B_0 (2.8 nm). Since the lasing action is onset at the mode with the lowest cavity loss (α_{cv}), Fig. 1(b) indicates that mode B_0 (α_{cv}=26.9 cm^{-1}) will be the first mode to reach the threshold. Note that the second and third lowest-cavity-loss modes are A_0 (α_{cv}=40.3 cm^{-1}) and B_1 (α_{cv}=44.7 cm^{-1}), respectively. However, above the threshold, we find that the cavity loss of the fundamental mode B_0 (or A_0) naturally increases whereas mode B_1's cavity loss decreases due to the SHB effect [3], which eventually deteriorates the mode stability. To mitigate this undesirable SHB effect, we perform device optimization by judiciously engineering unit cell structures and current injection profiles to force the laser to operate stably at the fundamental mode even at high injection current levels far above the threshold. Our finding presents important guidelines for designing stable single-mode high-power PCSELs. Detailed analyses will be presented at the conference. *This work was partly supported by C-PhoST, ACCEL, and JSPS.*

References: [1] E. Miyai *et al., Nature*, **441,** 946 (2006). [2] 廣瀬他, 2013 年秋応物 18p-A3-10. [3] Y. Liang 他, 2013 年秋応物 18p-A3-9. [4] Y. Liang *et al.,* Phys. Rev. B **84,** 195119 (2011). [5] C. Peng *et al.,* Phys. Rev. B **86,** 035108 (2012). [6] Y. Liang *et al.*, Opt. Express **20,** 15945 (2012).

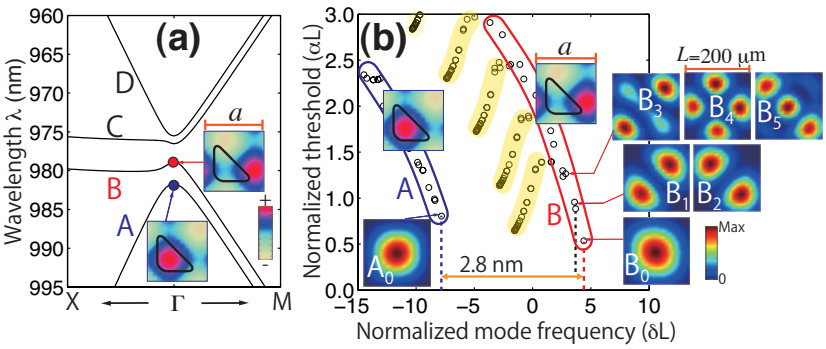

Fig. 1 (a) Calculated TE-mode band structure. Insets show the H-field patterns (in color) of band-edge modes A and B, where triangles indicate air holes. (b) Mode spectra calculated for a PCSEL with L=200 μm. Insets show the field intensity envelopes of the modes labeled as A_0, B_0, and B_1-B_5. Additional modes between A and B (highlighted in yellow) are artifacts due to the numerical algorithm.