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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 (XI)
－ゲインの空間的不均一性－

Coupled-wave analysis for photonic-crystal surface-emitting lasers (XI)
–Nonuniformity of gain profile–

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Photonic-crystal surface-emitting lasers (PC-SELs) can potentially achieve single-mode operations with the largest cavity area and the highest output power [1, 2]. Generally, the output power scales naturally with the square of the cavity side length L. However, the long cavity side length usually tends to result in a highly inhomogeneous profile of the photon density, which in turn induces a spatially nonuniform carrier density and degrades the device performance. This is so-called spatial hole burning (SHB). To investigate the influence of SHB in PC-SELs, we developed an above-threshold coupled-wave model [3] by taking into account of the spatially-varying refractive index. For the purpose of ascertaining the physical picture, we assumed a uniform gain distribution in our previous model. However, in reality, the gain profile is usually nonuniform, distributed in a very complicated shape due to the SHB and current injection. Here, we improve the above-threshold model by including the nonuniformity of gain profile.

Figure 1(a) shows a typical photon density distribution calculated for a square-lattice PC laser cavity with L=200 μm (the coupling coefficient κ=570 cm^{-1} and the normalized coupling coefficient κL ~11). This inhomogeneous photon density leads to a relatively larger stimulated recombination rate at the cavity center, and thus the local carrier density is remarkably reduced near the cavity center. On the other hand, the amplitude gain g is closely related to the carrier density N inside the active region and can be approximated by $g(N)=\Gamma A_0(N-N_{tr})$ [4], where Γ is the confinement factor, A_0 is a proportionality constant (differential gain), and N_{tr} is the transparent carrier density (N_{tr}=1-1.5×10^{18} cm^{-3}). Therefore, the amplitude gain g exhibits a reverse bell-shaped profile as shown in Fig. 1(b).

Based on the steady-state rate equations [4], we derive an explicit formulation describing the relation between the injection current density J and the amplitude gain profile g. Then, the nonuniform gain profile is incorporated into the linear three-dimensional coupled-wave equations [5, 6]. By solving the resultant nonlinear couple-wave equations using a self-consistent technique [3], we can calculate the modal properties at any injection current level above threshold. Figure 2 shows the normalized threshold gain (αL) as a function of the amplitude gain variation for two different air-hole shapes. It can be seen that threshold gain steadily increases with an increasing gain variation (i.e., increasing injection current) for both air-hole shapes. The increased threshold can be understood by considering the fact that the overlap integral between the spatial distribution of the gain and that of the modal intensity is decreased, as depicted in Fig. 1. This result implies that the nonuniform gain profile due to the SHB may degrade the performance of the PCSELs with large Ls particularly at high current levels. Detailed theory and discussions including the methods to suppress such effects will be presented at the conference. *This work was partly supported by C-PhoST, CREST, and JSPS.*

References: [1] E. Miyai *et al., Nature*, **441,** 946 (2006). [2] 廣瀬他, 2013 年春応物 28p-C1-18. [3] Y. Liang 他, 2013 年春応物 29p-PA7-15. [4] G. P. Agrawal and A. H. Bobeck, *IEEE J. Quantum Electron.* **24,** 2407 (1988). [5] Y. Liang *et al.,* Phys. Rev. B **84,** 195119 (2011). [6] Y. Liang *et al.*, Opt. Express **20,** 15945 (2012).

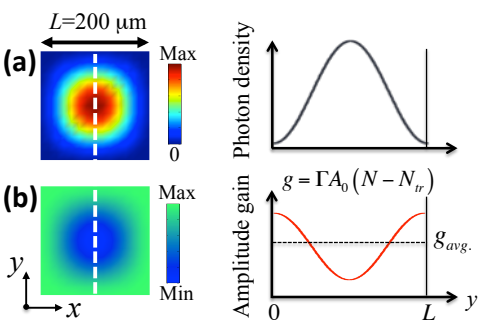

Fig. 1 Illustration of (a) the in-plane photon density distribution and (b) the nonuniform gain profile due to spatial hole burning. Curves on the right are the cross-sectional plots along the y axis.

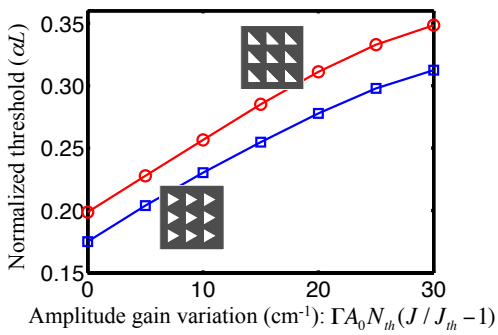

Fig. 2 Normalized threshold gain versus amplitude gain variation for two different air-hole shapes: right-angled triangle (red curve) and equilateral triangle (blue curve). In the calculations, L=200 μm, filling factor=0.16.

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