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2 次元フォトニック結晶レーザの結合波理論による解析 (X)
―発振閾値以上の解析－

Coupled-wave analysis for photonic-crystal surface-emitting lasers (X)
–Above-threshold analysis–

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Recently, we demonstrated a three-dimensional (3D) coupled-wave theory (CWT) [1, 2] that affords a semi-analytical treatment of the full 3D structure of photonic-crystal surface-emitting lasers (PC-SELs) [3]. Based on this 3D CWT analysis, various modal properties can be calculated efficiently and show good agreement with experimental observations at the threshold condition. Above threshold, however, most of the photons may concentrate at the cavity center for devices with a fairly strong coupling coefficient or a very large area. This may result in a highly inhomogeneous carrier density. Therefore, in such cases, the prediction based on the analysis at the threshold is no longer valid [4]. Here, we develop an above-threshold CWT model to describe the photon and carrier density inhomogeneity.

The schematic structure of a square-lattice PC laser cavity is depicted in Fig. 1(a). The side length of the cavity is L and the Bragg wave number of the PC is $\beta_0=2\pi/a$ (a: lattice constant). Figure 1(b) shows the calculated spatial distribution of photons for the lasing mode. In the calculation, the normalized coupling coefficient κL equals ~9 (initial coupling coefficient κ=570 cm^{-1}, L=150 μm, and a=295 nm). As the photons concentrate near the cavity center, the carrier density in the active layer near the center is reduced remarkably due to the stimulated recombination, as shown in Fig. 1(c). Such an inhomogeneous carrier distribution is known as spatial hole burning (SHB) and could give rise to a spatially-varying effective refractive index. As a consequence, the propagation constant of the lasing mode is modified by an additional factor $[1+\zeta P(x,y)]$, where ζ represents the strength of the SHB induced scattering and is generally proportional to the injection current, and $P(x,y)$ represents the normalized photon density.

We extend the 3D couple-wave equations by carefully taking into account the above-mentioned spatial inhomogeneity. The effective refractive index profile and the parameter ζ were explicitly formulated based on the steady-state spatially-varying rate equations. By solving the extended couple-wave equations, we can calculate the modal properties at any injection current level above threshold. Figure 2 shows the normalized threshold gain (αL) and the differential quantum efficiency (i.e., the ratio of the surface-emitted power to the total stimulated emission power) as a function of the normalized SHB strength (ζ/β_0). In the calculation, $P(x,y)$ was approximated by a cosine function [4]. From Fig. 2, we can clearly see that threshold gain steadily increases with an increase in the SHB strength ζ (i.e., an increased injection current) and that the differential quantum efficiency reduces considerably compared to that at the threshold (i.e., ζ=0). We attribute the increased threshold gain to the decreased effective reflectivity (i.e., the effective coupling coefficient κ') of the PCs at high injection currents. The presented above-threshold analysis indicates that the SHB may drastically degrade the performance of the PCSELs particularly at high current levels and therefore PC structures with reduced SHB must be considered for the design of high-power laser devices. Details of the calculated results for various air-hole shapes and discussions of the SHB effect on mode stability will be presented at the conference. *This work was partly supported by C-PhoST, CREST, and JSPS.*

References: [1] Y. Liang *et al.*, Phys. Rev. B **84,** 195119 (2011). [2] Y. Liang *et al.*, Opt. Express **20,** 15945 (2012). [3] E. Miyai *et al., Nature*, **441,** 946 (2006). [4] M. C. Wu, *et al.*, Appl. Phys. Lett. **52,** 1119 (1988).

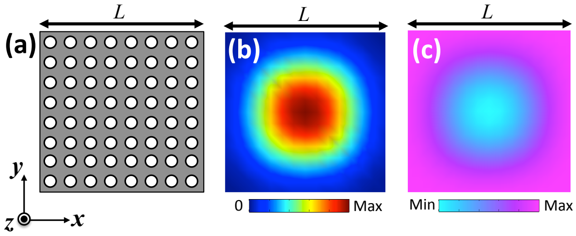

Fig. 1 (a) Schematic of a square-lattice photonic-crystal laser cavity with circular air-holes. (b) Photon density distribution. (c) Carrier density distribution.

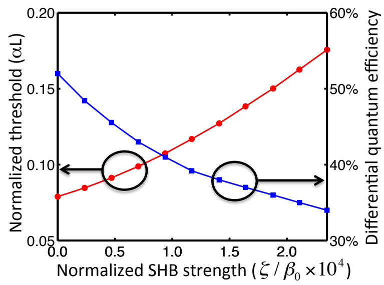

Fig. 2 Normalized threshold gain (red curve) and differential quantum efficiency (blue curve) versus the normalized SHB strength. In the calculation, L=150 μm, a=295 nm, filling factor=0.16.