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フォトニック結晶レーザの大面積高出力動作に向けた ダブルホール孔形状の設計

Double-hole design for realizing large-area high-power operation in photonic-crystal surface-emitting lasers

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Photonic-crystal surface-emitting lasers (PCSELs) are inherently suitable for single-mode high-power operation because of their capability for large-area coherent lasing oscillation, based on the two-dimensional feedback effect at the band edge [1]. Very recently, we have successfully demonstrated a watt-class high-power, high-beam-quality PCSEL under room-temperature, continuous-wave conditions [2]. Single-mode output power can be further improved by increasing the laser cavity's area. However, a large cavity area tends to give rise to smaller modal discrimination and results in spatial hole burning (SHB) due to spatial nonuniformity of the intra-cavity photon density distribution [3]. For this reason, careful design of the PC structure is required. Here, we propose a double-hole (DH) unit cell structure with asymmetric air-hole shapes for enhancing the output power of PCSELs. We perform three-dimensional (3D) coupled-wave analysis [4, 5] to show that our proposed DH structure is able to reduce the in-plane feedback strength while maintaining a high surface-emitting capability.

Figure 1(a) shows calculated coupling coefficient (κ) of DH PCs with two kinds of air-hole shapes: right-angled triangular and circular. The distance between the center of mass of the air holes with filling factors of f1 and f2 is set to $0.25\sqrt{2}a$ (a: lattice constant). We optimize the DH structure by varying f2 while keeping f1+f2=0.18 (note that f2=0 represents a single hole). From Fig. 1(a), we clearly see that κ of both air-hole shapes monotonically decreases with increasing f2 and finally becomes zero when f1=f2=0.09. To examine the surface-emitting capability of these structures, we show the radiation constant versus f2 in Fig. 1(b). The radiation constant of the triangular DH structure initially increases with increasing f2 and then begins to decrease when f2>0.03. In contrast, for the circular DH structure proposed previously [6], the radiation constant remains small (less than 3 cm^{-1}). This reveals the advantage of using triangular-shaped DHs for higher-power operation. Generally, a smaller coupling coefficient leads to a more uniform photon density distribution and thus weaker SHB [7]. However, the trade-off between radiation constant and coupling coefficient must be considered when designing an optimal DH structure. We find that at f2=0.05, the radiation constant is as high as 47 cm^{-1}; this is almost a factor of three of that (16.5 cm^{-1}) of the conventional triangular single hole (with f2=0) and is even slightly larger than that of the state-of-the-art high-power device demonstrated recently [2]. Meanwhile, at f2=0.05, the coupling coefficient (κ=211 cm^{-1}) is less than half of that (κ=478 cm^{-1}) of the single-hole case. Thanks to this reduced κ, a flatter photon density profile is obtained for the DH structure even after the cavity length L is increased, as shown in Fig. 1(c). Therefore, both weakened SHB and further increase of the laser cavity size (thus higher power) can be expected. Our finding presents important guidelines for designing stable large-area high-power PCSELs. Detailed analyses, including 3D DH structures with vertical asymmetries, as well as the effect of SHB on mode stabilities in the above-threshold regime, etc. will be presented at the conference. *This work was partly supported by C-PhoST and JSPS.*

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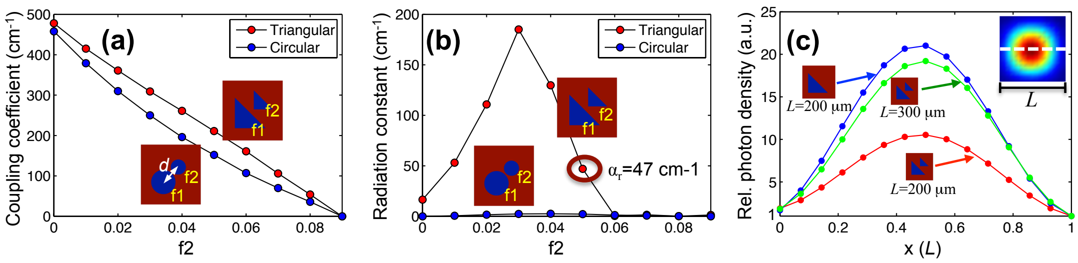

Fig. 1 (a) Calculated coupling coefficient versus filling factor (f2) for double holes with triangular and circular shapes; f1 and f2 are the air-hole filling factors, and d is the distance between the two air-hole centers of mass. (b) Radiation constant versus f2. At f2=0.05, the radiation constant equals 47 cm^{-1} (red circle). (c) Relative photon density distribution of the double-hole (f2=0.05) PC cavities with side length L=200 μm (red curve), L=300 μm (green curve), and the conventional single-hole case with L=200 μm (blue curve).