Optimization of Double-Circular-Hole Photonic-Crystal Surface-Emitting Lasers

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***Abstract* – Photonic-crystal surface-emitting lasers (PC-SELs) with double circular holes in the unit cell are optimized in terms of slope efficiency and single-mode stability. For PC-SELs with double-hole shift of one-fourth and one-third lattice constant, the area ratios of two holes are optimized separately and fall in completely different range; moreover, their threshold gain discrimination values are determined and compared.**

Index Terms - photonic crystals; surface-emitting lasers; coupled-wave theory; band-edge modes; double-hole lattice.

I. INTRODUCTION

Square-lattice photonic-crystal surface-emitting lasers (PC-SELs) with double holes in the unit cell (or double-lattice PC-SELs) were introduced to maintain single-mode oscillation while achieve high power optical output under large area emissions [1]. The double holes in the unit cell were shifted around quarter lattice constant with certain shapes for better threshold gain discrimination [1]; however, their filling factors were not optimized. Besides, we observed enhanced radiation as double-hole shift deviated from quarter lattice constant. Improved slope efficiency (S.E.) or power conversion efficiency (PCE) can therefore be expected.

Three-dimensional (3D) coupled-wave theory (CWT) model was developed first for PC-SELs with regrown air-hole structure [2] and then applied to those without regrowth, *i.e.* air-pillar PC-SELs [3]. In this paper, double-hole PC-SELs are theoretically investigated by CWT in terms of slope efficiency and single-mode stability. Circular shaped holes are simulated with double-hole shift, sizes and ratio of two holes as the parameters for optimization.

II. SIMULATED STRUCTURES

Fig. 1 shows the schematic structure of air-hole PC-SEL in [2]. The active region consisted of three layers of 8-nm InGaAs quantum well (QW) spaced by 20-nm GaAs layers. The air-hole PC layer of 118-nm thickness was buried within 160-nm GaAs layer, which was 40 nm adjacent to the active region. The detailed information of thickness and refractive index can be found in [2,3].

The PCs are in square lattice with lattice constant a = 295 nm. In this paper, we investigate the unit cell of double circular holes shown in Fig. 2. The filling factors f_1 and f_2 are defined as area fraction of large and small holes, respectively. The average refractive index of PC layer is given by,

$$n_{av} = \sqrt{(f_1 + f_2)n_a^2 + (1 - f_1 - f_2)n_b^2}, \qquad (1)$$

where n_a and n_b are refractive indices of air and background material, respectively. The two holes are diagonally offset or shifted in x and y directions by equal distance of Δ.

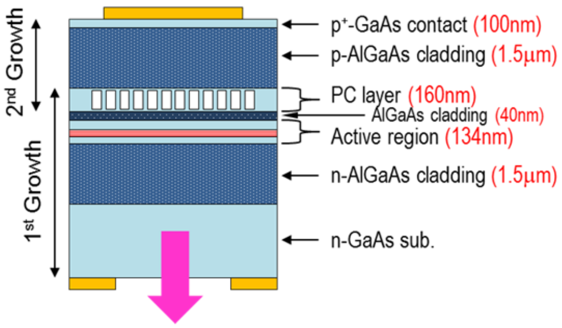

Fig. 1 The schematic structure of air-hole PC-SEL under simulation.

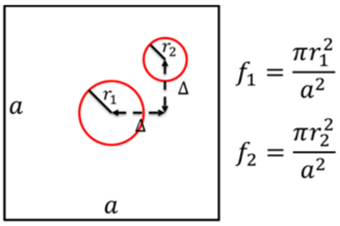

Fig. 2 The unit cell of double circular holes under investigation.

III. RESULTS AND DISCUSSIONS

In the limit of infinite cavity (without edge losses or $\alpha_{edge} \approx 0$), the normalized frequencies and modal losses (*i.e.* radiation losses α_{rad}) of four band-edge modes A, B, C and D are calculated by CWT with f_1 in a multiple series of f_2, that is, f_1/f_2 = 1.5, 1.8, 2, 2.5, 3, 3.5, and 4. The S.E. can be estimated according to the formula,

$$S.E. \approx \frac{1.24}{\lambda_0}\frac{(1/2)\alpha_{rad}}{\alpha_{rad}+\alpha_{edge}+\alpha_{int}}\left(\frac{W}{A}\right), \qquad (2)$$

where λ_0 is free-space wavelength in unit of μm and α_{int} is internal power loss with assumed value of 5 cm^{-1}. The factor 1/2 takes into account that only upward radiation contributes to lasing output.

According to our previous study [3], double-hole PC-SELs can harvest best threshold gain discrimination and maximum S.E. by double-hole shift around one-fourth and one-third lattice constant, respectively. The optimum filling factors of double holes are therefore determined for these two specific conditions as follows.

A. *Hole-shift of One-fourth Lattice* (Δ = *a/4*)

For double-hole PC-SEL with Δ = *a/4*, the modal loss of lowest threshold mode is plotted against f_2 as shown in Fig. 3. The lasing modes are all band-edge mode A in the investigated range of f_1 and f_2. As f_1 increases from 1.5 up to 4.0 times f_2, the modal loss or surface radiation increases at first and then decreases. The lasing wavelength is obtained from the normalized frequency of mode A (not shown). With equation (2), maximum S.E. of 0.48±0.01 W/A is obtained with f_1/f_2 = 1.5-2.0 and f_2 = 0.025-0.04.

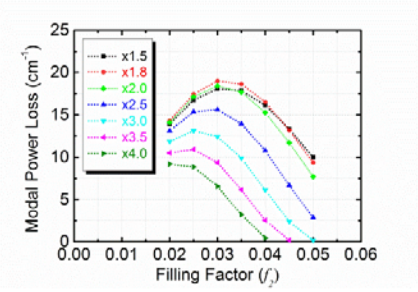

Fig. 3 The modal loss of lowest threshold mode as a function of f_2 for double-hole PC-SEL with Δ = *a/4*.

B. *Hole-shift of One-third Lattice* (Δ = *a/3*)

For double-hole PC-SEL with Δ = *a/3*, the modal loss of lowest threshold mode is plotted against f_2 as shown in Fig. 4. The lasing band-edge modes are either mode A or mode D (in red circle and frames). The modal loss or surface radiation first increases with increasing f_1/f_2 and then almost overlapped with f_1/f_2 = 2.5-4.0. Nonetheless, there are three diversion points away from these overlapped lines, which is attributed to switching from mode A to mode D. The maximum S.E. of 0.6±0.01 W/A is obtained with f_1/f_2 = 2.5-4.0 and f_2 = 0.035-0.05. The S.E. increases by 25% as Δ shifts from *a/4* to *a/3*; however, the price to be paid is larger modal loss or higher threshold.

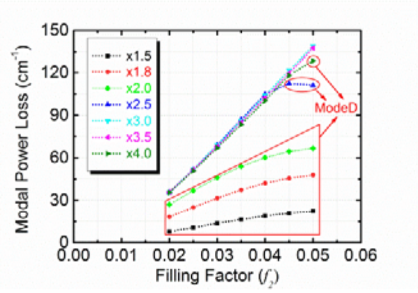

Fig. 4 The modal loss of lowest threshold mode as a function of f_2 for double-hole PC-SEL with Δ = *a/3*.

C. *Finite Size Effect*

In a finite-size cavity, the in-plane or edge loss decreases rapidly with increasing cavity size but never be zero. Besides, large cavity size increases number of high-order modes and decreases loss (or gain) difference between adjacent modes. To quantify stability of single-mode emissions, threshold gain discrimination is determined by calculating loss difference between lowest threshold mode and associated first high-order mode, *i.e.*, $(\alpha_{1st} - \alpha_{0th})$.

The square PC cavity with side length of 300 μm is taken as an finite-cavity example. Table 1 shows the calculated modal losses for two specific cases (f_1, f_2, Δ) = (0.035, 0.063, *a/4*) and (0.04, 0.12, *a/3*). For both two cases, the lowest threshold and first high-order modes are band-edge A0 and A1 modes, respectively. The double-hole PC-SEL with Δ = *a/4* exhibits larger discrimination than that with Δ = *a/3*, which guarantees its single-mode operation.

Table 1 The loss parameters of A0 and A1 modes for 2 specific PC-SELs.

modal parameters / loss parameters	(f_1, f_2, Δ)			
	(0.035, 0.063, *a/4*)		(0.04, 0.12, *a/3*)	
	A0	A1	A0	A1
edge loss, α_{edge} (cm^{-1})	7.382	17.711	1.321	3.344
radiation loss, α_{rad} (cm^{-1})	24.315	31.301	104.337	104.897
total power loss (cm^{-1})	31.697	49.012	105.658	108.241
discrimination (cm^{-1})	17.315		2.583	

D. *Air-pillar PC-SELs*

The above simulations are also performed for air-pillar PC-SEL. Instead of regrowth, the p-cladding layer is reduced to 400 nm and double-circular PC holes are deeply etched down to 100-nm contact layer and 400-nm p-cladding layer. The detail structure and refractive indices can be found in [3].

In general, air-pillar PC-SELs exhibit similar dependence as shown in Fig. 3 and 4 except their modal losses are less than one-third the losses of air-hole PCSELs. For infinite cavity with Δ = *a/4*, maximum S.E. of 0.31±0.01 W/A is obtained with f_1/f_2 = 1.5-2.0 and f_2 = 0.025-0.04. For Δ = *a/3*, maximum S.E. of 0.54±0.02 W/A is obtained with f_1/f_2 = 2.5-4.0 and f_2 = 0.035-0.05. The S.E. increases by 74% as Δ shifts from *a/4* to *a/3*. In the same scenario of finite-cavity simulation, air-pillar PC-SEL with Δ = *a/4* also shows larger discrimination than that with Δ = *a/3*. More details will be presented in the conference.

IV. CONCLUSIONS

In this paper, we optimize the S.E. of PC-SELs with double circular holes in the unit cell by determining their filling factors. The optimized filling factors for Δ = *a/4* are f_1/f_2 = 1.5-2.0 and f_2 = 0.025-0.04, while those for Δ = *a/3* are f_1/f_2 = 2.5-4.0 and f_2 = 0.035-0.05. For high-brightness applications where single-mode lasing output is demanded, double-hole PC-SELs with Δ = *a/4* are first choice. However for high-efficiency applications where max PCE is required, we recommend double-hole PC-SELs with Δ = *a/3*.

ACKNOWLEDGMENT

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