

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,

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

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 .

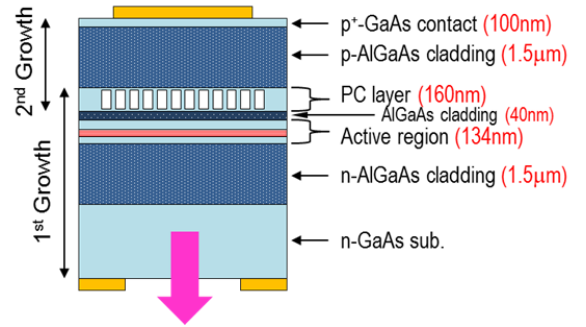


Fig. 1 The schematic structure of air-hole PC-SEL under simulation.

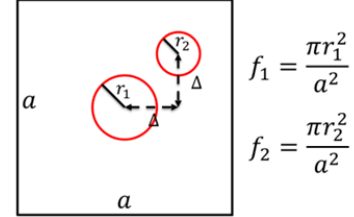


Fig. 2 The unit cell of double circular holes under investigation.

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,

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

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 ($\Delta = a/4$)

For double-hole PC-SEL with $\Delta = a/4$, 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.

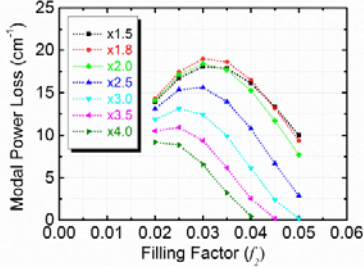


Fig. 3 The modal loss of lowest threshold mode as a function of f_2 for double-hole PC-SEL with $\Delta = a/4$.

B. Hole-shift of One-third Lattice ($\Delta = a/3$)

For double-hole PC-SEL with $\Delta = a/3$, 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.

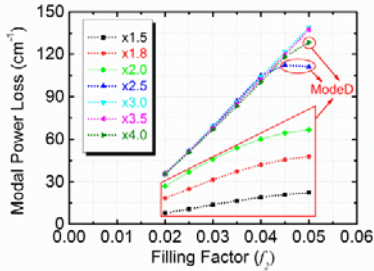


Fig. 4 The modal loss of lowest threshold mode as a function of f_2 for double-hole PC-SEL with $\Delta = a/3$.

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 $(f_1, f_2, \Delta) = (0.035, 0.063, a/4)$ 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 $\Delta = a/4$ exhibits larger discrimination than that with $\Delta = a/3$, which guarantees its single-mode operation.

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

loss parameters	modal 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 $\Delta = a/4$, 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 $\Delta = a/3$, 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 $\Delta = a/4$ also shows larger discrimination than that with $\Delta = a/3$. 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 $\Delta = a/4$ are $f_1/f_2 = 1.5$ -2.0 and $f_2 = 0.025$ -0.04, while those for $\Delta = a/3$ 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 $\Delta = a/4$ are first choice. However for high-efficiency applications where max PCE is required, we recommend double-hole PC-SELs with $\Delta = a/3$.

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