Improvement of current crowding effect in VCSEL arrays with non-uniform oxidation aperture design

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Abstract. A compact electro-opto-thermal model of 2-D vertical cavity surface emitting laser (VCSEL) arrays considering the current crowding effect in each array cell is established to study the impact of oxidation aperture on the device performance. Simulated results shows that increasing oxidation aperture of array cell is helpful to improve the uniformity of current density distribution. With careful design of non-uniform oxidation aperture layout, both the uniformity of the temperature distribution and the current distribution is improved by 36.52% and 42.08%, respectively. Furthermore, 3×3 VCSEL arrays with uniform oxidation aperture (array-1) and non-uniform oxidation aperture (array-2) are fabricated and the L-I-V curves of two types of VCSEL arrays at different biases are also measured. The peak output optical power of array-2 is enhanced to 1.83mW with an improvement of 8.91% when compared with that of array-1. Moreover, the total optical output power of array-2 is always superior to that of array-1 over a wide bias current range.

1 Introduction

The vertical cavity surface emitting laser (VCSEL) arrays are low power consumption devices with high conversion efficiency so they can be used for many applications in various fields like in data- and tele-communication, optical interconnects and free space interconnects [1-3]. In these applications, high power is required. The most common way to increase output power is to integrate numbers of individual VCSELs into a two-dimensional array [4-5]. However, self-heating can seriously affect the performance of VCSELs. The temperature of

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the central cell is higher than of the surrounding cell, due to the central cell is injected with greater current, the output power of VCSELs is severely limited by the thermal rollover caused by the temperature rise [6-8]. Meanwhile, VCSELs have so-called current crowding problem [9]. Since the current path in VCSELs is not sufficient for uniform current diffusion throughout the active region, the injected currents tend to shunt toward the periphery of the oxide aperture, leading to increased non-radiative recombination near periphery, increased self-heating, and reduced output power, especially, at higher injection currents [10]. Therefore, how to improve the current crowding effect in VCSELs has become a key issue to be solved.

In this paper, an electro-opto-thermal model of VCSELs array is established for the first time to study the current crowding effect, and in order to alleviate the thermal effects caused by the current crowding effect and improve the optical output power in VCSELs, the technology of non-uniform oxidation aperture is presented, which is shown to be a relative simple and convenient method for alleviating current crowding effect and improving the non-uniformity of temperature profile. And two types of 3×3 VCSEL with non-uniform oxidation aperture and uniform oxidation aperture are fabricated and measured, the experiment results exhibit that, for VCSEL with non-uniform oxidation aperture, the total optical output power is improved significantly compared with the VCSEL with uniform oxidation aperture. The simulation results are consistent with experimental results.

2 Electro-opto-thermal model

The schematic device structure of a VCSEL array with 3×3 cells is shown in Fig. 1(a) [11]. R, r, and d are the diameter of cylindrical mesas, the diameter of lasing area, and the spacing of two adjacent cells, respectively. The current flow path in the VCSEL cell is shown in Fig. 1(b), which represented by the red line. l is the length of the active region, r_w represents oxidation aperture. S' and S'' are the area of in the region of $l \le r_w$ and $l > r_w$, respectively.

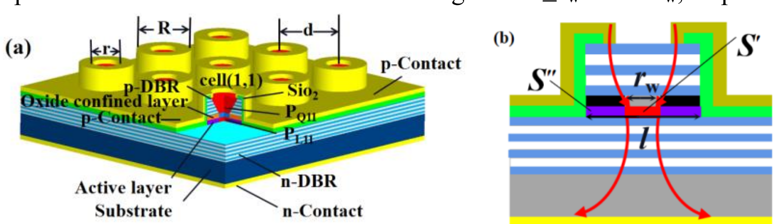

Fig. 1. Schematic device structure of a 3×3 VCSEL array with (a) cross section of cell (1,1) and (b)current flow path.

The cell junction temperature T_{ij} of the cell (i, j) in the 3×3 VCSEL array can be expressed as:

$$T_{ij} = T_{rij} + T_0 = R_{ij}(P_{Lij} + P_{Qij}) + T_0 \tag{1}$$

where the T_{rij} is the temperature rise and T_0 represents the ambient temperature of 25 °C, R_{ij} is the thermal resistance. P_{Lij} and P_{Qij} are represent linear power dissipation and quadratic power dissipation, respectively. The current I_{ij} can be expressed as:

$$I_{ij}(l) = \begin{cases} \left(\dfrac{I'_{ij} r_w^2 (1 + I'_{ij} / I_{ij})}{\pi[r_w^2 (1 + I'_{ij} / I_{ij}) - l^2]}\right) S'_{ij}, & l \le r_w \\ \left(\dfrac{I''_{ij} r_w^2 (1 - I''_{ij} / I_{ij})}{\pi\left\{l^2 - r_w^2 [1 - I''_{ij} / I'_{ij}]\right\}}\right) S''_{ij}, & l > r_w \end{cases} \tag{2}$$

where I'_{ij} and I''_{ij} is radial current components in the region of $l \leq r_w$ and $l > r_w$ respectively. S'_{ij} and S''_{ij}represents the area of the cell (i, j) in the region of $l \leq r_w$ and $l > r_w$ respectively. The optical output power P_{Oij} can be expressed as:

$$P_{Oij} = \frac{(I_{ij} - I_{thij}) E_L(T_{ij}) \eta_i(T_{ij}) a_m^T(T_{ij})}{q[\alpha_i\left(T_{ij}\right) + \alpha_m^T\left(T_{ij}\right) + \alpha_m^B(T_{ij})]}, I_{ij} > I_{thij} \tag{3}$$

where $\eta_i(T_{ij})$ represents internal quantum efficiency, $E_L(T_{ij})$ is the laser photon energy, $\alpha^T{}_m(T_{ij})$ and $\alpha^B{}_m(T_{ij})$ are the transmission loss rates through the top and bottom DBRs, respectively, I_{ij} is the bias current and I_{thij} is the lasing threshold current, $\alpha_i(T_{ij})$ is the internal optical loss rate.

The temperature profile of the 3×3 VCSEL array (array-1) is shown in Fig. 2(a). Due to the symmetry of the device structure, those with the same distance from the center of VCSEL array can be divided into three groups, as shown in the Fig. 2(b). The current density of the three groups cells of the array-1 shows a non-uniform distribution with low middle and high edge, which is shown in Fig. 3.

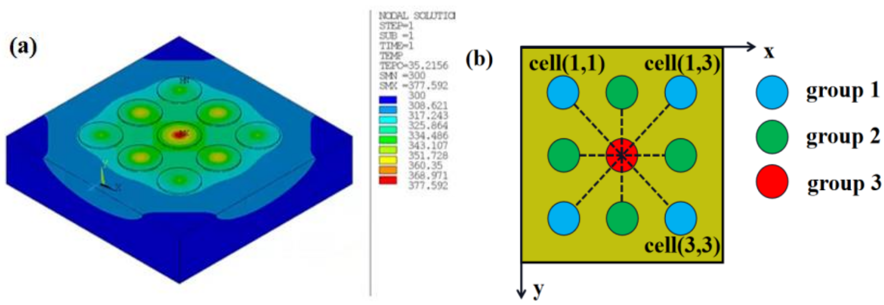

Fig. 2. (a) Temperature profile and (b) three groups cells of the array-1.

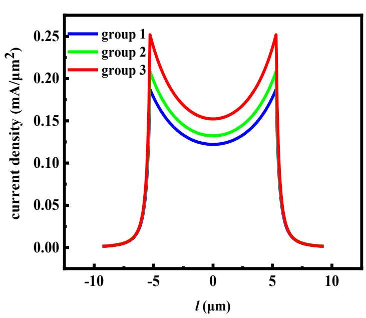

Fig. 3. Current density distribution of the array-1.

3 Non-uniform oxidation aperture distribution design and analysis

In order to improve the thermal problem caused by current crowding effect in VCSEL arrays, the influence of non-uniform oxidation aperture design on current crowding effect is studied. The oxidation aperture of the central cell is reduced to 3.3μm, and the oxidation aperture of the surrounding cell is still 5.3μm(array-2). The temperature profile is shown in Fig. 4(a).

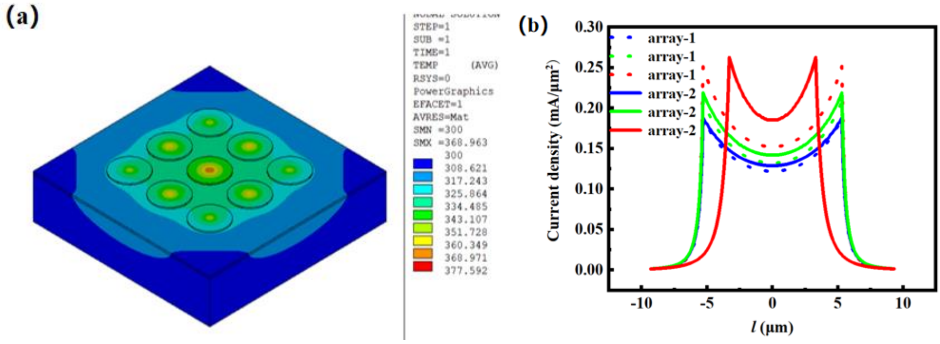

Fig. 4. (a) Temperature profile and (b) current density distribution of array-2.

With the aid of the electro-optical-thermal model, the current density of array-1 and array-2 is calculated, which is shown in Fig. 4(b). Take the group 3 as an example, it can be seen that the current densities at the edge and center of the active region in array-2 are 0.252 and 0.183 mA/μm^2, respectively, the current density difference is lower by 0.028 mA/μm^2. Therefore, reducing the oxidation aperture of the central cell from 5.3μm to 3.3μm is helpful to improve the uniformity of the current density distribution with an improvement of 28.87%.

Due to the oxidation aperture is reduced, the time required for the current to flow from the electrode to the center of the laser becomes shorter, ultimately resulting in a smaller difference in current density between the edge and center positions of the active region, and improving the current crowding effect.

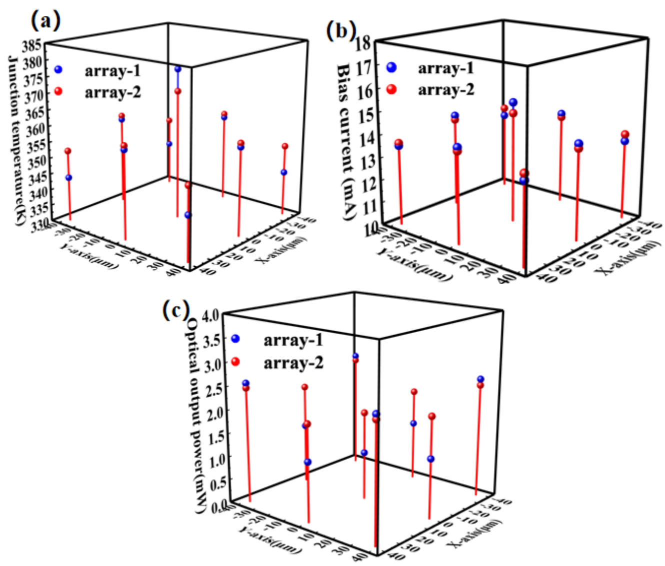

Fig. 5. Comparison of (a)current density distribution (b) temperature distribution and (c) optical output power distribution between array-1 and array-2**.**

Furthermore, the junction temperature distribution of the two types of VCSELs are also compared in Fig. 5(a). VCSEL with non-uniform oxidation aperture has the lower peak junction temperature of 370.11K, which is lowered by 6.73K when compared with the uniform one. The junction temperature distribute of array-2 is more uniform than array-1, which is improved by 36.52%.

The bias current distribution of VCSEL with uniform oxidation aperture and non-uniform oxidation aperture are shown in Fig. 5(b). Cleary, for VCSEL with the non-uniform oxidation aperture , the peak current is lowered by 0.47mA and the maximum current diffenence is only 1.06mA, which is improved by 42.08% when compared with the VCSEL with the uniform oxidation aperture.

A direct comparised of the optical output power distribution in VCSELs with uniform oxidation aperture and optimized non-uniform oxidation aperture are shown in Fig. 5(c), which shows the peak optical output power is lowered by 0.87mW, and the maximum optical output power difference is improved by 61.39%.

4 Device fabrication and experiment

VCSEL arrays with different oxidation aperture designs (including array-1, array-2) are fabricated, and the micrographs of the two types VCSEL arrays are shown in Fig. 6(a) and (b), respectively, both two types of the VCSELs have the same vertical structure.

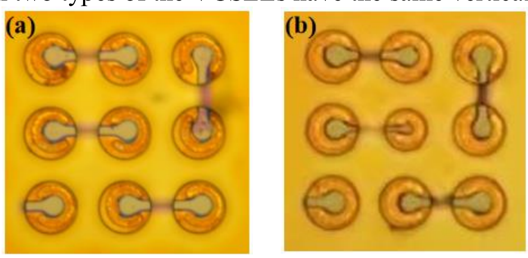

Fig. 6. Microscope images of (a) array-1, (b) array-2.

Furthermore, the simulated L–I–V curves with the experimental data are also presented for comparison, and shown in Fig. 7. The simulated total optical output power of two types of devices matches well with the measured data, and at the same time, the peak total optical output power on array-2 is higher than that on array-1, verifying the validity of the non-uniform oxidation aperture design in improving the current crowding effect presented in this paper. All the VCSEL arrays presented increasing total optical output power and then decreasing as the total bias current increased.

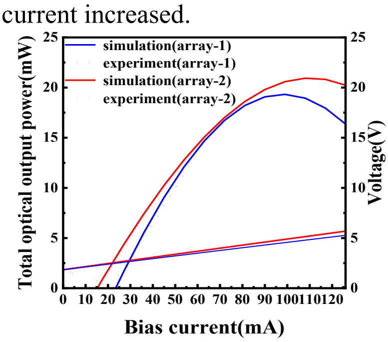

Fig. 7. Measured and simulated L–I–V curves for two types of VCSEL arrays (array-1, array-2).

5 Conclusion

With the aid of a compact electro-opto-thermal model of 2-D VCSEL arrays considering the current crowding effect in each array cell, the non-uniform oxidation aperture design of VCSEL array is studied numerically and experimentally to improve the current crowding effect. For VCSEL array with 3×3 cells, reducing the oxidation aperture of the central cell from 5.3μm to 3.3μm is helpful to improve the uniformity of the current density distribution with an improvement of 28.87%. At the same time, all of the uniformity of the temperature distribution, bias current distribution, and optical output power distribution in the VCSEL array is improved by 36.52%, 42.08%, and 61.39%, respectively. Experimental results show that the improvement of current crowding effect with non-uniform oxidation aperture design in 2-D VCSEL arrays can enhance the total optical output power effectively over a wide bias current range.

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