Improvement of thermally induced current bifurcation in VCSEL arrays with non-uniform series resistance design

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Abstract. Non-uniform series resistance design of VCSEL arrays is studied to improve thermally induced current bifurcation based on an electro-opto-thermal model of VCSEL arrays. Taking an 850nm VCSEL array with 4×4 cells for example, the impact of series resistance on current bifurcation is investigated. Increasing series resistance is helpful to enhance the critical current values of current bifurcation point (I_{rc}) and hence delay the current bifurcation phenomenon. For VCSEL array with non-uniform series resistance, I_{rc} is increased by 28.6% and the total output optical power is enhanced by 14.3% when compared with that of VCSEL array with uniform series resistance. Therefore, non-uniform series resistance design is a better method for delaying the current bifurcation phenomenon and enhancing the output optical power of VCSEL arrays.

1 Introduction

Vertical cavity surface emitting laser (VCSEL) is a widely used semiconductor laser due to their significant advantages, such as single longitudinal mode output, low threshold current, small device structure, easy to two-dimensional integration [1-4]. With the development of long-distance communication and laser phased array radar in recent years, higher requirements are putting forward for the optical output power of laser and the parallel output of beam array [5-6]. However, as the increasing number of cells in VCSEL arrays to reach higher optical output power, the electro-opto-thermal characteristic is more intricate. The temperature, injection current and output optical power distribution are governed by thermal coupling between individual cells. It leads to a non-uniform injection

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current distribution among multiple cells, which in turn can lead to electro-opto-thermal instability where the hottest cell drains most of the current from the other cells, and hence restraining the optical output performance of the VCSEL arrays. The point at which this occurs is commonly known as the bifurcation point and the phenomenal is called current bifurcation. [7-10]. Therefore, how to study and restrain the effects of thermally induced current bifurcation in VCSEL arrays has become one of the key issues to be solved.

In this paper, Non-uniform series resistance design of VCSEL arrays is studied to improve thermally induced current bifurcation based on an electro-opto-thermal model of VCSEL arrays. Taking an 850nm VCSEL array with 4×4 cells as an example, VCSEL array with non-uniform series resistance distribution are designed to govern the injection current distribution of VCSEL array with 4×4 cells. It is proved that non-uniform series resistance design is a feasible method to delay the thermally induced current bifurcation, which not only improving the non-uniformity of the distribution of the peak junction temperature and the injection current, but enhancing the total optical power of VCSEL arrays.

2 Electro-opto-thermal model

Before designing the non-uniform series resistance distribution, an electro-opto-thermal model is requested to predict the injection current, output optical power and junction temperature profile of the VCSEL array [11]. The schematic device structure of a VCSEL array with 4×4 cells is shown in Fig. 1(a), including P-type electrode, SiO_2 layer, p-type doping distributed Bragg reflectors (P-DBR), oxide confined layer, active region, n-type doping distributed Bragg reflectors (N-DBR), GaAs substrate and N-type electrode. R = 20μm, r = 5μm, and d = 100μm are the radius of cylindrical mesas, the radius of lasing area, and the spacing of two adjacent cells, respectively.

The injection current $I_{\rm rij}$ of the cell (i, j) in the 4×4 VCSEL array can be expressed as

$$I_{\rm rij} = I_{\rm s} \exp\left[q(V_b - V_{\rm ij}) - 1 \right] \big/ kT_{\rm ij} \tag{1}$$

where $I_{\rm s}$ is the saturation current, $V_{\rm b}$ is the bias voltage, $V_{\rm ij} = I_{\rm rij} \times R_{\rm ij}$ is the voltage drop caused by series resistance $R_{\rm ij}$, q is the electronic charge and k is the Boltzmann constant. $T_{\rm ij}$ is the peak junction temperature of the cell (i, j). The total injection current $I_{\rm rt}$ is the sum of the injection currents of each cell in the VCSEL array.

The peak junction temperature $T_{\rm ij}$ can be expressed as

$$T_{\rm ij} = T_0 + R_{\rm Tij} P_{\rm Tij} = T_0 + R_{\rm Tij}\left(P_{\rm Lij} + P_{\rm Qij} \right) \tag{2}$$

where the ambient temperature T_0 represents the ground-referenced thermal voltage, $R_{\rm Tij}$ is the thermal resistance and $P_{\rm Tij}$ is the power dissipation (including linear power dissipation $P_{\rm Lij}$ and quadratic power dissipation $P_{\rm Qij}$). $P_{\rm Qij}$ is the power dissipated across $R_{\rm ij}$ and $P_{\rm Lij}$ is composed of 4 power dissipation mechanisms including carrier leakage ($P_{\rm leij}$), carrier thermalization ($P_{\rm thij}$), internal optical loss ($P_{\rm abij}$), and spontaneous carrier recombination ($P_{\rm reij}$). The total power $P_{\rm ij}$ can be expressed as $P_{\rm ij} = P_{\rm Tij} + P_{\rm Oij}$.

The output optical power $P_{\rm Oij}$ can be expressed as

$$P_{\rm Oij} = \frac{\eta_{\rm i}(T_{\rm ij})[I_{\rm rij} - I_{\rm th}(T_{\rm ij})]\alpha_{\rm m}^{T}(T_{\rm ij})}{\alpha_{\rm m}^{T}(T_{\rm ij}) + \alpha_{\rm m}^{B}(T_{\rm ij}) + \alpha_{\rm i}(T_{\rm ij})} \left(\frac{hc}{q\lambda(T_{\rm ij})} \right) \tag{3}$$

where $I_{th}(T_{ij})$ is the threshold current, $\eta_i(T_{ij})$ is the internal quantum efficiency, $\alpha_i(T_{ij})$ is the cavity loss, $\lambda(T_{ij})$ is the emission wavelength of the fundamental mode, $\alpha_m^T(T_{ij})$ and $\alpha_m^B(T_{ij})$ are the light loss through the top and bottom DBR, h is the Planck constant, c is the speed of light, respectively. And the total output optical power P_{Ot} is the sum of the output optical power of each cell in the VCSEL array.

Due to the symmetrical distribution of VCSEL cells, those with the same distance from the center of VCSEL array can be divided into 3 groups, as shown in the Fig. 1(b) and Table 1.

The electrical and optical model is established with MATLAB, which has considered the temperature dependencies of injection current and output optical power of each array cell mentioned above. As a result, the electro-opto-thermal model is established on the iterative solution between ANSYS and MATLAB.

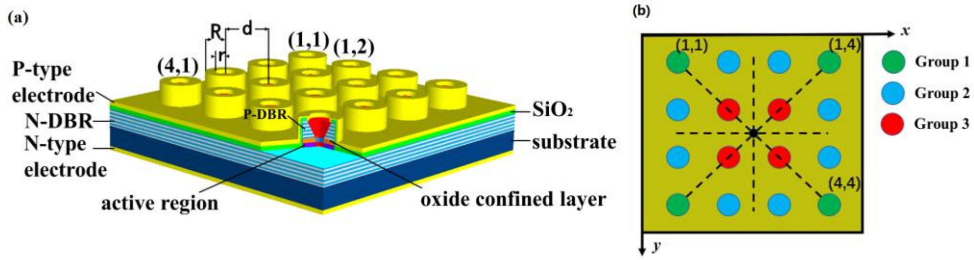

Fig. 1. (a) Schematic device structure of VCSEL array with 4×4 cells and (b) Schematic diagram VCSEL array grouping.

Table 1. VCSEL array grouping.

Group number	Cell number
Group 1	(1,1), (1,4), (4,1), (4,4)
Group 2	(1,2), (1,3), (2,1), (2,4), (3,1), (3,4), (4,2), (4,3)
Group 3	(2,2), (2,3), (3,2), (3,3)

3 Non-uniform series resistance distribution design and analysis

For a 4×4 VCSEL array with uniform series resistance distribution (array-A), each array cell (i, j) has the same series resistance R_{ij} = 150Ω. Improvement of thermally induced current bifurcation of the VCSEL array is designed by non-uniform series resistance to adjust the injection current distribution of the VCSEL array cell. The series resistance of cells from group 1 remain constant. The series resistance of cells from group 2 and group 3 are $R_{12} = R_{13} = R_{21} = R_{24} = R_{31} = R_{34} = R_{42} = R_{43}$ = 160Ω and $R_{22} = R_{23} = R_{32} = R_{33}$ = 170Ω, respectively.

With the aid of the electro-opto-thermal model, the injection current and total output optical power varies with Irt of 4×4 VCSEL array with uniform series resistance distribution (array-A) and non-uniform series resistance distribution (array-B) is extracted as shown in Fig. 2. Due to tiny process variations between the VCSEL cells in array-A, Irij of group 3 is slightly higher than that of other cells and all of them are increased linearly as Irt increases. The critical current values of current bifurcation point of array-A is Irc = 224mA, then Irij of cells in group 3 increase rapidly, and other cells decrease dramatically after current bifurcation. However, since non-uniform series resistance distribution has been introduced in array-B, the injection current of each cell are proportionally distributed at the beginning of operation. The current difference between the cells in group 3 and other cells of array-B is less than that of array-A, and the current bifurcation is delayed by 64mA based on the design of non-uniform series resistance distribution. The Irc of array-B is increased by 28.6% compared with that of array-A.

Cells in array-A group 3 drains most of the current and leads to thermal rollover firstly, which is caused by a rapid reduction of the internal quantum efficiency at high injection current, and results in drastically collapse of output optical power of array-A. The thermal rollover of cells in array-B group 3 occurs at a larger total injection current in comparison with array-A based on the design of non-uniform series resistance distribution. The total output optical power P_{Ot} of array-B reaches saturation at I_{rc} = 288mA, and it is 21.82mW higher and increased by 14.3% compared with that of array-A.

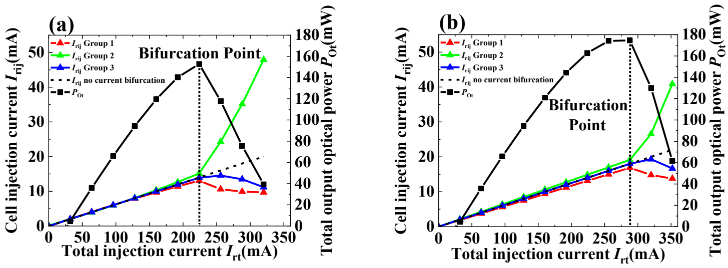

Fig. 2. Injection current I_{rij} and total output optical power P_{Ot} varies with I_{rt} of 4×4 VCSEL arrays with (a) uniform series resistance distribution (array-A) and (b) non-uniform series resistance distribution (array-B).

The junction temperature profile of two types of 4×4 VCSEL arrays under the total injection current I_{rt} = 256mA is shown in Fig. 3. The non-uniform series resistance distribution of array-B leads to a more uniform junction temperature profile than array-A. Although the peak junction temperature of the cells from group 1 and 2 increase slightly, the maximum peak junction temperature difference is significantly reduced by 68% compared with that of array-A.

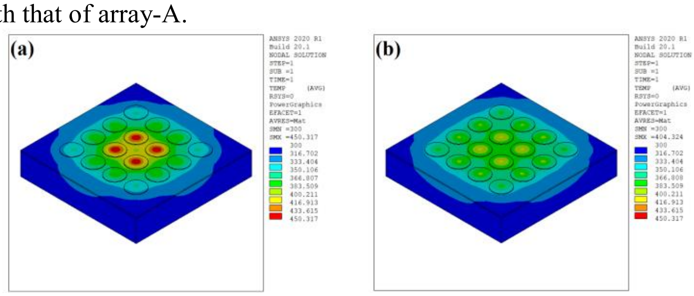

Fig. 3. The junction temperature profile of 4×4 VCSEL arrays with (a) uniform series resistance distribution (array-A) and (b) non-uniform series resistance distribution (array-B).

The I_{rij} profile of two types of 4×4 VCSEL arrays under the total injection current I_{rt} = 256mA is shown in Fig. 4(a). The non-uniform series resistance distribution regulates the cell injection current distribution of array-B, the maximum cell injection current difference is significantly reduced by 85.3% compared with that of array-A. The output optical power profile of two types of VCSEL arrays under the total injection current I_{rt} = 256mA is shown in Fig. 4(b). Array-B is more uniform in both junction temperature and injection current profile in comparison with array-A, due to the design of non-uniform series resistance distribution. Therefore, the cell output optical power of array B is not only more uniform but also higher than that of array A. The maximum cell output optical power difference is significantly reduced by 76.8% compared with that of array-A.

With the design of non-uniform series resistance distribution in the VCSEL arrays, the injection current difference and peak junction temperature difference between the cells of the VCSEL array can be explicitly regulated, the thermally induced current bifurcation effect of the VCSEL array can be effectively restrained, and the total output optical power of the VCSEL array can be greatly improved.

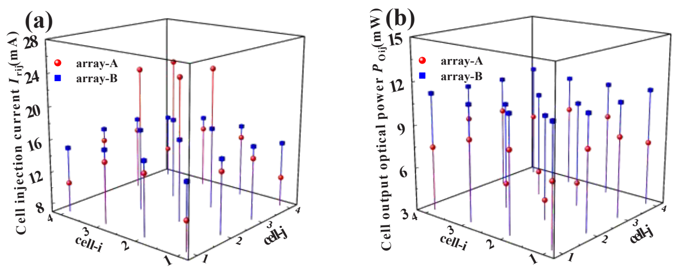

Fig. 4. (a)The injection current and (b) output optical power profile of 4×4 VCSEL arrays with uniform series resistance distribution (array-A) and non-uniform series resistance distribution (array-B).

4 Conclusion

Thermally induced current bifurcation of VCSEL arrays with 4×4 cells are simulated and studied based on an electro-opto-thermal model. With the aid of the non-uniform series resistance design, thermally induced current bifurcation in VCSEL arrays is improved by controlling the injection current profile of VCSEL array cells. It is shown that, for VCSEL array with non-uniform series resistance, I_{rc} is increased to 288mA with an improvement of 28.6% when compared with that of VCSEL array with uniform series resistance. At the same time, the total output power of the array is also increased by 14.3%. Therefore, the non-uniform series resistance design is a feasible method to improve the thermally induced current bifurcation of VCSEL arrays.

References

1. T. Katayama, D. Hayashi and H. Kawaguchi, PTL, **28**, 2062 (2016)
2. A. Pissis, E. Duda, S. Tirelli, Ur. Siegenthaler, D. Quandt, D. Bonfrate, P. Das Kanungo, M. Spieser, E. Zibik, PTL, **35**, **7** (2023)
3. J. -C. Shih, Z. Khan, Y. -H. Chang and J. -W. Shi, J-STQE, **28**, 1 (2022)
4. D. Guo, C. Liu, J. Chen, J. Chramowicz, D. Gong, H. He, S. Hou, T. Liu, A. Prosser, P. Teng, A. C. Xiang, L. Xiao, J. Ye, NUCL INSTRUM METH A, 831, 276 (2016)
5. S. Zhuo, Y. Wang, T. Xia, Y. Wu, W. Zheng, M. Sun, Z. Lin, P. Yin Chang, IEEE T. CIRCUITS-II, **70**,2 (2023)
6. G. Pan , M. Xun , Y. Sun , Z. Zhao , C. Xu , Y. Xie , D. Wu , J. Zhou, Opt Laser Technol, **149** (2022)
7. P. P. Baveja, B. Kögel, P.r Westbergh, J. S. Gustavsson, A. Haglund, D. N. Maywar, G. P. Agrawal, and A. Larsson, OPT EXPRESS, **19**, 16 (2011)
8. L. La Spina, N. Nenadovic, V. d'Alessandro, F. Tamigi, N. Rinaldi, L.K. Nanver, J.W. Slotboom, Solid State Electron, **50**, 5 (2011)
9. K. Lu and C. M. Snowden, IEEE T ELECTRON DEV, **43**, 11 (1996)
10. S. J Gillgrass, C. P Allford, T. Peach, J. Baker, A. D Johnson, J I Davies, A. M Joel, S. Shutts and P. M Smowton, J. Phys. D, 56, 15 (2023)
11. D. Jin, S. Yang, F. Zhang, L. Wu, B. Guan, Y. Yang, and W. Zhang, T-ED, **69**, 7 (2022)