Data Article

A representative dataset of the self-reproducing light ray family between the multiple distributed Bragg reflectors of multiple VCSELs and the inner surface of plane-convex mirror

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A B S T R A C T

A system consisting of a plano-convex mirror and reflecting surfaces of Vertical Cavity Surface-Emitting Laser (VCSEL) Strip Array of Diode Lasers has been calculated and proved to have a self-reproducing ray sink in it. The initial positions and slopes of two representative groups of light rays are set, and the position and slope of each light ray at each Distributed Bragg Reflector (DBR) of Diode lasers are obtained by computation. The system is a folded resonator, every VCSEL is connected by the axis of the resonator, and this axis is formed by linking the correspondent reflective points on the inner spherical surface of the mirror and the reflective points on the Bragg mirrors. One approach could be to fabricate the array directly on a plane of a GaAs (or Si) plano-convex mirror. The resonator can contain many VCSELs, and therefore can afford a high quality laser beam and high-power output.

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Specifications Table

| Subject                  | Optics                                                                 |
|--------------------------|------------------------------------------------------------------------|
| Specific subject area    | The subject area is the output power and beam quality improvement of the |
|                          | vertical cavity surface-emitting array of Diode lasers [1–7].          |
| Type of data             | Table                                                                   |
| How data were acquired   | Based on Multiple-pass cell (MPC) theory [8], Matrix Optics theory [9], |
|                          | and some initial assumptions, these data are obtained by computation.   |
| Data format              | Raw                                                                     |
| Parameters for data collection | The machining accuracy of the plane-convex reflective mirror is reasonably assumed to be in the range of ±0.004mm. The number of round trips of a light ray in the MPC, which is a folded cavity equipped with a VCSEL array, is decided by the refractive index $n_1$ and the thickness $d$ of the plane-convex reflective mirror, the radius of curvature $\rho_2$ of convex surface of the plane-convex mirror, and the refractive index $n_3$ of VCSEL. Since the thickness $b$ of each VCSEL is totally negligible, the positions of reflection points are decided by $\rho_2$ and $d$. |
| Description of data collection | The light ray data described by this paper is computed by using the equations (1)–(3) in “Data Description” section. The initial beam is the line which matches the axial beam characteristic of the resonator. Based on the propagation equation of the light in the folded cavity and the connection equation between the mirror and the laser medium, the positions and slopes of the initial light ray at each VCSEL and the return to the starting point are calculated. |
| Data source location     | Institution: Sichuan University                                         |
|                          | City: Chengdu                                                           |
|                          | Country: China                                                         |
| Data accessibility       | With the article                                                       |
| Related research article | Yude Li, Zheng Li, Mei Chen, Jinglun Liu, Folded Resonators of Vertical Cavity Surface-emitting Stripe Array of Diode Laser, Optics and Laser Technology, DOI: 10.1016/j.optlastec.2021.106990. |

Value of the Data

- VCSEL has good beam quality but its output power is very low. Either series or parallel connection of multiple VCSELs is an effective solution of this problem [1–7]. The data in this paper provide the basis for the solution based on the series connection of VCSELs, and therefore also provide the basis for the development of the VCSEL array with high quality and high output power. Some interesting results may be obtained from the light ray data in Table 1. Assume that the number of VCSELs is $2n_0 + 1$, where $n_0\theta = 90^\circ$ and $\theta$ is decided by $\rho_2$ and $d$ (see the explanation in field “Parameters for data collection” in the specification table). For the case in Table 1, since $\theta = 15^\circ$, we have $n_0 = 6$. In a general case, the folded cavity can contain more VCSELs if $\theta$ is smaller. However, the beam quality affected by VCSELs should be taken into account [1].
- The semiconductor laser with high quality and high output power developed by using these data may be applied in material processing and remote transmitting.
- According to these data, multiple VCSELs may be arranged as a strip array, and it may be mounted on the plane of the plane-convex mirror, such as the mirror of GaAs or Si, whose refractive index is equal to or approximately equal to that of VCSEL.

1. Data Description

The VCSELs can avoid emitting through the cleavage plane, which causes the lateral lasing, and the filamentation. Therefore, the VCSELs have good beam characters, and have no obvious damage property to laser emitting. The output power of VCSEL is very low because of very thin active layer. To overcome this shortcoming of a single VCSEL, in the system consisting of a plano-
Table 1
calculated results of point coordinates and slopes of rays (units: mm, rad).

| Ray | X₀ | X'₀ | R₀ | R'₀ | X₁ | R₁ | X₂ | R₂ | X₃ | R₃ | X₄ | R₄ | X₅ | X₆ | X₇ | X₈ | X₉ | R₉ |
|-----|----|-----|----|-----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| 1   | 0  | 0   | 3  | 0   | 0  | 2.8977 | 0  | 2.5980 | 0  | 2.1213 | 0 |
| 2   | 0  | 2.95 | 0  | 0   | 0  | 2.8494 | 0  | 2.5547 | 0  | 2.0859 | 0 |
| 3   | 0  | 3.05 | 0  | 0   | 0  | 2.9460 | 0  | 2.6413 | 0  | 2.1566 | 0 |
| 4   | 0  | 2.95 | 0   | 0.001 | 0  | 2.8211 | 0  | 2.5000 | 0  | 2.0086 | 0 |
| 5   | 0  | 3.05 | 0   | 0.001 | 0  | 2.9743 | 0  | 2.5980 | 0  | 2.2340 | 0 |
| 6   | 0.1 | 0.001 | 3  | 0   | 0.1249 | 2.8977 | 0.1413 | 2.5980 | 0.1480 | 2.1213 | 0.1447 |
| 7   | −0.1 | −0.001 | 3  | 0   | −0.1249 | 2.8977 | −0.1413 | 2.5980 | −0.1480 | 2.1213 | −0.1447 |
| (1) | 0  | 4.5000 | 0  | 0   | 0  | 4.3465 | 0  | 3.8970 | 0  | 3.1819 | 0 |
| (2) | 0  | 4.4250 | 0   | 0.0015 | 0  | 4.2317 | 0  | 3.7501 | 0  | 3.0129 | 0 |
| (3) | 0  | 4.5750 | 0.0015 | 0  | 0  | 4.4615 | 0  | 4.0441 | 0  | 3.3510 | 0 |

| X₁₀ | R₁₀ | X₁₁ | R₁₁ | X₁₂ | R₁₂ | X₁₃ | R₁₃ | X₁₄ | R₁₄ | X₁₅ | R₁₅ | X₁₆ | X₁₇ | X₁₈ | X₁₉ | X₂₀ | R₂₀ |
|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 1   | 0   | −2.5980 | 0   | −2.8977 | 0   | −3   | 0   | −2.8977 | 0   | −2.5980 | 0 |
| 2   | 0   | −2.5547 | 0   | −2.8494 | 0   | −2.95 | 0   | −2.8494 | 0   | −2.5547 | 0 |
| 3   | 0   | −2.6413 | 0   | −2.9460 | 0   | −3.05 | 0   | −2.9460 | 0   | −2.6413 | 0 |
| 4   | 0   | −2.6094 | 0   | −2.8777 | 0   | −2.95 | 0   | −2.8211 | 0   | −2.5000 | 0 |
| 5   | 0   | −2.5866 | 0   | −2.9177 | 0   | −3.05 | 0   | −2.9743 | 0   | −2.6960 | 0 |
| 6   | −0.0319 | −2.5980 | −0.0682 | −2.8977 | −0.1 | −3   | −0.1249 | −2.8977 | −0.1413 | −2.5980 | −0.1480 |
| 7   | 0.0319 | −2.5980 | 0.0682 | −2.8977 | 0.1 | −3   | 0.1249 | −2.8977 | 0.1413 | −2.5980 | 0.1480 |
| (1) | 0   | −3.8971 | 0   | −4.3465 | 0   | −4.5000 | 0   | −4.3465 | 0   | −3.8970 | 0 |
| (2) | 0   | −3.9142 | 0   | −4.3166 | 0   | −4.4250 | 0   | −4.2317 | 0   | −3.7501 | 0 |
| (3) | 0   | −3.8800 | 0   | −4.3766 | 0   | −4.5750 | 0   | −4.4615 | 0   | −4.0441 | 0 |

| X₂₁ | R₂₁ | X₂₂ | R₂₂ | X₂₃ | R₂₃ | X₂₄ | R₂₄ | X₂₄ | R'₂₄ |
|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 1   | 0   | 2.1213 | 0   | 2.5980 | 0   | 2.8977 | 0   | 3   | 0   |
| 2   | 0   | 2.0859 | 0   | 2.5547 | 0   | 2.8494 | 0   | 2.95 | 0   |
| 3   | 0   | 2.1566 | 0   | 2.6413 | 0   | 2.9460 | 0   | 3.05 | 0   |
| 4   | 0   | 2.1633 | 0   | 2.6094 | 0   | 2.8777 | 0   | 2.95 | 0   |
| 5   | 0   | 2.0793 | 0   | 2.5866 | 0   | 2.8687 | 0   | 3.05 | 0   |
| 6   | −0.0066 | 2.1213 | 0.0319 | 2.5980 | 0.0682 | 2.8977 | 0.1 | 3   | 0.001 |
| 7   | 0.0066 | 2.1213 | −0.0319 | 2.5980 | −0.0682 | 2.8977 | −0.1 | 3   | −0.001 |
| (1) | 0   | 3.1819 | 0   | 3.8971 | 0   | 4.3466 | 0   | 4.5000 | 0   |
| (2) | 0   | 3.2449 | 0   | 3.9142 | 0   | 4.3166 | 0   | 4.4250 | 0   |
| (3) | 0   | 3.1189 | 0   | 3.8800 | 0   | 4.3039 | 0   | 4.5750 | 0   |

(ρ₁ = ∞, ρ₂ = 352.2462506, d = 6.0008333, b = 0.001, η₁ = 1.5, η₂ = 3.6, θ = 15).

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convex mirror and reflecting surfaces of VCSELs, VCSELs can be connected with a folded axis to form a folded cavity laser, thus high beam quality and high power laser output can be obtained. Let \( \rho_2 \) be the radius of curvature of convex surface of the plane-convex mirror, \( d \) be the thickness of the plane-convex mirror, \( \eta_1 \) be the refractive indexes. \( S_0, S_2, S_4 \ldots \) are VCSELs, and their refractive indexes is \( \eta_3 \). Top ends of the VCSELs are placed on the same plane, and the bottom ends (Bragg-mirrors) are placed on a parallel plane. The VCSELs have the same thickness \( b \) and the central lines (x-direction) of the ends are placed at the y-axis, and their centers are placed at \( n(x_n, y_n) \) points: \( 0(0, r_0),1(0, r_1) \ldots n_0(0, r_n_0) \ldots n(0, r_n) \ldots \). \( n_0 \) is emitter number. We note that there are three rays at \( S_0 \) and \( S_24 \) respectively, representing a set of rays that travel from \( S_0 \) to \( S_24 \) and back again, reproducing themselves at \( S_0 \). This shows that there is an oscillatory mode in the cavity. Let \( x_n \) and \( y_n \) be the coordinates of the ray in the plane on the nth round trip, \( x_n' \) and \( y_n' \) be the correspondent ray slopes, \( r_n \) be the ray displacements from the optic axis (o-z), \( r_n' \) be the ray slopes, \( x_0, y_0, x_n' \) and \( y_n' \) be the initial conditions, respectively. When \( x_0 = x_n' = 0 \), we have \( y_0 = r_0 \) and \( y_n' = r_n' \). Then \( r_n \) and \( r_n' \) can be obtained from \( r_0 \) and \( r_0' \) by transformation, namely,

\[
\begin{pmatrix}
\rho_n \\
\rho_n'
\end{pmatrix} = \begin{pmatrix}
A' & B' \\
C' & D'
\end{pmatrix} \begin{pmatrix}
\rho_0 \\
\rho_0'
\end{pmatrix} = \frac{1}{\sin \theta} \begin{pmatrix}
A \sin n\theta - \sin((n-1)\theta) & B \sin n\theta \\
C \sin n\theta & D \sin n\theta - \sin((n-1)\theta)
\end{pmatrix} \begin{pmatrix}
\rho_0 \\
\rho_0'
\end{pmatrix}
\]

where

\[
\cos \theta = \frac{A + D}{2} = 1 - \frac{2}{\rho_2} \left( d + \frac{\eta_1}{\eta_3} b \right)
\]

and

\[
\begin{pmatrix}
A & B \\
C & D
\end{pmatrix} = \begin{pmatrix}
1 - \frac{2}{\rho_2} \left( d + \frac{\eta_1}{\eta_3} \right) & 2(b + d\eta_3/\eta_1) \\
\frac{-2}{\rho_2} \left( \eta_1/\eta_3 \right) & 1 - \frac{2}{\rho_2} \left( d + \frac{\eta_1}{\eta_3} \right)
\end{pmatrix}
\]

When \( \eta_3 \approx \eta_1, b \approx 0 \), we have

\[
\begin{pmatrix}
A & B \\
C & D
\end{pmatrix} = \begin{pmatrix}
1 - \frac{2d}{\rho_2} & 2d \left( 1 - \frac{d}{\rho_2} \right) \\
\frac{-2}{\rho_2} & 1 - \frac{2d}{\rho_2}
\end{pmatrix}
\]

And, when \( b \approx 0 \), we have

\[
\cos \theta = \frac{A + D}{2} = 1 - \frac{2d}{\rho_2}
\]

Correspondingly, the off-axis distance of the incident point of the light at the lower end face of VCSEL \( r_n'' \), and the slope of the light from the upper end face \( r_n'' \). Usually, we have

\[
\begin{pmatrix}
r_n'' \\
r_n'''
\end{pmatrix} = \begin{pmatrix}
1 & 2b\eta_1/\eta_3 \\
0 & 1
\end{pmatrix} \approx \begin{pmatrix}
r_0 \\
r_0'
\end{pmatrix}
\]

(2)

Usually, we have

\[
\begin{pmatrix}
x_n \\
x_n'
\end{pmatrix} = \frac{1}{\sin \theta} \begin{pmatrix}
A \sin n\theta - \sin((n-1)\theta) & B \sin n\theta \\
C \sin n\theta & D \sin n\theta - \sin((n-1)\theta)
\end{pmatrix} \begin{pmatrix}
x_0 \\
x_0'
\end{pmatrix}
\]

(3)

In Table 1, the initial position and slope of two representative groups of light rays are set, and the transmitting and reproducing situations of these light rays in the folded resonator are described by computation results obtained by Eqs. (1)–(3). Moreover, \( X_n \) or \( X_n' \) represents a value in X direction; \( R_n \) or \( R_n' \) represents a value in Y direction, \( \rho_1 \) is the radius of curvature of plane surface of the plane-convex mirror. The parameter \( \theta \) is decided by the formula \( \cos \theta = (A + D)/2 = 1 - 2d/\rho_2 \).
There are 7 light rays in the first group. The initial slope and position of a specific ray (ray 1) are \((X'_0, R'_0) = (0, 0)\) and \((X_0 = 0, R_0 = 3)\), respectively. The incident and reflection points on 13 VCSELs, which are \((X_0, R_0), (X_1, R_1), (X_2, R_2), \ldots\), and \((X_{12}, R_{12})\). These 13 points also represent the centre position of 13 VCSELs. This ray finally goes back to the initial position \((X_{24} = X_0, R_{24} = R_0)\) and repeats the initial slope \((X'_{24} = X'_0 = 0, R'_{24} = R'_0 = 0)\). Therefore, this ray represents the axis of the resonator.

The initial parameters of the other 6 rays in the first group are constrained by the ranges \(X_0 \pm 0.1\) mm, \(X'_0 \pm 0.001\), \(R_0 \pm 0.1\) mm, and \(R'_0 \pm 0.001\). \(\Delta R_n\) and \(\Delta X_n\) denote the \(Y\)-directional and \(X\)-directional distance between the corresponding incident and reflection points of the \(n\)-th ray and those of ray 1 (the axis of resonator). Moreover, \(\Delta R_n\) and \(\Delta X_n\) also represent the \(Y\)-directional and \(X\)-directional size of the corresponding VCSEL.

The second group contains three rays, namely, ray (1), (2), and (3). Different from group 1, ray (1), which is the axis of resonator, is with the initial condition \(R_0 = 4.5\) mm. Consequently, the gap between two centres of neighbouring VCSELs is enlarged by 1.5 times. The requirement for the beam quality should be lowered for this change.

2. Experimental Design, Materials and Methods

The experimental design described here is a couple of assumptions for data computation in Table 1. Based on MPC theory [8], Matrix Optics theory [9], and the following assumptions, the data in Table 1 are computed by Eqs. (1)–(3). The fundamental theory about these two formulas can also be found in references [10,11].

Assume that a striped plane-convex mirror is made by optical glass. The length, width, and thickness of the mirror are 6.6 mm, 3 mm, 6.00083 mm, respectively. The radius of curvature of the convex surface is 352.246250 mm. A total reflection film is added to either convex or plane surface of the mirror, the only transparent part of the mirror is a strip whose distance from the centre is 3 mm and the valid range is \(\pm 50\) μm. Let a fine visible light beam be the incident beam at the transparent region, and let the incident direction be parallel to the mirror axis. Moreover, assume that the divergence angle of this light beam is very small. By 24 round trips in the plane-convex mirror, this light beam go back to the initial incident position. However, the realization of pattern-matching between the incident beam and the plane-convex mirror is both difficult and normal.

Assume that a striped plane-convex mirror is made by GaAs semiconductor crystal materials. The length, width, and thickness of the mirror are 66 mm, 3 mm, 6.00083 mm, respectively. The radius of curvature of the convex surface is 352.246250 mm. Let the length of a VCSEL be 100 μm, and let the width range of a VCSEL be 30 ~ 60 μm. A VCSEL is mounted on the centre point of the centre line (Y-axis) of the striped plane. Furthermore, on the centre line of the striped plane, 12 such VCSELs are mounted on the points whose offsets from the centre point are \(\pm 0.77\) mm, \(\pm 1.5\) mm, \(\pm 2.12\) mm, \(\pm 2.59\) mm, \(\pm 2.89\) mm, and \(\pm 3\) mm, respectively. The fully reflection surface of each VCSEL is maintained, but the side which touches the striped plane is antireflective. On the touched point, the striped plane is transparent, but any other positions on the striped plane is fully reflective. The striped VCSEL array is easy to work under the stable conditions, because the machining accuracy of the plane-convex mirror reaches the wavelength magnitude, the application temperature is in the application temperature range of VCSEL, the lateral structure of VCSEL has concentration effect, and the optical amplification of the VCSEL array is significant.

Ethics Statement

All authors listed on the paper confirm that the content of this paper is entirely original and that neither this paper nor any of its essential components have been published previously or submitted to another journal.
CRediT Author Statement

Yude Li: Conceptualization, Methodology, Writing- Original draft preparation; Zheng Li: Conceptualization, Methodology, Computation, Writing - original draft preparation, Writing - reviewing and editing; Mei Chen: Methodology, Supervision, Writing - reviewing and editing; Jinglun Liu: Methodology, Computation, Writing - reviewing and editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships which have or could be perceived to have influenced the work reported in this article.

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