A Comparative Study of Modal Properties of Surface-Emitting Circular Bragg Micro-Lasers

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Abstract: Modal properties of two types of surface-emitting circular Bragg micro-lasers (CBMLs) are compared. Disk CBMLs are suitable for low-threshold, high-efficiency, ultracompact laser design, while ring CBMLs are an excellent candidate for high-efficiency, large-area, high-power applications.

Keywords: Surface-emitting lasers; Semiconductor lasers; Bragg lasers; Modal property; Integrated optoelectronics

1. INTRODUCTION

Surface-emitting lasers with a circular emission aperture are particularly useful in optical communications because they can produce circularly-symmetric, narrow-divergence laser beams [1-3]. With optical gain, circular Bragg micro-resonators can be engineered for such applications – the radial Bragg reflector not only provides feedback for the in-plane fields but also couples the laser radiation out of the plane vertically. The lasers based on such circular Bragg resonance are referred to as circular Bragg micro-lasers (CBMLs).

Similar to the circular resonators, the CBMLs can be classified into two configurations: disk- and ring- CBMLs. As shown in Fig. 1, disk CBML has a center disk surrounded by a radial Bragg grating extending from \( x_0 \) to \( x_b \). Ring CBML has an annular defect surrounded by inner and outer gratings which extend, respectively, from the center to \( x_R \) and from \( x_L \) to \( x_b \). In this paper we compare their modal properties such as modal field pattern, threshold gain, detuning factor, and far-field pattern. In order to demonstrate their advantages as surface-emitting lasers, circular DFB laser will be introduced as a reference in comparing the quality factor, emission efficiency, and modal area.

2. COMPARISON OF MODAL PROPERTIES OF SURFACE-EMITTING CBMLS

The characteristic equations which govern the laser modes were derived in [4] by resonance condition theory:

\[
e^{i(x-x_0)\delta}v\sinh[S(x_i-x_0)] - \sinh[S(x_i-x_0)]S\cosh[S(x_i-x_0)] = 1 \quad \text{for disk CBML,}
\]

\[
e^{i(x-x_0)\delta}v\sinh[S(x_i-x_0)]v\sinh[S(x_i-x_0)] - \sinh[S(x_i-x_0)]S\cosh[S(x_i-x_0)]
\]

\[
\left[(u-v-i\delta)\sinh[S(x_i-x_0)] + S\cosh[S(x_i-x_0)]\right] \times \left[-(u-v-i\delta)\sinh[S(x_i)] + S\cosh[S(x_i)]\right] = 1 \quad \text{for ring CBML.}
\]

Table I

<table>
<thead>
<tr>
<th>Laser type</th>
<th>Disk CBML</th>
<th>Ring CBML</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mode 1</td>
<td>( g_4 = 0.127 )</td>
<td>( g_4 = 0.457 )</td>
</tr>
<tr>
<td>Mode 2</td>
<td>( g_4 = 0.288 )</td>
<td>( g_4 = 1.06 )</td>
</tr>
<tr>
<td>Mode 3</td>
<td>( g_4 = 0.454 )</td>
<td>( g_4 = 1.92 )</td>
</tr>
<tr>
<td>Mode 4</td>
<td>( g_4 = 0.690 )</td>
<td>( g_4 = 3.14 )</td>
</tr>
<tr>
<td>Mode 5</td>
<td>( g_4 = 1.21 )</td>
<td>( g_4 = 4.09 )</td>
</tr>
</tbody>
</table>

2.1. MODAL FIELD PATTERNS, THRESHOLD GAINS (\( g_4 \), IN UNIT OF \( 10^{-3} \)), AND FREQUENCY DETUNING FACTORS (\( \delta \), IN UNIT OF \( 10^{-7} \)) OF THE DISK CBML AND RING CBML WITH EXTERIOR BOUNDARY RADIUS \( x_b = 200 \)

Fig. 2. Far-field intensity patterns of the fundamental modes of disk CBML and ring CBML (both with \( x_b = 200 \)).

In the left equations, \( g_4 \) is the gain coefficient, \( \delta = (\beta_{\text{design}} - \beta)\beta \) is the frequency detuning factor, where \( \beta \) is the in-plane propagation constant. \( u \) and \( v \) are defined as \( u = g_4 - h_1 \), \( v = h_1 \).
Table I for devices with a larger size \((x_0, y_0)\). As seen from comparison, only the disk- and ring-CBMLs achieve high emission efficiencies. This is because their fundamental modes are bandgap modes while that of the circular DFB laser is an in-band mode.

The effective modal area in a 2-D case is defined as

\[ A_{\text{eff}} = \left\{ \int_{x=0}^{x=x_b} \int_{\beta=0}^{\beta=2\pi} |\mathbf{E}|^2 \, d\beta \, dx \right\} / \max \{ |\mathbf{E}|^2 \}, \]

where \(x\) and \(\beta\) are radial and angular coordinates, respectively. It is a measure of how the modal field is distributed in the laser. Plotted in Fig. 3(c), the modal area of the disk CBML was found to be the smallest. This is not surprising and can be inferred from their unique modal profiles listed in Table I. Actually our prior experimental work has demonstrated single-mode lasing with ultrasmall modal volume in a nanosized disk CBML fabricated in InGaAsP [3]. Clearly, a disk configuration is preferable in ultracompact laser design. Alternatively, ring CBMLs have a large modal area with high emission efficiency, rendering them suitable for high-efficiency, high-power, large-area laser applications.

3. CONCLUSIONS

By comparing the modal properties of disk- and ring-CBMLs, we demonstrated their advantages as surface-emitting lasers and concluded that disk CBMLs are most useful in low-threshold, high-efficiency, ultracompact laser design, while ring CBMLs are excellent candidates for high-efficiency, high-power, large-area lasers.

REFERENCES


