Mode analysis of Oxide-Confined VCSELs using near-far field approaches

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We analyze the transverse mode structure of selectively oxidized vertical cavity surface emitting lasers (VCSELs) in the 850 nm spectral region using both near and far field approaches. The relatively strong index guiding devices show a noticeable reduction of the spot size whereas weak index guiding devices show large spot size. Also, we report a study on the butt-coupling efficiency of these devices using flat-cut uncoated single mode fibers (SMF) with different core diameters. The large core SMF diameter \( D_F = 8.3 \, \mu m \) for standard 1300 nm wavelength data transmission require a simple filter to reduce the contribution of the excited higher order fiber modes.

1. Introduction

In recent years the performance of vertical-cavity surface-emitting semiconductor lasers (VCSELs) has advanced. Using \( \mathrm{Al}_2\mathrm{O}_3 \) layers for fabrication, low threshold currents [1] and high efficiencies have been achieved [2]. The high index semiconductor surrounding the low index dielectric oxide material forms a lens-like element. This lens can partially compensate for the diffraction of the mode in the spacer regions and DBR’s. In this paper, we present the Near Field (NF) and Far Field (FF) approaches that study the fundamental mode confinement of 850 nm VCSELs in which the oxide layer has different positions from the active layer and the node of the standing wave pattern.

2. Device Structure and Output Characteristics

The lasers studied are designed for emission near 850 nm wavelength, where the one wavelength thick inner cavity contains three active quantum wells, each has 8 nm thick GaAs separated by 10 nm \( \mathrm{Al}_{0.2}\mathrm{Ga}_{0.8}\mathrm{As} \) barriers, surrounded by carbon doped p-type \( \mathrm{Al}_{0.9}\mathrm{Ga}_{0.1}\mathrm{As}-\mathrm{Al}_{0.2}\mathrm{Ga}_{0.8}\mathrm{As} \) and silicon doped n-type \( \mathrm{AlAs}-\mathrm{Al}_{0.2}\mathrm{Ga}_{0.8}\mathrm{As} \) quarter wavelength Bragg reflector stacks. Lateral current confinement is achieved by selective wet oxidation of a single 30 nm thick AlAs layer embedded in a quarter wavelength layer, three mirror periods from the active region for sample A, and directly above the active region for sample B. Evaporation of TiPtAu ring contacts on the top side and GeNiAu on the bottom side is the final process of fabrication. Using the one-dimensional transfer matrix method [3] in such VCSEL structure we could determine the electric field amplitude and the wavelength detuning \( \Delta \lambda_{ox} \) due to presence of oxide layer. Also, we used the formula \( \Delta n_{eff} = n_{eff} \cdot \Delta \lambda_{ox} / \lambda_0 \) to determine the effective cavity index \( \Delta n_{eff} \) in relation to the wavelength detuning \( \Delta \lambda_{ox} \), the effective cavity index \( n_{eff} \) and the wavelength in the absence of the oxide layer \( \lambda_0 \). The position of the oxide layer is adjusted to be a small step far away from the node of the electric field for sample A, see Fig. 1 and for sample B to lie exactly in the node as shown in Fig. 2. The results indicate that the effective cavity index of sample A is five times larger than that of sample B and the latter has \( \Delta n_{eff} = 1 \cdot 10^{-3} \). This indicates that the more the oxide layer approaches the node of electric field amplitude, the less the built-in effective index guiding. Fig. 3 depicts the continuous wave (cw) output characteristics of two different active diameter devices.
from sample A. The inset illustrates the oscillation of the two different VCSELs on the fundamental mode ($\lambda = 815 \text{ nm}$) at 2.5 mA current. Fig. 4 depicts also the characteristics of the different devices from sample B in cw operation, where the inset illustrates the spectra of the fundamental mode for these devices ($\lambda = 844.5 \text{ nm}$) at 2 mA current.

3. Experiment and Analysis

A) Experimental Setup

The setup for the NF experiment shown in Fig. 5 consists of a high precision 3-dimensional piezoelectric driven stage and the digital control electronics. High resolution sensors are installed as a feedback for positioning all three axes. Within the operating range of 100 $\mu$m for the three directions the resolution is better than 50 nm. Optical output power from the VCSEL is launched into the tapered tip of a single mode optical fiber with 10 $\mu$m core diameter and 2 m length. These fibers were fabricated specifically for these purposes where the tip is a semispherical lens with curvature radius $R = 6 \mu$m. The tip collects
Tab. 1. The measured spot sizes $w_L$ and the corresponding active diameters $a$ for samples A and B.

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<thead>
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<th>Sample A</th>
<th></th>
<th>Sample B</th>
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<tbody>
<tr>
<td>$a$ (µm)</td>
<td>$w_L$ (µm)</td>
<td>$a$ (µm)</td>
<td>$w_L$ (µm)</td>
</tr>
<tr>
<td>4.0</td>
<td>2.1</td>
<td>3.5</td>
<td>2.5</td>
</tr>
<tr>
<td>6.0</td>
<td>2.6</td>
<td>5.5</td>
<td>3.0</td>
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the light and couples it to the core of the fiber during scanning process. The transmitted signal is detected with a Germanium pin photodiode and converted into an analog signal through the optical power meter (OPM), which is connected with one of the general purpose analog inputs of the control electronics. The control electronics can thus read simultaneously the positioning through the three sensors and the analog input. Finally these data can be collected with the help of a simple PC program.

B) Comparison between Measurements and Calculations

The theoretical procedure outlined in [4] is used to calculate the NF and FF intensities of the Gaussian beam of full $1/e^2$ width $2 \cdot w_L$. The results of NF scanning for the smallest device from sample A at a single mode operating current are shown in Fig. 6 where the solid line represents the calculations and the triangle symbols represent the measurements. The measured FF intensity of this device is compared with the calculations and shown in Fig. 7. For sample B the results of NF scanning for the smallest device at a single mode operating current are shown in Fig. 8. Fig. 9 depicts the measured FF intensity of this device in comparison with the calculations. From these figures we can see the calculations fit well the experimental data. Table 1 summarizes the values of spot size corresponding to the different devices of the two samples. As one can see, the spot size of the devices belonging to sample A are less than that of sample B although the active diameter of these devices are larger than that of sample B. This indicates the presence of strong optical confinement in sample A which is due to the large effective index step.

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Fig. 5. Experimental setup for measurement of NF pattern from VCSEL.
C) Coupling Efficiency

The butt-coupling efficiency $\eta_c$ of VCSEL into flat cut single mode optical fiber (SMF) is measured using the NF scanning system with two different fibers of core diameters $D_F = 5 \, \mu m$ and $8.3 \, \mu m$, respectively. Calculations using an overlap integral between Gaussian functions along with the parameters of the spot sizes given in Table 1 fit the experimental data well, as shown in Fig. 10 for the $5 \, \mu m$ core diameter SMF. In the case of $8.3 \, \mu m$ core diameter standard telecommunication SMF for 1300 nm, the given 850 nm range operating wavelengths results in a frequency parameter above the higher order mode cutoff value so that the fiber supports two modes. The contribution of the second mode is reduced by using a fiber loop with 12 mm diameter and 7 windings as shown in Fig. 11 where the solid line represents the calculations, the triangle symbols represent the measured data without filter and the plus symbols represent the measured data using the simple filter.
4. Concluding Remarks

- The simple theoretical procedure predicts well the measured data which indicate that a stable positioning is achieved using the NF scanning system.
- The calculated butt-coupling efficiency of VCSELs into flat cut fiber using the measured parameters of beam half width yields good agreement with the measured data, i.e. the tapered tip optical fiber is suitable in NF scanning system.
- The inclusion of the simple filter in the case of large core diameter SMF leads to sufficient losses of the high order modes.

References


