Three-Terminal Dual-Stage Vertical-Cavity Surface-Emitting Laser

T. Knödl and M. Golling

*We have fabricated a three-terminal dual-stage VCSEL, operating continuous-wave (cw) at room temperature. Independent biasing of the two active stages leads to an extended singlemode regime compared to conventional VCSELs. The parallel configuration reveals singlemode operation with a differential series resistance of less than 35Ω.*

1. Introduction

The successful research into conventional vertical-cavity surface-emitting lasers (VCSELs) at 850 nm wavelength has led to mass-production of these devices for commercial short-distance high-speed and parallel optical data communication systems. Today, the research is mainly focused on the development of reliable 1.3 and 1.55μm VCSELs but also on the realization and investigation of new design concepts to overcome the bottlenecks of standard VCSELs such as tunability [1], singlemode power [2], dynamic behavior [3] and roundtrip gain [4]. In this letter we present the experimental results on a fabricated three-terminal dual-stage p-n-p VCSEL at 980 nm wavelength. This approach offers the possibility to address several bottlenecks at once. The parallel configuration can reduce the series resistance at a similar threshold current as conventional VCSELs. The independent three-terminal design could allow active wavelength stabilization, an increase of singlemode power and may even lead to higher modulation frequencies.

2. Device Structure

Fig. 1 depicts a schematic cross-section of the selectively oxidized dual-stage VCSEL that is grown by molecular beam epitaxy. The device contains two active pn-junctions, each of which comprises three undoped 8 nm thick In$_{0.2}$Ga$_{0.8}$As quantum wells separated by 10 nm thick GaAs barriers. Both active regions are placed in the antinodes of the standing wave pattern. The p-type top and bottom Bragg reflector stacks consist of 19 and 32 Al$_{0.9}$Ga$_{0.1}$As/GaAs layer pairs, respectively. Current confinement is achieved by mesa etching and subsequent selective oxidation of two 30 nm thick AlAs layers incorporated in the node of the standing wave pattern on each p-side of the cavity. The active regions are sharing a common ground intracavity contact placed in the middle of the about 1.3 μm thick n-type spacer. For the top stage, a ring contact is deposited on the mesa that allows
for top surface emission. The bottom stage is connected by a full-area contact on the backside of the n-GaAs substrate. Thus, the three-terminal design offers the possibility to either drive the active stages in parallel with only one current source or independently from each other. In order to favor the growth on an n-type substrate, a highly doped reverse biased GaAs tunnel junction is placed between the bottom Bragg reflector and the substrate. For the p- and n-type doping we use C and Si, respectively.

3. Experimental Results

The successful fabrication of the p-n-p VCSEL is verified through the light versus current (L-I) curves in Fig. 2. The minimum total threshold current is about 2.3 mA and can be provided either in parallel driving mode or with various current ratios between top and bottom stage. For simplicity reasons, the results for independent biasing are reported only for the case of varying the current through the top active stage while maintaining various fixed pumping currents for the bottom stage. Similar results are obtained for the inverse contact configuration. It is seen that the pumping current levels of the bottom stage strongly influence the threshold of the driving stage and the output power of the VCSEL. The threshold current of the top active region decreases to about 0.5 mA with increasing current of the bottom stage. Further reduction is not observed for this sample because the design does not allow to optically bleach out one stage by electrically pumping the other in the regime of cw operation at room temperature. This is confirmed by biasing only the bottom active stage in pulsed mode ($I_{\text{Top}} = 0$ mA) where the threshold of the laser is found at about 40 mA. The relatively high total threshold current of the dual-stage VCSEL in cw operation is, besides an unintended negative detuning, probably mainly caused by the $3.5 \mu m$ deviation of the oxide aperture diameters of top ($\sim 6.5 \mu m$) and bottom stage ($\sim 3 \mu m$). This is because the smaller aperture determines the lasing diameter of the
The dual-stage VCSEL and therefore leads to carrier leakage in the larger aperture stage. On the one hand side, this could be prevented in an optimized structure with two identical apertures. On the other hand, two different oxide apertures offer the possibility of large effective area singlemode VCSELs. The dominance of the smaller oxide aperture with respect to transverse mode selection is suggested by optical spectrum measurements at various current levels. Changing the driving current in the large diameter top stage from 2 to 16 mA at a constant pumping current of 2 mA in the small diameter bottom stage gives no significant influence on the transverse mode behaviour, as shown in Fig. 3. Singlemode emission with a side-mode suppression ratio (SMSR) of more than 30 dB is preserved over the hole driving range. For comparison, the inset of Fig. 3 shows the optical spectrum of a conventional VCSEL with 5.5 μm aperture. The multimode behaviour is clearly seen at an already low injection level, in contrast to the dual-stage VCSEL with even larger diameter. Thus, the design with different apertures allows a significant extension of the singlemode regime for larger area lasers. Moreover, the parallel configuration of the dual-stage VCSEL reduces the total series resistance compared to conventional lasers. As seen in Fig. 4, the independently operated stages show series resistances of 70 and 50 Ω for the 3 μm bottom and the 6.5 μm top active region, respectively. These values are already very low compared to standard VCSELs and confirm the successful realization of a low resistivity intracavity contact. Driving the device in parallel, the total differential resistance decreases to about 32 Ω as expected. The inset of Fig. 4 shows the optical spectrum at a total current of 8 mA. Singlemode operation with a SMSR of more than 35 dB is observed. Thus, the dual-stage VCSEL design offers the possibility of singlemode devices with a differential series resistance of even less than 50 Ω.
Fig. 3. Optical spectra of the dual-stage VCSEL at different top stage driving currents. The bottom stage current is fixed at 2 mA. The inset shows the spectrum of a conventional VCSEL with 5.5 µm aperture at 3 mA current on a 70 dB vertical and 4 nm horizontal scale.

Fig. 4. L-I performance for parallel biasing and I-V characteristics for the independent and parallel driving configuration. The inset shows the optical spectrum at a current of 8 mA on a 70 dB vertical and 4.5 nm horizontal scale.
4. Conclusion

We have successfully fabricated a three-terminal dual-stage VCSEL where the active regions can be operated independently from each other or in parallel. The singlemode regime could be significantly extended with respect to conventional VCSELs due to different oxide apertures for the top and bottom stage. The differential series resistance of the singlemode VCSEL is reduced to 32 Ω in parallel driving configuration. Further work will include the investigation of active wavelength stabilization and modulation properties.

References


