Vertical-Extended-Cavity Surface-Emitting Lasers

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We present first results on electrically pumped vertical-extended-cavity surface-emitting lasers (VECSELs). Experimental characterization of VECSELs with an external mirror and theoretical investigation of devices with an integrated on-substrate mirror are discussed.

1. Introduction

Applications like pumping of optical amplifiers or frequency doubling for visible laser light generation require high-power laser sources operating in a single transverse mode. Most efforts have concentrated on edge-emitting laser designs such as single-mode ridge waveguide lasers or broad-area lasers with various ways to overcome beam filamentation (e.g. master oscillator power amplifiers, unstable resonators).

However, in the past few years devices based on vertical-cavity surface-emitting laser (VCSEL) technology have appeared as a promising alternative to edge emitters. Since oxide-confined VCSEL emission becomes multimode when the active region diameter is larger than a few micrometers, their single-mode output power is restricted to a few mW [1]. The use of an external cavity defined by one distributed Bragg reflector (DBR) stack of the VCSEL chip and an external curved mirror allows to achieve lasing in a single optical mode with a beam diameter of tens of micrometers. Single-mode optical output powers of several hundreds of mW have been observed [2]. In the first part of this article, we describe the structure of an electrically pumped VECSEL and present our first characterization results.

An inherent drawback of external mirror VECSELs compared to usual VCSELs is given by the facts that they cannot be easily tested on chip level and that the formation of arrays is not possible. Furthermore, the alignment of the external mirror makes packaging a crucial step. One possibility to overcome this is to integrate the external mirror onto the substrate by using microlens technology [3, 4]. However, this comes with the penalty of reducing the optical mode diameter, thus reducing the output power. The second part of this report presents a feasibility study of VECSELs with on-chip integrated mirrors.

2. Device Structure and Principle of Operation

A VECSEL has a structure similar to that of a standard bottom-emitting VCSEL, as described in [5], except that it has a reduced n-DBR mirror stack. The main reason for using a bottom emitter (in which the output light is emitted through the substrate) for broad-area VCSELs is to obtain a uniform current distribution in the active region. A second advantage is the possibility to solder the device p-side down onto a heat sink, thus having the active region as close as possible to the heat sink. In the present devices, the n-DBR stack has only 14 layers, corresponding to a reflectivity of 97 %. Such a small reflectivity is not sufficient to observe lasing, i.e. the cavity defined by the p- and n-DBRs alone has a prohibitively high threshold gain. By placing an external mirror of adequate reflectivity in front of the output facet, thus feeding back laser emission into the active region, one obtains a three-mirror laser cavity whose threshold is much lower that of the solitary Fabry-Perot cavity. Thus for driving currents lying between these two threshold currents, only the optical modes of the three-mirror cavity will be lasing. Choosing a curved external mirror yields a stable cavity configuration and allows control of the transverse lasing mode.

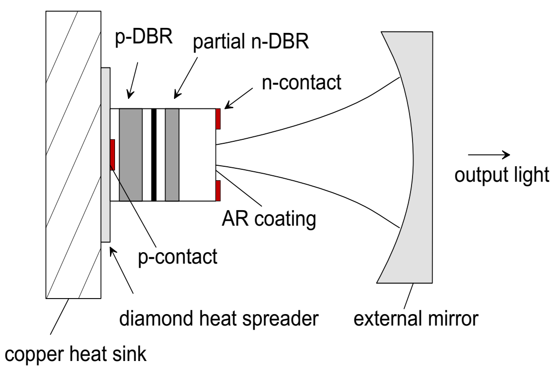

Fig. 1: Schematic drawing of the external mirror VECSEL. The chip is mounted p-side-down on a heat sink.

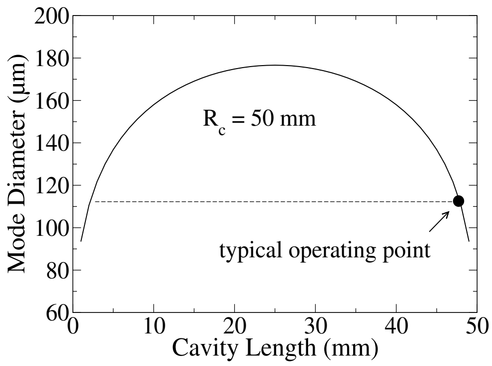

Fig. 2: Optical mode diameter in the active layer versus external cavity length for an external mirror with a radius of curvature of 50 mm. Typical operating cavity length is from 45 mm to 50 mm ($\lambda = 980$ nm).

Figure 1 shows a schematic drawing of the device. The VECSEL has no oxide aperture and is soldered p-side down onto a diamond heat spreader, which is attached to a copper heat sink. The diamond is metallized with AuSn solder. Soldering is achieved in a one-step heating process at a temperature of about 300 °C. The n-DBR selects a single longitudinal mode in the semiconductor cavity. Furthermore it confines most of the optical power density in the epitaxial layers, thus reducing the optical losses in the external cavity, namely the light absorption in the GaAs substrate. In order to avoid parasitic reflections from the substrate–air interface, a silicon nitride anti-reflection coating is deposited. Figure 2 shows the diameter $2w$ of an assumed Gaussian mode selected by the VECSEL for different external cavity lengths L_c and an external mirror radius of curvature of $R_\mathrm{c} = 50$ mm.

The mode diameter is calculated from

$$w^2 = \frac{4\lambda L_c}{\pi}\sqrt{\frac{R_c - L_c}{L_c}}$$

with $\lambda = 980\,\mathrm{nm}$ and $R_c = 50\,\mathrm{mm}$.

3. Measurement Results

The results presented here have been obtained with a $125\,\mu$m p-contact diameter laser and an external mirror with $R_c = 50\,\mathrm{mm}$ and a reflectivity of 96 %. Figure 2 indicates a typical operating point. Lasing is observed for external cavity lengths ranging from 45 to 50 mm.

Figure 3 shows the L–I and I–V curves of the device in continuous waves (CW) operation. The threshold current is about 100 mA and the laser output power reaches a maximum of 6 mW at about 300 mA current, which is limited by thermal rollover. The optical spectrum in Fig. 3 shows a single laser line with a -10 dB width of about 0.09 nm for currents of roughly below 200 mA. For higher currents, the spectrum broadens with changes in modal structure and shifts toward longer wavelengths (thermally induced red-shift).

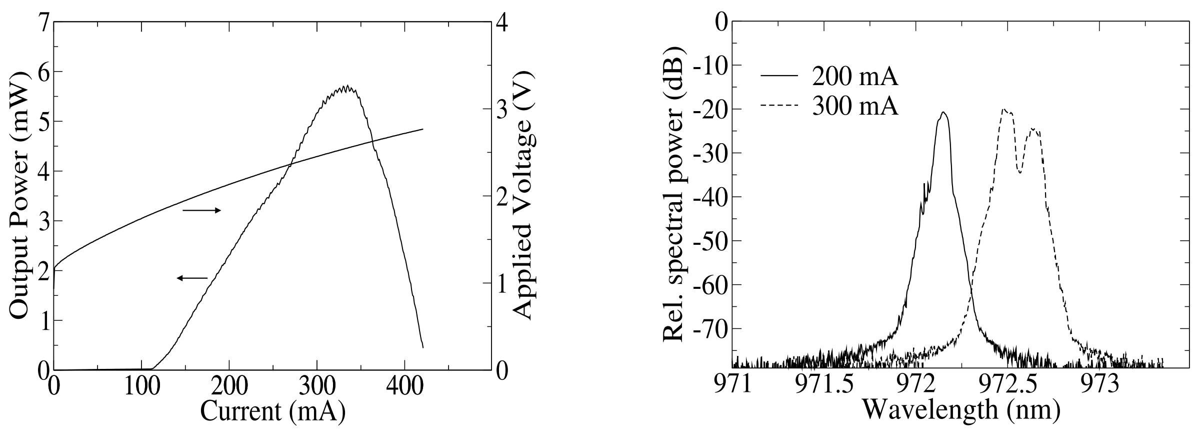

Fig. 3: L–I–V characteristics (left) and spectra for two driving currents (right) of a VECSEL with $125\,\mu$m p-contact diameter and 96 % external mirror reflectivity.

Since no oxide aperture is incorporated into the present design, current confinement is poor and efficiency is low. To get information about the epitaxial quality, we have processed standard broad-area VCSELs with the same fabrication procedure from epitaxial material with 21 instead of 14 n-DBR layer pairs. Much like the VECSELs before, these standard broad-area VCSELs exhibit poor output power, as can be seen in Fig. 4, which is also due to the lack of current confinement. This suggests that a next generation of devices with improved epitaxial quality and appropriate current confinement will show higher power output for the same geometry.

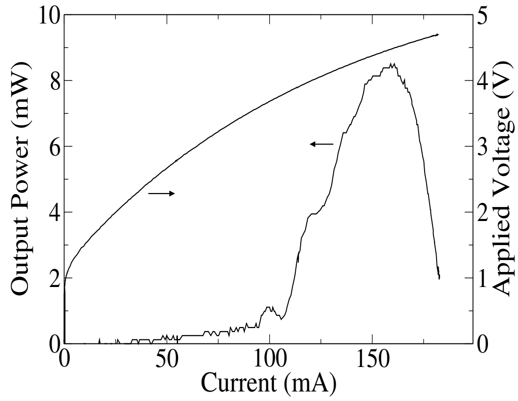

Fig. 4: L–I–V characteristics of a standard bottom-emitting VCSEL. The device is fabricated using epitaxial material similar to the VECSEL chip in Fig. 3, except for a higher number of 21 n-DBR layer pairs. The p-contact is 30 μm wide.

4. Design and Fabrication of Integrated External Mirrors

As a great advantage, the design presented above allows lasing in a broad (typically 100 μm) single transverse mode. However, the drawback of using an external mirror is the precise alignment required, which is a challenge for device packaging in view of large scale production.

The need for alignment during characterization or packaging can be eliminated if the mirror is integrated onto the substrate during fabrication. In what follows we present some preliminary tests and calculations relevant for the fabrication of such a VECSEL.

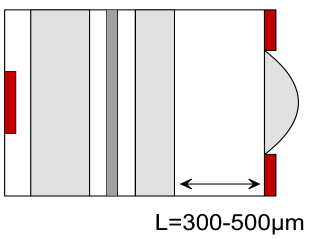

Fig. 5: Schematic drawing of an integrated mirror VECSEL device. Substrate thickness varies from 300 μm to 500 μm and defines the external cavity length.

Figure 5 illustrates a VECSEL chip with integrated micromirror. The mirror is fabricated using a technology developed for the realization of microlenses [6]. Photoresist is patterned into disks using a two-step lithographical process. As illustrated in Fig. 6, this is followed by a reflow process transforming the disks into lenses. The radius of curvature of the final lens depends on the diameter and the height of the initial disk.

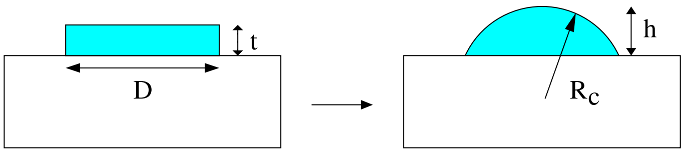

Fig. 6: Microlens fabrication using a reflow process. A patterned photoresist disk (diameter D, thickness t) takes a spherical lens shape (height h, radius of curvature R_c) after reflow.

We assume that the photoresist volume does not change during reflow. In this case the radius of curvature R_c can be expressed in terms of h and D by basic geometrical considerations as

$$R_\mathrm{c} = \frac{h^2 + (D/2)^2}{2h} \ .$$

Experimentally, radii of curvature of a few millimeter can be achieved. Figure 7 shows a comparison between the calculation and fabricated lenses, where the differences arise from the fact that the lenses are not perfectly spherical in shape. Furthermore, fabrication of lenses with a large radius of curvature is limited by the effect that the photoresist takes a concave shape in its center when the diameter of the disk is too large or its thickness too small, as seen in Fig. 8.

Since the refractive index n_l of the photoresist used for the lens is different from the index of the substrate n_s (1.5 compared to 3.5), the effective radius of curvature to be considered to calculate the optical mode diameter is $n_\mathrm{s}R_\mathrm{c}/n_\mathrm{l}$. Figure 9 shows the dependence of the mode diameter on the effective radius of curvature of the mirror for different substrate thicknesses.

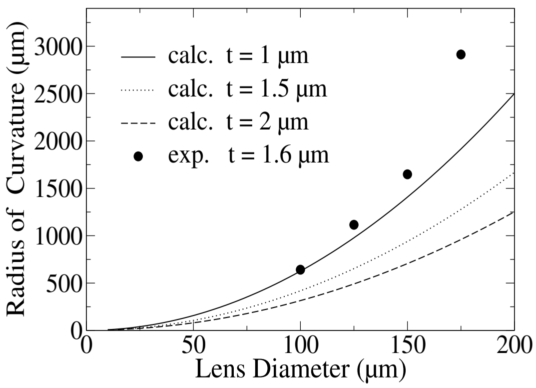

Fig. 7: Calculation and experimental results for the radius of curvature R_c as a function of lens diameter D for different photoresist thicknesses t.

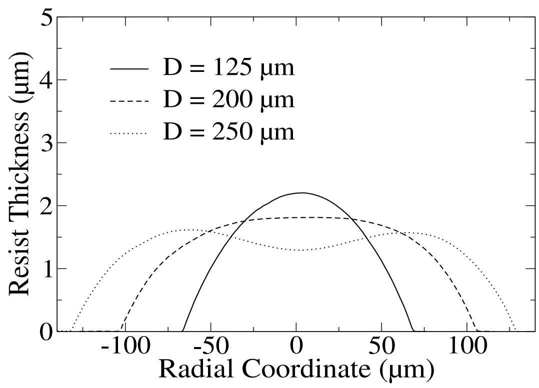

Fig. 8: Measured lens profiles for different lens diameters. For large lens diameters the radius of curvature becomes negative.

The external cavity length is fixed by the substrate thickness. Figure 9 shows that the optical mode diameter, considering the achievable effective radius of curvature, lies in the range of 20 to 25 μm.

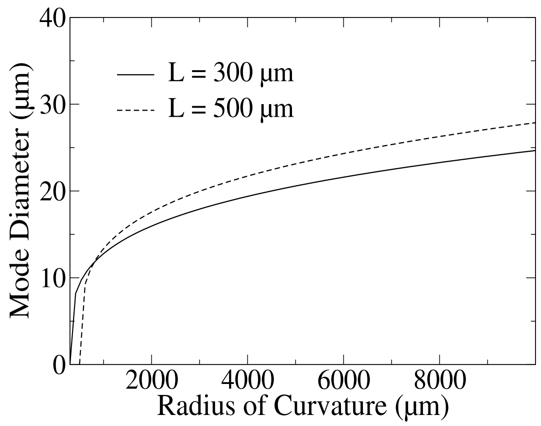

Fig. 9: Mode diameter versus effective radius of curvature for different substrate thicknesses L.

The microlens is later to be covered with a high reflectivity coating to form the external mirror. A simple calculation allows the estimation of the coating reflectivity needed. The three-mirror cavity is, for the purpose of the threshold current calculation, equivalent to a two-mirror cavity, one with the p-DBR reflectivity, and one with an effective reflectivity R_{eff} given by

$$R_{\text{eff}} = \left(\sqrt{R_{\text{n}}} + \frac{T_{\text{n}} \sqrt{R_{\text{ext}}}}{1 + \sqrt{R_{\text{n}} R_{\text{ext}}}} \right)^2$$

with R_{n} and R_{ext} as the reflectivities of the n-DBR and the external mirror, respectively, and T_{n} as the intensity transmission coefficient of the n-DBR. This relationship is plotted in Fig. 10.

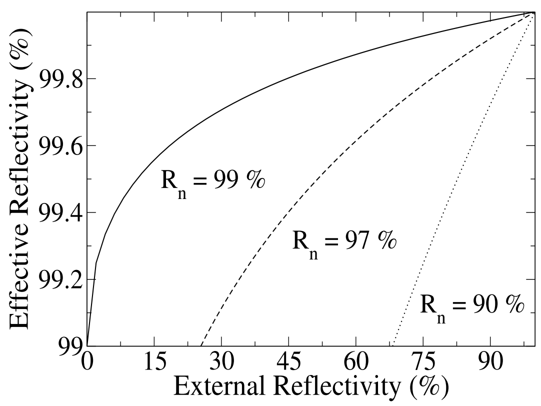

Fig. 10: Effective reflectivity of the extended cavity as a function of the external mirror reflectivity for different lossless n-DBRs with reflectivities R_{n}.

As can be seen, for a required reflectivity $R_{\mathrm{eff}} = 99.6\,\%$ and $R_{\mathrm{n}} = 90\,\%$ for the built-in n-DBR, an external mirror with $R_{\mathrm{ext}} = 86\,\%$ is required, where a lossless n-DBR has been assumed.

5. Conclusion

We have fabricated and characterized electrically pumped VECSELs operating in continuous wave. The devices deliver single-mode output powers of about 3 mW and maximum output powers of about 6 mW. Relatively low power and efficiency are due to the lack of current confinement. Preliminary theoretical investigations of integrated mirrors for monolithic devices are presented and show that a single transverse optical mode of 20 to 25 μm diameter can be achieved.

References

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