Cavity Optimization of Electrically Pumped VECSELs

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We have fabricated 960 nm wavelength vertical-external-cavity surface-emitting lasers (VECSELs) showing continuous-wave operation above room temperature. Absorption in the intra-cavity GaAs substrate has a strong impact on the efficiency and has to be considered for the design. Thus, apart from experimental results, in this work we deduce design rules from a numerical transfer matrix approach.

1. Introduction

Surface-emitting lasers with an external cavity delivering a diffraction-limited beam have shown the potential to outperform edge-emitting devices in applications demanding high brightness (emitted intensity per unit solid angle), like pumping of doped fiber amplifiers or frequency doubling [1]–[3]. Due to the large mode size, the VECSEL concept is power-scalable by expanding the pumped area and the heat-sink. This property makes VECSELs less susceptible to catastrophic optical mirror damage (COMD), spatial hole burning, and thermal lensing in comparison to edge-emitting devices. Similar to the sophisticated vertical-cavity surface-emitting laser (VCSEL), the optical resonator consists of a multiple quantum well gain material which is embedded between three distributed Bragg reflectors (DBRs).

2. Fabrication Steps

The semiconductor part of the device was grown by molecular beam epitaxy on GaAs (100)-oriented substrate and is similar to a conventional VCSEL. It consists of 30 p-doped DBR pairs and 7 n-DBR pairs ($Al_{0.11}Ga_{0.89}As/Al_{0.90}Ga_{0.10}As$) forming the internal resonant cavity. Silicon and carbon are used for n- and p-type doping, respectively. Graded heterojunction interfaces in both DBRs provide low electrical and optical losses. The active region is composed of three 8 nm thick $In_{0.15}Ga_{0.85}As$ quantum wells and 10 nm thick GaAs barriers. After growth, a 125 µm diameter circular ohmic contact was deposited on the top side and the n-doped ($\approx 7\,\mathrm{cm}^{-1}$ loss) substrate was thinned to 120 µm. An ohmic n-ring contact on the bottom side enables electric current flow. The opening of the n-contact was anti-reflection coated with a single 120 nm thick layer of plasma-enhanced chemical vapor deposited (PECVD) Si_3N_4. The laser structure was p-side down soldered with In onto a copper heat-sink.

3. Optical Resonator Issues and Transfer Matrix Model

The beam quality factor $M^2 = \pi\Theta w_0/\lambda$ indicates how much the far-field divergence angle Θ differs from that of a perfect Gaussian beam, where λ is the wavelength and w_0 the beam radius. Neglecting thermal lensing within the device mesa and antiguiding effects from carrier injection, the optical resonator of a VECSEL can be modelled by the plane epitaxial DBR mirror and the external concave-shaped mirror. In this resonator, the modal beam radius $w_0^2 = M^2\lambda\sqrt{L(\varrho - L)}/\pi$ is determined by the resonator length L and the radius of curvature of the external mirror ϱ, since the curvature of the phase fronts must match the curvature of the external mirror [4, 5]. A simple transfer matrix model [6] was used to solve the Helmholtz equation $\partial^2 E(z)/\partial z^2 + \gamma^2 E(z) = 0$ for the electric field $E(z)$ and the propagation constant γ to describe the laser threshold gain g_{th} and the differential quantum efficiency $\eta_{\mathrm{d}} = (\Delta P/\Delta I) \cdot q\lambda/(hc)$ with the emitted optical power P, the electric current I, the elementary charge q, the vacuum velocity of light c, and Planck's constant h.

4. Experimental Setup and Results

The experimental setup is sketched in Fig. 1. A curved mirror ($\varrho = 20$ mm, 98 % reflectivity) was placed at an axial distance of about 20 mm to the laser aperture. The differential quantum efficiency η_{d} was extracted from the light–current–voltage (LIV) characteristics shown in Fig. 2. The efficiency of 1.5 % is considerably lower than in common VCSELs. A maximum output power of 2 mW was measured with a large-area photodetector. It is limited by thermal rollover and is reduced at elevated temperatures.

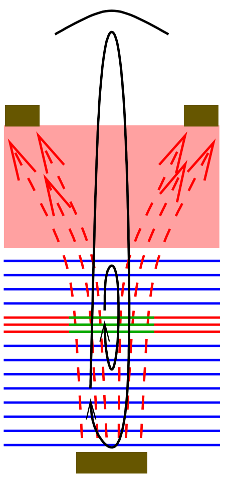

Fig. 1: Schematic VECSEL cross-section. The dashed and full lines indicate the current flow and the round-trip paths of the laser light, respectively.

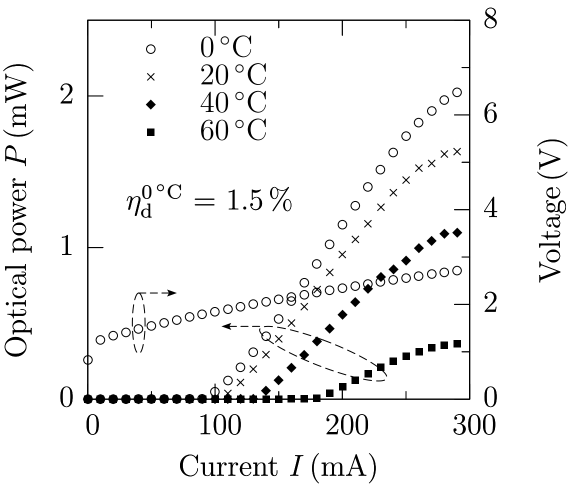

Fig. 2: Measured LIV characteristics of a VECSEL at different ambient temperatures. The p-contact diameter is 125 µm.

5. Discussion of the Results and Simulation

High losses in the external cavity seem to be the reason for the rather low device efficiency. For the simulation of the resonator losses, the transfer matrix method was employed. The absorption of the n-doped GaAs substrate was determined experimentally (Fig. 3). The measured substrate loss amounts to $\approx 7\,\mathrm{cm}^{-1}$ at 960 nm and is attributed to free-carrier absorption [7], corresponding to a doping density of $2.3 \cdot 10^{18}\,\mathrm{cm}^{-3}$. For the simulations, a n- and p-DBR absorption of $5.1\,\mathrm{cm}^{-1}$ and $7\,\mathrm{cm}^{-1}$, respectively, is assumed.

During every external cavity round-trip, a fraction of 15 % of the light is absorbed. In the resonator, this loss accumulates and the major part of the total generated light is absorbed. Consequently, the simulated efficiency drops down to 4 %. The simulated threshold gain and differential efficiency of an improved structure are depicted in Fig. 4 as a function of the number of epitaxial bottom mirror pairs for two different absorptions in the intra-cavity substrate. The re-design bears on a cavity incorporating a 90 % reflective external mirror and 7 n-doped mirror pairs, resulting in an efficiency of 20 % which is excelled by an efficiency of 60 % in case of an undoped substrate. This balance of internal and external cavity reflectivities provides a compromise beween both high efficiency and low threshold gain. The resulting threshold gain of $500\,\mathrm{cm}^{-1}$ for a device with 7 n-doped mirror pairs and 90 % external reflectivity is easily attainable in InGaAs/GaAs double heterostructures [8]. The dominant effect on the modal structure in the laser resonator is given by the finesse of both internal and external resonator. The inhomogeneous current injection profile resulting from large-area contacts usually does not support TEM_{00} operation. An external resonator with a sufficiently high finesse can be aligned such as to suppress higher-order transverse modes. For this reason, a higher ratio beween external and internal reflectivity might be favored when designing a device operating in the fundamental transverse mode.

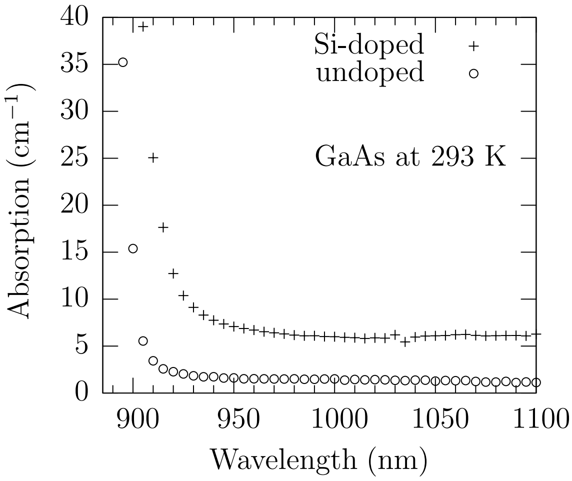

Fig. 3: Measured optical absorption in silicon-doped and undoped GaAs.

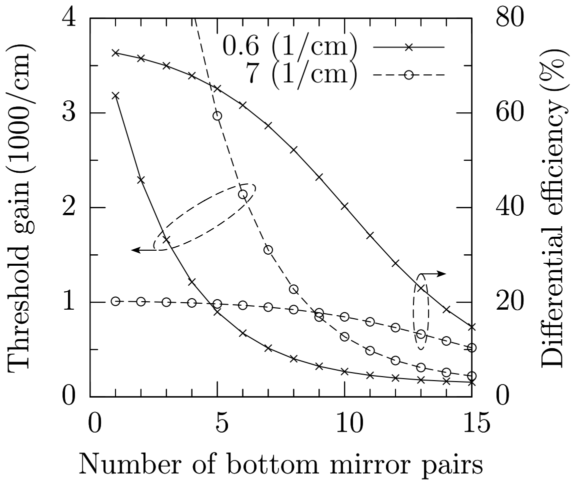

Fig. 4: Simulated threshold gain and differential efficiency in VECSELs incorporating doped and undoped GaAs substrates.

6. Conclusion

We have fabricated bottom-emitting electrially pumped InGaAs/GaAs VECSELs. In the present layout, the output performance is degraded by a high loss in the external cavity due to absorption in the doped GaAs substrate. As a result of transfer matrix calculations, this loss contribution limits the quantum efficiency to less than 4 %, in agreement with experimental results. It is suggested to minimize the impact of substrate absorption by choosing a 7-pairs epitaxial mirror and a 90 %-reflective external mirror. The absorption-induced loss scales with the substrate thickness, yet reducing the thickness below 100 µm makes device handling difficult. In order to get rid of parasitic absorption without the need for extreme wafer thinning, a moderatly doped substrate ($10^{17}\,\mathrm{cm}^{-3}$) is necessary. In this case an efficiency of more than 60 % is expected to be attainable.

References

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