VCSELs With Enhanced Single-Mode Power and Stabilized Polarization for Oxygen Sensing

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Vertical-cavity surface-emitting lasers (VCSELs) with single-mode, single-polarization emission at a wavelength of approximately 763 nm have become attractive for oxygen sensing. Up to now, VCSELs used for this application are single-mode because of a small active diameter which correspondingly leads to small optical output power. Employing the surface relief technique and in particular the surface grating relief technique, we have increased the single-mode output to more than 2.5 mW averaged over a large device quantity. To the best of our knowledge, this is the highest single-mode power ever reported for VCSELs in this wavelength range. Through the grating relief simultaneously we were able to stabilize the light polarization.

1. Introduction

Over the last years spectroscopy has emerged as a new application area for VCSELs. Especially oxygen sensing with VCSELs is well studied [1], [2]. The emission wavelength of the laser is first fine-tuned to the absorption line of interest by varying the substrate temperature. Then this absorption line is scanned by modulating the laser current. Fitting the measured line shape, the oxygen concentration in the examined gas can be determined. This method allows an in-situ and online monitoring of the oxygen concentration. The advantages of using VCSELs in these systems are their circular output beam with the associated ease of building an optical system, low operating currents, efficient tunability and the potential for low cost. While VCSELs are inherently longitudinal single-mode, they can emit in multiple transverse modes if the active diameter is not small enough. But a small active diameter has the drawback of the single-mode power of such devices to be also rather limited. In the past, a surface relief has been used to achieve a significant increase of the single-mode output power as well as of the active diameter of oxide-confined VCSELs [3], [4].

However, besides single-mode operation with a large side-mode suppression ratio also a stable polarization is required. Due to their isotropic gain, their cylindrical resonator and their mirrors with a polarization-independent reflectivity, VCSELs have a priori no preferred direction of polarization. Due to the electro-optic effect, VCSELs grown on (100)-oriented GaAs substrates are mainly polarized along the [011] and the [011] crystal axes. But if the current or the temperature is changed, the polarization can abruptly change its orientation from one of these crystal axes to the other. Such a polarization switch is accompanied by a change of the emission wavelength of up to 40 GHz (see [5] and
the references therein). Therefore in particular VCSELs used for oxygen sensing need a controlled polarization. In [6] a surface grating monolithically integrated in the top Bragg mirror of a VCSEL was proposed as a method for polarization control. This technique has been successfully demonstrated in [5], [7]. Also in [6] it was shown theoretically that a surface grating combined with a surface relief can simultaneously lead to a stable polarization and to an increased single-mode output power. In this contribution we report on the grating relief technique applied to 760 nm range VCSELs. The fabricated devices show record-high output power and stable polarization.

2. Fabrication

The wafer was grown by solid source molecular beam epitaxy on an n-doped GaAs (100)-substrate. The lower Bragg mirror is composed of 32 AlAs/AlGaAs and 8 AlGaAs/AlGaAs layer pairs. The active layer consists of three AlGaAs quantum wells with 14% aluminum content. Above the active region there is an AlAs layer for wet chemical oxidation and 26 AlGaAs/AlGaAs layer pairs forming the upper mirror.

![Figure 1: Photograph of a VCSEL with an integrated surface grating relief (left) and an atomic force microscope (AFM) measurement showing the grating relief in more detail (right).](image)

The structure has an extra topmost $\lambda/(4 \cdot n)$-thick GaAs layer (with $n$ as the refractive index of GaAs) to achieve an anti-phase reflection for all modes. By etching a circular area of 3 $\mu$m diameter in the center of this cap-layer, the reflectivity is again increased for the fundamental mode. If instead a grating with the same extension is etched into the cap-layer (see Fig. 1), this leads in addition to different reflectivities for the two polarizations of the fundamental mode.

3. Electro-Optical and Spectral Characteristics

The polarization-resolved light–current–voltage (LIV) characteristics of a typical device are shown in Fig. 2 for substrate temperatures between 10 and 60 °C. This device has an active diameter of approximately 4 $\mu$m, a grating relief with a diameter of 3 $\mu$m, a grating period of 0.8 $\mu$m and a grating depth of 44 nm. The VCSEL is single-mode up to 5 mA current with a side-mode suppression ratio (SMSR) of more than 30 dB. Depending on
the substrate temperature it has a single-mode output power between 1.8 and 2.7 mW, which is to the best of our knowledge the highest single-mode output power ever reported for VCSELs in this wavelength range.

As can be seen in Fig. 2, for the complete current and temperature range the fundamental mode of the VCSEL is polarized strictly along the [011] crystal axis, which is orthogonal to the grating grooves. The power of the orthogonal polarization of the device shown in Fig. 2 stays below 6 µW up to a current of 5 mA, where the first higher order mode starts to lase. The orthogonal polarization suppression ratio (OPSR) is therefore above 26 dB between 2.5 and 5 mA (Fig. 3, left side). The peak-to-peak OPSR measured in the spectra in Fig. 3 (right side) is 33 dB, which corresponds to the limit of the employed polarizer. The OPSR taken from the spectra is larger than the value calculated from the LI characteristics since spontaneous emission is not considered in the peak-to-peak definition of the OPSR.

![Graph](image1.png)

**Fig. 2:** Polarization-resolved LIV characteristics of a 4 µm VCSEL with a 3 µm diameter grating relief, a grating period of 0.8 µm and a grating depth of 44 nm for substrate temperatures varied between 10 and 60 °C in steps of 10 °C.

![Graph](image2.png)

**Fig. 3:** Polarization-resolved LI characteristics and the orthogonal polarization suppression ratio (OPSR) of the VCSEL from Fig. 2 for a substrate temperature of $T = 20^\circ C$ (left) and a polarization-resolved spectrum of the same VCSEL at $T = 20^\circ C$ and $I = 5$ mA (right).
Fig. 4: Spectra of the laser from Fig. 2 at $T = 35^\circ$C for currents varying from 1 to 5 mA in steps of 0.5 mA (left) and at a current of 5 mA for temperatures between 10 and 60$^\circ$C in steps of 10$^\circ$C (right).

The laser can be conveniently tuned over the wavelength range of interest by the current and the temperature, as illustrated in Fig. 4. Over the whole tuning range it stays single-mode with a SMSR of 30 dB. The current and temperature tuning coefficients are 0.6 nm/mA and 0.06 nm/K, respectively, which is comparable to the values measured in [2].

4. Emission Far-Field

Gratings can cause diffraction lobes in the far-field in the direction orthogonal to the grating grooves [7], but the present grating relief has almost no influence on the far-field. Hardly some small ripples can be seen in the far-field measured orthogonal to the grating, which is shown in Fig. 5 on the right side. The full width at half maximum far-field angle of 10.1$^\circ$ parallel and 9.4$^\circ$ orthogonal to the grating is comparable to 10.4$^\circ$ for a standard reference devices fabricated on the same sample.

Fig. 5: Far-field of the laser from Fig. 2 measured parallel (left) and orthogonal (right) to the grating grooves.
5. Increased Single-Mode Output Power

In Fig. 6 we compare four kinds of VCSELs, all on the same sample for best possible comparison, with an oxide diameter of 4 \( \mu \text{m} \). These are 3 \( \mu \text{m} \) diameter grating relief devices (34 to 74 nm grating depth and both 0.7 \( \mu \text{m} \) and 0.8 \( \mu \text{m} \) grating period), 3 \( \mu \text{m} \) standard relief VCSELs and reference devices with the cap-layer etched over the whole aperture to the same depth as the grating. We have realized devices with etch depths of 34, 44, 54, 64 and 74 nm, which corresponds roughly to \( \lambda/(4 \cdot n) \pm 20 \text{ nm} \). Since we couldn’t find a dependence of the device performance on the etch depth, in the following we will not distinguish between the different etch depths. Due to a layer thickness variation over the wafer, the investigated lasers have emission wavelengths between 750 to 790 nm. Some problems arose on that wafer due to some large defects with a diameter comparable to the mesa diameter of a VCSEL. These defects prevent some lasers from operating properly or even inhibit lasing. Thus we have not taken those lasers into account which have a distance from such a defect of less than 50 \( \mu \text{m} \), i.e. which have a defect within twice the mesa diameter. According to this rule twelve lasers had to be excluded. The statistics shown in Fig. 6 still considers 87 lasers. While the reference devices have an average single-mode output power of 1.08 mW and are therefore comparable to previously published lasers at
that wavelength [2], the VCSELs with a standard relief have a single-mode output power of 2.02 mW on average. In contrast, with a grating relief we could achieve an average single-mode output power of 2.29 mW for a grating period of 0.7 µm and even 2.65 mW for a grating period of 0.8 µm. This increase is due to higher outcoupling losses of the grating relief while the threshold current is almost unchanged.

6. Stabilized Polarization

To judge the influence of the grating on the polarization, we have measured the polarization-resolved LI characteristics of the devices shown in Fig. 6, but also of the same amount of devices with same parameters except for an active diameter of 3 µm. In these measurements the polarizer was strictly oriented along the [011] or [01̄1] crystal axis. The OPSR shown in Fig. 7 is defined as the ratio $P_{[011]} / P_{[011]}$ between optical powers in the respective crystal directions. The OPSR was calculated for data points in steps of 0.1 mA and then averaged over the current range yielding 10 to 100% of the maximum single-mode output power. While the lasers without a grating in Fig. 7 show an orientation of the polarization along both crystal axes, the polarization of the devices with a grating relief is defined by the orientation of the grating grooves. If they are oriented along the [011] crystal axis,
the lasers are polarized along the [0\overline{1}1] crystal axis. If the grating grooves are turned by
90°, also the polarization of the lasers is turned by 90°. Devices which have a polarization
not exactly oriented along one of the crystal axes have a reduced OPSR magnitude. Also
strain caused by the defects as well as polarization switches can explain lower OPSRs.
The latter have been observed for 15 out of 92 devices without a surface grating, but only
for one out of 80 devices with a grating. By eliminating the defects, one should be able
to achieve OPSR magnitudes of above 20 dB for all devices with a grating relief.

7. Conclusion

A monolithically integrated grating relief has shown to increase the maximum single-
mode output power of VCSELs from 1.08 mW to 2.65 mW on average in the emission
wavelength range from 750 to 790 nm. At the same time the orientation of the polarization
was defined by the orientation of the grating grooves and polarization switches could be
avoided with a yield of 98.75%, which is expected to be increased for a wafer with a
lower defect density. The grating relief has shown no negative influence on the overall
laser performance. Therefore an integrated grating relief is a very attractive approach
for increasing the single-mode output power and stabilizing the polarization at the same
time.

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References


