Polarization-Controlled Surface Grating VCSELs Under Unpolarized and Polarized Optical Feedback

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The polarization control of a surface grating vertical-cavity surface-emitting laser (VCSEL) and of a nominally identical standard VCSEL without a surface grating are compared for unpolarized and polarized optical feedback with different feedback levels in the long external cavity regime. While the polarization of the standard VCSEL is strongly influenced by isotropic feedback with a feedback level of just 1 % and can even be controlled by polarized feedback, the surface grating VCSEL remains polarization-stable under isotropic feedback. Its polarization can only be disturbed by optical feedback polarized orthogonal to the polarization of the solitary surface grating VCSEL for feedback levels exceeding 18 %.

1. Introduction

The polarization of common VCSELs is very sensitive to optical feedback [1]. It can be switched by means of polarization-selective optical feedback [2], by feedback with rotated polarization [3], or by varying the phase of the feedback in an extremely short external cavity [4]. While the polarization phenomena under feedback are very interesting from a laser physics point of view, VCSELs which are polarization-stable especially under feedback are highly sought-after for many applications, since feedback cannot be avoided in most optical setups. It can already be caused by a collimating lens without an anti-reflection coating or by the facet of an optical fiber into which the laser light is coupled.

While promising results for polarization control were achieved in the past by growth on substrates with higher indices in combination with strained quantum wells, in the last years semiconductor surface gratings have proven to reliably control the polarization of VCSELs fabricated on standard (001)-oriented GaAs substrates [5, 6] even under high-frequency modulation [7]. In the following, it is investigated whether this polarization control is robust enough to withstand even strong and polarized optical feedback.

It is beyond the scope of this article to provide a comprehensive and conclusive investigation of the polarization properties of grating VCSELs under feedback. Instead, we limit ourselves to the long external cavity regime, which is characterized [8] by an external roundtrip delay time (in the present case about 4 ns, corresponding to an approximately 60 cm long external cavity) larger than the inverse of the relaxation oscillation frequency of the laser (typically several GHz in the case of VCSELs). In this regime, the observed physical effects are expected to be qualitatively independent from phase variations in the feedback, which can result, for instance, from a change of the external cavity length. This assumption has been experimentally validated for the measurements presented in this article.

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2. Measurement Setup

The measurement setup used for the optical feedback experiments is schematically sketched in Fig. 1. The setup comprises the feedback path which consists of an external mirror, a polarizer, and a variable optical attenuator and the detection path with a second polarizer and a photodetector. In addition, there are a halogen lamp and a CCD camera to identify the VCSELs on the chip and facilitate probing. Behind the collimating lens with a transmittivity of 97 %, an uncoated wedge plate is inserted into the optical path to extract about 4 % of the light from the external cavity for detection. A polarization-independent beam splitter with a 50:50 splitting ratio, as it is often used in such setups, would limit the available feedback level (the portion of the laser emission reflected back on the laser facet) to a level below the one of interest, since the polarization properties of VCSELs with a surface grating are quite robust against feedback, as will be shown later. Due to a lack of space on the optical table, the wedge plate had to be inserted into the optical path of the external cavity under a relatively large angle of about 6 degrees. The reflectance at a single facet of the wedge plate is therefore about 3 % larger for the polarization orthogonal to the optical bench than for the polarization parallel to the optical bench, as follows from Fresnel's equations. Since during one round-trip in the external cavity, four facets of the wedge plate are passed, the transmission in the external cavity and thus the feedback level is about 12.5 % higher for the polarization parallel to the optical bench than for the orthogonal polarization, as long as no additional polarization-selective element is inserted into the cavity.

The optical attenuator behind the wedge plate has a variable transmittivity between 0 and 70 % and is used to adjust the feedback level. The polarizer, which can optionally be inserted into the feedback path, exhibits losses of about 6 %. The feedback loop is closed by an external dielectric mirror with a reflectivity exceeding 99 %. In total, the setup allows to vary the feedback level between 0 and 39 %. A typical feedback level to be expected in some applications is about 4 %, corresponding to a reflection from an uncoated glass surface. With the given measurement setup, this expected feedback level can be exceeded by almost a factor of ten.

Besides the reflectivities, the actual feedback strength depends also on the mechanical alignment. In all measurements presented here, the external cavity is carefully aligned. The external mirror and the collimating aspheric lens are iteratively adjusted several times to optimize for the smallest laser threshold current under feedback. Consequently, the feedback strengths are higher than the ones expected for unwanted feedback for a given external reflectivity.

3. VCSELs Under Investigation

To guarantee an as high as possible modal overlap between the laser mode and the feedback field, single-mode VCSELs are desirable for the investigation of feedback phenomena. Therefore VCSELs with a high single-mode current range and a high single-mode output power are chosen for this investigation. The lateral extent of the surface grating of the investigated devices is limited to five grating ridges to form a grating relief [9]. The purpose

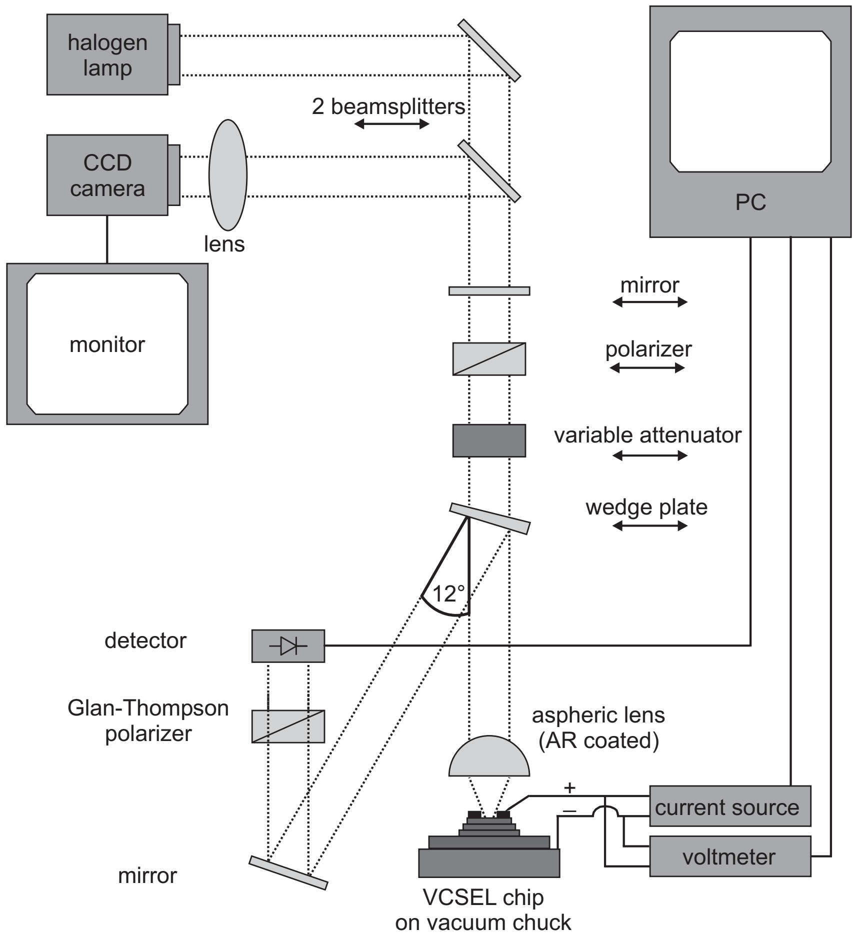

Fig. 1: Schematic drawing of the measurement setup used for the feedback investigations. The double arrows indicate components which can be removed from the optical path.

of such a grating relief is to increase the single-mode output power of the VCSELs. This concept has proven to be successful and single-mode output powers as high as 4.2 mW have been obtained [10]. Standard VCSELs on the same sample deliver single-mode output powers up to 3.5 mW. A much stronger increase of the single-mode output power than with the given normal grating relief structure can be achieved with an inverted grating relief [11].

The polarization-resolved light–current (PR-LI) characteristics of the two VCSELs investigated in the following are shown in Fig. 2. Both VCSELs have an active diameter of about 4 μm and an emission wavelength of 924 nm. They are nominally identical, except that the VCSEL on the left is a standard VCSEL without any surface modification, while the laser on the right is a grating relief VCSEL with a grating period of 0.8 μm, a grating depth of 57 nm, and an outer grating diameter of 3.6 μm. Since the grating is laterally limited to the center of the VCSEL, the polarization control achieved by the grating is weakened. The reduced mirror reflectivity outside of the grating region of such a grating relief VCSEL makes it simultaneously more vulnerable to optical feedback. This reduced overall reflectivity of the Bragg mirror also causes the much higher threshold current of

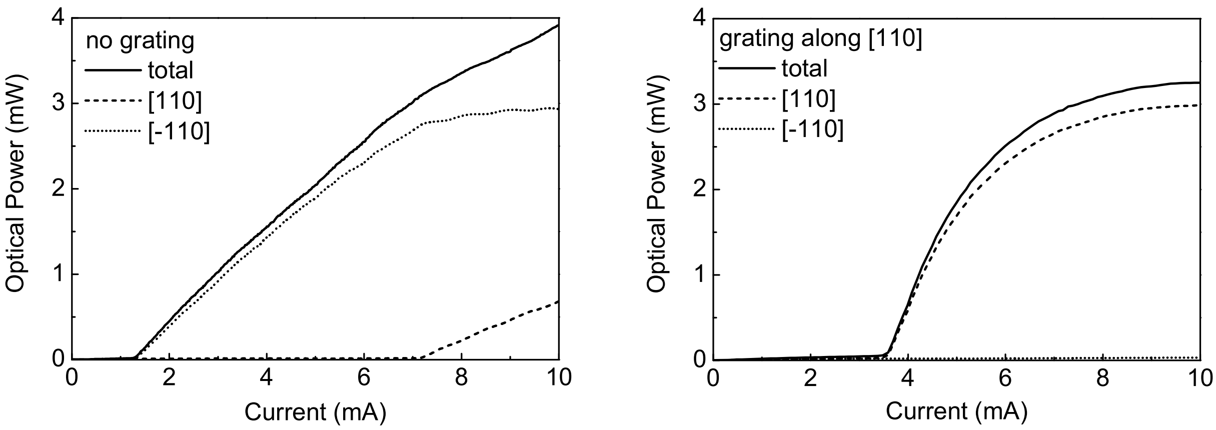

Fig. 2: PR-LI characteristics (without feedback) of a standard VCSEL (left) and a grating VCSEL (right) investigated in the following.

the grating VCSEL compared to the standard VCSEL in Fig. 2. However, the grating VCSEL is single-mode up to thermal rollover, while higher-order modes start to lase in the standard VCSEL at a current of 6.9 mA with a polarization orthogonal to that of the fundamental mode.

4. Isotropic Feedback

Without feedback, both, the standard VCSEL as well as the grating VCSEL exhibit a stable polarization of their fundamental mode. The polarization of the standard VCSEL is oriented along the $[\bar{1}10]$ crystal axis and the polarization of the grating VCSEL along the [110] crystal axis and therefore parallel to the grating grooves. Quasi-isotropic feedback is investigated first. The term quasi refers to the slight polarization asymmetry of the external cavity introduced by the wedge plate, as discussed above. The lasers are mounted in such a way that the $[\bar{1}10]$ and [110] crystal axes are oriented parallel and orthogonal to the optical bench, respectively. Thus the feedback strength along the $[\bar{1}10]$ crystal axis is higher than along [110]. Consequently, the dominant polarization of the standard VCSEL is favored and the dominant polarization of the grating VCSEL is disfavored. However, as soon as the quasi-isotropic feedback is applied, the standard VCSEL is no longer stable, as can be seen in the left graph of Fig. 3.

With increasing feedback strength, the standard VCSEL exhibits (at least in its single-mode range) an almost equal distribution of its output power between the polarization along the [110] (top half of the graph) and the $[\bar{1}10]$ crystal axis (bottom half). The influence of the feedback on the threshold current is enlarged as a total-output-power-versus-current diagram in the inset in the bottom half of the graph. As expected, the reduction of the threshold current with increasing feedback is larger for the grating VCSEL than for the standard VCSEL due to the reduced reflectivity of the upper Bragg mirror. This also explains the different shape of the LI characteristics of both lasers, especially close to threshold. However, virtually no influence of the feedback on the polarization properties of the grating VCSEL can be observed in the right graph of Fig. 3, even for a feedback level as high as 39 %.

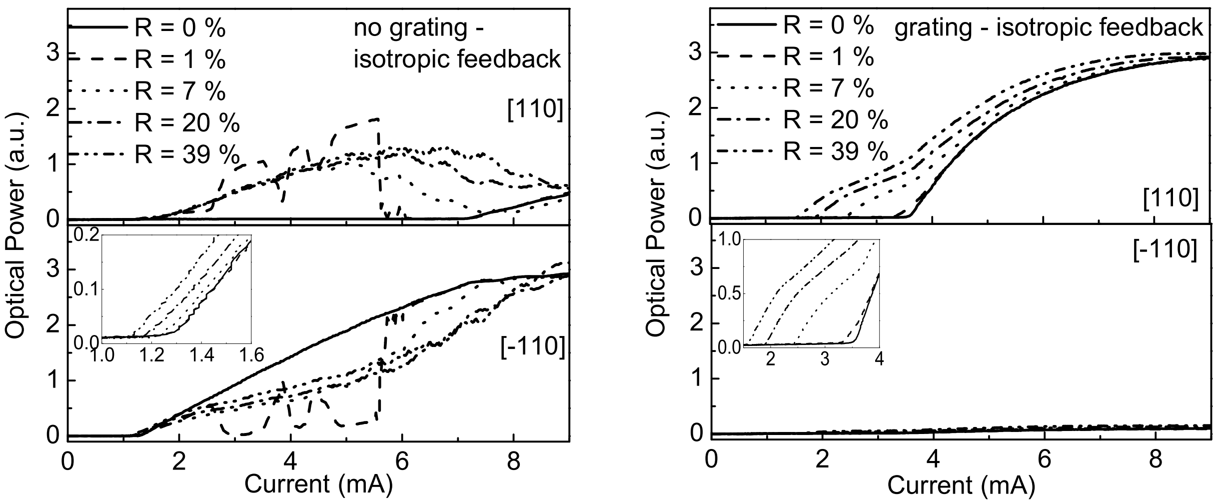

Fig. 3: PR-LI characteristics of the standard (left) and of the grating VCSEL (right) from Fig. 2 under quasi-isotropic feedback. The power in the [110] polarization is given in the top half of each graph, while the power in the [$\bar{1}$10] polarization is displayed in the bottom half. The reflectivity of the external cavity R and therefore the feedback level is varied between 0 and 39 %. The optical power is given in arbitrary units, which are chosen such that their magnitude corresponds to the optical power in mW emitted by the VCSELs in the case without feedback. The reduction of the threshold current with increasing feedback level can be read from the enlarged insets in both graphs, which give the total output power in the same arbitrary units versus the drive current in mA.

5. Polarized Feedback

Quasi-unpolarized feedback is the most probable type of feedback a VCSEL can be exposed to in common applications. Consequently, it is of high relevance that a grating VCSEL can withstand ten times the feedback level resulting from a single uncoated glass surface. However, besides isotropic feedback, also polarized feedback can occur in a setup with polarization-dependent optical elements. For testing highly polarized feedback, a polarizer is inserted into the external cavity.

The PR-LI characteristics of the standard VCSEL are shown in Fig. 4 under feedback polarized along the [$\bar{1}$10] crystal axis (left graph) and along the [110] crystal axis (right graph). Since the solitary standard VCSEL exhibits a dominant polarization along the [$\bar{1}$10] crystal axis, the feedback polarized parallel to that crystal axis in the left graph of Fig. 4 does not change the polarization properties of the device except for the case of a small feedback level of 1 %, for which a polarization switch from the [$\bar{1}$10] to the [110] crystal axis and back again is observed. When the polarizer is rotated by 90 degrees, so that the feedback is polarized along the [110] crystal axis and therefore orthogonal to the dominant polarization of the solitary standard VCSEL, already for a feedback level of 1 % its polarization is oriented parallel to the polarization of the feedback path and orthogonal to the dominant polarization of the VCSEL without feedback, as can be seen in the right graph of Fig. 4. The control of the polarization of the standard VCSEL by the polarized feedback is weakened somewhat for small feedback levels and higher drive currents. This is due to the heat dissipation inside the VCSEL, which results in a change

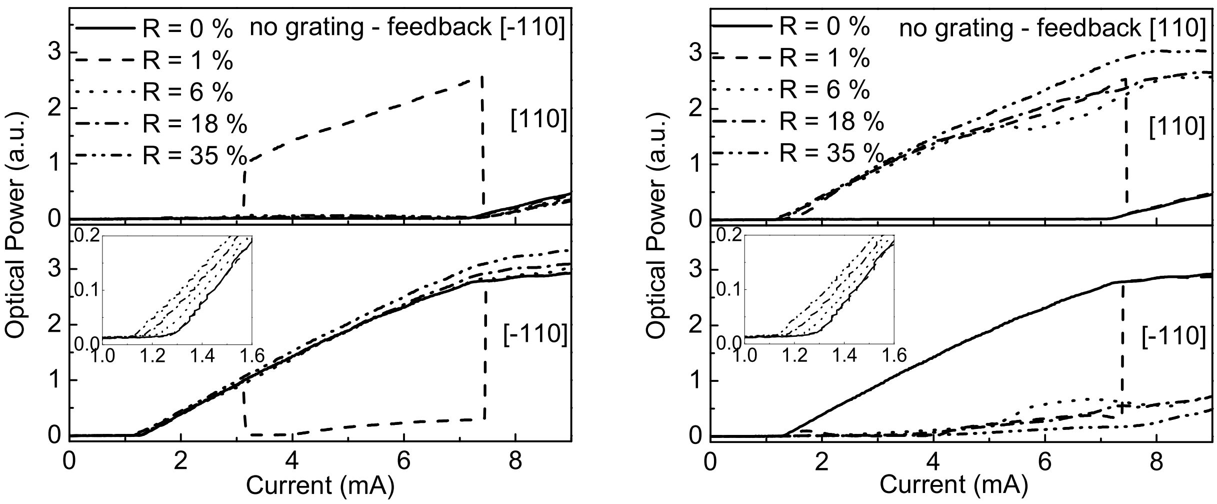

Fig. 4: PR-LI characteristics of the standard VCSEL from Fig. 2 under different levels of optical feedback polarized along the [$\bar{1}$10] crystal axis (left) and along the [110] crystal axis (right).

of the output beam profile and therefore in a less well-aligned external cavity.

In the measurements presented in Fig. 5, it is tested whether the polarization of a grating VCSEL can also be so easily controlled by polarized feedback as the polarization of the standard VCSEL above. As expected and shown in the left graph of Fig. 5, a feedback polarized parallel to the dominant polarization of the solitary grating VCSEL has no influence on its polarization properties. More interesting is the case presented in the right graph of the same figure, in which the feedback is polarized orthogonal to the dominant polarization of the solitary grating VCSEL. Since a surface grating is nothing else than a monolithically integrated type of polarization-dependent feedback, one intuitively expects that, above a certain feedback strength, a polarized external feedback can outbalance the feedback from the surface grating and cause a polarization switch if the orientations of the polarization preferred by the external feedback and preferred by the feedback from the grating are orthogonal to each other.

However, as can be seen in the right graph of Fig. 5, the feedback levels required to influence the polarization of the grating VCSEL are rather high. Even with 18 % of the suppressed polarization and no light in the dominant polarization of the solitary VCSEL reflected back on the laser facet, the polarization properties do not change compared to those of the solitary laser. Also no reduction of the threshold current can be observed for feedback levels up to 18 %. The latter effect is not caused by a less careful alignment, since just turning the polarizer by 90 degrees leads to the results displayed in the left graph of Fig. 5. Even for feedback levels exceeding 18 %, the current range in which the polarization is rotated with respect to the polarization of the solitary grating VCSEL is rather limited and is found close to threshold. Since the feedback is optimized for smallest threshold current and a higher current causes an increased heat dissipation inside the VCSEL and thus a modified emission characteristic of the laser, even a feedback level of 35 % is not high enough to control the polarization for all drive currents.

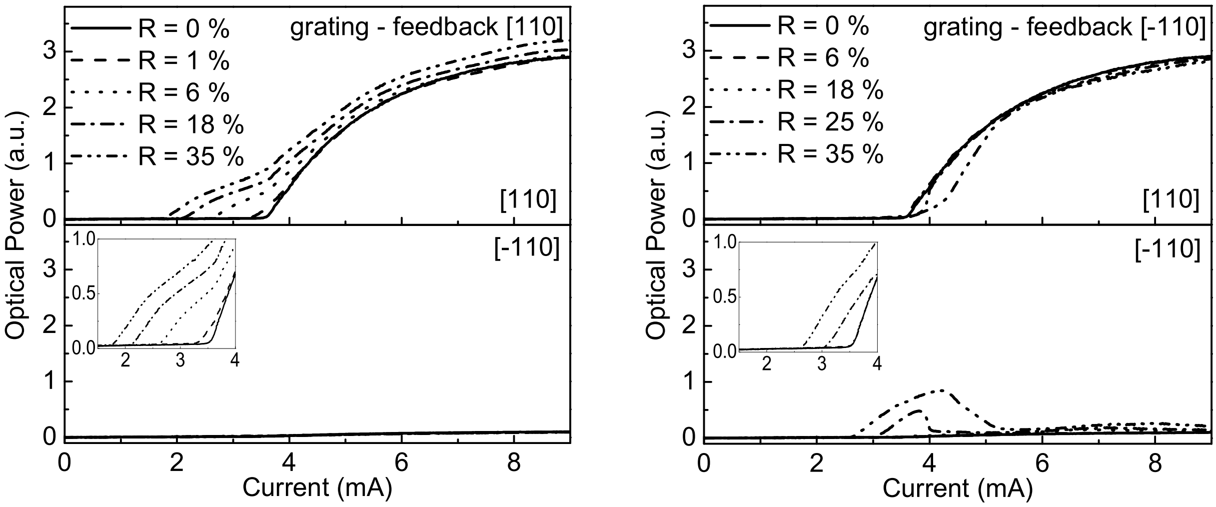

Fig. 5: PR-LI characteristics of the grating VCSEL from Fig. 2 under different levels of optical feedback polarized along the [110] crystal axis (left) and along the [$\bar{1}$10] crystal axis (right).

6. Conclusion

Surface gratings have proven to control the polarization of VCSELs also under isotropic feedback and even under orthogonally polarized optical feedback in the long external cavity regime up to feedback levels of 18 %. In contrast, the polarization of a nominally identical standard VCSEL which is stable without feedback becomes unstable already in case of 1 % isotropic feedback and can be controlled by polarized feedback from the external cavity. Although further investigations of the polarization properties of grating VCSELs under feedback are desirable especially in the short cavity regime, from the presented results one can already conclude that the polarization properties of grating VCSELs are much less sensitive to optical feedback than those of standard VCSELs and that surface gratings are capable of defining the polarization of VCSELs even under very strong external feedback.

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