Sensitivity of Surface Grating VCSELs to Externally Induced Anisotropic Strain

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Linearly polerized surface grating vertical-cavity surface-emitting lasers (VCSELs) are exposed to externally applied anisotropic stress. Their behavior is compared to that of a nominally identical standard VCSEL without a surface grating. The VCSEL chips are bent in a well-defined way. The induced anisotropic in-plane strain leads to a polarization switch of the standard VCSEL for rather moderate strain. In contrast, the polarization of the surface grating VCSELs is fixed by the grating and remains unchanged despite a high strain which causes a wavelength splitting of the two polarization modes of about 130 pm. Such result is of high practical relevance, since strain is unavoidably induced during VCSEL fabrication and mounting and counteracts any method applied for polarization control.

1. Introduction

The influence of strain on the polarization properties of standard VCSELs has been studied in detail [1–5]. Since strain is linked to the complex refractive indices of the different layers inside a VCSEL structure through the strain-optic tensor, it influences the polarization properties of VCSELs via the elasto-optic effect. A modified imaginary part of the complex refractive indices alters gain and absorption and a modified real part causes birefringence in addition to the birefringence already present in VCSELs due to the electro-optic effect [6]. Frequently, the consequence of strain is thus a polarization switch.

Strain in VCSELs can result either from a mismatch of the lattice constants of two layers or from defects introduced during growth and processing. It can also be caused by unintentional stress applied during the mounting and bonding processes. Even if a VCSEL is polarization-stable when tested on wafer, the strain induced during mounting and bonding can be such that the VCSEL exhibits a polarization switch afterwards. Strain can also be induced intentionally to study the polarization properties. This was done by focusing a laser beam to a small spot close to a VCSEL to create a localized heat source [1] or permanent crystal defects [2]. Alternatively, strain in VCSELs can be caused by bending a VCSEL chip mechanically [3].

In recent years, surface gratings have proven to control the polarization of VCSELs very reliably [7, 8]. In this paper, we study whether the polarization control resulting from a surface grating is strong enough to guarantee a stable polarization even under severe externally applied stress.

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2. Measurement Setup

The setup used for the investigations is shown in Fig. 1. Similar to [3] it is based on a mechanical deflection of the VCSEL chip, which is placed on a baseplate with an edge. The sample is clamped with a plate and a screw on one side. A seesaw driven by a micrometer screw on the other side of the sample bends the sample over the edge in the baseplate. The width of the seesaw exceeds the width of the sample to introduce a uniform strain along the direction defined by the edge. All three VCSELs investigated in the paper are located along one row parallel to the $[\bar{1}10]$ crystal axis on the sample. Consequently, they can be aligned simultaneously along the edge of the baseplate, so that the strain induced along the [110] crystal axis is the same in all three VCSELs, although its magnitude is not exactly known. The value Δx stated in the following is the deflection of the seesaw on the side of the sample in a distance of about 6 mm from the edge in the baseplate, as indicated in Fig. 1. However, the amount of strain is not directly proportional to Δx, since the zero point was chosen such that the seesaw does not touch the sample and thus does not induce any strain for $\Delta x = 0$.

To allow a rough estimation of the strain introduced in the VCSELs through the bending and to make the experiments comparable to others reported in the literature [3–5], polarization-resolved spectra are recorded close to threshold to measure the wavelength splitting between the two polarization modes for different deflections.

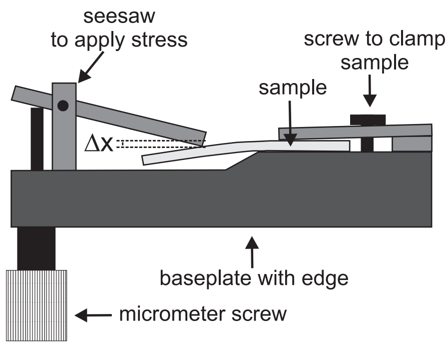

Fig. 1: Schematic drawing of the sample holder used for the investigations of the polarization properties of VCSELs under externally applied stress.

3. Investigated VCSELs

All three VCSELs investigated in this paper are on the same sample with a wafer thickness of 350 µm. They are nominally identical except for the different surface modifications. Their wavelengths vary slightly around 915 nm due to a variation of the thickness of the epitaxial layers over the sample. All three VCSELs have an active diameter of about 4 µm. The two grating VCSELs are adjacent to each other, separated by only 250 µm. Their surface gratings have orthogonal orientations, a period of 0.8 µm, and a depth of 57 nm. The outer diameter of the grating is limited to 3.6 µm to form a grating relief to achieve higher single-mode output powers [7, 9, 10]. The area outside the relief is etched to the same depth as the grating grooves. The mirror reflectivity outside the relief is consequently strongly reduced, which suppresses higher-order transverse modes. Therefore, the grating relief VCSELs are single-mode up to thermal rollover, while higher-order modes start to lase in the standard VCSEL at a current of about three times the threshold current. However, the grating relief causes an overall reduced mirror reflectivity, which explains the higher threshold current of the grating VCSELs compared to the standard VCSEL.

4. Standard VCSEL With Externally Induced Strain

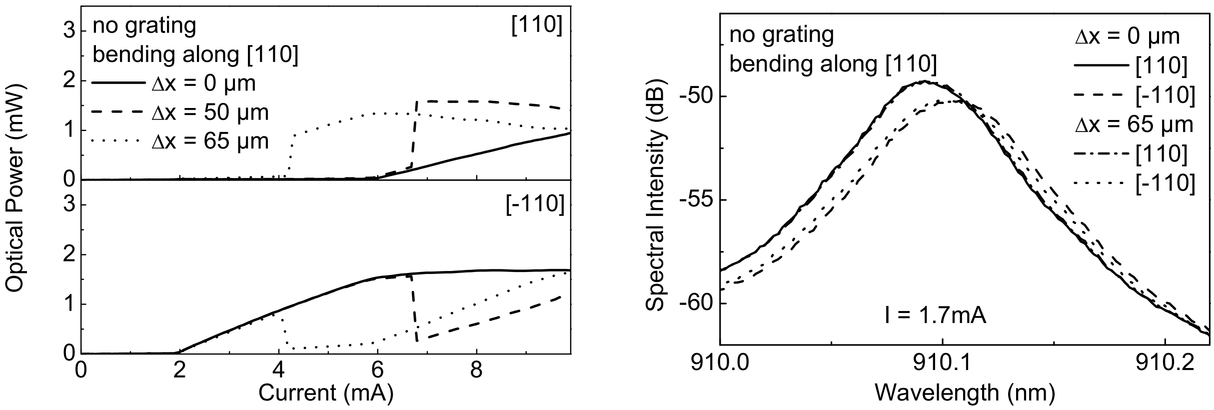

Fig. 2: PR-LI characteristics (left) and polarization-resolved spectra (right) of a standard VCSEL with an active diameter of 4 μm under varying externally applied stress.

Without strain, the fundamental mode of the standard VCSEL is polarized along the [$\bar{1}$10] crystal axis, while the first higher-order mode, which starts to lase at around 5.8 mA, is polarized along the [110] crystal axis, as can be seen from the polarization-resolved light–current (PR-LI) characteristics of this VCSEL shown in the left graph of Fig. 2. However, the fundamental mode of the standard VCSEL and also the higher-order mode exhibit a polarization switch as soon as the sample is bent over the edge of the baseplate. The strain that causes such polarization switches is quite small, since it does not even change the emission wavelengths of the two polarization modes significantly, which is concluded from the polarization-resolved spectra in the right graph of Fig. 2. The current at which the polarization switch occurs is decreasing with increasing bending. These measurements are just intended to illustrate the influence of the externally introduced strain on the polarization properties of standard VCSELs, since similar results were found before by other researchers [3–5]. Here, they serve to quantitatively illustrate the different behaviors of a standard VCSEL and surface grating VCSELs.

5. Surface Grating VCSELs With Externally Induced Strain

In this section we repeat the experiments from Sect. 4 while using grating VCSELs. The grating grooves of the VCSEL in the left (right) graph of Figs. 3 and 4 are oriented along the [110] ([$\bar{1}$10]) crystal axis. Since both grating VCSELs are polarized parallel to

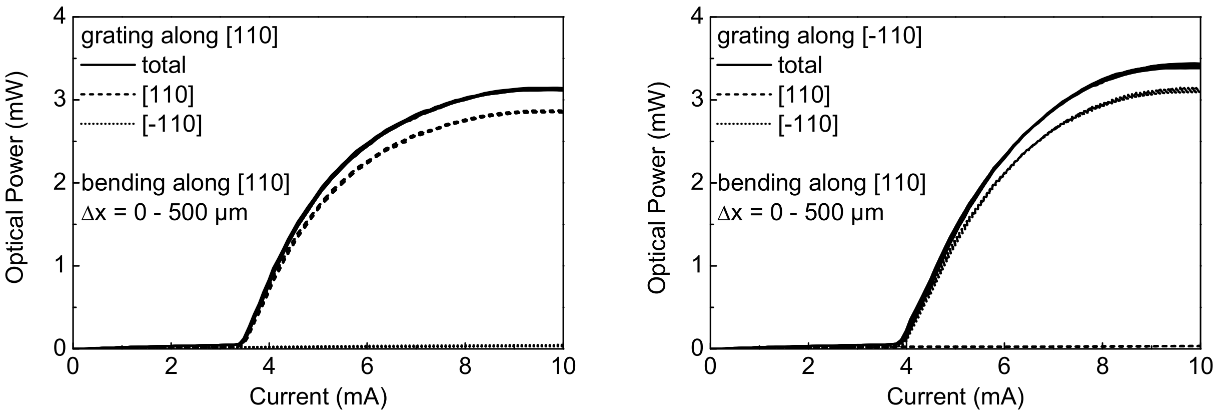

Fig. 3: PR-LI characteristics of grating VCSELs with their grating grooves oriented along the [110] crystal axis (left) and the [$\bar{1}$10] axis (right) under varying externally applied stress. The bending Δx of the sample is varied between 0 and 500 µm in steps of 50 µm. VCSEL parameters are described in Sect. 3.

their grating grooves without externally induced strain (see Fig. 3), they are orthogonally polarized with respect to each other. Consequently, the polarization of one of the two VCSELs is destabilized by the externally applied stress along the [110] crystal axis independent of whether the bending favors the mode parallel or orthogonal to the bending direction. However, even for a deflection exceeding the one causing a polarization switch in the standard VCSEL by a factor of ten, the LI characteristics of the grating VCSELs remain unchanged. Therefore the eleven curves for different bendings are almost indistinguishable in Fig. 3.

The polarization-resolved spectra of the [110]-oriented grating VCSEL in Fig. 4 (left), which are recorded close to threshold, show a birefringence of −20 pm (peak spectral positions of 920.78 and 920.80 nm for the [110] and [$\bar{1}$10] directions, respectively) without bending. It results from a combination of the electro-optic effect and the birefringence induced by the grating itself. For a deflection of $\Delta x = 500\,\mu$m, this value has changed to +100 pm (peaks at 920.85 and 920.75 nm for the [110] and [$\bar{1}$10] directions, respectively) owing to the contribution from the elasto-optic effect. Thus the emission wavelengths of the two polarization modes experience a relative shift of about 120 pm due to the induced strain.

In case of the [$\bar{1}$10]-oriented grating VCSEL in Fig. 4 (right), the birefringence changes from +10 pm to +140 pm for the same amount of bending, corresponding to a relative shift of 130 pm, which is very similar to that in the neighboring device. The observed wavelength shifts indicate an induced maximum strain level comparable to those reported in [3–5]. In all three previous studies using standard VCSELs without a surface grating, such strain causes a change of the polarization orientation by 90°. In contrast, the grating VCSELs remain polarization-stable.

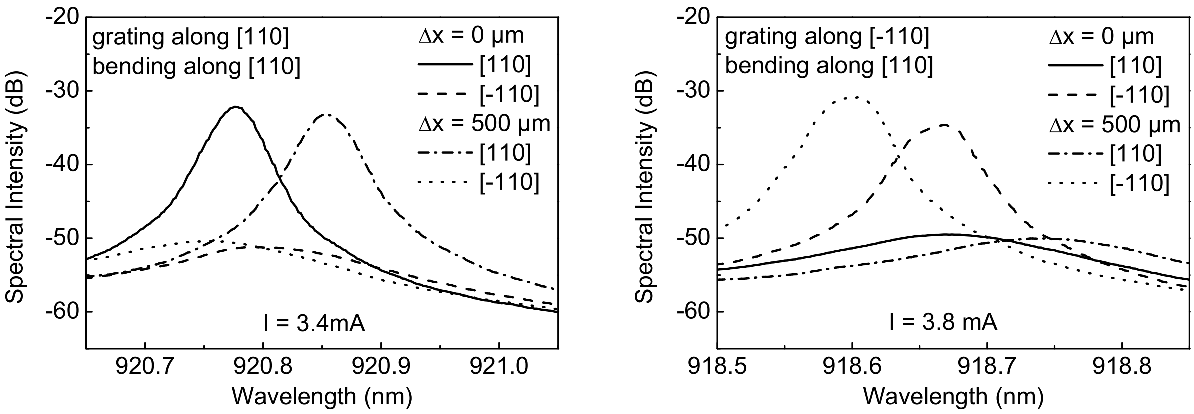

Fig. 4: Polarization-resolved spectra of the grating VCSELs from Fig. 3 close to threshold for the two extreme values of deflection Δx.

6. Conclusion

We have shown that surface gratings are able to control the polarization of VCSELs even for strong externally induced anisotropic in-plane strain, while a nominally identical standard VCSEL exhibits a polarization switch already for a fraction of this strain. The splitting of about 130 pm between the wavelengths of the polarization modes of the grating VCSELs, induced by the applied stress, is fully comparable to the ones reported in the literature [3–5], which inevitably caused polarization switches. This proves the high degree of reliability of the polarization control obtained by means of surface gratings. One can conclude from the measurements presented here that the polarization control of surface gratings is strong enough to outbalance the influence of any strain typically introduced during the fabrication process of VCSELs. To the best of our knowledge, this is the first successful study of VCSEL polarization control under strain conditions.

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