Surface Grating VCSELs With Dynamically Stable Light Output Polarization

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It has been shown recently that the polarization of single- and multi-mode VCSELs can be defined and stabilized very effectively with a monolithically integrated surface grating. Orthogonal polarization suppression ratios of 20 dB or more have been achieved even for transverse multi-mode devices. On the other hand it has not been investigated in detail yet whether these lasers are also polarization-stable under high-frequency modulation. In this paper we show that surface grating VCSELs remain polarization-stable for digital high-frequency modulation up to 10 Gbit/s, modulation amplitudes of up to 1.5 V_{pp} and different modulation patterns. Under modulation, neither polarization-resolved time traces nor polarization-resolved spectra nor the power ratio of the two polarizations indicate a deterioration of the polarization properties compared to the static case.

1. Introduction

The design and fabrication of vertical-cavity surface-emitting lasers (VCSELs) with a dynamically stable polarization has been a research topic since it has been discovered fourteen years ago that VCSELs do not exhibit a well defined light output polarization[1]. This is due to the isotropic gain, the cylindrical resonator and the polarization-independent reflectivity of the Bragg mirrors of standard VCSELs. In most cases, due to the electro-optic effect [2], the individual transverse modes of VCSELs grown on (100)-oriented GaAs substrates are polarized either along the [011] or the [0 ¯11] crystal axis, but they can abruptly change their orientation, which is then called a polarization switch [3]. There have been successful attempts to stabilize the polarization of VCSELs with non-cylindrical resonators, optical feedback, non-isotropic gain and mirrors with a polarization-dependent reflectivity (see [4] and the references therein). But up to now, only VCSELs grown on GaAs (311) B substrates could show a stable polarization under high-speed modulation due to non-isotropic gain. In [5] the orthogonal polarization suppression ratio (OPSR) of such VCSELs remained constant up to 10 Gbit/s modulation in case of multi-mode VCSELs. For single-mode VCSELs on the other hand, the OPSR decreased from 30 dB at static operation to 11 dB for a modulation frequency of 5 GHz.

Because most industrially fabricated VCSELs are realized on (100) substrates, we have been looking for a way to stabilize the polarization of VCSELs grown on these standard substrates. We have first theoretically [6] and then experimentally shown [7] that the

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polarization of single- and multi-mode VCSELs grown on (100) substrates can be well controlled with a monolithically integrated surface grating.

In this contribution we investigate the polarization properties of surface grating VCSELs under high-frequency modulation. All VCSELs are fabricated on the same sample and are tested on-wafer for the best possible comparison. The lasers are designed for an emission wavelength of 850 nm. The layer structure consists of three GaAs quantum wells inside a λ-cavity and of 21 and 37 Bragg-pairs for the upper and lower mirror, respectively. For more details on the investigated lasers we would like to refer the reader to [4], where one can find details on the fabrication process and static properties. Since it is in general more difficult to stabilize the polarization of multi-mode VCSELs than that of single-mode devices, in this paper we will mainly concentrate on the former. The polarization control induced by a surface grating works as well for single-mode VCSELs, as will also be shown. A possible application for polarization-stable multi-mode VCSELs is free-space optics employing polarization multiplexing for increased data throughput at high output powers.

![IV and polarization-resolved LI characteristics of four adjacent lasers with an active diameter of 7 µm. The two VCSELs in the top row are standard lasers without a surface grating, while the two VCSELs in the bottom row have surface gratings with a grating period of 0.7 µm and a grating depth of 36 nm. The grating grooves are oriented along the [011] (bottom left) and [011] (bottom right) crystal axis.](image-url)
2. Polarization Behavior Under Modulation

Figure 1 shows the light–current–voltage (LIV) characteristics of four adjacent lasers with an active diameter of 7\(\mu\)m. The lasers are nominally identical except that the two lasers in the upper row are standard VCSELs without a surface grating, while the lasers in the lower row have a monolithically integrated surface grating with a grating period of 0.7\(\mu\)m and a grating depth of 36 nm. As is the case for the majority of standard multi-mode VCSELs, the output power of the devices is distributed more or less equally between both polarizations, in the present case with a slight preference of the [0-11] direction. In contrast to that, the VCSELs with a monolithically integrated surface grating have one dominant polarization for all modes. The orientation of this dominant polarization is parallel to the grating grooves independent of their orientation along the [011] or [0\bar{1}1] crystal axis.

![Figure 1: Polarization behavior under modulation.](image)

Fig. 2: Polarization-resolved time traces of the bottom-right surface grating VCSEL from Fig. 1. The bias current is 8 mA, the modulation amplitude 1.5 Vpp, and the repetition rates of the alternating 1-0 patterns are 500 MHz (left) and 5 GHz (right).

Using an optical sampling oscilloscope we have measured polarization-resolved time traces of the laser from Fig.1 with the surface grating oriented along the [011] crystal axis for a bias current of 8 mA, an alternating 1-0 pattern and a modulation amplitude of 1.5 Vpp. The difference between the total optical power and the power in the polarization along the [011] crystal axis is due to the insertion loss of the polarization-dependent isolator used as polarizer for these measurements. Applying this large modulation amplitude, the laser is turned completely off and on again for a data rate of 1 Gbit/s (Fig. 2 left). But nevertheless, only the polarization parallel to the surface grating is modulated, while the orthogonal polarization remains clearly suppressed by 25 dB during the on-state. While at a modulation with 10 Gbit/s, due to the limited modulation bandwidth, the laser is no longer switched completely off and on (right side of Fig. 2), the on-off ratio of the modulation nevertheless exceeds 12 dB and the orthogonal polarization is still suppressed by 25 dB.

Under the same modulation conditions as for Fig. 2, we have measured the time-averaged output power in the two orthogonal polarizations with a photodiode under different modulation data rates and modulation patterns for all lasers from Fig. 1. From the data we have calculated the OPSRs which are shown in Fig. 3. The data rate was varied between...
Fig. 3: OPSRs of all lasers from Fig. 1 for different data rates measured at a bias current of 8 mA and with a modulation amplitude of 1.5 V_{pp}.

0 and 10 Gbit/s and we have used a 1-0 pattern as well as a pseudorandom bit sequence (PRBS) with a word length of 2^{31} – 1. As a result, the OPSRs of the surface grating VCSELs are not decreasing by more than 0.3 dB below their static values for any modulation parameter. Likewise, the OPSRs of the standard VCSELs remain very small, independent of the modulation speed.

As an example, the spectra of a standard VCSEL and a VCSEL with a surface grating from Fig. 1, modulated with a data rate of 3 Gbit/s around a bias current of 8 mA, are shown in Fig. 4. The modulation amplitude is 1.5 V_{pp} and we used a 1-0 pattern. The standard laser (left) has contributions from both polarizations in every individual mode, while in the spectra of the surface grating VCSEL (right) the orthogonal polarization is clearly suppressed for all modes.

Fig. 4: Polarization-resolved spectra of a standard VCSEL (left) and a VCSEL with a surface grating (right) from Fig. 1 under high-frequency modulation.
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Fig. 5: IV and polarization-resolved LI characteristics of a grating VCSEL with an active diameter of 4 µm (left) as well as its spectra at a bias current of 5 mA under modulation with a 1-0 pattern, 10 Gbit/s data rate and a modulation amplitude of 1.0 V_{pp} (right).

The left side of Fig. 5 displays the LIV characteristics of a surface grating VCSEL having the same grating parameters as the lasers in Fig. 1 but a smaller oxide diameter of 4 µm. The polarization-resolved spectra on the right side of Fig. 5 are taken at a bias current of 5 mA under a modulation with a 1-0 pattern, 10 Gbit/s data rate and a modulation amplitude of 1.0 V_{pp}. While the peak-to-peak difference between the two polarizations is 37 dB in the case of static operation, it does not decrease below 36 dB when the modulation is applied. Therefore also in the case of single-mode emission no significant decrease of the OPSR could be found.

3. Small-Signal Analysis and Eye Diagrams

The polarization-resolved small-signal analysis of a standard VCSEL in Fig. 6 (top left) reveals that both polarizations are modulated. The curves have been smoothened for better clarity. For the investigation of the small-signal frequency response as well as for displaying the eye diagrams we have used a detector with a 3-dB bandwidth of 10 GHz. For frequencies larger than 7 GHz the response in the [011] polarization seems to be higher than for the total power. But this is just due to a strongly increased noise level, which can be seen from the response in the [011] polarization at a bias current of 6 mA with the RF signal turned off, which is also included in the graph. If the OPSR of a VCSEL is small for a bias well above threshold, its two polarizations have a strong anticorrelation [8]. Therefore, if only one polarization is selected, the measured noise strongly increases, but the amount of increase depends on which polarization is selected. As a consequence of this anticorrelation between the two polarizations, the optical eye diagrams of both polarizations for 10 Gbit/s, PRBS 2^{31} − 1 modulation with 10 mA bias current and applied 1 V_{pp} modulation amplitude close when a polarizer is inserted in the optical path (Fig. 6, bottom row), while in contrast the eye is clearly open without a polarizer (top right) for the same total received power.

Quite in contrast, a VCSEL with a surface grating shows a response to the small-signal
Fig. 6: Small-signal frequency responses (top left) of a standard VCSEL (the top left one in Fig. 1) for bias currents of 4 and 6 mA as well as eye diagrams for 10 Gbit/s, PRBS $2^{31} - 1$ modulation without a polarizer in the optical link (top right) and with a polarizer (bottom; left: [011] polarization, right: [011] polarization).

modulation only in one polarization (Fig. 7, top left). When inserting a polarizer in the optical path, which is oriented to transmit the dominant [011] polarization, the quality of the 10 Gbit/s optical eye diagram remains basically unchanged (bottom right) compared to the case without a polarizer (top right), while there is no signal in the orthogonal polarization (bottom left) for 11 mA bias current and applied 1 V$_{pp}$ modulation amplitude.

4. Conclusion

VCSELs with monolithically integrated surface gratings have shown one dynamically stable polarization for all modes and all tested modulation parameters, namely digital modulation speeds up to 10 Gbit/s, modulation amplitudes up to 1.5 V$_{pp}$, and two different bit patterns (1-0 and PRBS $2^{31} - 1$). No significant decrease of the OPSR could be found for any device. Also when switching the laser on and off, the orthogonal polarization remains clearly suppressed, as can be seen from polarization-resolved time traces. Therefore surface grating VCSELs are well suited for high-frequency applications requiring a stable light output polarization.
Fig. 7: Small-signal frequency responses (top left) of a grating VCSEL (bottom right in Fig. 1) for bias currents of 4 to 12 mA in steps of 2 mA and 10 Gbit/s eye diagrams as in Fig. 6 (top right: without polarizer, bottom left: polarizer in [011] direction, bottom right: [0̅11]).

Acknowledgment

The authors would like to thank Philipp Gerlach and the former VCSEL group member Felix Mederer for their help in performing and discussing the measurements and U-L-M photonics and Yakiv Men for their processing support. The University of Ulm gratefully acknowledges the partial funding of this work by the German Research Foundation (DFG).
References


