Shallow Surface Gratings for High-Power VCSELs With One Preferred Polarization for All Modes

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Monolithically integrated full-aperture surface gratings are shown to control the polarization of all modes of even highly multi-mode 850 nm oxide-confined standard industrial vertical-cavity surface-emitting lasers (VCSELs). An orthogonal polarization suppression ratio (OPSR) of more than 11 dB up to thermal rollover is achieved for an output power of 23 mW. For devices with 8 mW output power, an OPSR of more than 20 dB at thermal rollover is observed, without major drawbacks to the overall laser performance.

1. Introduction

VCSELs show light emission lacking a strictly defined direction of polarization [1]. This is due to their isotropic gain, their usually circular resonator and the polarization-independent reflectivity of their Bragg mirrors. The electro-optic effect, induced by the doping in the Bragg mirrors, leads to a preferred polarization of the individual modes along the [011] and [0$\bar{1}$1] crystal axes [2]. In most cases the first higher order mode is polarized orthogonal to the fundamental mode. Further higher order modes can assume any of these two polarizations. If the current or the temperature changes or if optical feedback or strain is applied, a sudden change of the polarization direction of one or more modes from one of the preferred crystal axes to the other can take place. This is called a polarization switch [3].

Several approaches have been made to stabilize and control the polarization of VCSELs. These approaches can be classified in polarization-sensitive feedback (e.g. [4]), anisotropic gain (e.g. [5]), non-circular resonator geometries (e.g. [6]) or mirrors with polarization-dependent reflectivity (e.g. [7]). A main goal of our studies is to identify way of polarization control suitable for mass production. Direct incorporation into the fabrication sequence of standard industrial VCSELs grown on (100)-oriented GaAs substrates should be possible. Thus, many of the above mentioned methods have to be ruled out. As proposed in [8] we are using optical gratings which are etched into the cap-layer of the VCSELs. While previously pure metal or metal/semiconductor gratings have been used [7], simulations in [8] have shown that pure semiconductor gratings are more favorable due to smaller absorption.

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2. Fabrication

The VCSELs were processed from standard epitaxial material for 850 nm wavelength oxide-confined VCSELs, supplied by U-L-M photonics. As the first step the full-aperture grating was realized using electron-beam lithography and wet-chemical etching. The etching process produces grating ridge edges having an angle of about 30 degrees with respect to the surface. The ratio between ridge width and grating period is approximately 65 %. In Fig. 1 an atomic force microscope (AFM) image of a grating with a period of 1.0 μm and an etching depth of 24 nm is shown. In contrast to previous suggestions [9] we use shallow surface gratings of only several tens of nanometers depth in order to not degrade the overall laser performance.

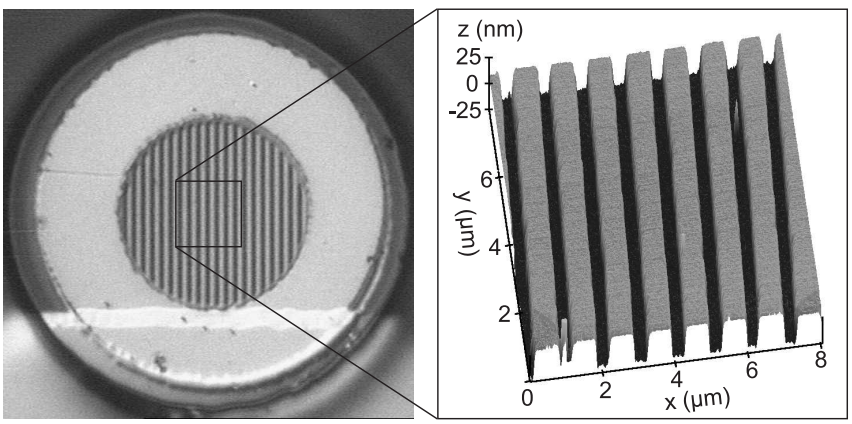

Fig. 1: Photograph of a VCSEL with an integrated surface grating (left) and an AFM measurement showing the grating in more detail (right, please note the change of scale between the x,y and the z-axis).

3. Electro-Optical and Spectral Characteristics

Figure 2 shows the polarization-resolved light–current–voltage (LIV) characteristics as well as the polarization-resolved spectra at a current of 15 mA of a standard VCSEL which is fabricated on the same chip adjacent to the grating devices. The spectra clearly reveal different modes to have different polarizations. As a consequence no polarization is preferred, which is also observed in the two LI curves recorded for the dominating [011] and [0$\bar{1}$1] crystal directions.

To be compared with Fig. 2, Fig. 3 shows the polarization-resolved LIV characteristics and polarization-resolved spectra at different currents of a VCSEL which is adjacent and nominally identical to the one shown in Fig. 2, but has an integrated surface grating as depicted in Fig. 1. This device clearly exhibits a preferred polarization orthogonal to the grating as predicted by the numerical simulations [10]. The difference between the measured total output power and the sum of the powers in both polarizations is due

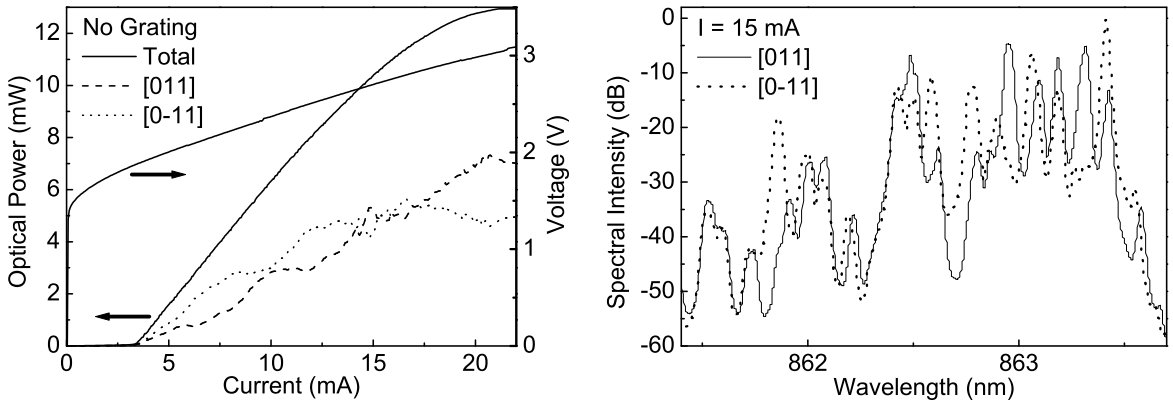

Fig. 2: Polarization-resolved LIV characteristics (left) and spectra (right) for a reference device with an active diameter of 9 μm.

to the transmission loss of the polarizer. Already below threshold (upper right graph in Fig. 3), one can see the two polarizations of one mode. They differ by 40 pm in wavelength due to the birefringence induced by the electro-optic effect and the surface grating. At a current of 15 mA the non-preferred polarization is well suppressed for all modes. The orthogonal polarization suppression ratio (OPSR) can either be defined by the peak-to-peak ratio between the strongest mode of the preferred polarization and the strongest mode of the suppressed polarization, which yields 24.9 dB for the present device at a current of 15 mA. Alternatively the OPSR may be understood as the optical power ratio which gives a reduced value of 18.6 dB. The difference is obviously due to the spectral integration done by the photodiode in the second measurement method. In what follows we will always refer to the OPSR calculated form the powers in the two polarizations.

The orientation of the polarization can be defined by the orientation of the grating grooves, as seen in Fig. 4. Both devices are nominally identical with the same grating parameters, but with their grating grooves oriented orthogonal to each other. While the polarization orientation of these two devices is therefore also mutually orthogonal, the other device properties remain essentially the same. In particular this is true for the OPSR, which for both devices exceeds 20 dB for currents above 11 mA.

As illustrated in Fig. 5, the grating even defines a preferred polarization for all modes of a high-power VCSEL with an output power exceeding 20 mW. However, the suppression for high-order modes by these shallow gratings is less effective than for low-order modes. This effect is already observed in the spectra taken at a current of 20 mA in Fig. 3 and explains the reduced OPSR for the device from Fig. 5. Nevertheless the OPSR remains larger than 11 dB up to thermal rollover.

The benefits from the surface gratings and their influence on other laser properties such as threshold current, differential quantum efficiency, and maximum output power is discussed in Fig. 6 for devices with oxide diameters between 7 and 18 μm. The open dots show the standard reference devices from the same sample, while the filled dots represent VCSELs with a surface grating with an etch depth of 24 nm and a period of 1 μm. For each oxide

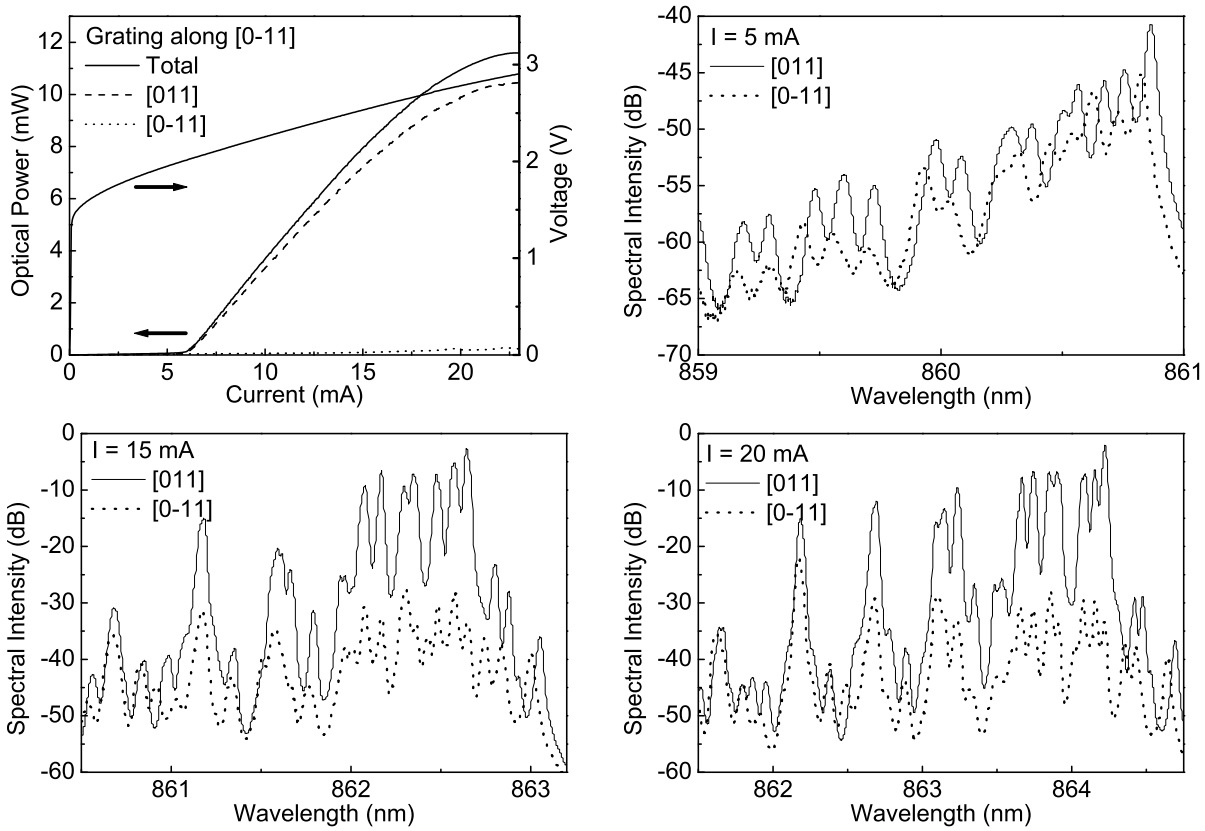

Fig. 3: Polarization-resolved LIV characteristics and spectra at different currents for a grating device with a grating period of 1.0 μm, a grating depth of 24 nm and an active diameter of 9 μm.

diameter we have measured all available VCSELs with this grating parameters on the chip, namely 5 or 6 reference devices and 5 to 7 grating devices. No reference VCSELs with 7 μm oxide diameter were processed. The OPSRs in the top–left graph are calculated from the polarization-resolved LI curves by averaging over the interval from 10 % of the maximum output power to thermal rollover. We define the OPSR as the power in the polarization parallel to the grating grooves divided by the power in the orthogonal polarization. As observed before and as expected by the simulations, the grating VCSELs are polarized orthogonal to the grating grooves, which leads to negative OPSRs. One can clearly see that VCSELs without a surface grating have no preferred direction of polarization, while VCSELs with a surface grating have a mean OPSR of -19.5 dB for the 7 μm devices. The mean magnitude of the OPSR decreases with increasing active diameter to 10.9 dB for 18 μm devices. As a drawback, depending on the epitaxial layer design, the surface grating can lead to an increase in threshold current, a small decrease of the differential efficiency and as a consequence to a smaller output power (see Fig. 6). But on one hand, in our opinion these drawbacks are not too severe in the present case. On the other hand, we have already shown that different epitaxial material VCSELs can yield increases of both the differential efficiency and the total output power as a result of grating integration [11].

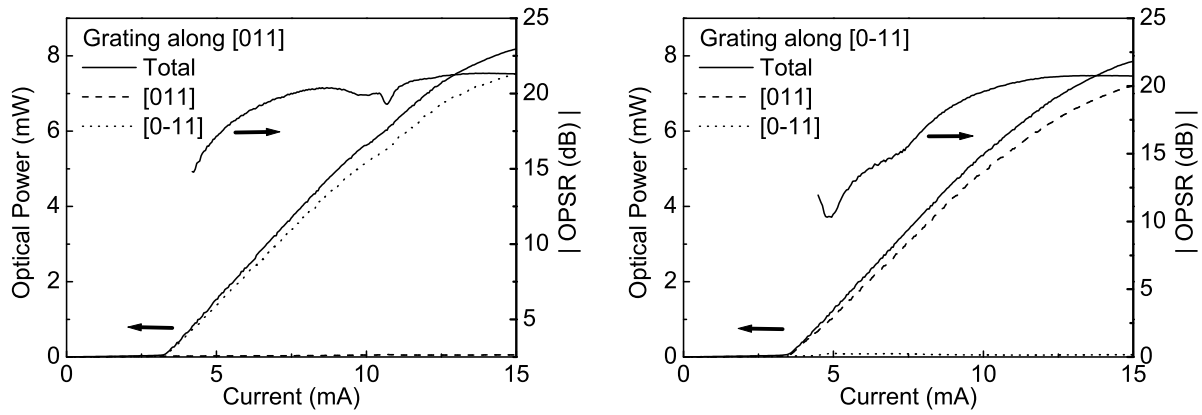

Fig. 4: Operation characteristics of two adjacent, nominally identical VCSELs with an active diameter of 6.5 μm and a nominally identical surface grating (1.0 μm period and 24 nm depth), but with their gratings turned by 90 degrees with respect to each other.

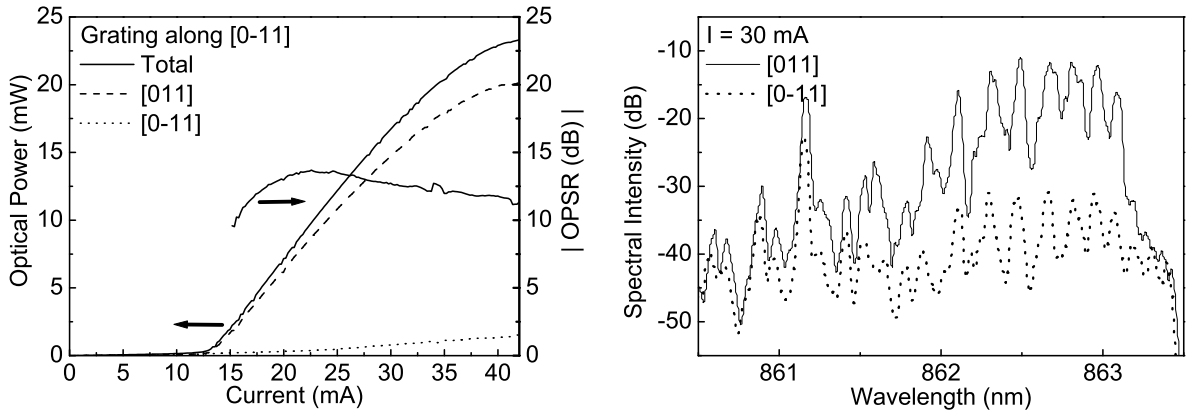

Fig. 5: Polarization-resolved LIV characteristics (left) and polarization-resolved spectra (right) for a high-power, highly multi-mode VCSEL with an active diameter of 18 μm.

4. Far-Field Emission

The left side of Fig. 7 shows the far-field of a 9 μm diameter standard VCSEL at an operating current of 15 mA. In the case of a grating VCSEL, one has to distinguish between the far-field orthogonal and parallel to the grating grooves. While no substantial difference to the reference device can be seen in Fig. 7 (right) in the far-field parallel to the grating grooves, the orthogonal far-field shows small side-lobes at an angle of approximately 50 degrees. For measuring the power of the VCSELs, the laser light is collimated with a AR-coated lens, which captures only the power within a ±30 degrees angular interval. To some extent this explains the reduced output powers of the grating devices in the previous LI curves. The central far-field lobe itself remains undisturbed. As has been shown in [10], the far-field side-lobes vanish for grating periods smaller than the emission wavelength, which will be considered in future designs.

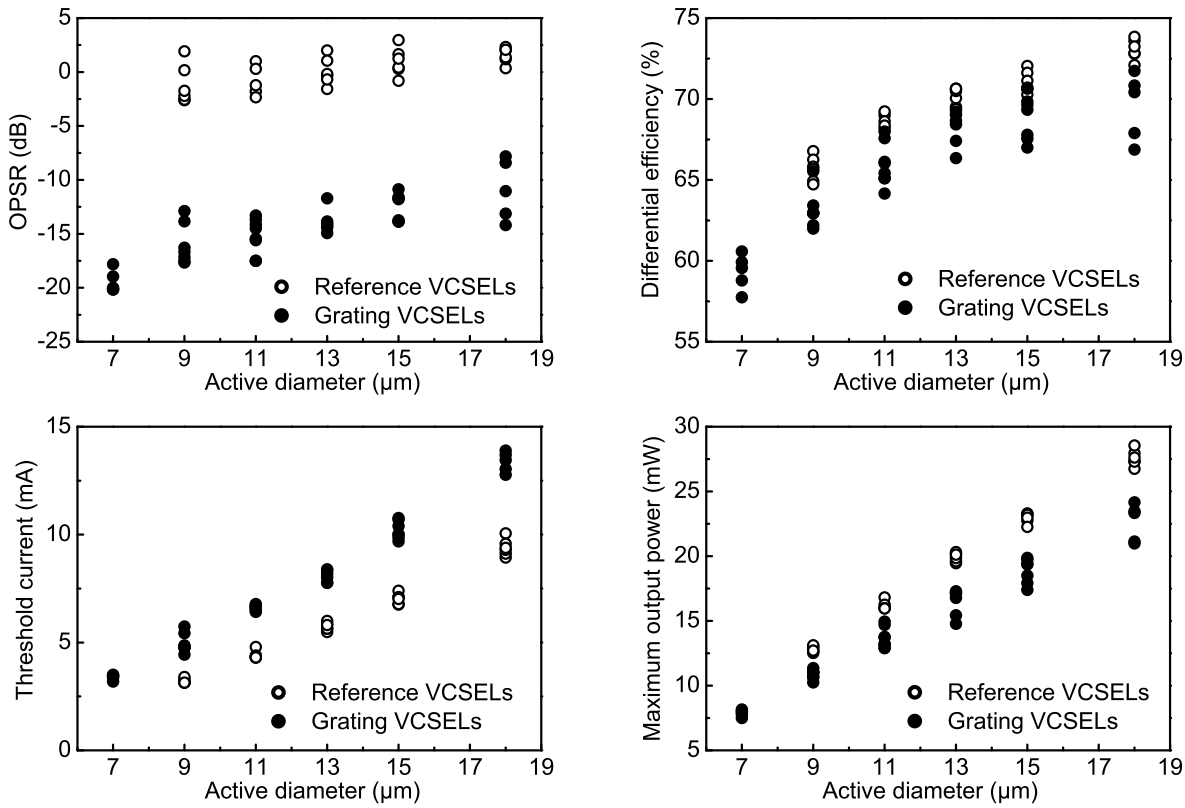

Fig. 6: Comparison of reference devices and grating devices with respect to OPSR (top–left), differential quantum efficiency (top–right), threshold current (bottom–left), and maximum output power (bottom–right).

5. Conclusion

High-power, highly multi-mode VCSELs with an integrated surface grating show one preferred and stable polarization for all transverse modes. Devices with 8 mW of output power have more than 20 dB OPSR. For carefully chosen grating parameters, especially for small etch depths, the overall performance with respect to threshold current, differential quantum efficiency, output power, and far-field properties decreases only slightly. With increasing active diameter and increasing number of modes the OPSR decreases. Nevertheless 11 dB are still achieved for an output power of more than 23 mW.

6. Acknowledgement

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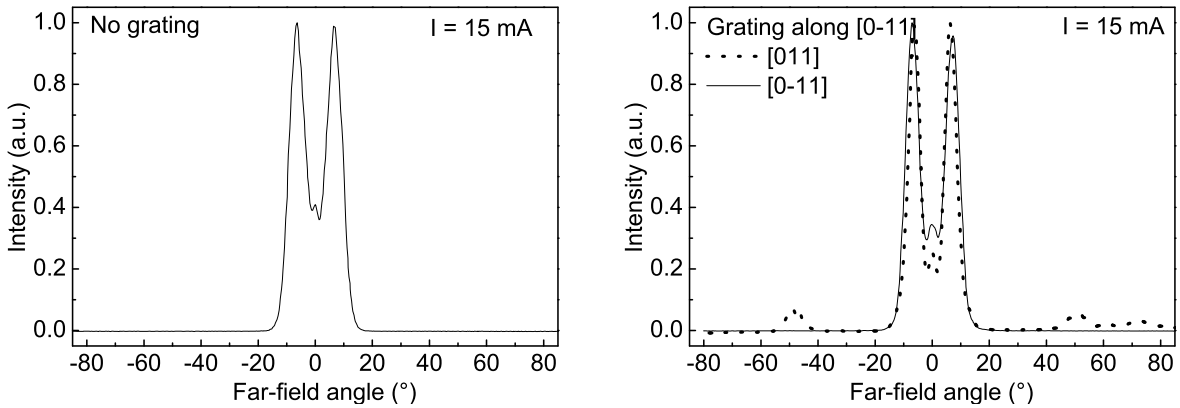

Fig. 7: The far-field of the standard VCSEL shown in Fig. 2 (left) and the parallel and orthogonal far-fields of the grating VCSEL from Fig. 3 (right), all at 15 mA current.

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