Polarization-Stable VCSELs for Optical Sensing and Communications

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Abstract
We review our work on short-wavelength transverse single-mode or multimode VCSELs that show stable linearly polarized light output owing to the incorporation of surface gratings. An emphasis is put on optical sensing and communications applications.

Introduction
Caused by their cylindrically symmetric cavity design, conventional vertical-cavity surface-emitting lasers (VCSELs) have no fixed, predictable polarization of their output light, quite in contrast to edge-emitting laser diodes. When grown on (100)-oriented GaAs substrates, VCSELs usually show laser emission polarized along the [011] or [0−11] crystal axes, which is mainly caused by internal electric fields in the doped Bragg reflectors and the associated electro-optic effect. Moreover, the polarization is not even stable, i.e., the polarization of a certain mode can turn abruptly with varying bias current (a so-called polarization switch) and different transverse modes have different polarizations. Many short-wavelength VCSEL applications demand polarization stability, in particular optical sensing and spectroscopy. However, also optical interconnect systems could benefit from the availability of linearly polarized single-mode or multimode lasers. In this paper we outline the grating VCSEL design and present applications in optical computer mice, oxygen sensing, miniaturized atomic clocks, as well as free-space data transmission.

Grating VCSEL Design Issues
Until recently no polarization control method suited for practical incorporation into a commercial monolithic oxide-confined short-wavelength VCSEL had been identified [1]. To solve this problem, since the year 2003 we have investigated in some detail the use of linear semiconductor surface gratings etched into the cap layer of the top mirror. This was done both theoretically and experimentally. Our aim was to find a manufacturable and highly reliable technique, such as required for mass production. Meanwhile we have demonstrated polarization control for VCSELs emitting in the 760, 780, 850, 920, and 980 nm wavelength regimes. An extension to other wavelengths is obvious. Device fabrication is described in [1]. Compared to standard VCSELs, it involves only a few additional processing steps, namely the definition of the grating and its subsequent etching at the beginning of the fabrication sequence. As a design

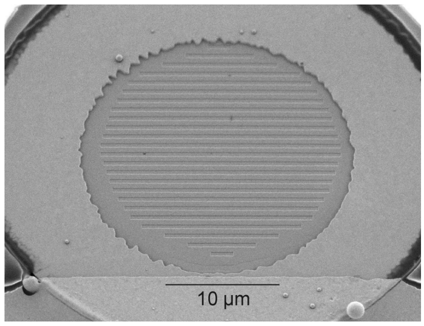

Fig. 1. Scanning electron micrograph of a fully processed VCSEL incorporating a surface grating [1].

example, Fig. 1 displays the light outcoupling facet of a manufactured grating VCSEL. The polarizing effect relies on the difference in optical losses and thus threshold gains of modes polarized parallel or orthogonal to the grating lines. It is important to note that the grating does not just interact with the transmitted radiation. Instead it has to be regarded as an integral part of the laser resonator, and its position in the longitudinal standing wave pattern is an important design parameter. Extensive three-dimensional vectorial modeling of wave propagation in the resonator has been performed and excellent agreement with experimental results is achieved. Strongest effects are expected for a duty cycle close to 50 % (i.e., the grating ridges are about as wide as the grooves) and most suitable grating periods are somewhat smaller than the emission wavelength. Grating depths are just a few tens of nanometers. Easily, with a wrong choice of parameters, the grating has a too weak effect for reliable polarization control. The grating design is studied in some detail in [2]. Variations of the grating period, depth, shape, lateral position, and duty cycle are considered in addition to the issues of top mirror reflectivity, wavelength scaling, bottom emission, and the use of hybrid instead of monolithic surface gratings. Detailed measurements of the actual strength of the polarization control are reported in [3]. A very good agreement between measurements and vectorial simulations is obtained. High differences of modal threshold gains in both polarizations of more than 20 cm^{-1} are found, indicating the excellent capability of integrated surface gratings for reliable polarization control even under extreme operating conditions. Indeed, experiments have yielded an unprecedented stability of grating VCSELs with respect to optical feedback [4] and externally induced anisotropic strain [5].

Best performance is achieved with so-called inverted grating VCSELs. Here, the grating is etched into an antiphase-terminated top Bragg mirror which differs from the regular design by an additional GaAs quarter-wave layer [6]. Such lasers show a polarization orthogonal to the grating lines, fully consistent with the simulations. Compared to regular grating VCSELs, fabrication tolerances are now much relaxed and quasi linearly polarized laser emission is obtained from devices with only moderately increased threshold current and no penalty in differential quantum efficiency and maximum output power. As a further advantage of inverted grating VCSELs, the investigations in [6] prove that this layer design moreover strongly reduces diffraction effects.

Combining single transverse mode emission with polarization stability is of major interest for, e.g., optical spectroscopy or data transmission over single-mode optical fibers. This is achieved particularly well by combining the surface relief approach [7] with a monolithic grating. Figure 2 shows a photograph and the grating profile of an inverted grating relief VCSEL, in which the grating occupies only a small fraction of the output facet. The diameter of such a grating relief has to be adjusted to the diameter of the active region, which is defined by the oxide aperture. It turns out that optimum ratios are equal to (or slightly larger than) 0.5. A systematic comparison between reference VCSELs and inverted grating relief lasers is made in [9].

Grating VCSEL Applications

Optical navigation devices, in particular computer mice have recently evolved as the first sensing-type mass market for VCSELs with production quantities exceeding 100 million units per year — much larger than those for communications applications. Usually the sensing scheme requires the laser to be dynamically polarization-stable; a polarization switch would induce unpredictable jumps of the mouse pointer on the screen. The grating technique developed at Ulm University has been commercialized [10] and is applied, e.g., in novel VCSEL sensors based on self-mixing interference of the laser light [11].

For applications in oxygen sensing, we have fabricated AlGaAs/GaAs-based single-mode VCSELs emitting in the 760 nm wavelength range. The inverted surface grating relief technique was proven to be very successful, yielding complete polarization stability under varying ambient temperature and record-high single-mode output powers of more than 2.6 mW at room temperature [8]. Practical measurement results employing the TDLAS (tunable diode laser absorption spectroscopy) method in which the laser line is tuned over the absorption lines under investigation are published in [12]. A mode-hop-free tuning range of more than 7 nm with a side-mode suppression ratio exceeding 30 dB has enabled simultaneous evaluations of temperature, pressure, and oxygen concentration in air as well as high-pressure measurements and improved accuracy due to averaging over a multiplicity of absorption lines.

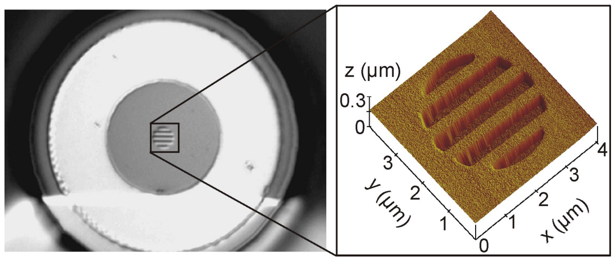

Fig. 2. Photograph of a VCSEL with an integrated surface grating relief (left) and an atomic force microscope measurement showing the grating relief in more detail (right) [8].

Miniaturized atomic clocks are another promising application field [13]. We are currently working on the optimization of VCSELs for Cs-based clocks, demanding single-mode, single-polarization emission at 894.6 nm wavelength under harmonic 4.6 GHz intensity modulation at elevated temperature. Results will be shown at the conference.

Polarization-stable short-wavelength VCSELs are of use not only for sensing but also for optical interconnection, i.e., data transmission over short distances. When, as in, e.g., free space, the polarization state of the signal is preserved, polarization-sensitive detection schemes can easily be applied. Free-space optical data transmission is in fact already a commercial market for 850 nm VCSELs, however, with link distances in the 100 m to few kilometer range. Because high output power levels are required, multimode lasers are chosen. The surface grating technique uniquely allows to produce also quasi linearly polarized multimode VCSELs. Their availability offers the new opportunity to utilize polarization division multiplexing in free-space optics. Very compact transmitter components are conceived, based on a monolithic, individually addressable two-laser chip with orthogonal polarization directions as defined by the grating orientations. The beams are sent through common optics, and polarizers serve to select the channel at the receiver. In [2], we have shown the basic functionality of such a system operating at an aggregate data rate of 16 Gbit/s.

Conclusions

Applying surface gratings is a very successful technique to stabilize the polarization of VCSELs. Such devices are already used in highest performance computer mice.

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