# Continuous-Wave Characteristics of MEMS Atomic Clock VCSELs

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*Vertical-cavity surface-emitting lasers (VCSELs) emitting at 894.6 nm wavelength have been fabricated for Cs-based atomic clock applications. For polarization control, a previously developed technique relying on the integration of a semiconducting surface grating in the top Bragg mirror of the VCSEL structure is employed. More specifically, we use a so-called inverted grating. The VCSELs are polarized orthogonal to the grating lines with no far-field diffraction side-lobes for sub-wavelength grating periods. Orthogonal polarization suppression ratios exceed 20 dB. The polarization stability has been investigated at different elevated substrate temperatures up to 80°C, where the VCSEL remains polarization-stable even well above thermal roll-over.*

## 1. Introduction

Atomic clocks are stable frequency sources which provide enhanced accuracy and stability required for many recent civil and military applications ranging from communication systems to global positioning as well as synchronization of communication networks. Nowadays these applications are increasingly demanding frequency sources with long-term instabilities below $10^{-11}$ over one day, which cannot be afforded by quartz-based clocks. Hence, research into miniaturized atomic clocks has been initiated in particular in the United States of America [1], [2]. In 2008, the European Commission (EC) started to fund a collaborative research project within its seventh framework programme (FP7) for research and technological development to realize the first European miniature-size atomic clock. It is called *MEMS atomic clocks for timing, frequency control & communications* (MAC-TFC, www.mac-tfc.eu). The objective of MAC-TFC is to develop and demonstrate all necessary technology to achieve an atomic clock having a volume less than 10 cm$^3$, a power consumption not exceeding 155 mW, and a short-term instability (Allan deviation) of $5 \times 10^{-11}$ over one hour averaging interval. The proposed atomic clock is based on coherent population trapping (CPT), obtained in an extremely compact Cs-based vapor cell of a few cubic millimeters volume which is illuminated by a high-frequency modulated VCSEL [3].

VCSELs are compelling light sources for MEMS atomic clocks, since they simultaneously meet the requirements of 65 to 80 °C temperature operation while emitting a low-noise, narrow-linewidth, single-mode, single-polarization beam with 894.6 nm wavelength under harmonic 4.6 GHz intensity modulation (as required for CPT using the Cs D1 line). Their sub-mA threshold currents are favorable for small power consumption, and hybrid integration with the clock microsystem is straightforward.

# 2. VCSEL Design and Fabrication

## 2.1 Layer structure

The VCSEL wafer was grown by solid source molecular beam epitaxy on an n-doped (100)-oriented GaAs substrate. Above the GaAs substrate, there is a 2 µm thick highly n-doped GaAs layer to allow n-contacting. The bottom n-type distributed Bragg reflector (DBR) consists of 38.5 $Al_{0.2}Ga_{0.8}As/Al_{0.9}Ga_{0.1}As$ layer pairs. The active region contains three compressively strained InGaAs quantum wells with 6 % indium content. Above the active region, there is a 30 nm thick AlAs layer for wet-chemical oxidation, required to achieve current confinement and lateral optical guiding of the laser radiation. To achieve single transverse mode laser oscillation, the active aperture formed by selective lateral oxidation is chosen to be 3 to 4 µm. A 25 $Al_{0.2}Ga_{0.8}As/Al_{0.9}Ga_{0.1}As$ layer pairs p-type DBR is grown on top of the AlAs layer. The DBRs are graded in composition and doping concentration for minimizing both the free-carrier absorption as well as the electrical resistance. Moreover, $\delta$-doping is incorporated into the DBRs for improved performance of the VCSEL in terms of low threshold currents and high differential quantum efficiencies [4]. The structure has an additional topmost GaAs quarter-wave layer in which the so-called inverted grating is etched to achieve laser emission with a single polarization mode.

## 2.2 Grating design and fabrication

Polarization stability of the VCSEL emission is of a great interest for MEMS atomic clock applications. The polarization control technique applied in this work relies on the integration of a semiconducting surface grating in the top Bragg mirror of the VCSEL structure [5]. Compared to standard VCSELs, the fabrication of grating VCSELs involves just a few additional processing steps, namely the definition of the grating and its subsequent etching at the beginning of the fabrication sequence. Moreover, for a special grating VCSEL type, an extra topmost GaAs quarter-wave layer has to be grown. This layer serves as an antiphase layer, creating so-called inverted grating VCSELs [6]. The emission of theses devices is polarized orthogonal to the grating lines. Compared to regular grating VCSELs, fabrication tolerances are 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, diffraction effects are strongly reduced [6]. Grating fabrication employs electron-beam lithography and wet-chemical etching using citric acid. Figure 1 displays the light outcoupling facet of an inverted grating VCSEL. The polarizing effect originates from the difference in optical losses (top mirror reflectivity) and thus threshold gains of modes polarized parallel or orthogonal to the grating lines. Surface gratings are easy to adapt to different devices, since the major grating parameters scale with the emission wavelength. Therefore the grating design parameters selected in this work are based on simulations and experimental results of VCSELs emitting in other wavelength regimes [6], [7]. Inverted gratings with quarter-wave etch depth, sub-wavelengh grating periods (specifically 0.6 and 0.7 µm), and 50 % duty cycle have been employed. These grating parameters have shown the best performance in terms of low threshold current, low diffraction loss, and high orthogonal polarization suppression ratio [6].

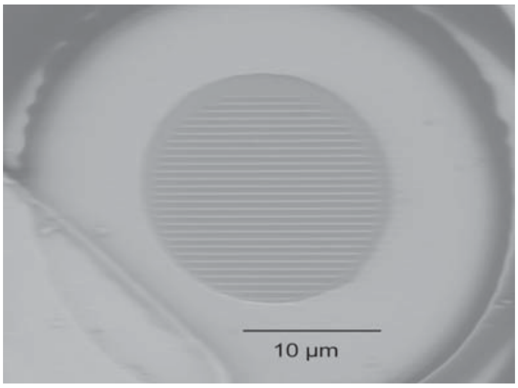


**Fig. 1:** Scanning electron micrograph of a fully processed surface grating VCSEL.

## 3. Characterization

The correct emission wavelength of 894.6 nm in the given case is the key selection parameter of VCSELs for MEMS atomic clocks. As mentioned above, the emission wavelength should be obtained at elevated ambient temperature and moderately high bias currents to guarantee a low power consumption and sufficient modulation bandwidth.

### 3.1 Operation characteristics and spectra

VCSELs having standard n-type substrate-side contacts have been successfully fabricated. Figure 2 (left) shows the light–current–voltage characteristics of a VCSEL with an active diameter of 4.4 µm. Its threshold current is lower than 0.5 mA. The continuous-wave spectrum at a current of 2.4 mA is illustrated in Figure 2 (right). The fundamental transverse mode is lasing at 894.6 nm. A higher-order mode is located on the short-wavelength side with a side-mode suppression ratio of more than 25 dB, which is large enough for the present application. Figure 3 shows the spectrum of another VCSEL with 3.3 µm active diameter. At an elevated temperature of 80 °C (as it might be expected in an integrated MEMS atomic clock) and a current of 4.7 mA, this device reaches the target wavelength with a side-mode suppression ratio of almost 40 dB.

### 3.2 Polarization control

In this subsection, we investigate the polarization stability of inverted grating VCSELs. Figure 4 (left) depicts the polarization-resolved light–current–voltage (PR-LIV) characteristics of a VCSEL with 4.1 µm active diameter, a grating period of 0.7 µm, and a grating depth of 60 nm. The dashed and dash-dotted lines represent the optical power measured behind a Glan–Thompson polarizer[2] whose transmission direction is oriented parallel and

[2]B. Halle GmbH, model PGT, long version, 60 dB extinction ratio

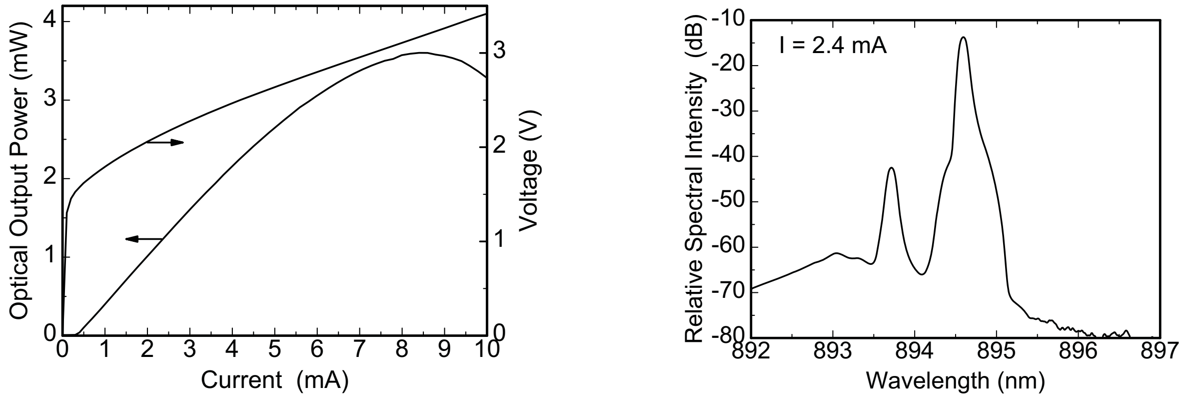


**Fig. 2:** Operation characteristics of an 895 nm VCSEL with 4.4 µm active diameter (left). Spectrum of the same VCSEL at 2.4 mA current and $T = 300$ K ambient temperature (right).

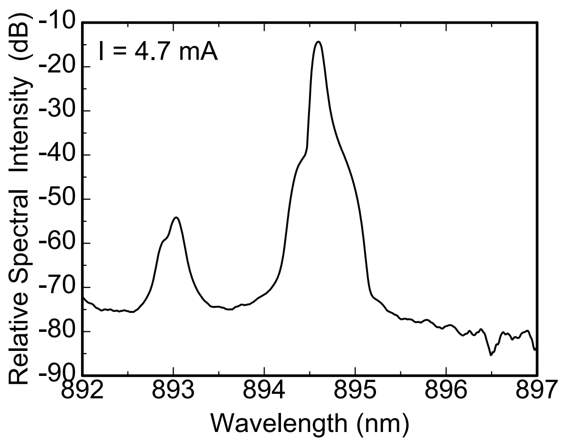


**Fig. 3:** Spectrum of a VCSEL with 3.3 µm active diameter at 4.7 mA current and $T = 80\,°$C ambient temperature.

orthogonal to the grating lines, respectively. The magnitude of the orthogonal polarization suppression ratio (OPSR) exceeds 20 dB for currents between 2.5 mA and thermal roll-over. Here, the OPSR is defined as the ratio between parallel and orthogonal output powers, namely

$$\mathrm{OPSR} = 10 \cdot \log \left( \frac{P_{\mathrm{parallel}}}{P_{\mathrm{orthognal}}} \right) \mathrm{dB}\ . \tag{1}$$

Since the VCSELs to be incorporated in MEMS atomic clock microsystems will experience high ambient temperatures (e.g., $T = 65\,°$C), the polarization control introduced by surface gratings has been investigated under elevated temperature conditions. Figure 4 (right) shows PR-LI characteristics of a grating VCSEL with the substrate temperature varied between 20 and 80 °C in steps of 20 °C. As can be seen, the grating VCSEL remains polarization-stable even well above thermal roll-over.

### 3.3 Far-field properties

For optimum light routing in the clock microsystem, it is important to know the beam properties of the VCSELs. The emission far-fields of a single-mode inverted grating

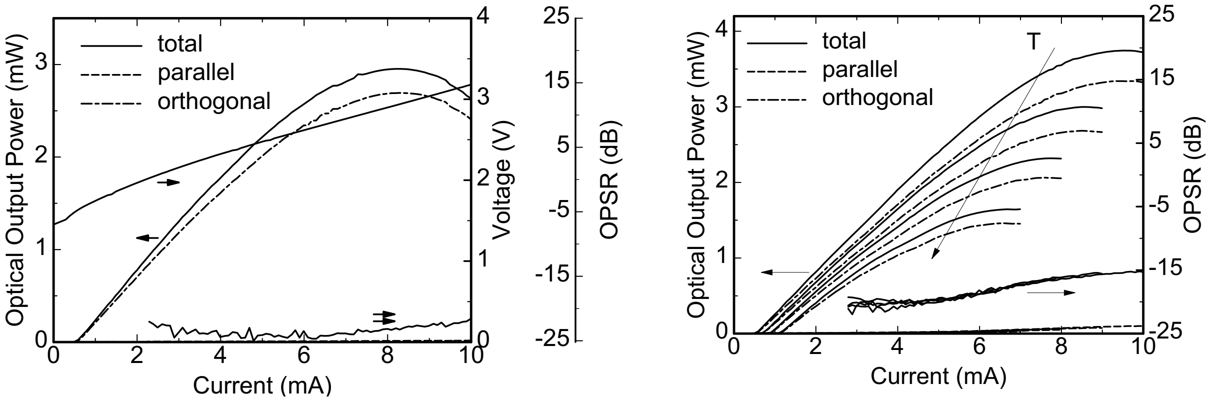


**Fig. 4:** Polarization-resolved operation characteristics of a grating VCSEL with 4.1 µm active diameter at room temperature (left) and of a grating VCSEL with 4.4 µm active diameter at substrate temperatures from 20 to 80 °C in steps of 20 °C (right). For both VCSELs, the surface grating has 60 nm grating depth, 0.7 µm grating period, and 50 % duty cycle. The quasi-vertical arrow in the right figure points towards higher temperature.

VCSEL with an active diameter of about 3.6 µm parallel and orthogonal to the grating lines are shown in Fig. 5. Both far-fields are almost identical, indicating an almost perfectly circular beam shape. There are no emission side-lobes, which proves the absence of diffraction effects by the sub-wavelength grating.

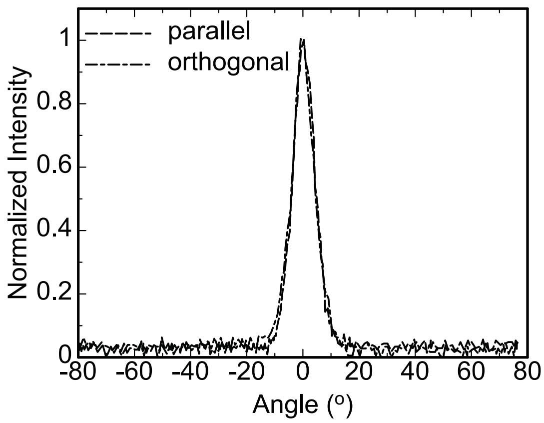


**Fig. 5:** Far-fields of an inverted grating VCSEL measured orthogonal and parallel to the grating lines at 4 mA bias. The laser has an active diameter of 3.6 µm. The grating period is 0.6 µm, the grating depth is 60 nm, and the duty cycle is 50 %.

## 4. Conclusion

We have reported the fabrication and characterization of 894.6 nm VCSELs to be incorporated in Cs-based MEMS atomic clocks. The main requirements on the lasers, such as correct emission wavelength, single-mode, single-polarization emission, low threshold currents, and high-temperature operation have been successfully met. For polarization control, inverted gratings have been employed. The VCSELs are polarized orthogonal to the grating lines with sufficient suppression of the competing polarization and no far-field diffraction side-lobes for sub-wavelength grating periods. At elevated substrate temperatures, the VCSELs remain polarization-stable even well above thermal roll-over.

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