The vertical-cavity semiconductor laser (VCSEL) is not a true single-mode laser, as typically 1% of the emitted power is present as polarization noise in a weak nonlasing mode orthogonally polarized to the lasing mode.1 The strong polarization noise in VCSELs is a limiting factor for many applications, since any polarization dependence of a detection scheme converts polarization noise into intensity noise, leading to a large degradation of the signal-to-noise ratio. As we will show here, novel insight in the polarization behavior can be obtained by studying both the dynamics of the lasing mode, which exhibits phase fluctuations,2 as well as that of the nonlasing mode, which contains the polarization fluctuations. In this article we quantitatively compare phase and polarization fluctuations in this mode are equal to its average power, and that the nonlasing mode is incoherent or thermal, i.e., the polarization fluctuations occur on a nanosecond time scale.

For a laser below threshold both the amplitude and phase fluctuate, so that the linewidth below threshold is twice the "standard" ST linewidth \(\Delta \nu_{ST}\),

\[
\Delta \nu_{below} = 2 \Delta \nu_{ST} = \frac{h \nu \eta^{ext}}{4 \pi P} \left( \frac{1 + \alpha^2}{\alpha^2} \right),
\]

where \(\Gamma_c\) is the cavity loss rate, i.e., the sum of the mirror loss rate \(\Gamma_m\) and the internal loss rate \(\Gamma_i\), \(h \nu\) the photon energy, \(\eta^{ext} = \Gamma_m/\Gamma_c\) the external quantum efficiency, and \(P\) the output power. We introduce the normalized injection current \(M = i/i_{th}\), where \(i\) is the injection current. Above threshold \((M > 1)\) the ST linewidth in semiconductor lasers is modified due to the linewidth enhancement factor \(\alpha\),

\[
\Delta \nu_{above} = (1 + \alpha^2) \Delta \nu_{ST} = \frac{h \nu \eta^{ext} \alpha^2}{4 \pi P}.
\]

From Eqs. (1) and (2) follows that the prefactor of the linewidth-power product of the lasing mode changes from 2 to \(1 + \alpha^2\) by passing through threshold. The nonlasing polarization mode is by definition always below threshold, so that Eq. (1) holds below and above threshold of the lasing mode. However, we will see that the nonlasing mode exhibits peculiar threshold behavior.

For the experiments we used oxide-confined VCSELs emitting around 830 nm. The VCSEL output beam was passed through a \(\lambda/4\) wave plate, an \(\lambda/2\) wave plate, and an optical Faraday isolator (60 dB) in order to prevent optical feedback and to select either of the two polarization modes. For spectral diagnostics we used mostly a Fabry–Pérot interferometer (FP) with an adjustable free spectral range (FSR) between 5 and 150 GHz.

First we discuss the threshold behavior and linewidth of the lasing polarization mode. Curve (a) in Fig. 1 shows the power of this mode, selected with the FP, as a function of \(M\). The threshold current \(i_{th}\) was found to be 0.43 mA and the VCSEL still emitted in the fundamental transverse mode up to currents of 2.0 mA.

Figure 2 the linewidth [full width at half maximum (FWHM)] of the lasing mode below and above threshold. Please note the high quality of the data, which run over four orders of magnitude in both the horizontal and vertical scale. The linewidth below and around threshold was determined from the Lorentzian peak in the optical spectrum, as measured with the FP with several convenient FSRe/s, resulting in errors less than 5%. The linewidth below threshold was...
found to be proportional to the inverse output power, and the corresponding ST fit (dashed curve in Fig. 2) yields a value of 1.6(2) MHz mW for the linewidth-power product below threshold.

Higher above threshold ($M>1.2$) the linewidth was measured with a self-heterodyne setup (kHz-resolution), where one path contained a 650-MHz acoustic optic modulator while the other path contained either a fiber-delay of 200 m or a free-space delay of 2 m, i.e., a super- and sub-coherence delay, respectively. Generally, we found a good agreement between the linewidth determined from the long (fiber) and short (free-space) delay, as demonstrated by the triangles and squares in Fig. 2. After passing through the threshold transition from below, the linewidth was again found to be proportional to the inverse output power, and we extracted a value of 4.6(3) MHz mW for the linewidth-power product (dotted curve in Fig. 2). The $\alpha$ factor can be determined from the ratio of the linewidth-power products above and below threshold, which is $(1+\alpha^2)/2$ according to Eqs. (1) and (2), yielding a value of $\alpha=2.2(3)$.

The cavity loss rate can be determined from the linewidth-power product below threshold in combination with the measured slope in the input–output curve (a) in Fig. 1; the latter slope corresponds to a quantum efficiency of $\eta_{\text{eff}}=\eta_{\text{int}}\eta_{\text{ext}}=0.46$. If we assume 100% internal efficiency ($\eta_{\text{int}}=1.0$) and insert $\eta_{\text{ext}}=0.46$ in Eq. (1) we find $\Gamma_c = 3.0 \times 10^{11}$ s$^{-1}$. If we assume the other extreme of low internal efficiency $\eta_{\text{int}}=0.46$ we get $\Gamma_c = 2.0 \times 10^{11}$ s$^{-1}$. An alternative way to determine $\Gamma_c$ is from the relaxation oscillations (not shown). Here we find $\Gamma_c = 2.0(5) \times 10^{11}$ s$^{-1}$, which is in reasonable agreement with the latter value and suggests that $\eta_{\text{int}}$ is considerably smaller than 1; this has been found previously for proton-implanted VCSELs.

Figure 1 also shows the input–output curve (b) of the nonlasing polarization mode, selected with the FP. One can distinguish three regimes: (i) below threshold, (ii) around threshold, where the intensity in the nonlasing mode increases rapidly, peaks at $M=1.05$, and drops fast from $M=1.05$ to $M=1.26$, followed by (iii) a slower decrease in power for $M>1.26$. Regime (ii), which might be called anomalous spontaneous emission is rather intriguing, as a corresponding effect shows up in the linewidth of the nonlasing mode.

The linewidth of the nonlasing mode as a function of its inverse power is shown in Fig. 3. The linewidth increases rapidly, peaks at $M=1.26$, and drops fast from $M=1.26$ to $M=1.05$. The measurements around and below threshold were done with the Fabry–Pérot interferometer (solid circles), whereas higher above threshold we used a self-heterodyne technique with a super- and sub-coherence delay, triangles and squares, respectively.

\[ \text{FIG. 1. Input–output curve of the lasing (a) and the nonlasing (b) polarization mode, as measured with the Fabry–Pérot interferometer.} \]

\[ \text{FIG. 2. Linewidth (FWHM) of the lasing polarization mode below and above threshold as a function of the inverse power. The measurements around and below threshold were done with the Fabry–Pérot interferometer (solid circles), whereas higher above threshold we used a self-heterodyne technique with a super- and sub-coherence delay, triangles and squares, respectively.} \]

\[ \text{FIG. 3. Linewidth (FWHM) of the nonlasing polarization mode as a function of its inverse power, measured with the Fabry–Pérot interferometer. The squares, triangles, and solid circles correspond to } M<1.00, 1.00<M<1.26, \text{ and } 1.26<M<3.00, \text{ respectively. The linewidth-power product for } M>1.26 \text{ is the same as below threshold } (M<1.0). \]

\[ \text{From the measured linewidths of typically a few } \text{GHz follows that polarization fluctuations occur on a nano-second time scale. The fact that we find the same value for the linewidth power product for the nonlasing polarization mode as for the lasing mode below threshold demonstrates that the polarization fluctuations in a TEM}_00 \text{ VCSEL are lim-} \]
It cannot be neglected as compared to the linewidth of the nonlasing mode. For a VCSEL operating above threshold, it has been limited by the same quantum noise that sets the ST line-width, \( \Delta \nu_{ST} \), of a VCSEL, being defined as the ratio of the power from the nonlasing mode \( P_{\text{non}} \) and the lasing mode \( P_{\text{lasing}} \), limited by the same quantum noise that sets the ST line-width. For a VCSEL operating above threshold, it has been derived theoretically \(^7\) that (for \( D \ll \gamma_0 \))

\[
I = \frac{P_{\text{non}}}{P_{\text{lasing}}} = \frac{D}{\gamma_0},
\]

where \( \gamma_0 \) is the dichroism, or the difference in gain between the polarization modes, and \( D \) the phase diffusion coefficient (\( D = 2\pi \Delta \nu_{ST} \)). Figure 4 shows the modal impurity as a function of \( M \), determined either directly from the input–output curves of Fig. 1 or from a calculation based on Eq. (3). In the latter case we determined \( D \) from the measured product of \( (D/2\pi)P_{\text{out}} = 0.8\, \text{MHz mW} \) (see above), and the measured total output power. The dichroism \( \gamma_0 \) was determined, as a function of laser current, from the difference in width [half width at half maximum (HWHM)] of the polarization modes in the optical spectrum. The good agreement demonstrates that the modal purity of a VCSEL, given a certain dichroism \( \gamma_0 \), is indeed limited by the inevitable spontaneous emission noise. Far below threshold the two Lorentzian shaped polarization modes had almost the same (large) width, resulting in a modal impurity that approaches 1 (see Fig. 4).

In conclusion, polarization-resolved linewidth measurements show that not only the lasing but also the nonlasing polarization mode show clear threshold behavior. The linewidth-power product of the lasing mode changes relatively from 2 to \( 1 + \alpha^2 \) by passing through threshold. For the nonlasing polarization mode the linewidth-power product below and above threshold was found to be the same, demonstrating that polarization fluctuations are thermal-like. However, around threshold an anomaly in the linewidth showed up, due to (carrier-induced) refractive index fluctuations.

\(^3\)Using a self-heterodyne setup we are also sensitive to optical frequency fluctuations during the delay time. This was a problem for measurements with the longer fiber delay high above threshold, where the linewidth is narrow. In this case we determined the linewidth by extracting the Lorentzian component out of a noise spectrum, with a Voigt-like shape.
\(^6\)A closer inspection of Fig. 2 shows that the linewidth of the lasing mode also exhibits anomalous behavior, as for \( M = 1.0 \text{--} 1.26 \) it is slightly above the ST value.