Quantum noise in VCSELs

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\textit{New Journal of Physics} 2 (2000) 26.1–26.13 (http://www.njp.org/)
Received 3 April 2000; online 23 October 2000

Abstract. In this paper, we study in detail the intensity noise characteristics of vertical-cavity surface-emitting lasers (VCSELs). We demonstrate the possibility of generating intensity squeezed light with free-running or injection-locked VCSELs. Sub-shot noise operation results from very strong anticorrelations between the transverse modes. These anticorrelations have also been analysed through the transverse spatial distribution of the intensity noise. In the case of two transverse modes above threshold, our experimental results are found to be in good agreement with the predictions of a phenomenological model.

1. Introduction

Vertical-cavity surface-emitting lasers (VCSELs) have been studied extensively over the past few years because of several useful characteristics which make them very attractive for various applications such as telecommunications. Indeed, they show many advantages with respect to the standard semiconductor laser architectures, such as their small size and the possibility to connect them directly to optical fibres. They also present a very low threshold, a high quantum efficiency and they can exhibit single longitudinal and transverse mode operation \cite{1}. However, the maximum single-mode power is limited by the onset of higher order transverse modes and changes in the polarization states of the emitted field are observed as the driving current is increased \cite{2, 3}. At the same time the noise can vary from shot noise to high levels of 10 dB and more above shot noise. Understanding the dynamics of higher order transverse modes is of great importance when optimizing the coupling of the laser into an optical fibre.
In this paper, we investigate the intensity noise of free-running or injection-locked high quantum efficiency oxide-confined VCSELs. Their features suggest that they are good candidates for the generation of amplitude squeezed light [4]. In general, single mode operation is most suitable to achieve squeezing, as was observed in [5]. However, as theoretically predicted [6, 7], in the case of two-mode operation, the strong anticorrelations between the two transverse modes allow one to achieve squeezed light [8]. We generalize the results of previous authors and we report the experimental generation of amplitude squeezing with VCSELs operating with several (up to six) transverse modes.

We also report generation of amplitude squeezed light by injection-locked VCSELs. This technique, already used to reduce the intensity noise of other semiconductor lasers [9, 10], is applied with success to VCSELs that did not exhibit squeezing in free-running operation. More generally, we give an overview of the intensity noise properties of a large number of devices and we describe the general features favourable to squeezing.

Finally, we investigate the influence of transverse modes on the intensity noise of semiconductor lasers. The spatial distribution of noise within the transverse profile of the laser beam has also been analysed by measuring its intensity noise after screening part of it in the far field with a movable razor blade. Fitting of the noise profile allows us to infer the presence of correlations between transverse modes. We also compare our experimental results with the predictions of a phenomenological quantum model and we find good agreement between the theoretical predictions and the experimental results.

2. Free-running VCSELs

2.1. Experimental set-up

We use oxide-confined VCSELs (made at the Department of Optoelectronics of the University of Ulm) with different active media diameters of 5, 7 and 10 µm. The devices are schematically represented in figure 1. They consist of carbon-doped p-type AlGaAs/AlGaAs and silicon-doped n-type AlAs/AlGaAs Bragg reflectors with pairs of quarter-wavelength thick layers. The top (respectively bottom) mirror has a reflectivity of 99.8% (respectively 99%). The present structure is a top emitter. They are coated on each side of a cladding layer containing the three active 8 nm thick GaAs quantum wells. They have an emission wavelength of about 840 nm. The oxide aperture provides both current and optical confinement. The devices are attached to a copper plate using silver paste.

Figure 2 shows the detail of the experimental set-up for the free-running lasers. We take advantage of the principle of pump-noise suppression [4] to minimize the noise in the laser output. For this purpose, a low-noise power supply provides the regulated electrical current which drives the VCSELs. The VCSELs are also thermally stabilized with an active temperature stabilization. With this stabilization, we are able to operate at a fixed temperature with a drift as small as 0.01 °C h⁻¹. The emitted beam is collimated by an anti-reflection coated microscope objective located at a distance of 2 mm from the laser output. This objective has a large numerical aperture (NA = 0.6) to avoid optical losses that would deteriorate the squeezing. To measure the intensity noise and the corresponding shot noise, the standard scheme consists of a polarizing beamsplitter that separates the beam emitted by the laser into two equal parts that are detected by means of high quantum efficiency balanced photodiodes. The dc parts of the photodiode currents are filtered out while the ac parts are amplified using 20 MHz bandwidth amplifiers. The amplified outputs,
proportional to the noise signals, are either subtracted or added by a RF $-/+ \text{ power combiner}$. When set on the difference position, the circuit gives a signal proportional to the shot noise, while in the sum position, it gives the full intensity noise of the diode beam impinging on the beamsplitter. However, in our case, it is better to use only one photodiode (FND100, bandwidth 1–20 MHz, quantum efficiency of 90%). Indeed, because of the multimode operation with two orthogonal linear polarizations, the shot noise obtained with a balanced detection would not be reliable and we prefer to use a separately calibrated shot noise obtained with the balanced detection of a laser diode beam. The shot noise obtained in this way is in very good agreement with the noise obtained by a thermal light generating the same dc current on the photodiode. From these measurements, we estimate the shot noise reference to be reliable within 0.1 dB. We also carefully checked the linear dependence of the calibrated shot noise signal with the optical power incident on the photodiodes. The photodiode is connected via a low-noise home-made amplifier (with a CLC425) and electronic amplifier (Nucletude 4-40-1A) to a spectrum analyser (Tektronics 2753P). With this set-up, the electronic noise was more than 6 dB below the signal we measured for a typical detected power of 1.5 mW. In our experiment, we could also perform a spectral analysis of the laser beam with a high-resolution monochromator (0.03 nm at 840 nm). At the output of the monochromator, the relative powers of the individual transverse modes are measured with a photodetector and their polarizations are determined using a Glan polarizer (extinction ratio $10^{-4}$).
Table 1. Threshold and differential quantum efficiency for several chips of VCSELs.

| Diameter (µm) | Quantum efficiency | Threshold (mA) | Number of lasers | Squeezing |
|---------------|--------------------|----------------|------------------|-----------|
| 5             | 51.5%              | 0.67           | 6                | 3         |
| 7             | 46.6%              | 1.15           | 6                | 2         |
| 10            | 42%                | 1.73           | 6                | 0         |

2.2. Experimental results

We have studied the threshold and the differential quantum efficiency of oxide-confined VCSELs from several chips (table 1), each of them comprising about 50 lasers. After repeated measurements on a large number of devices we found that the differential quantum efficiency decreases when the diameter of the laser increases while the threshold increases when the diameter increases. However, while the values of quantum efficiency and threshold characteristics are reproducible from one device to another one of the same size, the noise characteristics exhibit a dispersion within a batch of similar VCSELs, as described hereafter.

In the chip showing the best performances, there are 18 VCSELs with small diameters. The six VCSELs with a diameter of 5 µm have an average differential quantum efficiency of 51.5% and an average threshold of 0.67 mA, the six VCSELs with a diameter of 7 µm have an average differential quantum efficiency of 46.6% and an average threshold of 1.15 mA, while the six VCSELs with a diameter of 10 µm present an average differential quantum efficiency of 42% and an average threshold of 1.73 mA. The variances on these numbers are less than 5%, which shows that these two characteristics do not depend strongly on the device. These values are among the best obtained worldwide with similar structures. Because a low threshold and a high quantum efficiency are required to obtain squeezing, it appears that VCSELs with the lowest diameter have the most promising features.

Among the six devices with a diameter of 5 µm, three emitted intensity squeezed beams. The best squeezing obtained is about −0.75 dB at the laser output (after correction for optical losses). The normalized intensity noise spectrum corresponding to this result is plotted in figure 3. The free-running VCSEL is driven with a current of $I = 5.68$ mA and delivers an output power of 3.3 mW. The intensity noise of the three other VCSELs is very close to shot noise (less than 1 dB above this limit) for driving currents below 10 times the threshold and is several dBs above shot noise for higher driving currents. As can be seen, squeezing is observed for intermediate values of the driving current. While in principle, best squeezing is expected far above threshold, in the case of VCSELs, the occurrence of an increasing number of transverse modes with increasing driving current is deleterious for squeezing at strong pumping.

We also obtained intensity squeezing with two devices among the six VCSELs with a diameter of 7 µm. The maximum amount of squeezing (after correction for optical losses) was about −0.6 dB. The other devices with a diameter of 7 µm showed a intensity noise close to the shot noise (between 1 and 2 dB above this limit) in some restricted driving current range. Outside this range, the noise was in the range of 10 dB above shot noise. For the VCSELs with a diameter of 10 µm, the intensity noise we measured for various electrical driving currents was...
always far above the shot noise level (at least 5 dB, for moderate values of the current, and up to 10 dB and more at high current), with broad variations among the samples.

From this study, we can deduce some general trends. As expected, the VCSELs with the lowest diameters have the best performances as far as squeezing is concerned. This appears to be due in part to their higher quantum efficiency. However, we also observe that the noise characteristics are linked to the multimode behaviour of the VCSELs. The larger the VCSEL, the higher the number of transverse modes it can sustain (even at low driving current) and the higher the intensity noise. The noise characteristics also vary widely from one sample to the other, as does the transverse mode behaviour. These variations have been observed by other groups [19] and may be linked to some specific fabrication parameter in the devices that is yet to be identified. Only in the case of VCSELs with small diameter that consistently support a smaller number of modes could we observe low noise regimes that were qualitatively reproducible among lasers on the same chip.

The new feature of the observed squeezing is that it occurs in strongly multimode VCSELs. In figure 4, we show the above threshold transverse modes of the VCSELs whose squeezing spectrum is represented in figure 3. We have plotted the optical power (in dB) of the various modes versus their frequencies taking the TEM$_{00}$ mode, which has the lowest frequency and power, as the reference for the two scales. With that scale, the TEM$_{00}$ power is equal to zero. It can be seen that three high-intensity and three low-intensity modes oscillate together. This clearly demonstrates the occurrence of squeezing in a multimode case. We will see below that the noise of each mode is very large, so if the total intensity noise of the beam is under the shot noise, large anticorrelations between the fluctuations of the different modes are expected, as observed in other experiments with laser diodes and VCSELs [6, 8, 11, 16, 17].

To demonstrate the importance of these anticorrelations, we analysed the simple case of two transverse modes TEM$_{00}$ and TEM$_{10}$ that are orthogonally linearly polarized [18]. By means of a polarizer placed before the photodiode that measures the intensity noise, we can separate the two modes and measure their respective intensity noise. In figure 5, we have plotted the results obtained for a VCSEL with a diameter of 7 $\mu$m driven with a current of 2.58 mA. Even if the total intensity noise is above the shot noise, we see that it is much lower than the intensity noise

**Figure 3.** Normalized intensity noise spectrum (0–20 MHz) for a VCSEL with a diameter of 5 $\mu$m.
Figure 4. Spectral analysis of the intensity squeezed light beam of which intensity noise spectrum is represented in figure 3.

Figure 5. Normalized intensity noise spectrum (0–20 MHz) of the total beam (a) and normalized intensity noise of each transverse mode in the beam. Curve (b) corresponds to TEM\(_{00}\) and curve (c) to TEM\(_{10}\). The TEM\(_{00}\) (respectively, TEM\(_{10}\)) intensity is 0.80 mW (respectively, 0.53 mW).

of each mode. Using the data of figure 5, we can calculate the degree of correlation, \(C\), between the two modes as follows:

\[
C = \frac{\langle \delta I^2_{\text{tot}} \rangle - (\langle \delta I^2_{00} \rangle + \langle \delta I^2_{10} \rangle)}{2 \sqrt{\langle \delta I^2_{00} \rangle \langle \delta I^2_{10} \rangle}} \tag{1}
\]

\[-1 \leq C \leq 1 \tag{2}\]

where \(\langle \delta I^2_{\text{tot}} \rangle\) is the intensity noise of the total beam, and \(\langle \delta I^2_{00} \rangle\) (respectively \(\langle \delta I^2_{10} \rangle\)) is the intensity noise of TEM\(_{00}\) (respectively TEM\(_{10}\)) mode. In the case of perfect correlations, \(C\) is equal to 1 while, in the case of perfect anticorrelations, \(C\) is equal to \(-1\). At 10 MHz, for example, we calculate that \(C\) is equal to \(-0.993\). This confirms the existence of strong anticorrelations between the transverse modes.

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In the case of perfect anticorrelations between the various lasing modes, the total intensity noise is expected to be independent of the number of the oscillating modes [6]. It depends only on the quantum efficiency and the pumping rate as in the case of a perfectly single-mode laser. However the anticorrelations are not perfect, hence the increase of the number of lasing modes implies an enhancement of the intensity noise. This is an additional reason why VCSELs with the lowest diameter present the best intensity noise reduction. That is also why we chose to operate with moderate driving currents.

To improve the noise feature of the free-running VCSELs that does not exhibit intensity squeezing, we have used the injection-locking technique.

3. Injection-locked VCSELs

3.1. Experimental set-up

The detailed set-up for the injection is shown in figure 6. We choose to inject the VCSELs fundamental Gaussian transverse mode TEM\(_{00}\). We use an index-guided quantum well GaAlAs laser diode operating at 830 nm as a master laser. Low-noise operation is achieved by driving the laser diode with a high-impedance constant-current source and suppressing the side modes using feedback from an external grating in an extended cavity [9, 10]. By tilting the grating, the laser diode wavelength can be tuned coarsely to match the wavelength of the VCSEL TEM\(_{00}\) mode. The grating is mounted on a piezoelectric ceramic to precisely tune the wavelength of the laser diode. Astigmatism in the beam is corrected by means of an anamorphic prism. Two optical isolators (for a total isolation of 50 dB) are used to prevent back reflection into the laser diode. A single-mode optical fibre filters the laser diode beam and selects the TEM\(_{00}\) mode. The waists of the master beam and of the slave laser mode are set to be equal. Hence the master beam and the VCSEL transverse mode we want to inject have the same transverse geometry, which ensures an efficient mode matching with the slave laser. A half-wave plate permits us to match the polarization of the laser diode beam to the one of the VCSEL TEM\(_{00}\) mode. Finally, the master laser beam is coupled to the VCSEL one by means of a beamsplitter.
3.2. Experimental results

In figure 7, we have plotted the normalized intensity noise measured versus the frequency for a VCSEL with a diameter of 7 $\mu$m. In free-running operation this particular device always exhibits excessive noise. Curve (a) shows the normalized intensity noise in free-running operation while curve (b) shows the intensity noise of the VCSEL when it is injection locked (the injection power is equal to 2% of the power of the free-running laser). The best squeezing (after correction for optical losses) obtained is about $-0.8$ dB. The VCSELs with higher diameters present the same property: the injection-locking technique reduces the intensity noise. However, the intensity noise remains above shot noise level. Spectral analysis shows that the intensity of the TEM$_{00}$ mode is increased by injection locking. However, despite injection, several transverse modes still oscillate. As for laser diodes [9], the injection-locking technique reduces the power of the noninjected modes and improves the anticorrelations between the transverse modes. The injection-locking technique reduces the intensity noise but does not ensure single-mode operation.

In section 2, we have demonstrated that there were strong anticorrelations between the different transverse modes. Intensity correlations can also be studied through the spatial distribution of the intensity noise.

4. Spatial distribution of the intensity noise

4.1. Model

In our set-up, the laser beam is screened by a movable razor blade, and the intensity noise is measured as a function of the position $y$ of the blade [12] (figure 8). In our situation, the only two relevant modes are the orthogonally linearly polarized TEM$_{00}$ and TEM$_{01}$ modes. As they exhibit different transverse intensity distributions, we expect that their respective contributions to the total intensity noise depend on the position of the blade.
To model the processes involved in our experiment, we consider a beam composed of two transverse modes TEM\(_{00}\) and TEM\(_{01}\) with different frequencies and orthogonal linear polarizations. We will therefore consider these two modes to be incoherent. In order to calculate the intensity noise of the detected part of the beam, the razor blade may be modelled as a beamsplitter with position-dependent transmissivity \(t\) and reflectivity \(r\). Since the transverse intensity distribution is different for the two modes, we will have to consider different transmissivities and reflectivities for each mode. We denote as \(n\), \(n_{00}\) and \(n_{01}\) the photon number operators corresponding, respectively, to the overall beam, TEM\(_{00}\) and TEM\(_{01}\) modes. The intensity transmissivities for mode \(i\) at a given position \(y\) of the blade are given by

\[
T_{00}(y) = \sqrt{2/(w\sqrt{\pi})} \int_{y}^{\infty} \exp(-2u^2/w^2)du
\]

\[
T_{01}(y) = 4\sqrt{2/(w^3\sqrt{\pi})} \int_{y}^{\infty} u^2 \exp(-2u^2/w^2)du,
\]

where \(w\) is the size of the beam. The degree of correlation \(C\) between the two modes is defined as for equation 1

\[
C = \frac{\langle \delta n^2 \rangle - \langle \langle \delta n_{00}^2 \rangle + \langle \delta n_{01}^2 \rangle \rangle}{2\sqrt{\langle \delta n_{00}^2 \rangle \langle \delta n_{01}^2 \rangle}}.
\]

where the \(\delta n\) are the variances of the corresponding quantities. We define the normalized variance \(v_{0i} = \langle \delta n^2 \rangle / \langle n_i \rangle\), where : : means that normal ordering is used. The value of \(v_{0i}\) represents excess noise if positive, and squeezing if negative. The ratio between the intensities of the two modes \(q\) is defined as \(q = \langle n_{00} \rangle / \langle n_{01} \rangle\). All the parameters used in this model have a physical significance and can be measured independently.
The total intensity noise $S(y)$ (normalized to the shot noise of the cut beam), when the razor blade is at position $y$, can be calculated by standard methods used for beamsplitters [13, 14]:

$$
S(y) = \frac{T_{00}(y)q}{T_{00}(y)q + T_{01}(y)} \left(1 + T_{00}(y)v_{00}\right) \\
+ \frac{T_{01}(y)}{T_{00}(y)q + T_{01}(y)} \left(1 + T_{01}(y)v_{01}\right) \\
+ 2\frac{T_{00}(y)T_{01}(y)}{T_{00}(y)q + T_{01}(y)} C \sqrt{q(1 + v_{00})(1 + v_{01})}
$$

Let us now consider the case of perfect anticorrelations for which $C = -1$. In figure 9, we have plotted the shot noise level and the normalized intensity noise versus the position of the blade. The normalization of the intensity noise is made with the shot noise corresponding to the intensity of the beam, which is a function of the position of the blade. The most interesting feature is that amplitude noise squeezing is possible for some positions of the blade. Amplitude squeezing may therefore be obtained from a beam having a intensity noise above the shot noise by partially screening it, even if the intensity noise of each transverse mode is above the shot noise level.

4.2. Experimental set-up

The VCSELs used in the experiment have a 7 µm diameter and an emission wavelength of approximately 840 nm. The thresholds of the various transverse modes are the following: $I_{\text{th0}} = 1.2$ mA for mode TEM$_{00}$, $I_{\text{th1}} = 2.4$ mA for mode TEM$_{01}$, and $I_{\text{th2}} = 2.8$ mA for the next transverse mode.

The experimental procedure consists first in the independent measurement of each parameter of equation (6). The total intensity noise and the total intensity of the beam are then recorded versus the position of the blade and compared with the prediction of equation (6) with no adjustable parameters. The electrical driving current is adjusted to have the VCSEL operating with only two transverse modes, i.e. $I_{\text{th1}} < I_{\text{op}} = 2.52$ mA $< I_{\text{th2}}$. Using a monochromator

Figure 9. Normalized intensity noise spectrum versus the position of the razor blade normalized to the size of the beam. $v_{00} = 480.6$, $v_{01} = 28.22$, $C = -1$ and $q = 0.11$. 

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and a polarizer we can check that the TEM$_{00}$ and the TEM$_{01}$ modes have linear and mutually orthogonal polarizations. We measure the intensity of each mode (separating them with a Glan polarizer), which gives the values of the quantities $\langle n_{00} \rangle$, $\langle n_{01} \rangle$ and $q$. From the measured intensity noise of each mode, we determine the values of the excess noise $v_{00}$ and $v_{01}$. The measured total intensity noise gives the value of $\langle \delta n^2 \rangle$. We then calculate the correlation $C$ using equation (5). The size $w$ of the beam is measured when the laser is single mode, i.e. for a driving current $I$ such that $I_{th0} < I < I_{th1}$.

4.3. Experimental results

In figure 10(a), we have plotted the experimental results and the predictions of our model for a first VCSEL at an analysis frequency of 15 MHz. The anticorrelations are equal to $-0.75$ for these curves. As expected since $v_{00}$ and $v_{01}$ are large, we observe large variations of the

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intensity noise with the position of the blade. The agreement between theory and experiment is also very good. In figure 10(b), we have plotted the experimental results and the predictions of our model for a second VCSEL presenting a higher parameter anticorrelation: $C = -0.98$. The variations of the intensity noise are even larger. If we compare the results of figure 10(a) and figure 10(b), we also notice that the shape of the curves depends on the value of the correlations. The agreement between experimental results and theoretical predictions is again very good. These results confirm the validity of our hypothesis, in particular the fact that we have only taken two modes into account and that we have neglected the contribution of the non-lasing modes.

Let us point out that the partial screening by the blade can reduce the noise more than a simple attenuation effect. This is shown in figure 10(a) and figure 10(b) where for some ranges of the blade position, the intensity noise goes clearly below the noise of the full beam attenuated down to the actual intensity of the cut beam. For various positions of the blade, the intensity noise can be considerably increased or decreased depending on the contributions of the two modes and their correlation.

It can also be noted that when the blade is exactly halfway through ($y = 0$), the intensity noise is equal to the intensity noise of the beam uniformly attenuated by 50%. This comes from the fact that intensity noise profiles of the different transverse modes are even functions.

5. Conclusion

In this paper, we have demonstrated that high-quality VCSELs, operating with several transverse modes, can exhibit a total intensity noise below the shot noise level. Our measurements also confirmed the influence of the active media diameter aperture on the intensity noise. The VCSELs with lowest diameter, which have the best quantum efficiency, the lowest threshold, and the lowest number of transverse modes have the best intensity noise characteristics. Moreover, we have shown that the observed squeezing was due to very strong anticorrelations between the transverse modes.

We have shown that the injection-locking technique can be applied with success to reduce the intensity noise of the VCSELs but does not imply single-mode operation.

The intensity noise relative to shot noise can be reduced by partially screening the beam owing to the noise correlations between the different transverse modes. The VCSELs present intensity anticorrelations coming from mode competition owing to the homogeneous part of the gain spectrum as in [6, 11, 15, 16, 17]. For some positions of the blade we can even reduce the intensity noise by more than a mere attenuation effect. So, the anticorrelations between the transverses modes imply a complex spatial structure of the intensity noise. This shows that spatial control may be of great importance when it is related to the intensity noise of VCSELs.

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