Extremely Low-Noise High-Speed VCSELs for Optical Interconnects

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When looking into high-speed data transmission using data rates greater than $10\,Gb/s$ the noise behavior of the transmitter becomes more and more important. Vertical-cavity surface-emitting lasers (VCSELs) emitting at $850\,nm$ wavelength are characterised for this purpose. Relative intensity noise (RIN) and small signal modulation measurements have been performed and resulting spectra are fitted to theoretical curves in order to obtain internal device parameters. Different operation regimes, where transverse single- or multi-mode emission occurs, are investigated. At low temperatures the quantum efficiency of the VCSEL is increased, leading to photon-number fluctuations $1.4\,dB$ below the shot noise limit. A special electrical probing is used to minimize parasitics and to inhibit RF-interference.

1. Introduction

Demonstrated CMOS speeds in the few GHz range together with the demand for ultra large scale integration turn optoelectronic interconnect technology into one of of the ideal building blocks for future high performance data links. Owing to the surface-normal operation and many other favorable properties like low power dissipation, high-speed modulation, and Si IC compatible low-cost manufacturing, VCSELs are going to be the preferred choice for the transmitter part. Single channel as well as one-dimensional fiber ribbonized parallel interconnect modules using VCSEL technology are already on the market [1, 2, 3]. Inter- and intra-cabinet data links as well as optical backplanes in advanced computer environments are target for these components [4]. In future Si IC generations electrical interconnects are foreseen to be a major bottleneck. This will open up a new area of Si CMOS and III/V optoelectronic component interaction and integration.

2. Device structure

Fig. 1 shows a schematic drawing of the crossection of a VCSEL emitting at $850\,\mathrm{nm}$. Layers are grown by solid sorce molecular beam epitaxy. The active region is formed by three $8\,\mathrm{nm}$ thick GaAs quantum wells (QWs) embedded in $Al_{0.2}Ga_{0.8}As$ barriers. The lower n-type Si-doped and the upper p-type C-doped Bragg reflector consists of $Al_{0.2}Ga_{0.8}As/Al_{0.9}Ga_{0.1}As$ quarter-wavelength layer pairs, with graded interfaces and δ-doping to reduce series resistance [5]. Current is injected through the upper Bragg reflector by a ring contact. Current confinement is achieved by selective lateral oxidation of a 30 nm thick AlAs layer after mesa etching [6]. Stable single-mode emission is enforced by small oxide aperture and low optical confinement [5]. Small diameter mesa with steep side-walls are required to obtain a low oxide capacitance. Therefore, mesa are formed by chemically assisted ion beam etching (CAIBE). The mesa is passivated and a second etching step gives access to the n-doped GaAs substrate on which a large area n-contact is evaporated. After planarization with photosensitive polyimide the n-contact is electroplated up to the height of the p-contact [7].

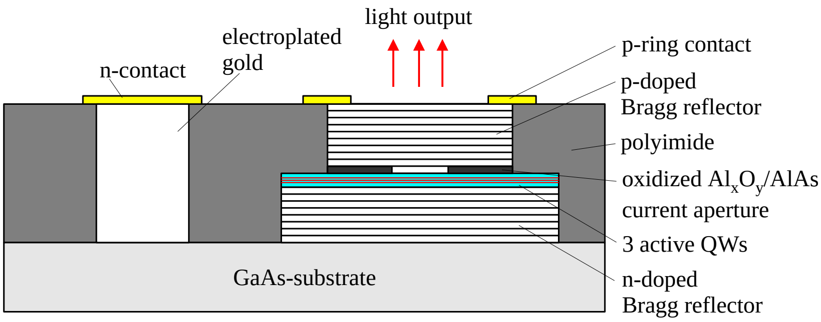

Fig. 1. Schematic drawing of the crossection of a top emittig VCSEL. The n-contact is electroplated up to the height of the p-contact.

3. Measurement setup

Fig. 2 shows the setup for RIN measurements. The VCSEL is driven by a current source in order to suppress pump current fluctuations [10]. The included bias-T serves as a low-pass filter. For measuring intensity noise, in the low frequency region, a large area Si PIN photodiode is used as light to current converter. The responsivity of the diode is approximately $0.55\,\mathrm{A/W}$ at the VCSEL emission wavelength of about $850\,\mathrm{nm}$, corresponding to a quantum efficiency of $80\,\%$. In order to measure high frequency noise components, a smaller $16\mathrm{x}16\,\mu\mathrm{m}^2$ InGaAs PIN photodiode with a bandwidth of $14\,\mathrm{GHz}$ is used. Its responsivity is approximately $0.45\,\mathrm{A/W}$. The photodiodes are always biased using a bias-T. The average photocurrent I_{ph}, which is proportional to the average light intensity, can be measured at the dc output of the bias-T. The ac current is fed to a low noise RF amplifier with a $50\,\Omega$ input resistance. For the larger detector a bandwidth exceeding $300\,\mathrm{MHz}$ is achieved. The output signal of the amplifier is transmitted to an electrical spectrum analyzer to record the power spectral density of the photocurrent. From

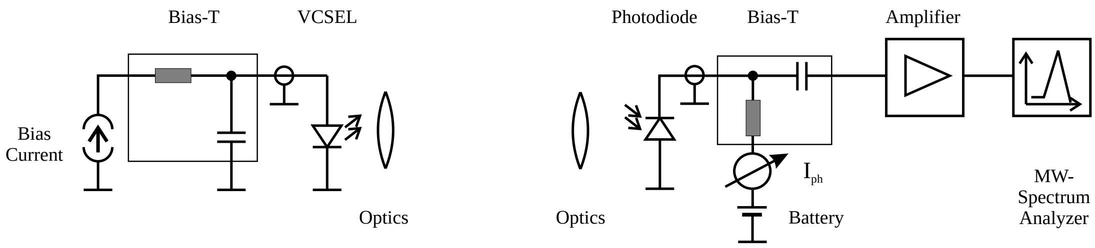

Fig. 2. Measurement setup for RIN measurements on VCSELs. Different photodiodes and amplifiers may be used, depending on the frequency range of interest.

the relation between average photocurrent I_{ph} measured at the bias-T and the power spectral density of the photocurrent at the amplifier input P_{AC}, the RIN_D is calculated according to [8]

$$RIN_D = \frac{P_{AC}}{I_{ph}^2 \cdot 50\Omega}. \tag{1}$$

For shot noise calibration the large area photodiode can be illuminated with a red-filtered halogen lamp, with the optical power adjusted to get the same average photocurrent as with the VCSEL. The shot noise limited $RIN_{D,shot}$ is given by

$$RIN_{D,shot} = \frac{2q_0}{I_{ph}}. \tag{2}$$

Calculated and measured values are in good agreement for different photodiodes. Care is taken to exclude saturation effects of the photodiode due to different spatial power density distributions of the incident light on the detector surface. Variations of the spot diameter on the photodiode at high power levels gave no changes in the measured photocurrent power spectral density.

4. Measurement results

The laser under study here has a threshold current of $I_{th} = 1.1\,\mathrm{mA}$ and emits in a single transverse mode over the whole operation range. Fig. 3 shows measured RIN_D spectra for various driving currents of this VCSEL. Fitted theoretical curves are included for three of the curves. From the theoretical description a linear dependency of the damping constant γ on the squared resonance frequency ν_r^2 can be deduced [9].

$$\gamma = K\nu_r^2 + \frac{1}{\chi\tau_{w,sp}} \tag{3}$$

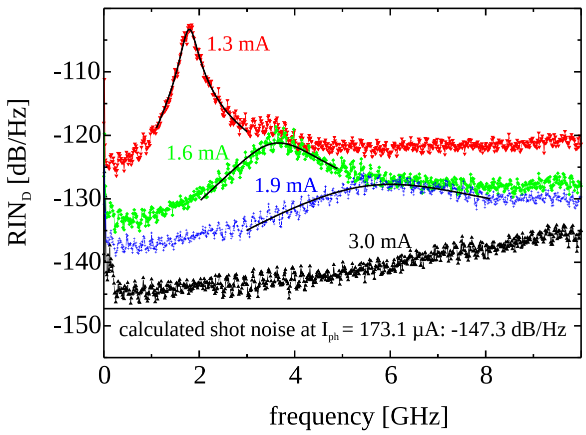

Fig. 3. Measured RIN_D spectra and fitted theoretical curves. The calculated shot noise level for the maximum photocurrent is shown as well.

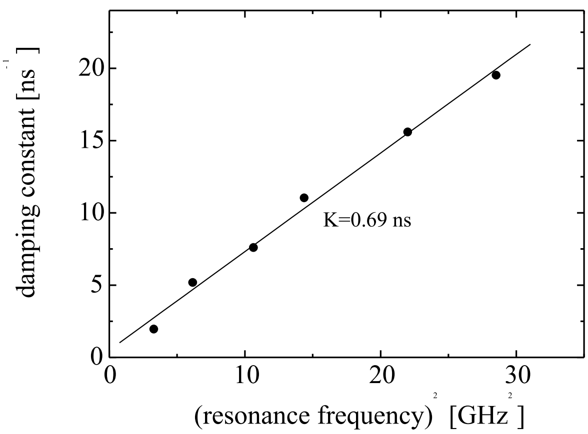

Fig. 4. Extracted values of damping constant versus squared resonance frequency. The slope of this plot is called the K-factor.

Where $\tau_{w,sp}$ denotes the spontaniou carrier lifetime and χ is a carrier transport factor. Extracted values are plotted in Fig. 4. The proportionality factor K is determined from the slope. It can be used to calculate the maximum modulation bandwidth $\nu_{3dB,max}$ of the intrinsic laser diode according to

$$\nu_{3dB,max} = \sqrt{2}\frac{2\pi}{K}. \tag{4}$$

Here it yields $\nu_{3dB,max} = 13\,\mathrm{GHz}$. Fig. 5 shows measured small signal modulation resonse curves for the same laser, again at different driving currents. The maximum bandwidth deter-

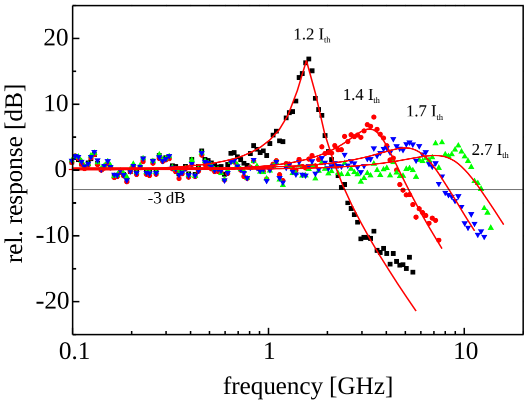

Fig. 5. Measured modulation resonse curves and fitted theoretical curves for different driving currents.

mined from these is about 12 GHz. The good agreement of measured bandwidth and predicted bandwidth from RIN mesasurements gives no evidence of parasitics, like transport effects. In that sense the VCSEL under investigation shows purely damping limited behavior.

In Fig. 3 the calculated shot noise level for a photocurrent of $173.1\,\mu\mathrm{A}$ is shown as a horizontal line. This photocurrent is generated, when the laser is operated at a driving current of $3\,\mathrm{mA}$. In the low frequency range, the laser noise lies only a few dB above the shot noise limit.

For a different laser we have measured the low frequency RIN of the VCSEL at low temperatures. This is done to prevent early rollover of the light-current characteristics and to increase the single-mode operation range as well as the quantum efficiency. The resonance frequency of the cavity of this laser is detuned to the short wavelength side of the gain curve. Therefore, low substrate temperatures give reasonably good matching of the resonance frequency and the gain curve, depending on the bias point. No rollover of the characteristics occurs up to a current density of approximately $180\,\mathrm{kA/cm^2}$. Measurement of the emission spectrum shows operation in the fundamental mode up to currents of $3.5\,\mathrm{mA}$ with a side mode suppression of better than 30 dB. For higher currents higher order modes begin to lase. The overall maximum quantum efficiency of the system is as high as $40\,\%$. In Fig. 6, the intensity noise of the VCSEL measured in a 1 MHz band around 55 MHz is displayed as a function of photocurrent. For comparison, the measured shot noise from the halogen lamp is also shown. From the intensity noise and the average current induced in the photodiode the relative intensity noise of the VCSEL is calculated and drawn as open circles. Above threshold, with increasing photocurrent the VCSEL intensity noise drops very fast reaching shot noise level at a photocurrent of $250\,\mu\mathrm{A}$. At a photocurrent of approximately $0.5\,\mathrm{mA}$ polarization instability causes a slight increase of intensity noise above the shot noise level. At 1.14 mA photocurrent, intensity noise is 1.4 dB below the shot noise level. With further increased laser current, at 1.3 mA photocurrent a higher order mode starts lasing which results in higher intensity noise. For still higher laser currents a stable operation range is reached, and intensity noise again drops below the shot noise level. The general noise versus photocurrent characteristic is not influenced by temperature, while the increased quantum efficiency allows for an extended laser operation range and higher level of squeezing. Theoretically, from the overall quantum efficiency of the measuring system of 37 % at the corresponding bias point, a maximum amplitude squeezing of 2 dB can be expected assuming poissonian loss mechanisms [11]. The measured figure of 1.4 dB below the shot noise level is in excellent agreement with this theoretical prediction.

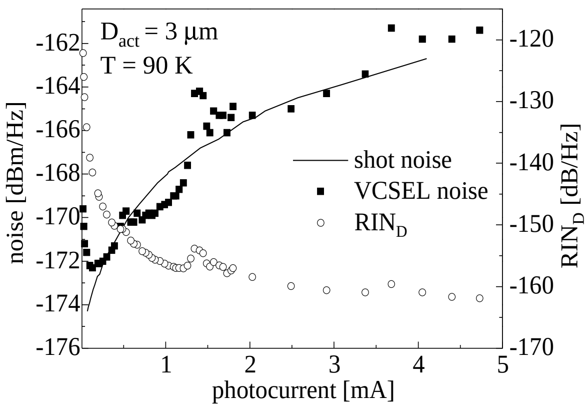

Fig. 6. Measured amplitude noise and RIN of VCSEL. For comparison the measured shot noise from a halogen lamp is included as the solid line.

5. Conclusion

We have investigated intensity noise of high performance transverse single- and multi-mode VCSELs in the 850 nm wavelength regime, where high quantum efficiency Si photodiodes can be used. Damping limited operation of a single-mode VCSEL has been demonstrated at room temperature. In a single-mode VCSEL emitter Si photodiode detector transmitting system with an overall quantum efficiency of 37 % an intensity noise of 1.4 dB below the shot noise limit has been observed at 90 K operating temerature of the laser. This figure is the largest amount of squeezing ever reported for VCSELs. Polarization instability, mode competition noise and thermal rollover determine the noise characteristics at room temperature. Further investigation of the non linear effects involved remains to be conducted.

6. Acknowledgment

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