Intensity noise of ultrabroadband Quantum Dot Light Emitting Diodes and Lasers at 1.3 µm

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ABSTRACT

We present high precision intensity noise measurements of Quantum Dot Superluminescent LEDs and lasers emitting at 1.3µm. For the QD-SLEDs we investigate the intensity noise behavior and identify the relevant noise parameters by comparing the experimental results to theoretical calculations. We find an Excess Noise behavior due to amplified spontaneous emission, the dominant origin of noise. The investigation of the spectrally resolved emission enables further characterization of the noise properties. The influence of a resonator on the noise behavior is discussed for QD-Lasers. The noise of the laser is compared to the SLED’s, and shows strong deviation from the Excess Noise character above threshold.

Keywords: Quantum Dot, Intensity Noise, SLED, Excess Noise, Amplified Spontaneous Emission, Laser, Correlation

1. INTRODUCTION

Quantum Dot (QD) Superluminescent Light Emitting Diodes (SLEDs) are promising light sources for incoherent light application, as for example Optical Coherence Tomography. In QD gain media the three dimensional lateral confinement of the carriers leads to discrete allowed energy levels. The absolute values of the energy levels are given by the dot properties. This offers the possibility of tailoring the emission wavelength of the QD gain material. However, fluctuations in the single dot sizes occur as a consequence of the self-assembled growth process. This Gaussian distributed size variation results in a large inhomogeneous broadening of the QD gain medium. Therefore, the large spectral bandwidths that are necessary for incoherent light application or Semiconductor Optical Amplifiers can be achieved.

To maintain the unique gain properties of QDs an appropriate light emitting medium has to be chosen. Here Superluminescent LEDs are suitable candidates. They allow for large spectral bandwidths as modal emission is suppressed. Their smooth optical emission spectrum results from a special waveguide design. A common technique is to tilt the optical waveguide by a few degrees with respect to the optical axis combined with anti reflection coatings on the facets. Hence the dominant photon emission process in SLEDs is Amplified Spontaneous Emission (ASE). Due to the high optical gain and the large inhomogeneous broadening of the QD gain material, QD-SLEDs emit several milliwatt of optical power with more than 100nm spectral bandwidth. In QD-Lasers the onset of stimulated emission leads to higher output powers at desired wavelengths. Above threshold, multimode emission increases the spectral bandwidth and enables the utilization of QD-Lasers in wavelength division multiplexing or modelocked systems. Recently developed QD-Lasers exhibit a spectral bandwidth of more than 25nm.

In low coherence interferometry the intensity of the backscattered light that contains the depth information is usually very small. Here the intensity noise of the light source becomes a performance limiting factor. The intensity noise, that describes the fluctuations of the intensity, determines the Signal to Noise Ratio (SNR) of the light source. Optimization of the SNR requires the identification of the relevant intensity noise parameters. Beyond the application point of view the investigation of the intensity noise is necessary to gain insight into the device’s physics. According to their dominant photon emission process light sources show different intensity noise behavior.

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Fig. 1. Direct detection setup for high precision intensity noise measurements.

In this letter, we present intensity noise measurements of QD-SLEDs and QD-Lasers emitting at 1.3μm. In section 2 the experimental setup is introduced. In section 3.1 we present experimental results for QD-SLEDs and compare them with theoretical calculations. Here, we identify the relevant noise parameters for SLEDs. We further discuss correlations in the QD-SLEDs emission in section 3.2 and compare the QD-SLED and QD-Laser noise behavior in section 3.3. The letter closes with a conclusion and the outlook.

2. EXPERIMENTAL SETUP

We investigate the intensity noise of the QD-light sources with a direct detection setup (figure 1). The electromagnetically shielded measurements are performed at room temperature. The light sources are driven by a low-noise DC current source at different pump currents $I_{Pump}$. An aspherical lens focuses the emission onto a large area InGaAs photodiode. On demand an interference filter can be inserted into the beam path to accomplish spectral filtering. The generated electrical current is separated into its AC and DC components with a Bias-Tee. The DC component of the current $I_{Photo}$ is proportional to the source’s optical power. The AC component comprises information about the intensity noise. Here the noise current $I_{Noise}$ is calculated from radiofrequency spectra of the amplified AC component, that are measured with an Electrical Spectrum Analyzer well above the $1/f$-noise.

3. EXPERIMENTAL RESULTS

3.1 QD-SLED intensity noise

Experimental intensity noise

The intensity noise per 1Hz detection bandwidth of the QD-SLED is shown in figure 2 in a double logarithmic depiction. Over several decades the intensity noise, given as the square of the noise current $I_{Noise}^2$, increases with increasing photo current $I_{Photo}$, which is proportional to the SLED’s optical power. Around 1mA photo current the noise shows a plateau-like flattening that is followed by subsequent increase. At the plateau the squared noise current of $1^{-20}A^2/Hz$ corresponds to a SNR of 135dB per 1Hz detection bandwidth.

Intensity noise theory

To identify the relevant intensity noise parameters we compare the experimental data to theoretical calculations that were based on expressions for black body radiation. The photons of black body radiation follow the degenerated Bose-Einstein statistic. Therefore the square of the intensity noise current per 1Hz detection bandwidth consists of two contributions:

$$I_{Noise}^2 = 2eI_{Photo} + \frac{I_{Photo}^2}{\Delta\lambda} \cdot \frac{\lambda_c^2}{c}$$

(1)

The first summand is the well-known expression for the Shot Noise with $e$ being the electric charge. While the Shot Noise is linear in the photo current the second summand, the Excess Noise contribution is proportional to the square of the photo current. Furthermore, the Excess Noise depends inversely on the spectral bandwidth $\Delta\lambda$ of the light source. The proportionality constant includes the center wavelength $\lambda_c$ and the velocity of light $c$. Depending on the photon emission process, either the Shot or the Excess Noise contribution can dominate. For the spontaneous emission process in LEDs Shot Noise behavior is expected, whereas for ASE sources, as SLEDs, the Excess Noise component should become dominant.
To calculate the theoretical Excess Noise we investigated the spectral bandwidth of the SLED, that is a function of the pump current. Figure 3.a shows the optical spectra of the QD-SLED for 100mA, 500mA and 900mA pump current. For 100mA, the SLED emits solely on the ground state (GS) at 1270nm. With increasing pump current the GS saturates and the excited state (ES) at 1207nm appears. For 500mA, we observe equally intense emission from the ground and excited state. A higher pump current leads to an exited state dominated emission. This development is reflected in the spectral bandwidth that is shown in figure 3.b. For low pump currents the GS emits with a spectral bandwidth of 50nm. As the ES is activated, the spectral bandwidth increases until it reaches a maximum value of 100nm when GS and ES emission are equally intense. For higher pump currents the ES gets dominant and the spectral bandwidth reduces to 50nm.
Discussion
Regarding the QD-SLED values for photo current and spectral bandwidth, we calculated the theoretical noise currents for an ideal Shot and Excess Noise source. The comparison of the calculated squared noise currents with the experimental data is shown in figure 4. Here the Excess Noise current shows an excellent quantitative and qualitative agreement. The quadratic proportionality of the Excess Noise to the photo current reproduces the increase in the QD-SLED noise current properly whereas the separation of the Shot Noise increases to several decades. In addition, the good qualitative agreement of Excess and QD-SLED noise confirms the inverse dependence on the spectral bandwidth. The reduction in the noise current that is observed for photo currents around 1mA corresponds to the increase in spectral bandwidth from figure 3.b. At the plateau GS and ES emission are equally intense. For higher photo currents the increase in noise results from the decrease in the spectral bandwidth when the ES becomes dominant.

In conclusion, the intensity noise of QD-SLEDs can be described as ideal Excess Noise. The dominant origin of noise is amplified spontaneous emission and the relevant intensity noise parameters are $I_{\text{Photo}}^2$ and $1/\Delta \lambda$. Operating QD-SLEDs at maximum spectral bandwidth is therefore advantageous as it causes a reduction in noise and simultaneously guarantees the maximum axial resolution in low coherence interferometry.

3.2 QD-SLED noise correlations
Further insight into the QD-SLED intensity noise properties can be gained from a correlation analysis of the emission. Here the intensity noise of different emission contributions is measured and compared to the total noise. In the following we will present noise measurements for the spectrally resolved GS and ES emission.

Spectral filtering
By inserting interference filters into the beam path the emission of the ground and excited state was separated. Figure 5.a shows the normalized filter transmission at a pump current of 900mA where the ES emission dominates. The dashed line represents the filtered ground state emission centered at 1270nm with a full width half maximum of 10nm. The solid line represents the filtered excited state emission centered at 1207nm with a width of 11nm. The normalization takes the limited transmission of the interference filters into account. The dotted line shows the optical spectrum of the total emission.
Experimental results
The intensity noise of the GS, ES and total emission is shown in figure 5.b as a function of the pump current. For low currents the intensity noise of the GS emission delivers the dominant contribution to the total noise. The ES noise contribution is several decades less. Around 500mA the intensity noise of the ES emission equals the GS noise. For higher pump currents the intensity noise of the ES contribution becomes dominant whereas the noise from the GS is reduced. The normalization takes the limited filter transmission into account and includes the incomplete masking of the full GS and ES spectral bandwidths.

Discussion
The intensity noise of the total emission is the direct sum of the GS and ES contributions. Therefore the GS and ES emission are uncorrelated. For correlated contributions the sum would either exceed or lie beneath the total noise. Each contribution exhibits ideal Excess Noise behavior being quadratically proportional to the photo current and inversely proportional to the spectral bandwidth. As the spectral bandwidth of the filtered transmission is independent of the pump current the intensity noise of the GS and ES emission follows the development of the spectrally filtered photo currents. For low pump currents the GS emission delivers the dominant photo current, and therefore, noise contribution. At 500mA the GS photo current equals the ES photo current. For higher pump currents the intensity of the GS emission is reduced and the ES contribution becomes dominant.

In conclusion, the GS and ES contribution can be treated as independent ASE sources that show Excess Noise behavior. This indicates that the total emission is composed of uncorrelated contributions due to the weak waveguiding effect that is present in SLEDs. Further investigations of spatially and polarization resolved emission contributions also showed no significant correlation. For the polarization resolved measurements a Glan-Thompson polarizer was inserted into the beam path. The strong linear polarization of the QD-SLED delivered the dominant noise contribution. For the spatially resolved measurements, aspherical lenses with different numerical apertures where used to select different solid angles of the SLED’s emission. In contrast to the intensity noise of Resonant Cavity LEDs, where an external resonator provides additional optical waveguiding, no spatial correlation in noise was observed.

3.3 QD-Laser intensity noise
To investigate the influence of a resonator on the intensity noise behavior we performed noise measurements on QD-Lasers. We compared the QD-Laser noise to the theoretical Shot and Excess Noise and to the noise of a similar QD-SLED. To allow for direct comparison with the SLED, we have chosen a laser utilizing the same QD gain material with identical geometrical dimensions as the SLED. The maximum optical output power of the laser is 50mW.
QD-Laser spectral properties
The calculation of the theoretical Excess Noise based on the experimental QD-Laser values requires the determination of the spectral bandwidth. The optical spectra for different pump currents are shown in figure 6.a. Below threshold spontaneous emission leads to a broad spectral emission. At a pump current of 48mA the device starts lasing on a single ground state mode at 1317nm. For higher currents multiple GS modes are lasing simultaneously between 1310nm and 1320nm. Then the threshold of the excited state is reached and in addition to the multimodal GS lasing single mode ES lasing sets in at 1307nm. With increasing pump current the whole spectra shifts to longer wavelengths. An upper limit for the spectral bandwidth of the laser is given by

\[ \Delta \lambda \approx \Delta \lambda \cdot \left( \sum \frac{P_{\lambda}}{P_{\lambda}} \right)^2. \]  

Here \( P_{\lambda} \) denotes the discretized spectral power and \( \Delta \lambda \) is the spectral spacing between neighbored \( P_{\lambda} \)s.

The spectral bandwidth of the laser as a function of the pump current is shown in figure 6.b. Below threshold, spontaneous emission leads to an 80nm broad bandwidth. At threshold the bandwidth jumps below 20nm. The activation of additional lasing modes reduces the spectral bandwidth as more power is deposited in a smaller spectral region. At a pump current of about 150mA the spontaneous emission from the excited state raises the spectral bandwidth to above 20nm.

QD-Laser versus theory
The measured squared intensity noise current of the QD-Laser is shown with double logarithmic scales in figure 7. The dashed line represents the calculated intensity noise of an ideal Shot Noise source, the solid line represents an ideal Excess Noise source. The QD-Laser noise increases with the pump current. At a photo current of 1mA the ground state threshold is reached and the noise reaches a maximum of \( 3E-17A^2/Hz \) which corresponds to a SNR of 110dB per 1Hz detection bandwidth. Above the GS threshold the noise decreases. * The Shot Noise increases linear with the photo current and lies below the QD-Laser’s noise. The separation of more than four decades at the GS threshold reduces to below three decades when the laser noise decreases above threshold. Below threshold the Excess Noise model shows good agreement with the QD-Laser noise. However, the abrupt increase in the Excess Noise at 0.09mA photo current, due to the reduction of the spectral bandwidth, is not reproduced. Furthermore, the reduction of the laser’s noise above threshold is not predicted by Excess Noise theory. The separation in noise current increases rapidly to more than two decades.

*At the ES state threshold, that is not displayed, another less pronounced increase in noise is observed.
Discussion
The QD-Laser shows a typical behavior of increased noise at threshold. For an ideal single mode laser Shot Noise behavior is expected. The QD-Laser exhibits neither ideal Shot, nor Excess Noise. Below threshold there is the quadratic dependance on the photo current predicted by the Excess Noise, however the laser noise is less sensitive to development of the spectral bandwidth as the abrupt increase is not reproduced. Above threshold the laser noise moves towards the Shot Noise level but shows a significant offset. We attribute the offset to a fraction of amplified spontaneous emission that is still present in the laser’s total emission, as can be seen in figure 6.a.

QD-Laser versus QD-SLED
The laser resonator has a strong influence on the photon fluctuations. This becomes also evident from the comparison of QD-Laser noise with the noise of similar QD-SLED. To allow for comparison laser and SLED utilize gain material from the same wafer and possess identical geometrical dimensions. Their noise currents as a function
of the photo current are shown in figure 8. Below threshold laser and SLED exhibit almost equal intensity noise confirming a quadratic proportionality to the photo current. Amplified spontaneous emission is the dominant origin of noise. This is also supported by the similar values of the photo currents below threshold. Above threshold stimulated emission in the laser becomes dominant and more optical power is emitted. However, when the laser approaches threshold its noise behavior changes significantly. For an ideal Excess Noise source an increase in noise is expected when the spectral bandwidth reduces. In contrast, the intensity noise decreases without approaching the Shot Noise level. Therefore, we propose a combination of Shot and Excess Noise components due to lasing operation with an amplified spontaneous emission underground.

4. CONCLUSION AND OUTLOOK

We presented high precision intensity noise measurements for newly developed Quantum Dot light sources emitting at 1.3µm. We found an Excess Noise behavior for QD-SLEDs. Due to the high gain and the suppression of modal emission amplified spontaneous emission is the dominant origin of intensity noise. The relevant noise parameters \( I_{\text{photo}}^2 \) and \( 1/\Delta \lambda \) were identified. A reduction in noise is therefore possible when the maximum spectral bandwidth of the SLED is further increased. Considering the spectral properties, we presented a correlation analysis of the emission from the ground and excited state. The noncorrelation, that we also observed for spatially and polarization resolved measurements, was attributed to the weak waveguiding effect that is present in a SLED design. The influence on the intensity noise of strong waveguiding due to resonant geometries was investigated with QD-Lasers. For the laser noise we found a quadratic dependence on the photo current below threshold that we also related to amplified spontaneous emission. The reduction in noise above threshold is proposed to be the consequence of a principal Shot Noise behavior with an Excess Noise underground that remains present. Next we will address the photon counting statistics of the QD-SLEDs to get further insight into carrier dynamics. Another important task is the investigation how optical feedback effects the emission properties of the SLED. Regarding the QD-Laser additional noise measurements will be carried out concerning correlations.

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