C1

Experimental investigation of Diode Laser Quantum Noise

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Introduction

Fundamental TDLS limit achieved for trace molecules absorption detection is determined by DL radiation quantum noise [1, 2]. Four DL quantum noise mechanisms were introduced and analyzed (see B1).
Purposes of present paper:
- Experimental technique development to investigate stationary and noise characteristics of different diode laser types.
- Compare experimental results with model prediction.
- Determine model parameters using model comparison with experimental data.
- Determine dominant quantum noise type.

Two different diode laser types were selected for present investigation: NIR DL and QCL.

[1] A.Nadezhdinskii, Fundamental Noises in TDLS, Abstracts of TDLS 2009, Zermatt, Switzerland, p.43.
[2] http://www.dls.gpi.ru/rus/conf/TDLS2009/Posters/B1_Fundamental%20noises%20in%20TDLS.pdf

Back to basic

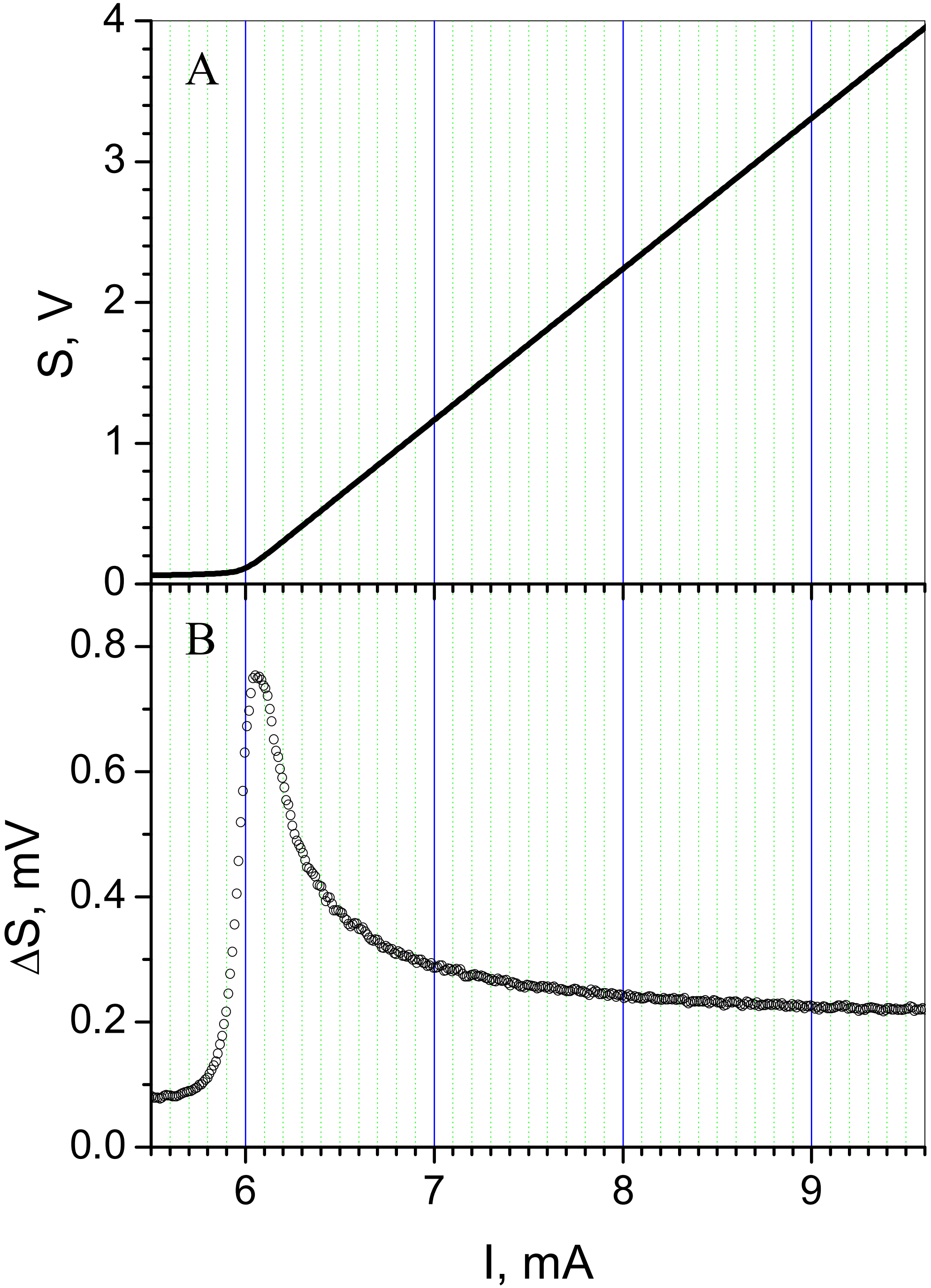
In quantum physics object don't know is it particle or wave. Our method of measurement determine what parameter of the system we are measuring. To determine what the object parameter is measuring in particular experiment, characteristic experiment dimension has to be compared with the object wave length.

Electron: electron wave length (kinetic energy ~ kT) is equal to 1.2 nm. Electron is wave in quantum well. Electron is particle in photo-detector.

Photon: Photon behavior also depends on its wavelength and characteristic dimension of experiment.

γ quant with energy 124 keV has wavelength 0.01 nm. For atom it is particle. Atom is totally transparent for such γ quant. For nuclei this quant is wave: γ-spectroscopy.

Our spectral range: Both for molecule and electron photon is wave. This results in dipole approximation of radiation theory: DL generation and molecular absorption.



Signal and noise

Trace molecules detection by TDLS is determined by recorded signal and its noise.

Signal (A) and signal noise (B) dependence vs. excitation current near threshold for one of the DL under investigation (near IR DL).

Both signal and noise depend on DL radiation part recorded by PD.

To exclude signal dependence on experimental setup, normalized signal S_{norm} is using.

$$S_{norm}(I) = \frac{S(I)}{S_0} I_{th}$$

Here $S_0 = S(2I_{th})$.

Rate equations

Let us consider rate equations describing radiation generation in DL.

$$\frac{dN_c}{dt} = \chi \frac{I}{e} - gN_c(N_p + 1) + gN_G N_p - \frac{N_c}{\tau_c}$$

$$\frac{dN_p}{dt} = gN_c(N_p + 1) - gN_G N_p - \frac{N_p}{\tau_p}$$

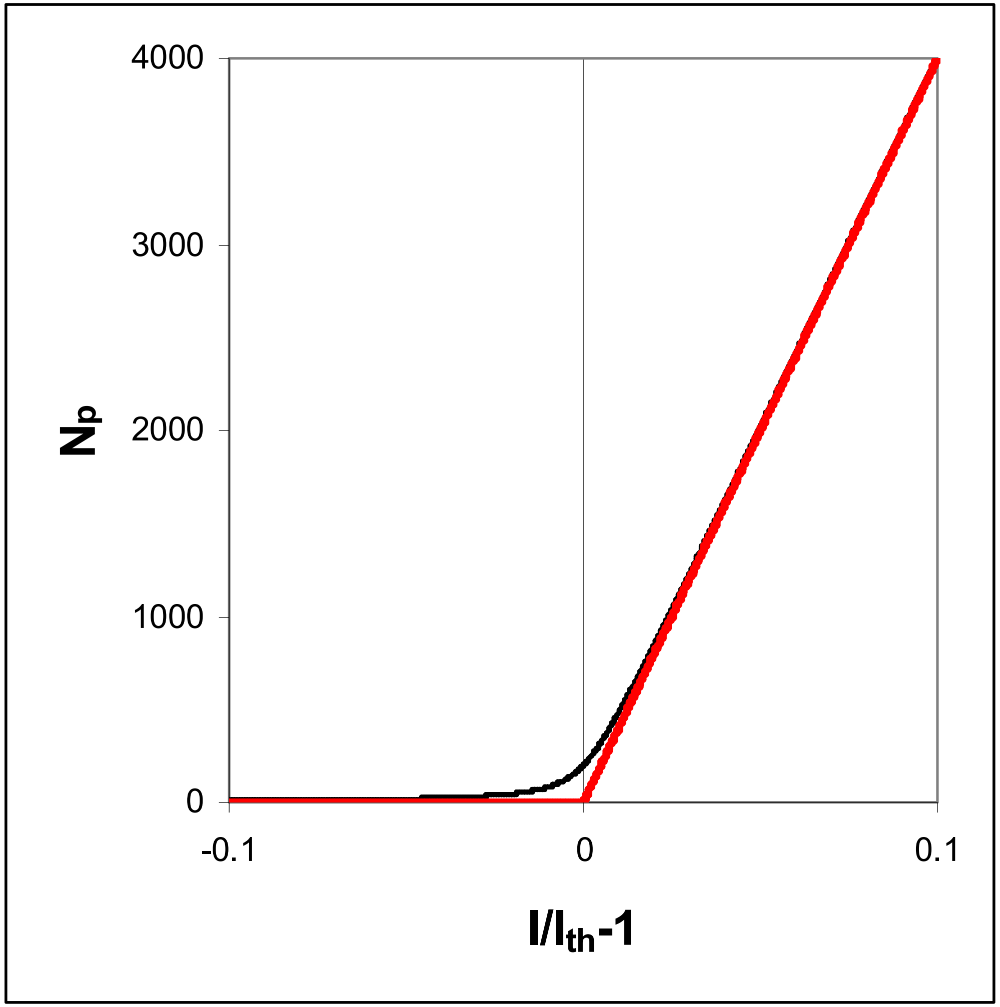
N_c – electrons number in DL active area, N_p – photons number in particular resonator mode, I – excitation current, e – electron charge, χ - quantum efficiency, τ_c – electron life time in energy state interacting with particular resonator mode, g – coefficient describing absorption and stimulated emission, N_G – electrons number when absorption is compensated by stimulated emission, τ_p – photon life time in resonator,

Quantum nature of light is related to presence of spontaneous emission (1 in brackets).

Rate equations stationary solution

$$N_p = N_p(I_{th})^2 \left\{ \frac{1}{2}\left[\frac{I - I_{th}}{I_{th}}\right] + \sqrt{\frac{1}{4}\left[\frac{I - I_{th}}{I_{th}}\right]^2 + \boxed{\frac{1}{N_p(I_{th})^2}\frac{I}{I_{th}}}} \right\}$$

$$N_c = \frac{\tau_c}{\tau_p}\frac{N_p(I_{th})^2 N_p}{(N_p + 1)}$$



Spontaneous emission is responsible for presence of term inside red rectangular.

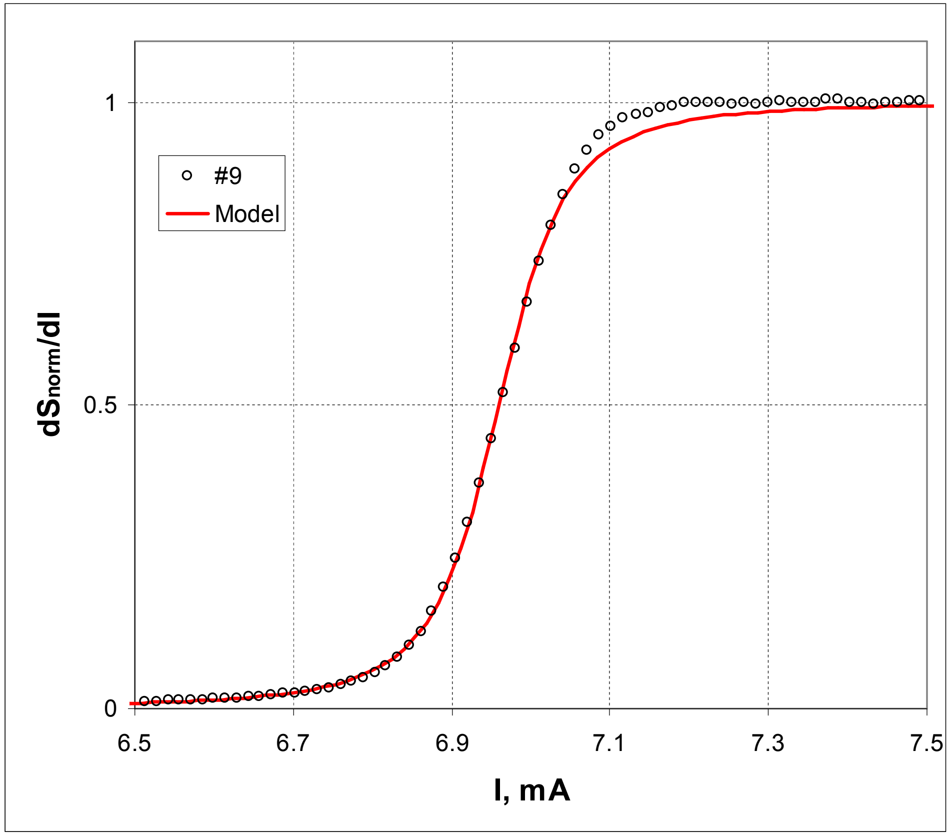
$$N_p(I_{th}) = \sqrt{N_p(2I_{th})} = \sqrt{\chi \frac{I_{th}}{e}\tau_p}$$

Photons number dependence of excitation current is determined by $N_p(I_{th})$ – photons number at threshold.
Red - classical electromagnetic field (no spontaneous emission, $N_p(I_{th}) \to \infty$).
Black – $N_p(I_{th})$ = 200 (typical for near IR DL). Below and above threshold black is similar to red. Near threshold - transition area with width reversely proportional to $N_p(I_{th})$.

Signal dependence vs. excitation current

Rate equations stationary solution for normalized signal.

$$S_{norm}(I) = \frac{N_p(I)}{N_p(I_{th})^2} I_{th} = \frac{1}{2}\left[I - I_{th}\right] + \sqrt{\frac{1}{4}\left[I - I_{th}\right]^2 + \frac{I_{th} I}{N_p(I_{th})^2}}$$



Derivative of normalized signal vs. excitation current for DL under investigation (black circles).

Dependence under consideration is determined by 2 parameters: I_{th} - threshold current (center of transition area from 0 to 1) and $N_p(I_{th})$ – photon number at threshold current (transition area width). Red curve - rate equations stationary solution with following parameters: I_{th} = 6.960 mA, $N_p(I_{th})$ = 158. Good agreement can be observed except area close to threshold – subject of linear approximation model used.

Based on parameters determined, photons number - N_p can be calculated for each excitation current - I.

DL noise spectral density

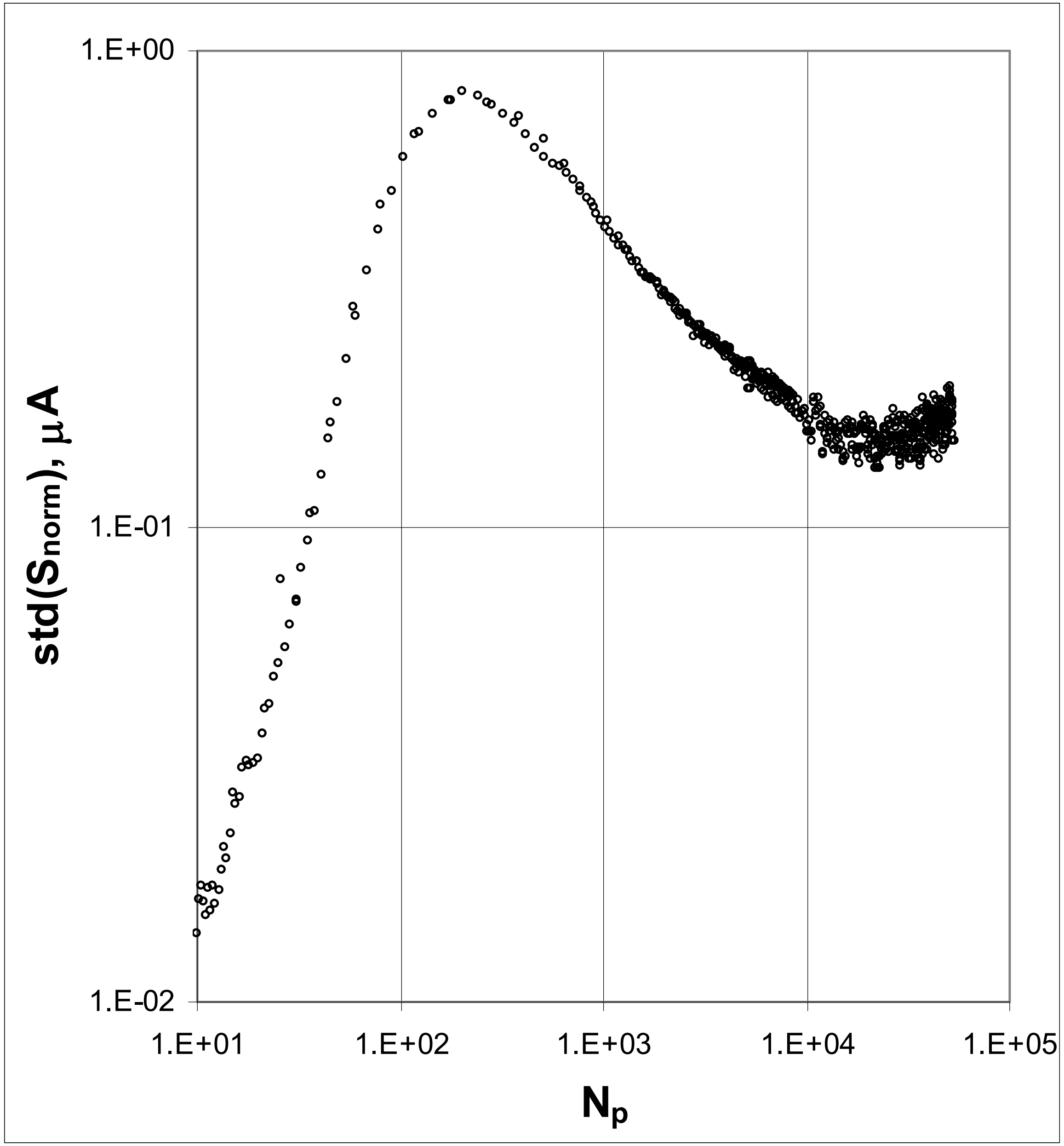
Four quantum noise mechanisms were introduced and analyzed (see B1): ΔI – excitation current shot noise; ΔV – Poison noise of electrons; ΔW – Poison noise of photons; ΔF – quantum noise of electromagnetic field. These noises lead to photons number noise - ΔN_p. As result signal noise will take place.

$$G(\Delta N_p) = \frac{N_p(I_{th})^2 (N_p+1)^2}{N_p(I_{th})^2 + (N_p+1)^2} \frac{G(\Delta I)}{I_{th}} + \frac{N_p(I_{th})^2 N_p}{N_p(I_{th})^2 + (N_p+1)^2} G(\Delta W) +$$

$$+ \frac{(N_p+1)^2}{N_p(I_{th})^2 + (N_p+1)^2} \frac{\tau_p}{\tau_c} G(\Delta V) + \frac{\tau_p}{\tau_c} \frac{(N_p+1) + g\tau_c (N_p+1)^2}{N_p(I_{th})^2 + (N_p+1)^2} G(\Delta F)$$

Photons number noise spectral density is determined by spectral density of particular noise mechanism. Two parameters in this equation are known from rate equations stationary solution: N_p and $N_p(I_{th})$. They determine particular noise dependence vs. photons number – N_p with photons number at threshold - $N_p(I_{th})$ as parameter. The rest parameters are subject of determination during model comparison with experiment.

Normalized signal noise



Normalized noise std of DL under investigation (NEL CO_2) as function of photons number - N_p.

Std is determined by PD preamplifier bandwidth – B. In present case B = 120 kHz.

Asymmetric noise peak dominates near threshold.

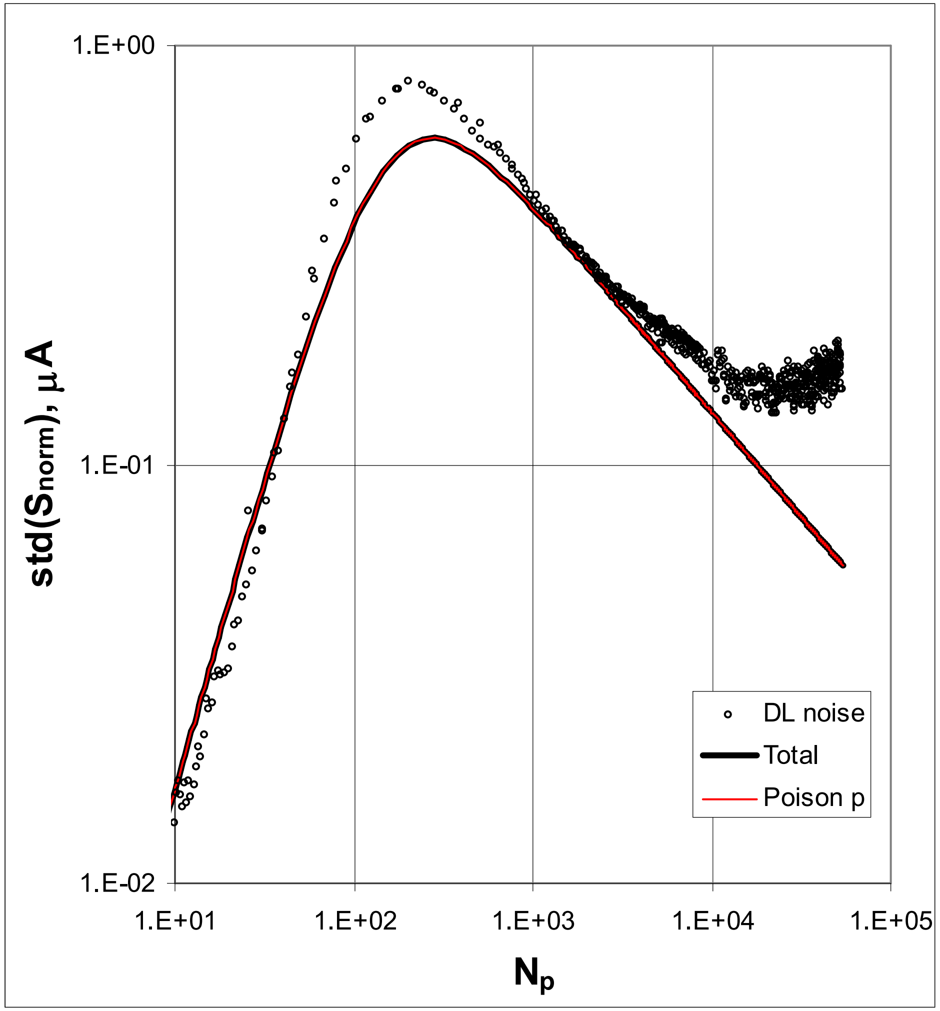
For high excitation currents noise increase can be observed.

Results of DL quantum noises analysis (see B1 and previous slide) will be used to fit experimental data under consideration.

Photons Poisson noise

Near threshold dominates asymmetric peak - photon Poisson noise (see B1).

$$std(S_{norm}) = \sqrt{2\tau_p B}\,\frac{I_{th} N_p^{\;3/2}}{N_p (I_{th})^2 + (N_p + 1)^2}$$

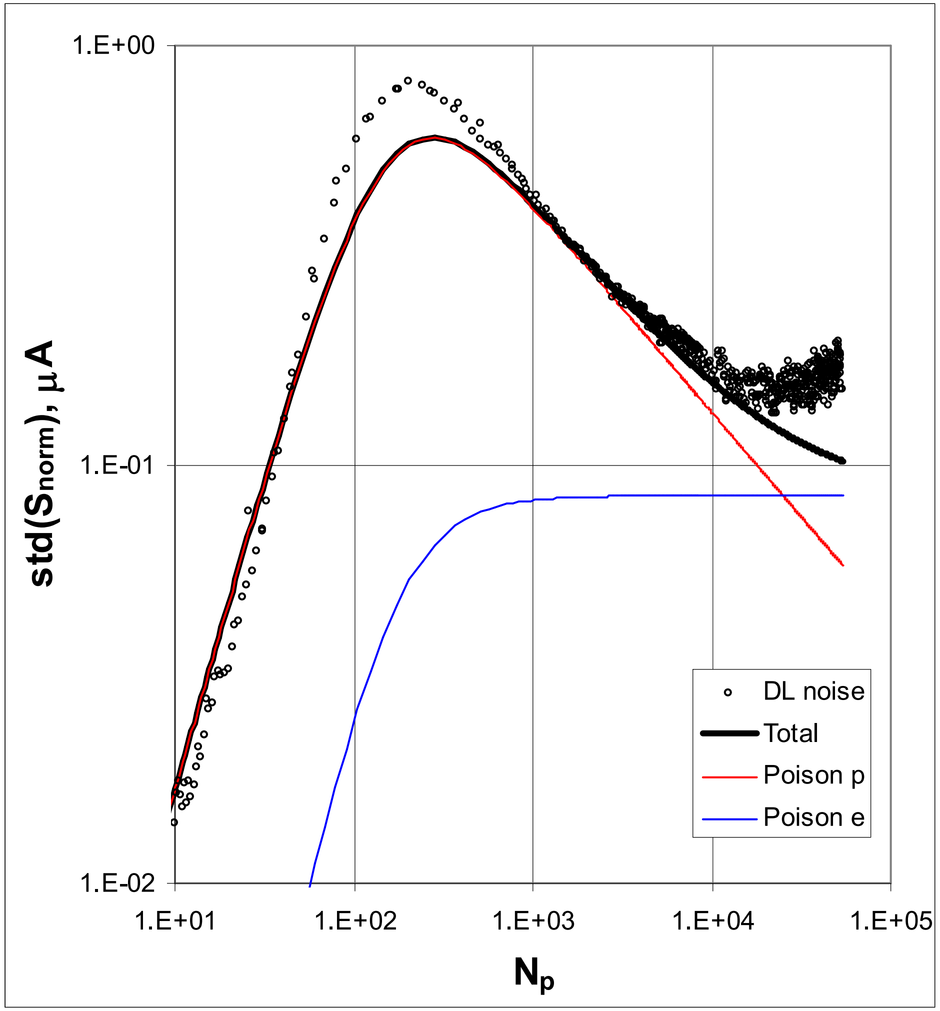


Normalized noise std of DL under investigation (NEL CO_2) as function of photons number - N_p.
Shape of the dependence under consideration is determined by already determined parameters N_p and $N_p(I_{th})$. Dependence amplitude is determined by one free parameter τ_p – photon life time. In present case τ_p = 1.55 psec close to estimation – light travel time in DL resonator. Experiment agreement with model can be considered as qualitative near threshold because of linear approximation model in use being not valid near threshold where std(N_p) > Np). The model is valid only above threshold.

Electrons Poisson noise

Electrons Poisson noise (see B1).

$$std_e(S_{norm}) = \sqrt{2\tau_p B}\frac{I_{th}}{N_p(I_{th})}\frac{\sqrt{N_p}(N_p+1)^{1.5}}{N_p(I_{th})^2+(N_p+1)^2}$$

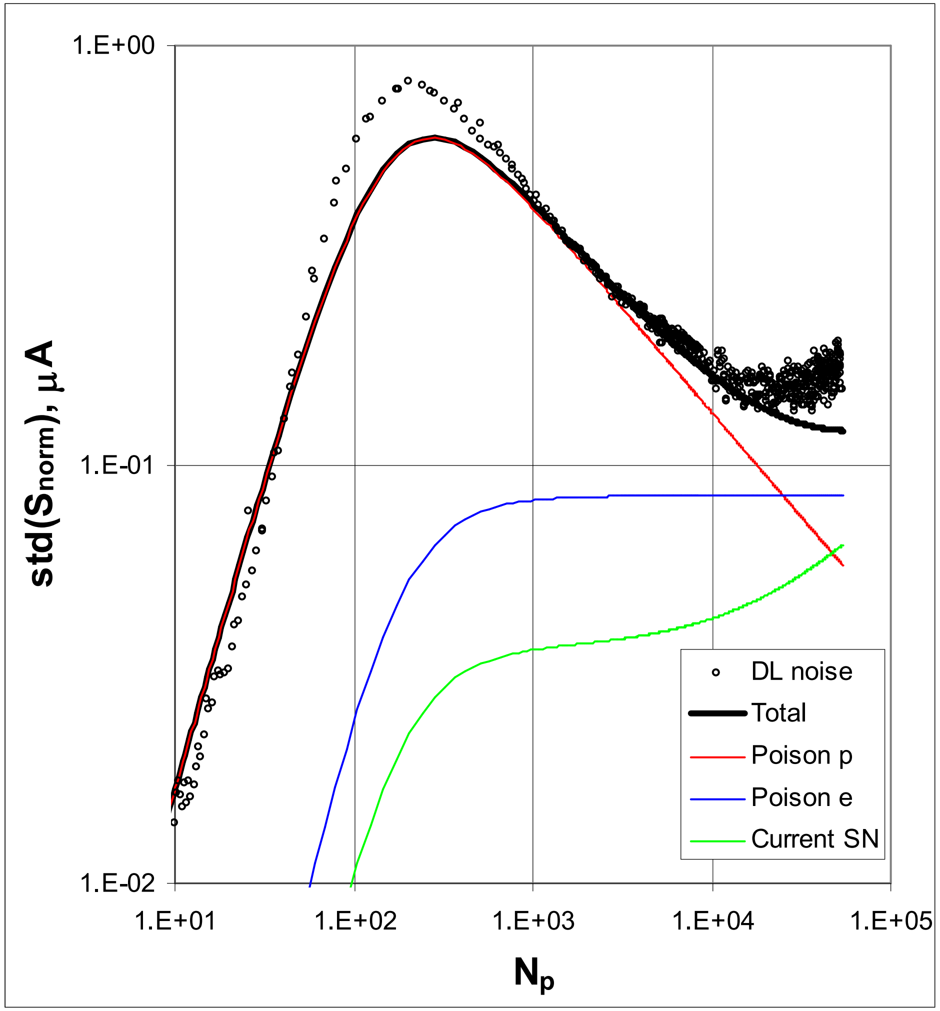


Normalized noise std of DL under investigation (NEL CO_2) as function of photons number - N_p.
Shape of the dependence under consideration is determined by already determined parameters N_p and $N_p(I_{th})$. τ_p – photon life time was already determined. No free parameters.

Excitation current shot noise

Excitation current shot noise (see B1).

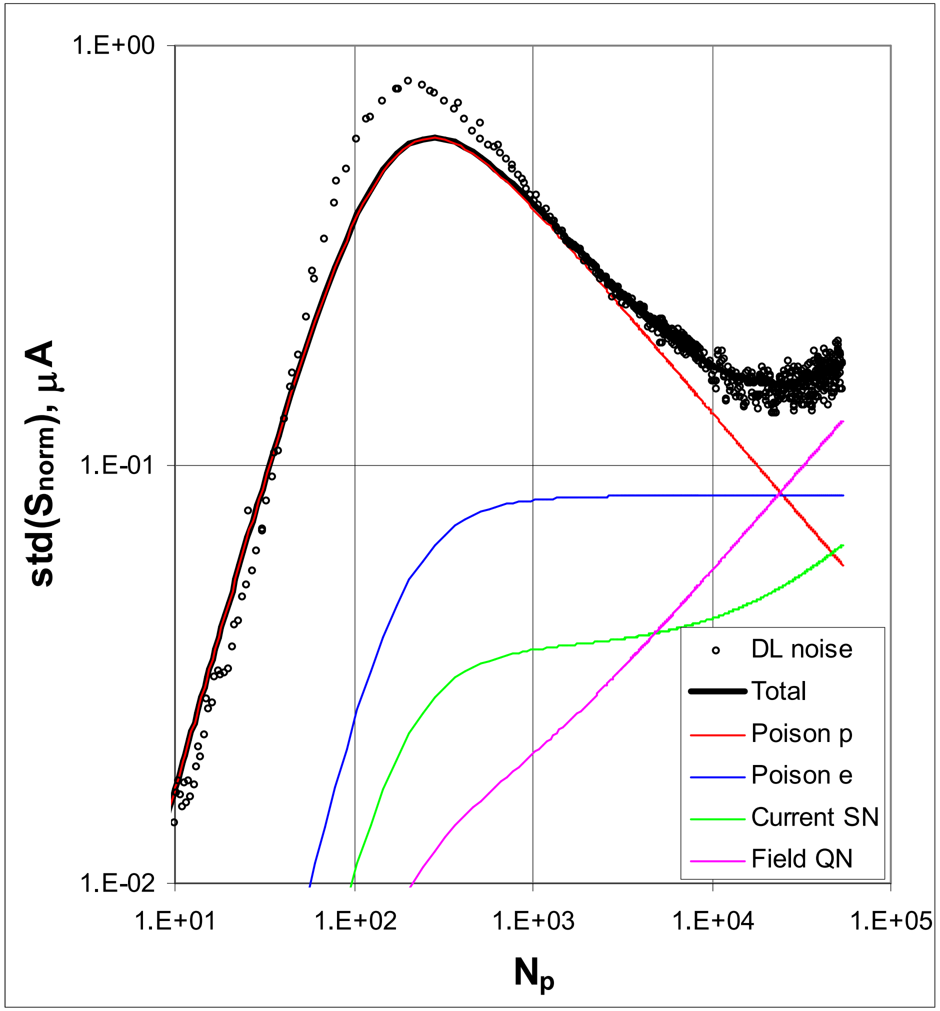
$$std_I(S_{Norm}) = \frac{(N_p+1)^2}{N_p(2I_{th})+(N_p+1)^2}\sqrt{eIB}$$



Normalized noise std of DL under investigation (NEL CO2) as function of photons number - N_p.
Shape of the dependence under consideration is determined by already determined parameters N_p and $N_p(I_{th})$. No free parameters.

Field quantum noise

$$std_F\left(S_{norm}\right) = 2\frac{1+g\tau_c(N_p+1)}{N_p(I_{th})^2+(N_p+1)^2}\frac{I_{th}}{N_p(I_{th})}N_p\sqrt{\tau_p B(N_p+1)}$$



Normalized noise std of DL under investigation (NEL CO2) as function of photons number - N_p.

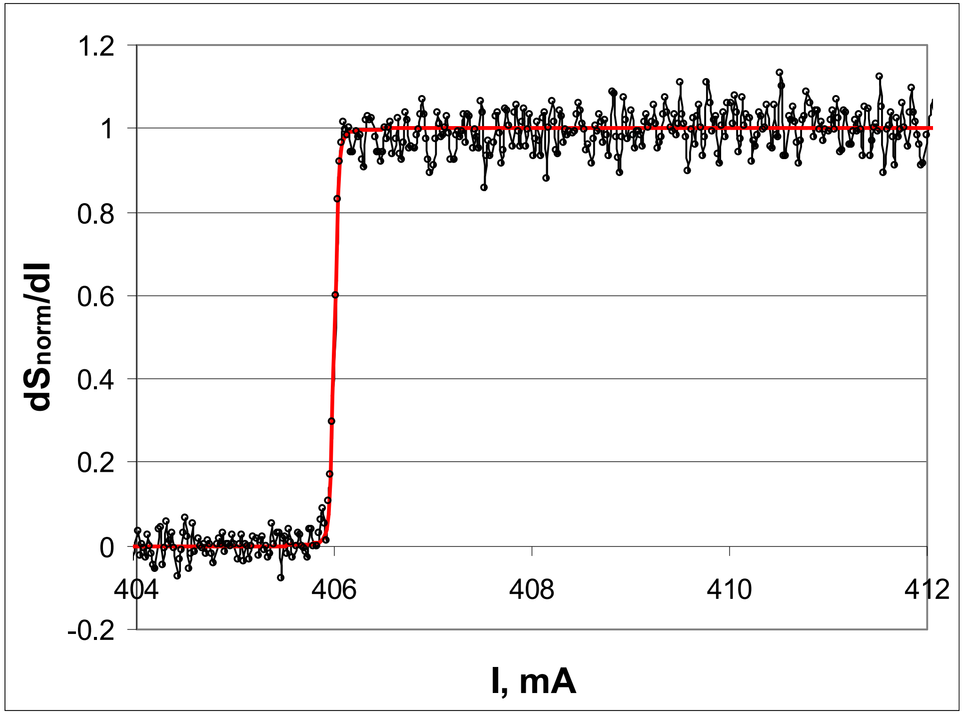
Following parameters were already determined N_p and $N_p(I_{th})$, τ_p – photon life time was already determined.

For the mechanism under consideration we have one new parameter - $g\tau_c$. For present DL parameter value obtained from experimental data fitting is 0.005. From the parameter value estimation we've found 0.025 being in qualitative agreement with result obtained.

For high excitation current field quantum noise dominates.

Quantum Cascade Laser

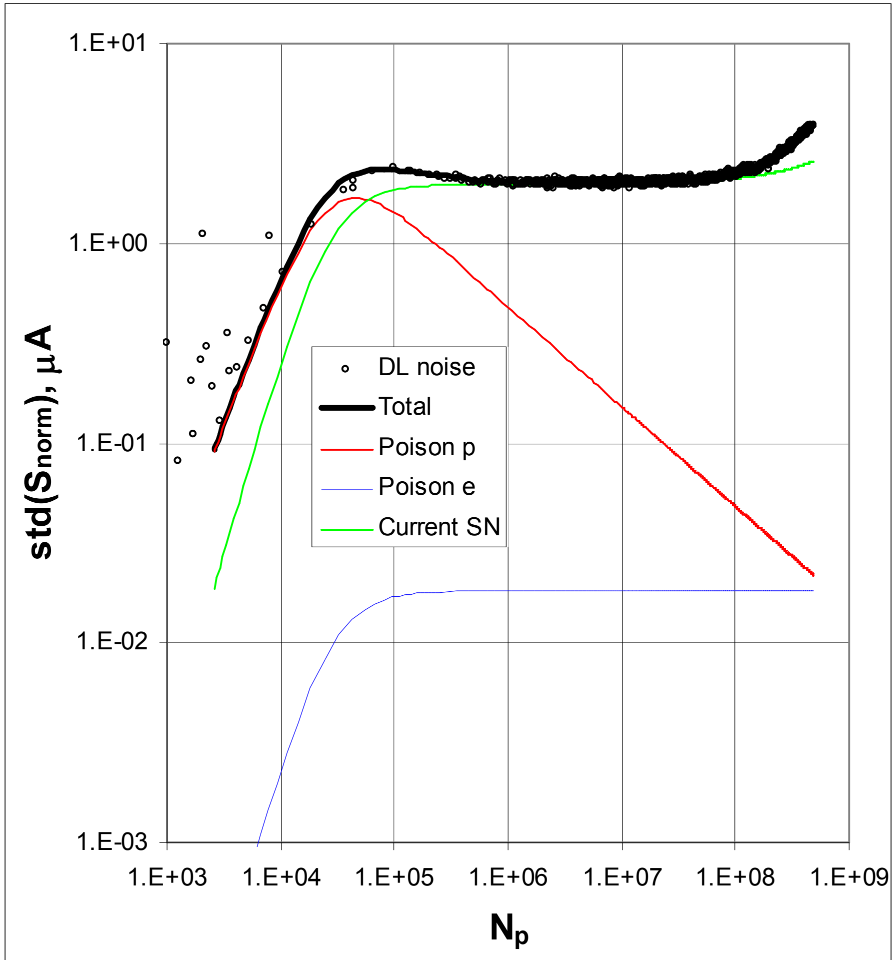
Room temperature QCL was investigated using method developed. Results were analyzed using model proposed.



Derivative of normalized signal vs. excitation current for DL under investigation (black circles). Red curve – model with parameters obtained: I_{th} = 406 mA, $N_p(I_{th})$ = 27000 – dramatically higher with respect to near IR DL.

For QCL electron participates in photon generation in each cascade. This explains high $N_p(I_{th})$ value, room operation, and high quantum efficiency. However, stationary solution of rate equations (model) is the same as for other diode laser types (see D1).

QCL noise



Normalized noise std of DL under investigation (QCL) as function of photons number - N_p. Nothing new for Poisson noises. Obtained value of τ_p = 14 psec is in agreement with light travel time in QCL resonator. Due to high $N_p(I_{th})$ value, field quantum noise is negligible (see B1).

Excitation current shot noise has new feature for QCL. Electron passes K cascades. In each cascade it generates the same shot noise.

$$std_I(S_{Norm}) = K\frac{(N_p+1)^2}{N_p(2I_{th})+(N_p+1)^2}\sqrt{eIB}$$

In present case K = 35 (green curve).

QCL noise is determined by excitation current shot noise. For high excitation currents additional noise proportional to signal was observed.

Conclusion

Two different diode laser types were selected for present investigation: NIR DL and QCL.

Technique was developed to investigate stationary and noise characteristics of different diode laser types.

Experimental data were compared with model proposed (see B1) to determine model parameters. Four DL quantum noise mechanisms were analyzed:

1. Excitation current shot noise.
2. Electrons Poisson noise.
3. Photons Poisson noise.
4. Quantum noise of electromagnetic field.

Model parameters obtained are in agreement with theory prediction.

Field quantum noise and excitation current shot noise were determined as dominant ones for NIR DL and QCL, respectively. Further comparison with experiment will be presented in D1.