D1

# Inter-comparison of different diode laser types

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DLS LAB

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# Introduction

Many DL types are using in TDLS.
Goal of present paper is to present comparison of their properties related to trace molecules detection. Technique of DL investigation was developed (see B1, C1). A lot of lasers was investigated. In present comparison results for 7 DL being representatives of different DL types of different suppliers are presented.

***<u>List of DLs under comparison</u>***

1. NEL CO2 – 1.602 $\mu$, DFB, косой наконечник, 50 dB optical isolator.
2. NEL – 1.392 $\mu$, DFB, прямой наконечник, 30 dB optical isolator.
3. Anritsu - 1.502 $\mu$, DFB, косой наконечник, no optical isolator.
4. Sensor unlimited - 1.392 $\mu$, DFB, DL chip, mesa structure.
5. LC - Laser components - 1.65 $\mu$, DFB, DL chip, limited amplification.
6. Mid IR - Laser components – 7.8 $\mu$, $A^{IV}B^{VI}$, FP resonator, DL chip.
7. QCL - Hamamatsu – 7.8 $\mu$, DFB, QCL, DL chip.

# Rate equations

Comparison is based on rate equations and their solution.

Let us consider rate equations describing radiation generation in DL.

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

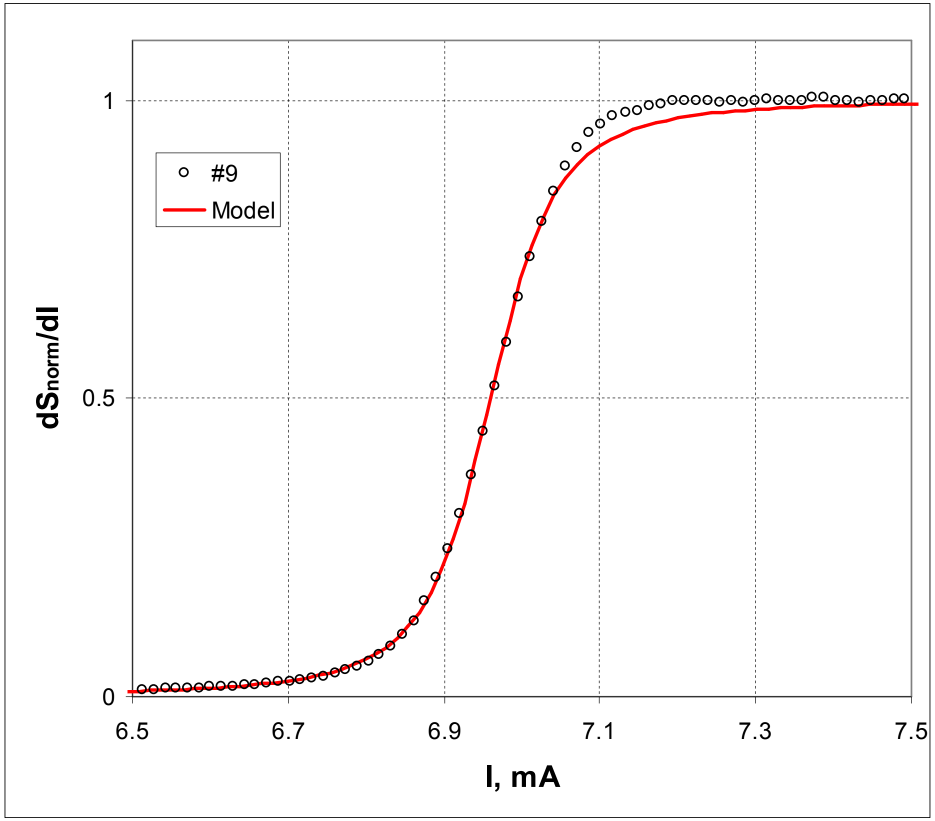
$$\frac{dN_p}{dt} = gN_c(N_p + 1) - gN_G N_p - \frac{N_p}{\tau_p}$$

$N_c$ – electrons number in DL active area, $N_p$ – photons number in particular resonator mode, I – excitation current, e – electron charge, $\chi$ - quantum efficiency, $\tau_c$ – 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, $\tau_p$ – photon life time in resonator, K – cascades number for QCL (each electron participates K times in photons emission), for rest DL K = 1.

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

# Signal dependence vs. excitation current

Derivative of normalized signal vs. excitation current (black circles – experiment for NEL CO2).




Rate equations stationary solution for photons.

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

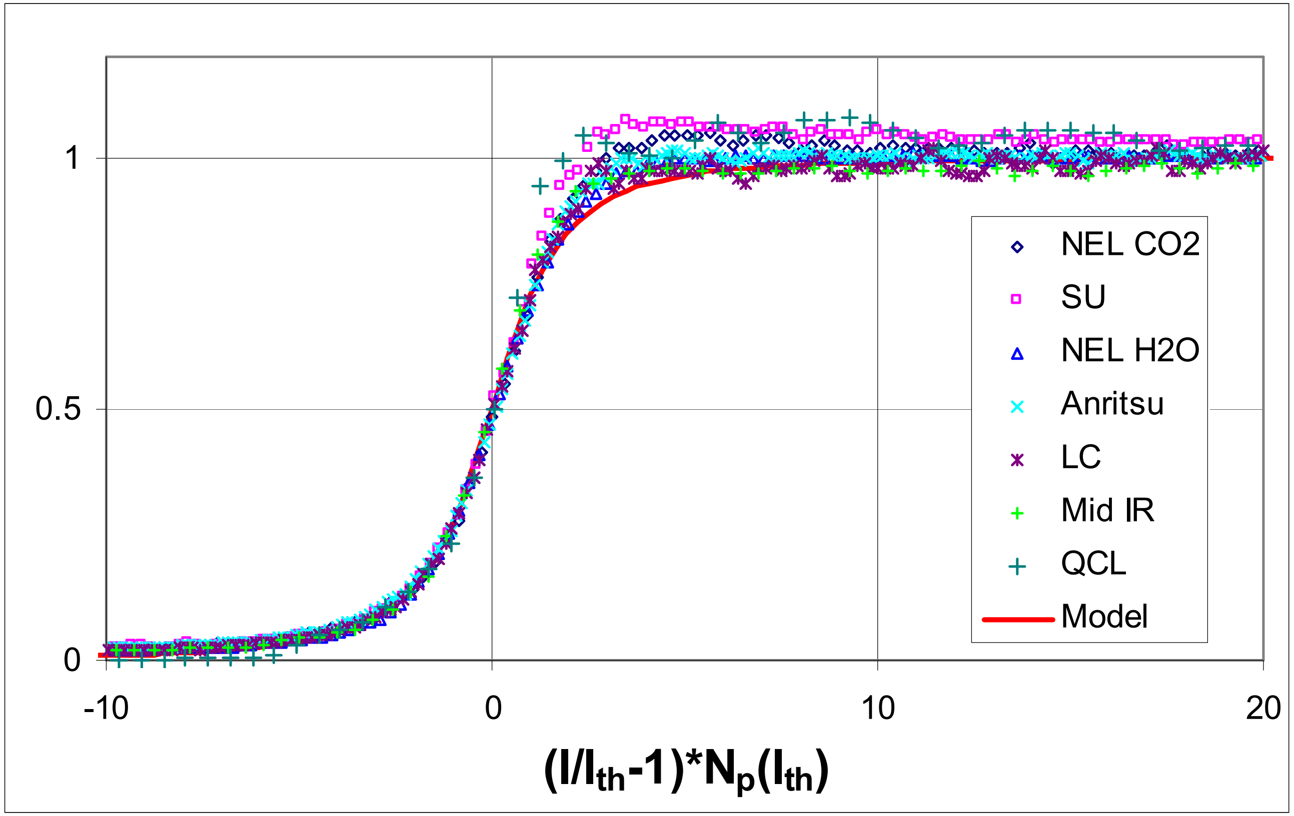
Dependence under consideration is determined by 2 parameters: $I_{th}$ - threshold current (center of transition area from 0 to 1) and $N_p(I_{th})$ – photon number at threshold current (transition area width).

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

Using experimental results both parameters can be determined. Red curve rate equations stationary solution with following parameters determined: $I_{th}$ = 6.960 mA, $N_p(I_{th})$ = 158. The parameters determined for other DLs are presented in final Table.

# Comparison of signal vs. excitation current dependence

Using parameters obtained with help of procedure described in previous slide different DL types can be compared.




Results obtained are in good agreement for different DL types and model except area close to threshold where quantum noises influence on signal vs. current dependence has to be taken into account (higher noise - higher difference with respect to model).

# Rate equations with quantum noise

$$\frac{d\Delta N_c}{dt} = \chi \frac{I + \Delta I}{e} - g[N_c + \Delta N_c + \Delta V][(N_p + 1) + \Delta N_p + \Delta W] +$$

$$+ gN_G[N_p + \Delta N_p] - \frac{N_c + \Delta N_c}{\tau_c}$$

$$\frac{d\Delta N_p}{dt} = g[N_c + \Delta N_c + \Delta V][(N_p + 1) + \Delta N_p + \Delta W] +$$

$$+ g\Delta F - gN_G[N_p + \Delta N_p] - \frac{N_p + \Delta N_p}{\tau_p}$$

Four quantum noise mechanisms were introduced and analyzed (see B2):
$\Delta$I – excitation current shot noise;
$\Delta$V – Poison noise of electrons;
$\Delta$W – Poison noise of photons;
$\Delta$F – electromagnetic field quantum noise.
These noises leads to noises of $\Delta N_c$ and $\Delta N_p$ – electrons and photons numbers, respectively. We are measuring photons number noise in Bandwidth – B (several orders of magnitude smaller with respect to other characteristic DL frequencies).

# Poisson noises of electrons and photons

Origins and solutions of linear approximation of rate equations for Poison noises.

Electron is particle, its number will fluctuate leading to detected DL intensity noise due to Poisson fluctuations of electron number.

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

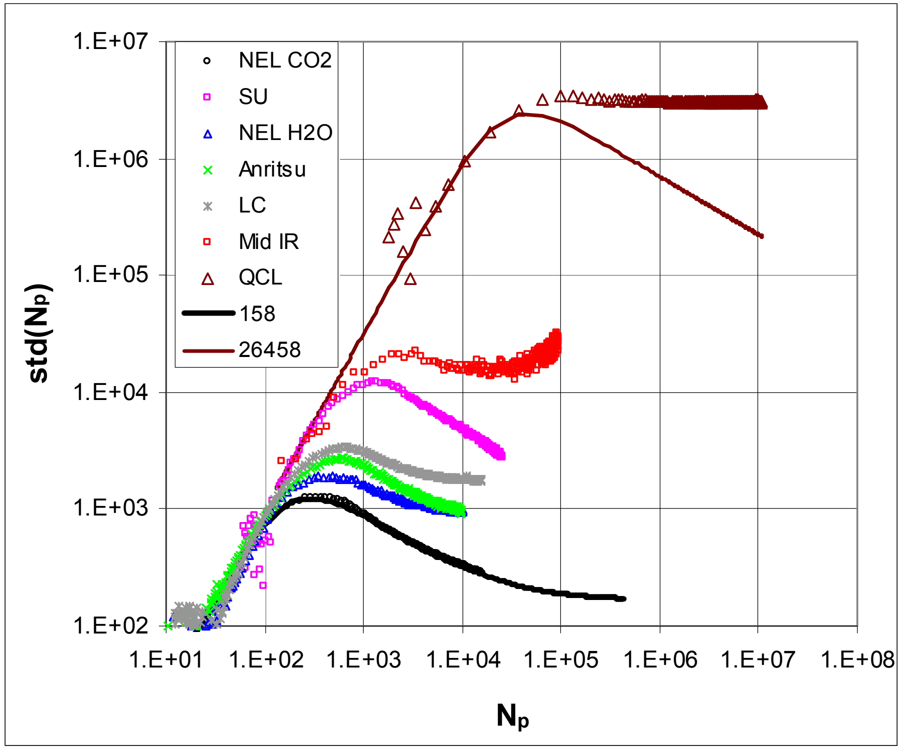
Coherent state of electromagnetic field (DL emission) has Poison distribution with respect to photon numbers in resonator mode. This distribution will fluctuate leading to detected DL intensity noise due to Poisson fluctuations of photons number.

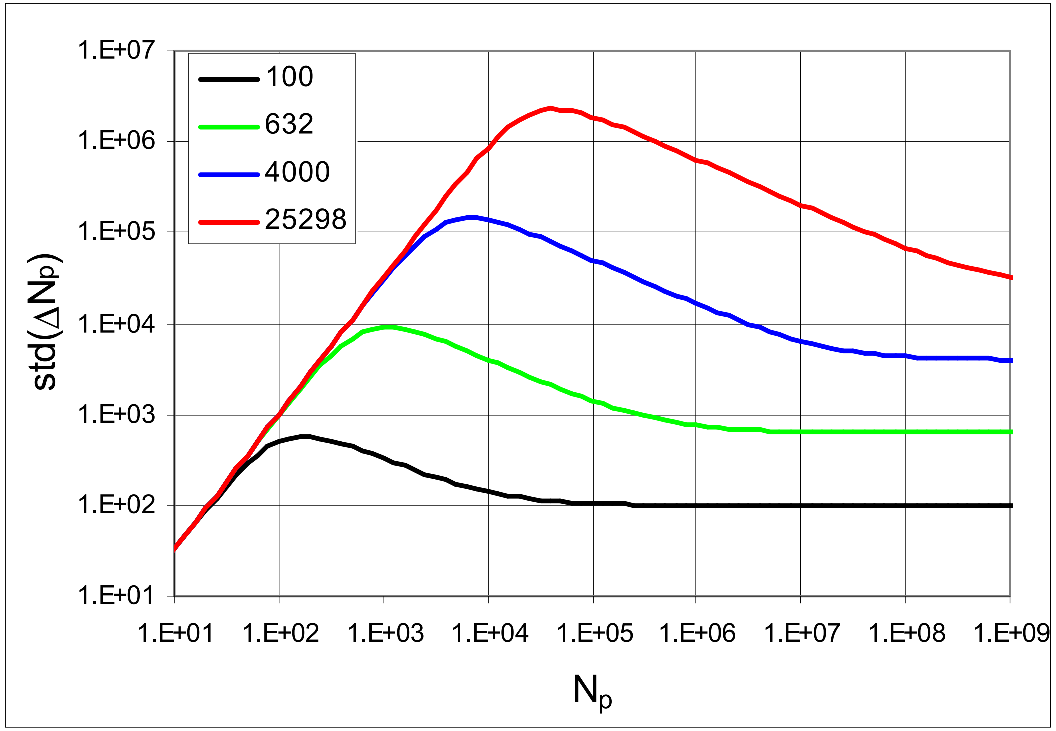
$$std(N_p) = \frac{N_p(I_{th})^2 N_p \sqrt{2\tau_p B N_p}}{N_p(I_{th})^2 + (N_p+1)^2}$$

Both Poisson noise mechanisms are determined by already known parameters: photon number, photon number at threshold and detector bandwidth. Additional parameter $\tau_p$ - photon life time in resonator can be determined from experiment and is included in final Table.

# DL noise

Using parameters obtained with help of procedures described in previous slides different DL types can be compared.




Left – noises of different DL types under consideration. Right – model of Poisson noise for different photons numbers at threshold. In left picture similar curves are presented for maximum and minimum values of photons number at threshold.

Near threshold DL intensity noise is determined by Poisson noise of photons and electrons. Higher threshold less influence of electrons Poisson noise.

# Two additional mechanisms of noises

Origins and solutions of linear approximation of rate equations for excitation current shot noise and quantum noise of electromagnetic field.

Electron is particle – shot noise of excitation current. No free parameter.

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

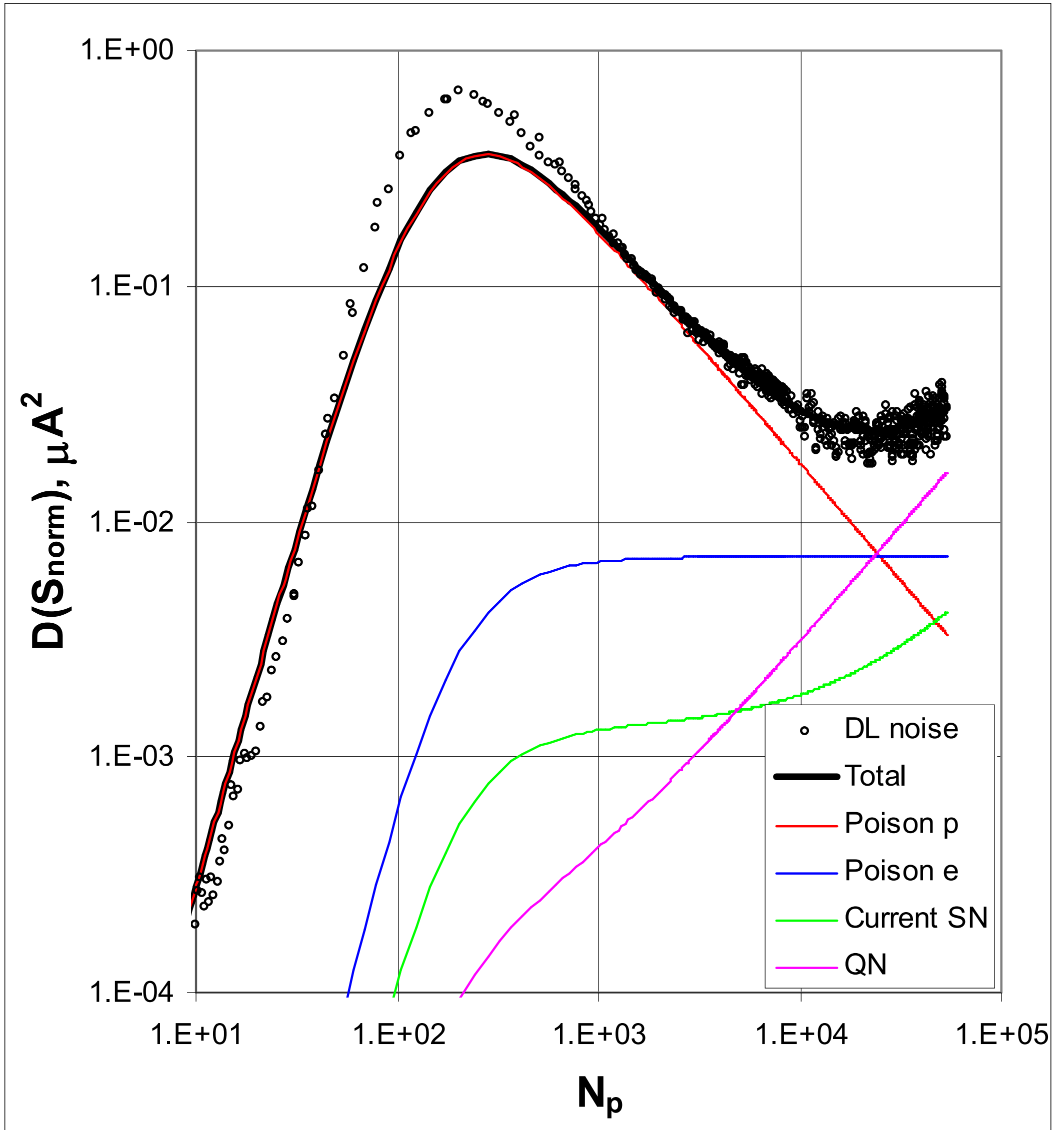
Quantum nature of light leads to quantum noise of electromagnetic field

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

Here is one more parameter - $g\tau_c$ that can be determined from experimental data and estimated from model under consideration. Both values are in reasonable agreement.

# DL quantum noise mechanisms

Using parameters obtained with help of procedures described in previous slide different DL noise types can be compared with experiment (NEL CO2).




DL dispersion of normalized signal noise as function of photons number in resonator mode under consideration.

Near threshold dominate Poisson photons and electrons noises. Near threshold agreement can be considered only as qualitative because linear approximation model is not correct here.

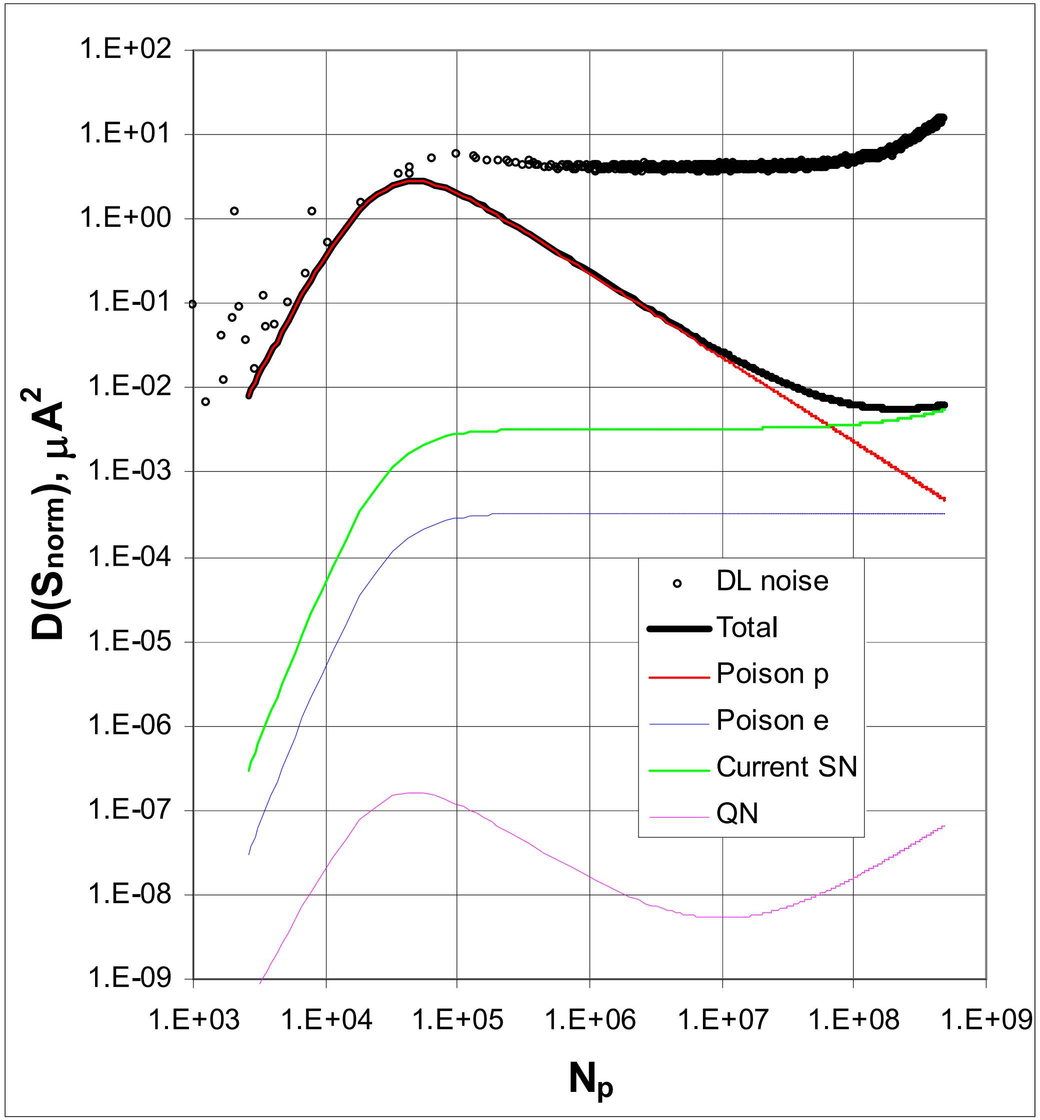
It is correct for current above threshold.

Noise due to excitation current shot noise is negligible.

For high excitation current quantum noise of electromagnetic field dominates.

# QCL noise

Using parameters obtained with help of procedures described in previous slides QCL noise was investigated.




Near threshold photons Poisson noise dominates.

Due to high number of photons at threshold both electrons Poisson and quantum electromagnetic field noises are negligible (electromagnetic field in this case is classical).

Excitation current shot noise dominates here. However, it can not explain results obtained.

# Excitation current shot noise in QCL

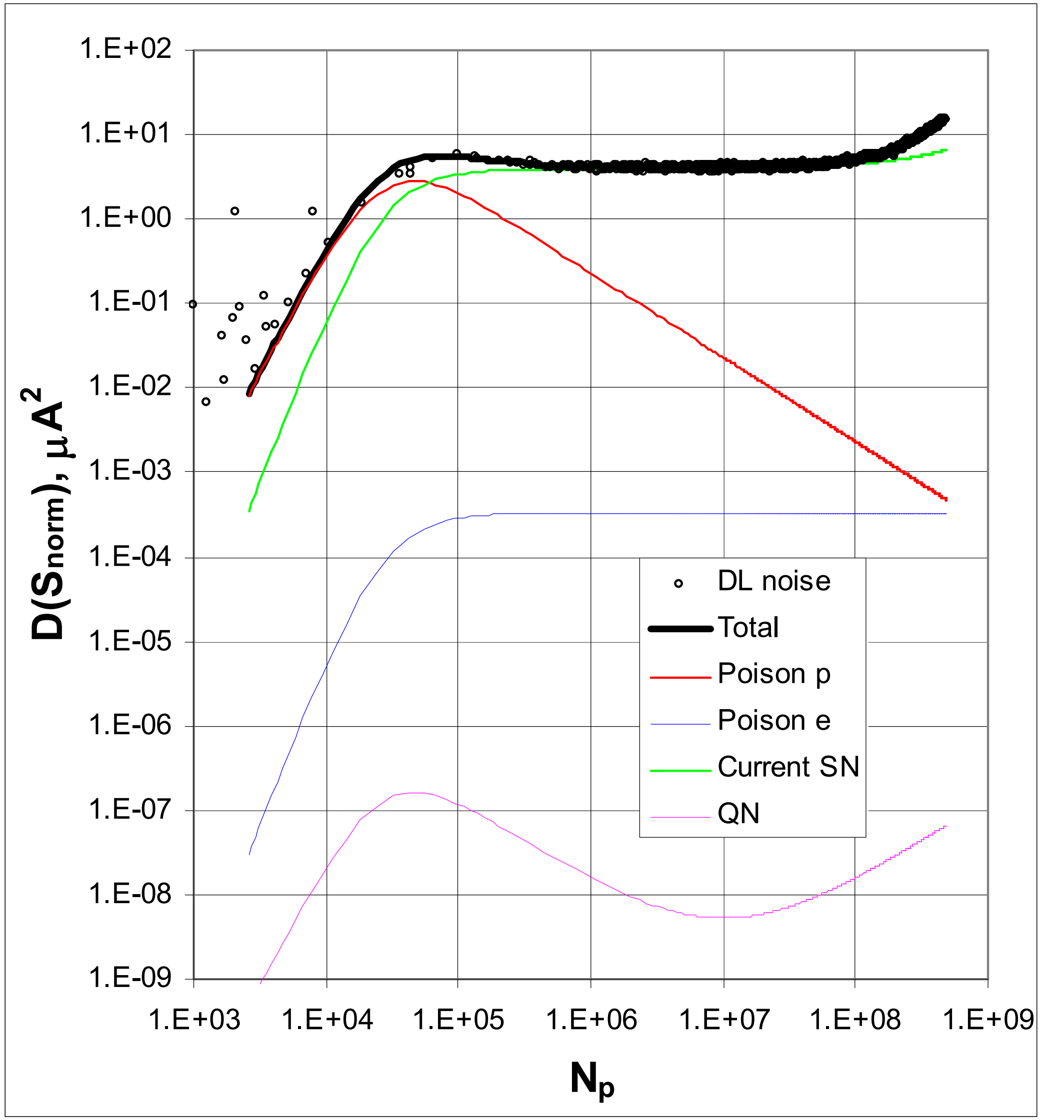
Specific QCL feature is presence of many cascades. Each electron passing these cascades emits photons. It is explanation of high final quantum QCL efficiency and operation near room temperature. Let us consider excitation current shot noise in QCL. Electron is particle that results in excitation current shot noise. Electron passes cascades and produces the same shot noise in each cascade. Hence, QCL excitation current shot noise is:

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

Here K is number of QCL cascades that can be determined from experiment.

# QCL noise

Using parameters obtained with help of procedures described in previous slides QCL noise was investigated.




Excitation current shot noise based on results presented in previous slide is shown by green curve.

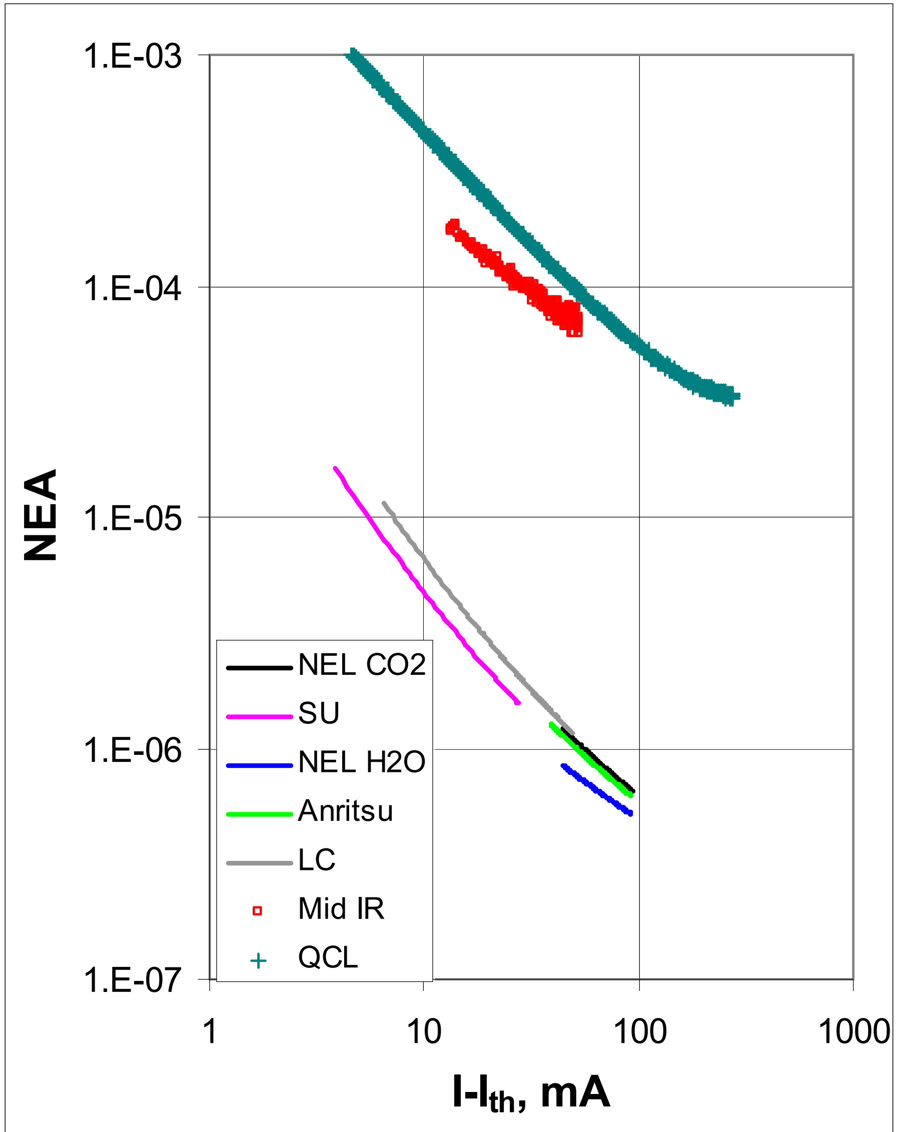
In present case cascades number determined from experimental data under consideration is K = 35. We don’t know real cascades number of particular laser, but result obtained is close to cascades number using in QCL.

Agreement between experiment and model can be considered as good enough.

For high excitation currents additional noise mechanism proportional to recorded signal can be observed. It can be result of QCL frequency quantum noise interaction with baseline.

# NEA

For trace molecules detection NEA - Noise Equivalent Absorbance (relative photocurrent noise) is using to compare different systems.




NEA of DLs under comparison as function of excitation current above threshold.

Different Near IR DL types of different suppliers show similar results. NEA is limited by Poisson noise and electromagnetic field quantum noise for small and high currents, respectively.

For mid IR DL photo detector noise dominates being 2 orders of magnitude larger with respect to near IR DLs.

For QCL dominant are photo detector noise (similar to mid IR) and excitation current shot noise being several times larger.

# Final Table

| DL | NEL $CO_2$ | SU | NEL $H_2O$ | Anritsu | LC | MID IR | QCL |
|---|---|---|---|---|---|---|---|
| $I_{th}$, mA | 6.96 | 25.51 | 5.665 | 11.16 | 15.16 | 449.2 | 406 |
| $N_p(I_{th})$ | 158 | 671 | 224 | 255 | 300 | 894 | 26458 |
| $K_\chi$ | 0.2 | 0.05 | 0.2 | 0.2 | 0.1 | 0.003 | 0.17 |
| $\tau_p$, psec | 1.55 | 1.25 | 2.5 | 2.5 | 2.5 | 0.2 | 14 |

For DLs under comparison threshold currents and photons number at threshold differ significantly by 80 and 170 times, respectively. Quantum efficiency for near IR DLs demonstrates technology progress during last decades from 5 to 20 %. Quantum efficiency of mid IR DL is 2 orders of magnitude worse. For QCL low quantum efficiency in each cascade is compensated by cascades number. Final QCL quantum efficiency is close to near IR DL.

Photon life time in resonator is close for all near IR DLs under comparison, as it is determined by DL resonator length. For QCL resonator length is larger (2 mm with respect to 0.4 mm for near IR DL). Hence, photon life time for QCL is proportionally larger. Low life time for mid IR DL means that there are additional mechanisms for photon to leave particular resonator mode (internal absorbance, scattering, etc.).

# Conclusion

Seven representatives of different DL types of different suppliers were investigated and compared. Four DL quantum noise mechanisms were identified and analyzed. Dominate noise for different DLs was determined. With respect to trace molecule detection NEA (Noise Equivalent Absorbance = relative photo current noise) was analyzed for DLs under comparison.

Different Near IR DL types of different suppliers show similar results. NEA is limited by Poisson noise and electromagnetic field quantum noise for small and high currents, respectively. To achieve best results usage of DL with smallest threshold and largest operation current is recommended.

For mid IR DL photo detector noise dominates being 2 orders of magnitude larger with respect to near IR DLs.

For QCL dominant are photo detector noise (similar to mid IR) and excitation current shot noise being several times larger.