Fundamental Noises in TDLS

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Introduction

There are 5 main subsystems in TDLS: electrons in PD; electrons, photons, and phonons in DL; and molecules under investigation. Each subsystem is origin of fundamental noises in TDLS. Interaction of several subsystems leads to special fundamental noise types to be considered in present poster.

Electron in PD is particle – shot noise of PD photocurrent.

Photon in DL – presence of spontaneous emission (quantum nature of light) – DL quantum noise.

Electron is particle in DL – DL flicker noise.

Electrons and phonons interaction in DL – DL active area temperature field fluctuations.

Electrons and photons interaction in DL – baseline.

If physical origin of particular noise is identified and its properties are known, this noise can be efficiently suppressed.

Back to basic: shot noise

Electron is particle in our experiments. Hence, time dependence of current **i** consists of δ - like peaks (counts).

$$i(t) = e\sum_{i} d\ (\mathrm{t} - \mathrm{t_i})$$

This effect results in **Shot Noise**. Shot noise spectral density $G_i(f)$ of current **i** can be found straightforward:

$$\langle i(t)\rangle = \frac{1}{T}\int_0^T i(t)dt = i_0$$

$$G_i(f) = \int_{-\infty}^{\infty}\exp(-j2pft_1)dt_1 \int_{-\infty}^{\infty}\exp(j2pft_2)dt_2\langle i(t_1)i(t_2)\rangle$$

Here <> is averaging over realizations

For **constant current** next electron appearance is random and $\langle i(t)i(t+\tau)\rangle \sim \delta(\tau)$. In this case well-known and simple formulae for shot noise spectral density of current **i** is valid (e – charge of electron):

$$G_i(f) = ei$$

Shot noise spectral density doesn't depend on frequency (white spectrum).

In TDLS **short noise** *takes place in photo-current and excitation current of diode laser.*

Photocurrent shot noise

Any current passing through photo-diode (PD) leads to Shot Noise (SN).

$$\Delta i_{SN} = \sqrt{e(i_{DL} + 2i_0 + i_{blackbody} + i_{ext})B}$$

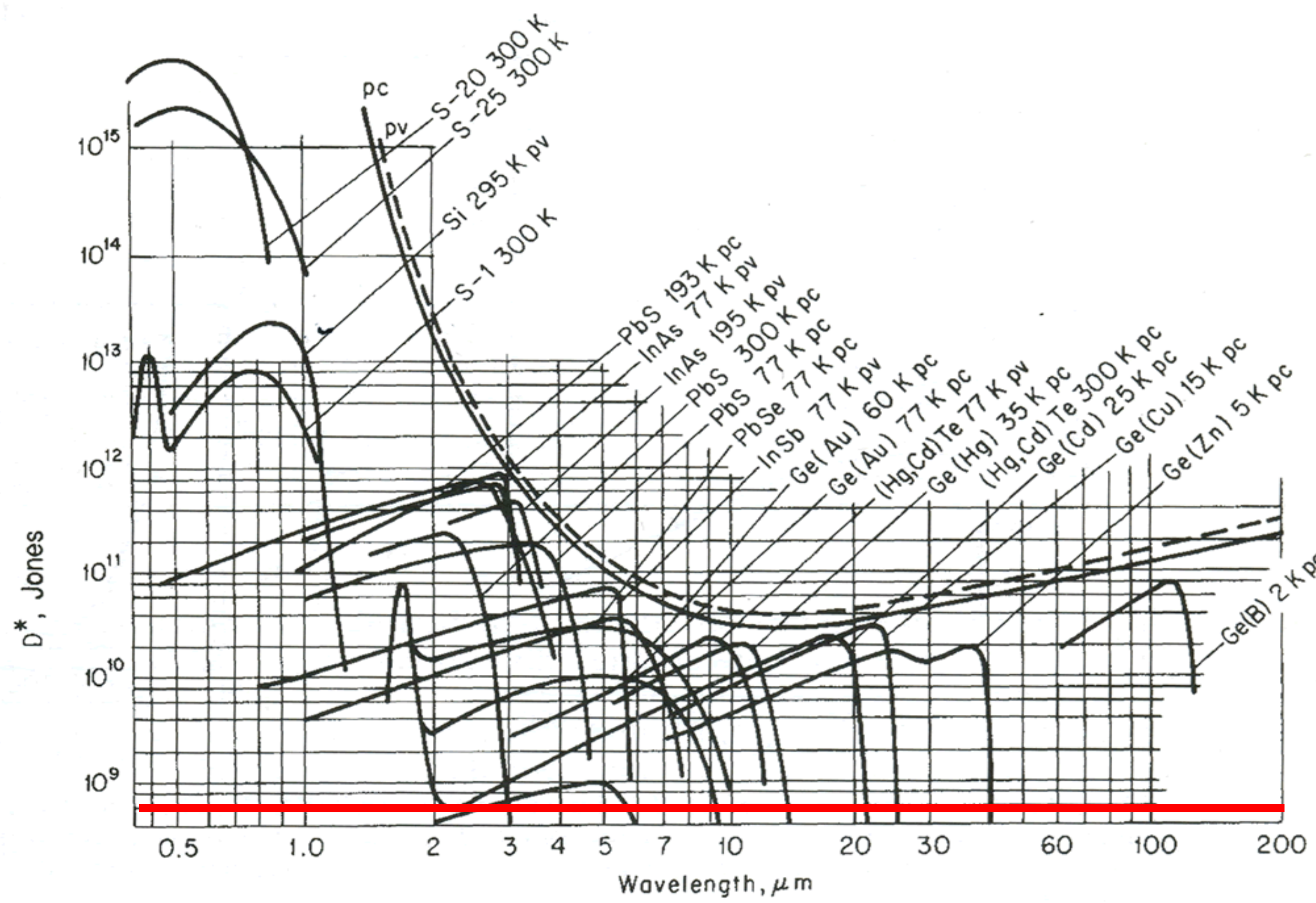
B – preamplifier bandwidth.

Photocurrent consists of several components:
First term – shot noise due to DL radiation registration.
Second term: Electrons in PD interacts with blackbody radiation inside PD (PD temperature). It leads to generation and recombination photocurrent. For U = 0 they are equal to dark current i_0: 1-10 μA and < 1 nA for Ge and InGaAs PDs, respectively.
Third term – PD detects blackbody radiation with room temperature. It determines D* of photo-detector in use. This term dominates in mid IR.
Forth term – photocurrent due to external illumination (Sun or light). It is important for TDLS system with topography reflector.

In different experiments different photocurrent components dominate. It needs preamplifier optimization for particular experiment. First term determines fundamental limit to be considered below.

Back to basic: blackbody limited TDLS

Photo detector is important TDLS component. For small signal, its noise is determined by blackbody radiation photocurrent shot noise determined by detectivity D* [1].



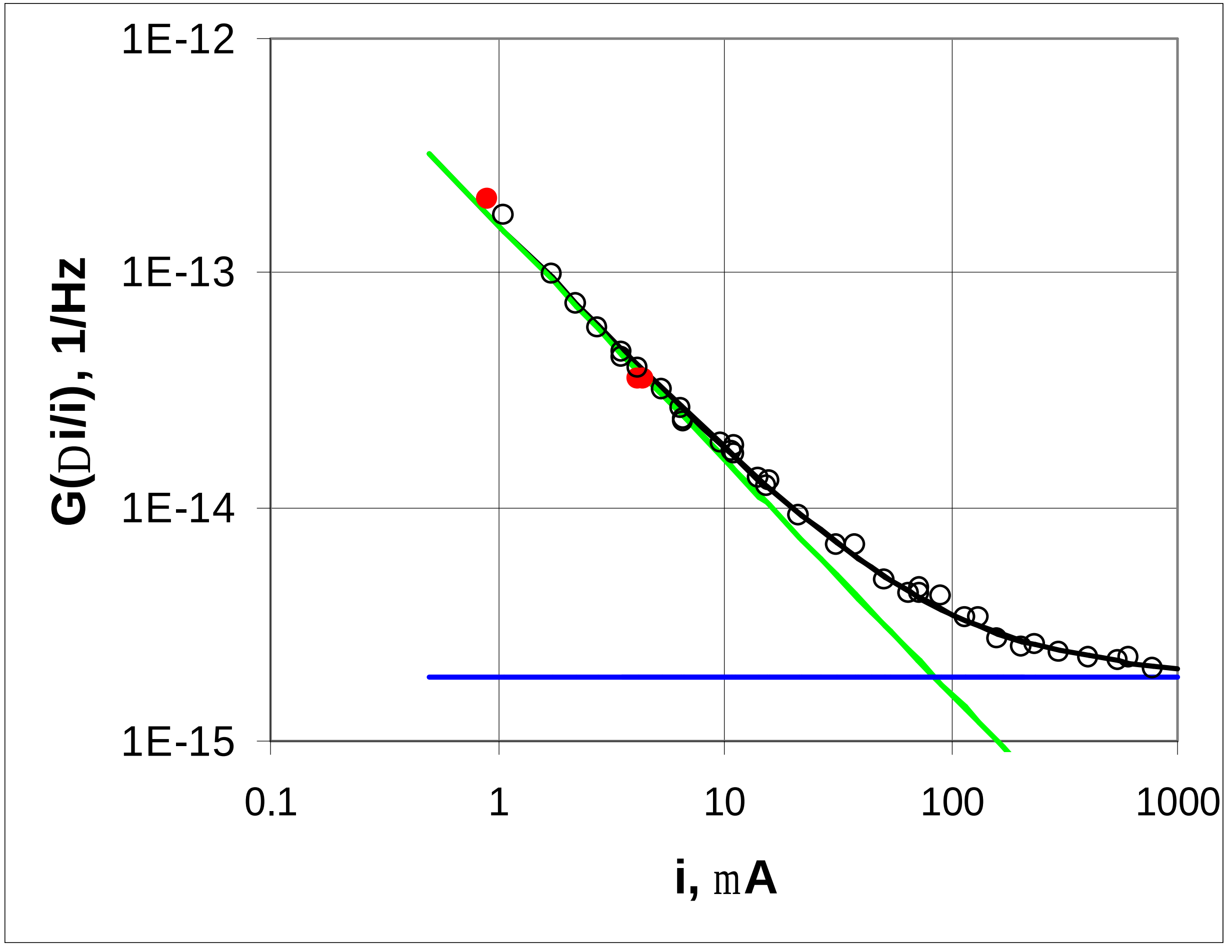
Traditionally for D* Jones=$cm\sqrt{Hz}/W$ is using as unit. Two upper curves represent theoretical limits for photo-conductivity (solid) and photo-voltaic (dashed) quantum photo-detector operation.

Red line represents theoretical limit for thermal photo detectors (bolometer, photo-acoustic, etc.).

[1] R.Smith, F.Jones, R.Chasmar, Detection and measurement of infrared radiation, Oxford University, London, (1957)

PD+DL – optimal spectral range is near IR.

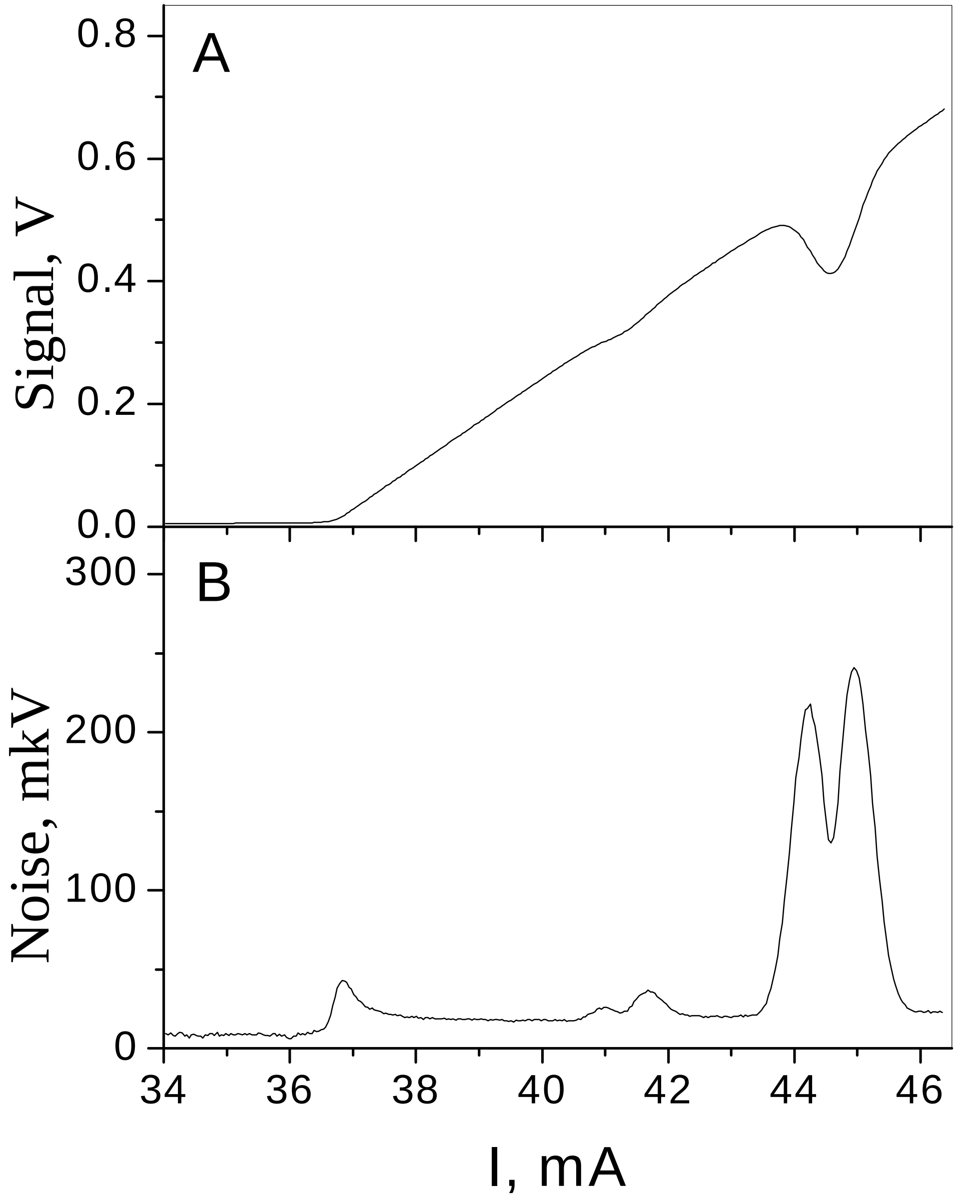
Shot Noise limited TDLS



Spectral density of relative photocurrent noise – **G(Δi/i)** as function of photocurrent value **i**. Circles correspond to registration of Sun (red) and diode laser (black) radiation; green line – theoretical value of stationary photocurrent shot noise - **e/i**. In experiment with DL, PD was located at different distances from DL to detect part (small part) of DL radiation for the same DL excitation current. ***When all DL radiation is focused on PD, photocurrent will be 20 mA.***

Photocurrent shot noise dominates below 100 μA. In our experiments it is important for systems with topography reflector. Above 100 μA new noise mechanism can be observed (blue line). ***For this mechanism relative noise is constant. It is due to DL radiation quantum noise.***

DL quantum noise measurement



Signal with water vapor (low pressure) absorption lines (A) and its noise (B) as function of excitation current value – I near DL threshold.

Presence of resonance absorption transforms frequency noise to intensity one.

Features to be mentioned:

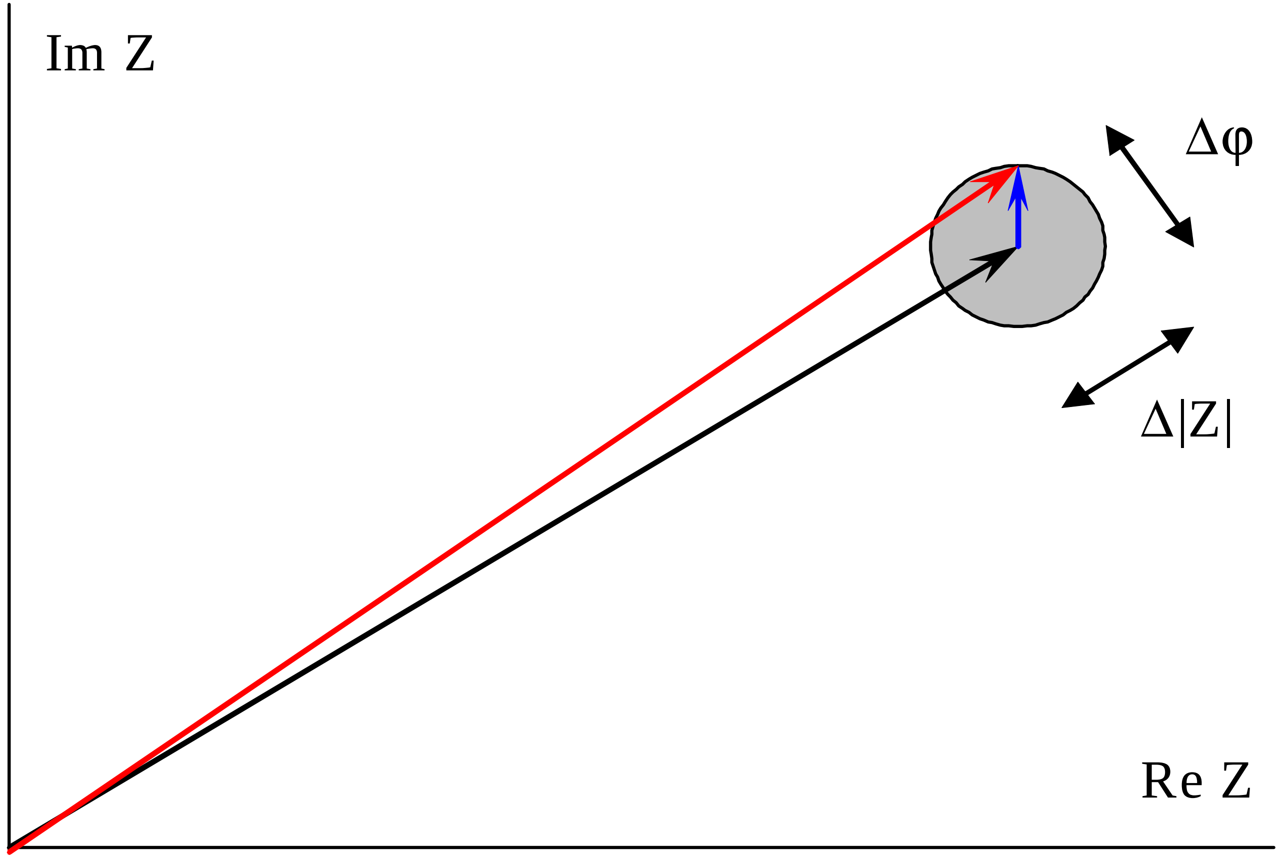
Noise peak near threshold;

Constant value of intensity quantum noise;

Noise asymmetry in vicinity of resonance spectral line;

For given value of excitation current relative intensity noise does not depend on DL radiation part detected by PD.

Back to basic: DL radiation quantum noise

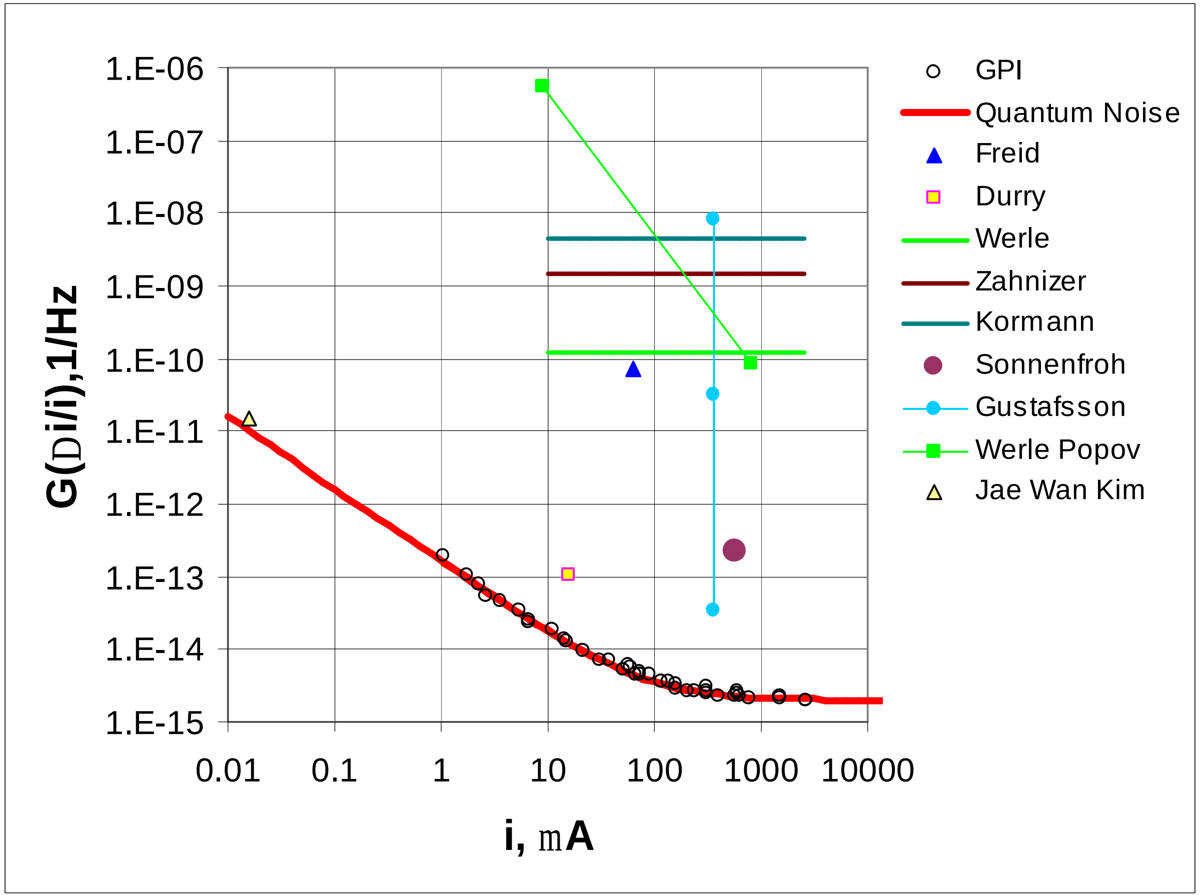


Vector presentation of complex electromagnetic field.
Black Arrow – stimulated emission;
Circle – spontaneous emission.
Presence of spontaneous emission (quantum nature of light) leads to quantum noise of DL radiation (red arrow) – both intensity and phase (frequency).

This simple model explains main experimental results. Intensity quantum noise doesn't depend on light intensity while frequency quantum noise is reversely proportional to it (Shawlov – Tawnes). Spontaneous emission spectrum is rather broad (~ 200 cm^{-1}). So, DL quantum noise can be considered as white in TDLS

Photo-current noise spectral density

G - spectral density of photo-current relative noise (Δi/i = NEA - Noise Equivalent Absorbance) as function of photo-current value - i.

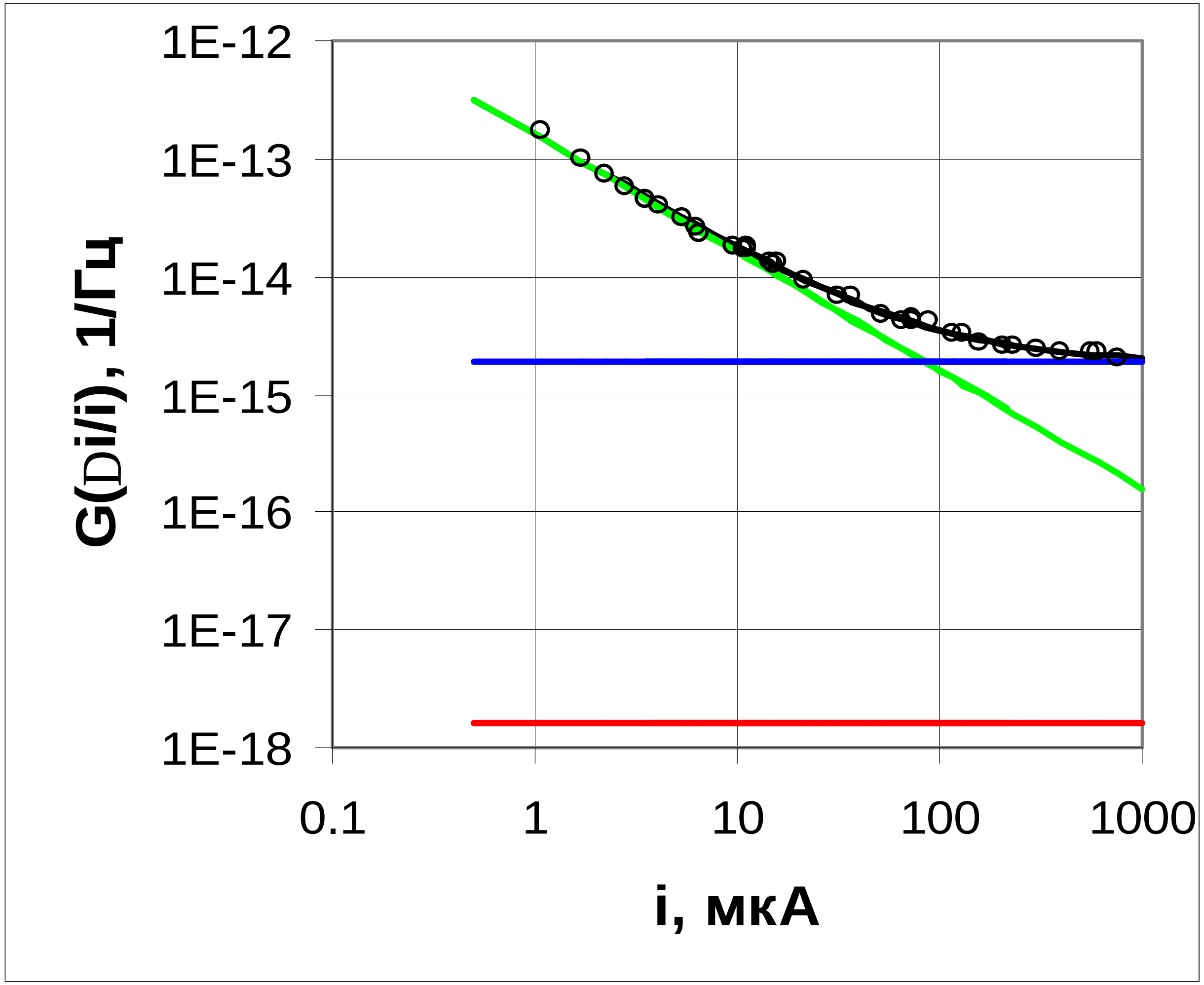


Best results known to author of relative photo-current noise spectral density measurements are presented. The information in referred papers was not enough for picture under consideration. Allan plots were used frequently to obtain necessary spectral density (see above).
Red line represents fundamental limit determined by quantum nature of electrons and photons.

<u>GPI achieved fundamental sensitivity limit and has significant advantage with respect to the best results obtained.</u>

Excitation current shot noise

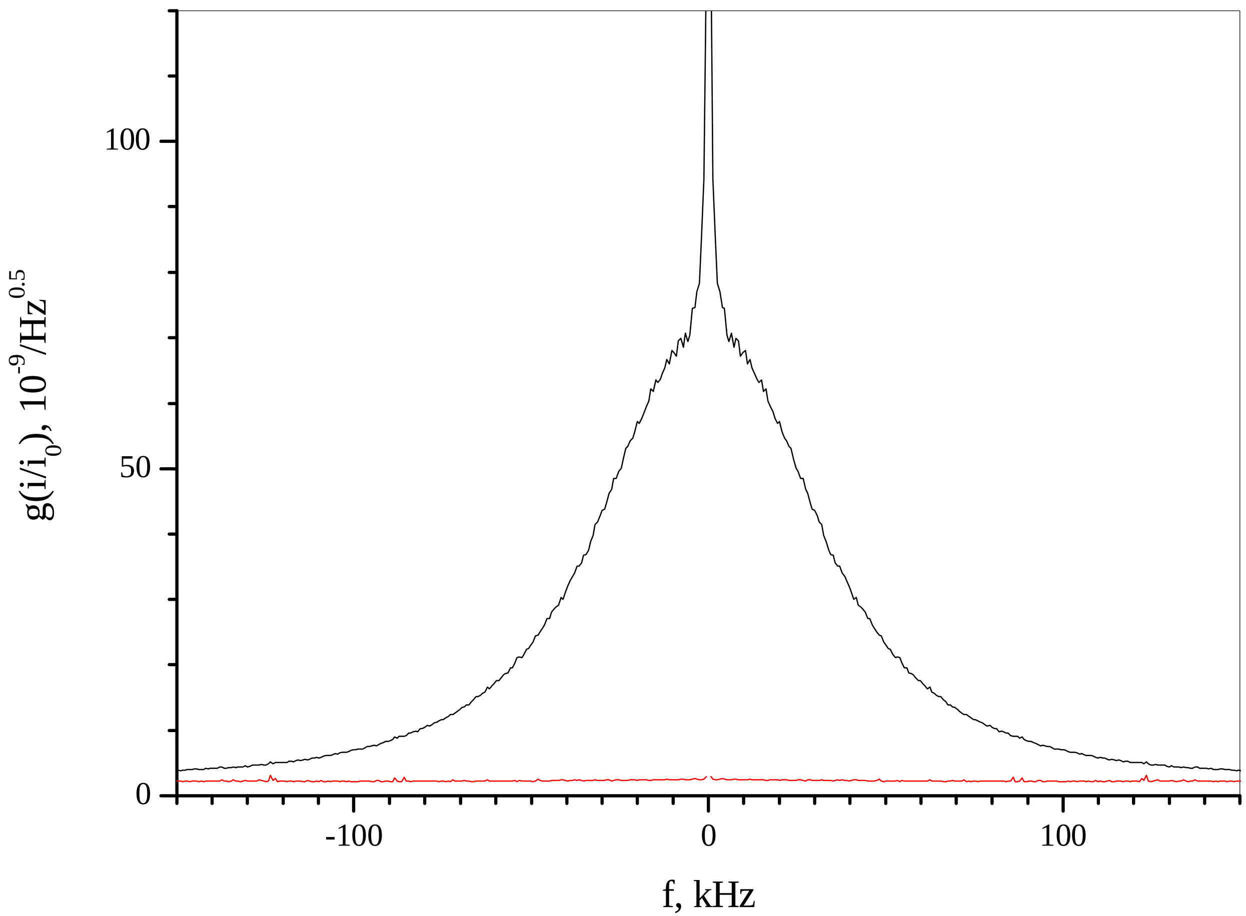
Next fundamental noise mechanism is excitation current shot noise.



Spectral density of photocurrent relative noise – **G(Di/i)** as function of photocurrent value **i**.
Green line – photocurrent relative shot noise.
Red line –photocurrent relative noise due to shot noise of excitation current I = 100 mA.
Blue line – DL quantum noise.

<u>Excitation current shot noise is not important. It is significantly below DL quantum noise.</u>

Photocurrent noise spectral density

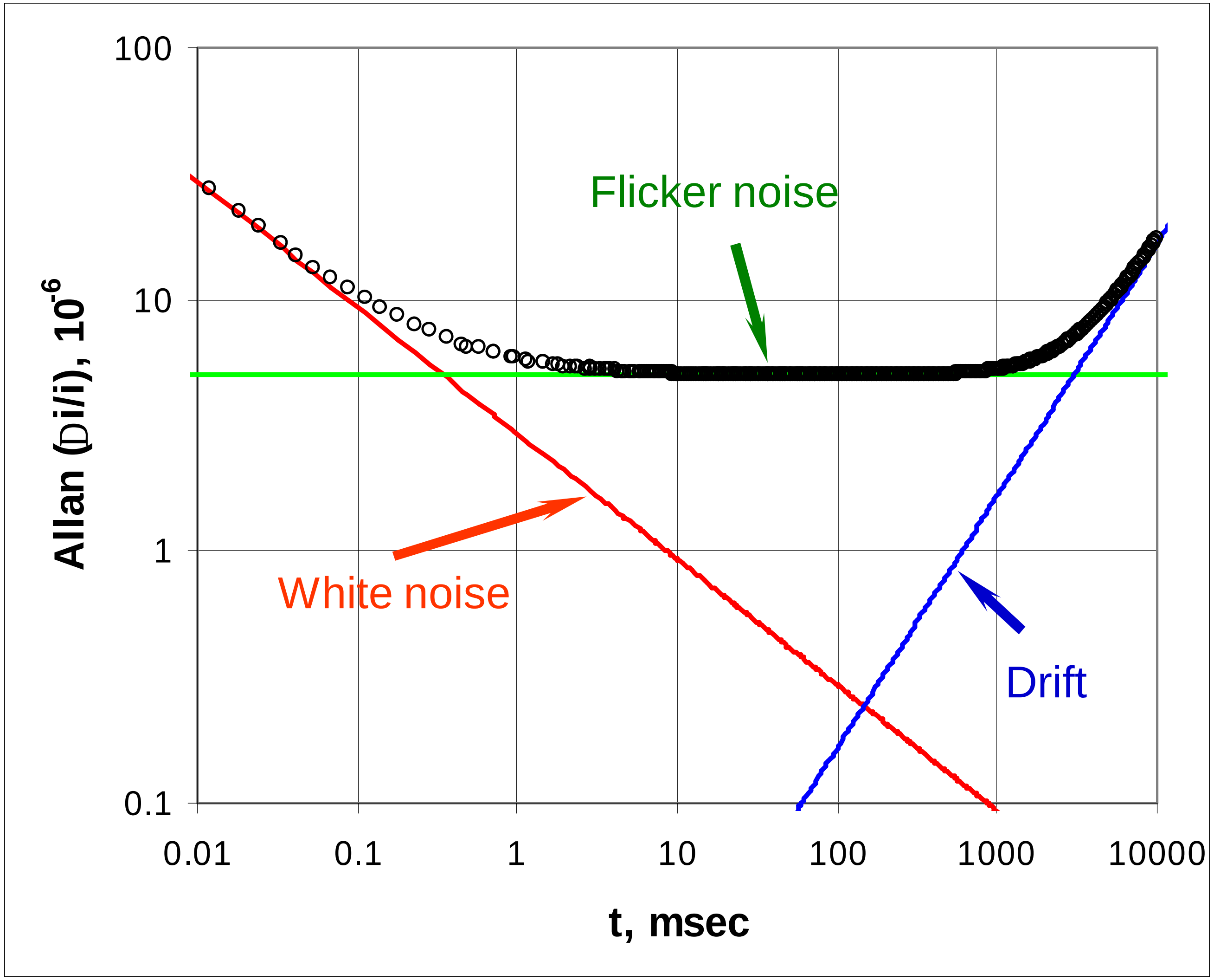


Photocurrent noise spectral density: black - DL on, red - DL off. Broad spectrum feature is determined by DL quantum noise and preamplifier in use (white noise). $\mathbf{i}_0$ corresponds photocurrent recorded for excitation current equal 2 threshold values.

Narrow peak is due to slower noises (flicker noise and drift).

The last two noise mechanisms limit sensitivity achieved in works where best results were obtained. Physical origins of these noises have to be identified and new strategy of TDLS operation to be developed to reduce their influence.

Back to basic: noise types in TDLS

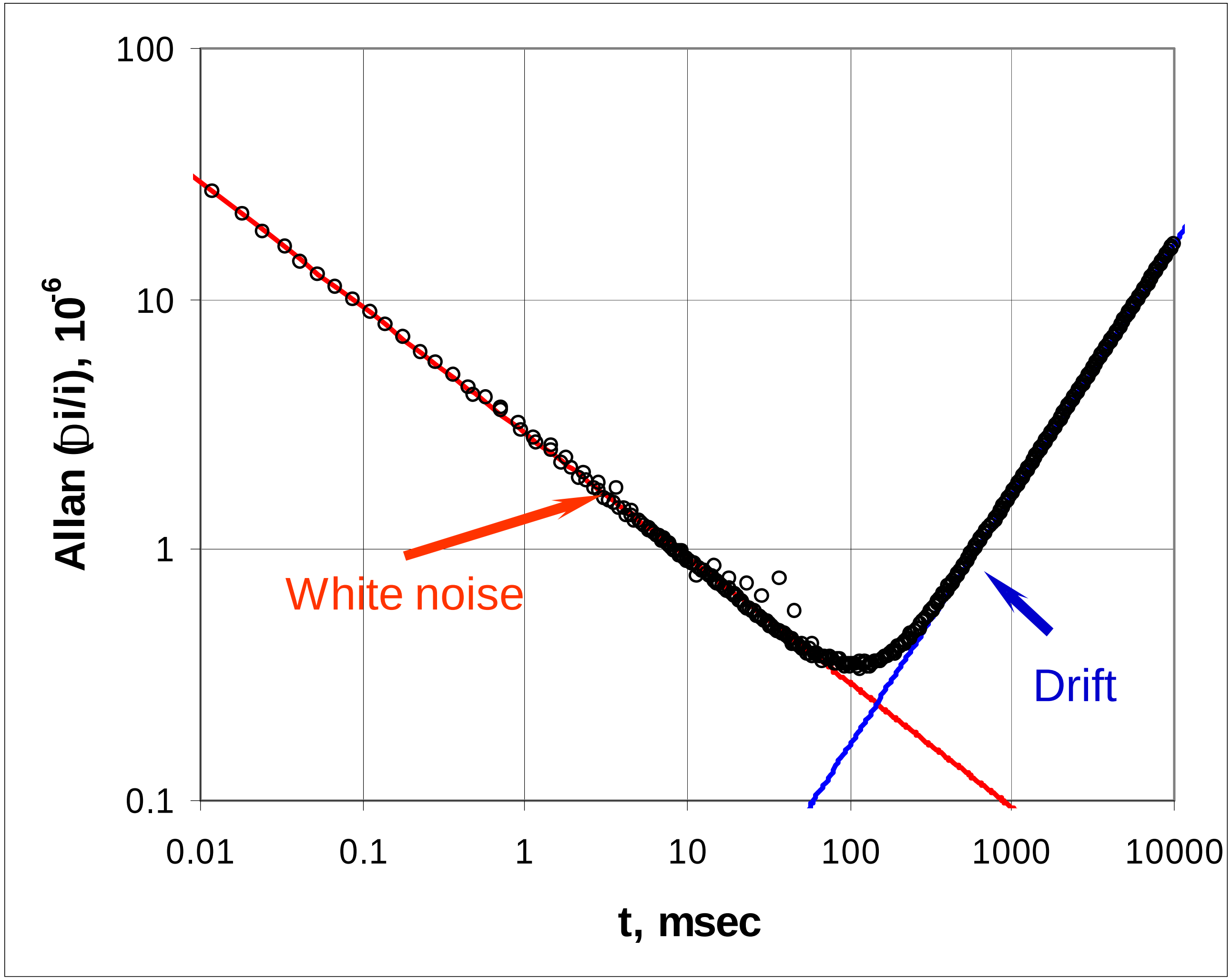


Allan plot of relative photocurrent noise as function of averaging time.

There are three main noise types limiting TDLS: white noise (red), Flicker noise (green), and drift (blue). For white noise fundamental limit due to DL quantum noise is achieved. Moreover, white noise can be reduced by increasing of averaging time.

Flicker noise and drift limit sensitivity and can not be reduced by averaging time increase. Physical origins of these noises have to be identified to reduce their influence.

Flicker noise suppression



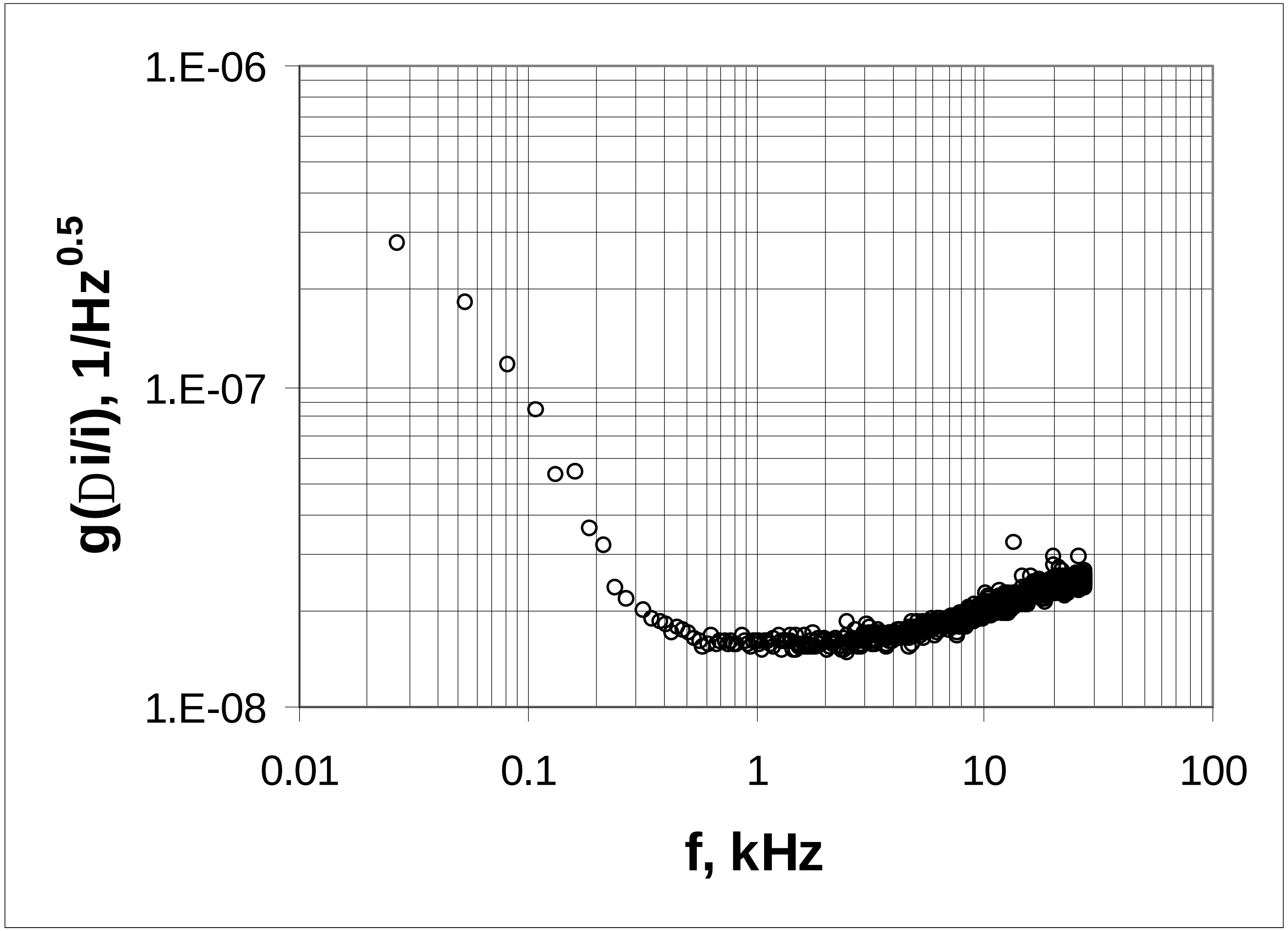
Flicker noise origin was identified – excitation current density fluctuations in DL active area (electron is particle) and strategy of its suppression was developed (see C1).

For white noise fundamental limit due to DL quantum noise is achieved and white noise can be reduced by increasing of averaging time. Flicker noise was suppressed.

__Now drift limits sensitivity.__

Allan plot of relative photocurrent noise as function of averaging time.

Temperature field fluctuations

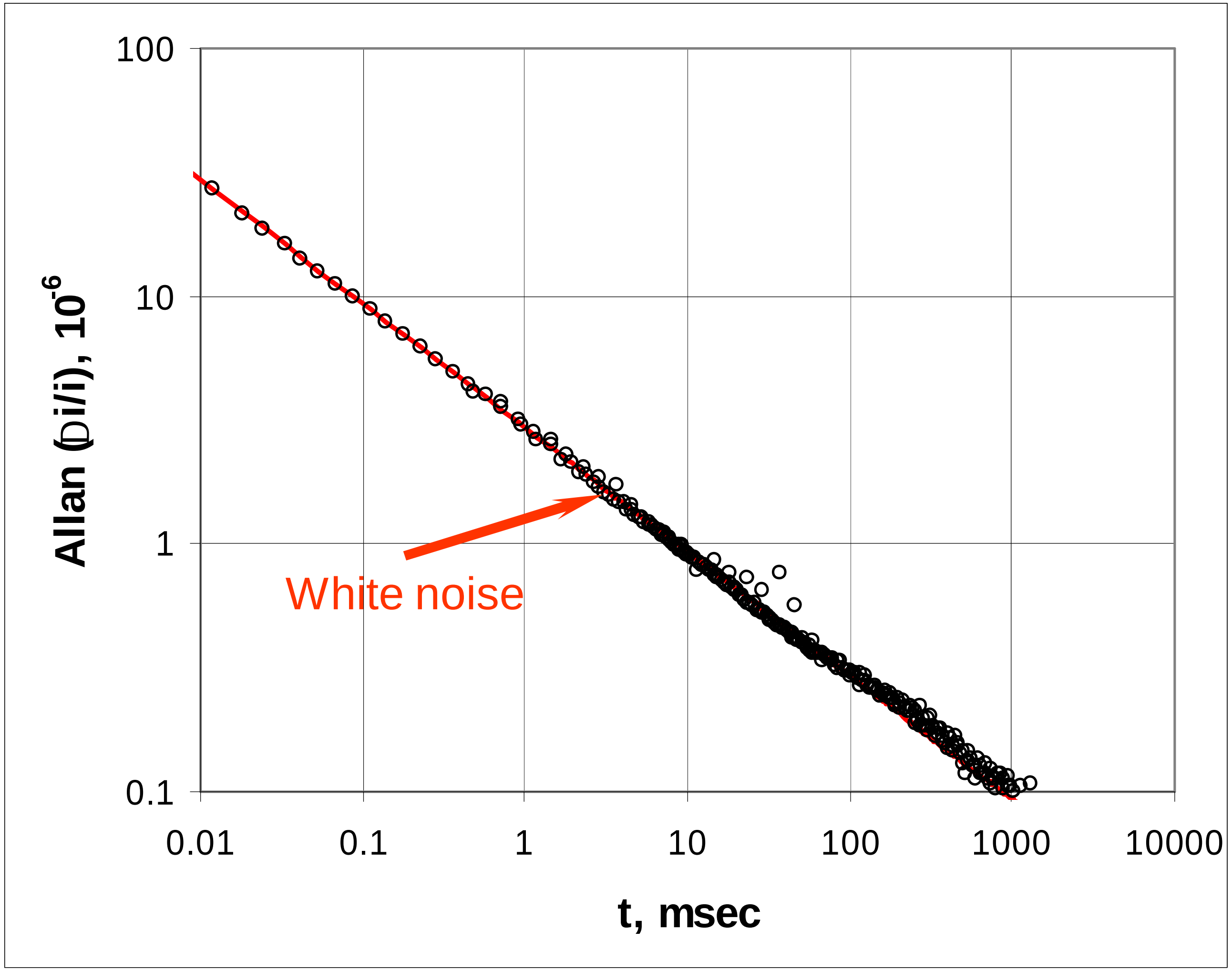


Temperature field fluctuation inside DL active area is origin of next fundamental noise. Excitation current density fluctuation considered above leads to temperature fluctuations in DL active area. Due to temperature diffusion (see D1) after 10 μsec temperature distribution will be homogeneous in DL active area. After 1 msec fluctuations in DL contacts will influence DL operation.

Between these times noise is limited by DL quantum noise.

<u>Resume: to achieve fundamental limit due to DL quantum noise all measurements have to be done between 10 μsec and 1 msec.</u>

Drift suppression

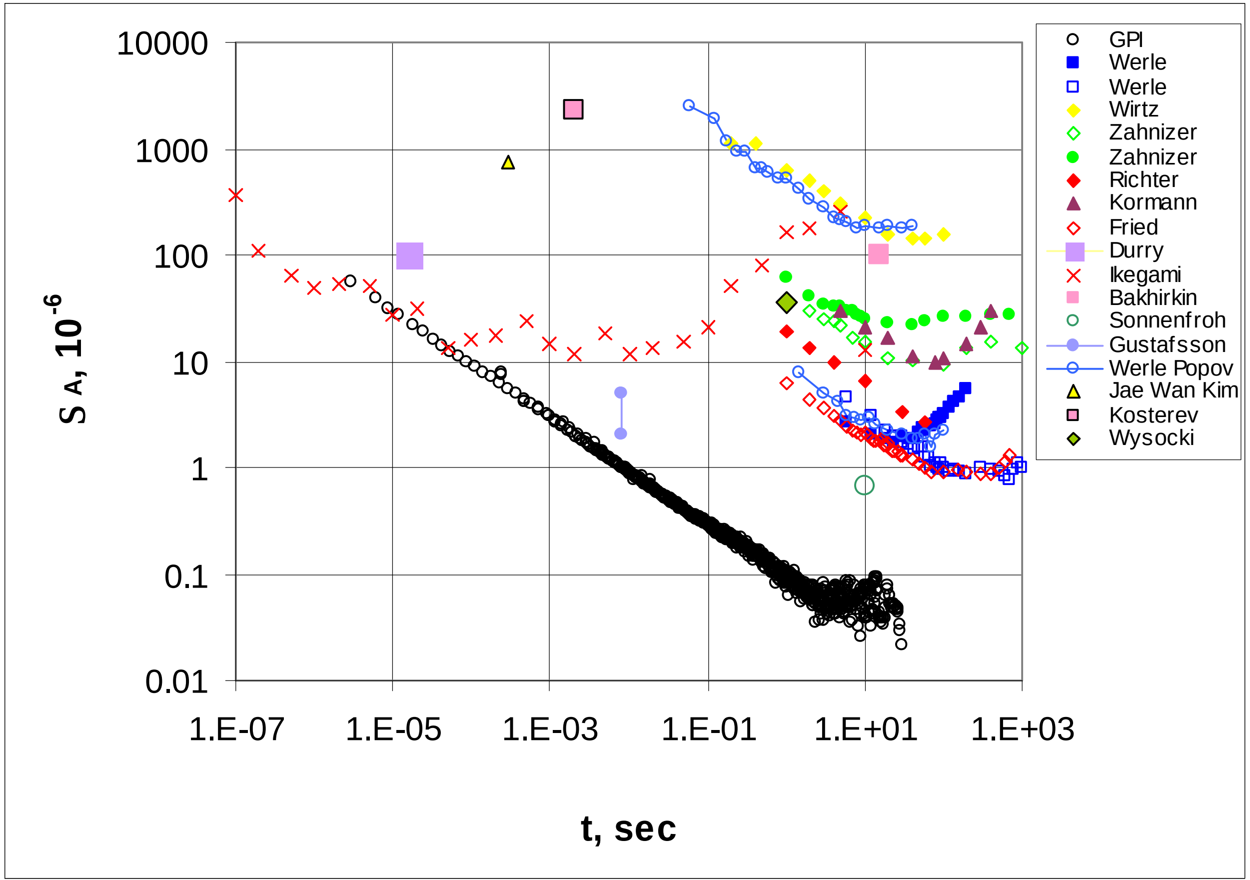


Drift origin was identified – interaction of standing wave with inhomogeneities in DL active area and strategy of its suppression was developed (see separate poster).

Fundamental limit due to DL quantum noise is achieved and can be reduced below 10^{-7} by increasing of averaging time.

Allan plot of relative photocurrent noise as function of averaging time.

Inter-comparison



Inter-comparison of best results achieved in the world. GPI has several orders of magnitude advantage. It was achieved because origins of main sensitivity limitation fundamental processes were identified and strategy to suppress them was developed.

Sensitivity limitation observed on picture for large averaging time was recently identified. It is due to temperature instability of electrical scheme components. Temperature stability of components in use is 50 ppm/ºC. For absorbance sensitivity 10^{-8} it corresponds to temperature stability around 2 10^{-4} ºC. To solve this problem there are two solutions: to stabilize temperature of electronics or to use components with less temperature dependence (probably it'll be presented on separate poster).

Conclusion

Fundamental limit of trace molecule detection due to diode laser quantum noise was achieved: noise equivalent absorbance below 10^{-7} for averaging time below 1 sec (best presented in this poster result is equal $6\ 10^{-8}$ for 5 sec averaging time). Frequently (in photo-acoustic and ring-down spectroscopy) minimum detectable absorption coefficient is considered. This parameter is equal to $2*10^{-12}$ cm^{-1} for our system (Chernin multi-pass cell in use: 0.5 m, 600 passes) and it is comparable with the best known results obtained in Stark spectroscopy. Next parameter widely used in literature is minimum detectable concentration. For HF detection in near IR and present system in use it corresponds to minimum detectable concentration - 0.8 ppt.

FFT and Allan plots are using for noise analysis in data series. Allan plots were proposed initially to analyze long-term laser frequency stability [1]. In TDLS it was used for the first time for concentration measurements in [2].

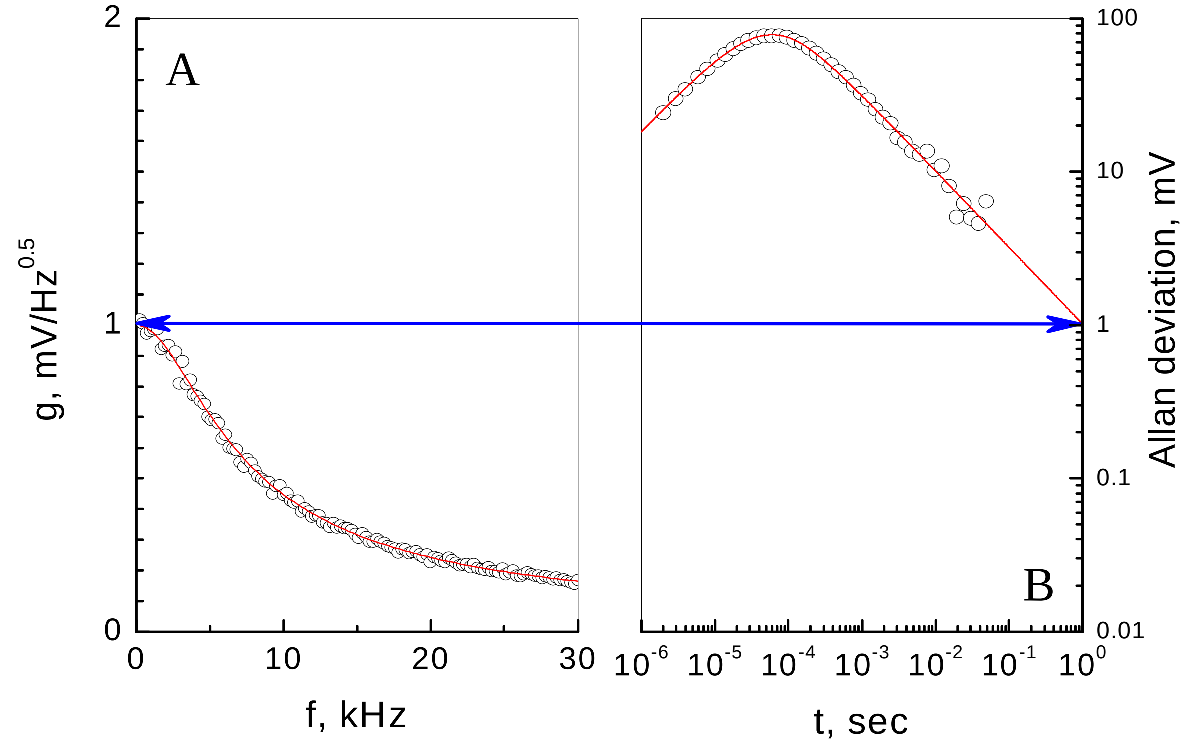
1. D.W. Allan, Proc. IEEE 54, 221-230 (1966).
2. P.Werle, R.Mucke, F.Slemr, Appl. Phys. B 57, 131-139 (1993).

Back to basic: white noise

$$\langle U(t)U(t+t)\rangle = s_0^{2}\exp(-2pB|t|) \qquad s_0^{2} = pG_0B$$

$$s_A(K) = s_0\sqrt{\frac{(1-e^{-CK})}{K^2}\left\{K + 2\frac{K-1}{e^{C}-1} - 2\frac{e^{-C}-e^{-CK}}{(e^{C}-1)(1-e^{-C})}\right\}}$$

$$C = 2pB\Delta t$$



Noise spectral density (left) and Allan deviation (right) for white noise after first order Bessel filter, open cycles – experiment, red lines – calculation.

***Important:** for white noise spectral density at f = 0 and Allan deviation at t = 1 sec have to have the same values.*