C1

DL Flicker Noise in TDLS and its Suppression

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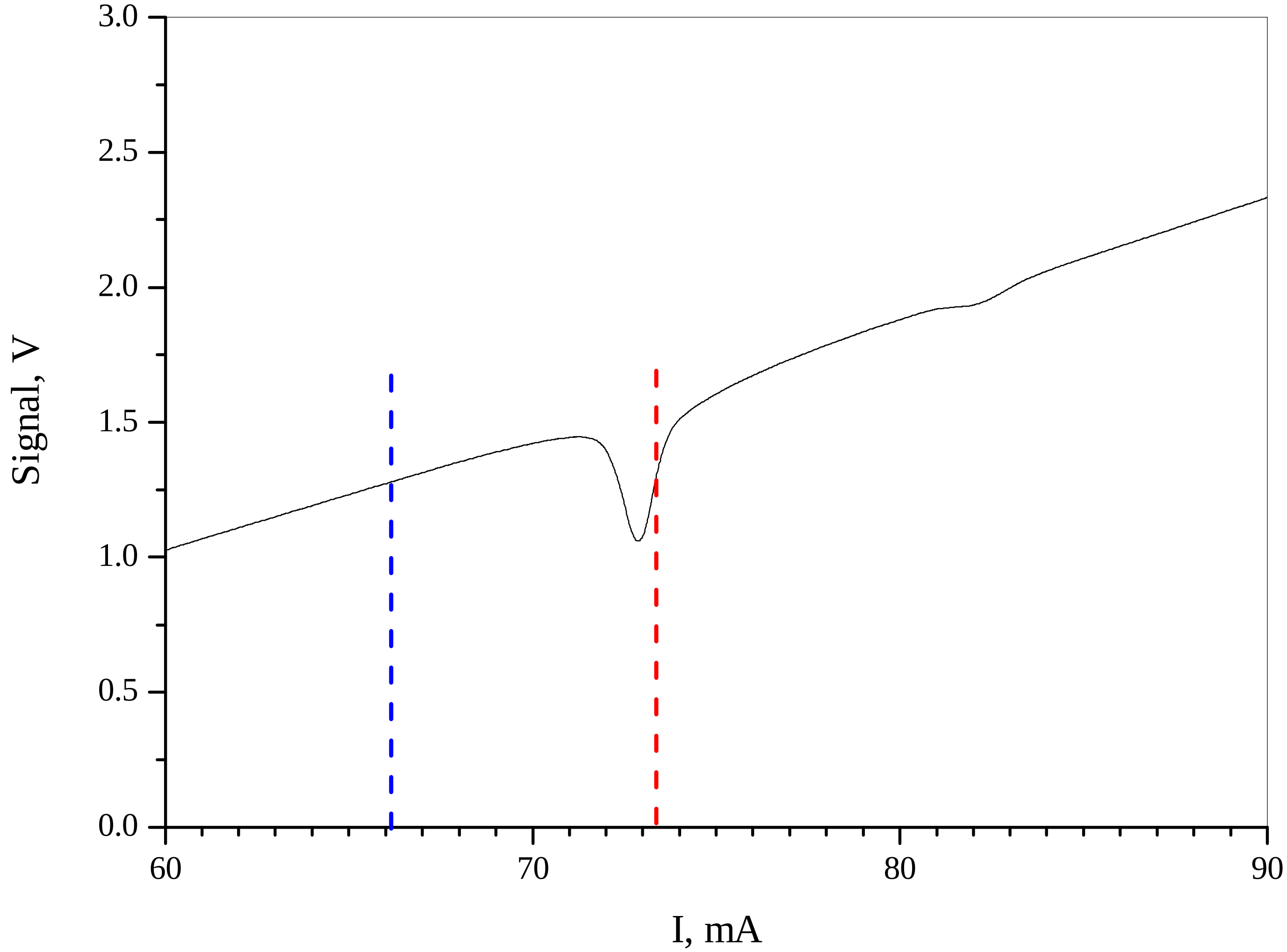
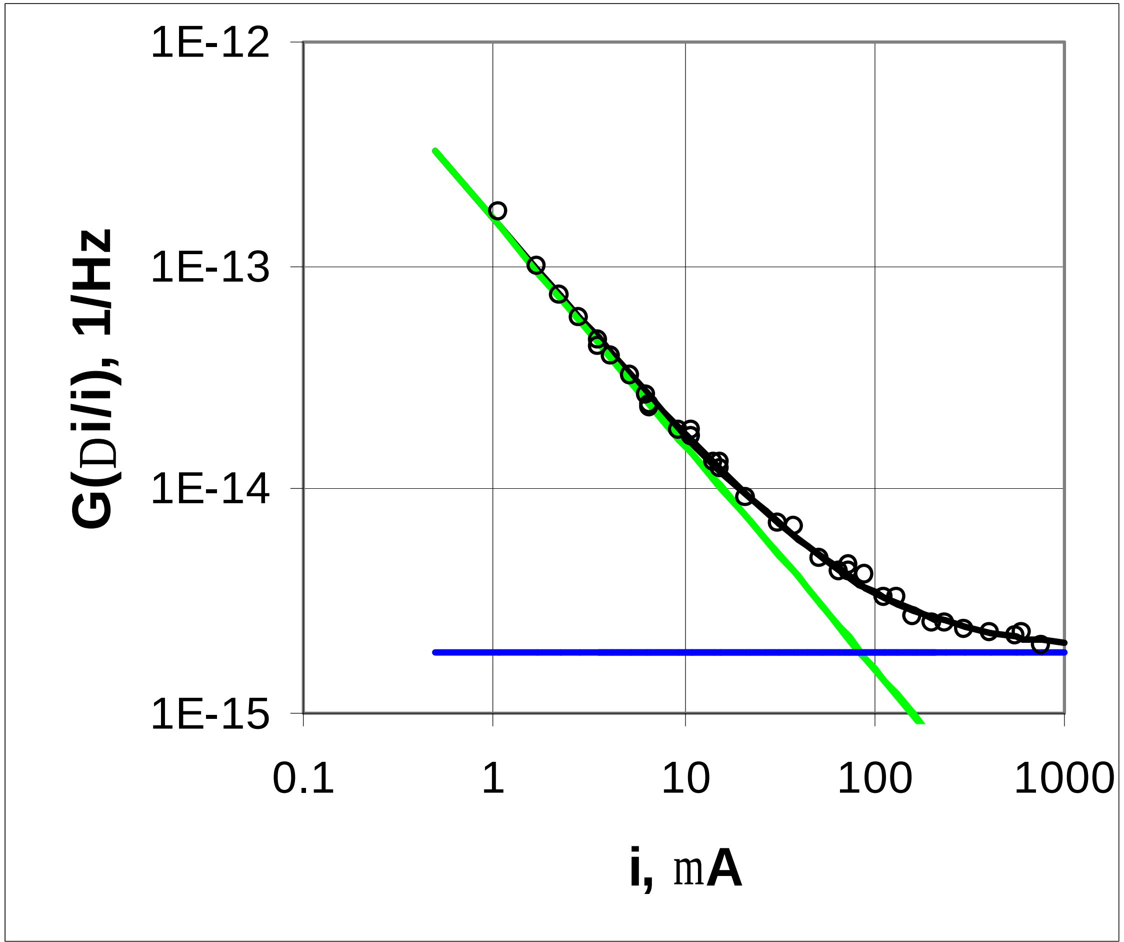
DLS LAB

DL Noise Measurement



Recorded signal as function of excitation current. Presence of resonant molecular line can be observed. For excitation current out of the line (blue dashed vertical line) DL intensity noise will be measured. For excitation current corresponding to line slope (red dashed vertical line) DL frequency noise will be transformed into intensity one and mainly this noise component will be measured.

DL quantum noises limited TDLS

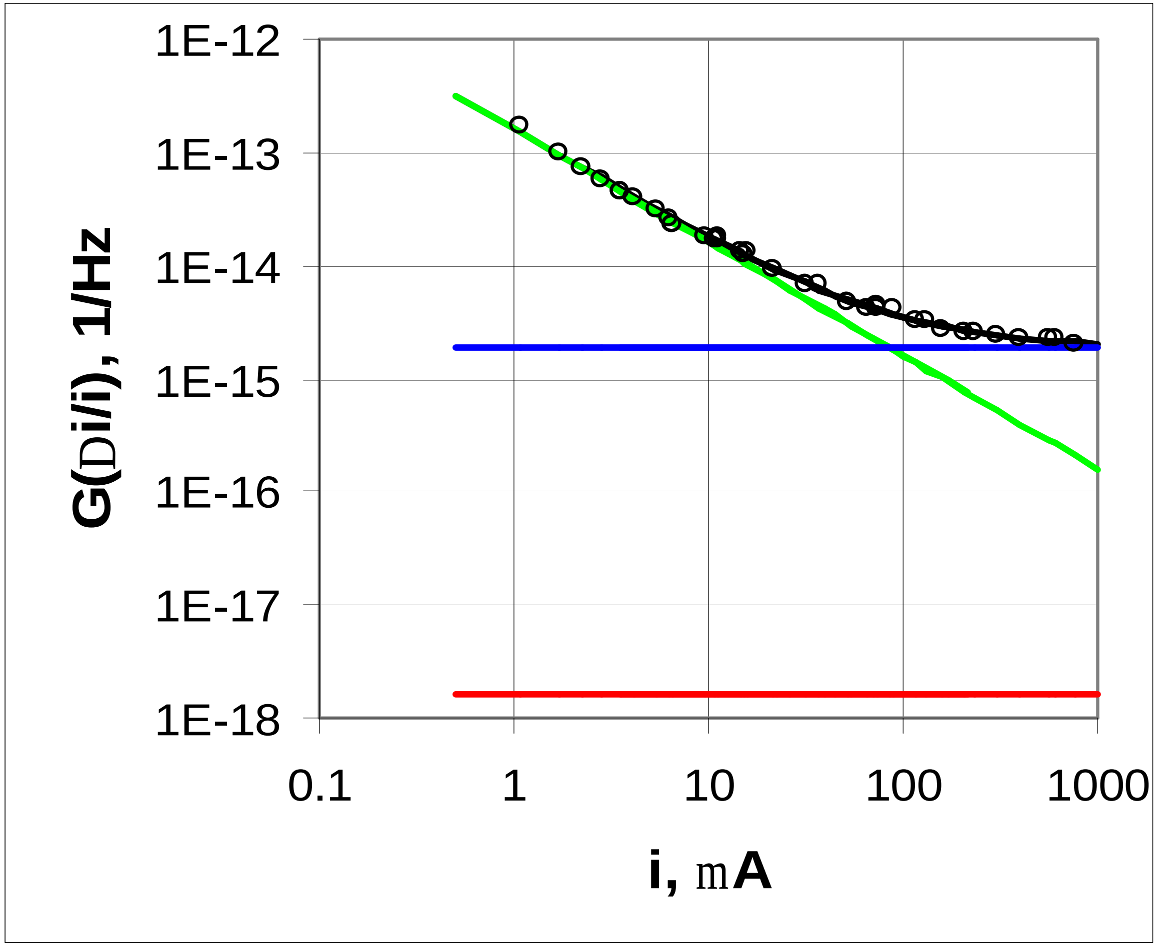


Spectral density of photocurrent relative noise – **G(Di/i)** as function of photocurrent value **i**.
Green line – photocurrent relative shot noise.
Blue line – DL quantum noise.

<u>For photocurrent above 100 mA and excitation current off spectral line, photocurrent spectral density is determined by DL intensity quantum noise.</u>

Now let us look on this picture from other point of view: what TDLS subsystem is characterized by these noises. In TDLS there are 5 subsystems: electrons in PD (PD photocurrent), electrons in DL (excitation current), photons in DL (DL emission), phonons in DL (DL temperature), and molecule under invertigation.

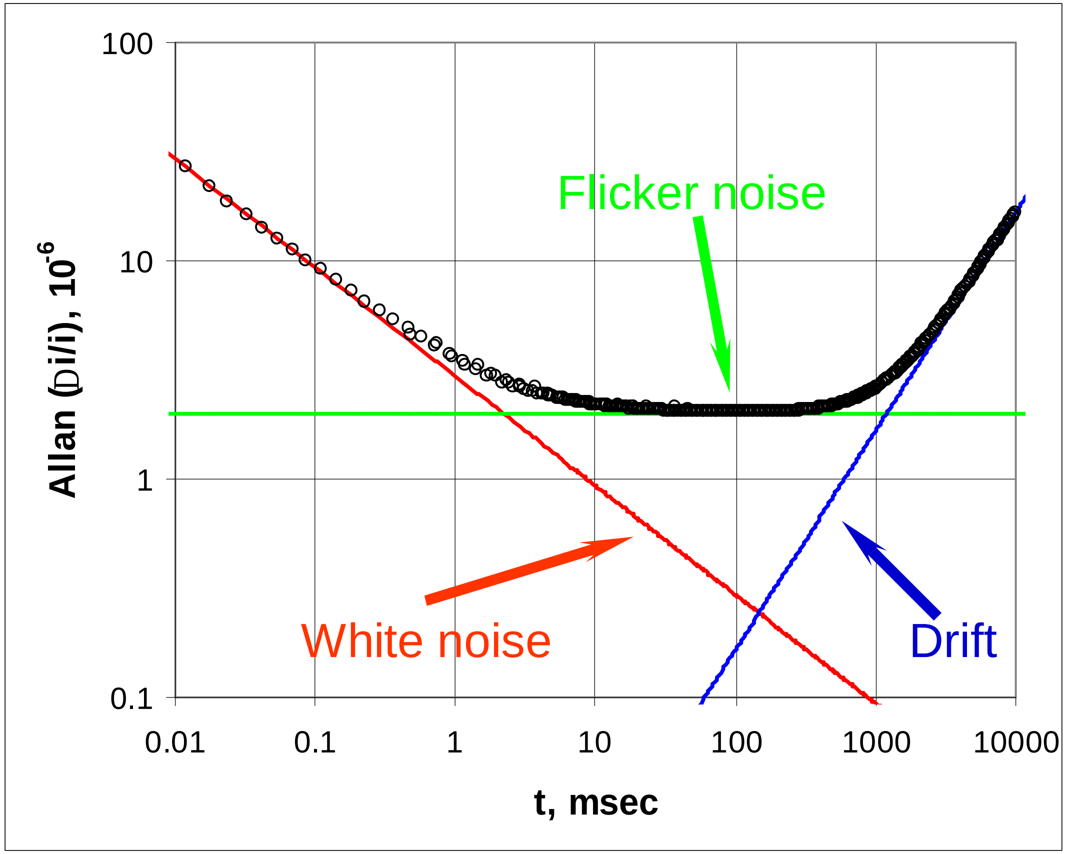
Main quantum noises in TDLS



Electrons in PD. Electrons are particles - photocurrent shot noise (green line).
Photons in DL. Presence of spontaneous emission (quantum nature of light) - DL quantum noise (Blue line).
Now it is time to consider electrons in DL. Electrons are particles – excitation current shot noise (red line). Red line corresponds to relative noise due to shot noise of excitation current I = 100 mA.
All these noises in TDLS have white spectrum.

Excitation current shot noise is not important. It is significantly below DL quantum noise.

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 can not be reduced by averaging time increase.
Physical origins of these noises have to be identified to reduce their influence.

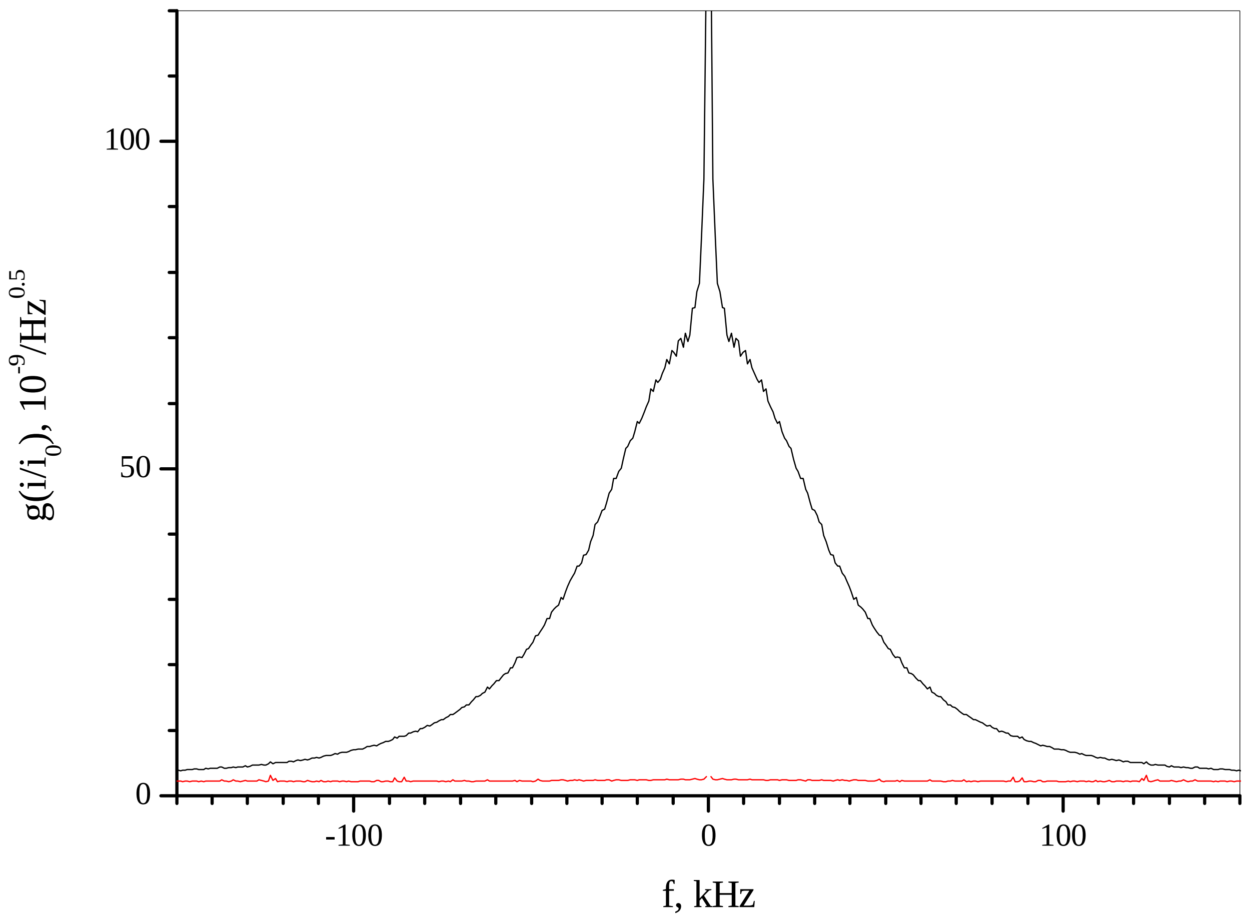
When problem of all technical origins of flicker noise is solved one will see practically the same flicker noise level (~ 2 10^{-5}) for all DL types (A^3B^5, A^4B^6, QCL, etc.) and techniques in use. Hence, this flicker noise is fundamental and has origin in operation of diode laser.

DL excitation current density flicker noise

Let us consider more carefully behavior of DL electrons subsystem. Next fundamental noise process in TDLS is DL excitation current density fluctuations, because electrons passing DL active area are particles. If electron appearance in given active area point at given time moment is random nothing new will happen. We'll have excitation current shot noise being significantly smaller DL quantum noise (see above).
It is not true. There are several physical processes leading to correlation of excitation current electrons appearance in the same point at the same time. Main - active area conductivity depends on excitation current density.

It is known that fluctuations of current density (electron is particle) in combination with nonlinear processes (correlation of electrons appearance in the same point of DL active area at the same time) results in excitation current density flicker noise. Let us consider integral characteristics. For constant excitation current it will result in no current noise and flicker noise of voltage on DL. However, we are interesting in DL radiation noises.

Photocurrent noise spectral density

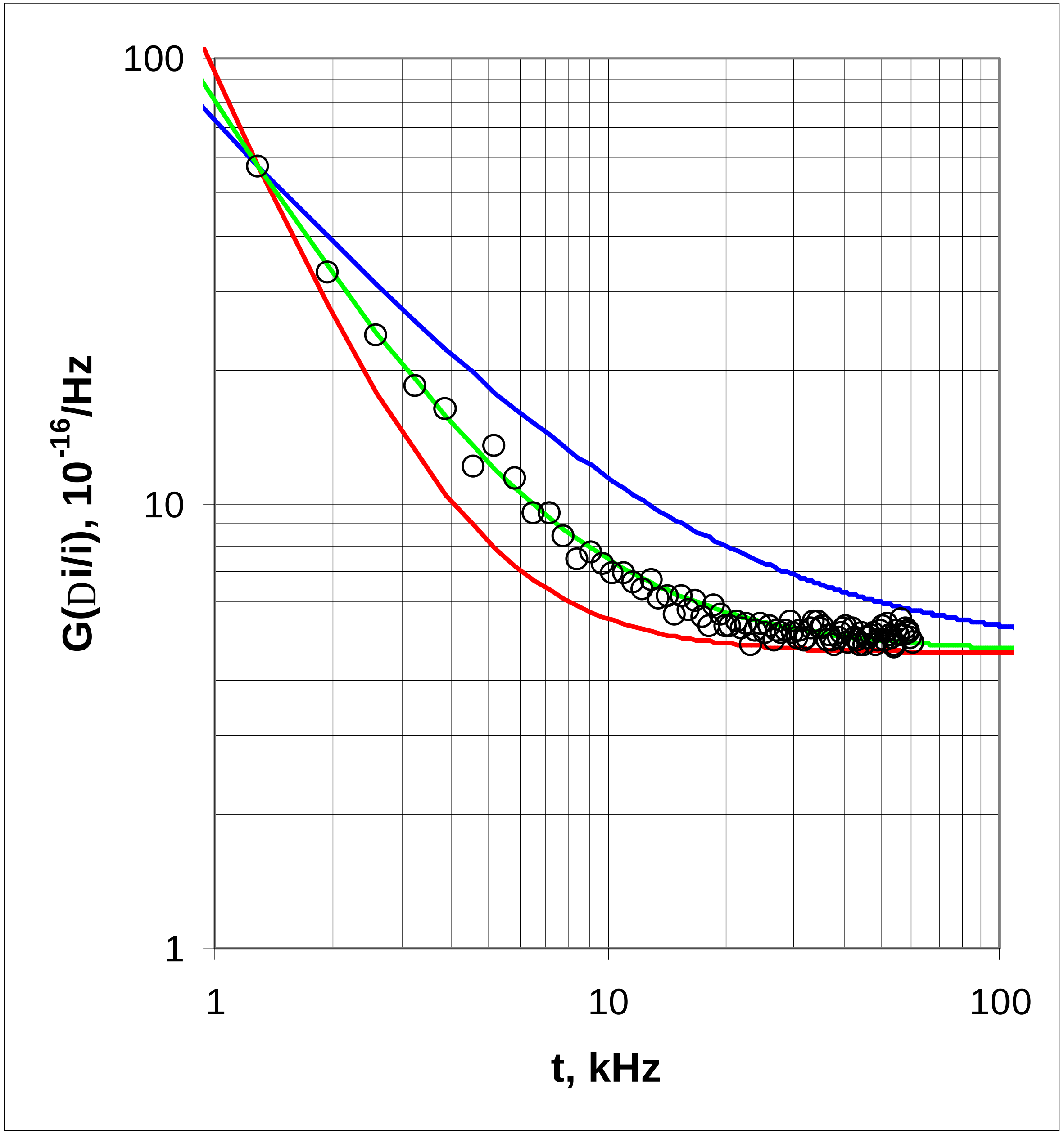


Photocurrent noise spectral density: black - DL on, red - DL off. Broad spectrum feature is determined by DL quantum noise and preamplifier in use (white noise). $\mathbf{i}_0$ corresponds photocurrent recorded for excitation current equal 2 threshold values.

Narrow peak is due to 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.

DL Intensity Flicker Noise



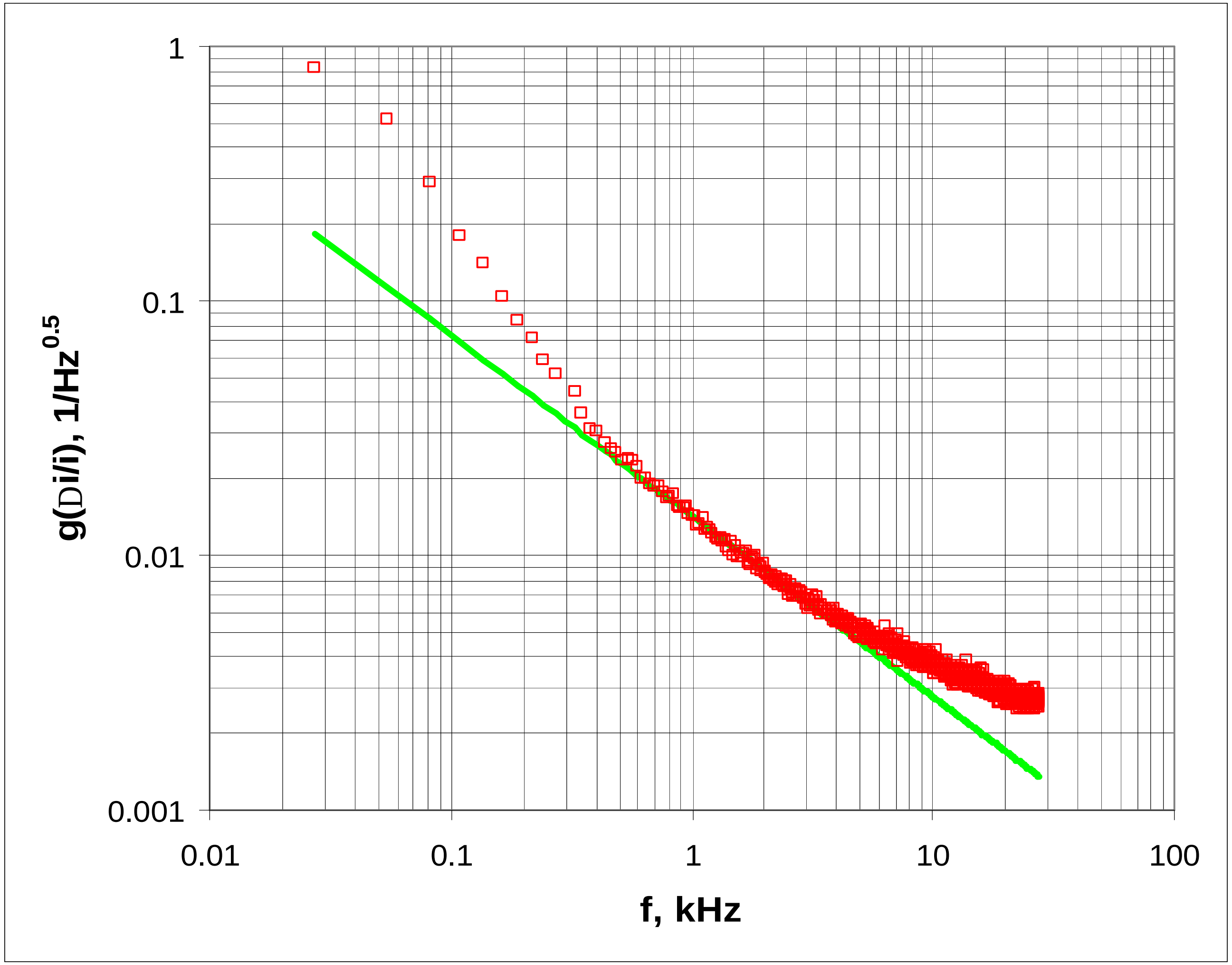
Spectral density G of relative photocurrent noise (intensity noise, excitation current was out of spectral line).

For high frequency range G is approaching to constant - DL quantum noise. For low frequency range:

$$\mathbf{G \sim 1/f^n}$$

Such noise is called Flicker noise if $1 \le n < 2$. n=1 - blue curve, n=2 (drift) – red curve. For present DL, Relative Intensity Noise (RIN) is characterized by n=1.42 (green curve).

DL Frequency Flicker Noise



Spectral density of DL frequency noise (excitation current was chosen to detect signal on slope of spectral line). Green line corresponds to n = 1.42, the same as for intensity noise.

<u>Hence, DL flicker intensity and frequency noises are determined by the same physical process.</u>

Additional noise mechanism presence due to temperature field fluctuation (see separate poster) can be observed also.

DL flicker noise fundamental origin

DL flicker noise has fundamental origin: excitation current density fluctuation and nonlinear DL behavior. It is known that combination of these two processes results in excitation current density flicker noise. ***This noise has important characteristic: its integral over DL active area is 0 (current is constant).***

Excitation current density fluctuations will result in excess current carriers concentration fluctuations. Gain and reflective index in DL active area are determined by this excess current carriers concentration. DL emission power and its frequency are integral characteristics of DL electromagnetic field. They can be calculated using integrals of gain and reflective index over longitudinal direction. Hence, they are constants (no flicker noise). There is no contradiction with experimental results presented on two previous slides (flicker intensity and frequency noises). Above statement is true if all DL radiation is recorded by PD. However, it is impossible from experimental point of view..

There is only transverse structure of electromagnetic field that can be influenced by this mechanism. Resume: flicker noise of excitation current density fluctuation can influence only DL near field pattern.

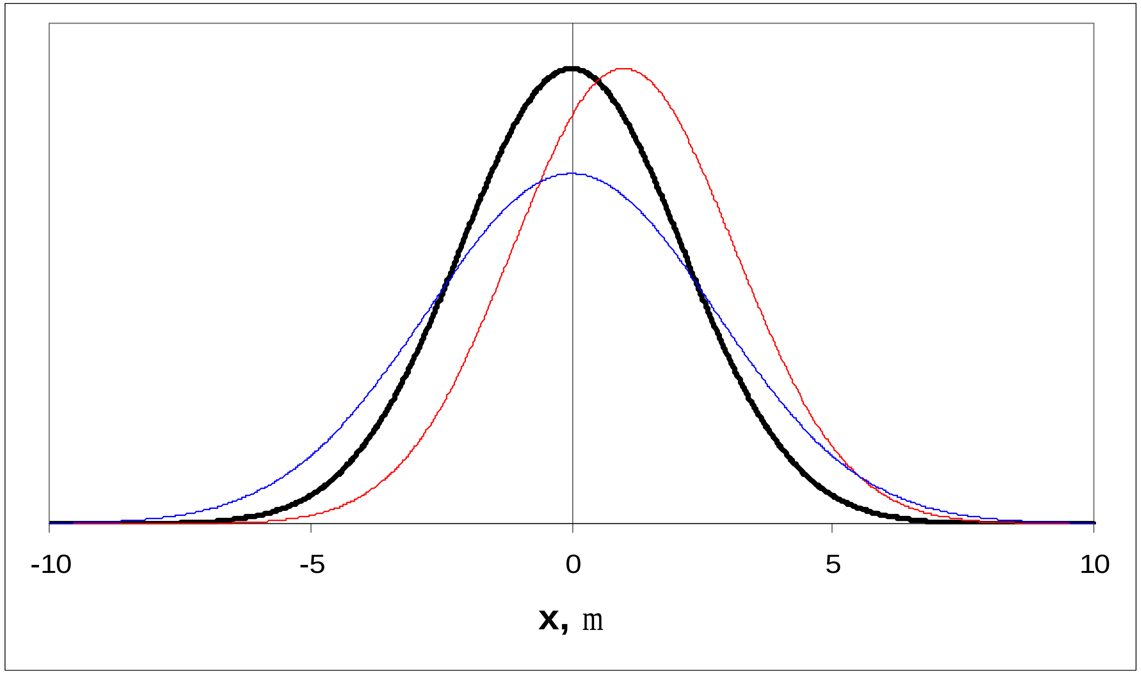
DL near field flicker noise

Only DL near field pattern can be influenced by flicker noise of excitation current density fluctuation. In general, this influence can lead to two flicker noise effects of DL near field pattern: its shift and width change.

Let us assume Gauss shape of DL near field pattern (black curve).

$$E(t,x) = E_0 \frac{1}{D - \Delta D(t)} \exp\left[- \frac{(x - \Delta x(t))^2}{(D - \Delta D(t))^2} \right]$$

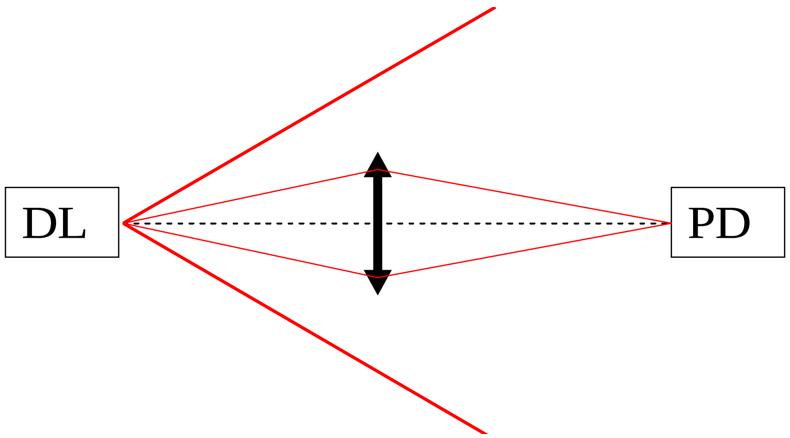
This assumption is close to real situation, it simplified future calculations, and don't influence further conclusions. D here characterized width of DL near field pattern.



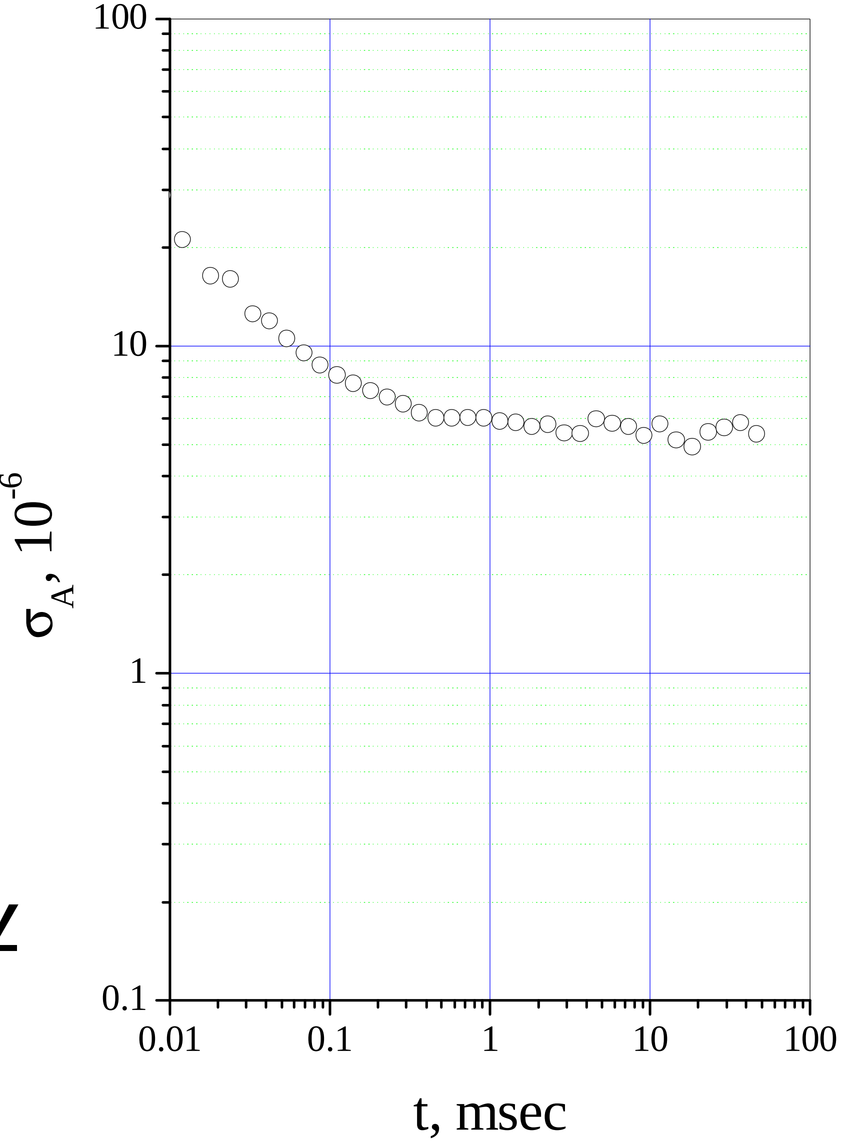
Δx describes flicker noise shift of DL near field pattern (red curve). ΔD – is the flicker noise pattern width change (blue curve). As excitation current shot noise is negligible, integral below curve has to be constant (***main characteristic of noise under consideration***). Hence, with increase of the pattern width, proper decrease of its maximum has to take place.

Traditional TDLS

If all DL radiation is recorded, flicker noise has to be 0 (see above).



Traditional experimental scheme in TDLS. Part of DL radiation is collected by objective on PD.



<u>As PD recorded only part of DL radiation, DL flicker noise can be observed. To overcome this problem all DL radiation has to be collected by optical scheme. However, it is experimentally impossible.</u>

DL far field flicker noise

DL far field is Fourier transformation of its near field:

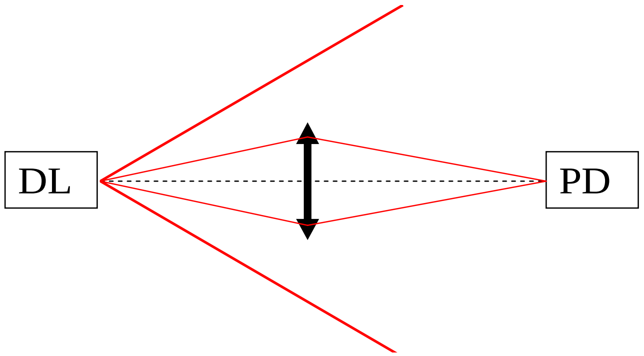
$$E(t,q) = \int_{-\infty}^{\infty} E(t,x)\exp\left[kx\sin(q)\right]dx$$

Using DL near field model presented above, far field in presence of near field flicker noise can be calculated:

$$E(t,q) \sim \exp\left[-\frac{\left[k\left(D+\Delta D(t)\right)\sin q\right]^2}{4}\right]\exp\left[i\Delta x(t)k\sin q\right]$$

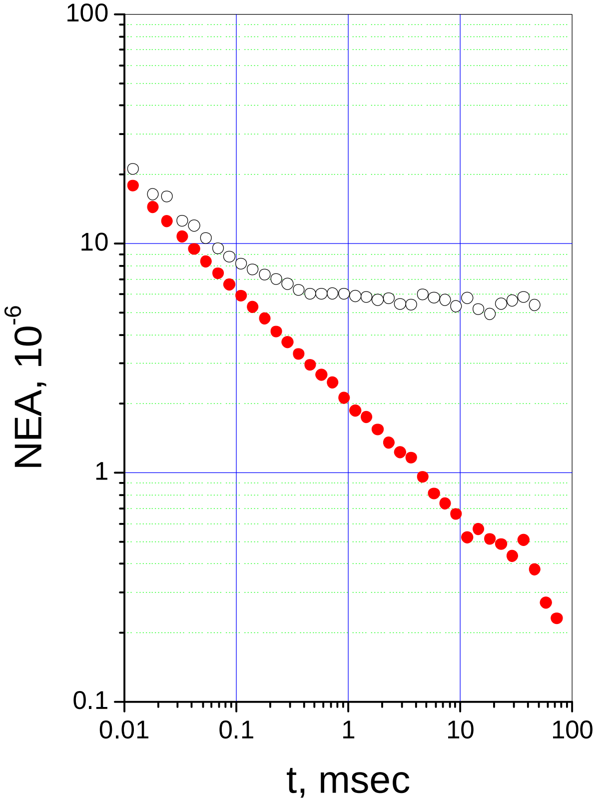
First and second terms represent intensity and frequency flicker noise of DL far field.
<u>There is one fundamental property of this noise. There is direction in DL diagram (q = 0) where flicker noise is equal 0.</u>

DL flicker noise suppression

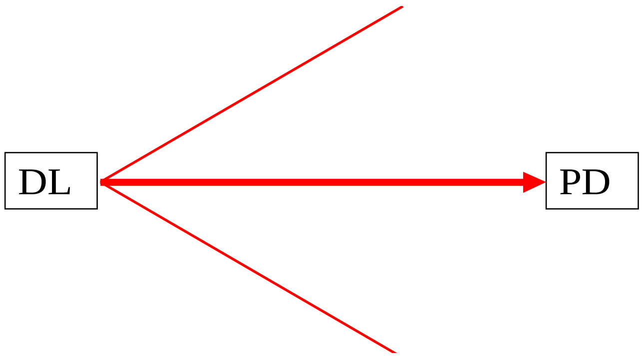


Traditional experimental scheme with objective.

As PD records only part of DL radiation, flicker noise is presenting (black open circles).



PD records small part of DL radiation (~ 0.5 %) where flicker noise is equal 0 (red solid circles).

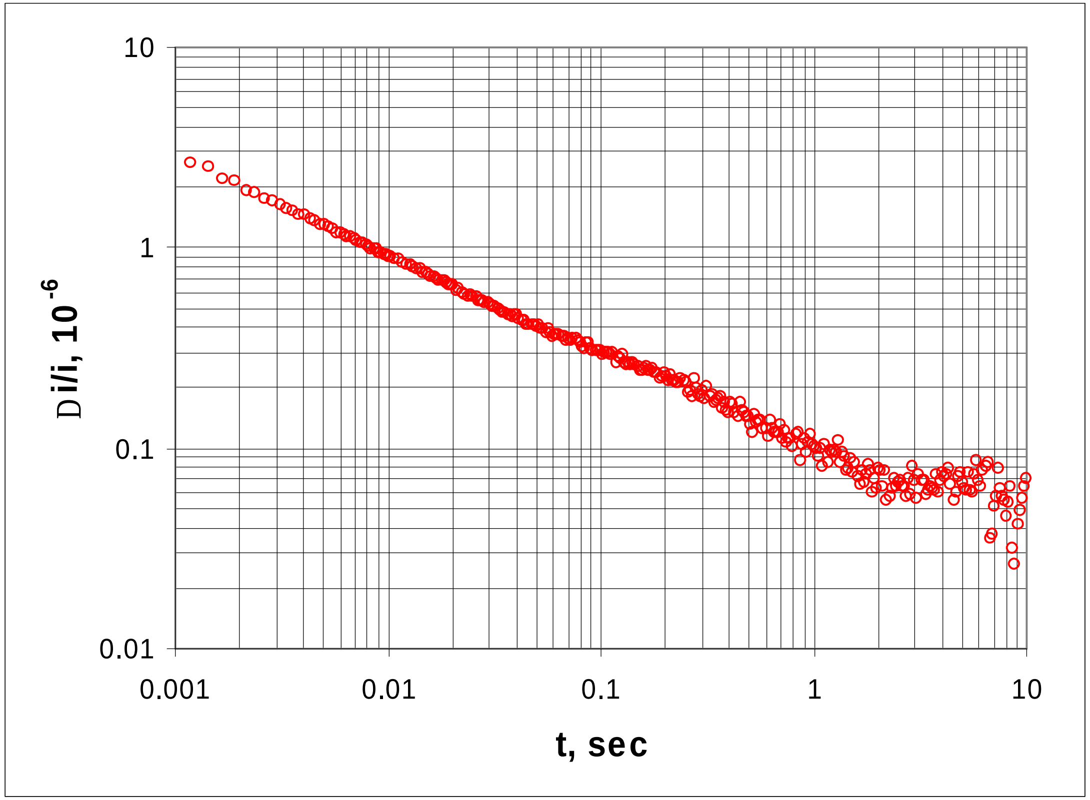


Correct experimental scheme: no objectives.

<u>Correct experimental strategy based on flicker noise origin and its properties provides possibility for total flicker noise suppression.</u>

Minimum detectable absorption below 10^{-7}

Using operation regime and data processing considered above fundamental limit of absorption detection due to diode laser quantum noise was achieved: below 10^{-7} for averaging time above 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 **$6*10^{-12}\ cm^{-1}$** for our system (Chernin multi-pass cell in use: 0.5 m, 200 passes) and it is comparable with the best known results obtained in Stark spectroscopy.

Next sensitivity parameter widely used in literature is minimum detectable molecular concentration. For example, above mentioned sensitivity for HF molecule corresponds to minimum detectable concentration **0.8 ppt**.

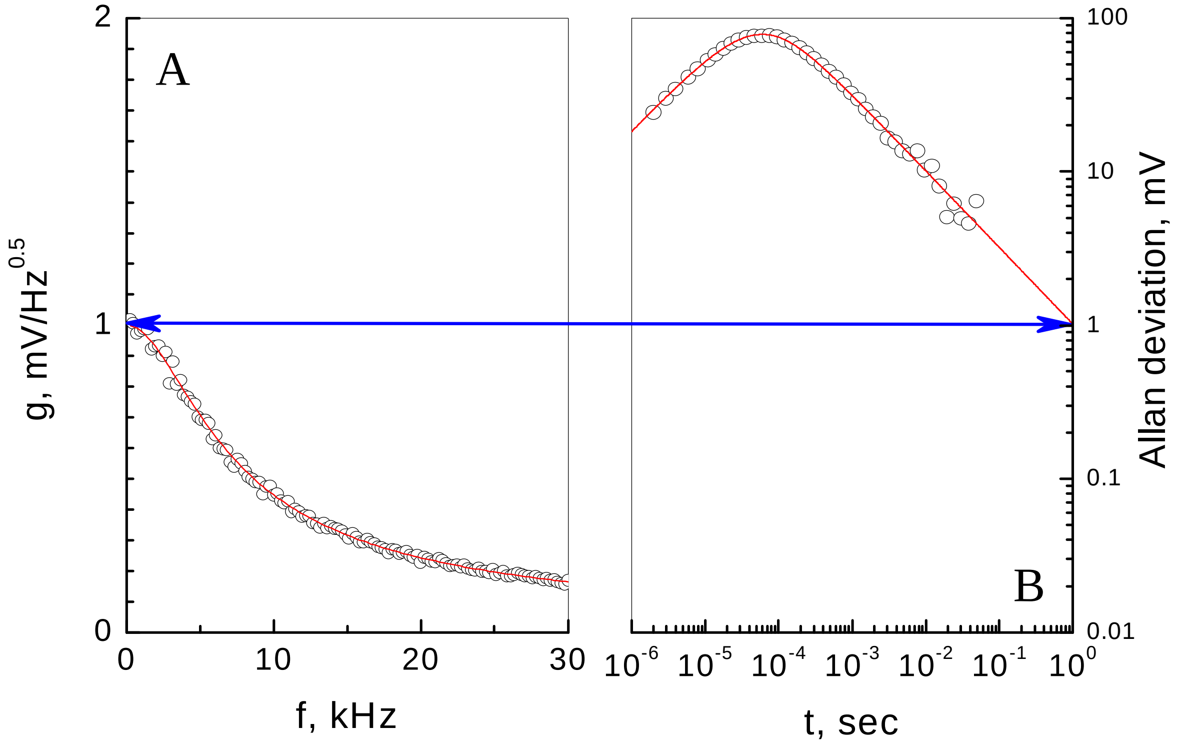
FFT and Allan plots are using for noise analysis in data series. Allan plots were proposed initially to analyze long-term laser frequency stability [1]. In TDLS it was used for the first time for concentration measurements in [2].

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.

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