SHOT NOISE LIMITED TDLS

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In literature related to TDLS many authors consider shot noise as fluctuation of photons number. This assumption conflicts with fundamentals of quantum physics. Shot noise is noise of current due to the fact that electron in our experiments is particle.
Brief shot noise description is given. Experimental technique necessary to achieve shot noise limit is considered. Some experiments of shot noise limited TDLS and comparison with literature results are presented.

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Elements of Quantum Physics

Classical mechanics: coordinates and velocities of each particle can be determined at each time moment. Hence, each particle trajectory can be predicted.

Quantum physics: system is characterized by wave function ψ. During experiment we perform some measurement characterized by operator O, and measure the operator mean value

$$\overline{O} = \left\langle \psi \middle| \hat{O} \middle| \psi \right\rangle$$

First quantization: non-commutation of coordinates and impulse operators.

$$\hat{\mathbf{r}} = \mathbf{r}; \qquad \hat{\mathbf{p}} = -i\hbar\nabla$$

$$\hat{\mathbf{r}}\hat{\mathbf{p}} - \hat{\mathbf{p}}\hat{\mathbf{r}} = -i\hbar\mathbf{r}\nabla + i\hbar\nabla\mathbf{r} = i\hbar$$

$$\Delta x \Delta p_x \approx \hbar$$

In quantum physics object don't know is it particle or wave (concept of wave particle duality). Our method of measurement determine what parameter of the system we are measuring.

This results in uncertainty principle. If one will try to measure coordinates, it will lead to total uncertainty of its impulse (velocity) and the object can be find anywhere at next moment. When impulse is measured information about object coordinates will be lost.
For light this effect results in diffraction.

Light Detection and Photocounts

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. Hence, electron is wave in quantum well. In photo-detector electron is particle.

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

γ quant with energy 124 keV has wavelength 0.01 nm and it is particle for atom and wave for nuclei.

Our spectral range: For atom and electron photon is wave. This results in dipole approximation in theory of radiation.

Resume: From physical point of view it is incorrect to speak about *photons counting*. Correct is *counting of photoelectrons* or *photocounts*.

Shot Noise

Electron is particle in our experiments. Hence, time dependence of current **i** consists of δ- like peaks (without taking into account time resolution of registration).

$$i(t) = e\sum_i \delta(\mathrm{t} - \mathrm{t_i})$$

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

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

$$G_i(f) = \int_{-\infty}^{\infty} \exp(-j2\pi f t_1)dt_1 \int_{-\infty}^{\infty} \exp(j2\pi f t_2)dt_2 \langle i(t_1)i(t_2) \rangle$$

Here <> is averaging over realizations

For **constant current** next electron appearance is random and $<i(t)i(t+\tau)>=\delta(\tau)$. In this case well-known formulae for shot noise spectral density is valid:

$$G_i(f) = ei$$

This formulae is valid when:

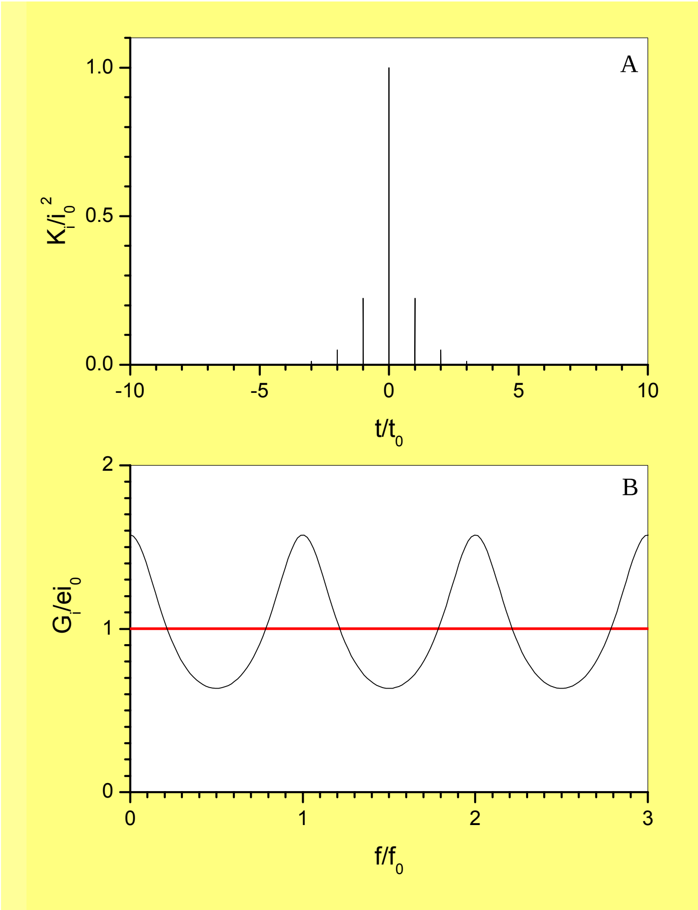
Current **i** is constant

Above mentioned Fourier Transformation is used.

*In TDLS **short noise** takes place in photo-current and excitation current of diode laser. The last one is not dominant in majority of TDL applications. However, it could be important for QCL when their sensitivity will be improved 2 – 3 orders of magnitude.*

“Sub-Poisson” Shot Noise

Stationary illumination: next photoelectron appearance is random
Non-stationary : next photoelectron appearance is correlated with previous one



Normalized photocurrent correlation function for DL with modes synchronization (non-stationary illumination).

Normalized photocurrent shot noise spectral density for DL with modes synchronization.
Red line corresponds to stationary illumination
In both cases it is *Shot Noise*.
There are frequency ranges where non-stationary shot noise spectral density is below (in literature it is known as sub-Poisson noise), as well as above stationary one

It is not too much physics here, there is more terminology problem.

Photo Diode and Preamplifier Optimization to Measure Shot Noise

Плата	std, мкV	214		208	44	4	16	5
Дискрет, bit	16	Total		SN	Rf	IN	UN	PD

Шум дискрета, bit	1
Шум платы, мкВ	10
Диапазон, В	1
Частота, кГц	333
Фотодиод	
r, кОм	25000
С, пФ	80
I, мкА	2
I_0, мкА	0.001
	79.6178
Предусилитель	
k	2
IN, пА/Гц$^{0.5}$	0.01
UN, нВ/Гц$^{0.5}$	3.9
R1, кОм	1000
C1, пФ	15
R2, кОм	0.15
C2, пФ	33000

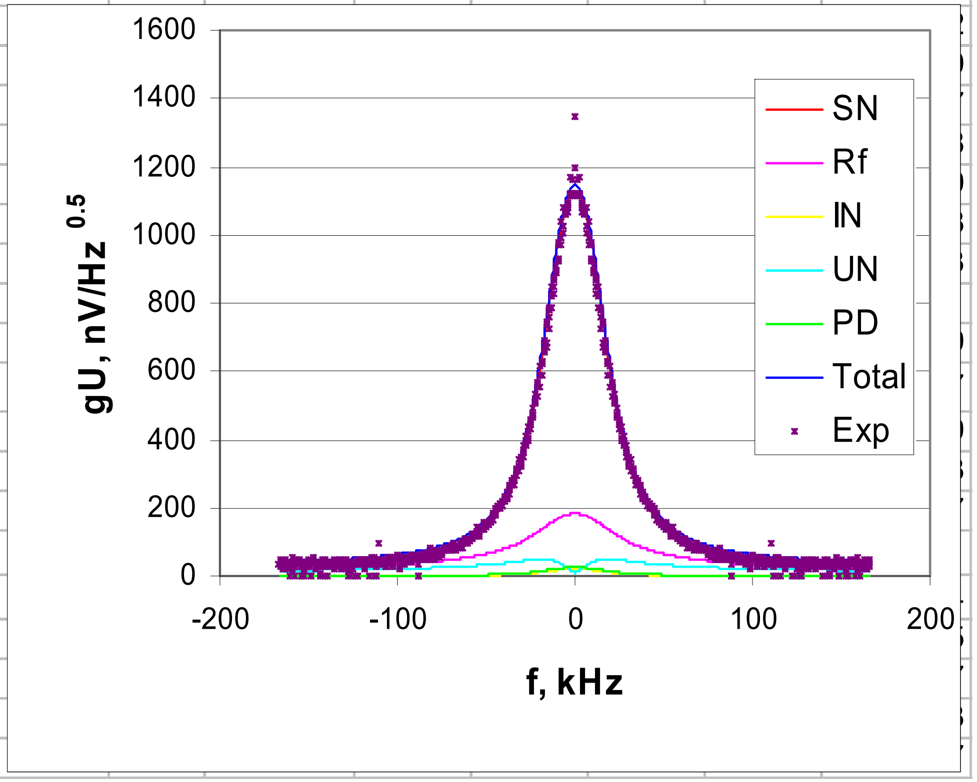
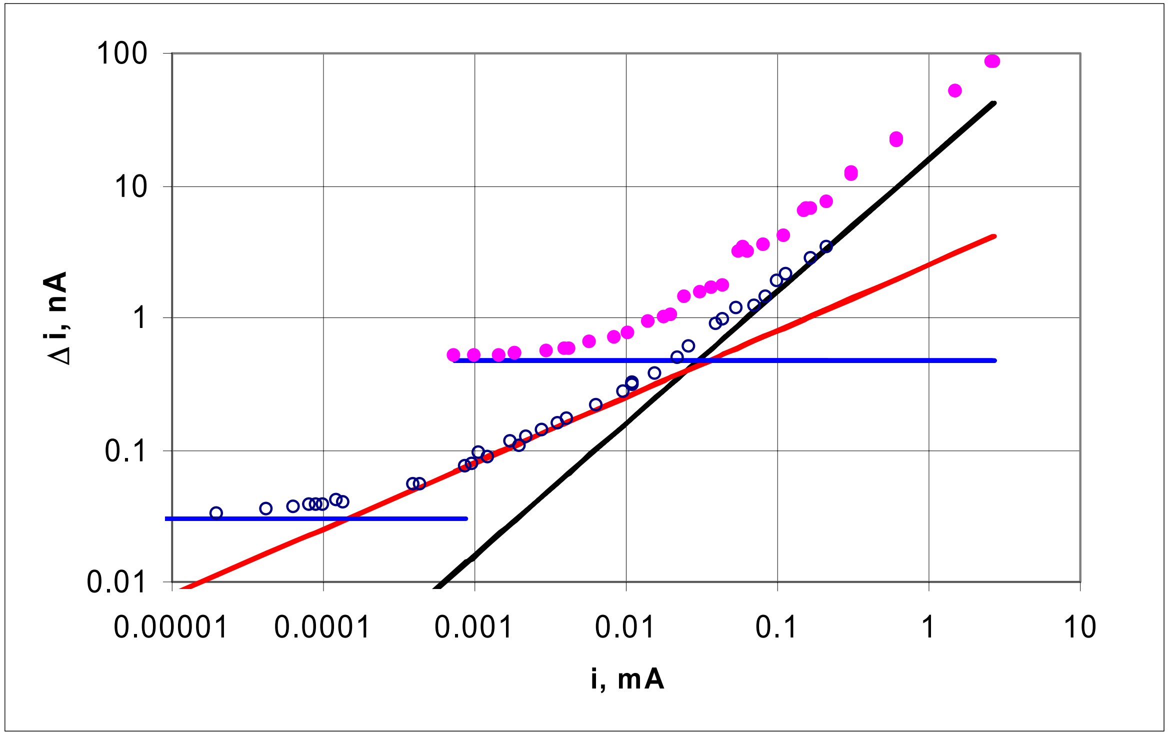


Photo diode and preamplifier development to measure shot noise.

Points represent experimental results, color lines shows different noise mechanisms

Photo Diode Current Noise

Shot noise $\Delta\mathbf{i}$ of photo diode current is determined by four components: photodiode generation and recombination currents (in our case each of them is equal to dark current - i_0) and photocurrents due to external and DL illumination.

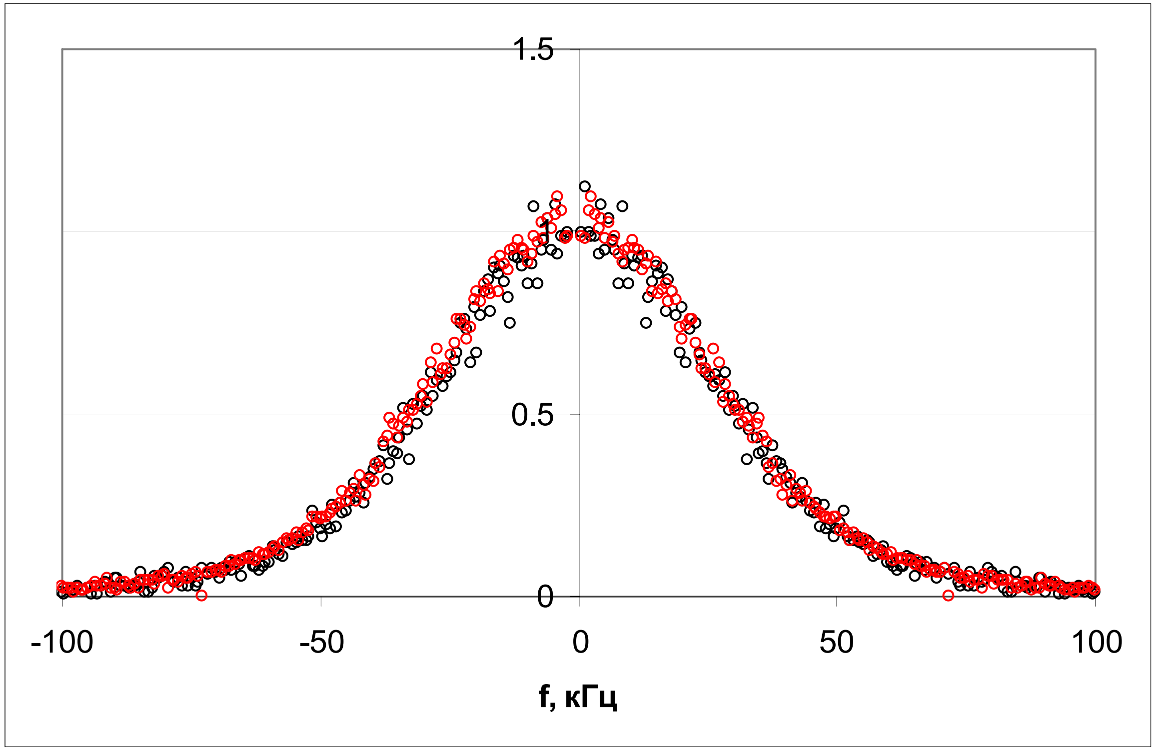


$$\Delta i = \sqrt{e\left[2i_0 + i_{ext} + i_{DL}\right]B}$$

In our experiments we've used several photo diodes with preamplifiers optimized to solve objective of particular experiment.

Noise of photocurrent as function of its value for two pairs of PD and preamplifiers in use (cycles); blue line - dark current shot noise, red line - DL photocurrent shot noise, black line - DL quantum noise (see separate poster).

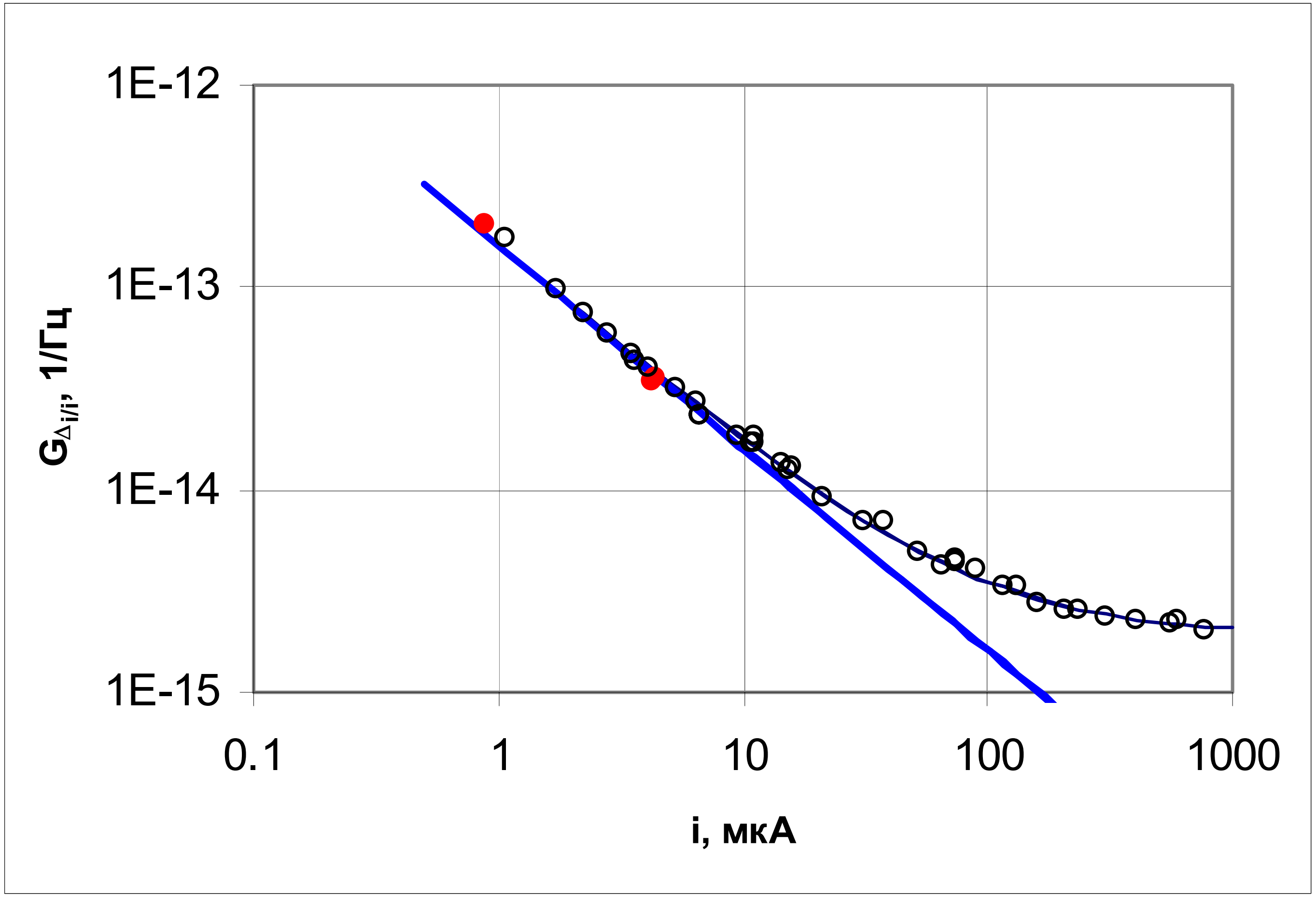
Photocurrent Shot Noise Spectral Density



Normalized photocurrent noise spectra when photodiode was illuminated by diode laser (red) and scattered Sun (black) radiation.

Spectra shape is determined by preamplifier used. Noise spectral density amplitude was normalized by theoretical value for shot noise - **ei**.

Shot Noise limited TDLS

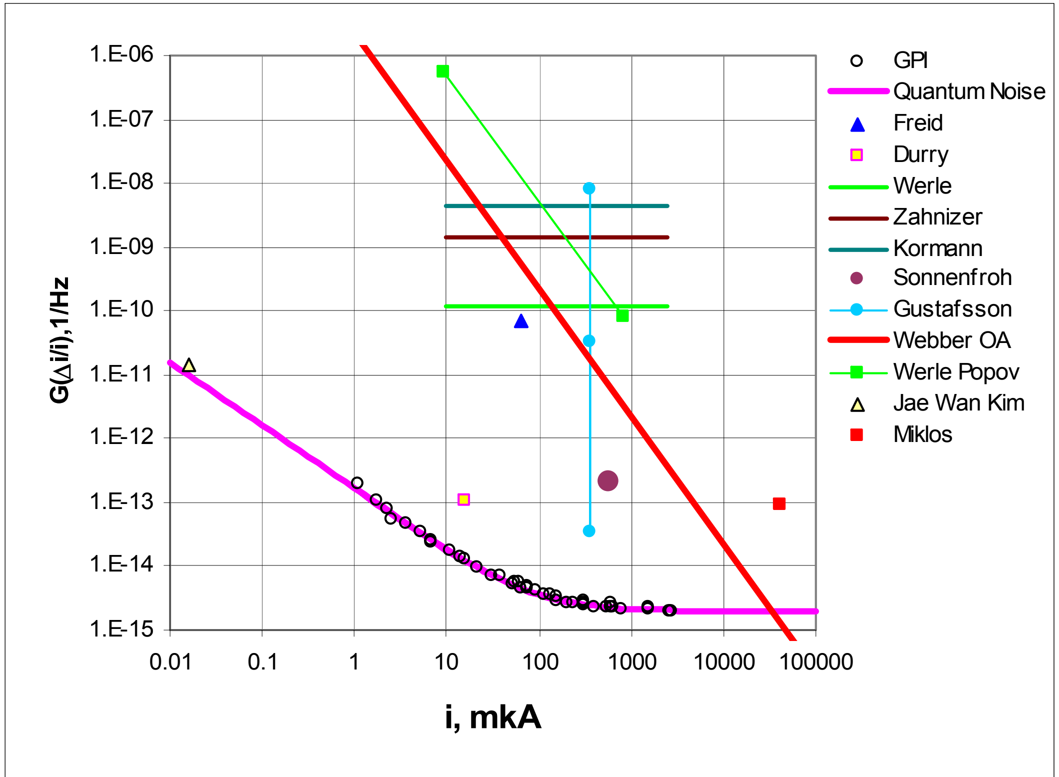


Spectral density of relative photocurrent noise - **GΔi/i** as function of photocurrent value **i**. Circles correspond to registration of Sun (red) and diode laser (black) radiation; blue line – theoretical value of stationary photocurrent shot noise - **e/i**.

Photocurrent shot noise dominates below 100 mkA, In our experiments it is important for systems with topography reflector [see separate poster]. Above 100 mkA new noise mechanism can be observed - diode laser quantum noise (see separate poster) that dominates for majority of applications.

Additional Noise Mechanisms

Best results known to author of spectral density measurements of relative photo-current noise are presented on picture below. Traditionally information in referred papers was not enough for picture under consideration. Allan plots were used frequently to obtain necessary spectral density (see separate poster). Quantum Noise line represents both photocurrent shot noise and DL quantum noise.



Spectral density of relative photocurrent noise **G(Δi/i)** as function of photocurrent value **i**.

Except our result there is only one paper (Jae Wan Kim) where shot noise limited sensitivity was achieved. All other results are from several times to several orders above fundamental shot noise level **e/i.** this was caused by additional (technical) noise mechanisms.

There are several additional mechanisms of sensitivity limitation:
cross talking;
high photo detector noise (mid IR PD and PA);
usage of non-optimal preamplifier;
DL excitation current excess noise.

Conclusion

Fundamental TDLS sensitivity limit due to photocurrent shot noise was experimentally achieved and analyzed.

It was shown that photocurrent shot noise dominates for small signal applications (for photocurrents less than 100 mkA). It is true for diode laser based systems with topographic reflector.

For photocurrent more than 100 mkA, other fundamental noise mechanism plays key role – diode laser quantum noise.