Quantum Physics and TDLS Fundamental Noises

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Abstract

In literature related to TDLS frequently wrong models are using to explain experimental results. For example, many authors consider shot noise as fluctuation of photons number. This assumption conflicts with fundamentals of quantum physics.
Brief introduction of most common models of Quantum Physics will be given related to TDLS needs. First and second quantization, as well as coherent states of electromagnetic field will be considered. Squeezed light and sub-Poisson noise will be touched. Diode laser quantum noise will be discussed. Physical nature of DL quantum noise is related to non-commutation of a and a+ operators of electromagnetic field (spontaneous emission). Examples of different fundamental noise types in TDLS will be given.

Незнание законов физики никого не освобождает от необходимости следования им.

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

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

First quantization (quantum mechanics): 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 Photo-counts

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.

g 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 photo-electrons* or *photo-counts*.

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).

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

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

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

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

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

$$G_i(f) = ei$$

This formulae is valid when:

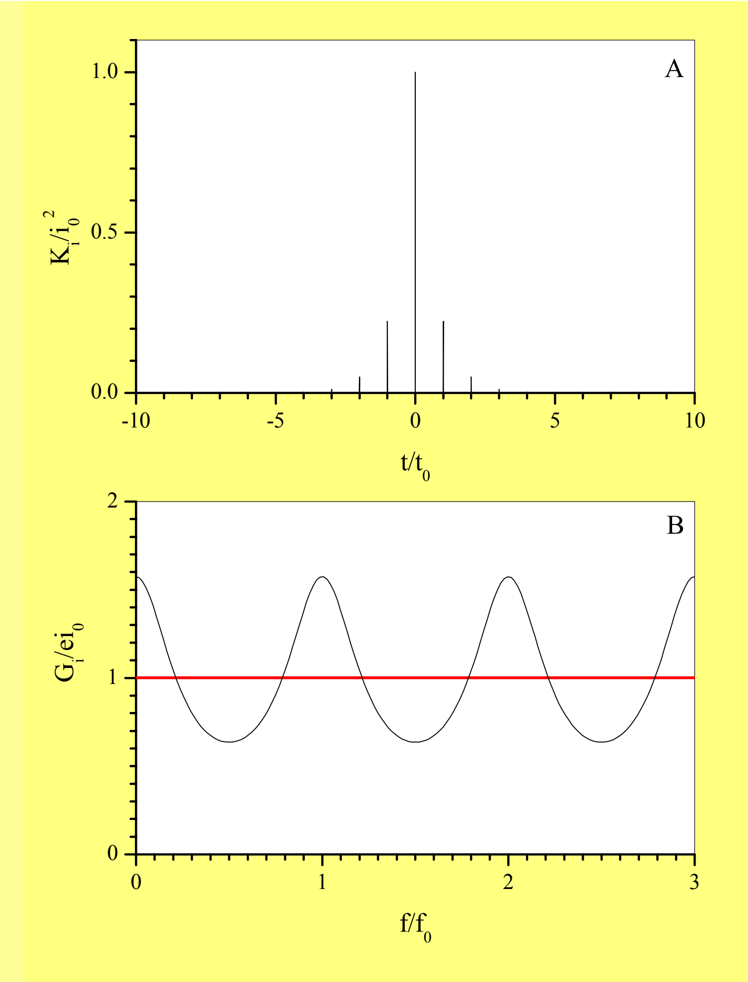
Current **i** is constant

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).

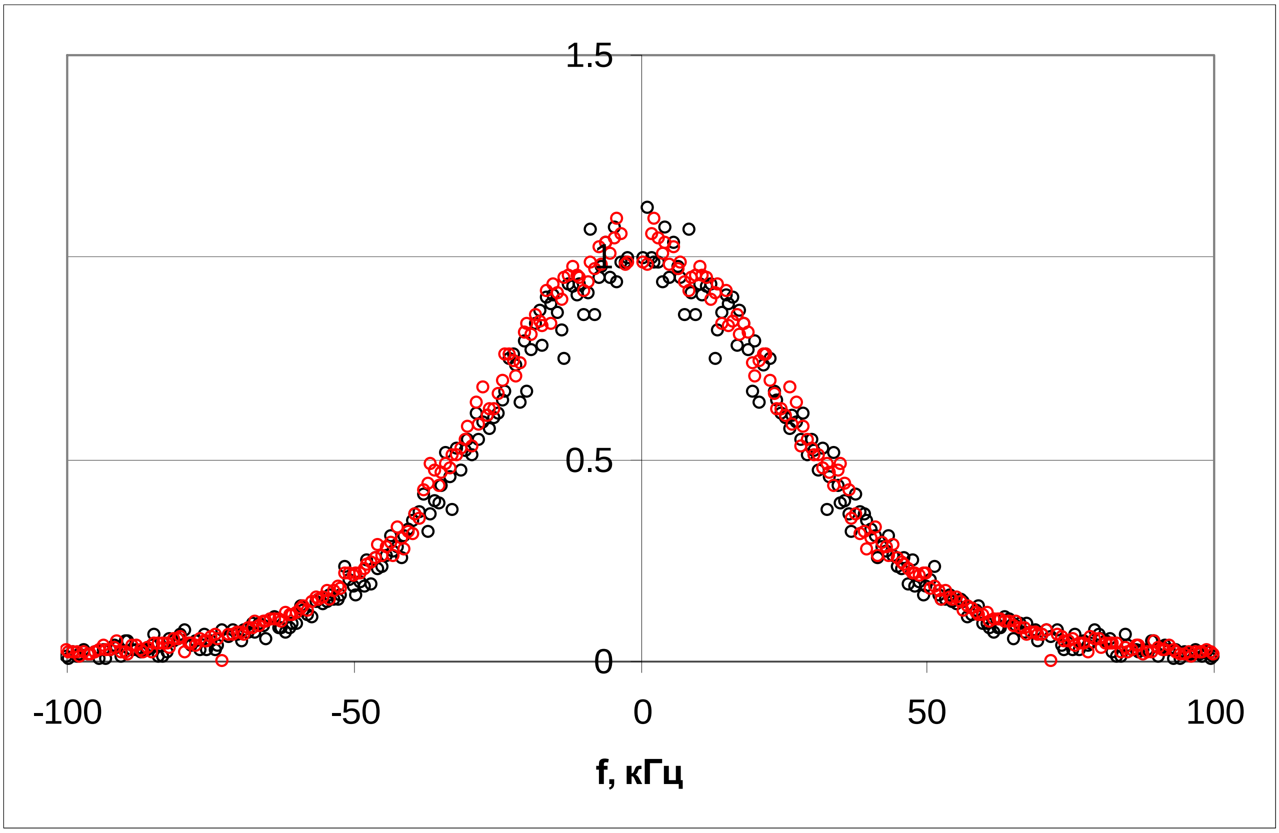
Normalized photocurrent shot noise spectral density for DL with modes synchronization.
Red line corresponds to stationary illumination

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

In both cases of stationary and non-stationary illumination it is *Shot Noise*.

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

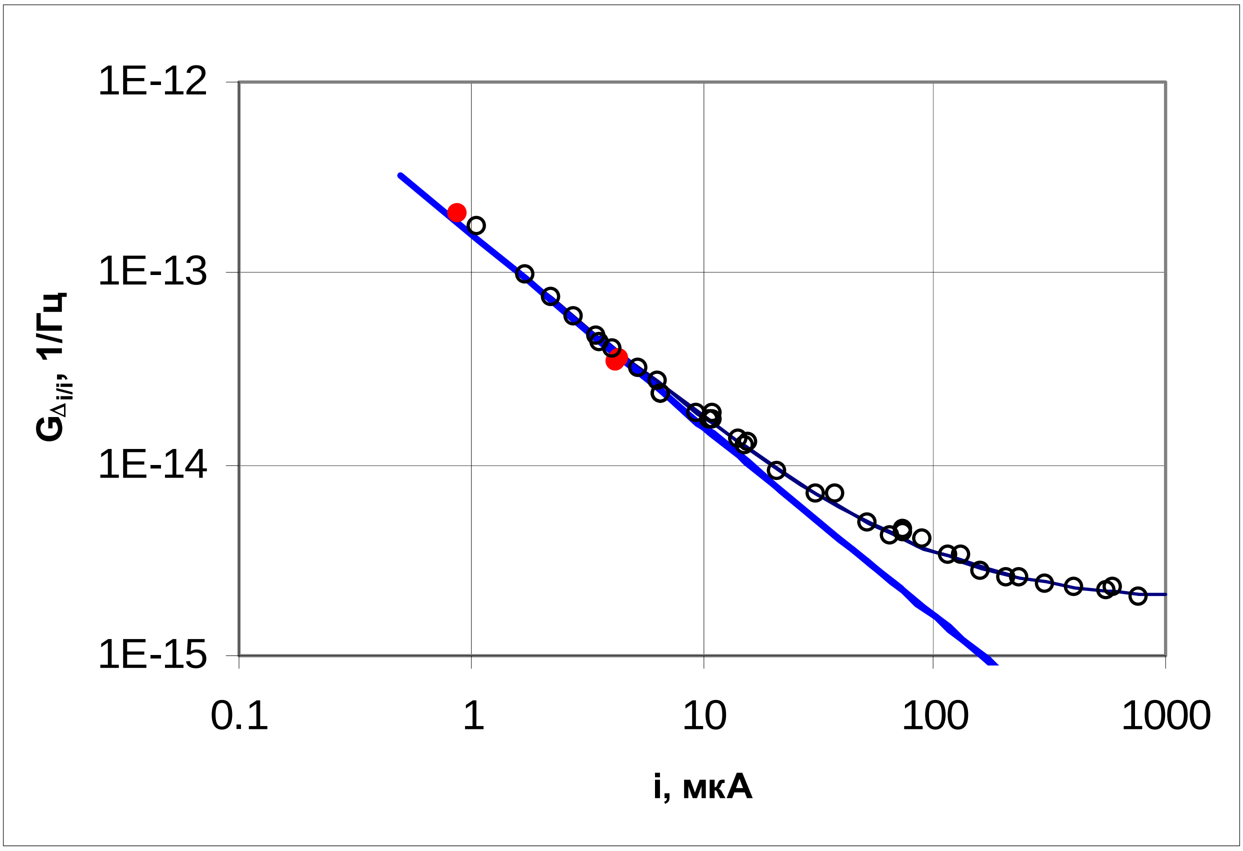
Photocurrent Shot Noise Spectral Density



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

Spectral 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, above this value diode laser quantum noise is more important.

Second Quantization of Light

Light is characterized by two values: electric and magnetic field strength. Its Hamiltonian looks similar to harmonic oscillator one.

<u>**Second Quantization**</u>: Following Quantum mechanics generalized coordinate and impulse have to be introduced. More convenient was introduction of creation and annihilation operators **a** and **a+**. These operators don't commutate:

$$\hat{a}\hat{a}^{+} - \hat{a}^{+}\hat{a} = 1$$

Physical nature of this non-commutation (quantum nature of light) is related to presence of spontaneous emission. This effect results in uncertainty principle: it is impossible to measure simultaneously number of photons and phase of electromagnetic field..

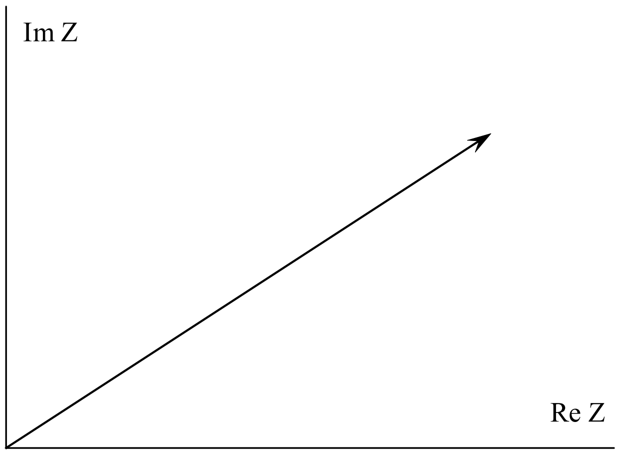
Usually eigenfunctions of operator a+a - $|N\rangle$ are considered. These functions correspond to electromagnetic field state with N photons in given mode and

$$\left\langle N \middle| \hat{a}^{+}\hat{a} \middle| N \right\rangle = N$$

For this state number of photons in mode is determined and, hence, due to uncertainty principle phase is totally undetermined.

Coherent States

<u>Coherent States</u> are playing key role in Quantum Optics as well as in TDLS.
Coherent states are eigenfunctions of annihilation operator **a**: **a**$|Z\rangle = Z\,|Z\rangle$.
Coherent states describe electromagnetic field with determined phase.
Coherent states of electromagnetic field have minimum uncertainty.



Complex electromagnetic field coherent state $|Z\rangle$ presentation

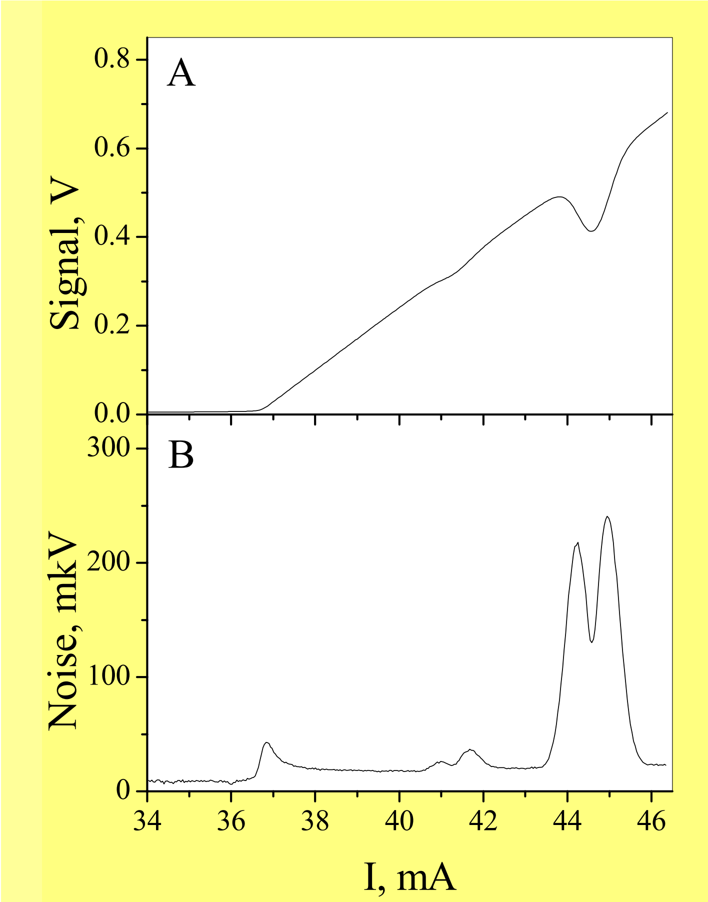
$$Z=|Z|\exp(-j\varphi)$$

Stationary coherent state $|Z\rangle$ can be presented using wave functions $|N\rangle$ in following way:

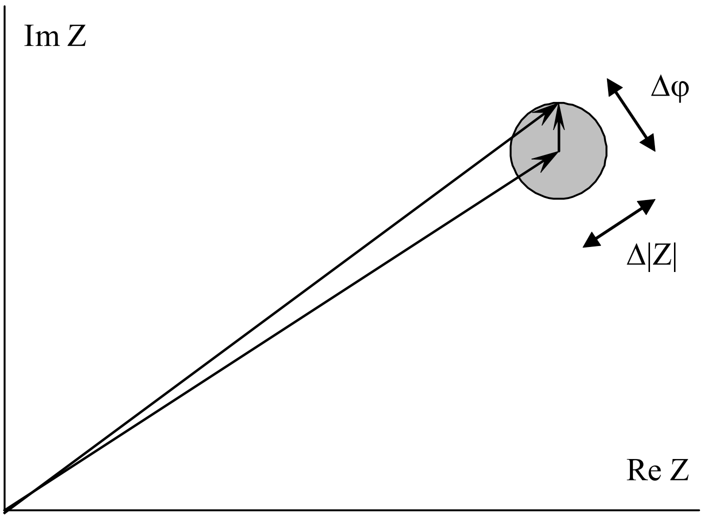
$$|Z\rangle = \exp\left(-\frac{1}{2}|Z|^2\right)\sum_{N=0}^{\infty}\frac{Z^N}{\sqrt{N!}}|N\rangle$$

It is Poisson distribution

Diode Laser Quantum Noise



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



Influence of spontaneous emission on complex electromagnetic field Z

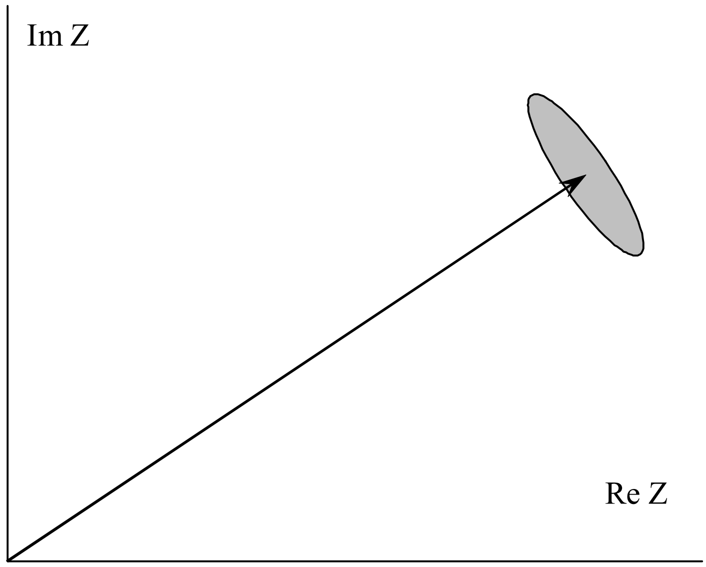
$$Z=|Z|\exp(-j\varphi)$$

Presence of spontaneous emission leads to intensity and frequency noises due to quantum nature of light.

This simple model explains main experimental results. Absolute intensity noise doesn't depend while frequency noise is reversely proportional to intensity (Shawlov – Tawnes).

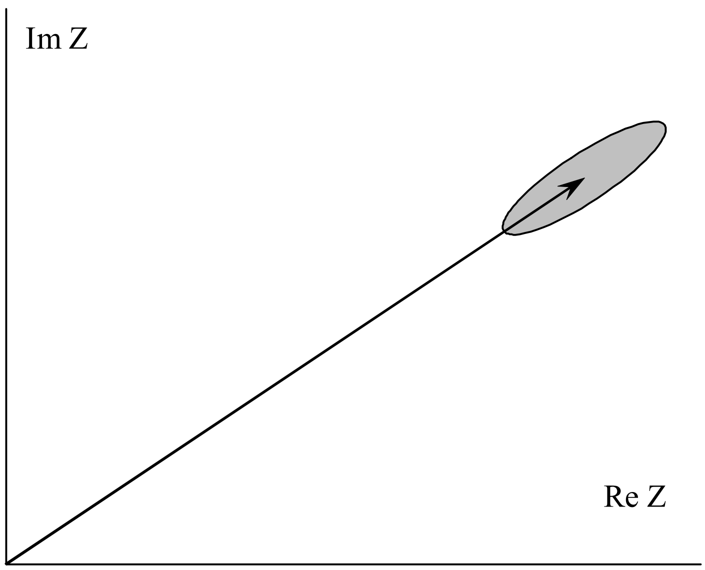
Squeezed States

Complex electromagnetic field diagram can be changed because of influence of experiment. There are several possibilities of such changing.
Let us assume stabilization of one of parameters (intensity or frequency).
For **coherent state** (minimum uncertainty) one parameter stabilization (due to uncertainty principle) will provide increase of other parameter noise. So circle will be replaced by ellipse with the same area equal 1.



Intensity stabilization

Frequency stabilization



Nonlinear Optics and Squeezed States

Different nonlinear optical effects are widely used to produce squeezed states.
Diode laser is very nonlinear system. It results in the fact that radiation of diode laser is squeezed. In literature this effect is known as α parameter explaining difference between frequency and intensity noises. However, in this case area under ellipse is sufficiently higher than 1.

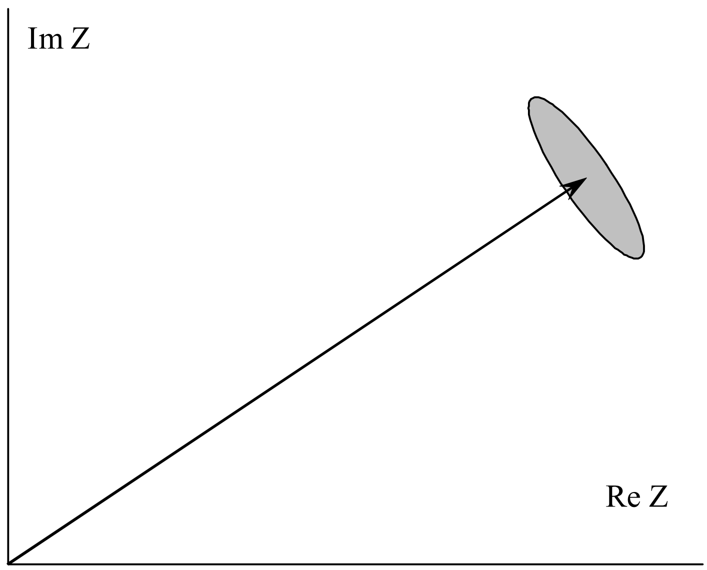


Diagram of diode laser complex electromagnetic field

In majority of TDL application it is not important because intensity quantum noise dominates.
In applications when frequency quantum noise dominates (in our experiments it was related to detection of trace ethanol and measurement of UF6 isotope ratio) following solutions can be recommended:
Develop diode laser with smaller nonlinearity.
Use short-cavity diode lasers.

Additional Noise Source

Additional noise source also can produce squeezed states with area under ellipse significantly higher than 1. Diode laser excitation current noise is one of such sources.

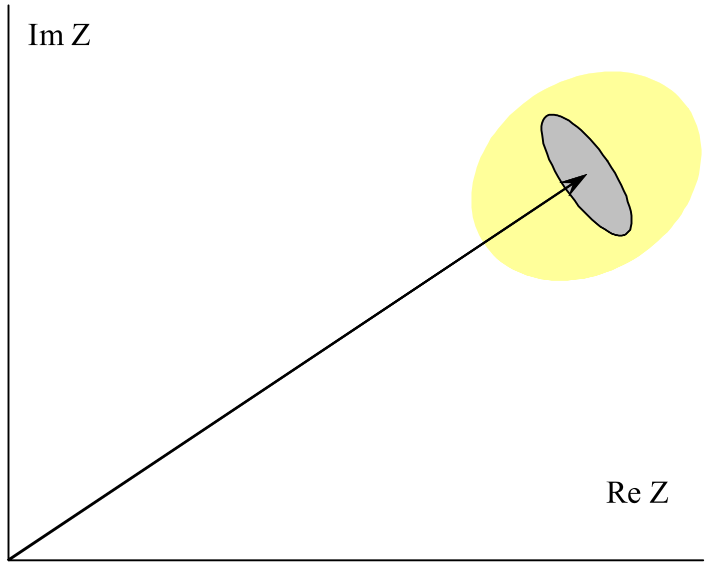
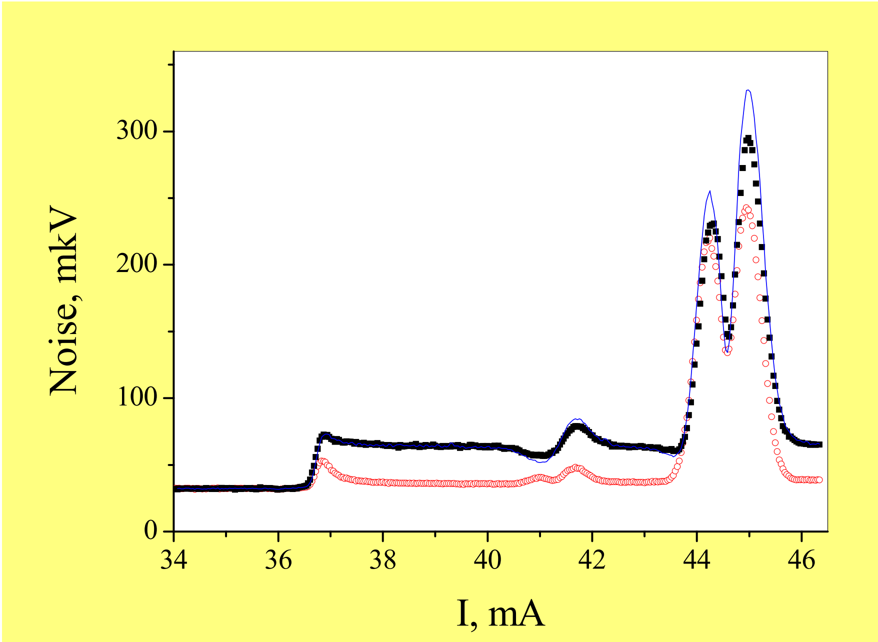


Diagram changing of diode laser complex electromagnetic field when noise is added to excitation current



Signal noise changing when noise was added to diode laser excitation current

Conclusion

There are four main fundamental noise mechanisms limiting TDLS

1. Photocurrent shot noise dominates for small signal applications (diode laser based systems with topographic reflector).
2. Diode laser excitation current shot noise doesn’t play important role in our systems. However, it can dominate in future for systems based on Quantum Cascade Lasers.
3. Diode laser frequency quantum noise can be important for some applications.
4. Diode laser intensity quantum noise is main fundamental mechanism of TDLS sensitivity limitations (for photocurrent higher than 100 mkA).