Diode Laser Quantum Noise

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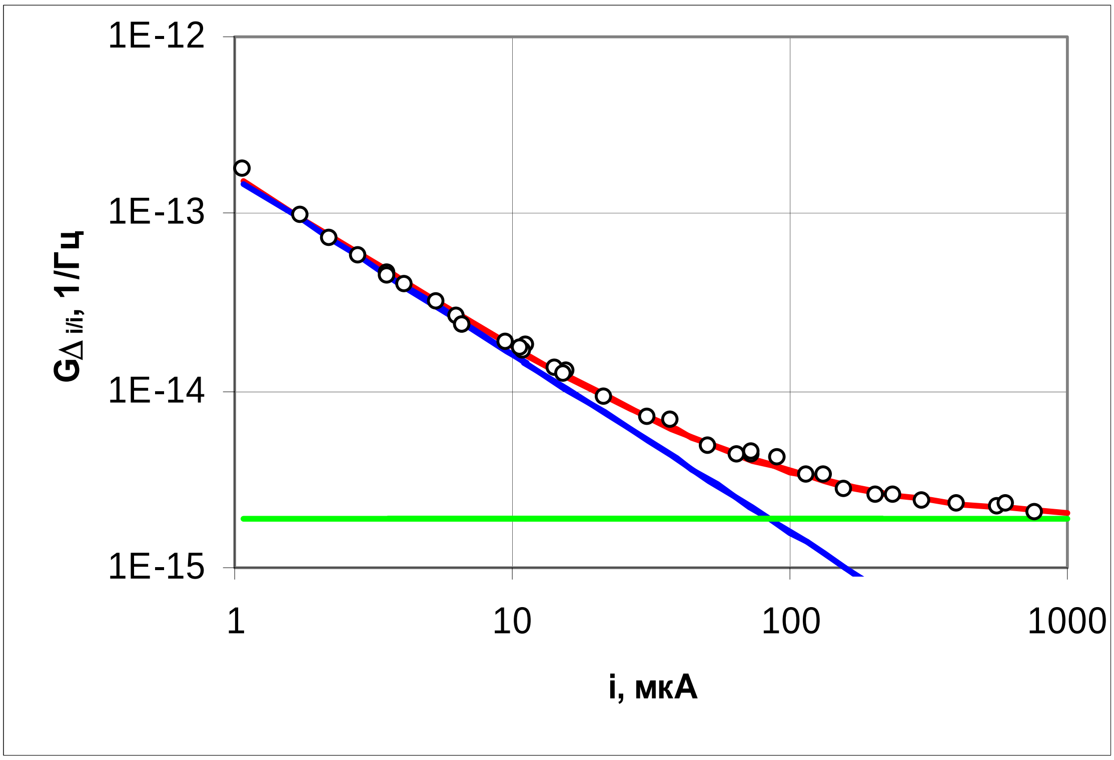
Abstract

Diode laser quantum noise is fundamental limit of possible TDLS sensitivity when trace molecule detection is considered. Spontaneous emission is physical origin of DL quantum noise (see separate poster).

Both intensity and frequency quantum noises can limit absorption TDLS sensitivity. Correlation of frequency and intensity quantum noises produces spectral line asymmetry and has to be taken into account for accurate line shape measurements.

Software developed is presented with several examples of diode laser noise investigation.

Shot Noise Limited TDLS



Spectral density of relative photocurrent noise - $\mathbf{G_{\Delta i/i}}$ as function of photocurrent value **i**. Black circles correspond to registration of diode laser radiation; blue line – theoretical value of stationary photocurrent shot noise.

Photocurrent shot noise dominates below 100 mkA. Above this value other noise mechanism is more important - diode laser quantum noise (green line). Spontaneous emission (second quantization) is physical origin of DL quantum noise.

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 annihilation and creation 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 $\mathbf{a^{+}a}$ - $|\mathbf{N}\rangle$ are considered. These functions correspond to electromagnetic field state with N photons in given mode and

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

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

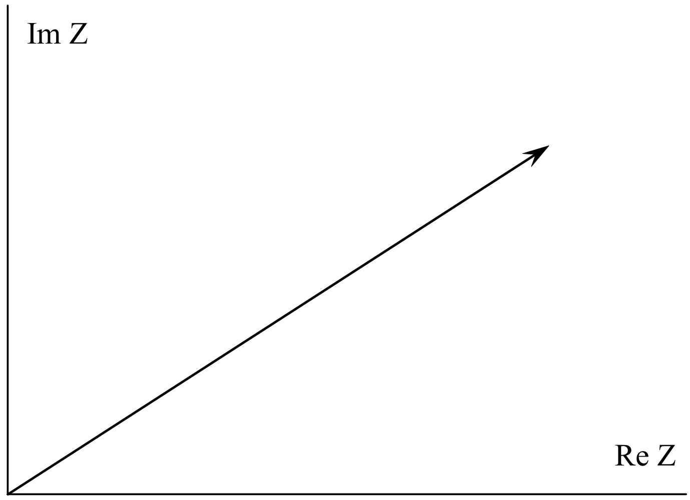
Coherent States

<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.

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

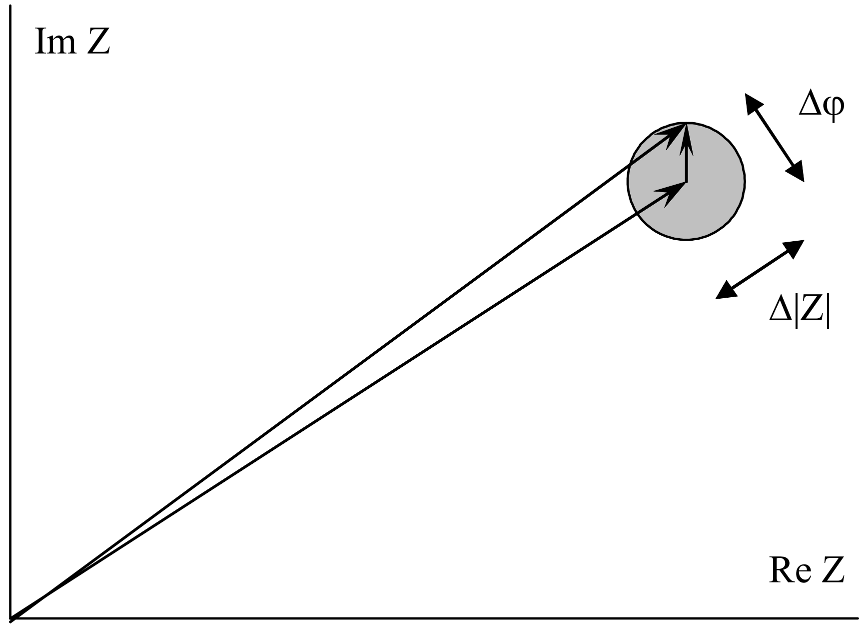


Complex electromagnetic field coherent state $|\mathbf{Z}\rangle$ presentation

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

Diode Laser Quantum Noise

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



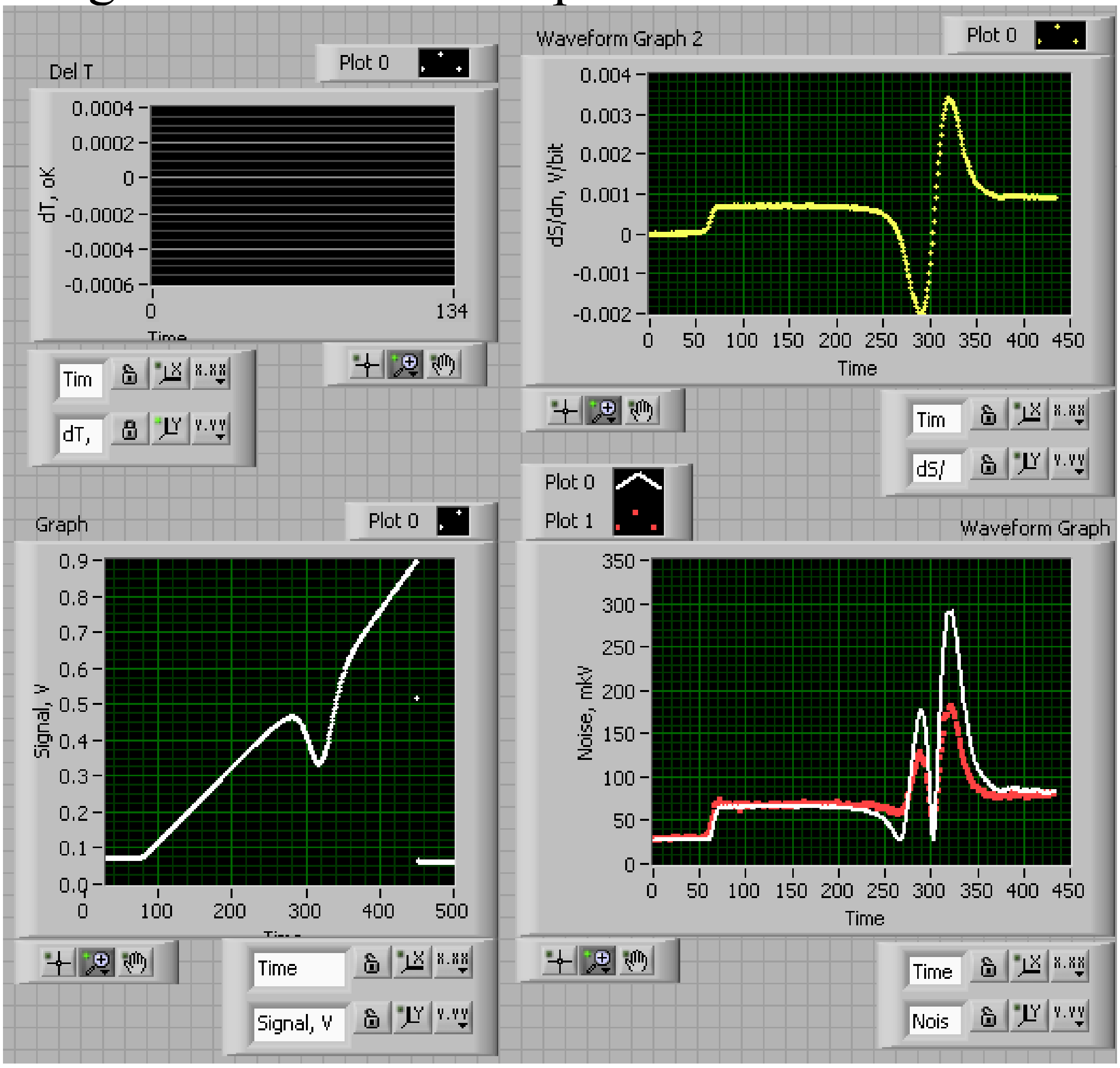
Influence of spontaneous emission (grey cycle with area equal to 1) on complex electromagnetic field Z

$$\mathbf{Z=|Z|exp(-j\varphi)}$$

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

DL Noise Software

Interface of software developed (DL Noise) to investigate diode laser and photodiode noise.



Signal with absorption line as function of DL excitation current (left down); signal derivative (up right); experimental and calculated noise (right down) red and white, respectively.

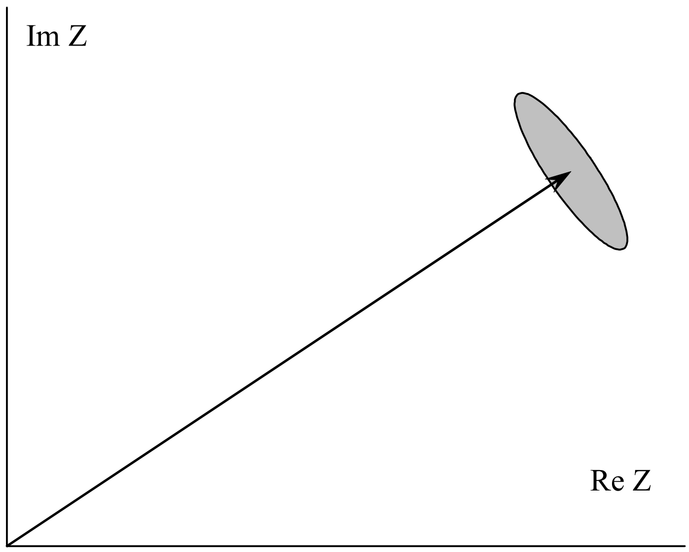
In present case noise was added to DL excitation current.

Squeezed States

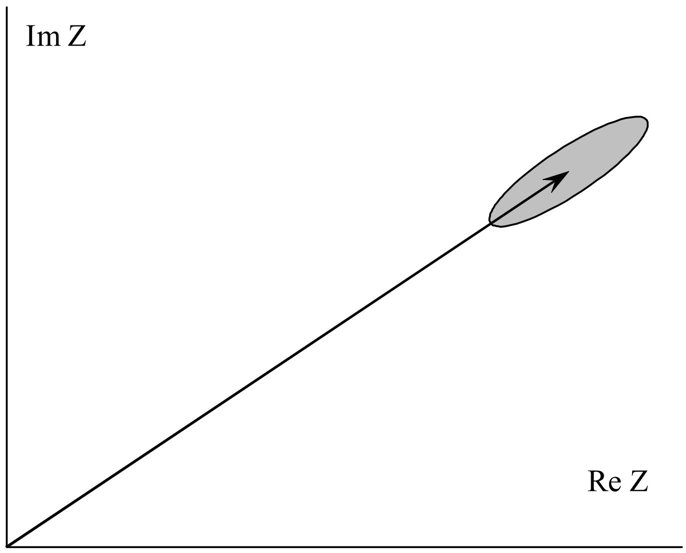
Complex electromagnetic field diagram can be changed because of influence of experiment. There are several possibilities of such changing.

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 to 1.

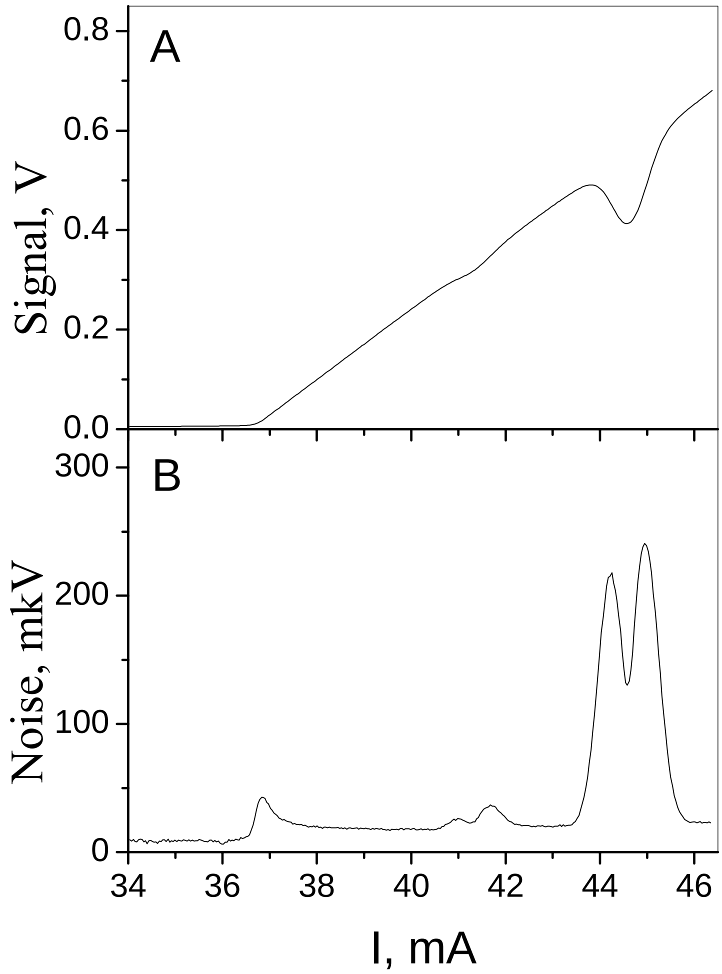


Intensity stabilization



Frequency stabilization

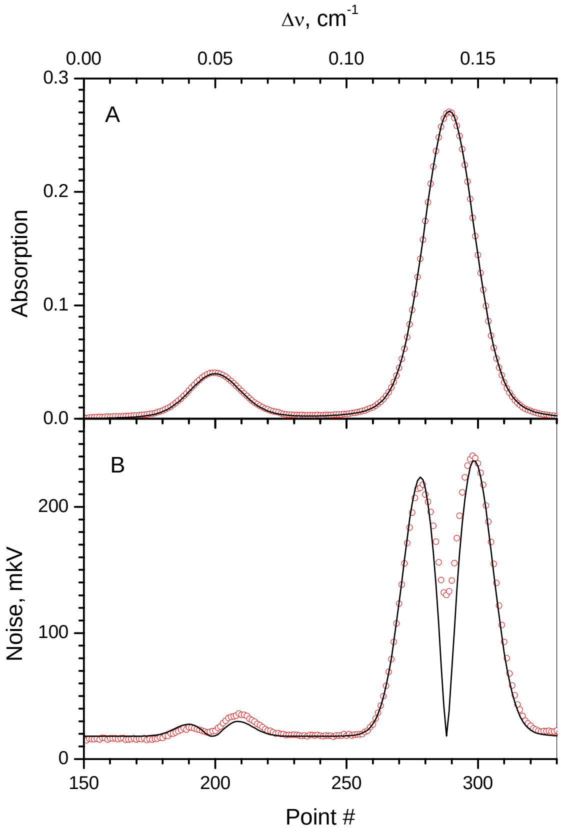
Experimental Measurement of Diode Laser Quantum Noise.



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

There is noise peak near threshold (typical to phase transitions). Intensity noise is constants. Additional noise on slopes of spectral line due to DL frequency quantum noise can be observed.

DL Frequency Quantum Noise.



Absorption (A) and DL quantum noise (B): red cycles - experiment; black line – calculations with following assumption: absence of correlation between DL intensity and frequency quantum noises

$$i(t) = i_0(t)\left[1 + \Delta\nu(t)\frac{\partial K_0}{\partial \nu}L\right]\exp(-K_0 L) + \Delta i$$

For center of strong line following DL quantum frequency noise spectral density was determined: $G_{\Delta\nu}$ = 28 MHz (DL was operated near threshold):

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 higher than 1.

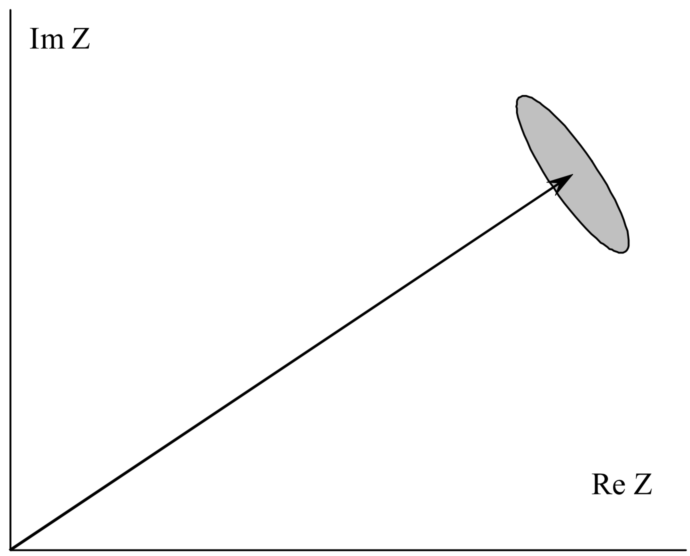
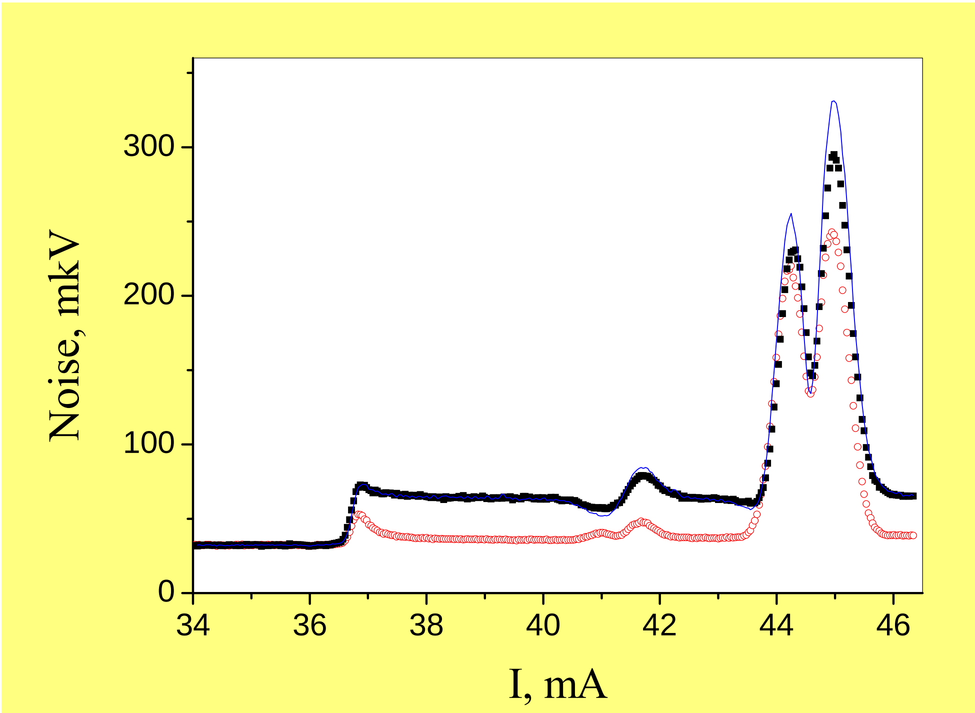


Diagram of diode laser complex electromagnetic field

In majority of TDL application it is not important because intensity quantum noise dominates.
In applications when frequency quantum noise dominates following solutions can be recommended:
Develop diode laser with smaller nonlinearity.
Use short-cavity diode lasers.

Additional Noise Source

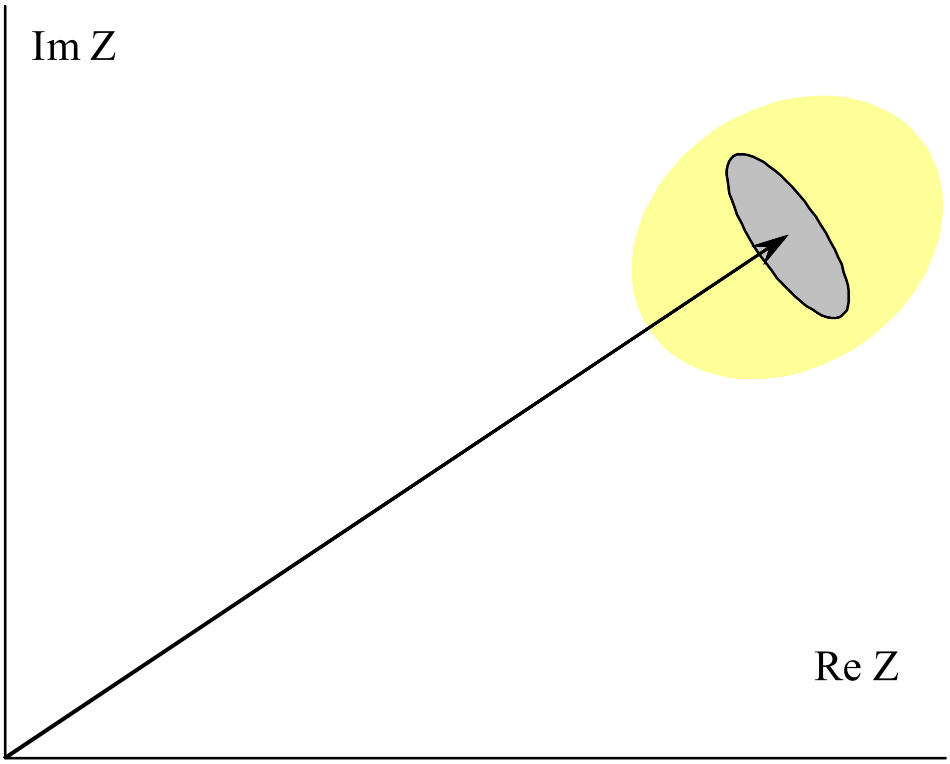
Additional noise source also can produce squeezed states Diode laser excitation current noise is one of such sources.



Signal noise changing when noise was added to diode laser excitation current. DL quantum noise (red); experimental data when current noise was added (black); calculated noise dependence based on set up parameters (blue). Calculated results reproduce very well intensity noise. Frequency experimental noise is smaller than calculated one. DL frequency tuning with current is determined by two processes: changing of excess carriers in active area and its heating. The last process is slow enough and does not participate in frequency noise.

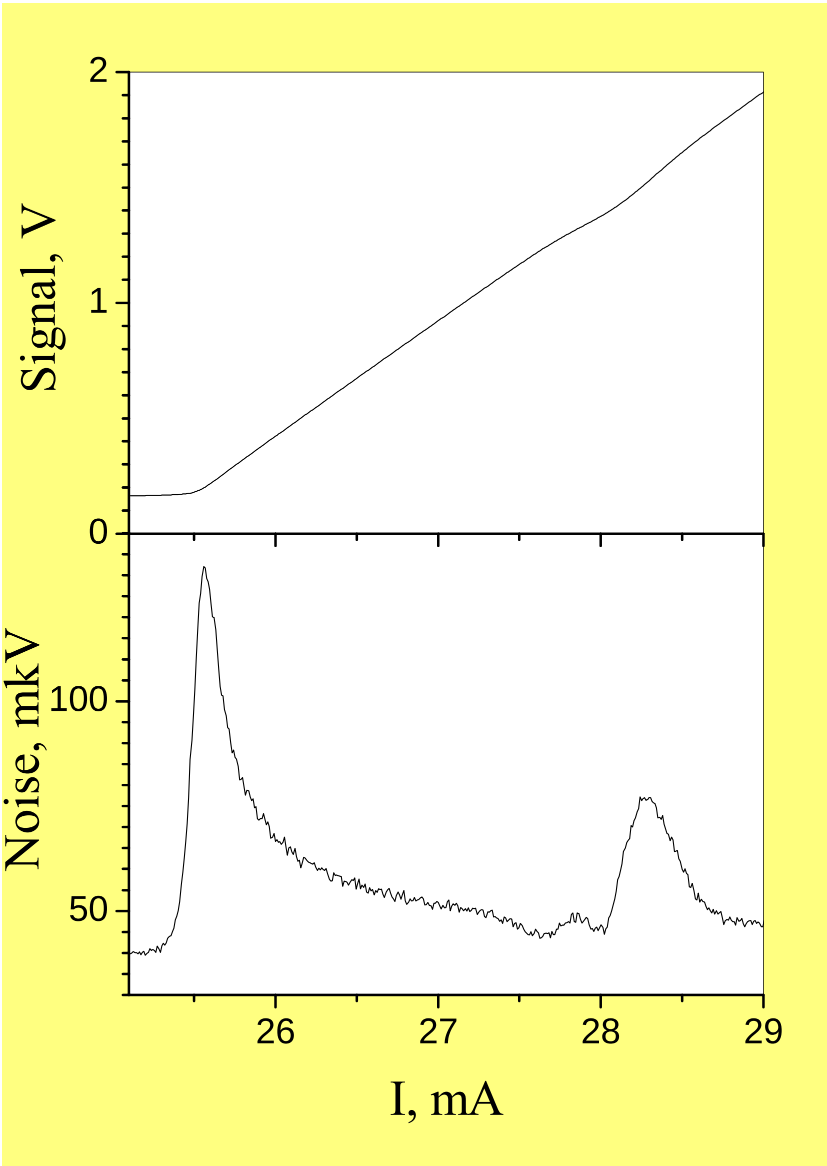
Additional Noise Source

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.



Changing of diode laser complex electromagnetic field diagram when noise is added to excitation current

Intensity and Frequency DL Quantum Noise Correlation



This effect has to be taken into account for accurate spectral line shape measurements because it produces line asymmetry and causes non-linear pressure shift

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).