Baseline in TDLS

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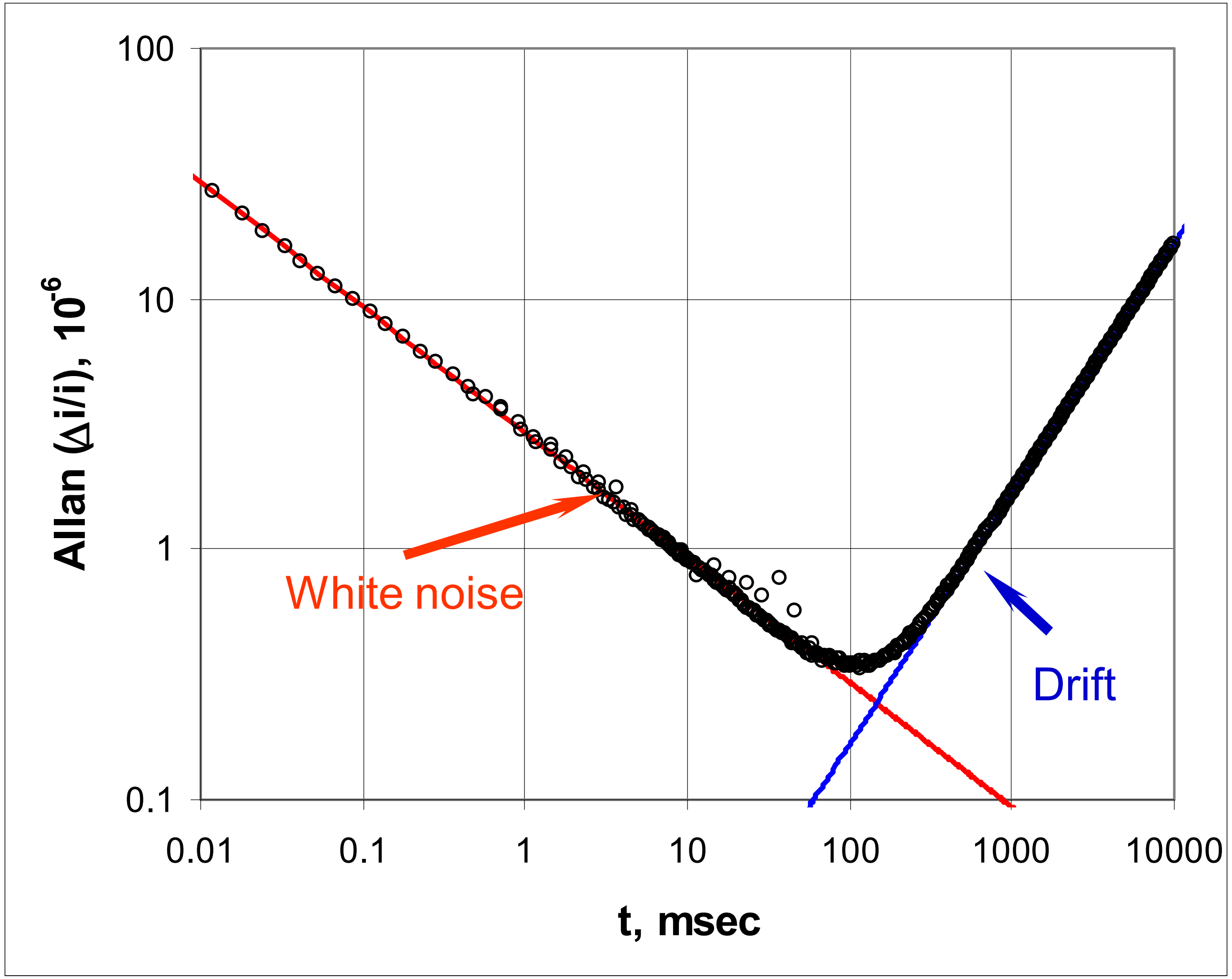
Introduction

Baseline plays key role for trace molecules detection using Tunable Diode Laser Spectroscopy (TDLS). For the first time for author knowledge it was mentioned in [1]. Baseline fundamental physical origin was proposed in [2]. Baseline in DL frequency tuning was investigated in [3].

1. J.Reid, D.Labrie, Appl.Phys., B26, 203-210 (1981)
2. A.Nadezhdinskii, I.Zasavitskii, in “Monitoring of gaseous pollutants by tunable diode lasers”, R.Grisar, H.Preier, G.Schmidtke, G.Restelli (Ed.), Proc. Int. Symposium, Freiburg, FRG 1986, D.Reidel Publ.Com., Dordrecht, 1987, p.95-106
3. A.Nadezhdinskii, Ya.Ponurovskii, M.Spiridonov, Quantum Electronics, 29, 916-920 (1999)

Drift limited TDLS



Allan plot of relative photocurrent noise as function of averaging time for baseline drift limited TDLS.

For white noise fundamental limit due to DL quantum noise is achieved and white noise can be reduced by increasing of averaging time. After Flicker noise was suppressed (see C1), TDLS is limited by drift - slow baseline change.

Requirement: to achieve fundamental level, baseline has to be suppressed to 10^{-7}.

Problem: there are variety of possible mechanisms. Each mechanism needs its own suppression strategy development.

B1 - DL active area conductivity inhomogeneity

Baseline mechanism – B1: Inhomogeneity of DL active area conductivity. Due to DL technology there are several mechanisms leading to this effect.

Next: Inhomogeneity of excitation current density.

Next: Inhomogeneity of excess carriers concentration.

Next: Interaction of electromagnetic field standing wave with inhomogeneity of excess carriers concentration.

Result: Baseline B1.

Baseline B1 characteristics:

1. ***B1 characteristics depend on particular DL.*** We've investigated a lot of DLs. Between them there were DL having no baseline B1 mechanism (see below).
2. Inhomogeneity under consideration is stable. Hence, if baseline is recorded once it can be subtracted from results obtained later.
3. Item #2 is true if electromagnetic field standing wave is stable.
4. ***As it'll be shown below item #3 leads to following requirements:***

    Temperature stability better than 10^{-5} K.

    Current stability better than 0.1 μA.

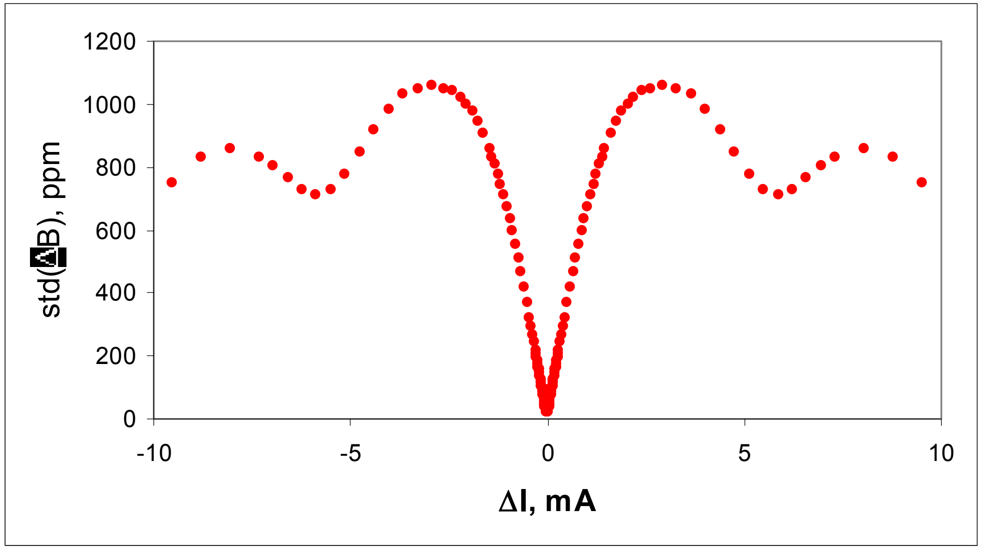
B2 - Excitation current fluctuations

Baseline mechanism – B2: Electron is particle - excitation current density fluctuations – flicker noise (see C1).

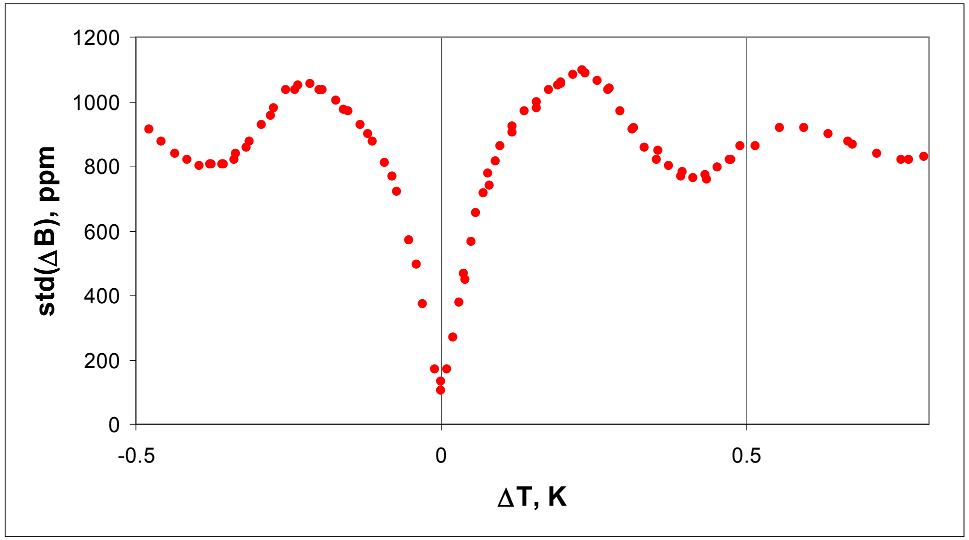
Next: Fluctuation of heating sources in DL active area.
Next: Fluctuation of temperature field in DL active area.
Next: Modulation of excitation current density.
Next: Inhomogeneity of excess carriers concentration.
Next: Interaction of electromagnetic field standing wave with inhomogeneity of excess carriers concentration.
Result: Baseline B2.
Baseline B2 characteristics:

1. ***B2 is fundamental and common for all DL types.***
2. Inhomogeneity under consideration is unstable. ***This results in the baseline slow changing with time.***
3. Additional instability is similar to B1 (item #3) with requirements for current and temperature stability.
4. B2 baseline is different (similar to flicker noise) for different directions in DL diagram.

B1 and B2 dependences



Baseline current dependence. Baseline was recorded for current I. Then it was subtracted from further results.



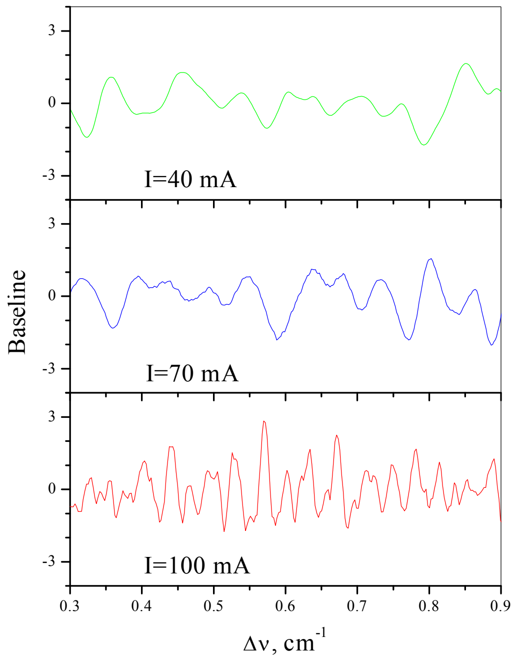
Baseline temperature dependence. Baseline was recorded at temperature T. Then it was subtracted from further results.

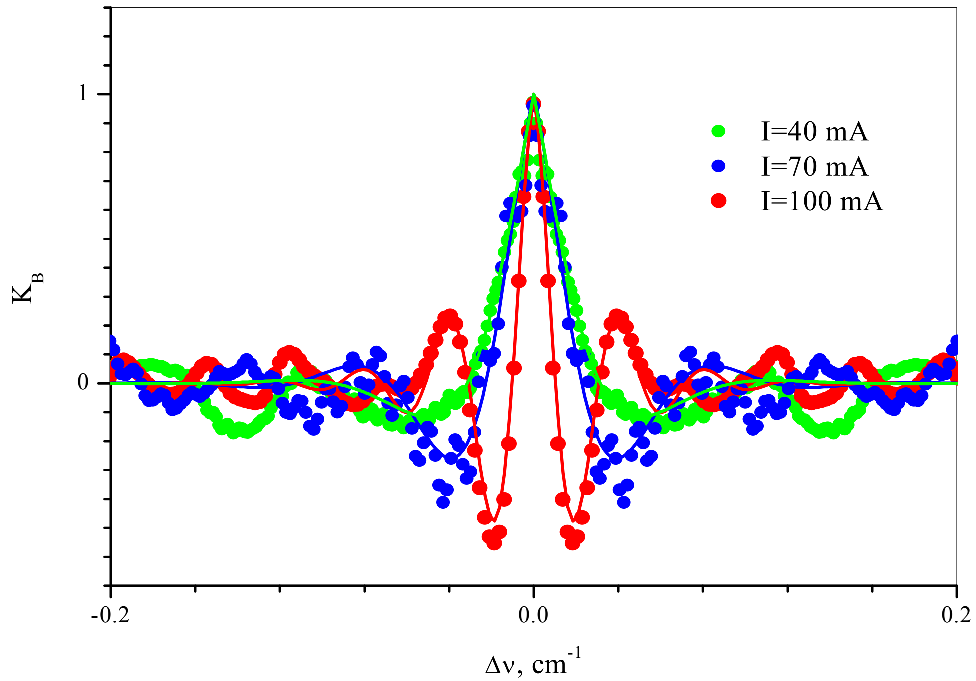
Conclusions:

1. ***B1 and B2 depend on current and temperature.***
2. ***For baseline suppression to 10^{-7} level, current and temperature have to be stable better than 1μA and 10^{-5} K, respectively.***
3. ***Both current and temperature baseline dependences demonstrate similar behavior – same origin.***

Baseline structure due to electrons diffusion

It was one step missed in B1 and B2 - between current and excess carriers concentration inhomogeneities. This step includes electrons diffusion.

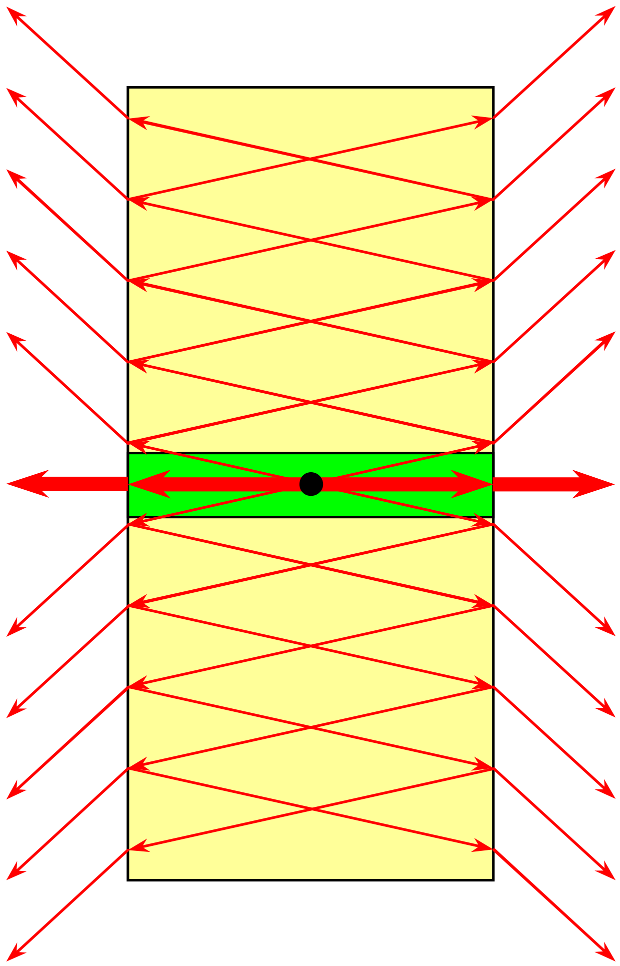




Baseline (left) and its autocorrelation function (right) for different excitation current values. Baseline is normalized to its std.

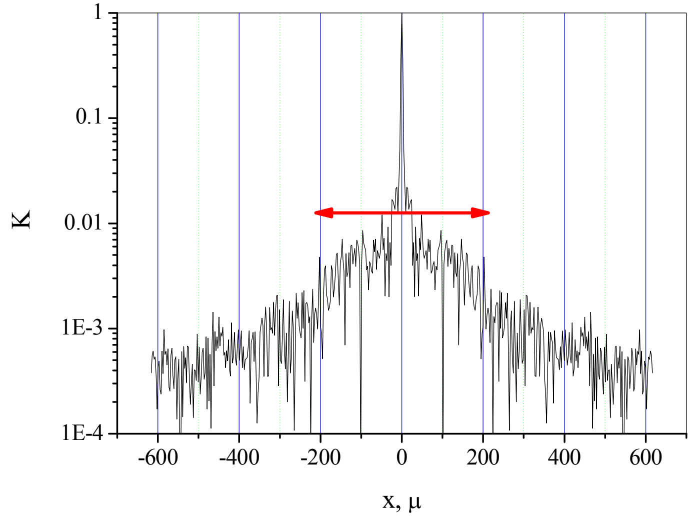
Baseline mechanism: excitation current inhomogeneity.
Next: Autocorrelation function width on right picture is proportional to diffusion length.
Next: Diffusion length is determined by characteristic time.
Next: Characteristic time for electrons in DL is determined by ***relaxation oscillations.***
Next: Higher excitation current – higher relaxation oscillation frequency – smaller characteristic time – smaller diffusion length.

B3 - light scattering inside DL chip

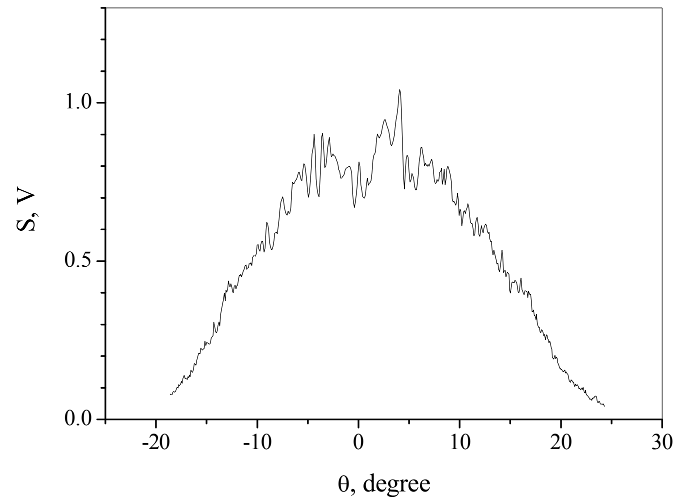


Scattering inside DL chip (Laser components) leads to:

speckle like near field structure on its facet



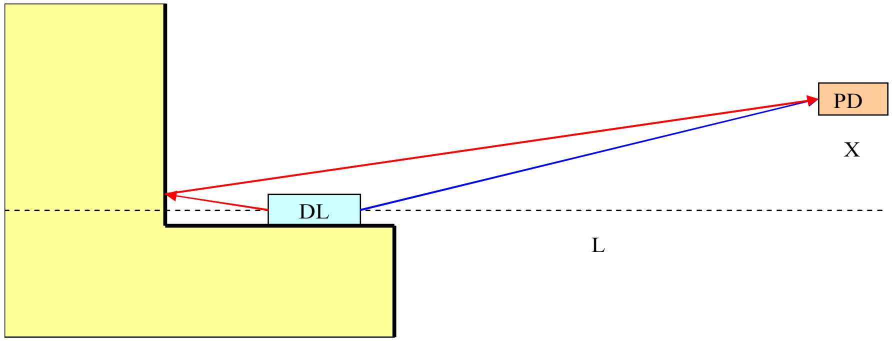
and far field fine structure



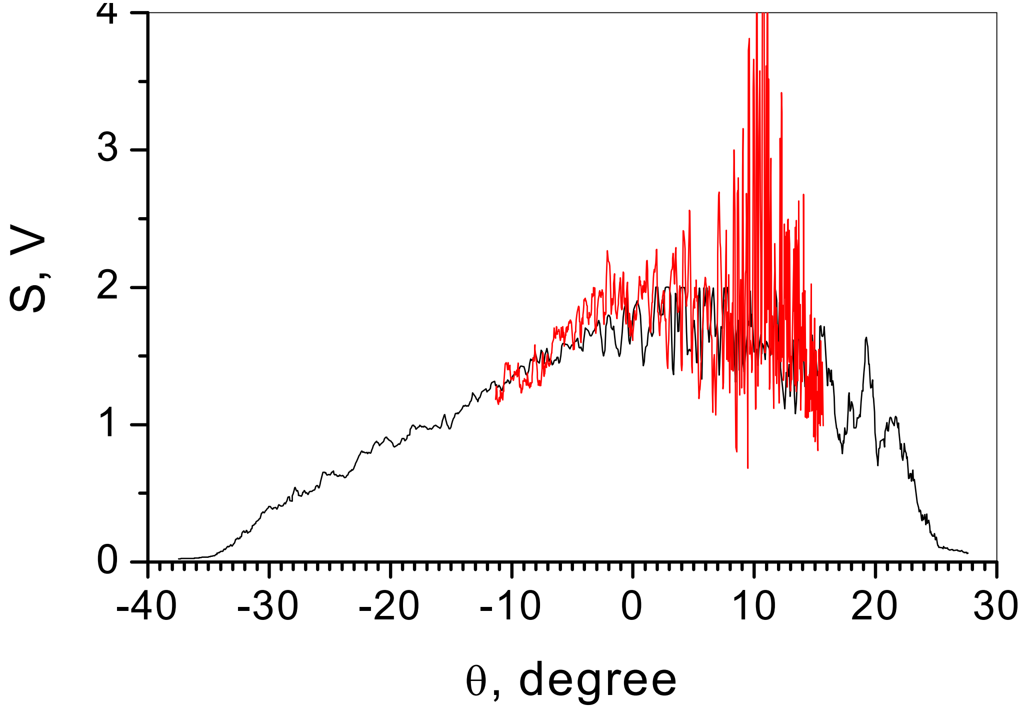
Temperature and current stability requirements are similar to B1 and B2.

<u>Additional requirement: due to far field fine structure no relative movements of TDLS system elements.</u>

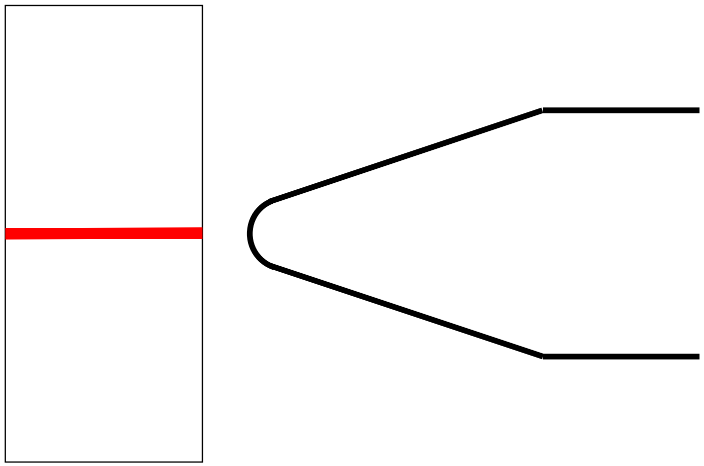
B4 - light scattering inside DL module



Scattering inside DL module causes far field fine structure and B4 baseline.



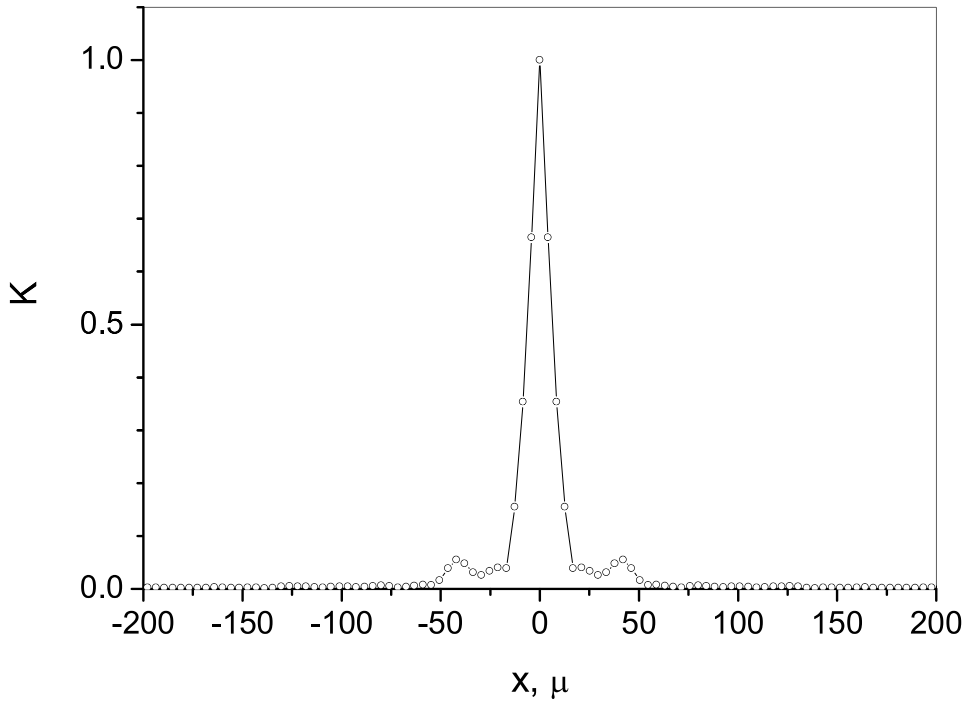
DL (Laser components) far field fine structure due to scattering inside DL module. ***Requirements are similar to B3.***

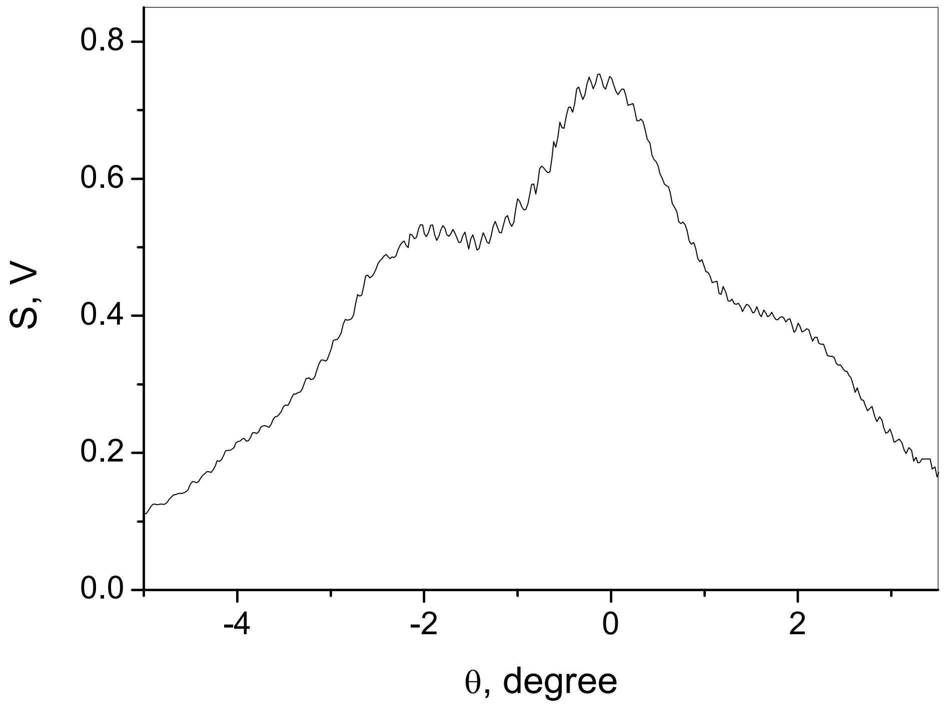


Both B3 and B4 mechanisms are not reproducible and stable.
Solution: DL connection with single mode fiber to collect light only from DL active area and remove scatted light.

B5 - light scattering inside fiber

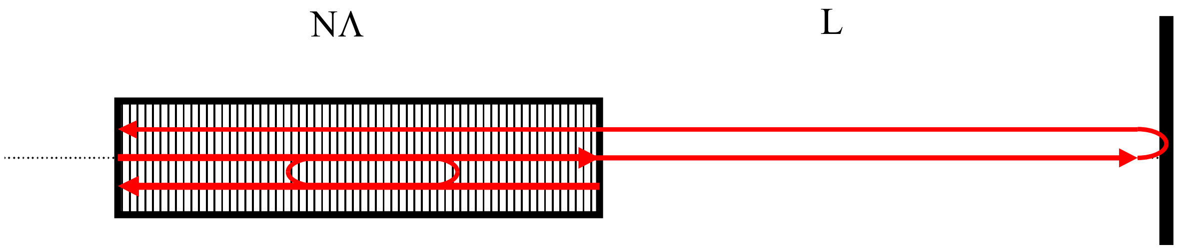
Scattering inside fiber leads to leakage modes and causes near field speckle pattern (left) and far field fine structure (right).



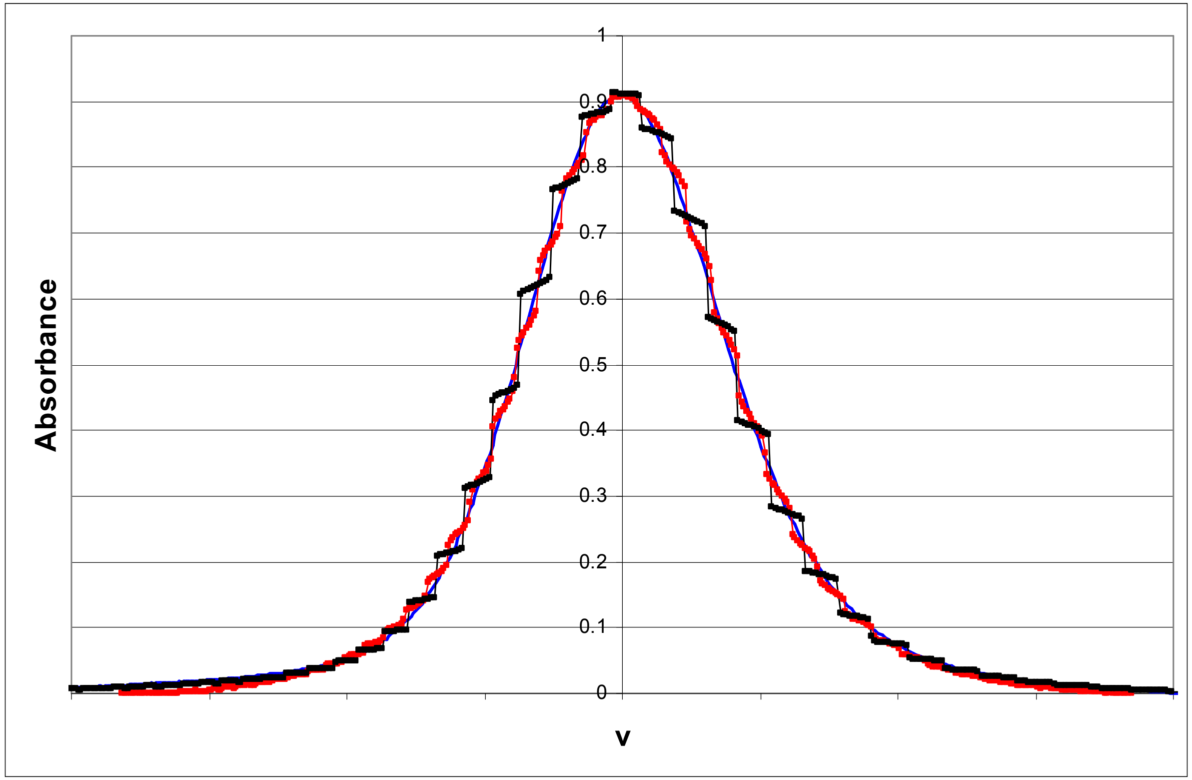


<u>Similar to B3 and B4, B5 is not reproducible and stable. Solution: Use good fibers without scattering inside (no leakage modes). Check your fiber with red light.</u>

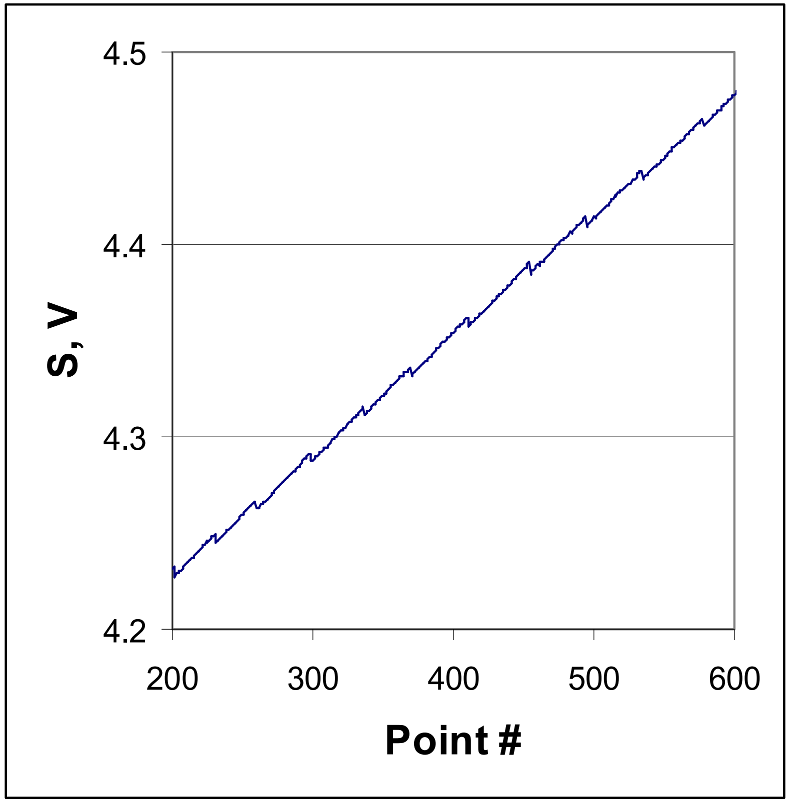
B6 due to optical feedback



Feedback formation in DL with fiber



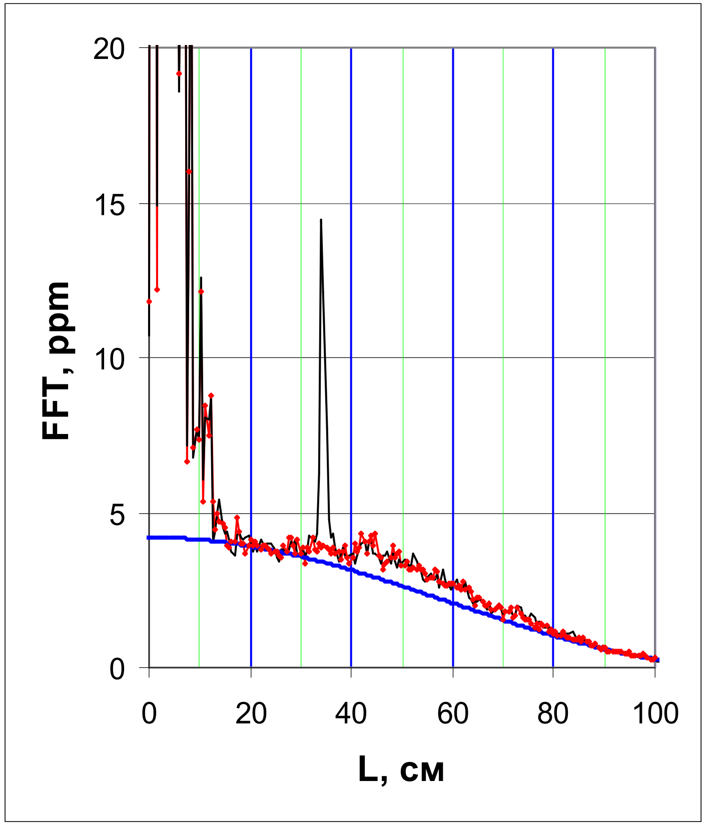
Spectral line recording with DLs having no, small, and high optical feedback – blue, red, and black, respectively.

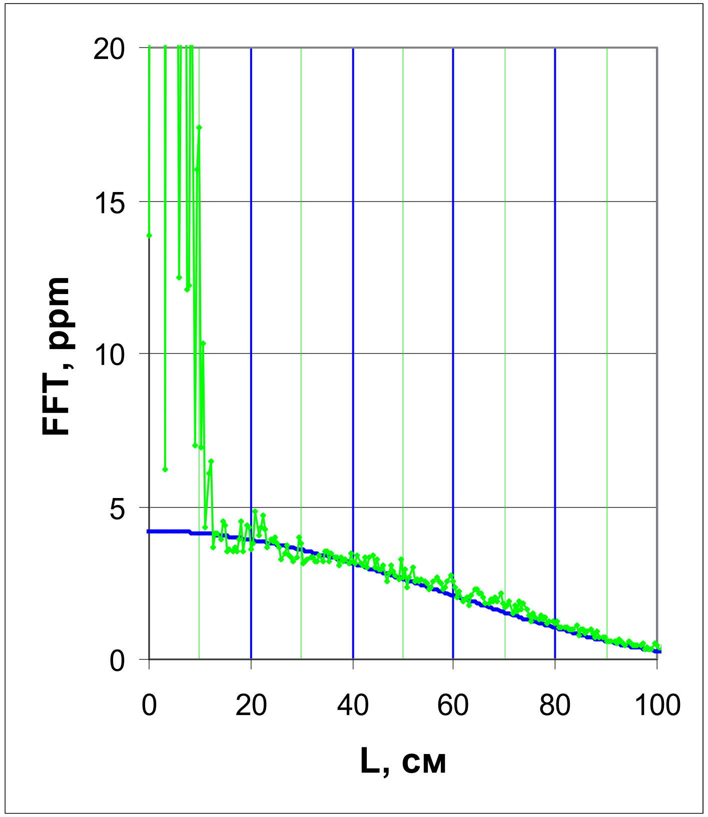


Baseline B6 for high optical feedback is very nonlinear.

B7 - interference in TDLS optical scheme

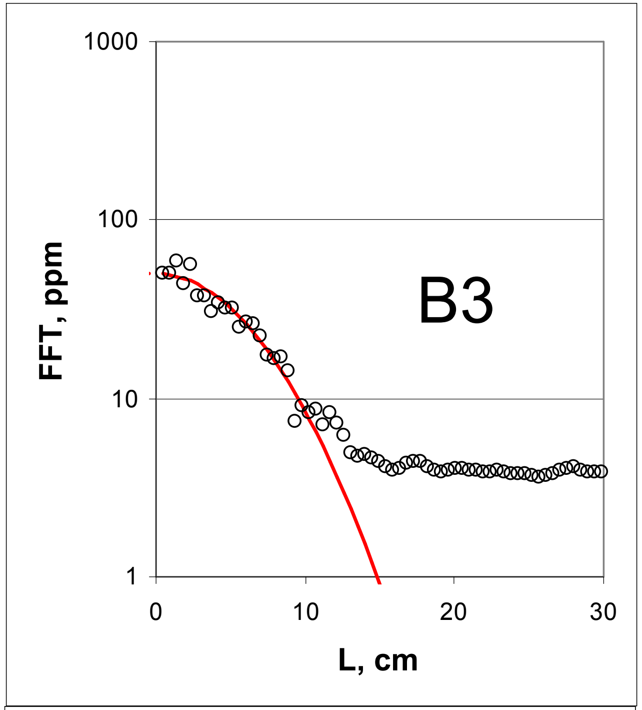
Interference between optical surfaces in TDLS scheme is simple problem: measure distance and remove this interference. Scattering is more complicated problem.



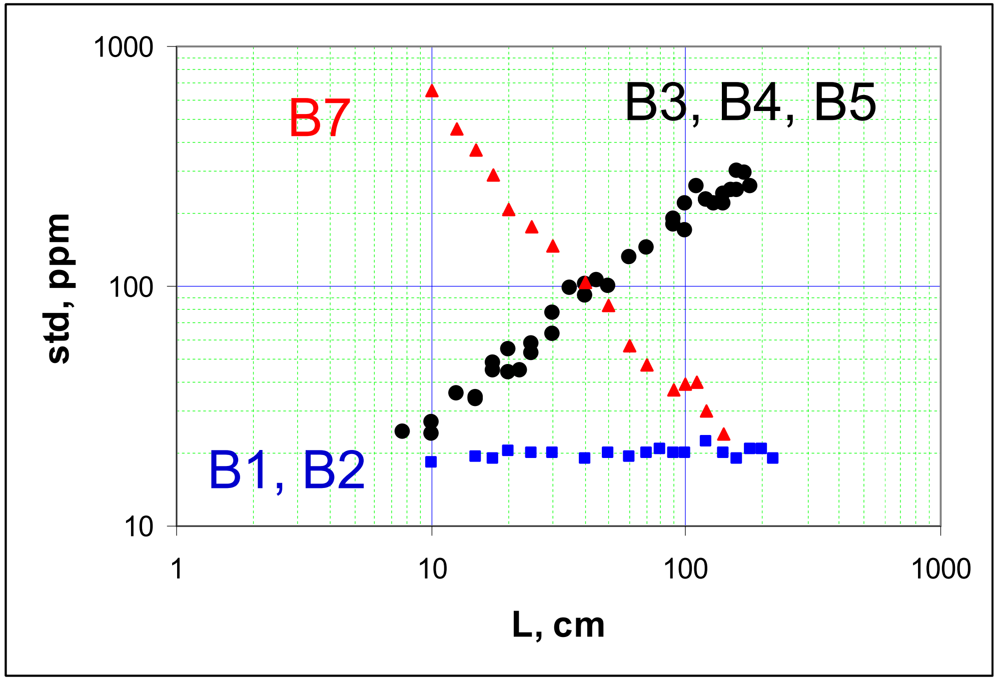


Left parts of FFT spectra are due to fundamental baseline, blue curve – theoretical limit. Black peak is due to white paper installed at 34 cm from DL. Difference between red and blue is due optical feedback because of scattering from optical table. Green was obtained when optical table surface was covered by mirror.

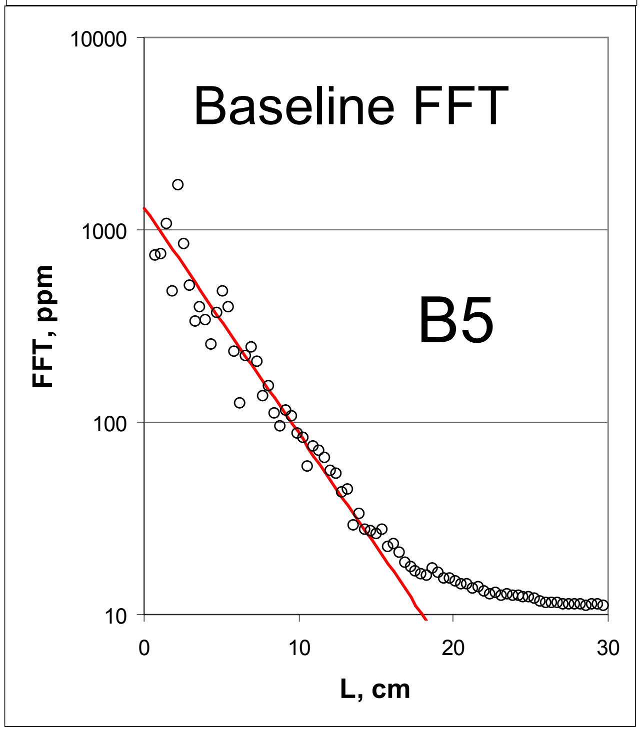
Baselines properties



__Different baseline mechanisms have different properties and behavior.__



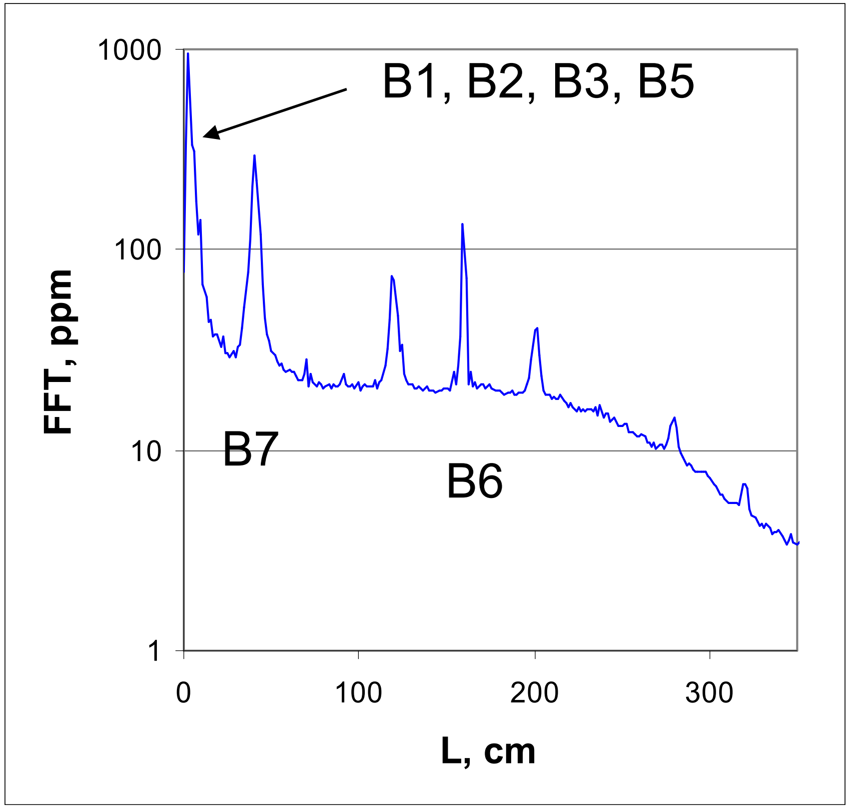
Baseline std as function of distance between fiber output and photo-detector.

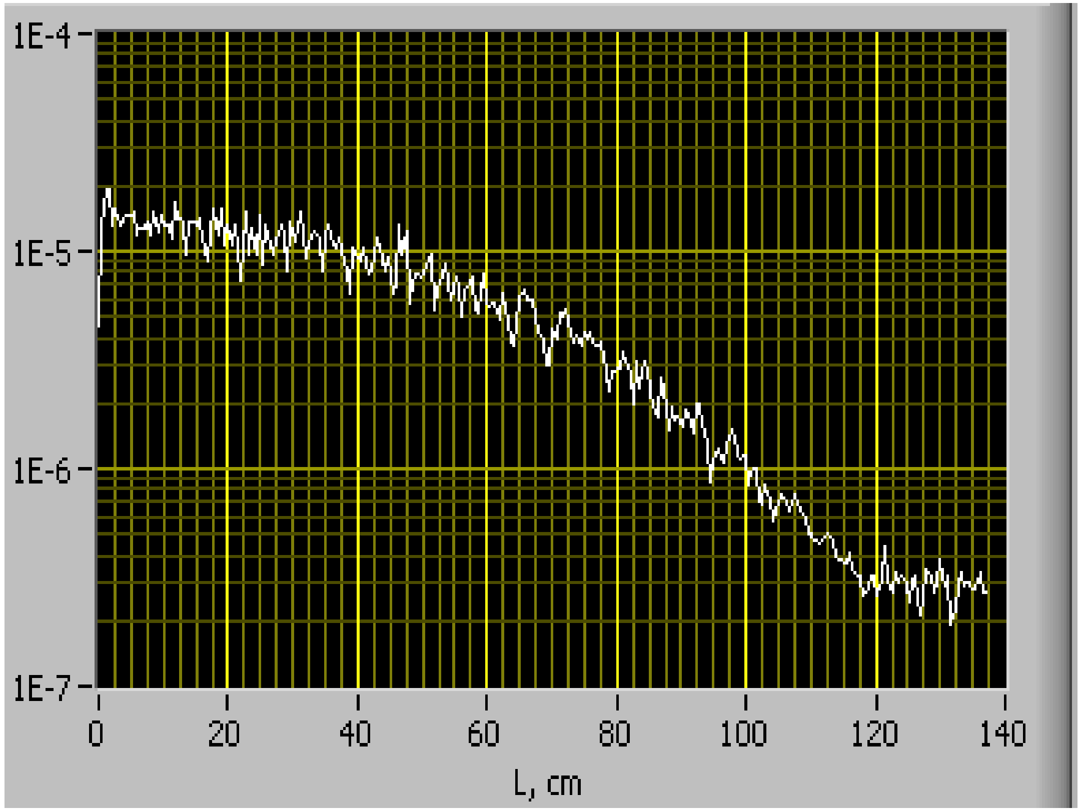


__When baselines properties are investigated, their origins can be identified and baselines suppression strategies can be developed.__

Baseline FFT

Different baseline mechanisms have different properties and behavior.



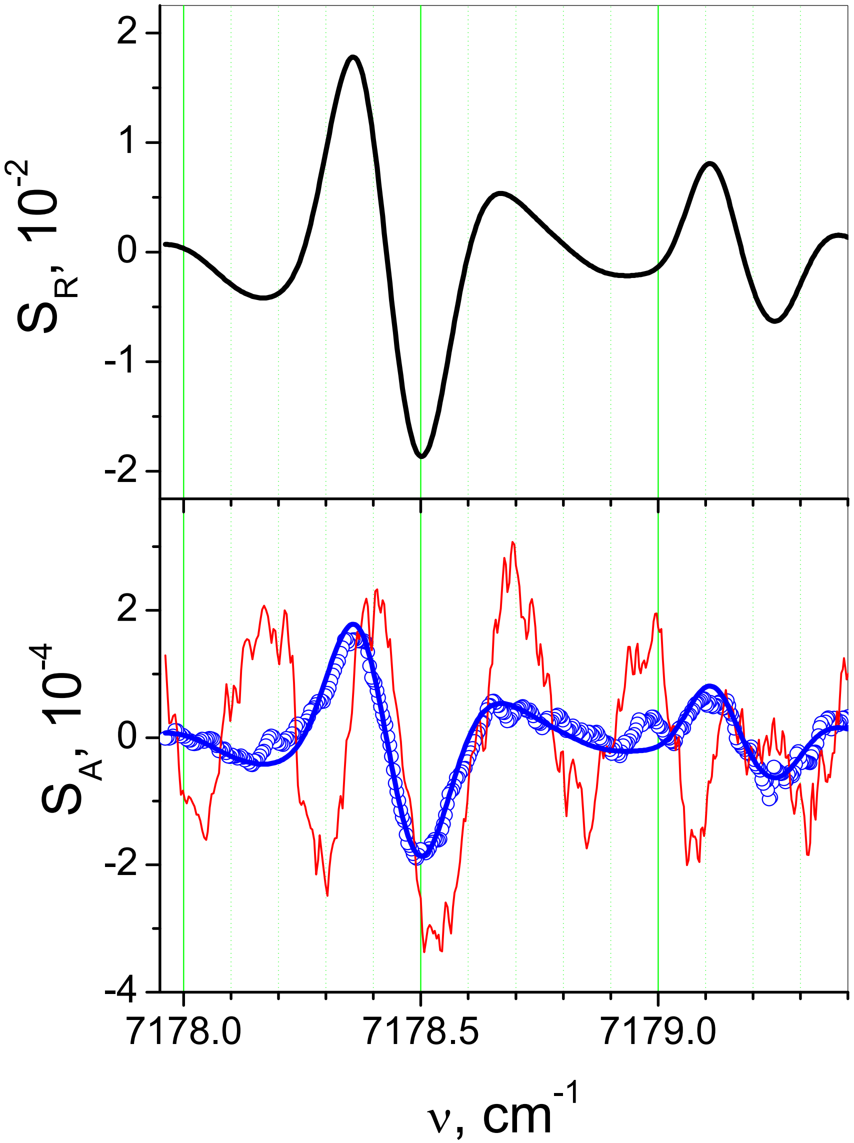


Example of baseline FFT demonstrating all baseline mechanisms considered above. B6 is nonlinear (see above) – one can see its overtone and combinations with other baseline origins.

When baseline origins are identified, algorithms of their suppression can be developed.

<u>Good baseline - no baseline.</u>

Good baseline – no baseline

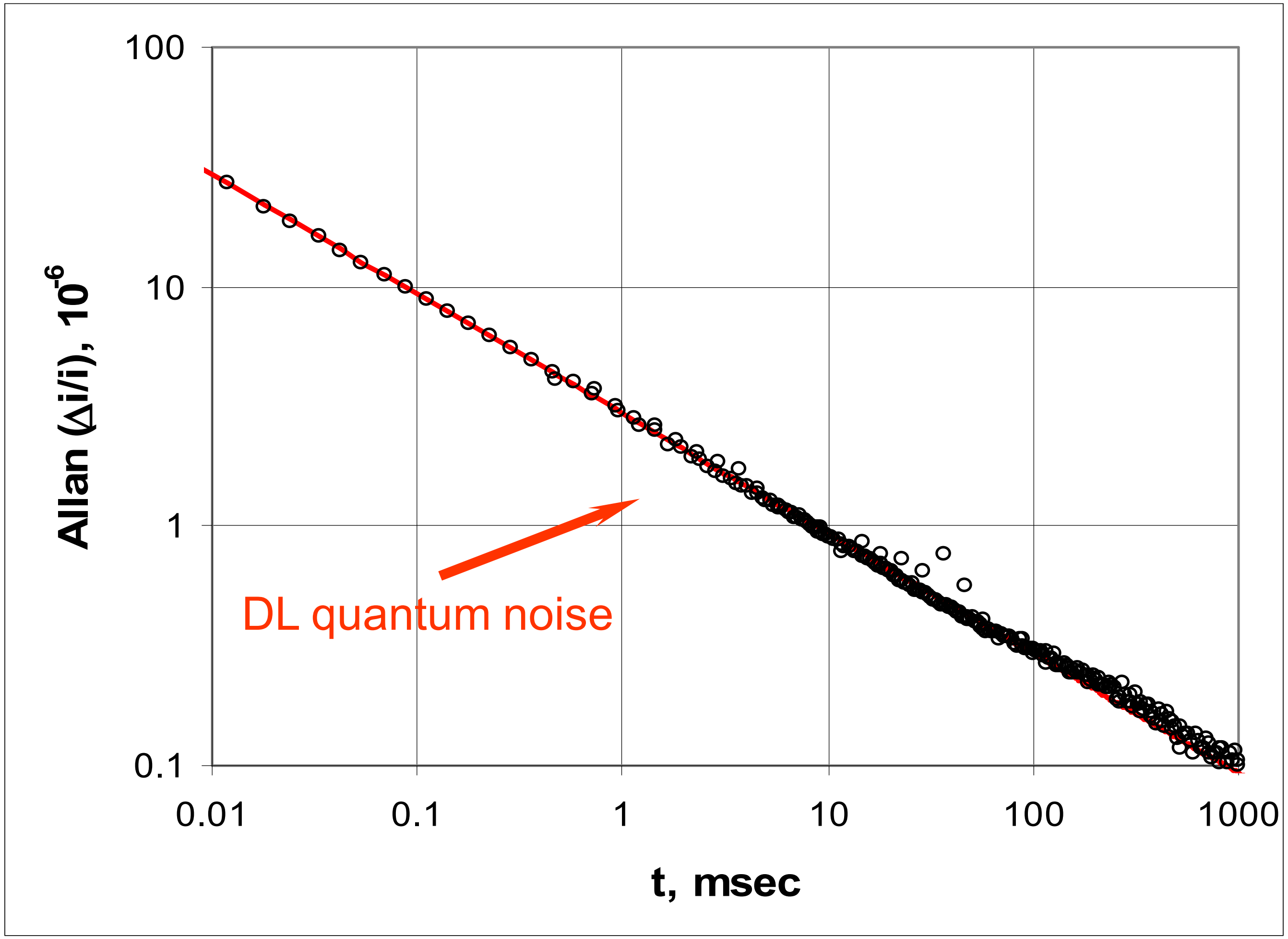


Reference channel signal with two weak water lines.

Red – baseline limited sensitivity (traditional approach), trace atmosphere water lines are below detection limit.
When baseline origins are identified, algorithms of their suppression can be developed. Now for the same DL, weak atmosphere water absorption lines (blue) can be detected with good S/N ratio.

Good baseline – no baseline.

Conclusion



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

Baseline origins were identified, algorithms of their suppression were developed.

Fundamental limit determined by DL quantum noise is achieved.

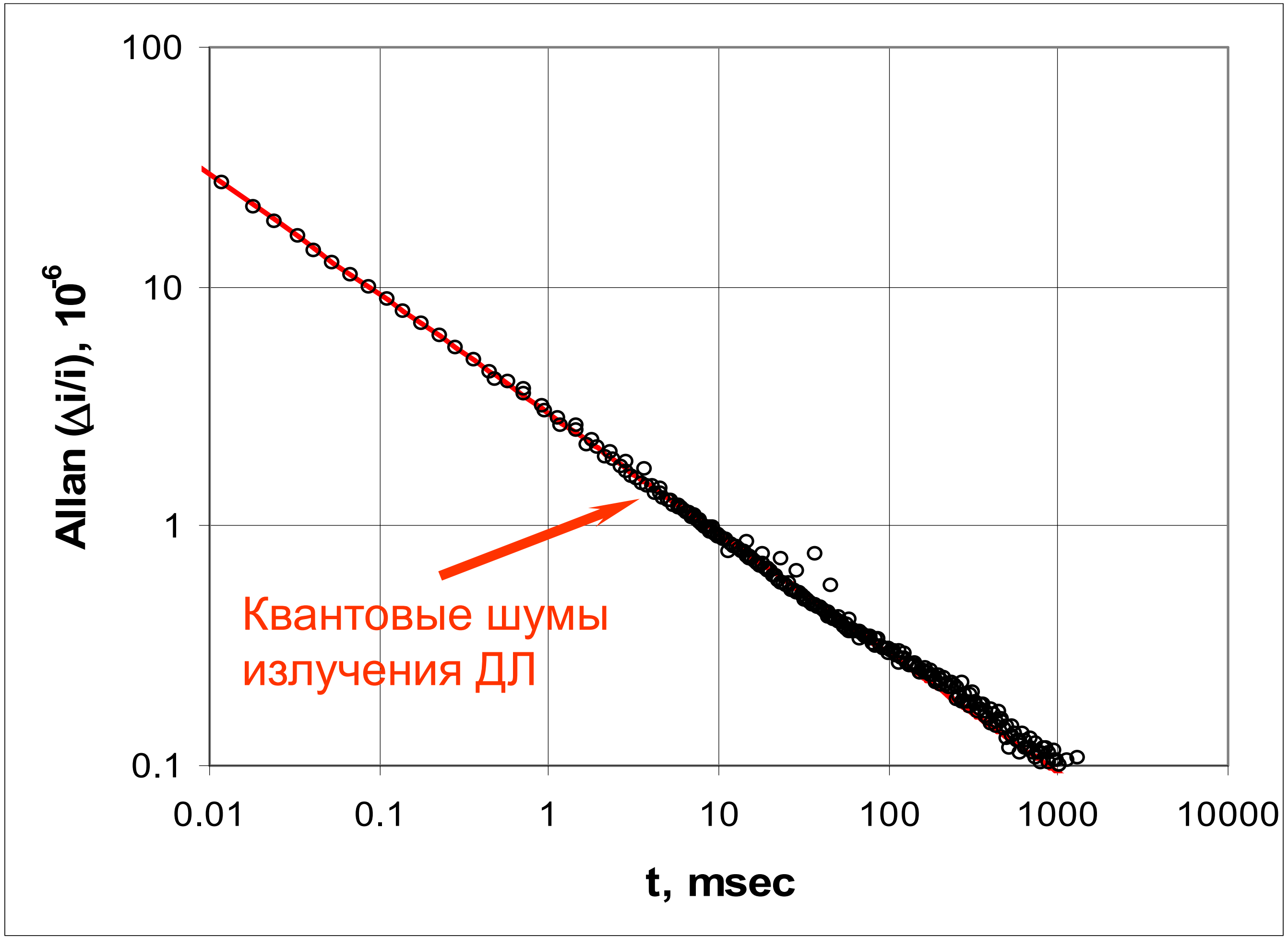
For 1 sec averaging time following noise equivalent values were obtained:

Absorbance - 10^{-7};

Absorption coefficient (500 m) – 2 10^{-12} cm^{-1};

Concentration (HF) – 1 ppt.

Устранение дрейфа

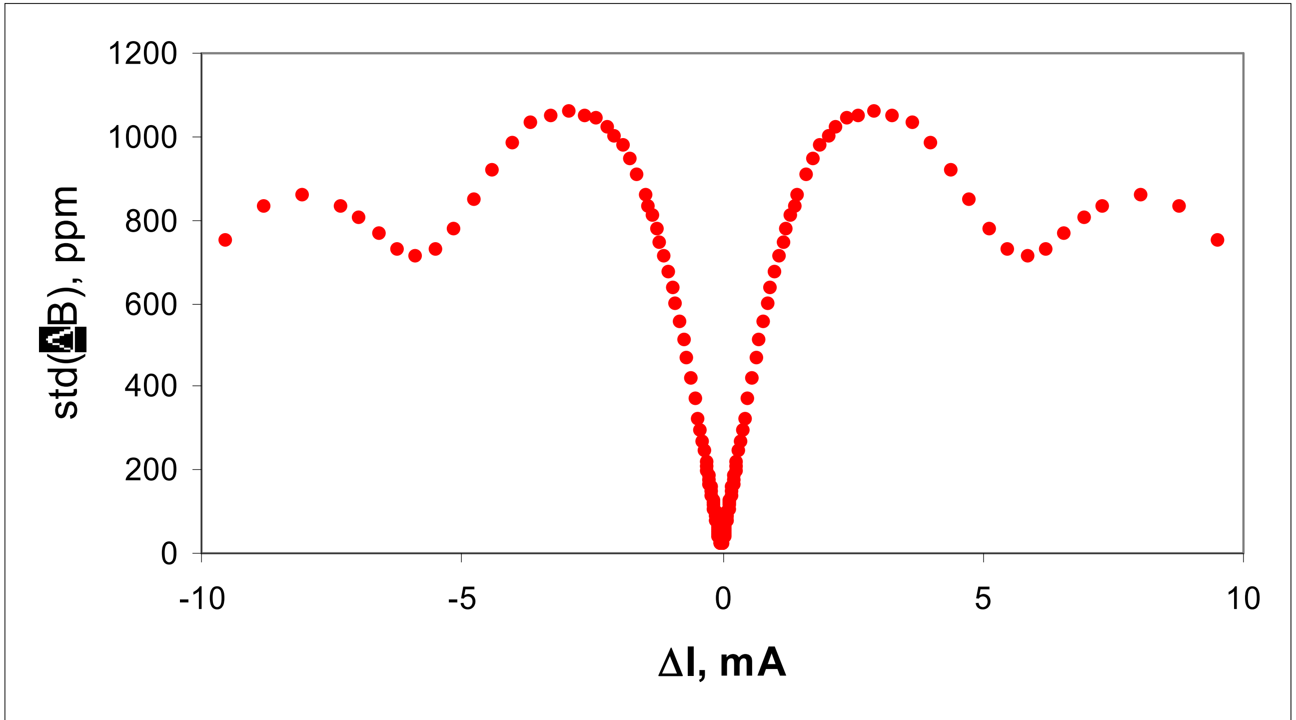


Влияние Фликкерного шума и дрейфа устранены. ***Достигнут фундаментальный предел, обусловленный квантовыми шумами излучения ДЛ.***

Зависимость отклонение Аллана σ_A относительных шумов фототока (минимально обнаружимое поглощение) от времени усреднения и основные типы шумов.

B1 and B2 current dependence

Baseline current dependence: $$std(\Delta B) = std\left[B(I+\Delta I) - B(I-\Delta I)\right]$$



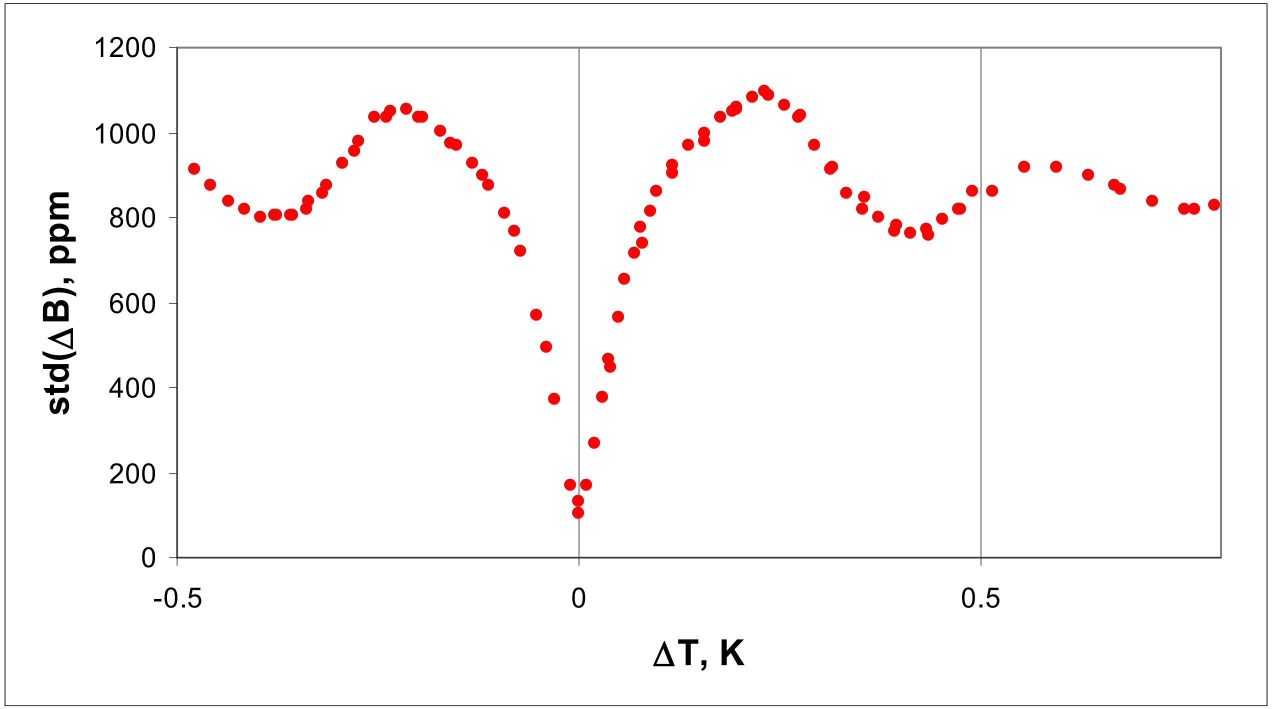
Baseline is equal 0 for modulation ΔI = 0. It increases with modulation - ΔI, achieves maximum, and after several oscillations approaches to constant value.

Conclusions:

1. ***Baselines considered above depends on modulation current amplitude.***
2. ***To achieve required baseline suppression up to 10^{-7} level, current has to be stable better than 1μA.***

B1 and B2 temperature dependence

Baseline temperature dependence: $$std(\Delta B) = std\left[B(T+\Delta T) - B(T)\right]$$

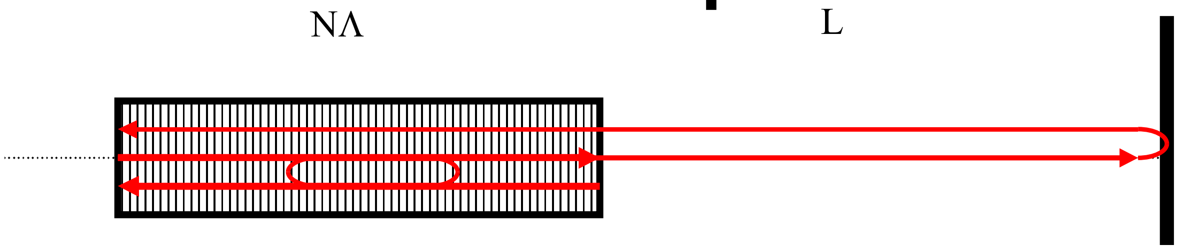


Baseline was recorded at temperature T. Then it was subtracted from further results. $\Delta B = 0$ for $\Delta T = 0$. It increases with ΔT increasing, achieves maximum, and after several oscillations approaches to constant value.

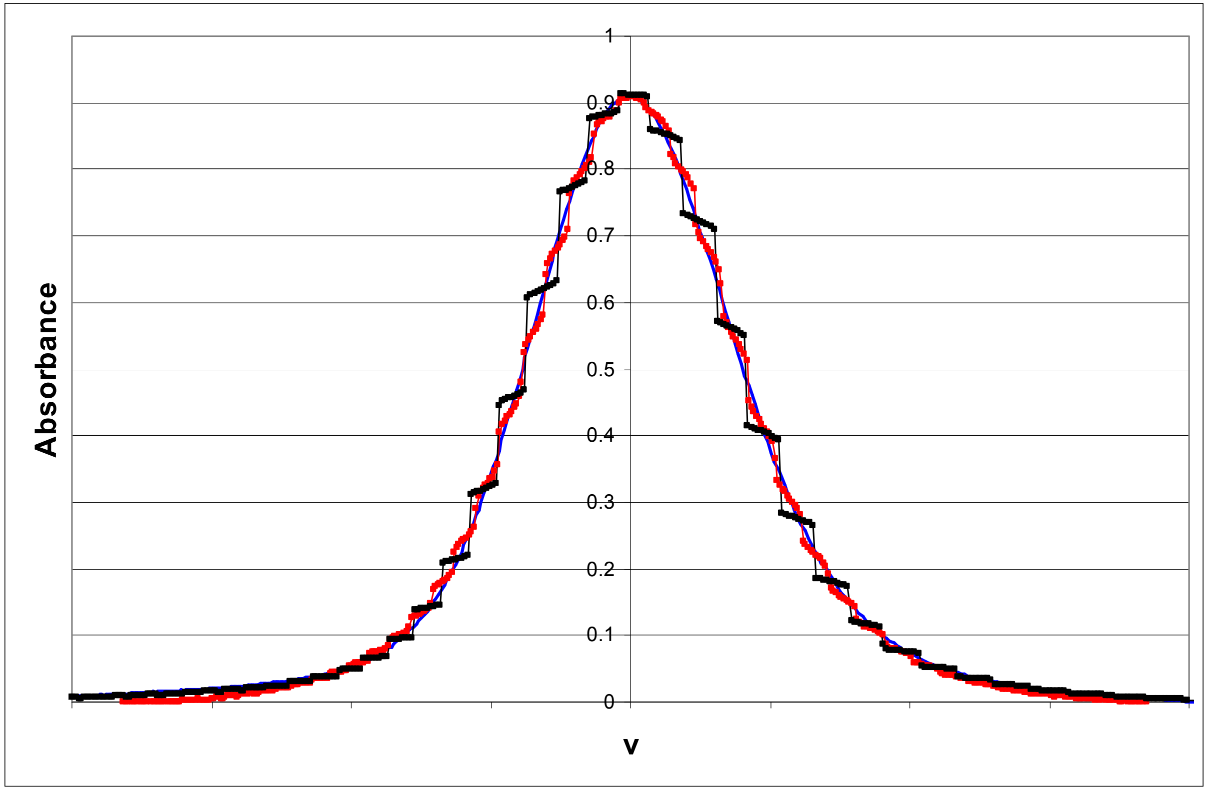
Conclusions:

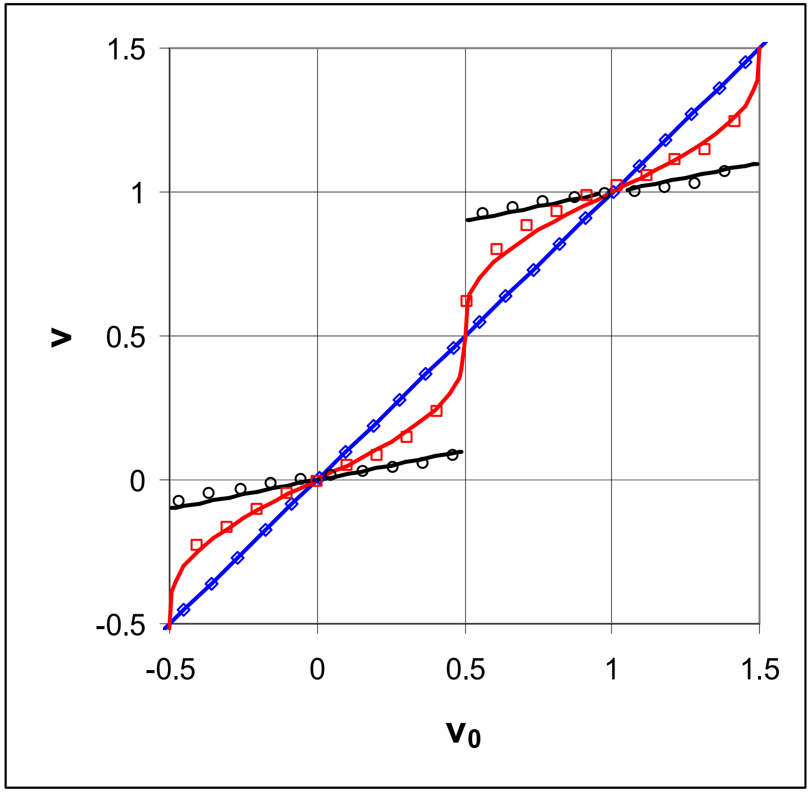
1. ***To achieve required baseline suppression up to 10^{-7} level, temperature has to be stable better than 10^{-5} K.***
2. ***Both current and temperature baseline dependences demonstrate similar behavior – same origin.***

Optical feedback



Feedback formation in DL with fiber

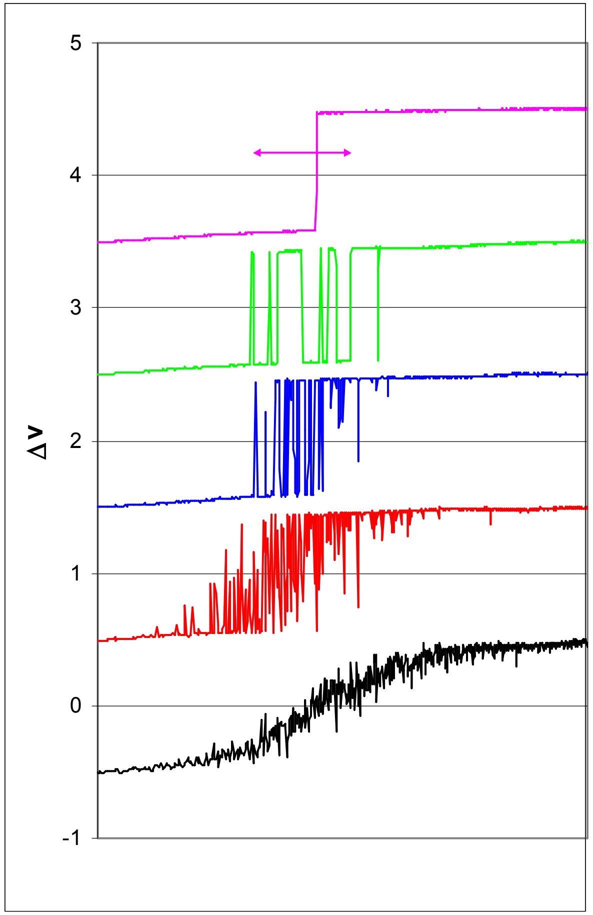




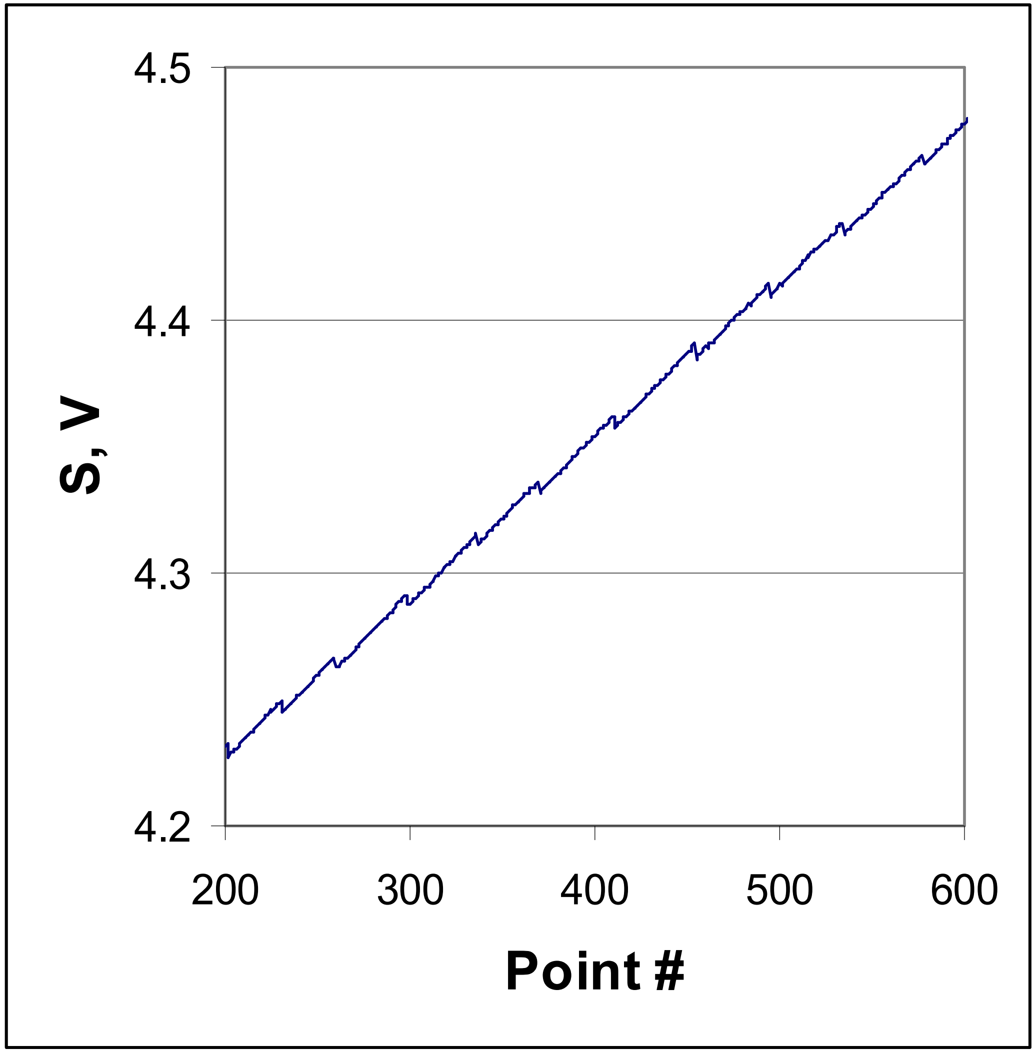
Spectral line recording with DLs having no, small, and high optical feedback – blue, red, and black, respectively.

Modeling of DL frequency tuning for feedback coefficients, corresponding left picture.

B6 due to optical feedback



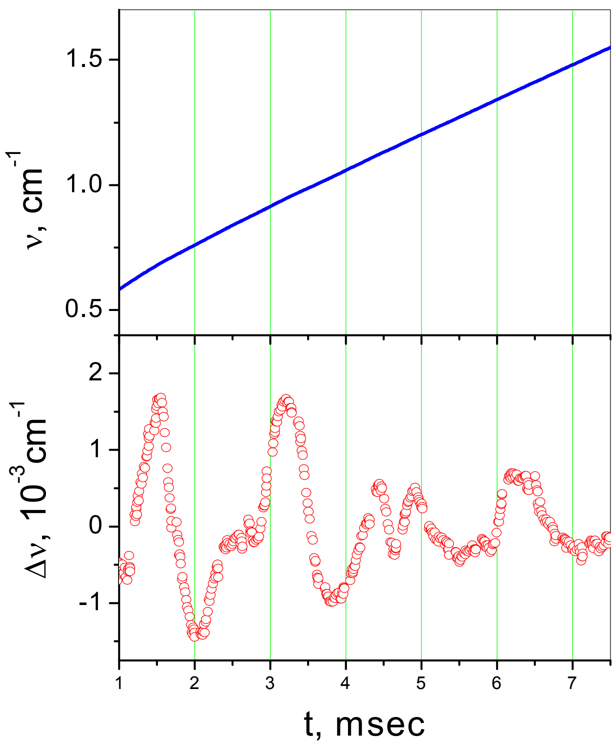
Form of DL frequency mode hopes due to optical feedback depends on feedback - highest corresponds upper curve.



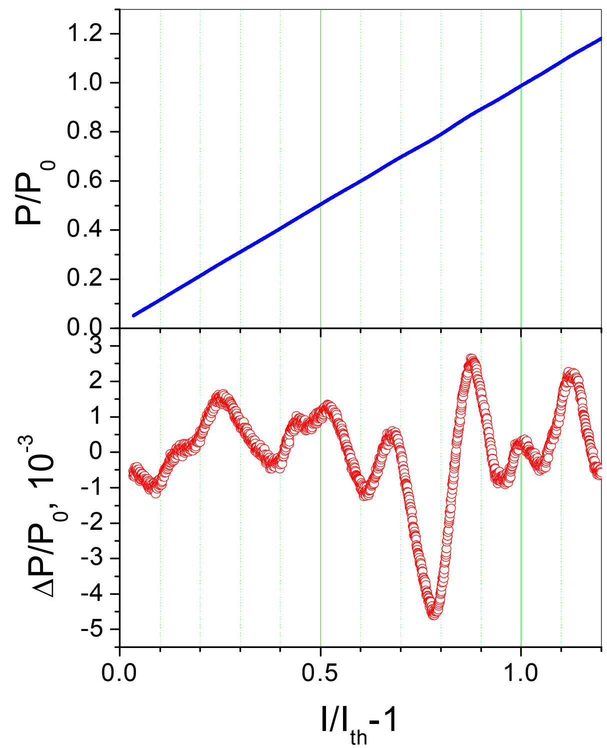
<u>Baseline B6 due to high optical feedback is very nonlinear.</u>

Baseline

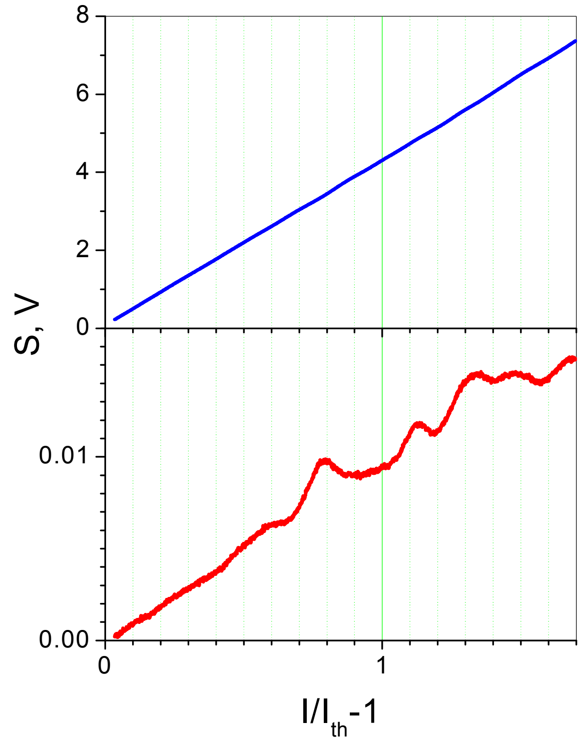
Interaction of electromagnetic wave with different inhomogeneities inside DL leads to small variations of all DL radiation parameters: intensity, frequency, near and far fields patterns – baseline [1].



DL frequency tuning (blue) and its difference from smoothed curve (red) [3].



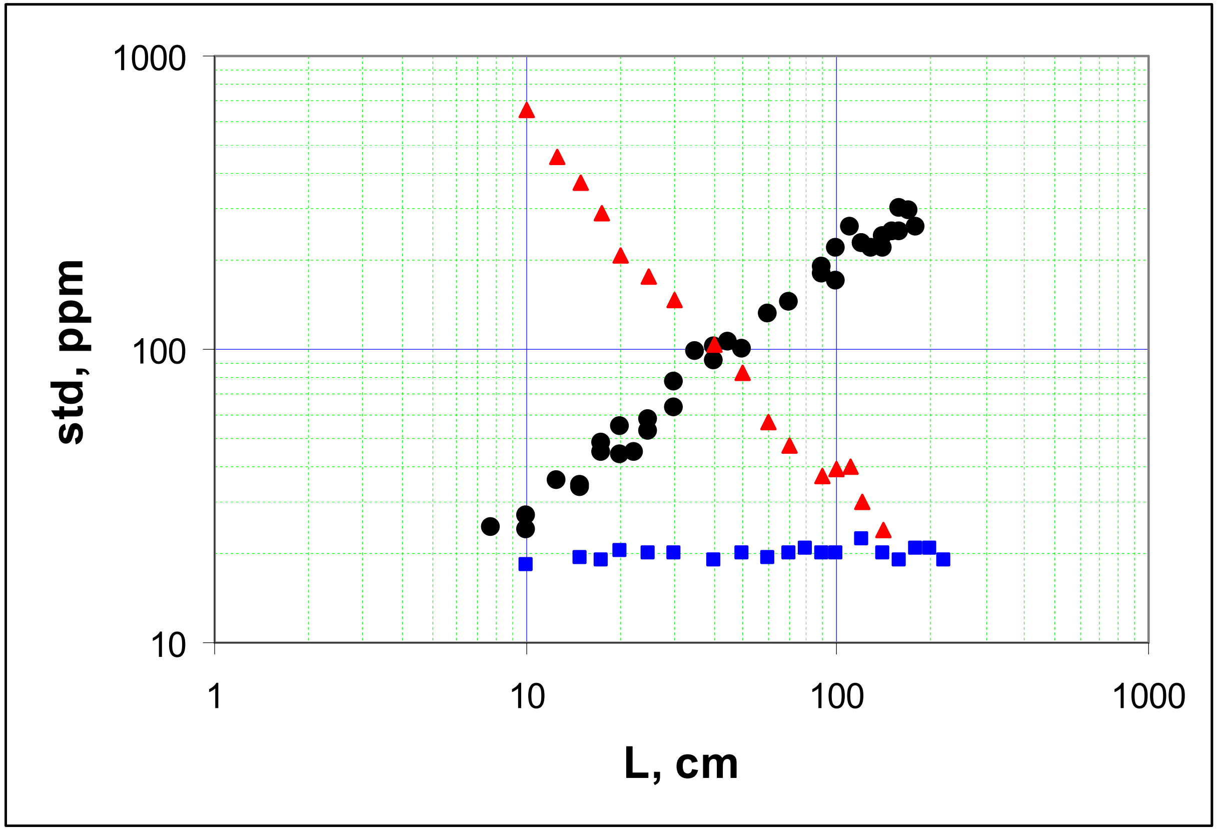
DL power as function of excitation current (blue) and its difference from line (red).



DL far field behavior in diagram center (blue) and out of center (red).

Baseline distance dependence

Different baseline mechanisms have different properties and behavior.



Baseline std as function of L - distance between DL output and PD.

Three different sources of baseline can be observed on this figure.

Blue - baseline due to fundamental mechanisms inside DL (B1 and B2) is constant.

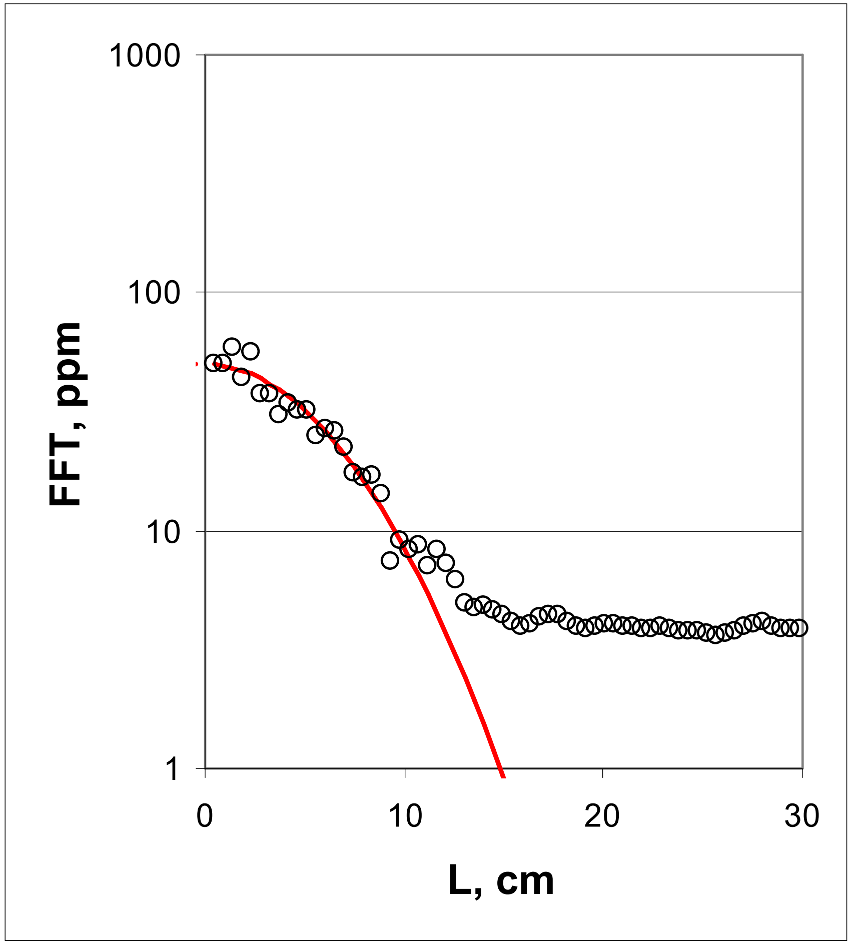
Black - baseline due to scattering inside DL or fiber (B3 and B5) is proportional to L.

Red – baseline due to interference or scattering inside TDLS optical scheme is reverse proportional to L.

<u>When baseline origin is identified, baseline can be experimentally suppressed.</u>

B3 and B5 baselines FFT

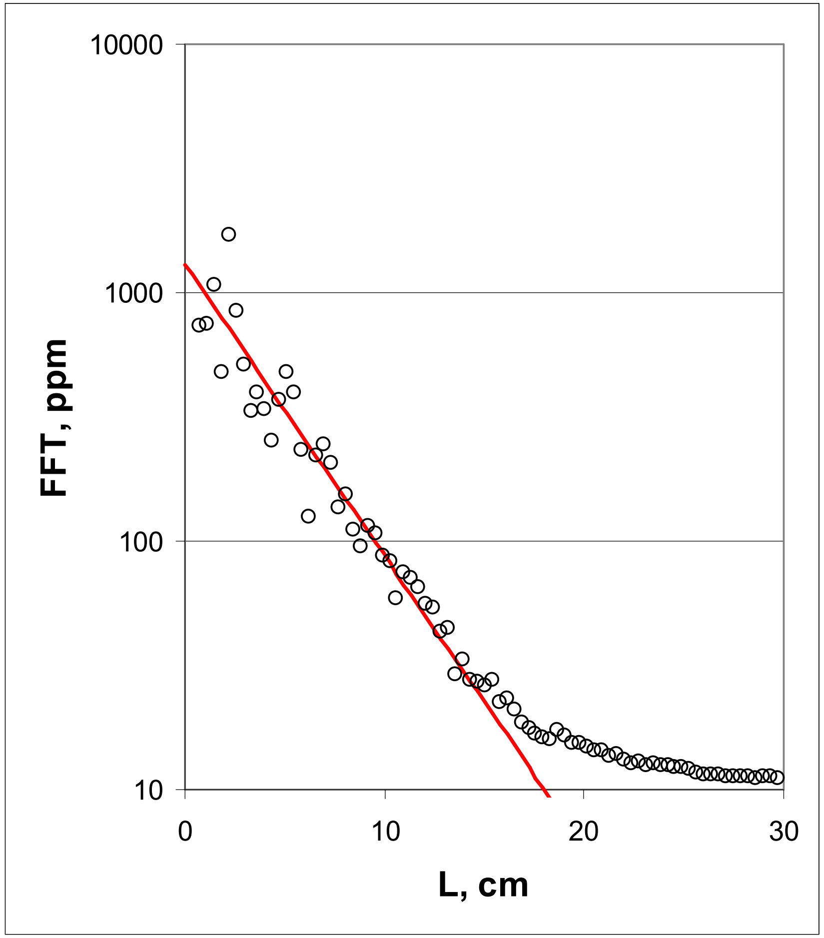
Different baseline mechanisms have different properties and behavior.



Baseline FFT

Left – B3

Right – B5



<u>When baseline FFT is measured, baseline mechanism origins can be identified.</u>