DL Frequency Tuning and Modulation by Current

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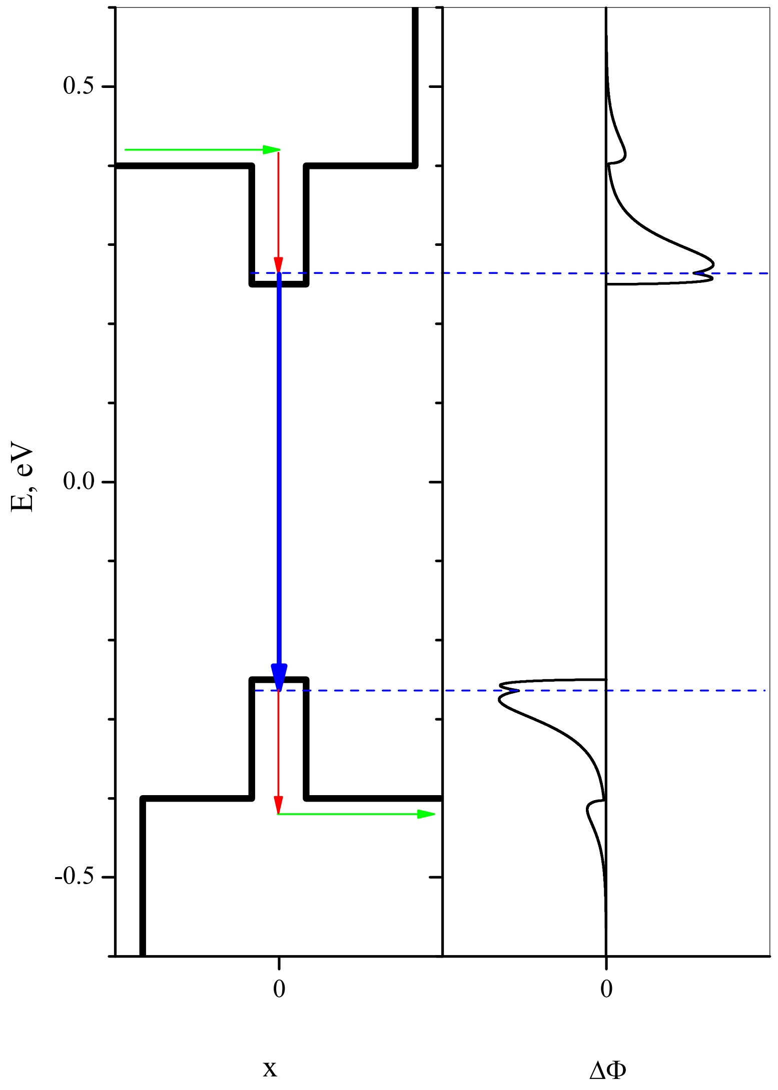
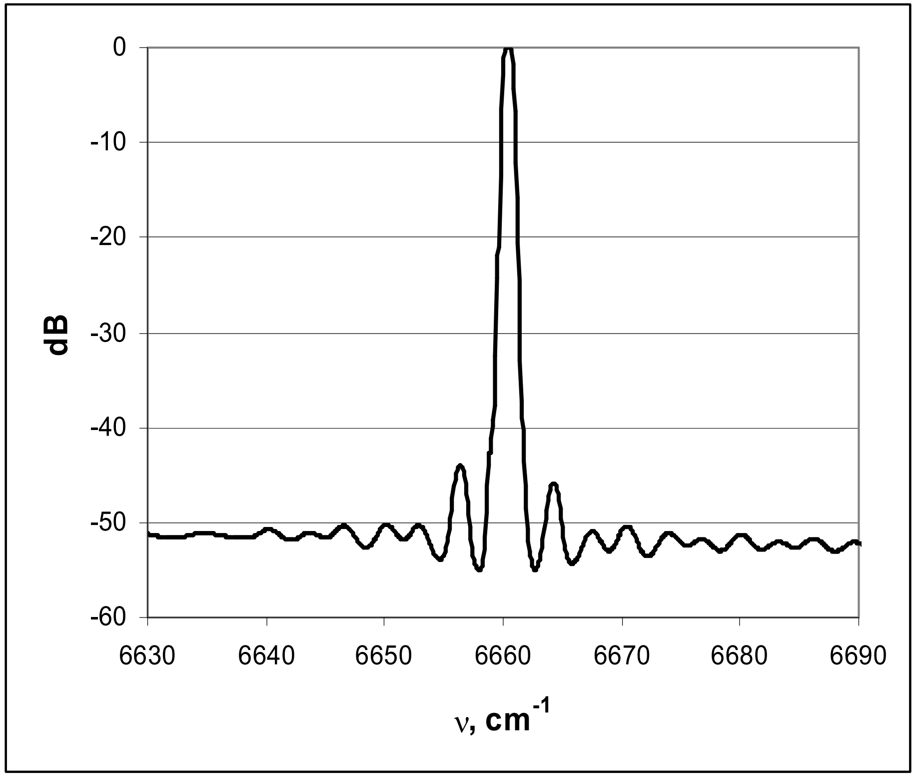
Diode Laser Operation



Right graph - non-equilibrium electrons energy distribution - ΔΦ(E) inside quantum well. Electrons on the left side of quantum well have thermal distribution. Injection of these electrons in quantum well will produce non-equilibrium electrons energy distribution in quantum well (upper pick in right graph). Next important step of DL operation is thermolization of these non-equilibrium electrons (red vertical arrow in left graph). This process takes place mainly through interaction between non-equilibrium electrons and optical phonons (~ 10^{-12} sec). ***Electrons excess energy will be transferred to semiconductor lattice temperature.***

After it, electrons have near thermal distribution in quantum well. The same processes take place in the diagram lower part. Moreover, due to electric charge conversation law one can say that ΔΦ integral over E has to be equal to 0. Now inverse population can be easily observed leading to stimulated emission (thick blue vertical arrow in left graph).

DL spectrum



Example of DL spectrum obtained with spectral analyzer. The spectrum contains central coherent peak demonstrating single frequency operation. However, spectral fine structure can be also observed. The center part of fine structure (two satellites) is due to DFB (diffraction on grating). The variations in broader spectral range are determined by DL resonator formed by DL chip facets with antireflection coating (reflection is not 0).

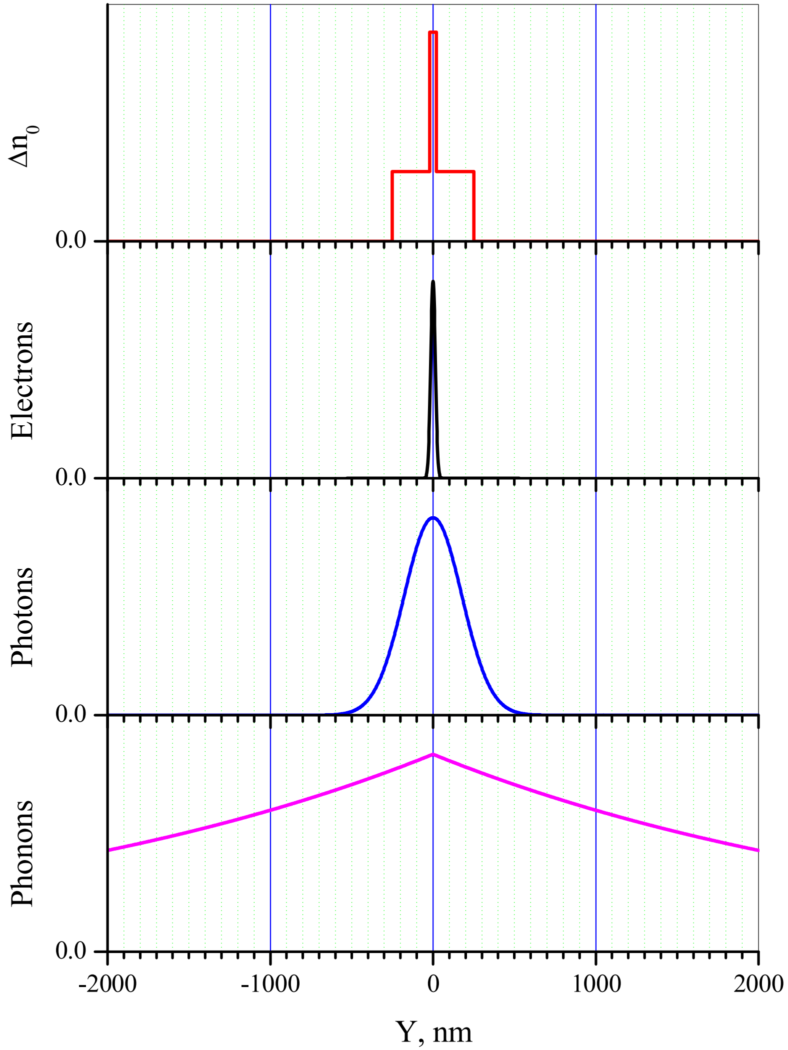
Central peak frequency depends on temperature - T and excitation current – I.

$$\nu\big(t, I(t), T\big) = \nu_0 + \left(\frac{\partial \nu}{\partial N_c}\right)_T N_c\big(I(t), T\big) + \left(\frac{\partial \nu}{\partial T}\right)_{N_c} \big[T - T_0 + \Delta T(t, I(t), T)\big]$$

DL frequency is determined by electrons (N_c) and phonons (T) subsystems of DL.

DL ⊥ p-n junction

DL behavior is determined by three subsystems: electrons, photons, and phonons.



Spatial distribution ⊥ p-n junction of

Reflective index due to heterostructure with double confinement;

Excess electrons (current) - quantum well

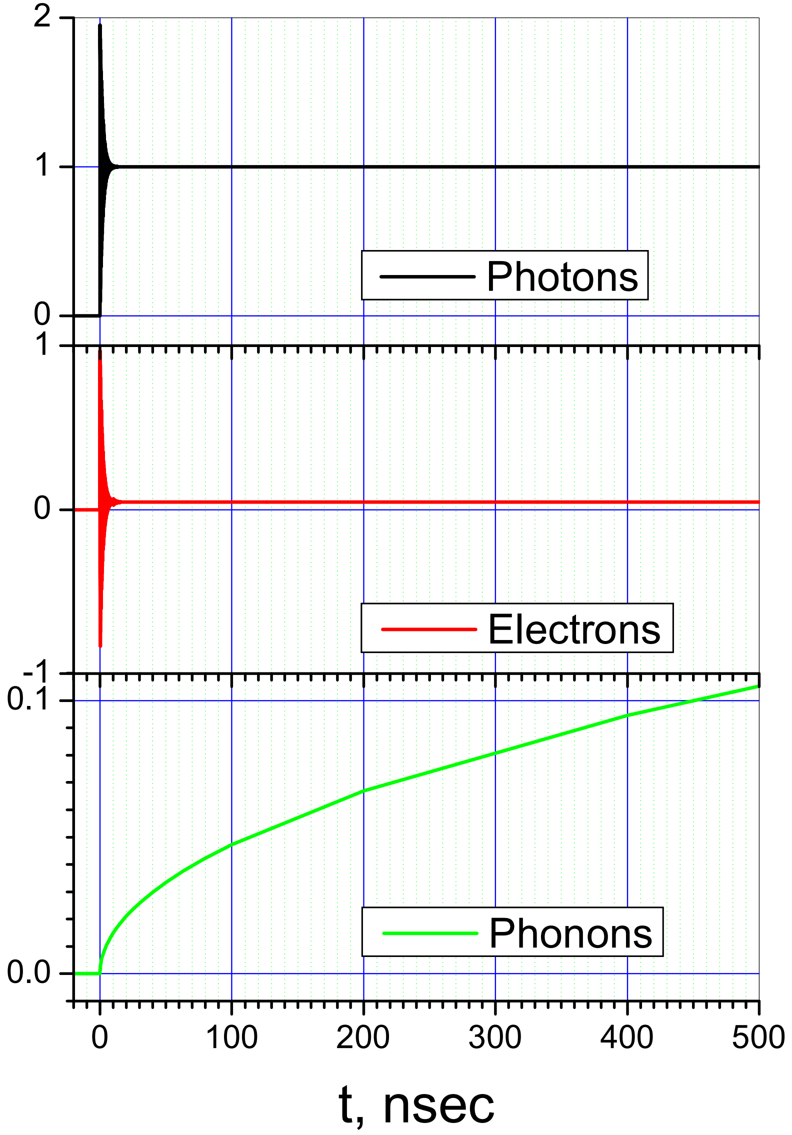
Photons (light) – second confinement

Phonons – temperature diffusion.

Light interacts with electrons distribution integral and local temperature at Y = 0.

Time domain

DL subsystems response on stepwise current pulse.



Photons (Intensity): relaxation oscillations during few nsec, then constant = 1.

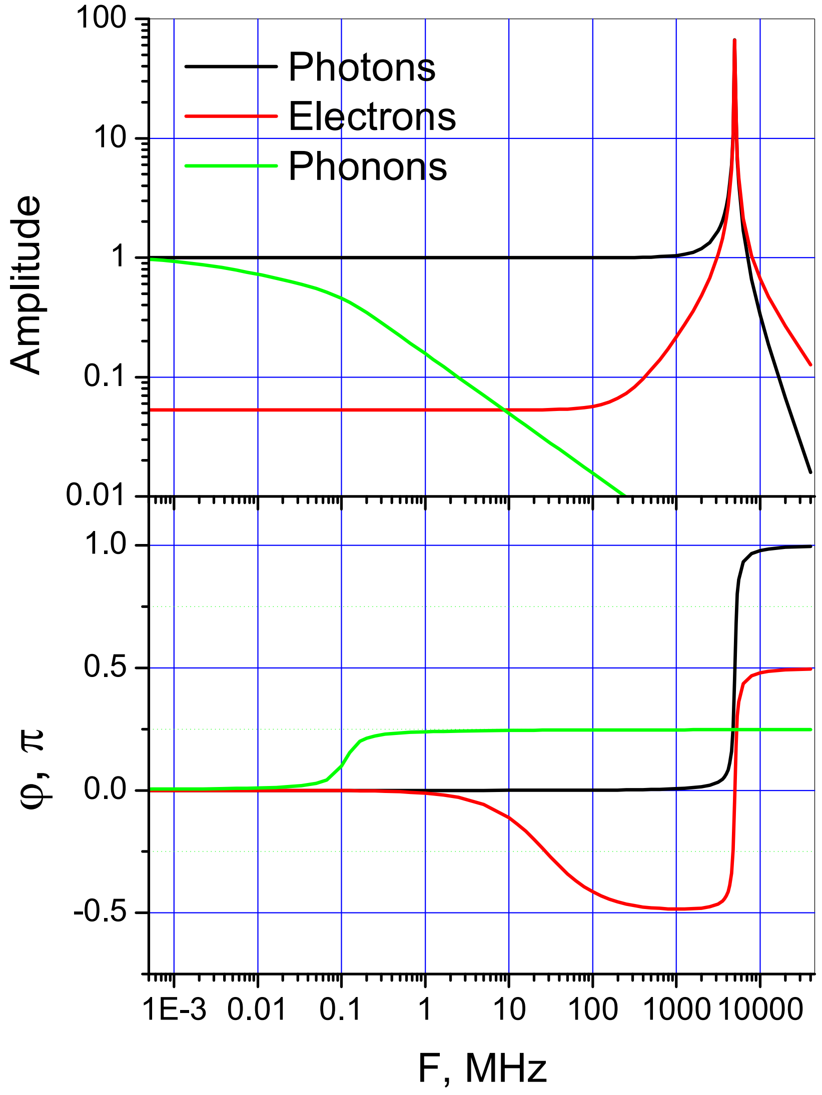
Electrons (Frequency): relaxation oscillations during few nsec, then small constant due to quantum nature of light (spontaneous emission).

When photons and electrons achieved constant value ***Temperature (frequency)*** starts changing and up to 10 μsec follows:

$$\Delta T(t) = I_0 2 A_1 \sqrt{t}$$

Frequency domain

DL subsystems response (amplitude and phase) on harmonic current modulation.

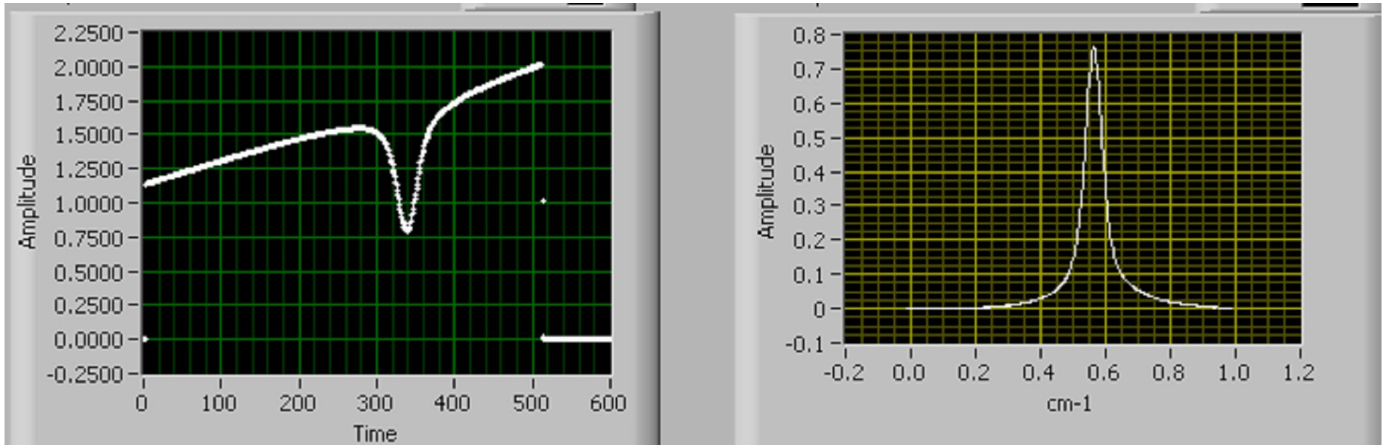


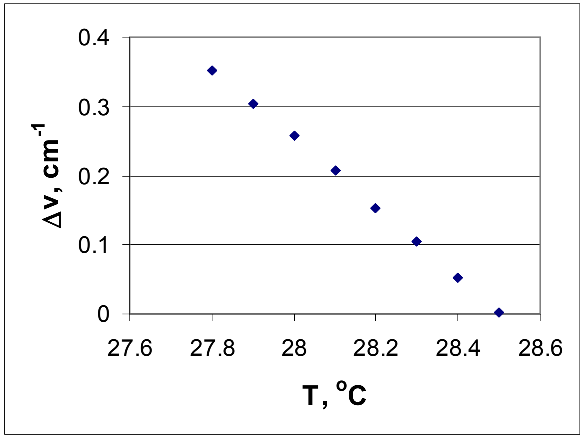
Photons (intensity) follow current modulation. In vicinity of relaxation oscillations phase changes from 0 to π. ***Electrons (frequency)*** follow current modulation up to 1 MHz, then phase shift approaches -π/2. In vicinity of relaxation oscillations phase changes from -π/2 до +π/2. ***Phonons (temperature)*** follow current modulation up to 100 kHz, then phase shift approaches +π/4. For modulation frequency range 100 kHz – 100 MHz being of interest for TDLS temperature follows:

$$\frac{\partial T(f)}{\partial I} = \frac{A_1}{2\sqrt{f}}[1+i]$$

DL frequency measurement

Program interface to measure DL frequency tuning. In present case DL was excided by trapezianform current pulse. Doppler water vapor line can be observed. Left – time of the line observation measurement (DL frequency time dependence). Right – frequency measurement (after DL tuning curve was calibrated by known FP).

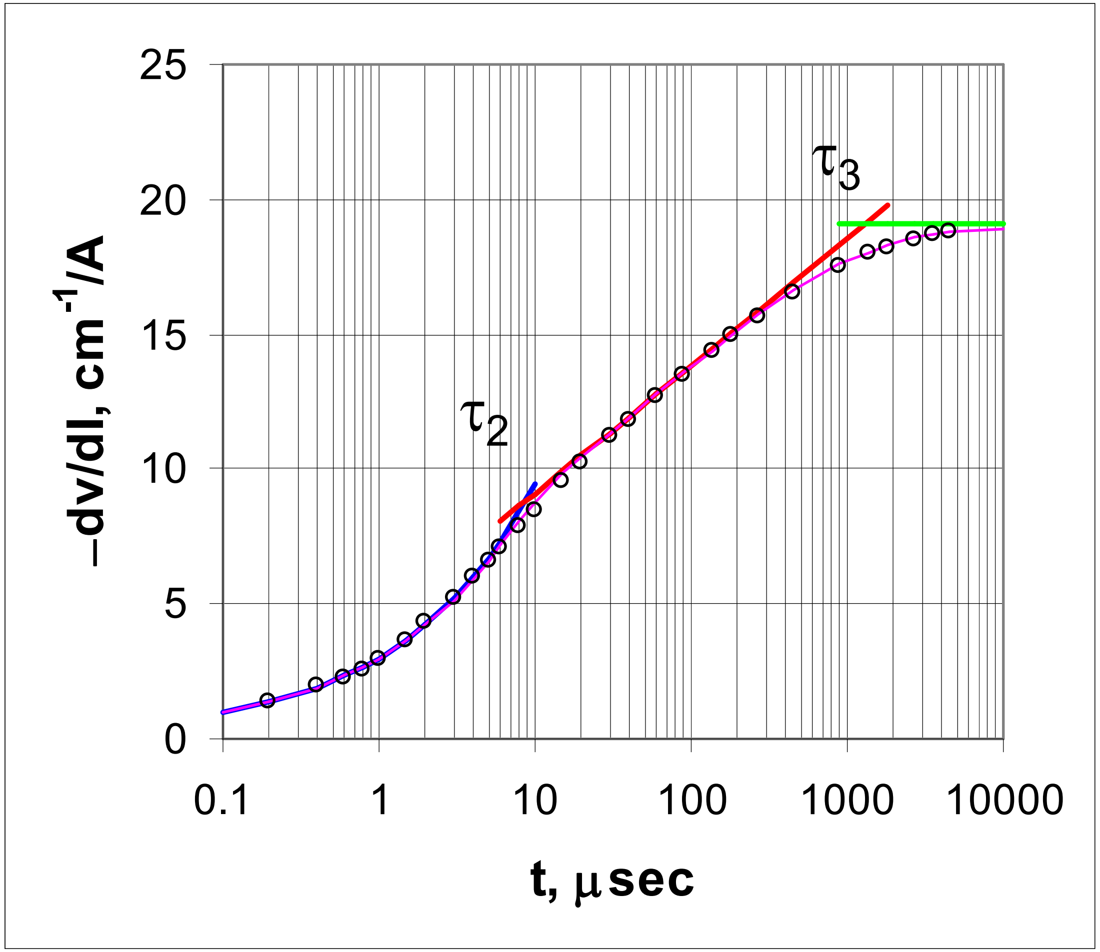




Example of DL frequency temperature dependence (NEL SN 625568). Using this data DL frequency temperature tuning coefficient was determined:

$$\frac{\partial \nu}{\partial T} = -0.502 \frac{\mathrm{cm}^{-1}}{\mathrm{K}}$$

DL frequency temperature tuning



Experiment (black open circles): time dependence of DL (excited by stepwise current) frequency tuning.

Based on DL geometry and temperature diffusion equations time dependence of DL active area heating can be determined:

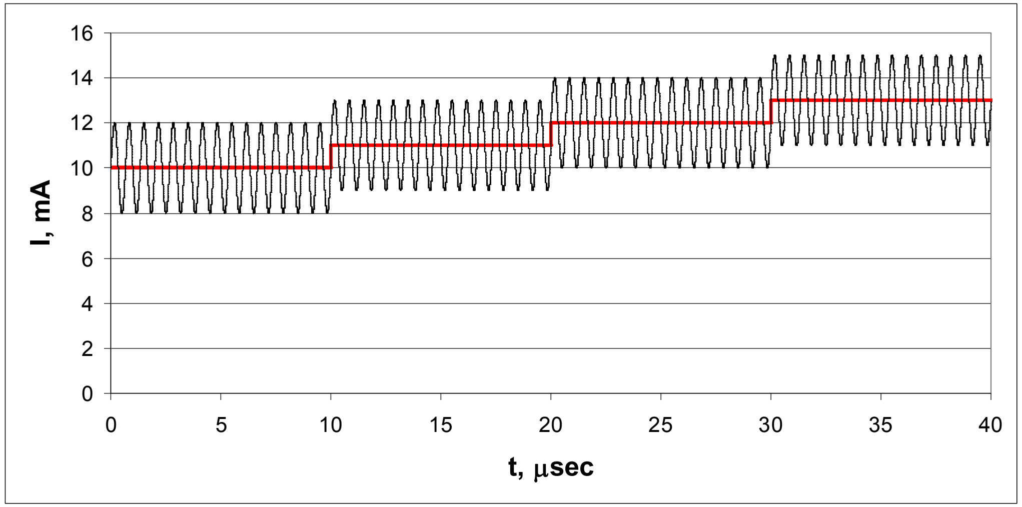
$$\Delta T(t) = I_0 \begin{cases} A_0 t & n = 0 \\ 2A_1\sqrt{t} & n = 1 \\ A_2 \ln(t/t_0) & n = 2 \end{cases}$$

Here n is diffusion process dimension. From data presented all parameters were determined.

Blue – 1D (n=1) ⊥ p-n, red – 2D diffusion (n=2), finally green – temperature equilibrium is established all over the DL crystal. Temperature diffusion characteristic times: τ_1 ~ 30 nsec (size ⊥ p-n ~1 μ), τ_2 ~ 10 μsec (size II p-n~10 μ), and τ_3 ~1 msec (DL dimension~200 μ).

Excitation current modulation

Excitation current harmonic modulation. Red – current due to computer. Time duration is due to NI DAQ (10 μсек).
Black – high frequency harmonic modulation is added.
PD + preamplifier are slow. They measure average signal.
DL spectrum with modulation.

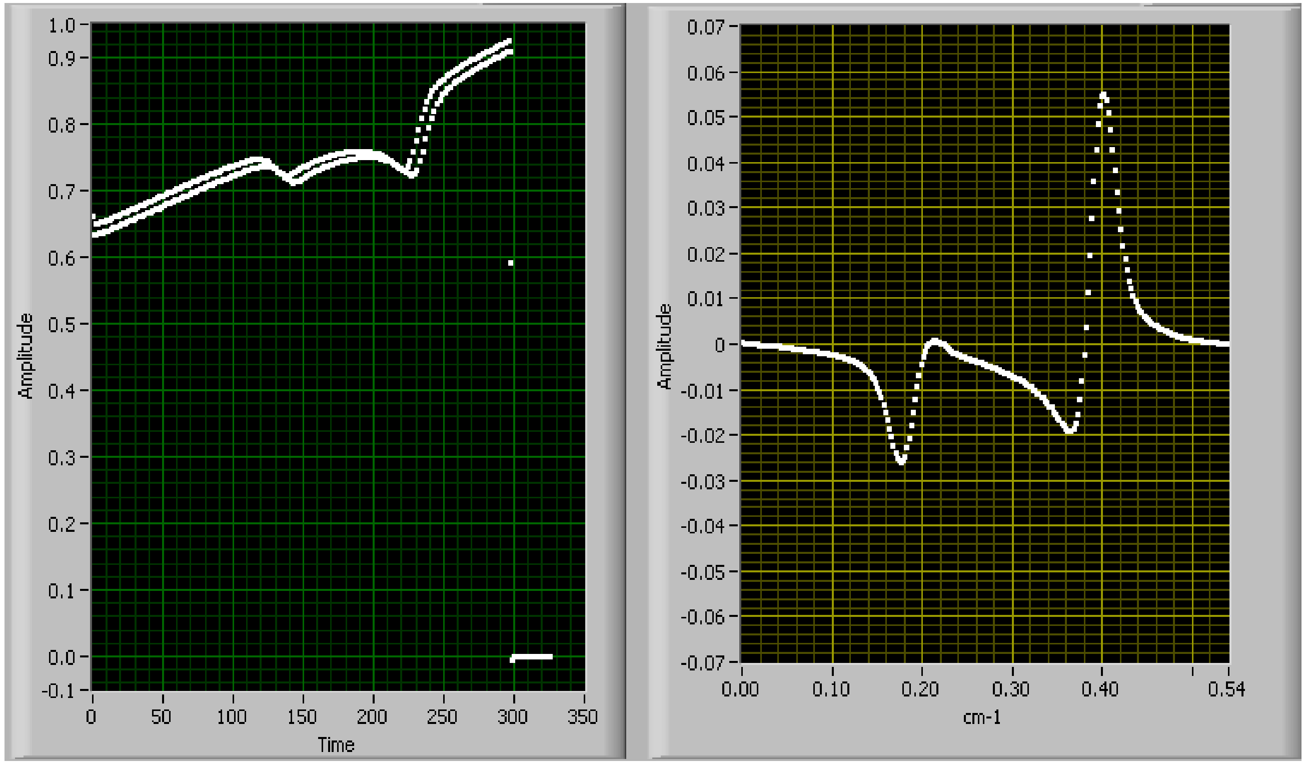


$$\vec{E}(t) = \vec{E}_0 \exp\left\{\frac{\Omega}{F}\exp\left(-i2\pi Ft\right)\right\} = \vec{E}_0 \sum_{n=0}^{\infty}\frac{1}{n!}\left[\frac{\Omega}{F}\exp\left(-i2\pi Ft\right)\right]^n$$

F [Hz] – modulation current frequency; Ω [Hz] – DL frequency deviation due to current modulation.
Ω/F<<1 – small phase modulation. DL spectrum consists of central line and two satellites shifted by ± F.
Ω/F<<1 – large phase modulation. DL spectrum is doublet shifted from center by Ω, and having width $\Omega/(\Omega/F)^{0.5} = (\Omega*F)^{0.5}$.

Poisson distribution

Line shape with modulation

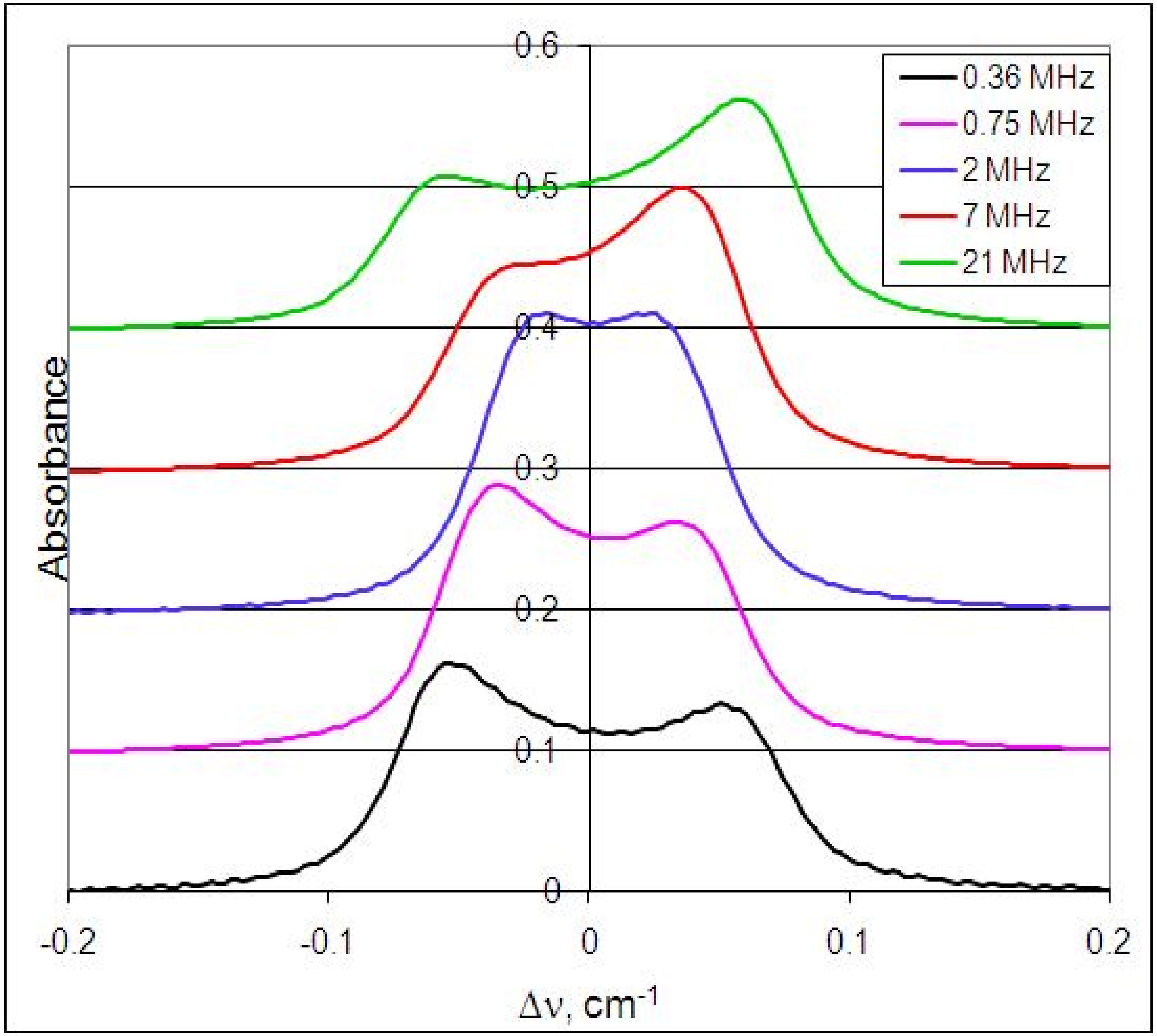


Program interface to measure spectral line shape (Doppler water vapor line) in case of DL excitation current high frequency modulation. Large amplitude modulation was used (frequency modulation larger than line width).

Left – recorded signal. Right – absorbance derivative after DL tuning curve was calibrated with known FP.

Two parameters can be obtained from these results: distance between peaks (frequency modulation amplitude) and lines amplitudes ratio (asymmetry).

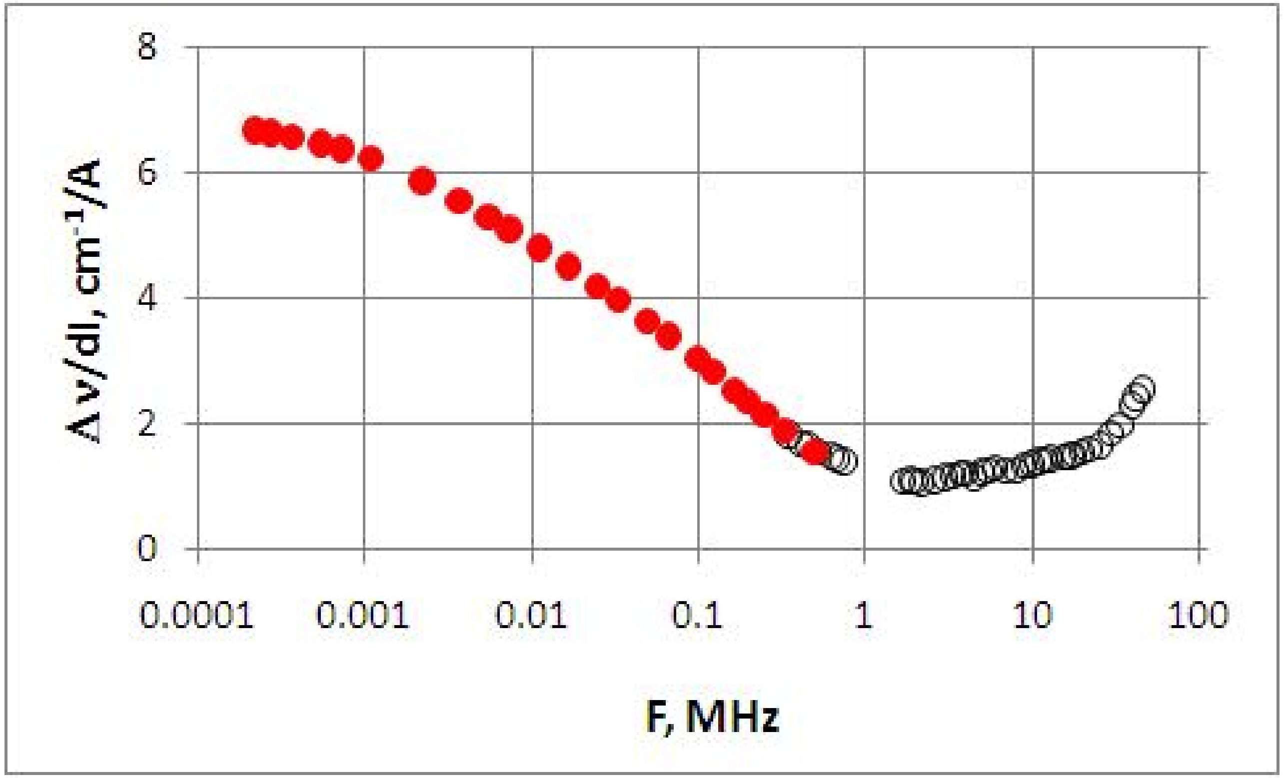
Frequency dependence



Recorded line shapes for different excitation current modulation frequencies.

With increasing of excitation current modulation frequency distance between peaks reduces, achieve minimum (around 2 MHz), and then demonstrates increasing. Frequency dependence of line shape asymmetry is very special. Left peak is higher for small frequencies, peaks are equal for 2 MHZ (minimum frequency modulation), for high modulation frequencies right peak is higher.

DL tuning and modulation



DL frequency modulation as function of excitation current modulation frequency – F.
Black open circles – frequency domain.
Red solid circles – time domain.

For current modulation frequencies where 1D temperature diffusion dominates results obtained in time and frequency domains are in good agreement. Hence, ***DL frequency modulation by excitation current can be analyzed in wide range of excitation current frequencies 100 Hz до 100 MHz.***

DL frequency modulation

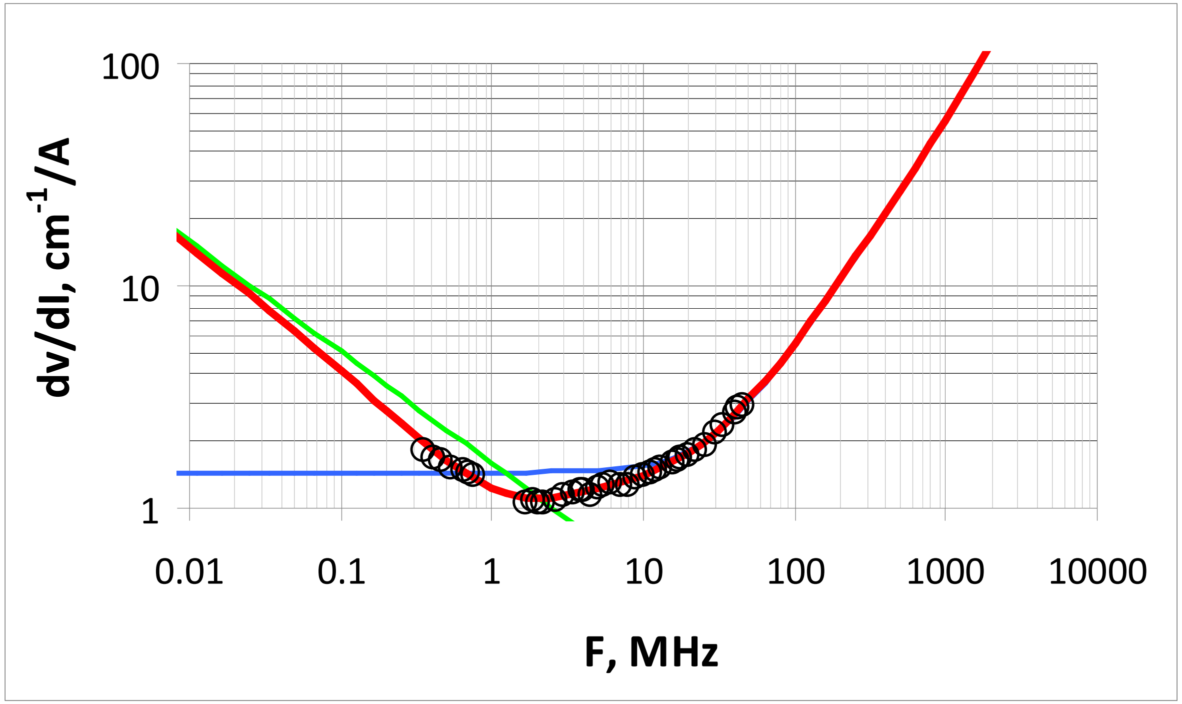
Comparison of experiment and modeling. DL frequency tuning is determined by electrons (current) and phonons (temperature).

$$\frac{\partial \nu}{\partial I} = \left.\frac{\partial \nu}{\partial T}\right|_I \frac{\partial T}{\partial I} + \left.\frac{\partial \nu}{\partial I}\right|_T$$

$$\frac{\partial \nu}{\partial T} = -0.502 \frac{\text{cm}^{-1}}{\text{K}}$$

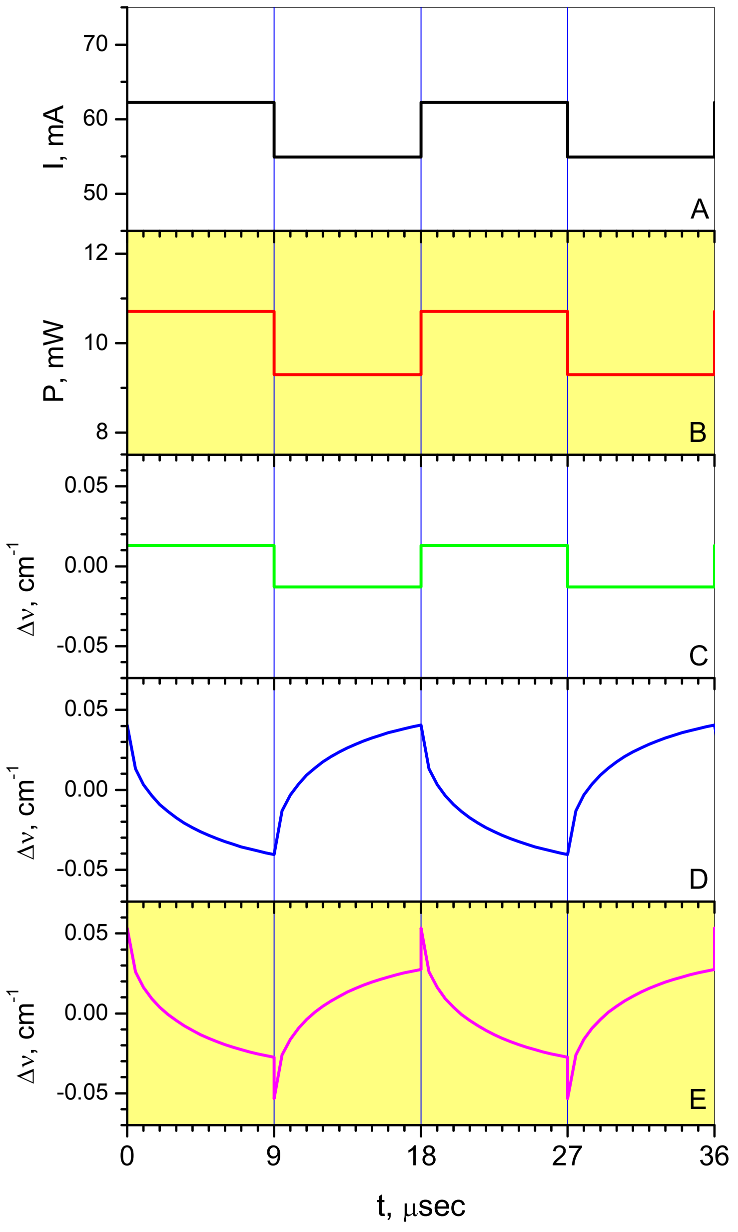
$$\frac{\partial T(f)}{\partial I} = \frac{A_1}{2\sqrt{f}}\left[1+i\right]$$

$$\left.\frac{\partial \nu}{\partial I}\right|_T = B_1 - B_2 i f$$



In modulation frequencies range interesting for TDLS (100 kHz – 100 MHz) in temperature tuning dominates 1D temperature diffusion. Its behavior is known (green). Two parameters B_1 и B_2 describing electrons have to be determined (blue). Final (red) is in good agreement with experiment. Near minimum final curve leis lower green and blue curves because these two mechanisms has opposite sign of current tuning.

DL behavior



Periodic rectangular excitation current modulation.

Intensity follows excitation current form.

Frequency due to electrons follows excitation current form.

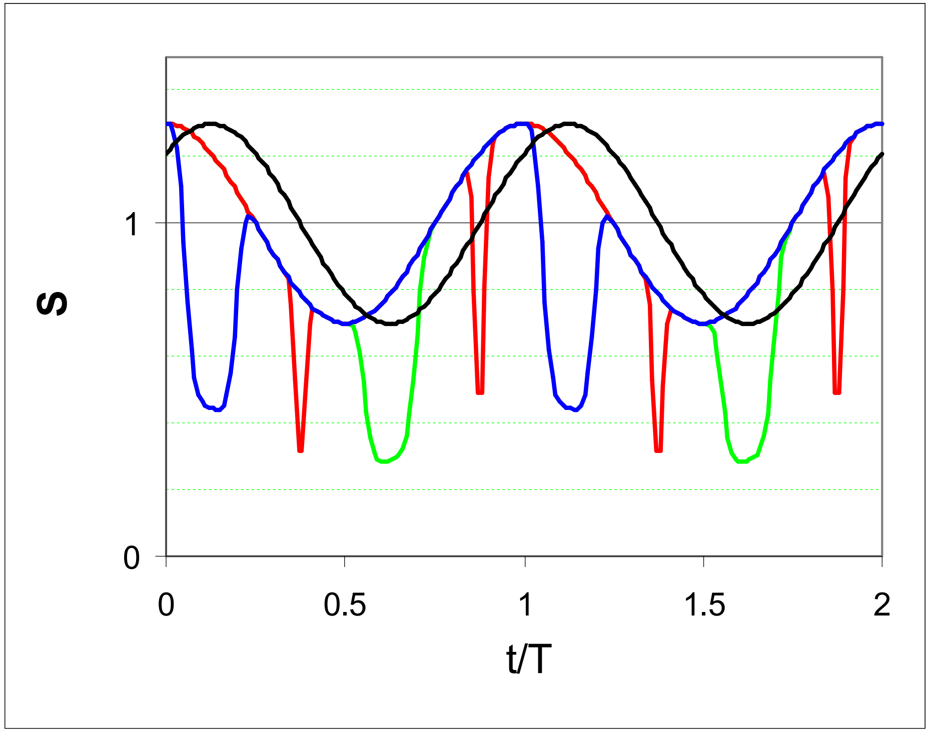
Frequency due to temperature (phonons) is slow system.

Final DL frequency time dependence due to electrons and phonons.

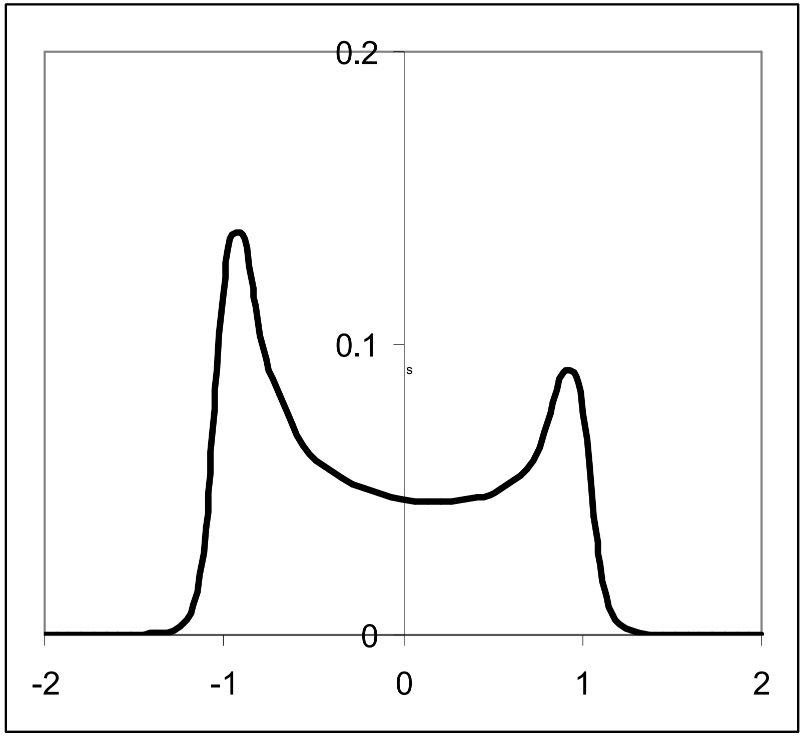
Yellow graphs – DL parameters using in TDLS.

Line shape asymmetry

Line shape asymmetry mechanism is due to DL intensity and frequency modulations by excitation current correlation.



DL (high frequency excitation current modulation) intensity after passing cell with molecule under investigation for different excitation currents. Black DL frequency modulation. Frequency is shifted from intensity by $\pi/4$.



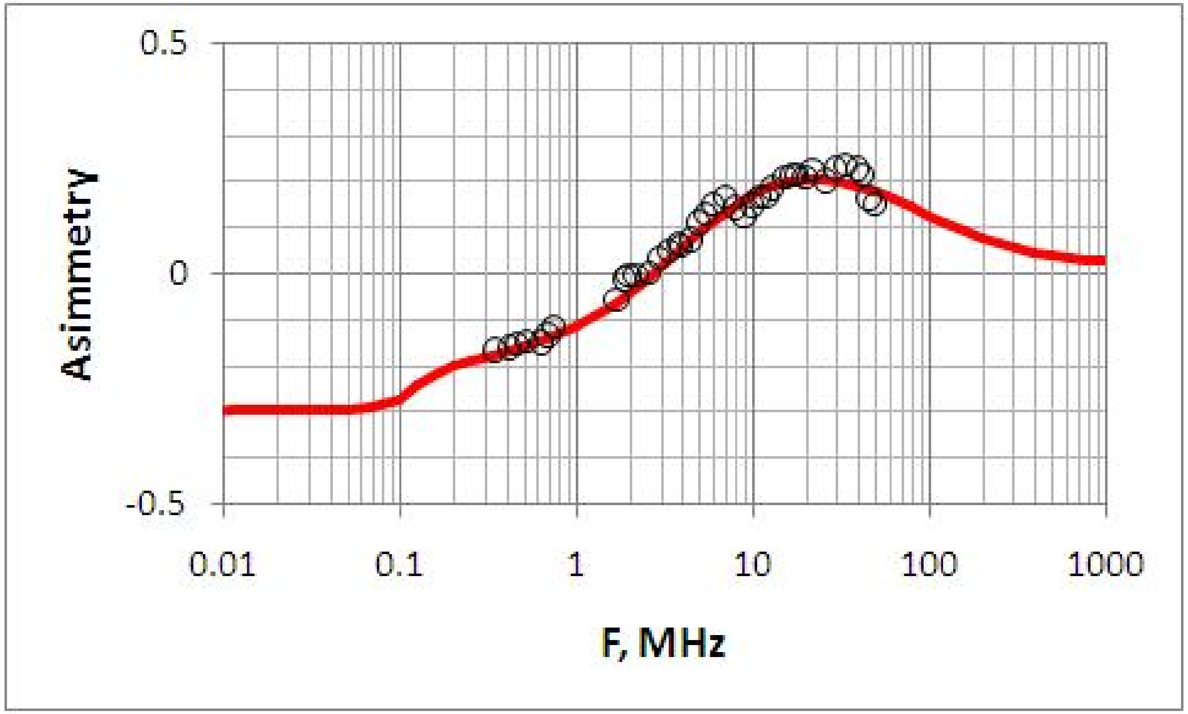
Recorded line asymmetry as calculated.

Experiment: line asymmetry

Line asymmetry $$\frac{A_+ - A_-}{A_+ + A_-} = \frac{\Delta P}{P_0}\cos(\theta)$$

Is determined by relative DL intensit modulation and phase shift between intensity and frequency.

Line asymmetry frequency dependence: experiment (black circles), modeling (red curve).



<u>Modeling is based on parameters determined independently (see above). Good agreement can be observed.</u>