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DL Frequency Large Amplitude Modulation

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Abstract

Intensity and frequency modulation by excitation current is well developed area of DL physics [1] with respect to rapid optical communication. We'll consider other subject of modulation related to TDLS operation.
The goal of present paper is to analyzed influence of DL excitation current modulation on recorded molecular line shape trace molecules detection.
Different modulation techniques were used in TDLS. However, these approaches were not optimal taking into account DL physical properties.
Resent TDLS operation regime includes DL frequency large amplitude modulation. Optimal modulation approach to achieve fundamental limit of minimum detectable absorption will be considered both based on theoretical and experimental investigations.
Achievement of minimum detectable absorption below 10^{-7} will be demonstrated.

References:

[1] See for example: G.Morthier, P.Vankwikelberge, Handbook of Distributed Feedback Laser Diodes, Artech House, Inc., Boston, 1997, and references

DL frequency modulation by current

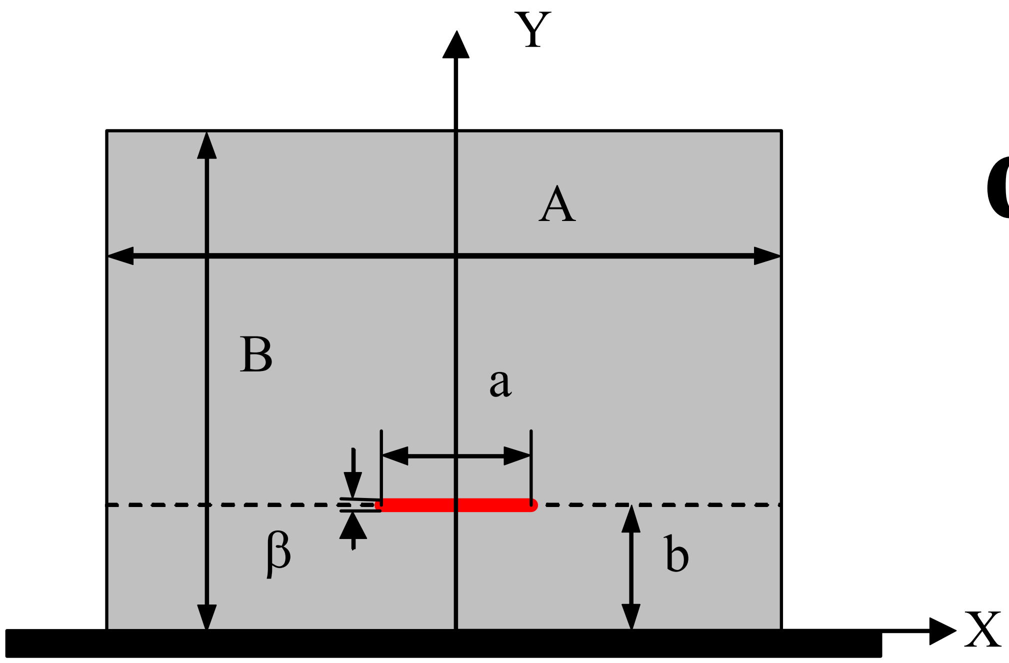
DL frequency tuning by excitation current modulation is determined by two processes

$$\frac{d\nu}{dI} = \left[\frac{\partial \nu}{\partial T}\right]_I \frac{\partial T}{\partial I} + \left[\frac{\partial \nu}{\partial I}\right]_T$$

Phonons system (temperature)

Electrons+photons system

Temperature diffusion in DL



Cross-section of diode laser

Heat equation

$$C\frac{\partial \Delta T(x,y,t)}{\partial t}-\eta\left\{\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}\right\}\Delta T(x,y,t)=W(x,y,t)$$

General solution heat equation

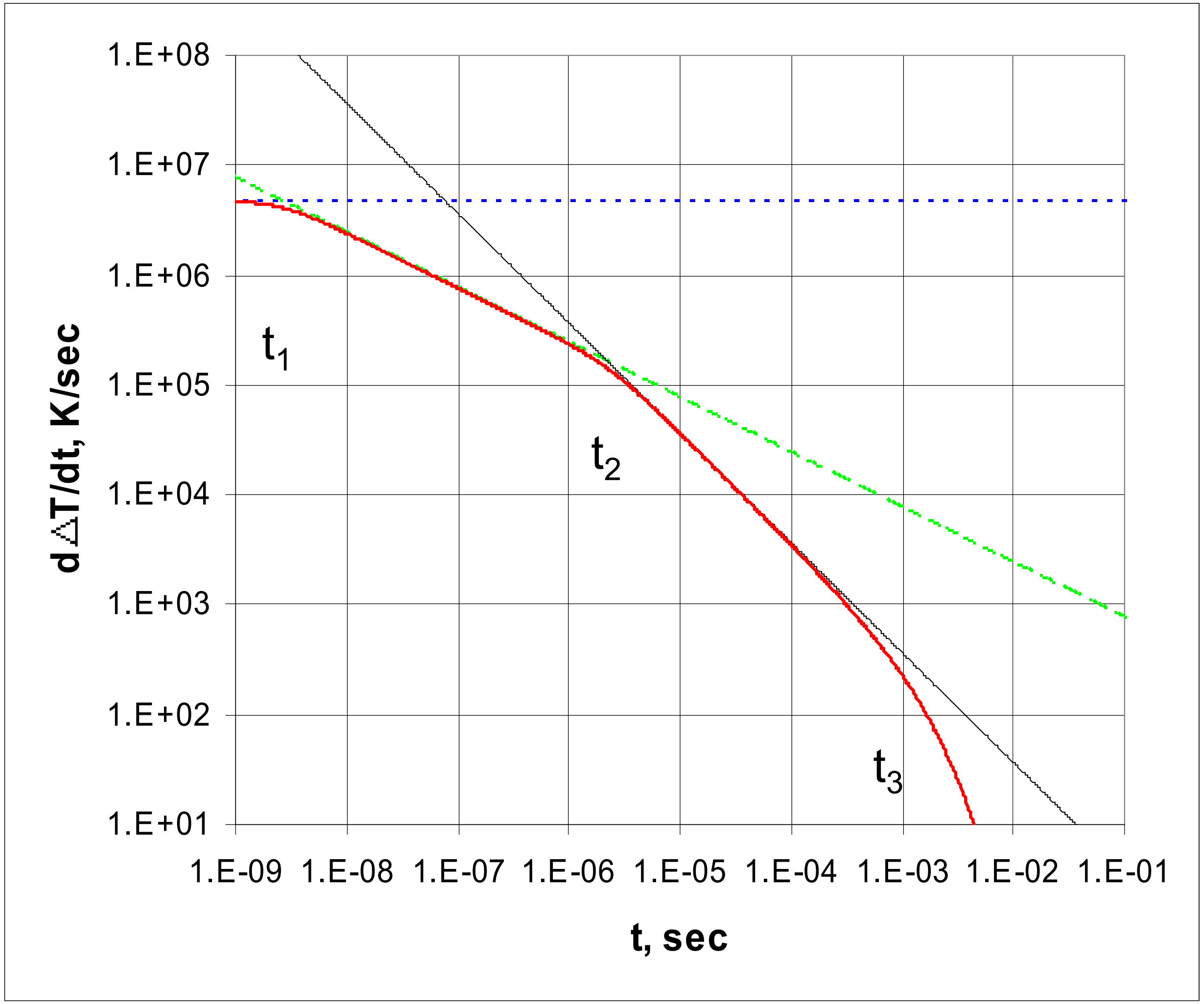
$$G(\vec{r},\vec{\xi},t)=\frac{1}{\sqrt{[4\pi Dt]^3}}\exp\left\{-\frac{\left(\vec{r}-\vec{\xi}\right)^2}{4Dt}\right\}$$

Boundary conditions

$$\Delta T\Big|_{y=0}=0,\qquad \frac{\partial \Delta \mathrm{T}}{\partial \mathrm{y}}\Big|_{\mathrm{y=B}}=\frac{\partial \Delta \mathrm{T}}{\partial x}\Big|_{\mathrm{x}=\pm A/2}=0$$

Active area heating

Significant difference of the laser structure dimensions provides possibility to four different steps of heating process depending on thermal diffusion length L.



L<< β - homogenious heating of the DL active area with constant speed.
β <<L<< a- thermal diffusion can be considered as one-dimentional process.
a <<L<< B - two-dimentional process will take place.
Finally, steady-state temperature distribution will be achieved after thermal diffusion length exceeds DL chip dimention - B.
This leads to three characteristic times: t_1, t_2, t_3

Rate equations

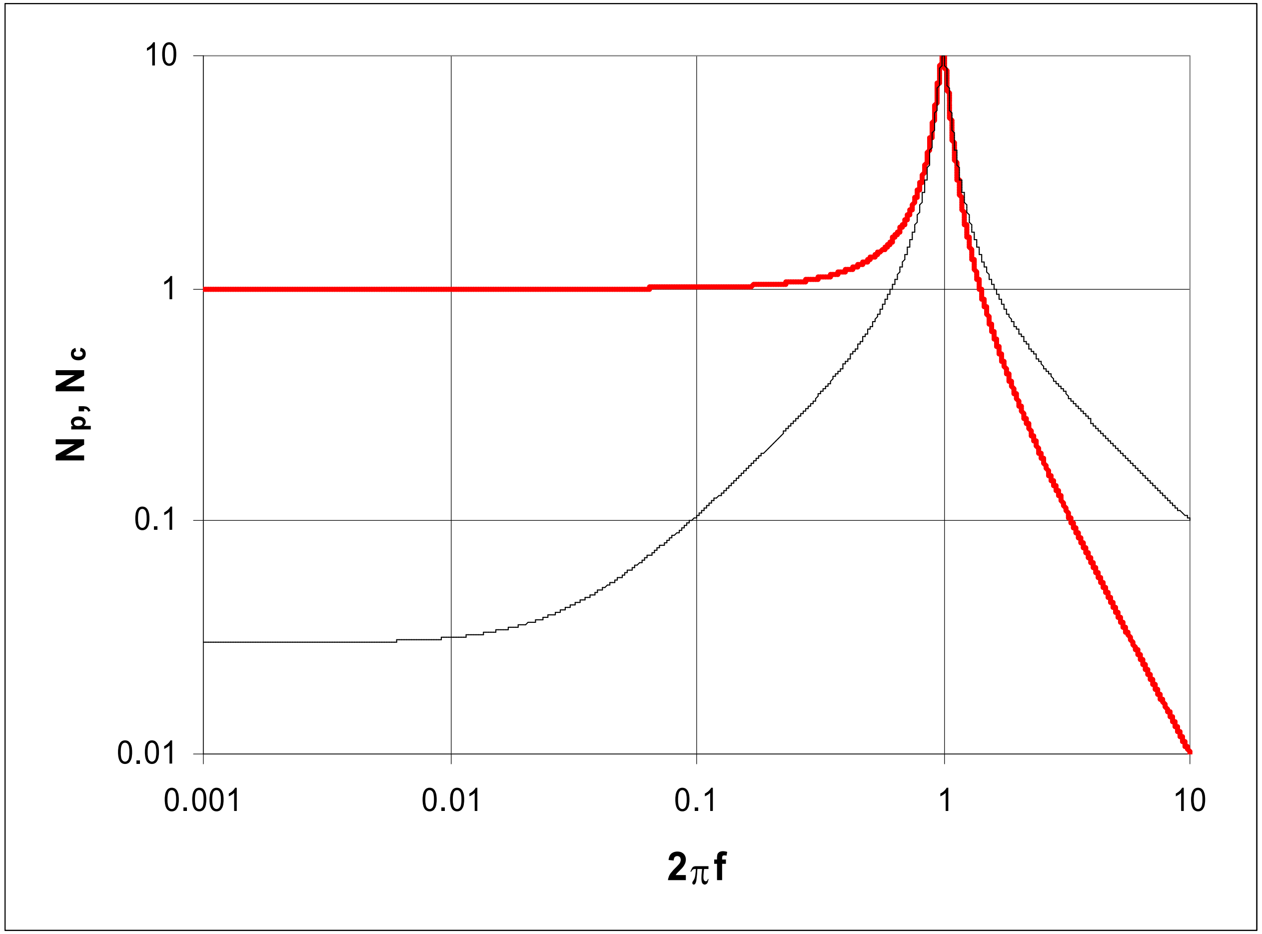
Electrons + photons system. The behaviour of the electron subsystem in a diode laser is described by N_c - the number of non-equilibrium current carriers in the DL active area. Electromagnetic field is characterized by the number of photons N_p of m-th axial mode within which generation occurs.

$$\frac{dN_c}{dt} = \frac{I}{e} - g(N_c - N_G)N_p - \frac{N_c}{\tau_c}$$

$$\frac{dN_p}{dt} = g(N_c - N_G)N_p + \frac{CN_c}{\tau_s} - \frac{N_p}{\tau_p}$$

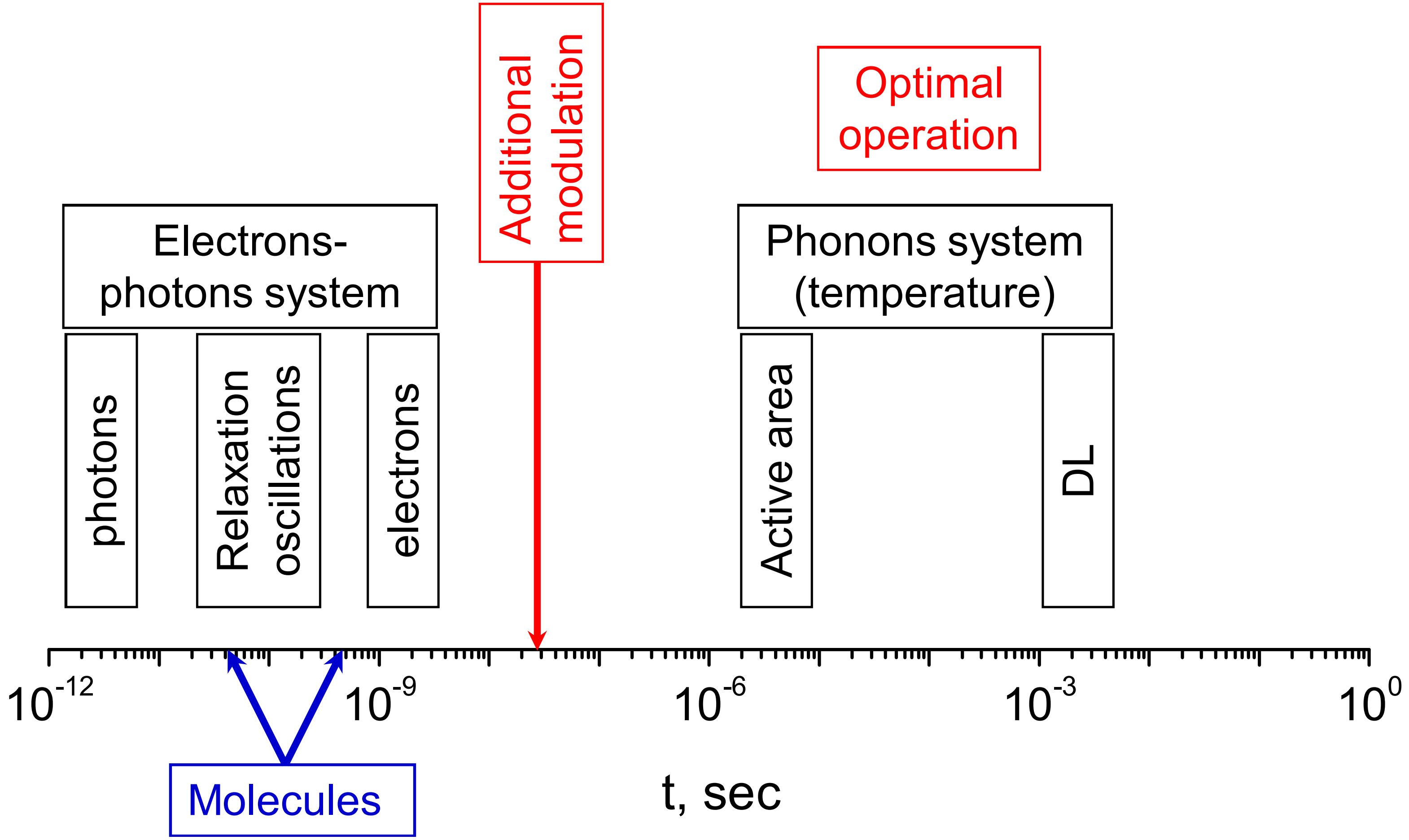
Here I is the excitation current; g - the constant proportional to the rate of the stimulated transition; N_G – the minimal number of the current carriers required for absorption compensation in a laser; τ_c – the life time of a excess current carriers (~ nsec); C – the contribution of a spontaneous emission into a given axial regime of a DL; τ_s – spontaneous emission time; τ_p – the life time of a photon in a resonator (~ psec).

Intensity and frequency modulation



DL power (N_p, black line) and frequency (N_c, red line) as function of modulation frequency. For a given case, frequency $2\pi f$ was normalized to value $\sqrt{(gN_p/\tau_p)}$ characterizing resonance known as “relaxation oscillations”.

Physical processes in DL and optimal TDLS operation regime



In DL there are two systems: electrons+photons (fast) and phonons (slow)

Frequency modulation

$$\vec{E}(t) = \vec{E}_0 \exp\left\{ -i \int_{-\infty}^{t} 2\pi \left[c\nu + \Omega \cos(2\pi F \theta) \right] d\theta \right\} =$$

$$= \vec{E}_0 \exp\left\{ -i \left[2\pi c \nu t + \frac{\Omega}{F} \sin(2\pi F t) \right] \right\}$$

c – light velocity;

$\nu = 1/\lambda$ [см$^{-1}$] - wavenumber;

F [Hz] – modulation current frequency;

Ω [Hz] – light frequency deviation due to current modulation

$$\vec{E}_{slow}(t) = \vec{E}_0 \exp\left\{ \frac{\Omega}{F} \exp(-i 2\pi F t) \right\} = \vec{E}_0 \sum_{n=0}^{\infty} \frac{1}{n!} \left[\frac{\Omega}{F} \exp(-i 2\pi F t) \right]^n$$

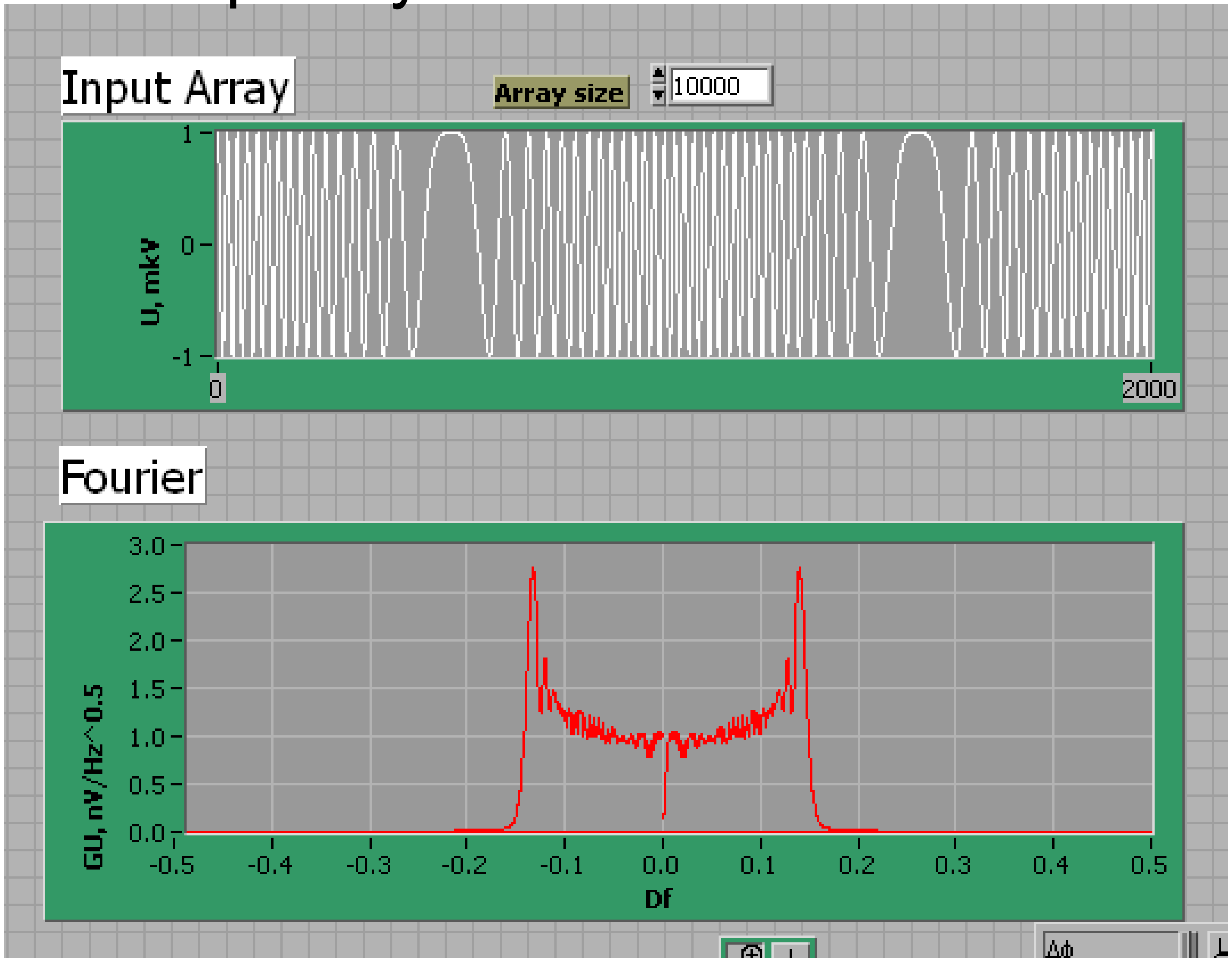
Poisson distribution

$\Omega/F \ll 1$ – small fast modulation with small phase modulation

$\Omega/F \ll 1$ – large slow modulation with large phase modulation

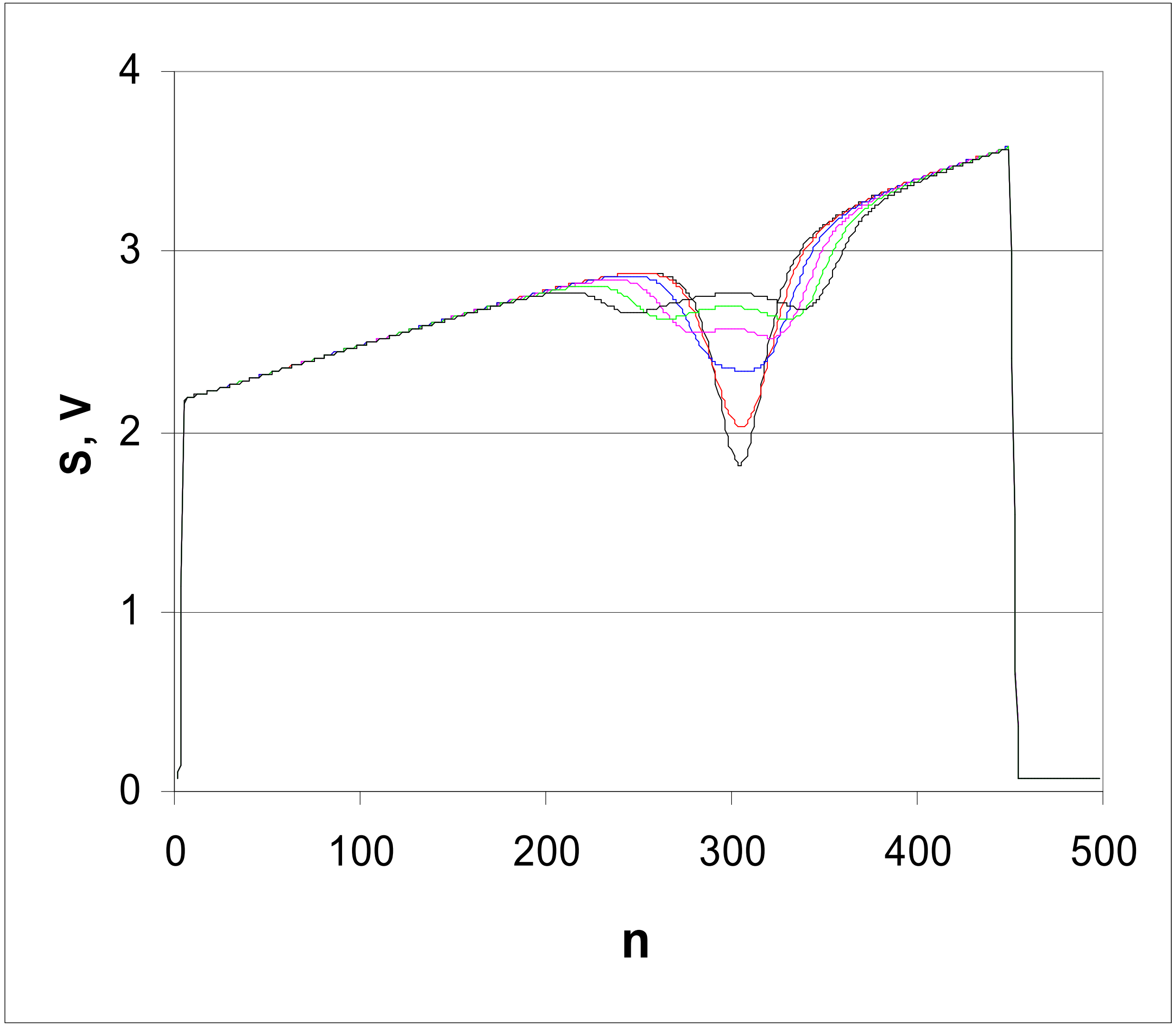
Large amplitude frequency modulation

Frequency deviation Ω >> F - modulation frequency



Time dependence of slow field component determined by modulation and related spectrum demonstrating two peaks with similar amplitude

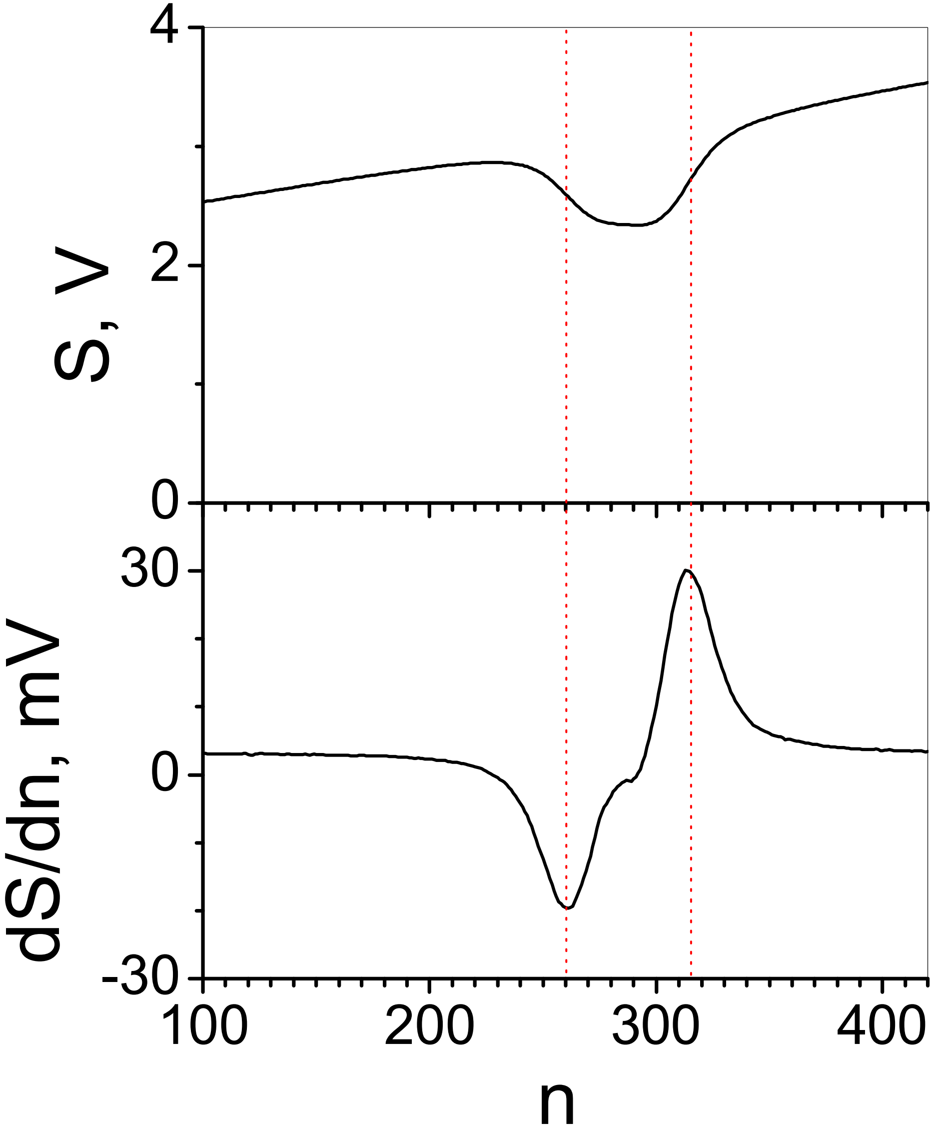
Signal with modulation



Recorded signal with Doppler line shape of water vapor for several modulation amplitudes: 0, 4.7, 9.4, 14.1, 18.8, 23.5 mA; F = 25 MHz

With modulation line broadening was observed with presence of two peaks having different amplitudes

Line broadening due to modulation



Upper figure: signal with water Doppler line

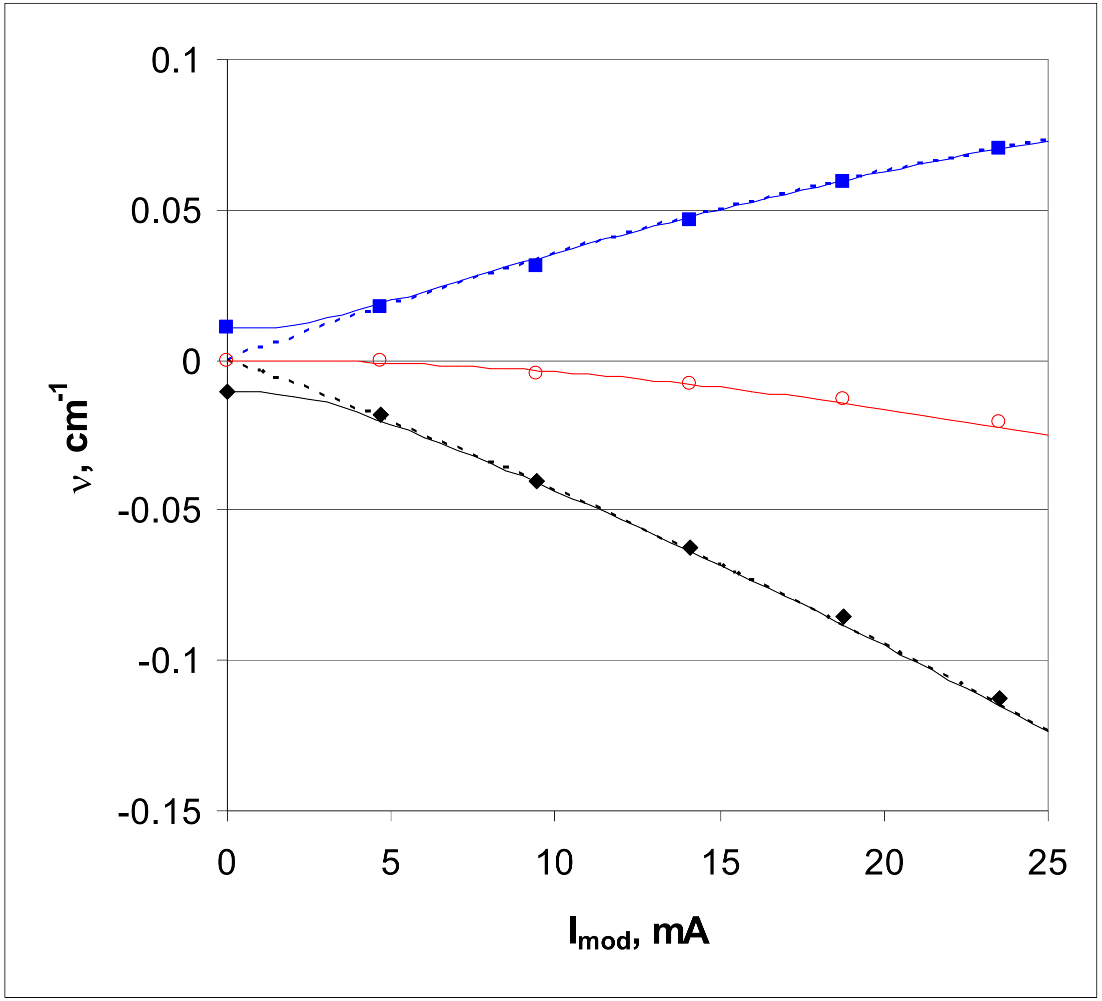
Lower figure: above spectrum derivative

Modulation frequency and amplitude were F = 25 MHz and ΔI= 9.4 mA, respectively

Peaks on lower picture were used to determined line width

Line broadening asymmetry

Line broadening due to modulation



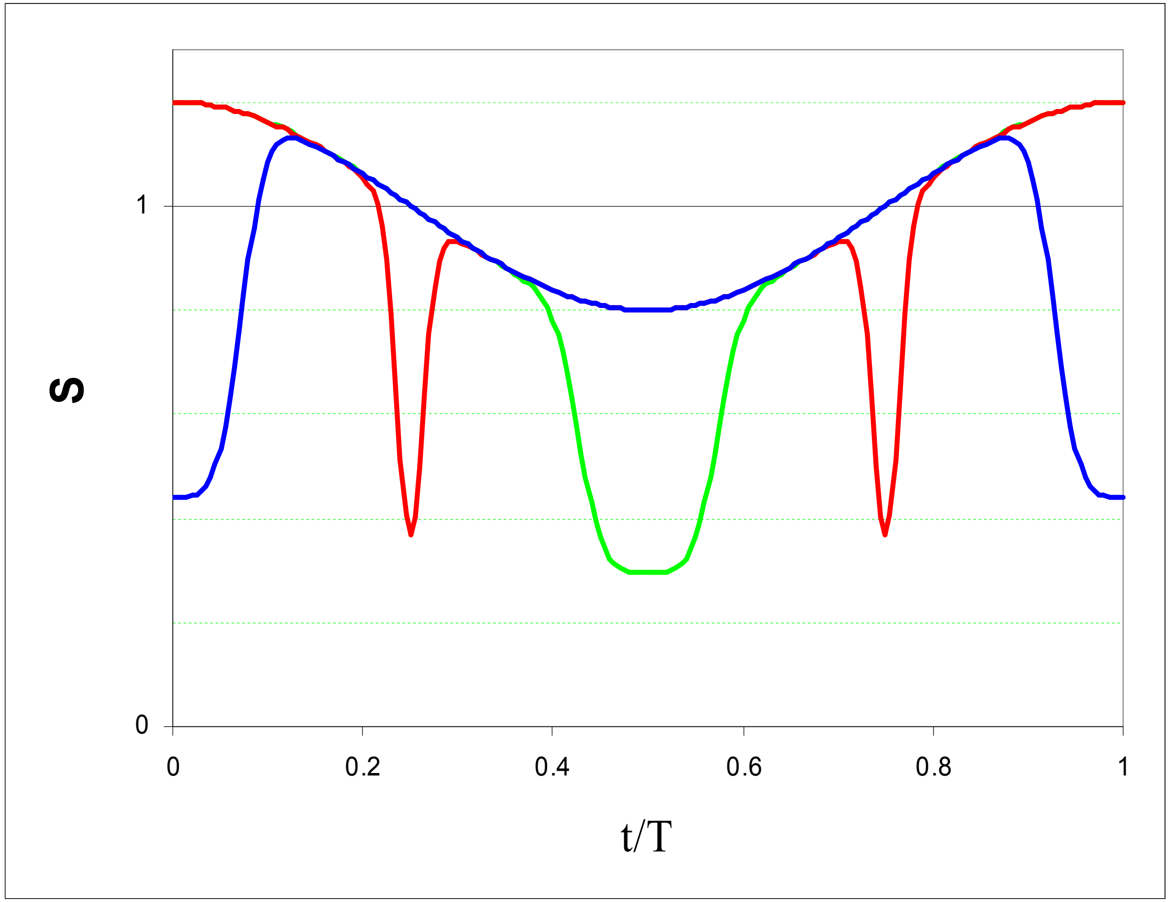
Broadening linear with ΔI – fast electrons

Shift quadratic with ΔI – slow temperature

Spectral line with large modulation

Electrons+photons system of DL is fast enough in comparison with modulation frequency - F. Hence, moment DL wavenumber – ν(t) can be introduced. Molecules are also fast with respect with F and there absorption can be determined as function of ν(t).

Fig. presents examples of transmitted light time dependence when line center corresponds to max, min, and center of ν(t).



Detection system is slow in comparison with F and record mean value of signals presented on Fig.

Spectral line shapes for large frequency modulation