DL frequency accurate calibration

DLS LAB

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Introduction

Accuracy is one of recent challenges for Tunable Diode Laser Spectroscopy (TDLS). In present paper DL frequency tuning accuracy will be considered and analyzed.

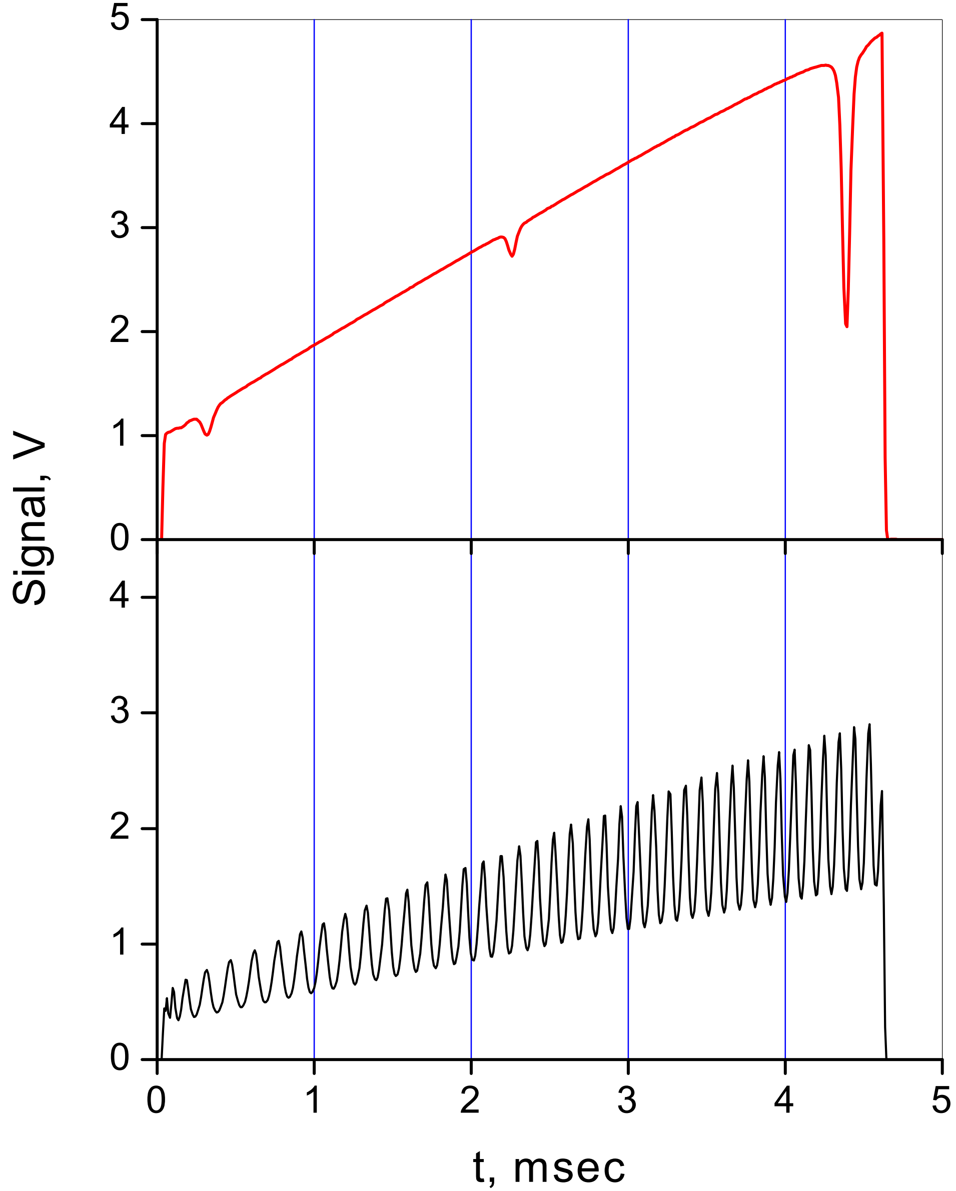
Motivations:

1. Traditional spectroscopy – accurate measurements of molecule under investigation spectral line frequency and intensity.
2. Spectral line shape – accurate measurements of spectral line shift, broadening, and shape (see B2).
3. TDLS based primary gas mixture standard – accurate measurement of impurity concentration in gas mixture under investigation (see A1).

DL frequency can be tuned both by DL temperature and excitation current.

Both techniques are using in our experiments.

DL frequency tuning calibration



Left - recorded signals when cell with low pressure water vapor (red) an FP etalon (black) were installed in DL beam.
DL frequency tuning is determined using FP transmittance. Absolute DL frequency calibration is based on reference spectral line frequency.
This TDLS operation mode is using when distance between closely spaced spectral lines has to be measured as well as spectral line shape is subject of investigation. Typical DL frequency tuning by current is ≈ 1 cm^{-1}.
Requirements:
1. Reference line frequency has to be known with highest possible accuracy.
2. DL frequency tuning has to be calibrated with accuracy better than 10^{-4} cm^{-1}.

Accuracy of reference line and DL frequency tuning

Usually HITRAN data are using as frequency of reference lines. HITRAN accuracy declared is 0.001 – 0.01 cm^{-1}. This accuracy is not enough for many applications. Higher accurate data for reference line frequencies have to be used.

For example, for C_2H_2 and HCN lines frequencies were measured by TDLS heterodyne technique with 10^{-5} cm^{-1} accuracy [1].

In many applications relative frequency with respect to reference line is subject of interest.

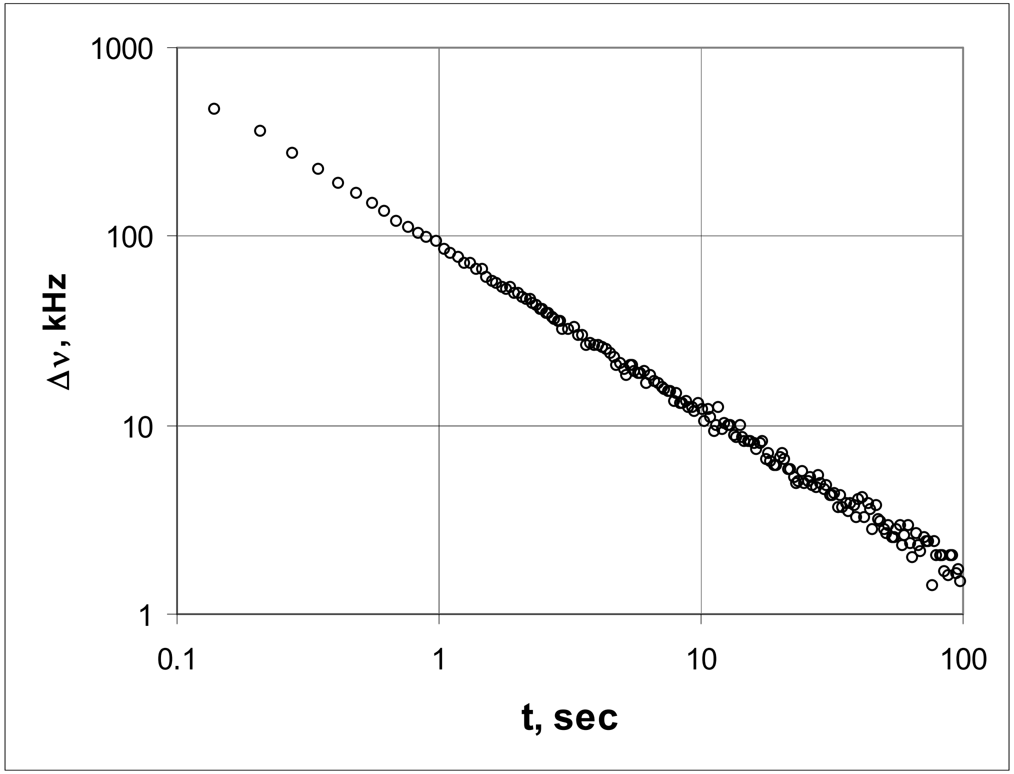
Requirements in this case.

1. Reference line position has to be stable within 10^{-4} cm^{-1}.
2. DL frequency tuning has to be calibrated with accuracy better than 10^{-4} cm^{-1}.

[1] K.Nakagawa, M.de Labachelerie, Y.Awaji, and M.Kourogi, J.Opt.Soc.Am.B, 13, 2708 (1996).

DL frequency tuning stabilization

First step is DL temperature stabilization. It is not enough for requirements mentioned above [2].



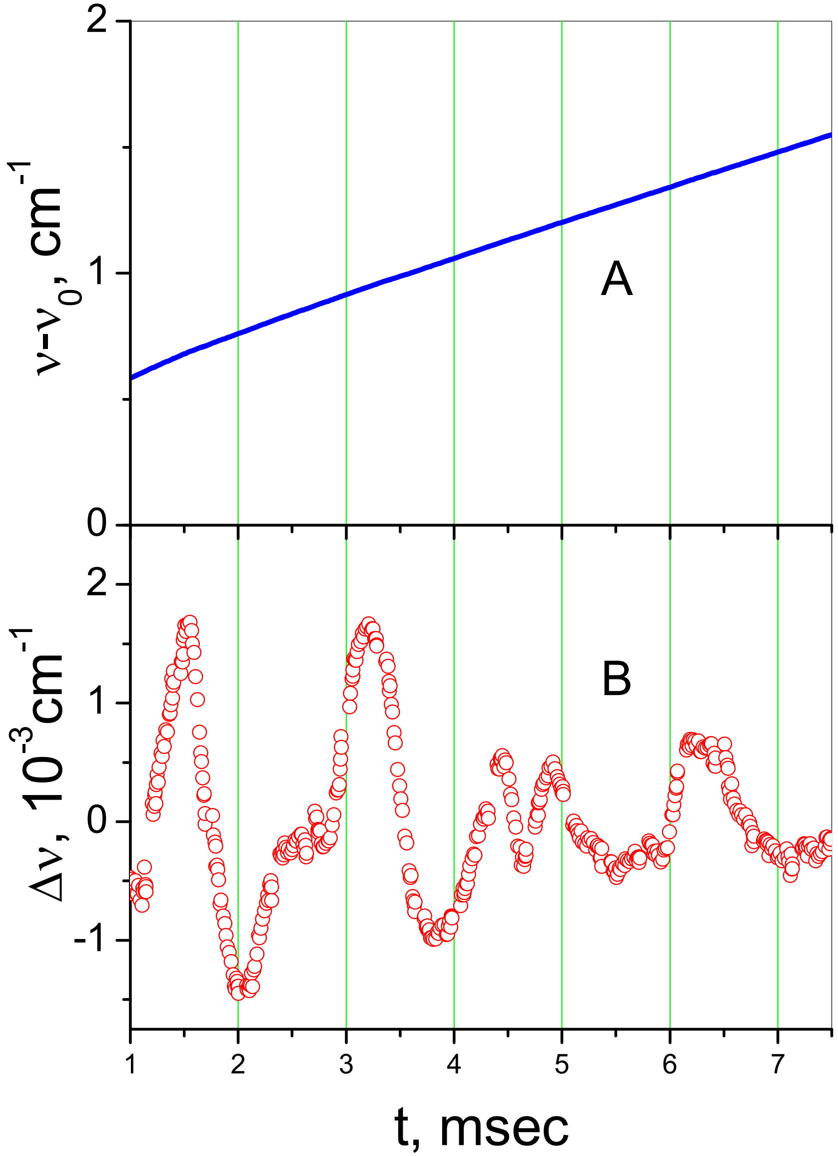
Solution was proposed in [3]. It is DL frequency tuning cycles stabilization. This approach combines stabilization with frequency tuning.

Using this approach DL frequency stabilization limited by DL frequency quantum noise was achieved [2, 4].

For averaging time of interest (1 sec) reference line stability is 3 10^{-5} cm^{-1} enough for requirements mentioned above.

[2] http://www.dls.gpi.ru/rus/conf/TDLS2005/Posters/B10.pdf
[3] Yu.Kosichkin, A.Kuznetsov, A.Nadezhdinskii, A.Perov, E.Stepanov, Sov.J.Quantum Electronics, 12, 518 (1982)
[4] A.Nadezhdinskii, Diode laser frequency tuning cycles stabilization at kHz level, Abstracts of TDLS 2005, Florence, Italy, p.92

Baseline influence



Baseline: Standing wave interaction with different inhomogeneities inside DL active area leads to small variations of all DL parameters. In present paper baseline influence on DL frequency tuning is considered.

DL frequency tuning (A) and its deviation from smoothed curve (B) [5]. The deviation is of the order of 10^{-3} cm^{-1}.

Results presented in Fig. were obtained using confocal resonator with free spectral range 0.00849 cm^{-1}. For FP etalon with higher free spectral range DL frequency tuning error up to 10^{-3} cm^{-1} can take place. It is far above mentioned accuracy requirements.

[5] A.Nadezhdinskii, Ya.Ponurovskii, M.Spiridonov, Quantum Electronics, 29, 916-920 (1999).

DL frequency tuning calibration

DL frequency tuning is calibrating by transmission spectra of etalons in use.

$$FD = \frac{1}{2Ln_{eff}} = \frac{1}{2L\left(n + \nu \frac{\partial n}{\partial \nu}\right)}$$

Difference between frequencies of successive etalon transmission maxima (range of etalon free dispersion – FD) is determined by etalon length – L, etalon material reflective index – n, and reflective index dispersion.

To fulfill previous slide requirements two etalons are using in our experiments.

Confocal resonator: L is unknown – calibration is necessary. Confocal resonator needs alignment. This is not efficient in each day work.

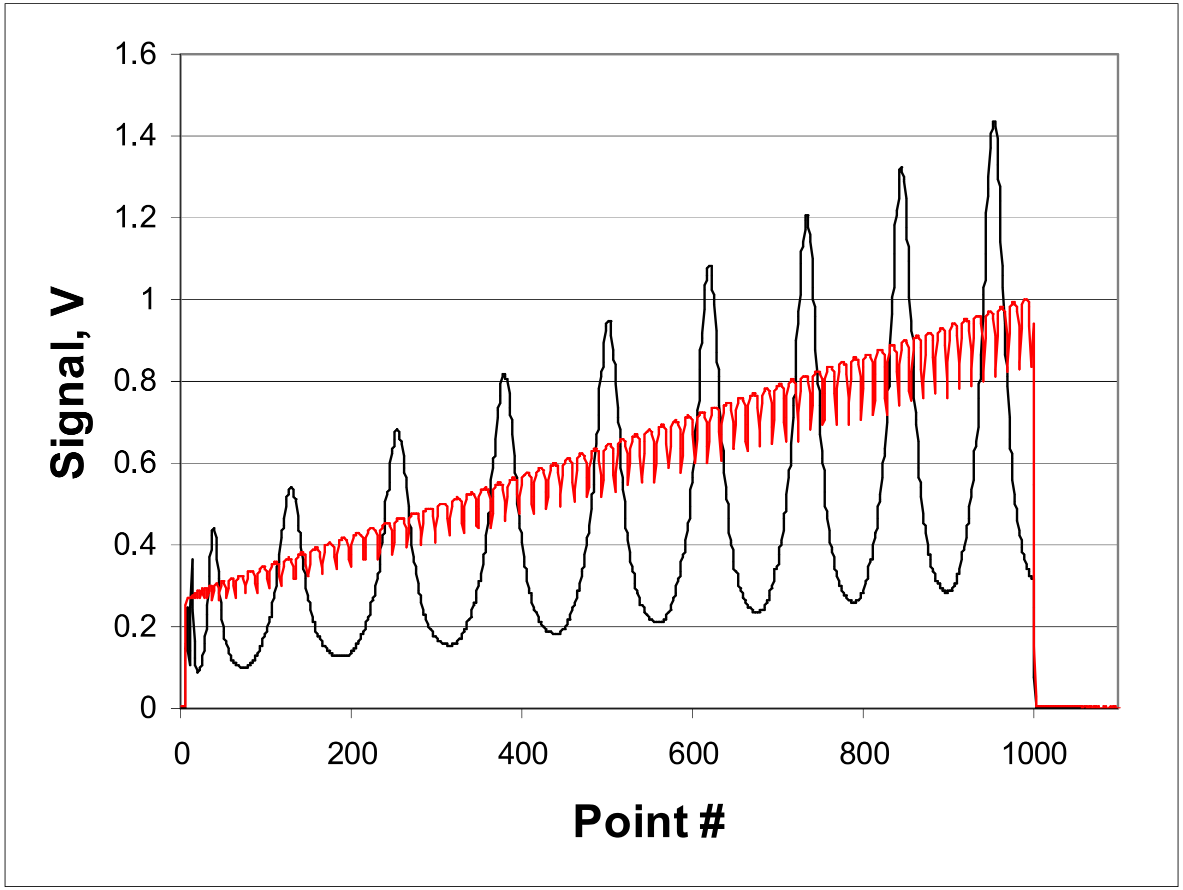
Now we are using fiber based etalon. It is convenient for each day work. However, it needs calibration for each experiment (see next slide).

Recent procedure of high accurate measurements looks like following: during molecule under investigation spectra recoding DL frequency tuning is determined by fiber based etalon. Fiber based etalon has to be calibrated for each experiment using calibrated FP etalon.

As calibrated one, FP glass etalon with L = 69.392(4) mm is using.

Fiber etalon calibration

For each experiment fiber etalon has to be calibrated.



Recorded signals when calibrated FP (black) and fiber (red) etalons were installed in DL beam.

Using data presented, fiber etalon free dispersion range refer to calibrated FP one was determined.

$FD_{fiber} = 0.131747(8)\ FD_{FP} =$

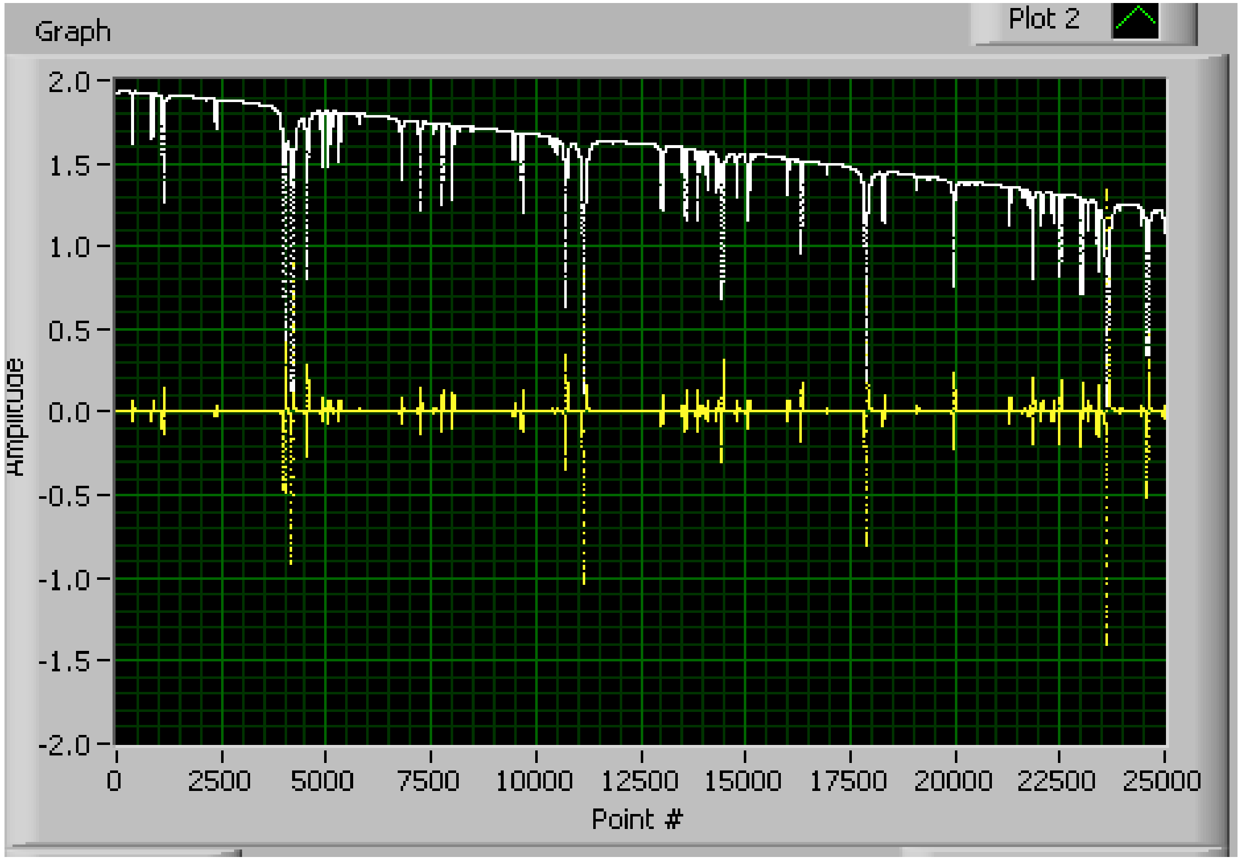
$= 0.131747(1 \pm 6\ 10^{-5})\ FD_{FP}$

Relative accuracy of fiber etalon calibration using calibrated FP etalon ($6\ 10^{-5}$) is reasonable refer accuracy requirements of DL frequency tuning considered above.

FP etalon has to be calibrated with highest possible accuracy.

FP etalon calibration

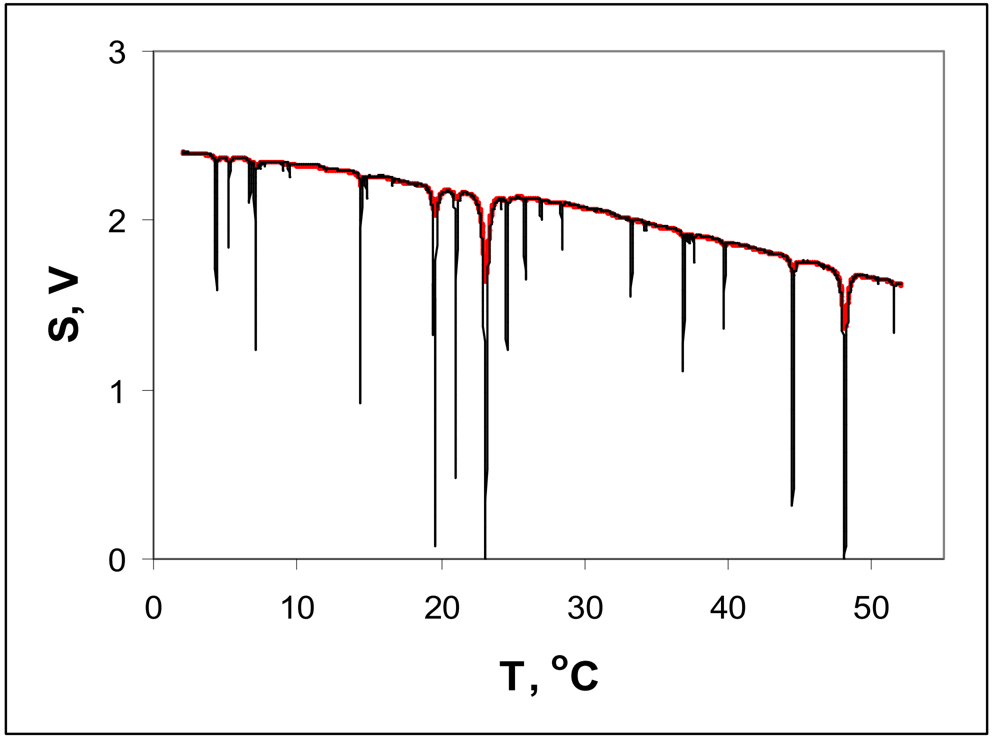
FP etalon was calibrated using spectral lines known frequencies. Typical frequency accuracy is ~ 0.001 cm^{-1}. To achieve required accuracy of FP calibration broad DL frequency tuning has to be used. For recent DLs temperature tuning provides broad tuning range up to 30 cm^{-1}. To perform this option software “Panorama” was developed.

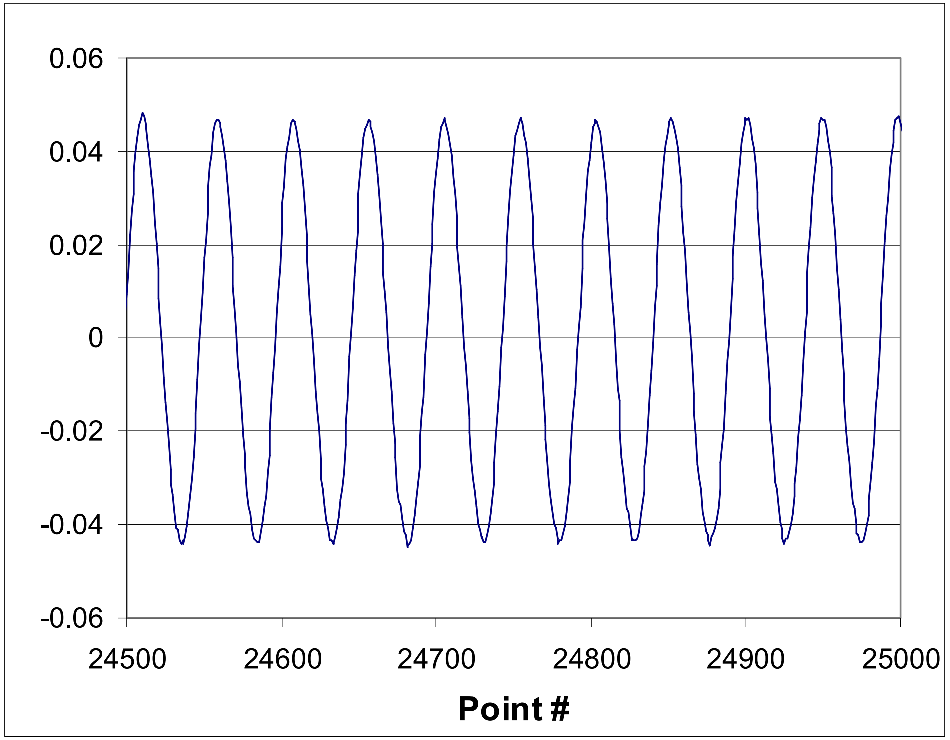


“Panorama” interface” when DL operated near 1.39 μ was investigated. Software automatically tunes DL temperature for fixed excitation current. Whole tuning takes 15 min (25000 points).
White line – recorded signal when cell containing low pressure water vapor was installed in DL beam.
Yellow curve – the signal logarithmic derivative.

Calibration procedure

3 spectra have to be recorded: empty cell, cell filled with molecular gas, and FP



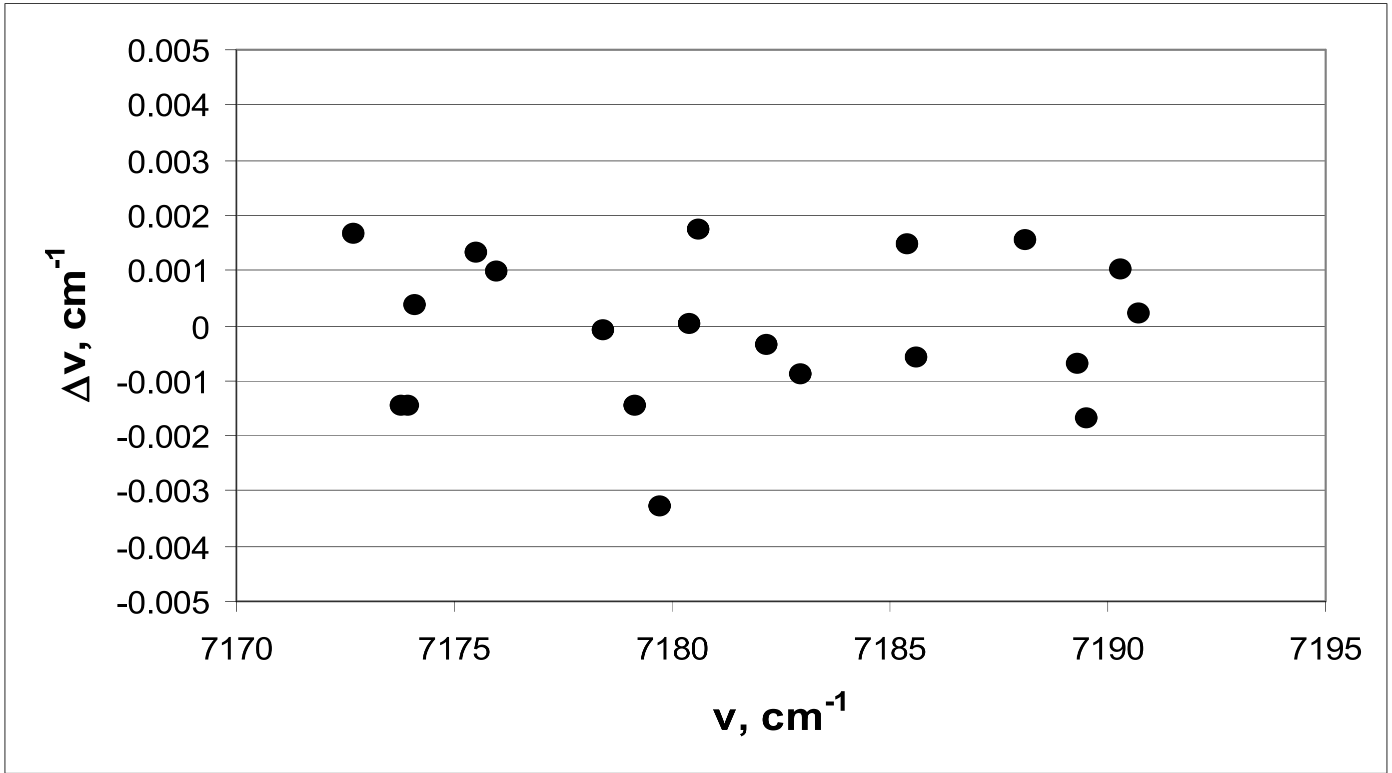


Recorded signals as function of DL temperature.
Black – signal when cell L = 2 m was filled with 8.81 mBar of water vapor.
Red - empty cell signal is using to normalize two other signals.

Fragment of FP etalon signal. Around 500 fringes are recording during tuning. Whole calibration procedure takes 45 min.

DL frequency temperature tuning accuracy

Temperature DL frequency tuning operation mode was used to investigate spectra of water vapor with different isotopes. Lines presented in previous slide were identified based on HITRAN. Data obtained were used to calibrate DL frequency tuning and determine FP etalon free dispersion range - FD_{FP}.



FD_{FP} = 0.049286(2) = 0.0492867(1 ± 4 10^{-5})

Difference between H_2O identified spectral lines frequencies (HITRAN) and ones measured in present experiment with calibrated DL frequency tuning.

The difference std = 0.0014 см$^{-1}$ is determined by HITRAN accuracy.

Obtained FP etalon calibration relative accuracy (4 10^{-5}) is in agreement with above accuracy requirements.

Program of experiment

Two FP etalons (#1 and #2) produced from the same material were calibrated.

To calibrate FP etalon several diode lasers operating in different spectral ranges were used:

№1 – 1.357 μ (NEL SN 722438 for H_2O);

№2 – 1.39 μ (NEL SN 503437 for H_2O);

№3 – 1.44 μ (NEL SN 537819 for CO_2);

№4 – 1.531 μ (Anritsu SN 74026 for C_2H_2);

№5 – 1.602 μ (NEL SN 503076 for CO_2);

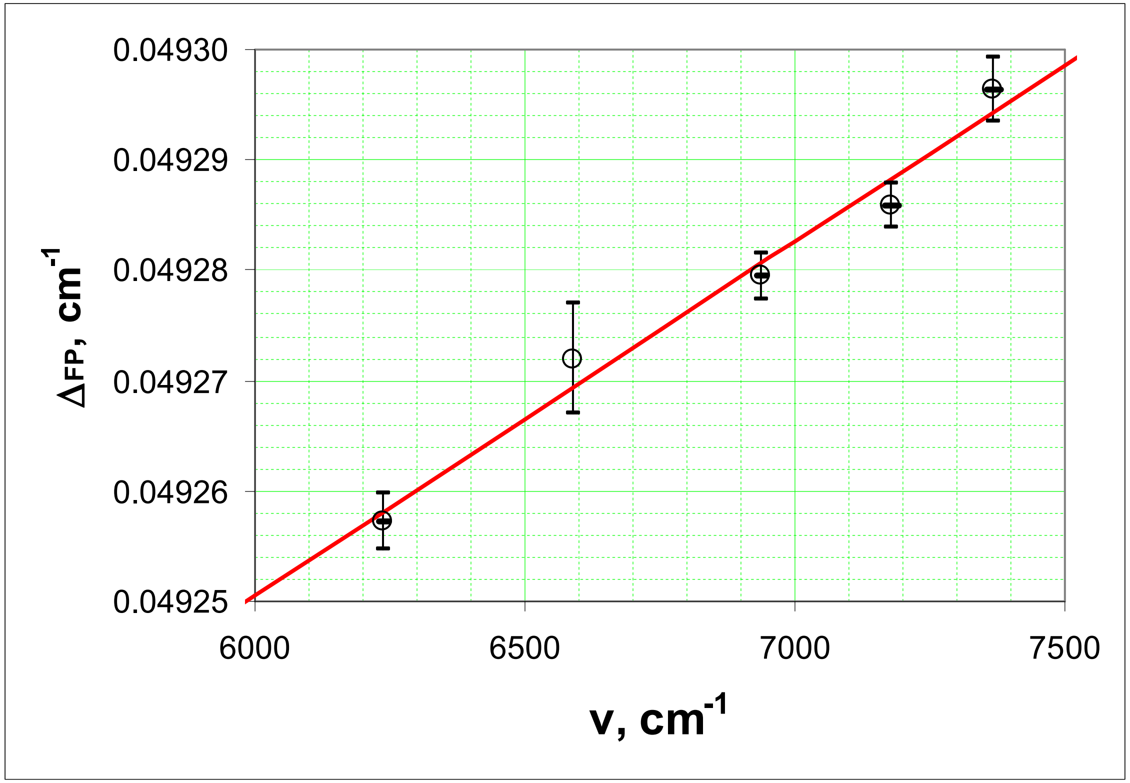
№6 – 1.65 μ (NEL 722496 for CH_4);

№7 – 1.79 μ (Nanoplus SN 289/21-7 for H_2O)

Spectra of several molecules (H_2O, CO_2, CH_4, C_2H_2) were recorded using above mentioned lasers in different spectral ranges.

Spectra were analyzed and observed spectral line were identified to measure FP etalon free dispersion range.

FP etalon free spectral range



Spectral dependence of calibrated FP etalon #1 free spectral range. Red line - linear approximation of observed spectral dependence.

$$\Delta_{FP} = A + B*(\nu-6000)$$

A	0.0492487(25)
B	3.34(25)E-08

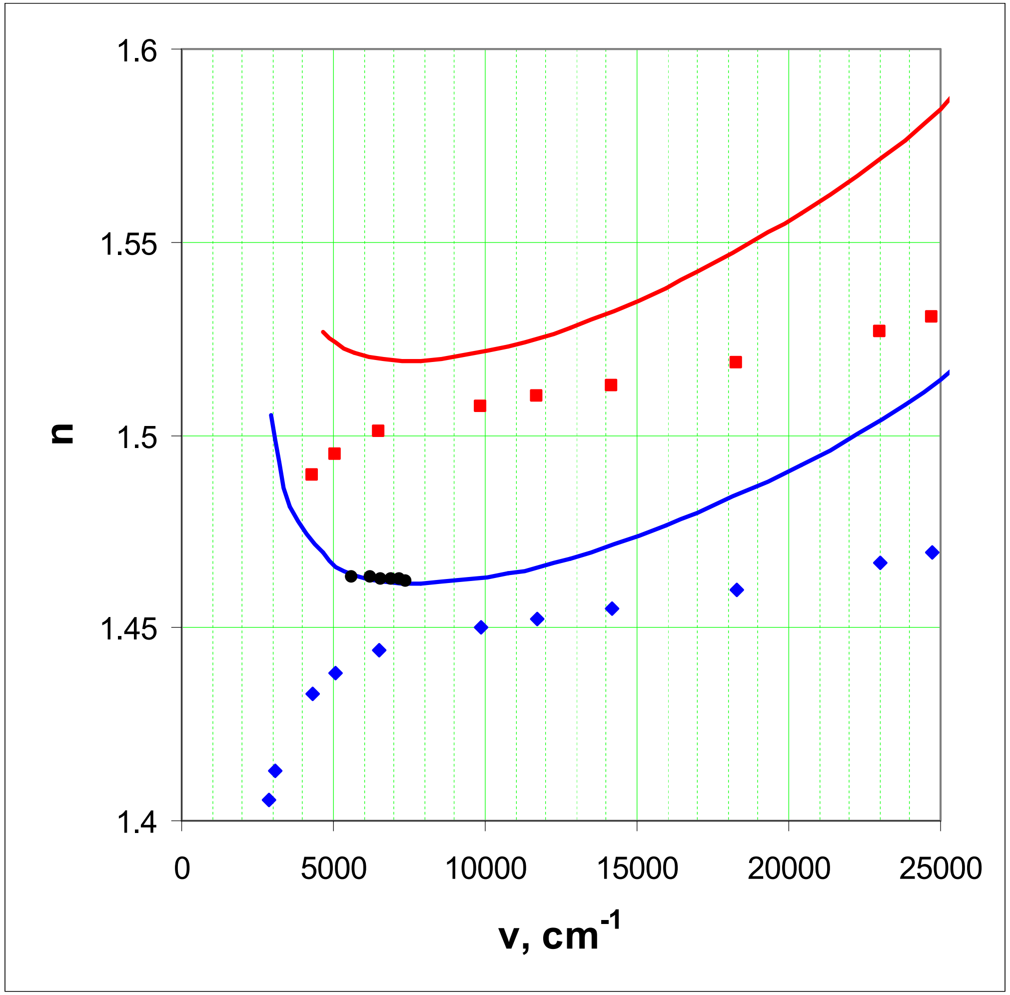
Is this spectral dependence significant or not?
For typical DL frequency tuning by current (~ 2 cм$^{-1}$) it leads to error 2 10^{-3} cм$^{-1}$. This value is dramatically higher than both errors due to other mechanisms and accuracy requirements considered above.

Conclusion: For accurate measurements, each FP etalon has to be calibrated and its spectral dependence has to be taken into account.

Back to basic: refractive index

$$FD = \frac{1}{2Ln_{eff}}$$

FP etalon free dispersion range – FD is determined by etalon length – L and effective reflective index n_{eff}. Using data obtained and measured L = 69.392(4) mm, n_{eff} of material used for etalon manufacturing can be determined (black solid cycles).



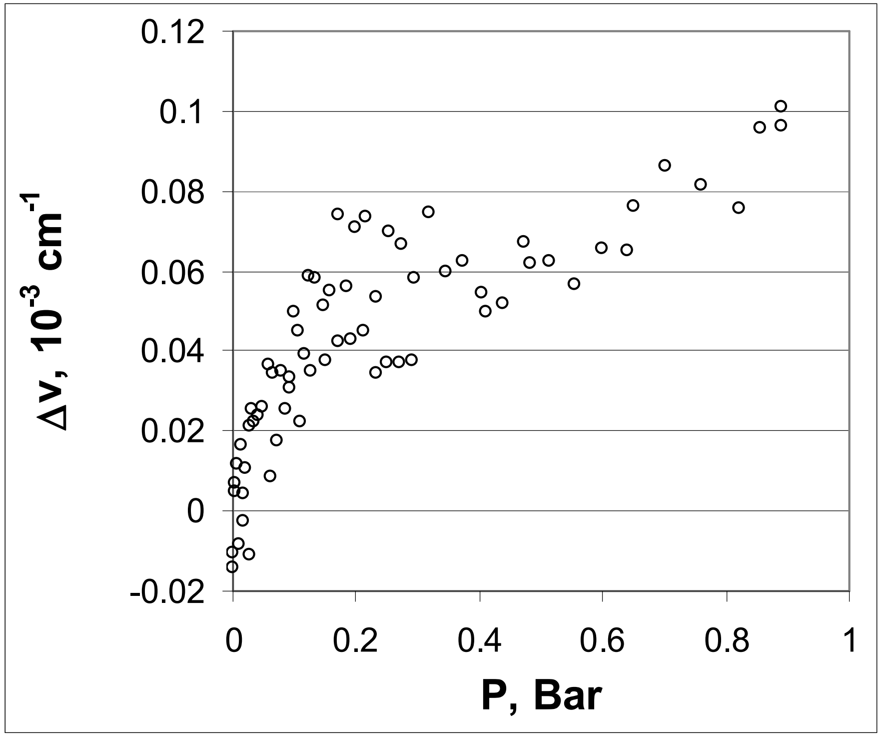
Red and blue points - reflective index of fused silica and BK7 glass [6], respectively. Color curves show n_{eff} obtained from these data. Significant reflective index dispersion influence can be easily observed.

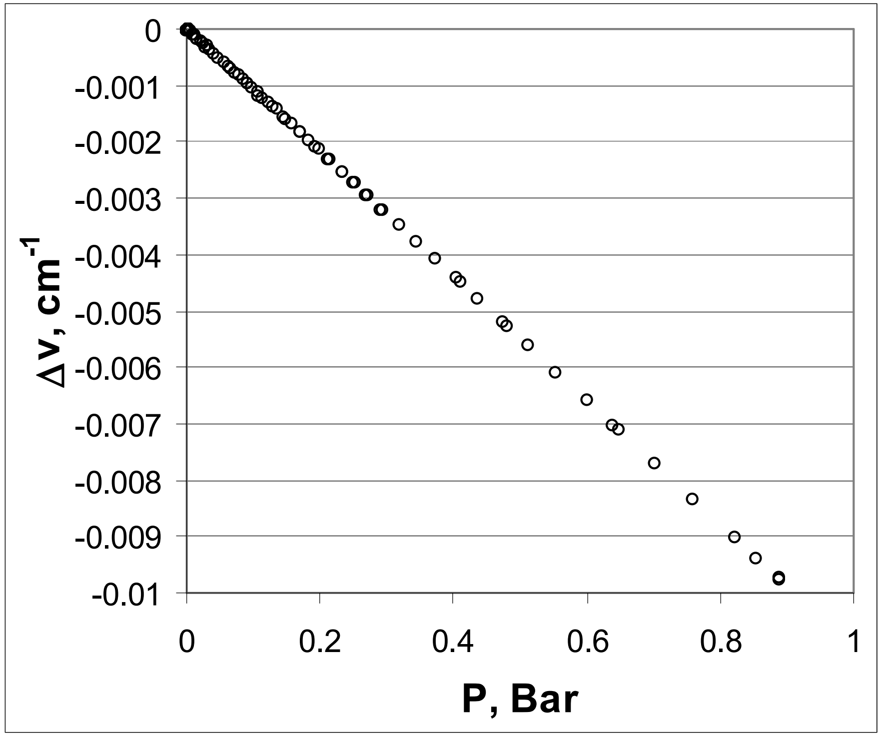
[6] http://www.escoproducts.com/html/bk-7_optical_glass.html

Glass used for FP etalon under consideration manufacturing, has optical properties close to BK7 glass.

Spectral line pressure shift

DL frequency tuning calibration procedure developed was tested during several experiments. Below some results of CO_2 line shape measurements are presented.





CO_2 line self pressure shift minus linear pressure dependence. Achieved DL frequency tuning accuracy provides possibility to detect several fine effects of dependence observed: spectral line asymmetry, non-linear gas behavior, etc.

CO_2 line self pressure shift as measured.

Details see B2.

Conclusion

- Mechanisms of DL frequency tuning errors were identified and analyzed. DL frequency calibrating procedure minimizing errors under consideration was proposed.

- DL frequency tuning calibration was developed using both FP calibrated and fiber etalons.

- FP etalon was calibrated with 4 10^{-5} relative accuracy.

- Fiber etalon calibration refer to calibrated FP etalon was developed and tested with 6 10^{-5} relative accuracy.

- Absolute accuracy of DL frequency tuning calibration below 10^{-4} cm^{-1} was demonstrated.