

Politecnico di Milano

INFN - Department of Electronics and Information Science
and CNR-CSTS



**Frequency stability measurements
of 1.5 *mm* erbium lasers
locked to acetylene absorption lines**

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INTRODUCTION

◆ DIODE-PUMPED SOLID-STATE LASERS find several **scientific and technical applications** due to their highest levels of **amplitude and frequency stability** e.g. in the fields of

- **Metrology**

Optical frequency standards and measurements

- **Physics**

Gravitational wave interferometers, QED tests

- **Doppler radar measurements in the atmosphere**

H₂O vapor and pollutant detection, wind velocity, geodesy

- **Optical communications**

Dense-WDM systems for long haul communications

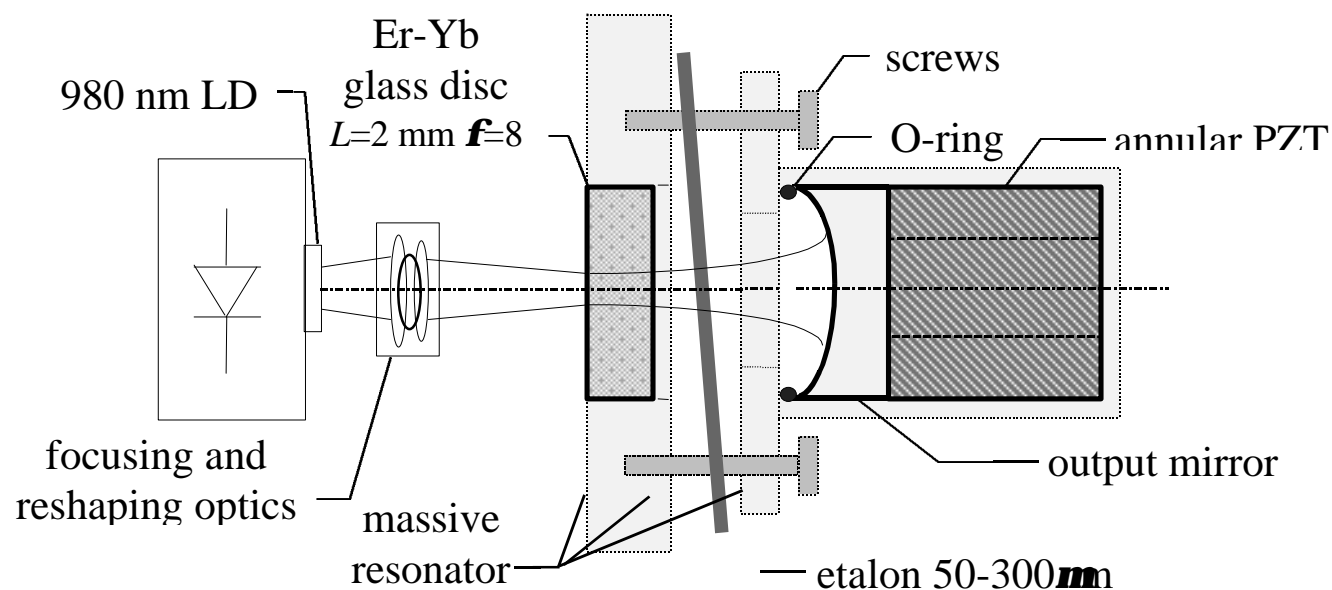
WDM AND D-WDM SYSTEMS REQUIREMENTS

- Widely spaced channels (WDM)
already in use with 4-8 channels, $D \sim 500$ GHz
- Tightly spaced channels (Dense-WDM)
now 32 and in next future 64 channels, $D \sim 50-100$ GHz
- ◆ **Grid of optical frequencies at 1.5 μm , $D=100$ GHz (0.8 nm)**
ITUT-T - *Draft recommendation G.692* (May 1997)
“Optical interfaces for Multichannel Systems with Optical Amplifiers”
- ◆ **Absolute frequency stability $\Delta n / n = 10^{-9}$ ($\Delta n \cong 200$ kHz)**
NPL - *Requirements Survey* (PRO_AFS-FR-2)
“Absolute frequency Standards for Optical Communications”
 $\Delta n / n = 10^{-10}$ for laboratory calibrations

PURPOSE OF THIS WORK

- ◆ **Frequency stabilization of Er-Yb lasers at 1.5 μm against absolute frequency references**
- Study and development of **novel Er-Yb lasers** for frequency stabilization in a **wide wavelength interval**
- Frequency stabilization against rovibrational lines of the acetylene molecule (**C_2H_2 and $^{13}\text{C}_2\text{H}_2$**)

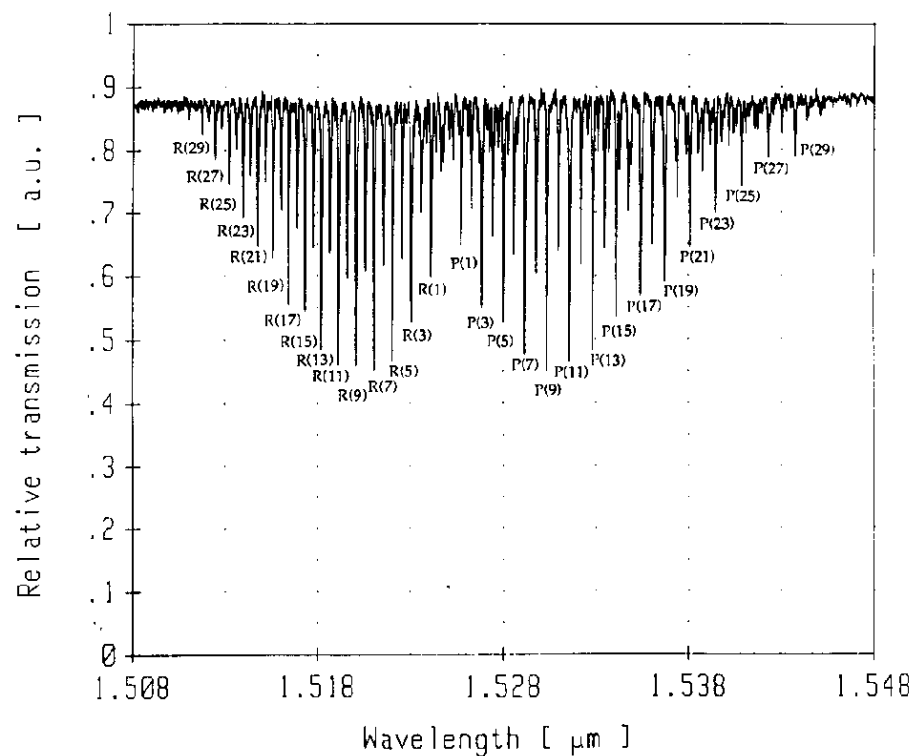
THE ERBIUM-YTTERBIUM TUNABLE MICROLASER



- ◆ **Novel Er-Yb:glass lasers** with $>10\text{ mW}$ single-frequency output power in the **1528-1571 nm** wavelength interval
- ◆ **Microlaser cavity** ($2\times 3\times 2\text{ cm}$), with thin etalon ($\sim 50\ \mu\text{m}$) for **single axial mode** selection, linear polarization and **wide wavelength tunability** ($>5\text{ THz}$) + **PZT for active frequency control** [possibility of 4-6 oscillating lines without the etalon]

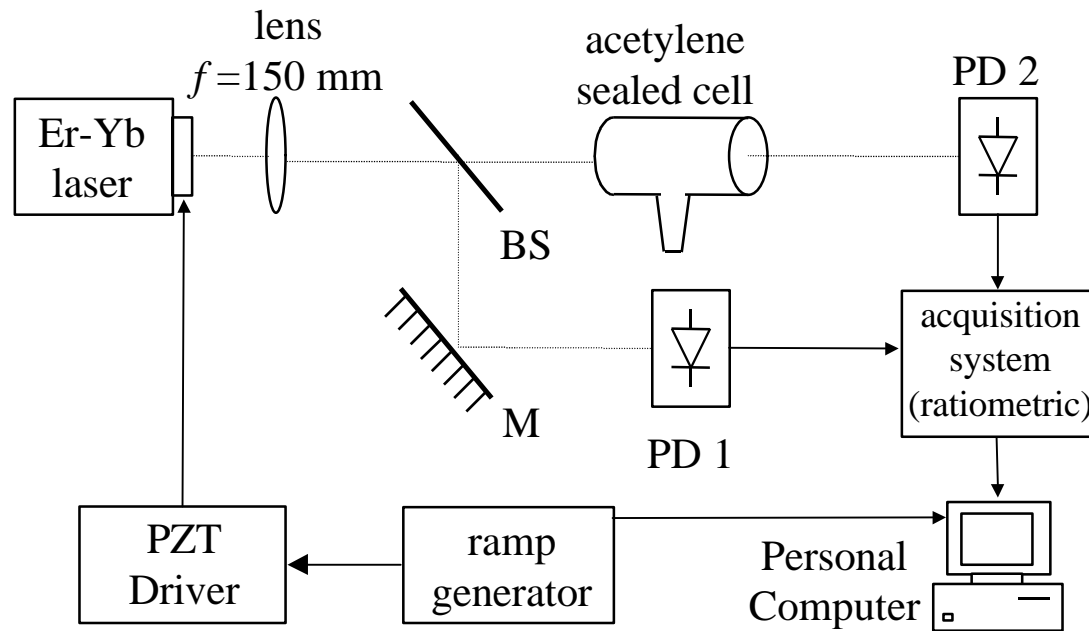
ABSOLUTE FREQUENCY REFERENCE AT 1.5 μm : ROVIBRATIONAL LINES OF THE C_2H_2 MOLECULE

- ◆ Acetylene (C_2H_2): strong rovibrational absorption lines, with ~ 70 GHz spacing, in the **1510-1540 nm spectral region**



- ◆ Isotopic acetylene ($^{13}\text{C}_2\text{H}_2$) for locking at **1530-1550 nm**

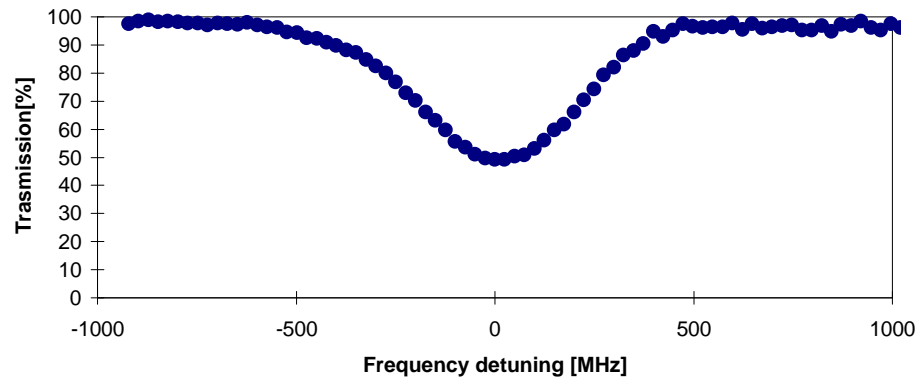
SPECTROSCOPIC MEASUREMENTS ON C₂H₂



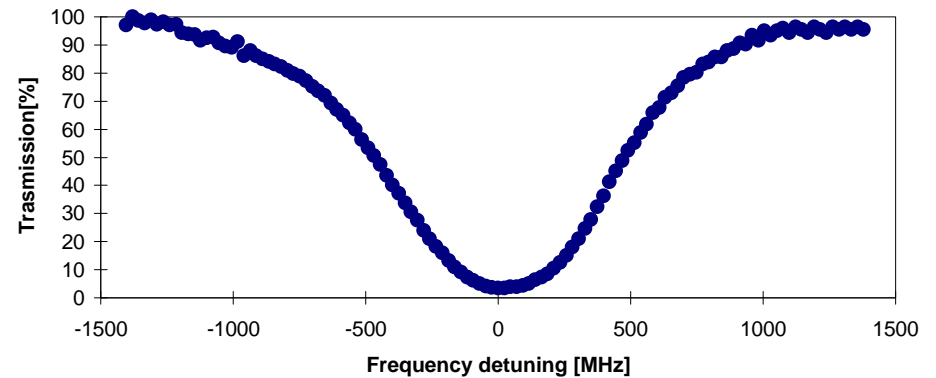
- ◆ **Experimental set-up** for the measurement of transmission profiles of C₂H₂ lines at different gas pressures (1 kPa, 2 kPa and 5 kPa)
- ◆ Amplitude noise compensation via numerical normalization

SPECTRAL PROFILES OF P(15) ABSORPTION LINE

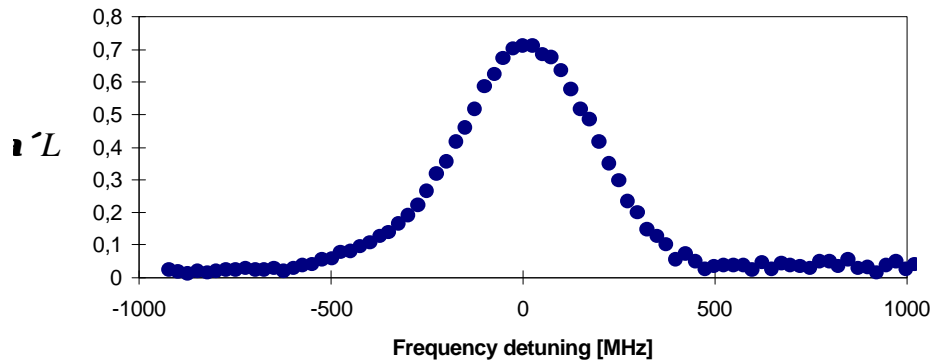
Cell transmission at 1 kPa
FWHM = 480 MHz



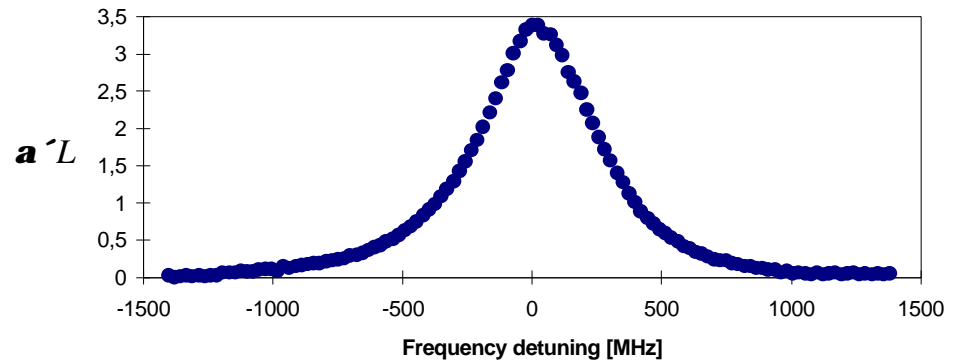
Cell transmission at 5 kPa
FWHM = 900 MHz



Absorption coefficient at 1 kPa
FWHM = 420 MHz



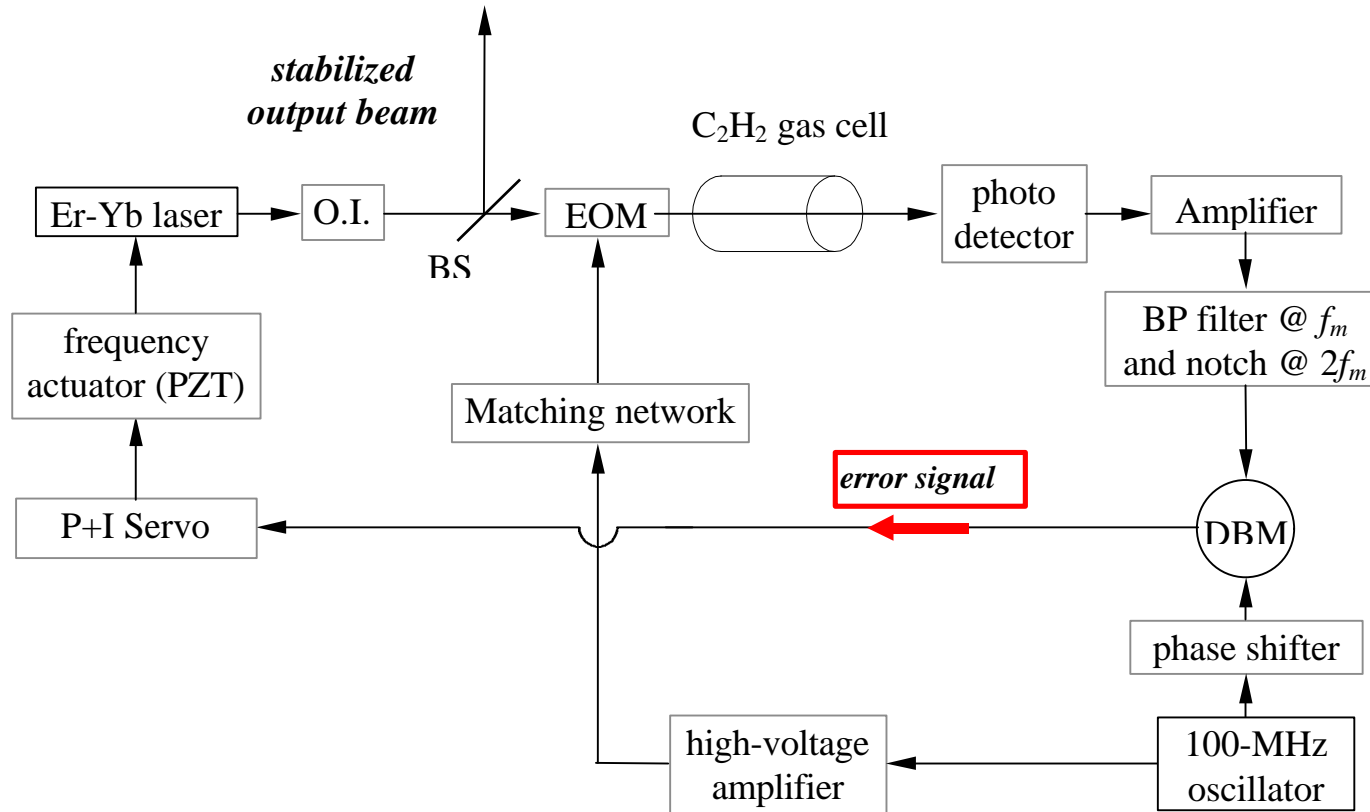
Absorption coefficient at 5 kPa
FWHM = 540 MHz



- ◆ **Transmission profiles** (C_2H_2 in quartz cells $L=0.1$ m)
- calculation of the absorption coefficient \mathbf{a} [m^{-1}]

POUND-DREVER FREQUENCY STABILIZATION

- ◆ **Electrooptic phase modulation** ($f_m=100$ MHz, $m=0.16$ rad) and **synchronous detection** (*mixer*: DBM)



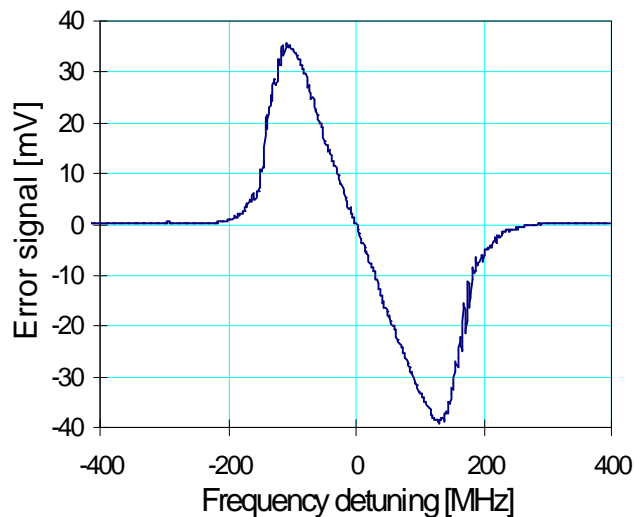
- ◆ **Two identical lasers** independently locked to the peak of

C₂H₂ P(15) line with a transition wavelength of 1534.099 nm

DISPERSION-LIKE PROFILES FOR THE P(15) LINE

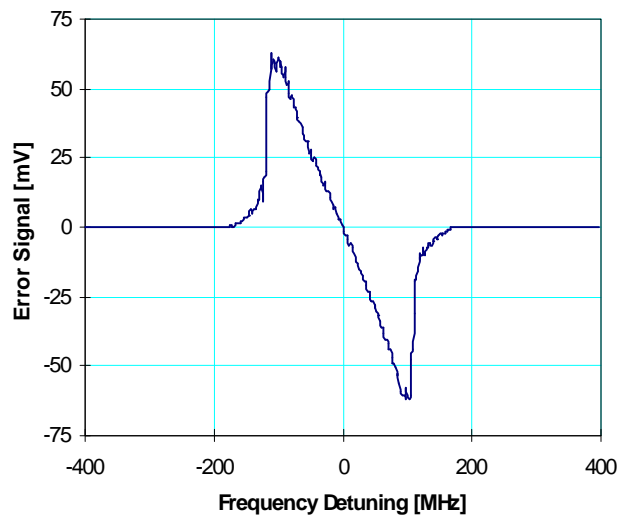
- ◆ **Discriminator curves** (voltage vs. frequency detuning) for C_2H_2 cells with $L=100$ mm at different pressures

slope = 0.40 mV/MHz



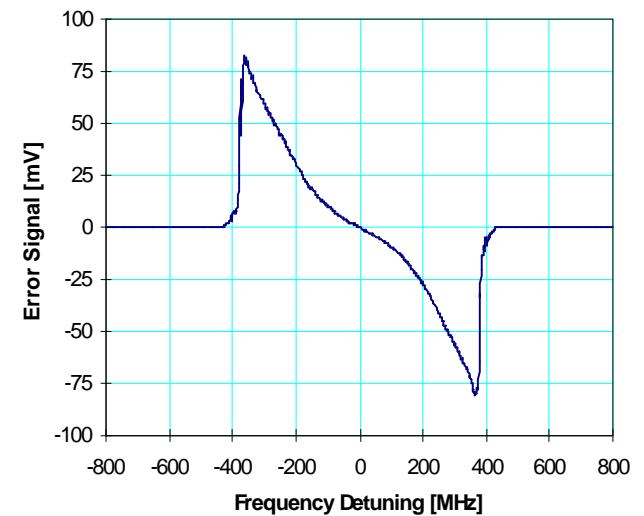
$p = 1$ kPa

slope = 0.52 mV/MHz



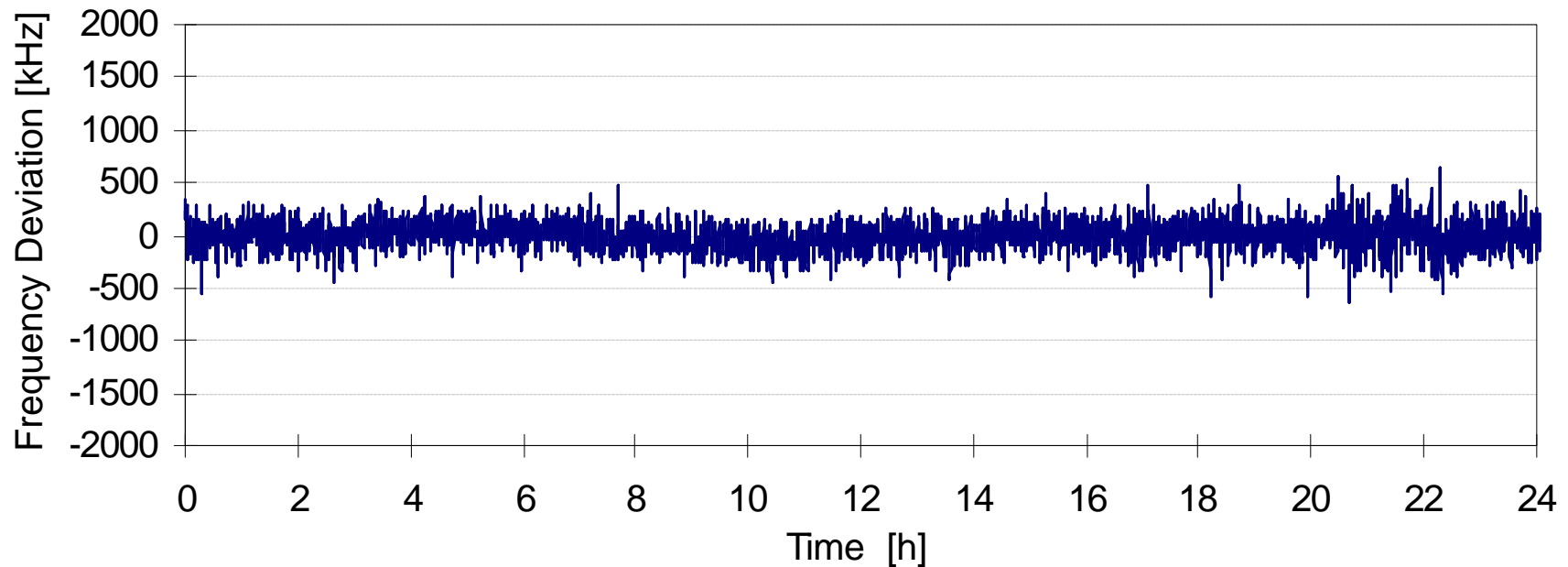
$p = 2$ kPa

slope = 0.09 mV/MHz



$p = 5$ kPa

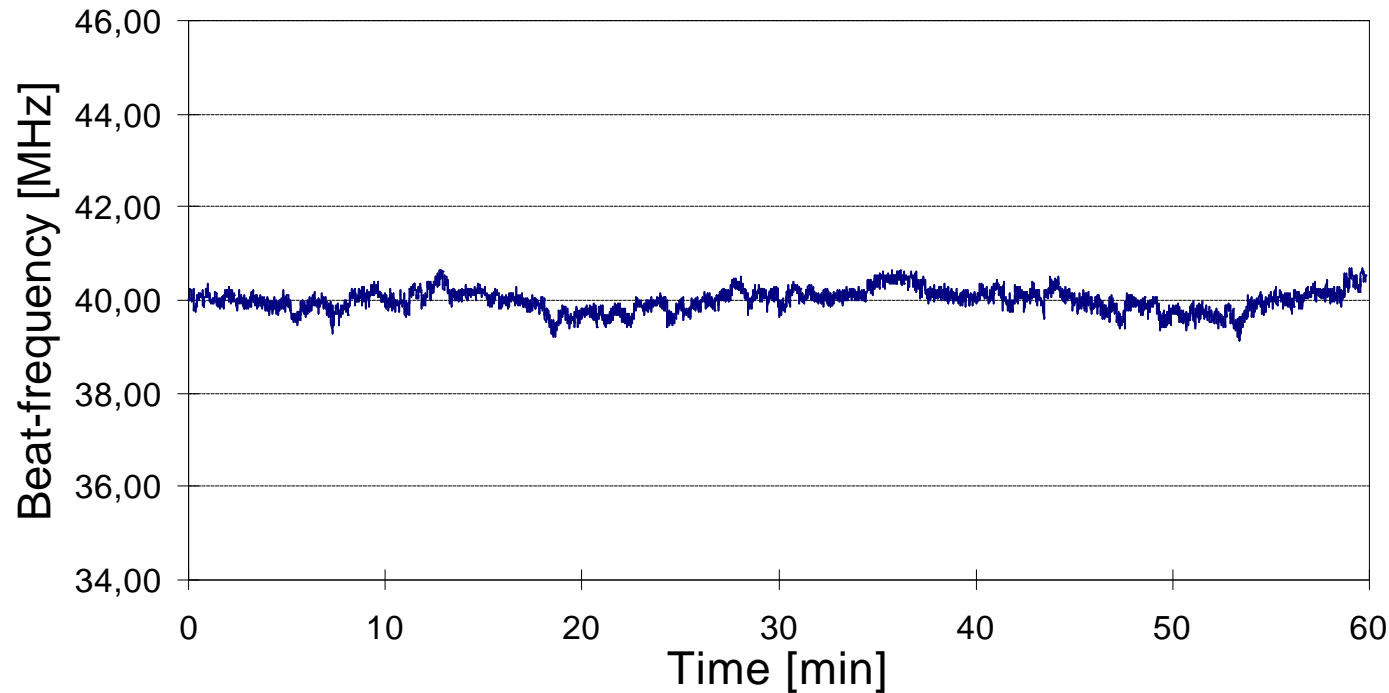
FREQUENCY STABILITY RESULTS WITH POUND-DREVER LOCKING AGAINST C₂H₂ P(15) LINE



Time behavior of the closed-loop error signal

◆ $n_{e,rms} = 160$ kHz over 24 h ($Dn/n < 1 \times 10^{-9}$); $f_{\text{sampl.}} = 0.05$ Hz

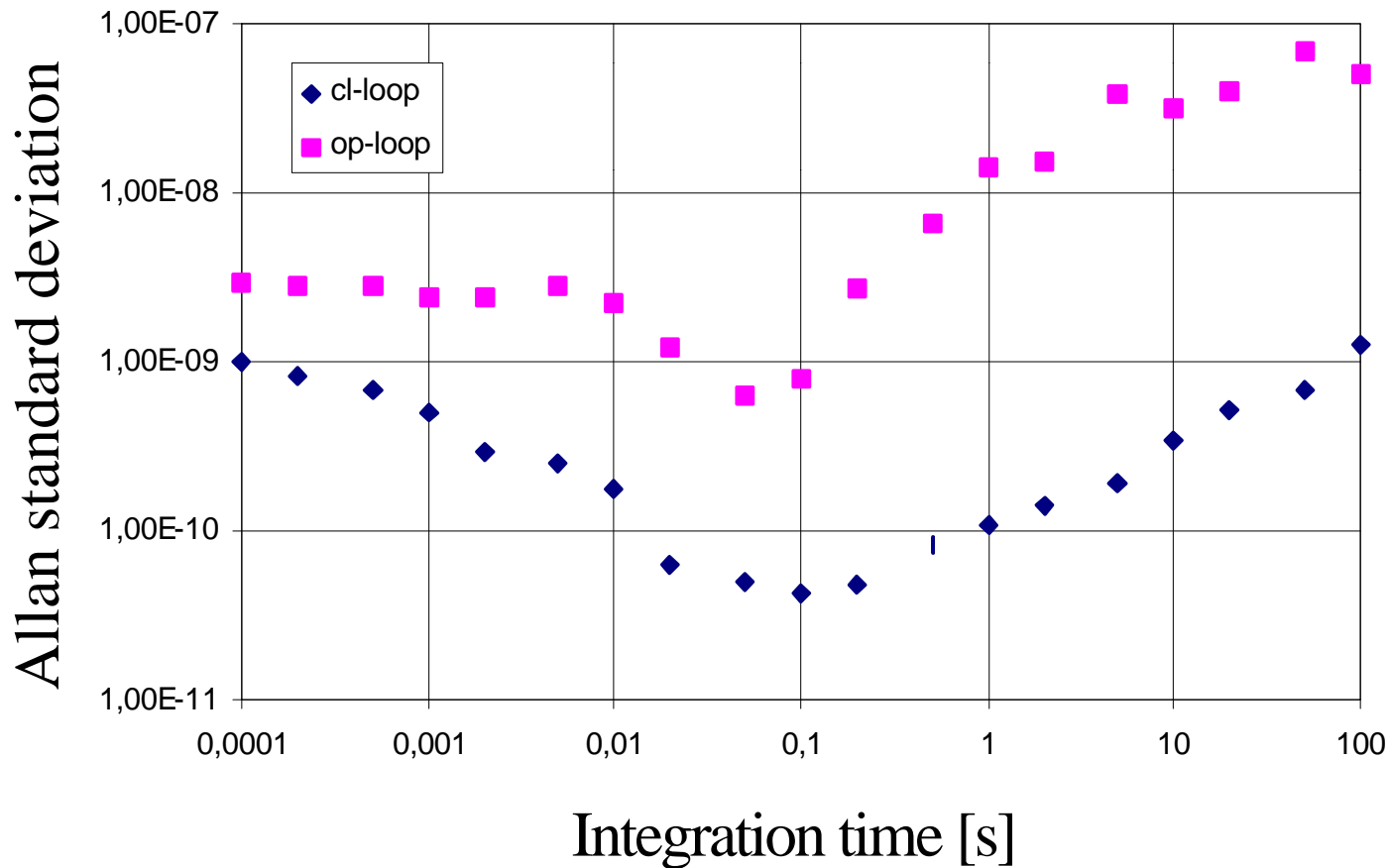
FREQUENCY STABILITY RESULTS WITH POUND-DREVER LOCKING AGAINST C₂H₂ P(15) LINE



Time behavior of the beat note frequency

- ◆ $n_{batt,rms} = 280 \text{ kHz}$ over **60 min** ($\mathbf{Dn/n} \cong 1.4 \times 10^{-9}$)
 $f_{\text{sampl.}} = 0.5 \text{ Hz}$

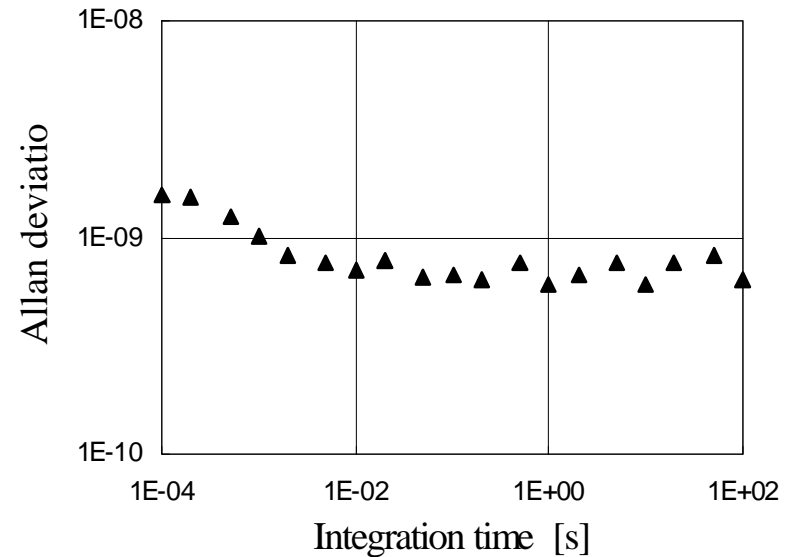
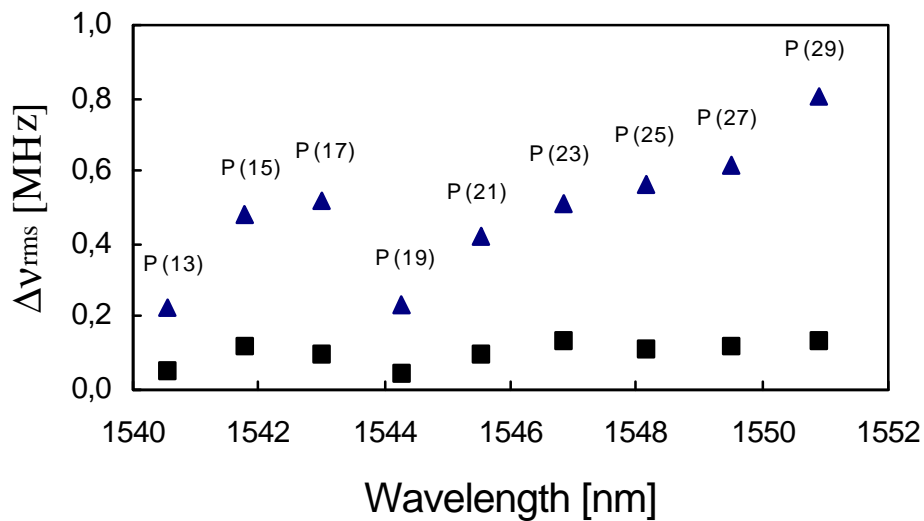
ALLAN STANDARD DEVIATION



- ◆ St.dev. $\mathbf{s}(2, \mathbf{t})$ of $\mathbf{n}_{batt} / \mathbf{n}_o < 1 \times 10^{-9}$ for $100 \mathbf{m} \leq \mathbf{t} \leq 100 \text{ s}$
 $\mathbf{s} = 4 \times 10^{-11}$ for $\mathbf{t} = 0.1 \text{ s}$
- ◆ Noise reduction between 20 and 40 dB

FRINGE-SIDE-LOCKING AGAINST $^{13}\text{C}_2\text{H}_2$

- ◆ **Wavelength tunability** and frequency locking from 1540.567 nm, **P(13)** line, to 1550.866 nm, **P(29)** line, of the $^{13}\text{C}_2\text{H}_2$ molecule

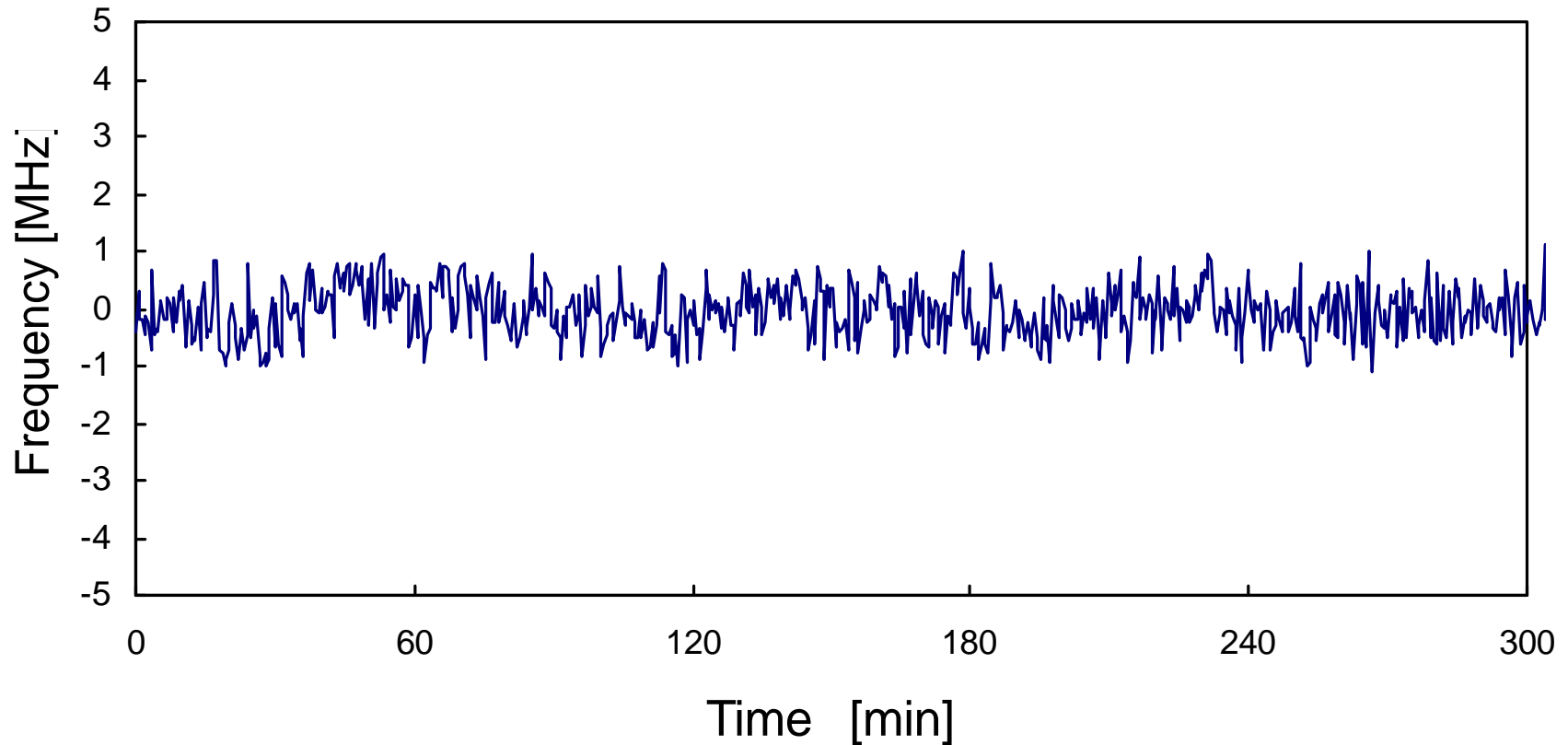


Tunability and frequency locking
Averaging time: “◆” 50 ms ;” “ 1 s

Allan standard deviation

- ◆ **10^{-9} Allan st. dev.** between 0.1 ms and 100 s when locked against P(13) line (strongest odd line)

BEAT NOTE RECORDING



Beat note frequency fluctuations [against C₂H₂ P(13) line]

◆ **$n_{e,rms} = 440$ kHz over 5 h ($\mathbf{Dn/n} < 2.7 \times 10^{-9}$); $f_{\text{sampl.}} = 0.04$ Hz**

CONCLUSIONS

- ◆ Novel widely-tunable Er-Yb microlasers with >40 nm wavelength tunability in single-frequency operation at >10 mW TEM₀₀ output power linearly polarized 100:1 + PZT and temperature cavity length control
- ◆ *Pound-Drever technique*
Er-Yb lasers frequency stabilized on **C₂H₂ P(15) line** at 1534.099 nm with $<10^{-10}$ Allan standard deviation
measured rms frequency stability: 160 kHz (error signal)
280 kHz (beat note)
- ◆ *Fringe-side-locking technique*
Er-Yb against frequency stabilized on **¹³C₂H₂ P(13)-P(29)** lines with $\sim 10^{-9}$ frequency stability

FUTURE DEVELOPMENTS

- Frequency stabilization of a comb of optical frequencies in multi-axial mode operation
- Use of simpler frequency references e.g. temperature stabilized gratings
- Linewidth reduction by a fast control loop employing an electro-optical modulator
- Frequency stabilization against C_2H_2 Doppler-free absorption lines by intra- or extra-cavity saturated absorption