DFB Diode Laser Based Sensor for Isotope Ratio Detection of Methane using Continuous Wave Cavity Ring-down Spectroscopy

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- **Temperature Tuning for DFB lasers**

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Motivation for Studying Methane Isotopes

1. Motivation for studying methane

On Earth

~1800 ppb

- ❖ CH_4 is a 80 times stronger green house gas than CO_2 on molecule-for molecule basis.
- ❖ Warms up atmosphere and helps form ozone.

On Mars

~10 ppb

- ❖ Peaking when it's warm in some regions.
- ❖ Might be a sign of biological activities.

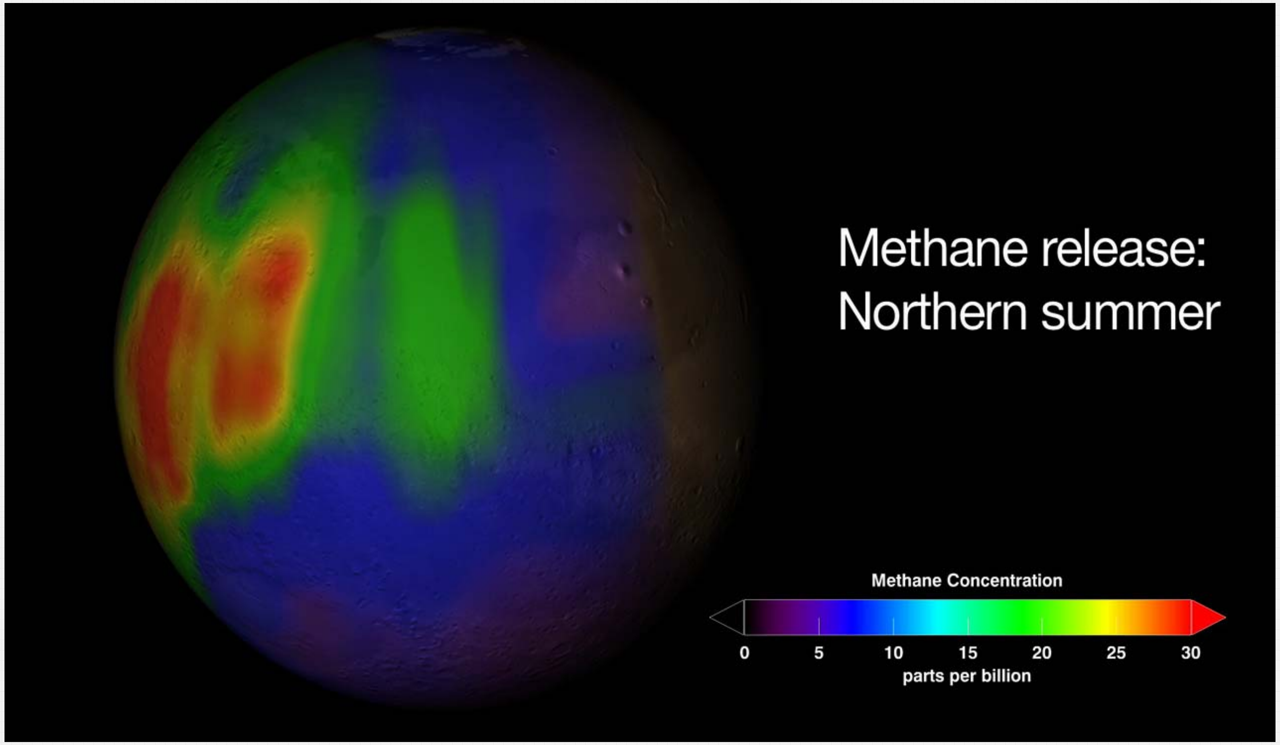


Fig 1. Concentrations of Methane discovered on Mars <1>

<1> Credit:NASA

Motivation for Studying Methane Isotopes

2. Motivation for studying methane's isotopes

Three major isotopes of methane: CH_4, CH_3D and $^{13}CH_4$

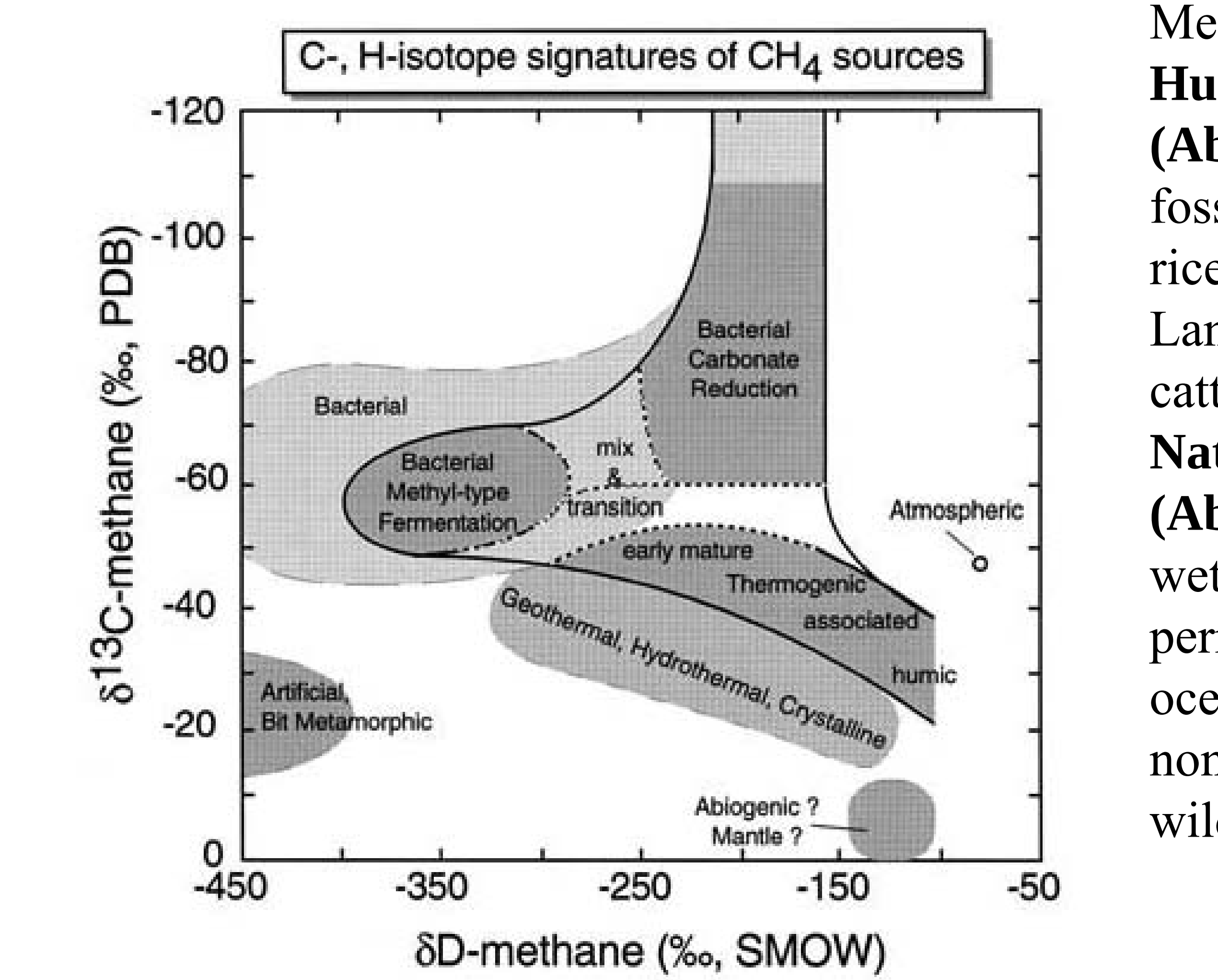


Fig 2. Isotope ratio measurements on CH_4 <2>

Methane sources on earth:

Human activities (About 2/3):

fossil-fuel extraction
rice paddies
Landfills
cattle…

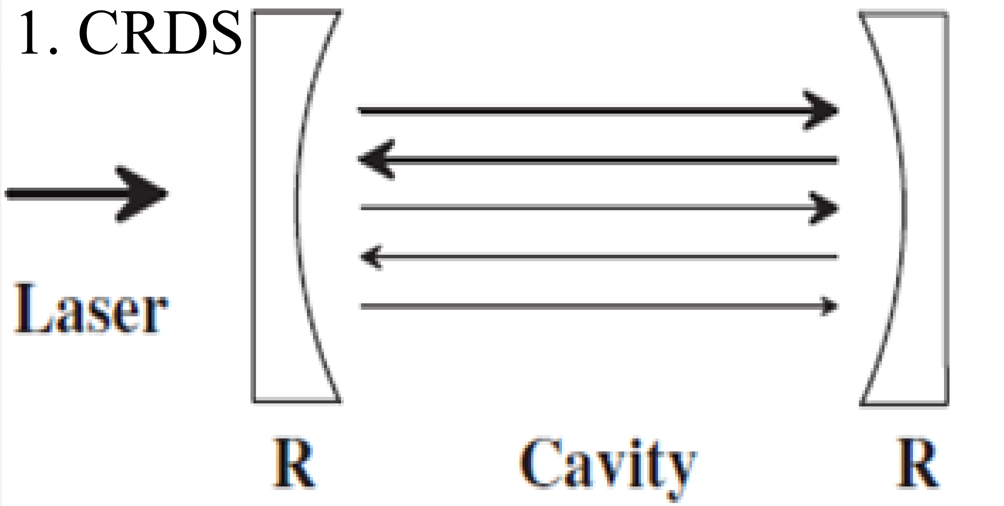
Natural sources (About 1/3):

wetlands, gas hydrates, permafrost, termites, oceans, freshwater bodies, non-wetland soils, wildfires…

<2> Onstott, Astrobiology, 2006

Cavity Ring-down Spectroscopy

1. CRDS



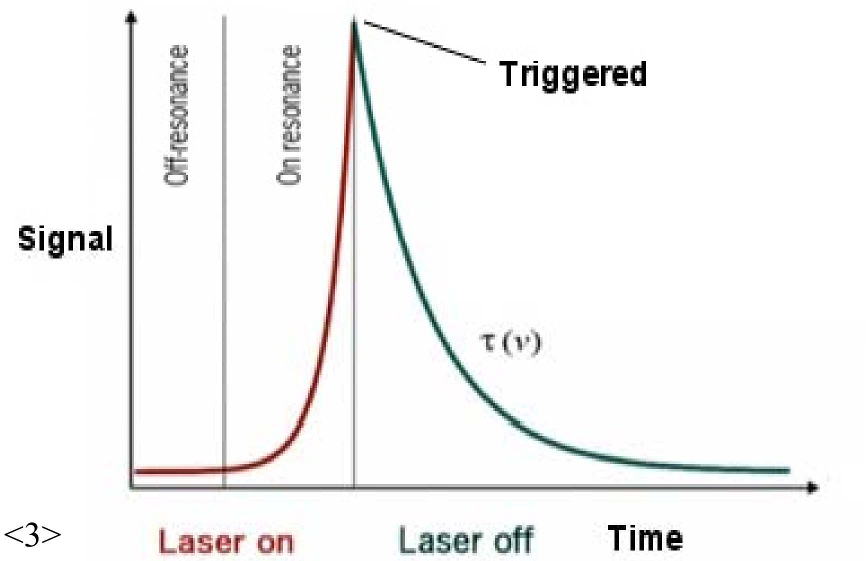


Fig 3. Schematic of pulsed CRD technique [3]

$$\frac{I}{I_0} = \cdot \exp\left(-\frac{t}{\tau}\right) \Rightarrow \Delta k(\nu) = \frac{1}{\tau} - \frac{1}{\tau_0} \Rightarrow \begin{cases} \sigma(\nu) = \dfrac{\Delta k(\nu)}{N \cdot c} \\ N = \dfrac{\Delta k(\nu)}{\sigma(\nu) \cdot c} \end{cases}$$

Advantages of CRDS:

- High sensitivity due to long absorption length.
- Immune to intensity variations in laser.
- High throughput: individual ring down events occur on the millisecond time scale.

<3> K. K. Lehmann *et. Al*, An Introduction to Cavity Ring-Down Spectroscopy, 2009

Cavity Ring-down Spectroscopy

2. Experimental Setup

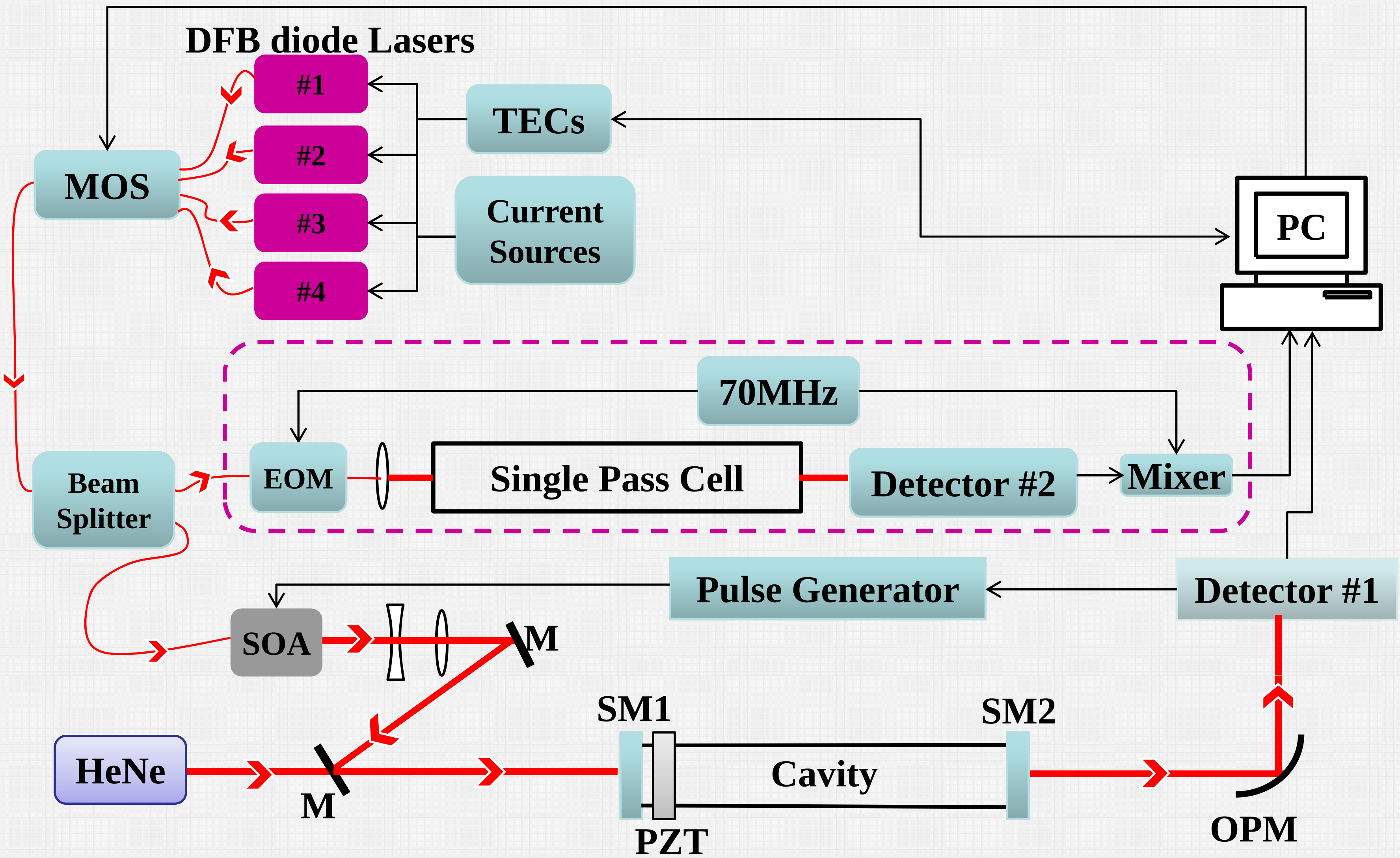


Fig 4. Schematic of Experimental Setup

Cavity Ring-down Spectroscopy

3. DFB laser diode

◆ Simple and small design.
◆ Grating structure within the semi-conductor material, to serve as the wavelength selective element and reflects light back into the cavity to form the resonator.
◆ Tuning is accomplished by modulating either laser current or operating temperature.

Advantages:

- Absence of any critical opto-mechanical components
- High long-term stability and reliability

Applications:

- High-resolution spectroscopy
- Laser cooling, ultra-cold atoms
- Plasma physics
- Trace gas analysis
- Combustion monitoring
- Seed laser for LIDAR measurements
- Generation of tunable CW THz radiation

1. CH_3D Measurements

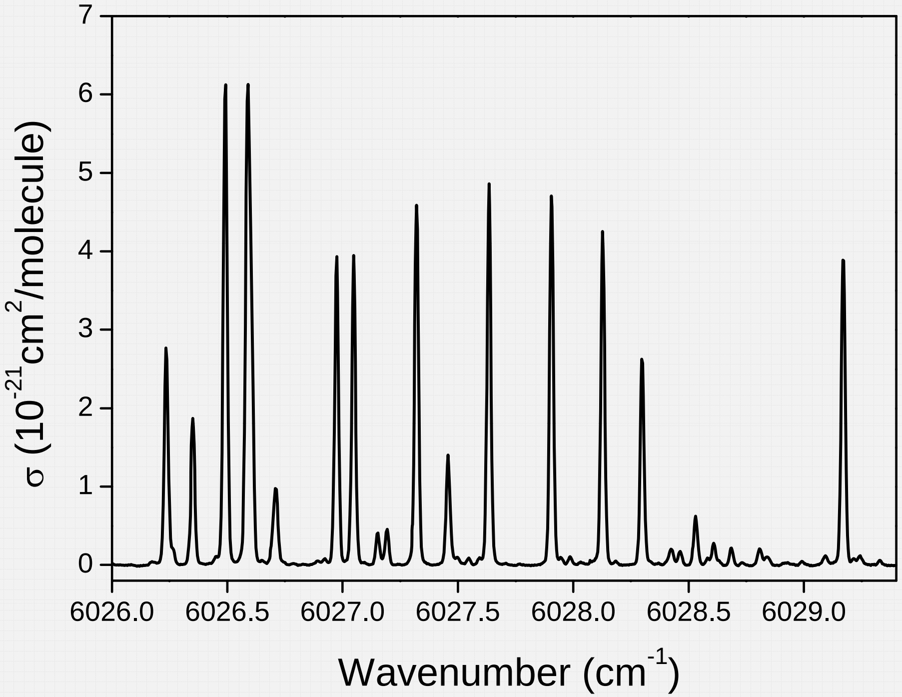


Fig 5. Cavity ring-down spectroscopy of CH_3D in ~ 8.3 Torr N_2 buffer gas. The CH_3D number density was 5.2×10^{13} molecule/cm^3.
The temperature tuning coefficient is approximately -12.5 GHz/^{o}C, i.e. -0.42 cm^{-1}/^{o}C.

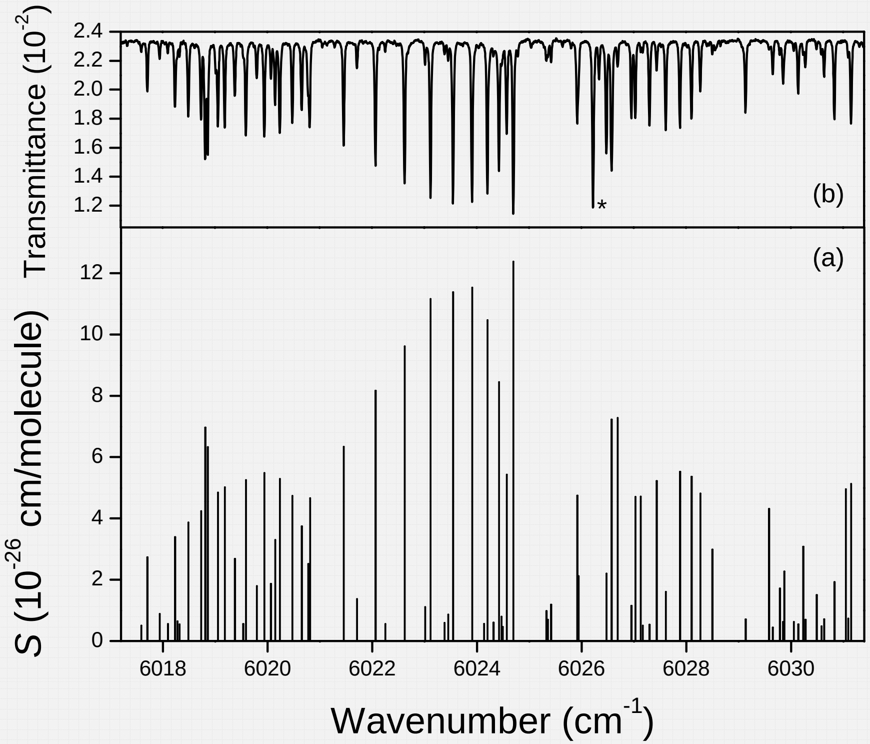


Fig 6 (a) Line strengths of CH_3D in the wavelength range of 6017.5 – 6031.5 cm^{-1}. The total pressure in the cavity was around 8.3 Torr. The CH_3D number densities varied between 0.5-2.0 $\times10^{14}$ molecule/cm^3.

Fig 6 (b) CH_3D absorption spectrum from reference (room temperature, 76.7 Torr pressure, 105 m absorption path length). Resolution is 0.01 cm^{-1}. A CH_4 absorption line is marked with an asterisk.

Table 1. Part of Line strengths of CH_3D in the 6017.5 – 6031.5 and 6046.5 – 6070.0 cm^{-1} wavenumber region, and the possible quantum numbers of the perpendicular band $2\nu_4(E)$ transitions along with their calculated absorption positions and intensities. Not all the CH_3D lines were assigned. Measured line strengths correspond to cm per CH_3D molecule. Transitions with star (*) belong to the parallel band $2\nu_4(A_1)$, whose absorption positions and intensities were not simulated.

Measured ν (cm^{-1})	Measured *S* (10^{-26} cm/molecule)	Calculated ν (cm^{-1})	Calculated Intensity (a.u.)	Transition Assignment
6017.590	0.506			
6017.706	2.74	6017.684	0.680	${}^PQ_1(10)$
6017.941	0.887	6017.767	0.633	${}^RQ_0(14)$
6018.098	0.553			
6018.235	3.40	6018.229	2.195	${}^PQ_1(9)$
6018.279	0.644			
6018.322	0.541			
6018.488	3.87	6018.586	0.990	${}^RQ_0(13)$
6018.731	4.24	6018.730	2.673	${}^PQ_1(8)$
6018.811	6.98	--	--	${}^QR_0(4)$ *
6018.858	6.34	--	--	${}^QR_1(4)$ *
6019.053	4.85	--	--	${}^QR_2(4)$ *
6019.184	5.02	6019.185	3.099	${}^PQ_1(7)$

1. CH_3D Measurements

Pressure-Broadening Coefficients

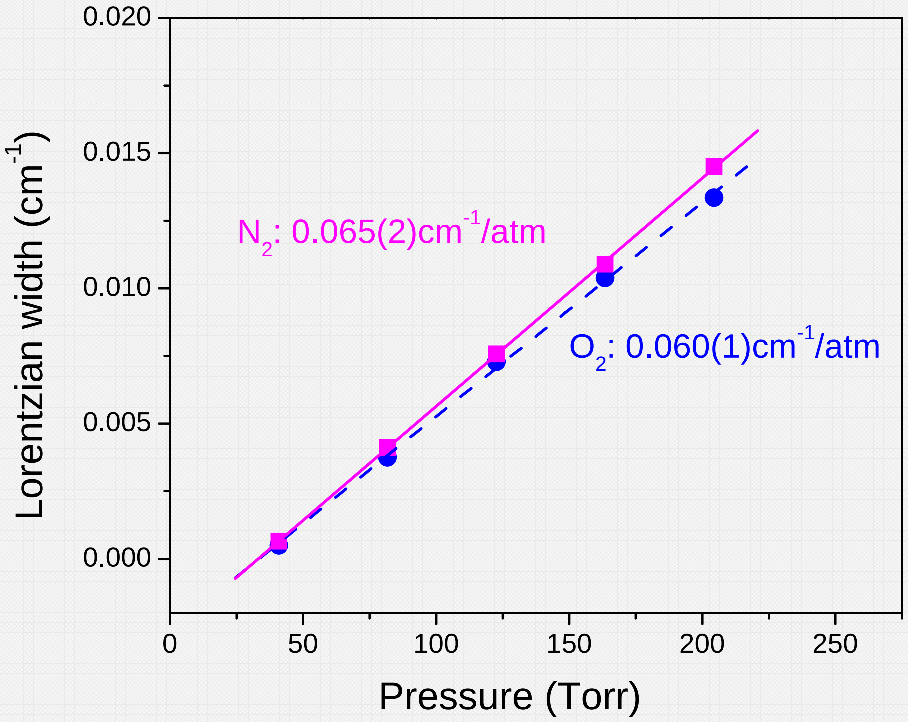


Fig 7. The N_2 (square and solid line) and O_2 (circle and dash line) pressure-broadening coefficients (HWHM) of the CH_3D absorption line at 6017.941 cm^{-1}. The scattering symbols are measurements and the lines are linear fits. The slope of the linear fit is defined as pressure-broadening coefficient for HWHM.

Pressure-Shift Coefficients

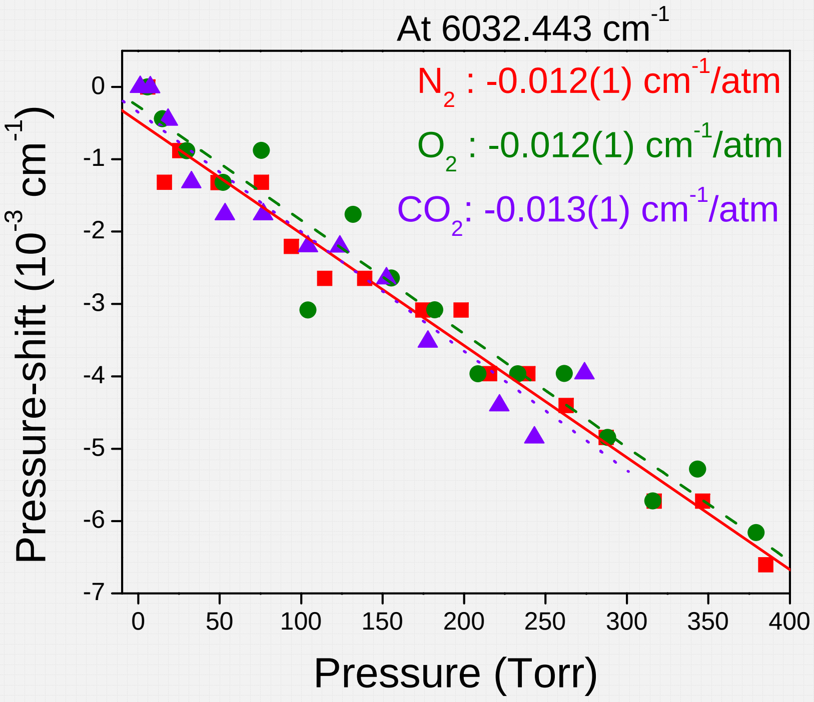


Fig 8. The N_2 (square and solid line), O_2 (circle and dash line), and CO_2 (triangle and dotted line) pressure dependence of the CH_3D absorption peak at ~ 6032.443 cm^{-1}. The scattering symbols are measurements and the lines are linear fits. The slope of the linear fit is defined as pressure-shift coefficient.

2. CH_2D_2 Measurements

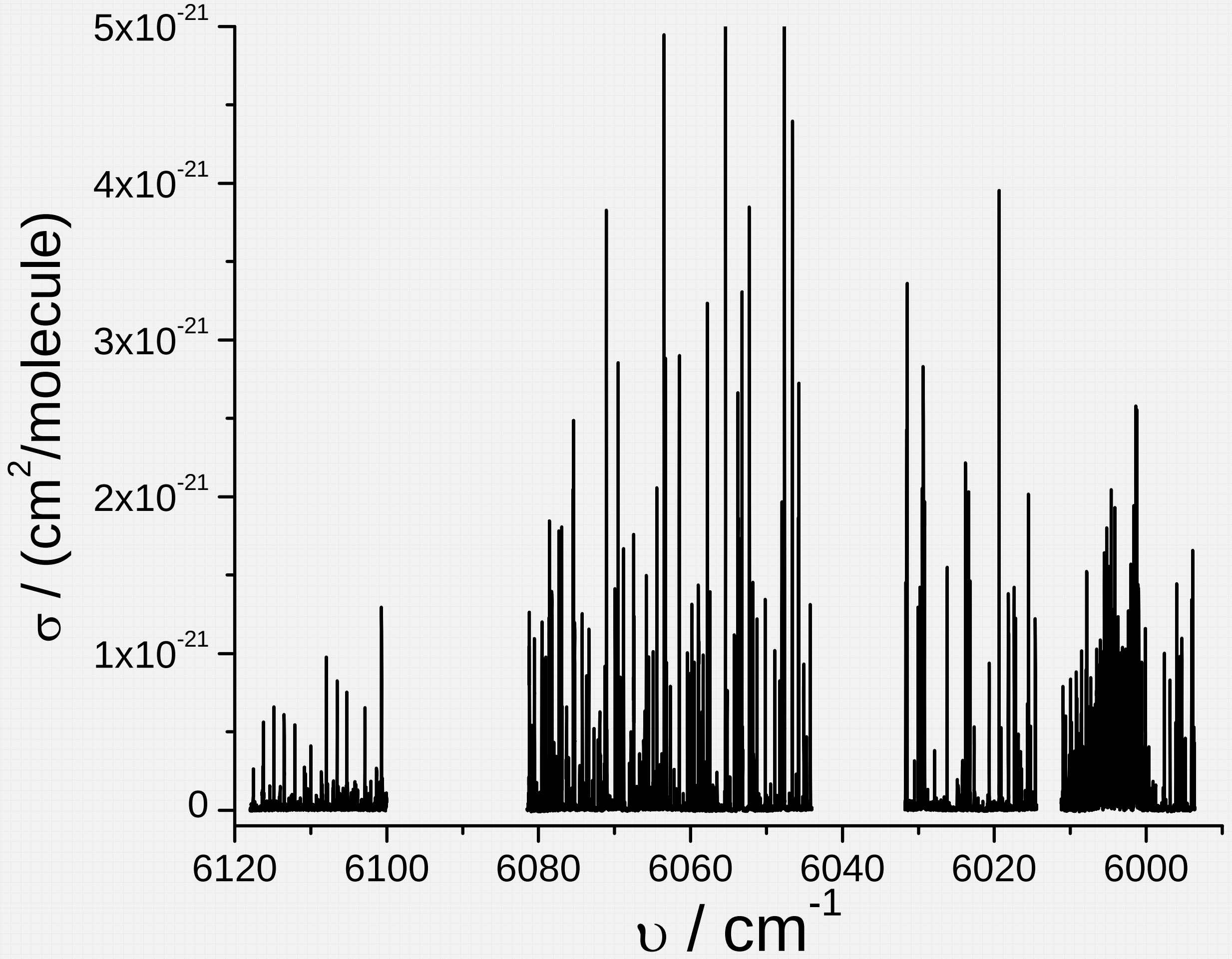


Fig 9. CRDS of CH_2D_2 absorption spectra in 16 Torr N_2 buffer gas measured by 6 different DFB diode lasers. The CH_2D_2 number density was 9.87×10^{13} molecule/cm^3.

3. Electronic Feedback for locking lasers

Why do we want to lock the laser:

1. Reduced absorption cross section error $\sigma(\nu) = \dfrac{\Delta k(\nu)}{N \cdot c}$
2. Improved cavity transmission $T_c = \dfrac{T^2}{(1-R)^2} \cdot \dfrac{1}{1+2\pi\tau \cdot \Delta\upsilon}$

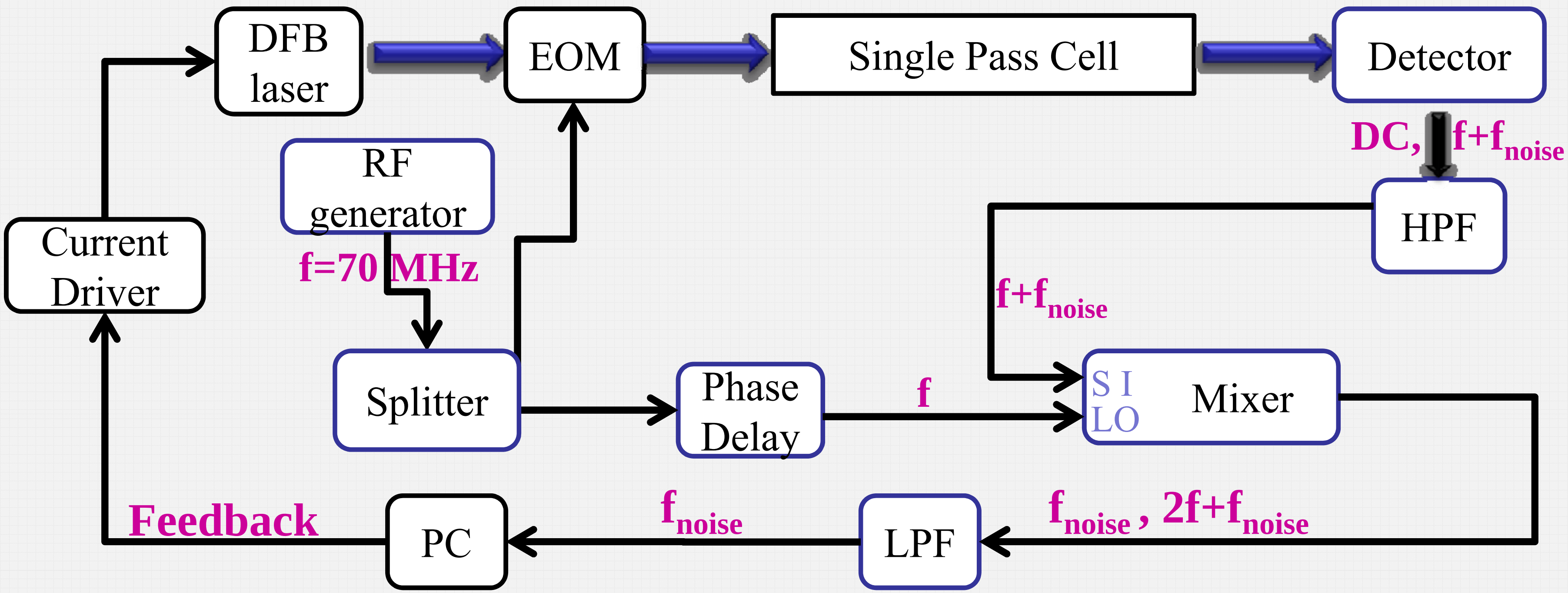


Fig 10. Schematic of 1f WMS feedback system

3. Electronic Feedback for locking lasers

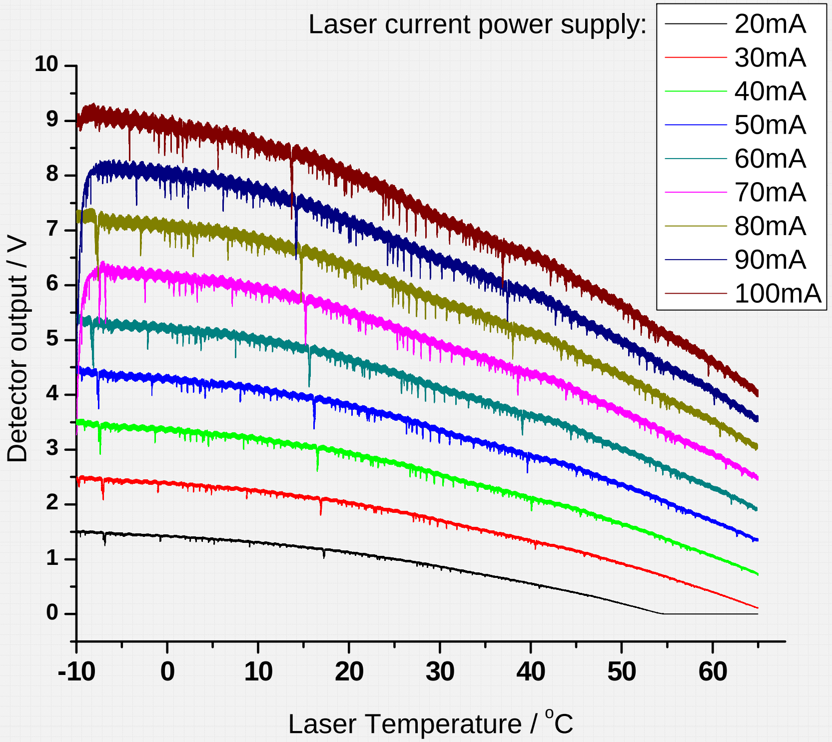


Fig 11. Detector output voltage of single pass cell filled with ~8torr 98% CH_3D at different laser driver current

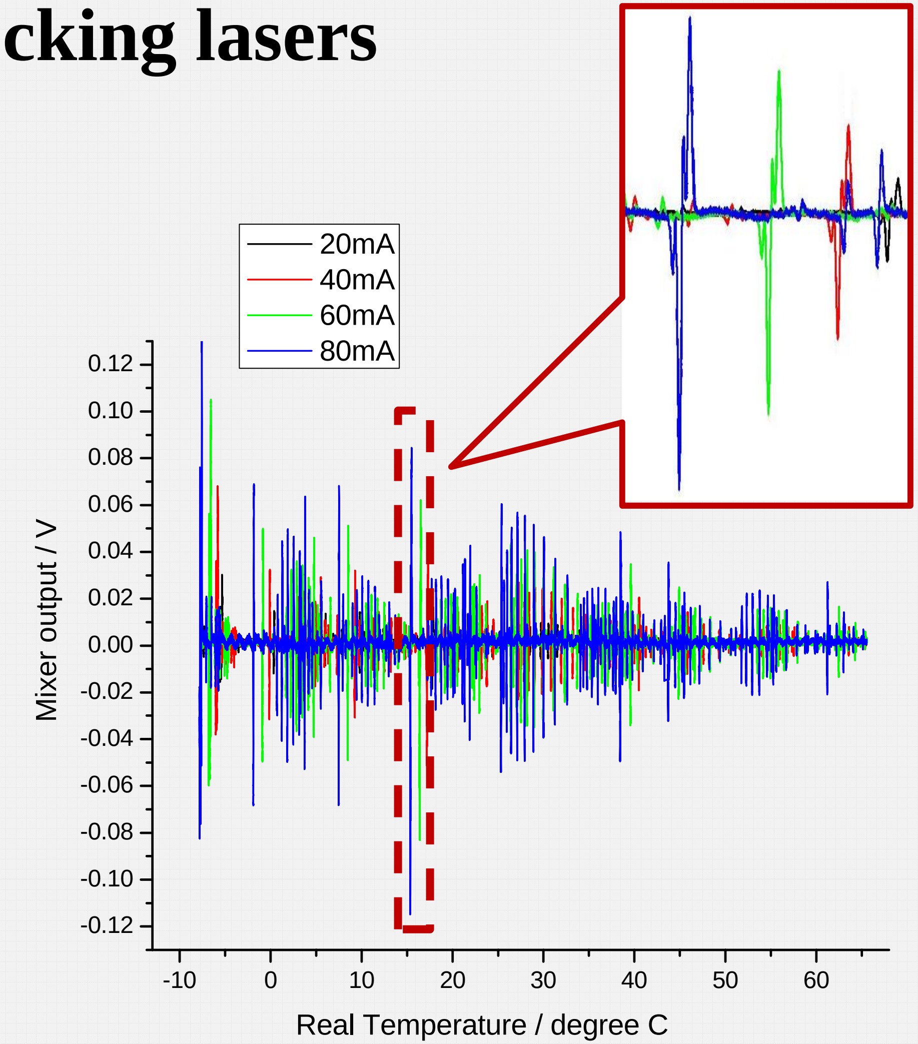


Fig 12. Mixer output variance with laser temperature tuning at different laser driver current

3. Tuning PID control

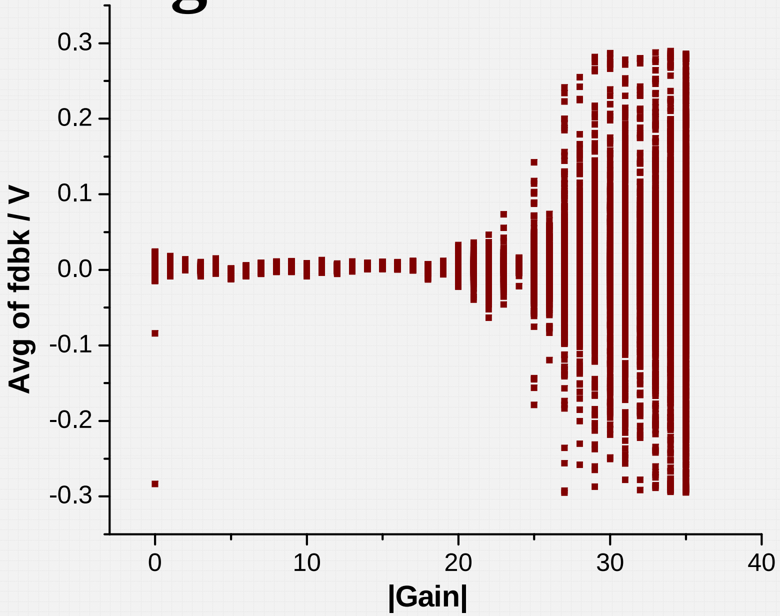


Fig 13. Feedback signal jitter with different PID total gain

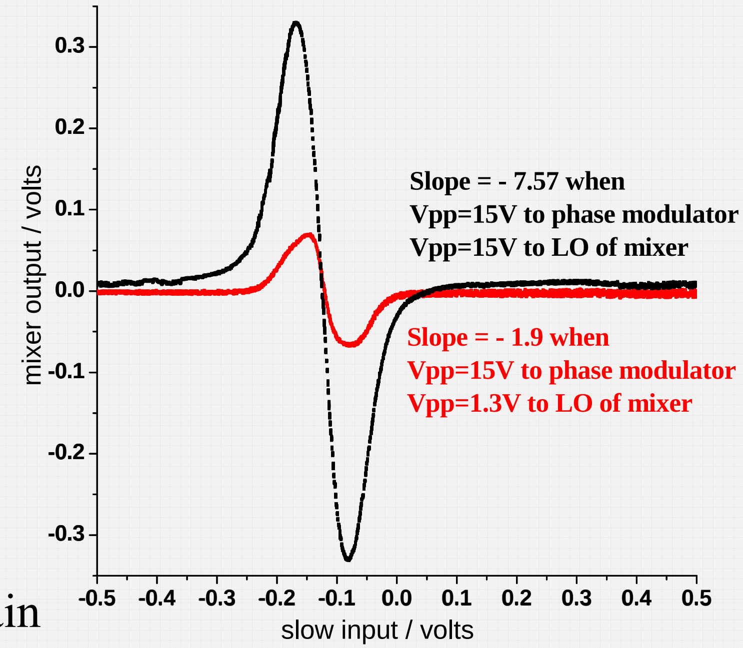


Fig 14. Examples of how modulation amplitudes affect the slope mixer output vs slow input.

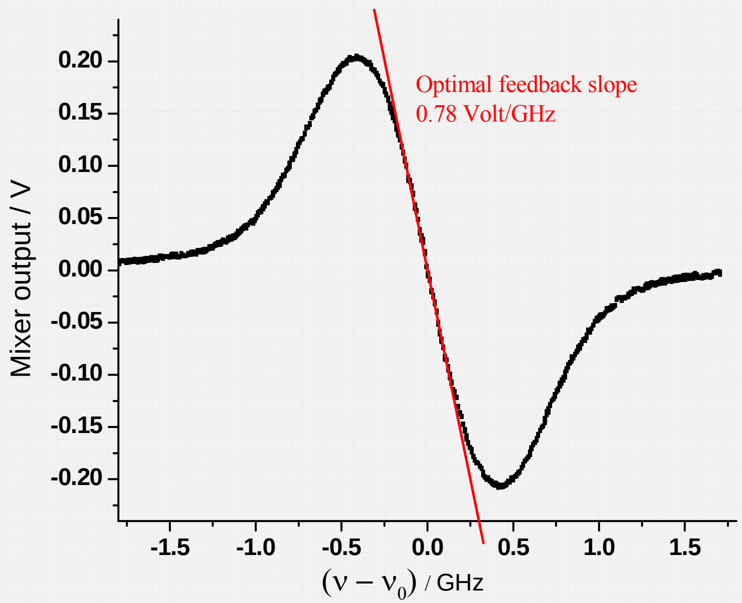


Fig 15. Optimal modulation amplitude

3. Tuning PID control

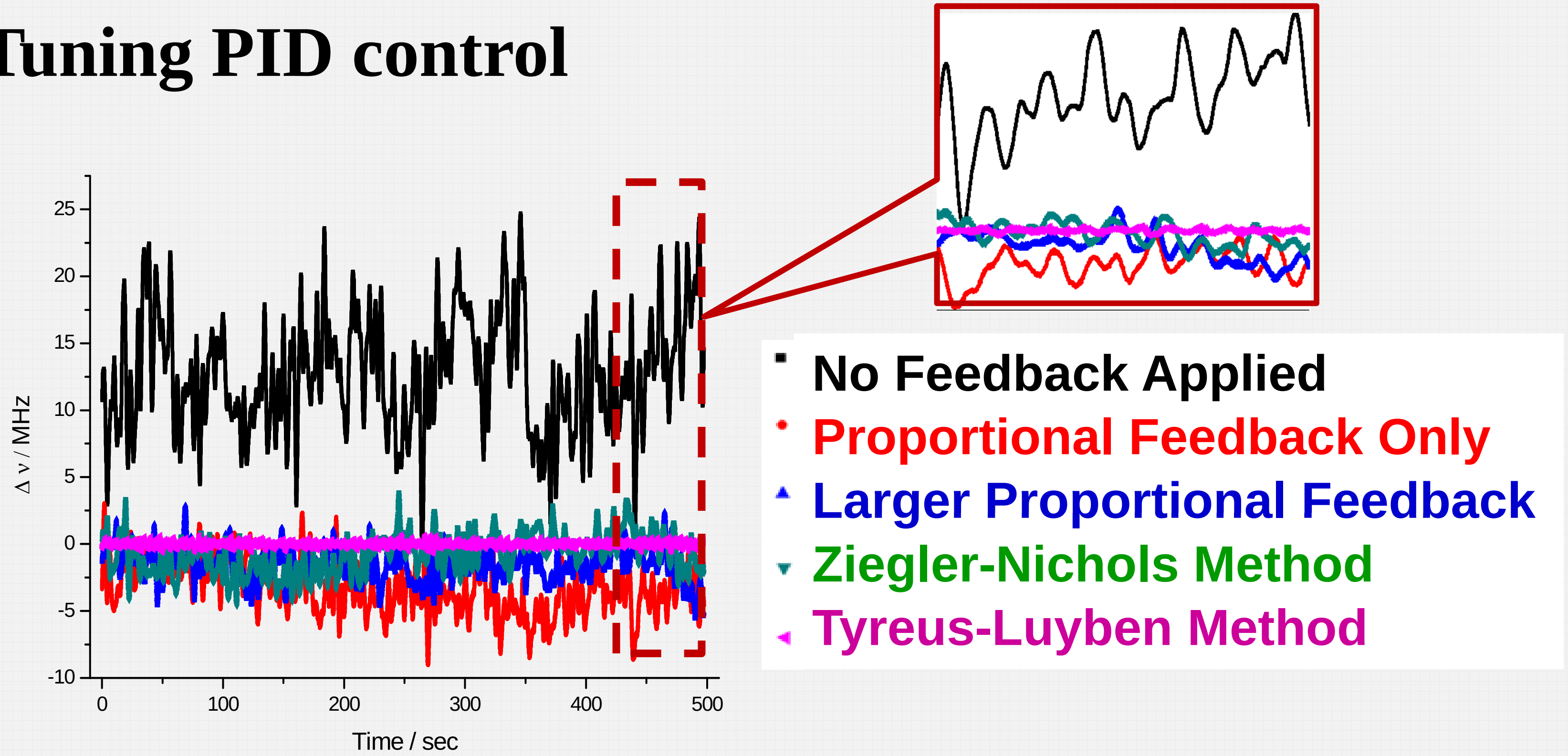


Fig 16. Comparison of laser jitter when using feedback with different PID parameters

PID parameters	Mean / MHz	Standard Deviation / MHz
No feedback applied	12.75845	4.3672
Proportional feedback only	-3.25909	1.93233
Larger Proportional feedback	-1.46707	1.25413
Ziegler-Nichols Method	-0.77357	1.44293
Tyreus-Luyben Method	-0.00046	0.18393

4. Temperature Tuning System

(1) Previous fixed current method

U is controlled by D/A and PC.

Temperature can be get from Steinhart Equation

$1/T = C_1 + C_2\, \mathit{ln}\, (R) + C_3\, [\mathit{ln}\, (R)]^3$

Where $C_1 = 1.1292E\text{-}3$, $C_2 = 2.3411E\text{-}4$,

$C_3 = 8.7755E\text{-}8$, $I = 100\ \mu A$, $R = U / I$.

(2) New voltage divider method

Instead of a fixed I, we used a voltage divider, with the thermistor in series with fixed resistor R', and both thermister R and fixed resistor R' are driven by a fixed voltage source U'. The output voltage will be proportional to R'. $R=R'\times U/(U'-U)$

4. Temperature Tuning System

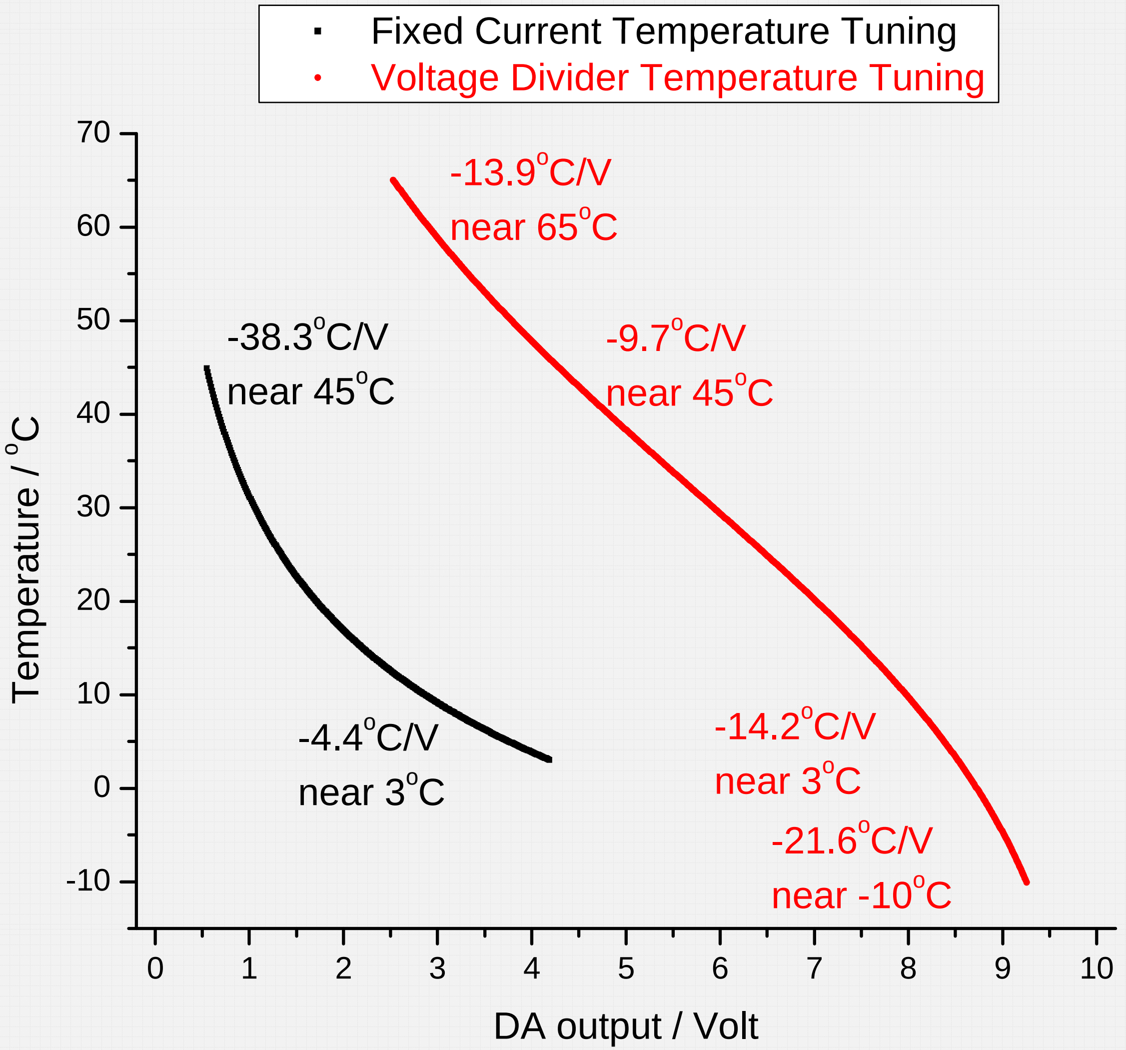


Fig 17. Comparison of two methods of temperature tuning

Future Plans

I. Super narrow linewidth DFB lasers
II. Electronic feedback and temperature tuning on all lasers
III. Implement cavity locking with predicted wavelength shift

Acknowledgements

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- NASA
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