Laser spectroscopy using AOM:
Application to saturation absorption

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Abstract

Acousto-optic modulator (AOM) is a popular tool in photonic laboratory for amplitude modulation or frequency tuning. Due to the unique feature of frequency-shifted diffraction, AOM can also be used as a key element in laser spectroscopy. In this talk, I will present our results on the AOM-based saturation spectroscopy, including

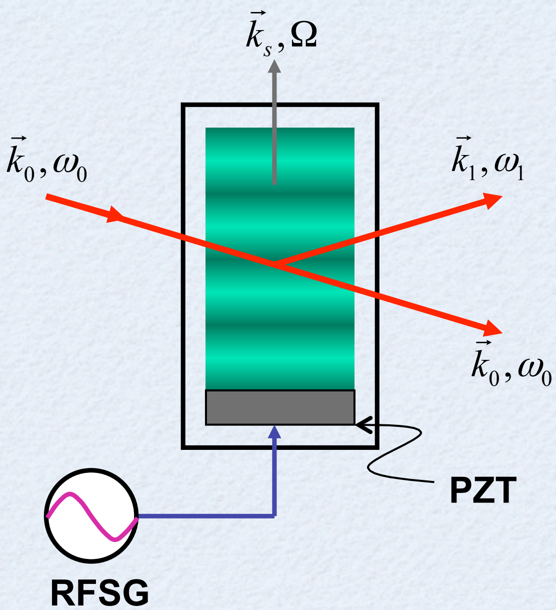
- Rb saturation dispersion
- Acetylene saturation absorption in a hollow-core photonic crystal fiber (HC-PCF).

PHOTONICS
FENG CHIA UNIVERSITY

OUTLINES

- Review on AOM
- Previous works on laser spectroscopy using AOM
  - ✳ Differential spectroscopy
  - ✳ Optical Heterodyne Spectroscopy — Etalon locking
- Recent works on saturation absorption
  - ✳ Rb saturation absorption
  - ✳ Acetylene saturation absorption in HC-PCF

Review on AOM

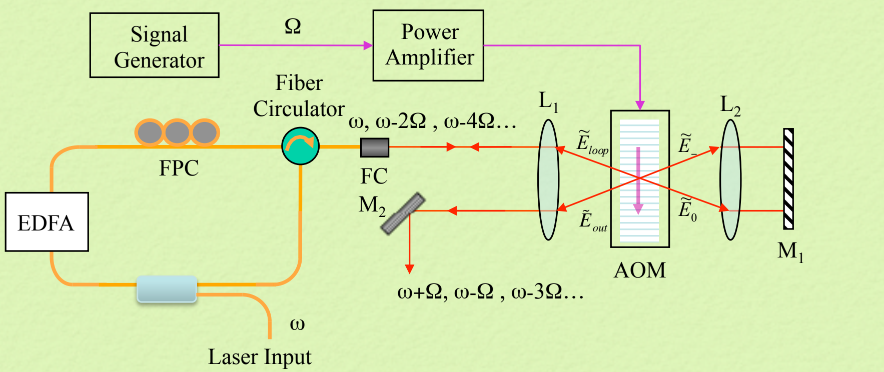


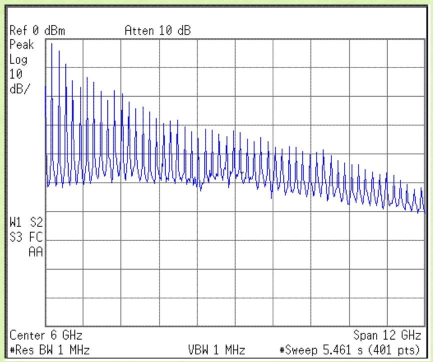
Conservation of momentum:

$$\vec{k}_1 = \vec{k}_0 + \vec{k}_s$$

Conservation of enery:

$$\omega_1 = \omega_0 + \omega_s$$

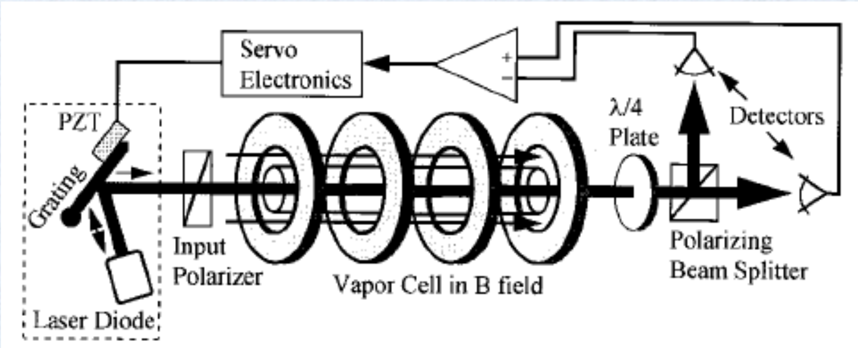


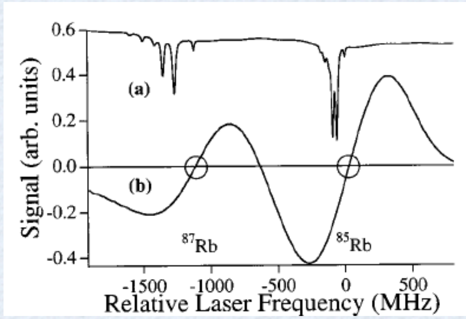


Differential Spectroscopy

Differential spectroscopy provides a easy way to for dithering-free laser frequency stabilization. Examples are

- Dichroic-atomic-vapor laser lock



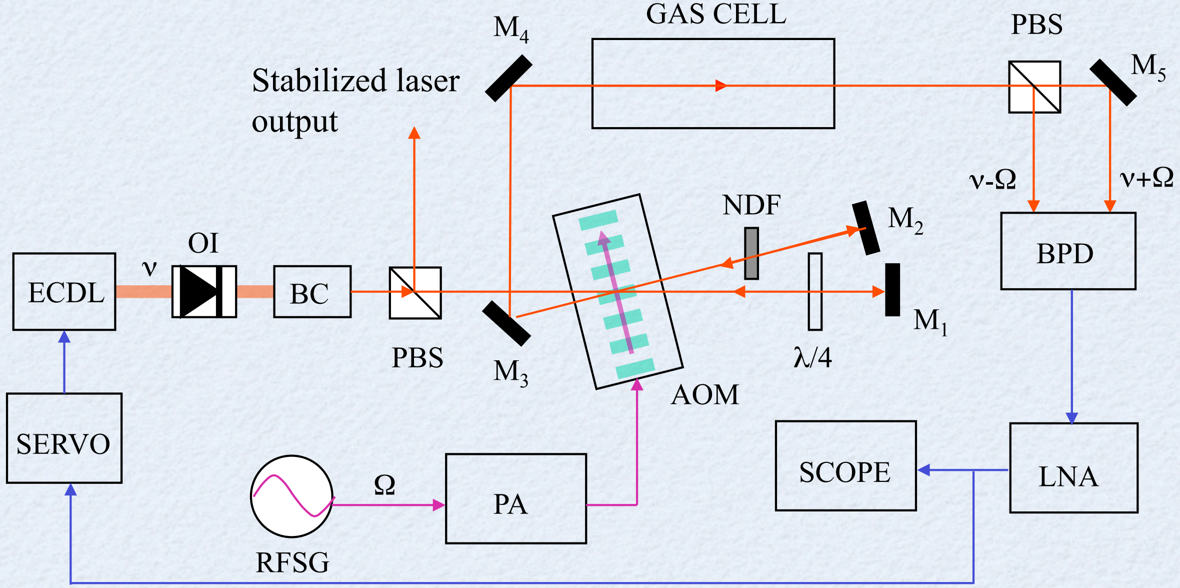


K. L. Corwin, Z.-T. Lu, C. F. Hand, R. J. Epstein, and C. E. Wieman, "Frequency-stabilized diode laser with the Zeeman shift in an atomicvapor," *Appl. Opt.*, vol. 37, pp. 3295–3298 (1998).

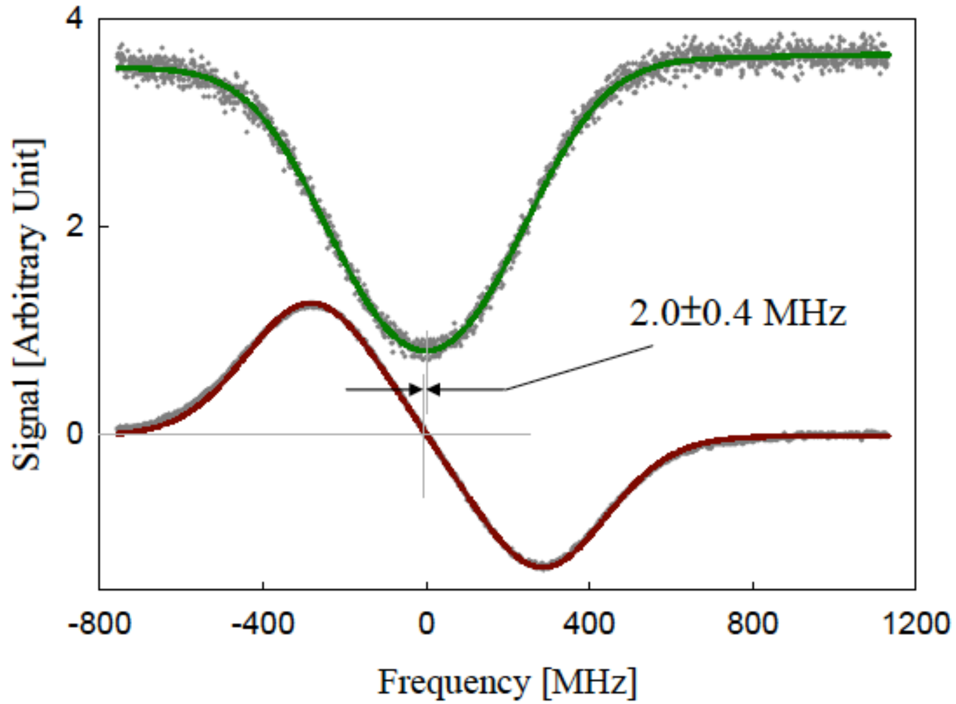
- Differential spectroscopy using AOM (our work)

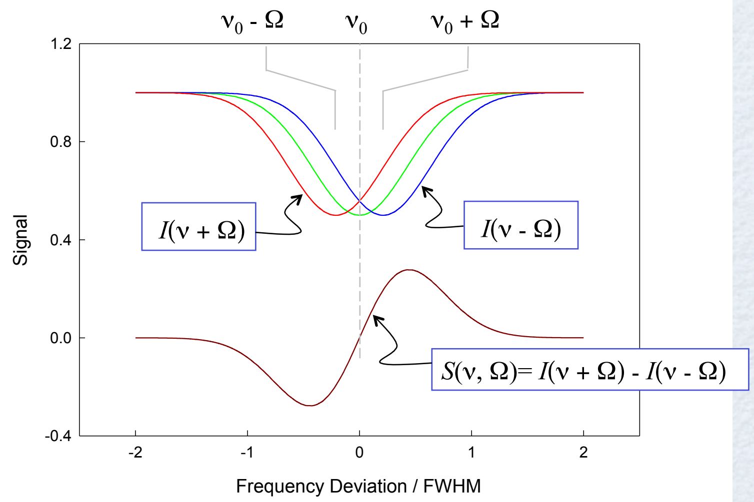
Differential Spectroscopy Using AOM

C.-C. Chou, T. Lin, P-C. Huang, and M.-H. Chien, "TModulation-Free Laser Frequency Stabilization to Molecular Absorption Using Single Acousto-optic Frequency Shifter," *IEEE Photon. Technology Lett.*, vol. 16, pp. 1948-1950 (2004).



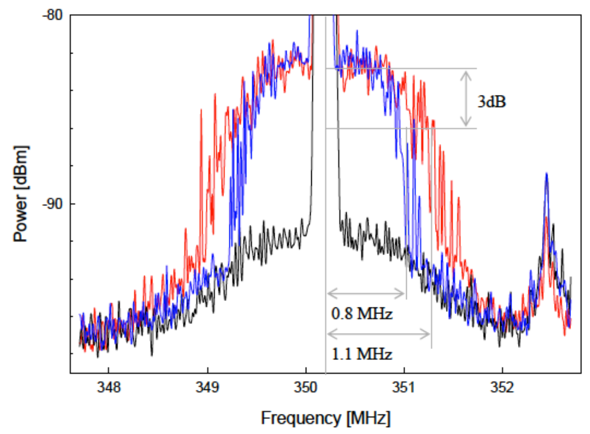
- Doppler-limited spectroscopy
- AOM in double-pass configuration
- Applicable to any atom or molecule



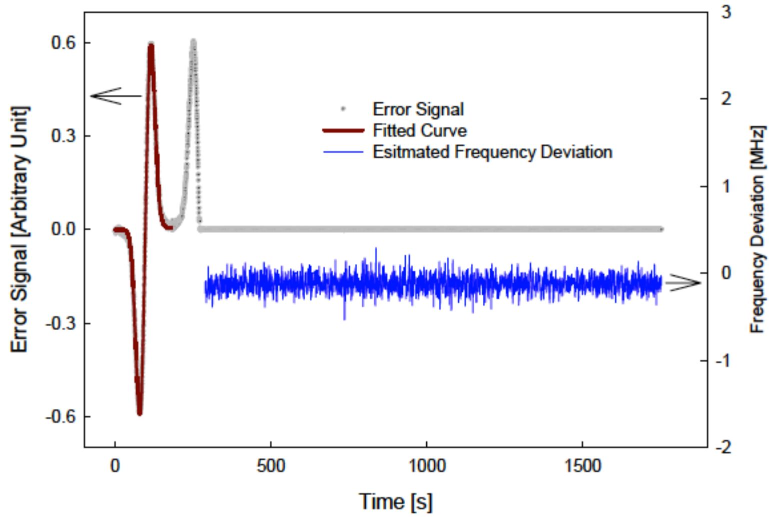


The C_2H_2 line is P(13) of $\nu_1+\nu_3$. The pressure is 830 mtorr. The AOM driven frequency is 100 MHz. The AOM driven power is 1 W.

Laser Linewidth Measurement Using DSH



—— : Local oscillator; —— : Free running laser; —— : Stabilized laser



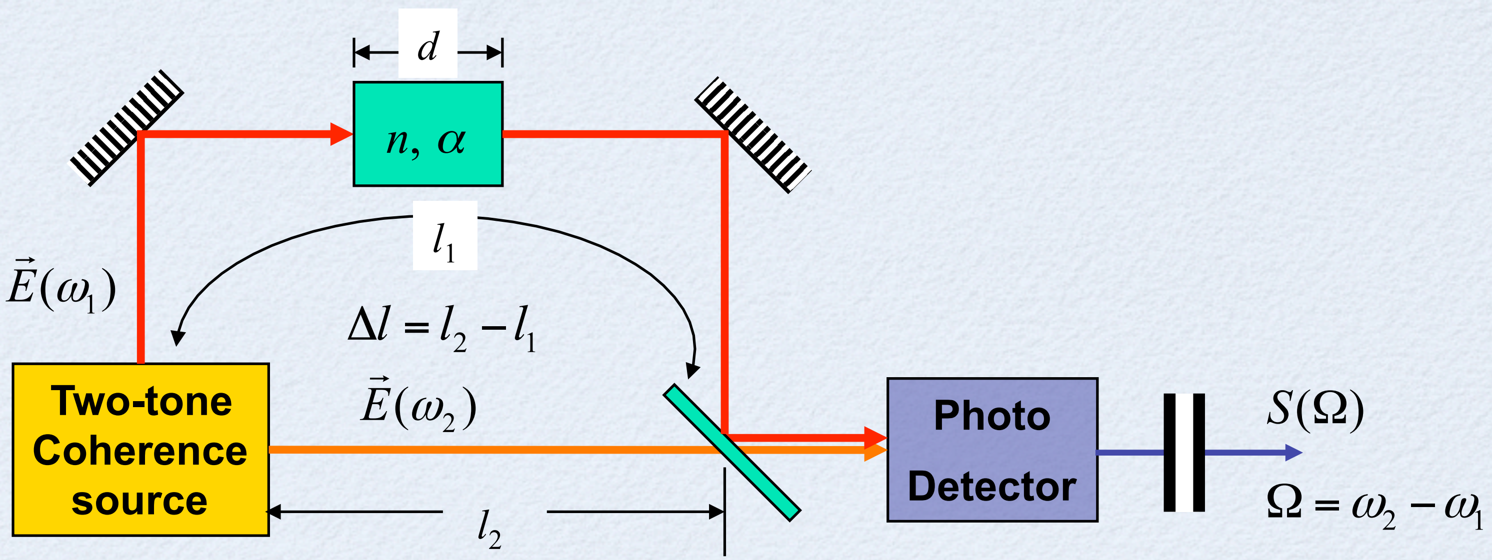
The C_2H_2 line is R(8) of $\nu_1+\nu_3$. The pressure is 1.0 torr. The AOM driven signal is 100 MHz with power of 2 W. Frequency fluctuation was estimated to be 70 kHz in one minute.

Optical Heterodyne Spectroscopy

Optical hetreodyne detection directly measures the relative phase between the probe and the reference beam. Hence, it is ideally for measuring the phase retardation due to the dispersion occurred in an absorption. Examples are

- Pond-Drever-Hall laser lock
- Optical heterodyne spectroscopy using EOM
- Optical heterodyne spectroscopy using AOM (our work)

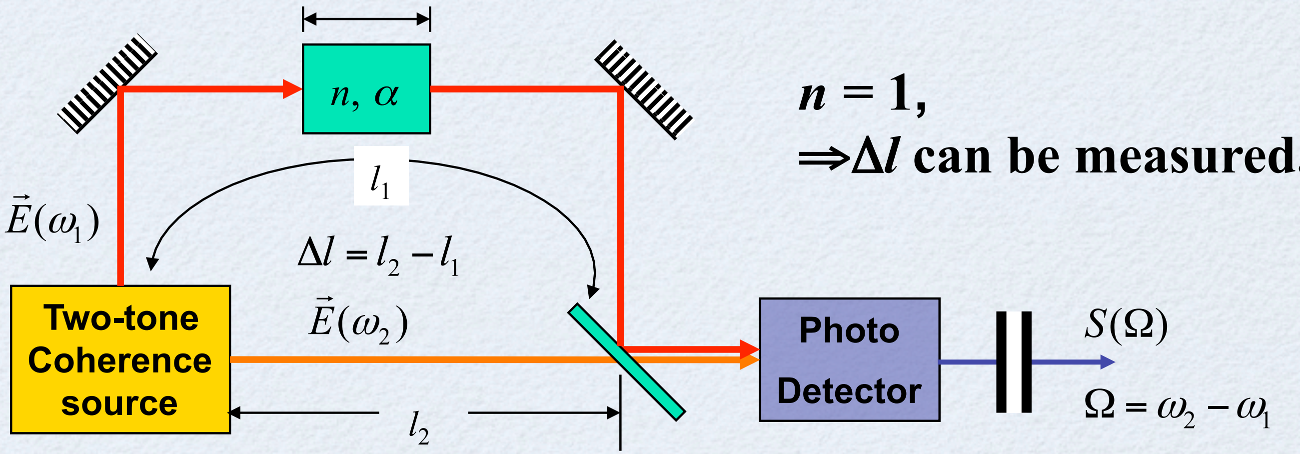
Basics of Optical Heterodyne Interferometry



$$S(\Omega) \propto \left\{ \left| \vec{E}(\omega_1) + \vec{E}(\omega_2) \right|^2 \right\}_{AC}$$

$$= 2E_1E_2e^{-\alpha d} \cos\left[2\pi(\frac{\Delta l}{\lambda_1}) + (\frac{\Omega}{c})l_2 - (\frac{\omega_1}{c})(n-1)d - \Omega t \right]$$

constant



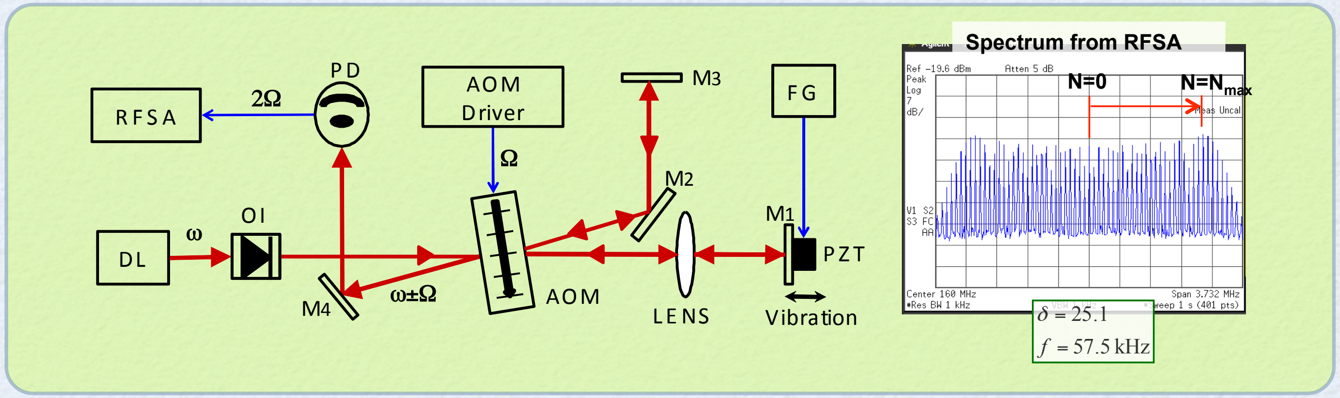
$n = 1$,

$\Rightarrow \Delta l$ can be measured.

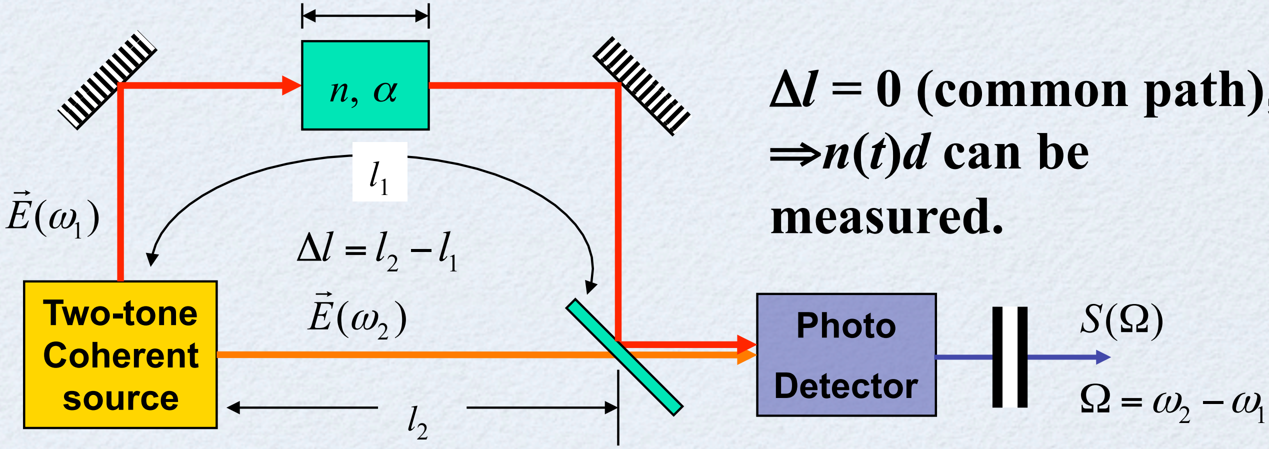
$$S(\Omega) = S_0 e^{-\alpha d} \cos\left[2\pi \left(\frac{\Delta l}{\lambda_1}\right) - \left(\frac{\omega_1}{c}\right)(n-1)d - \Omega t \right]$$

0

Laser Doppler Vibrometry



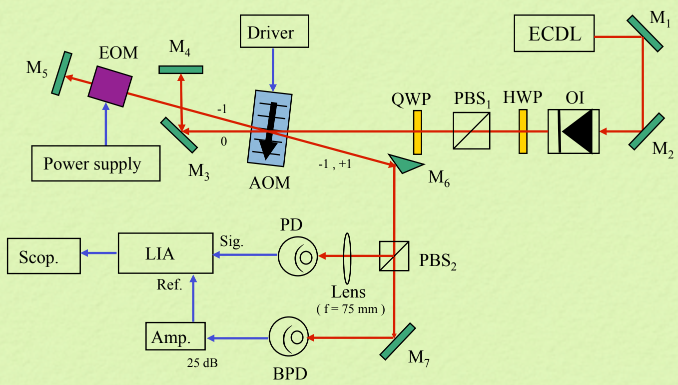
$\Delta l = 0$ (common path),
$\Rightarrow n(t)d$ can be measured.

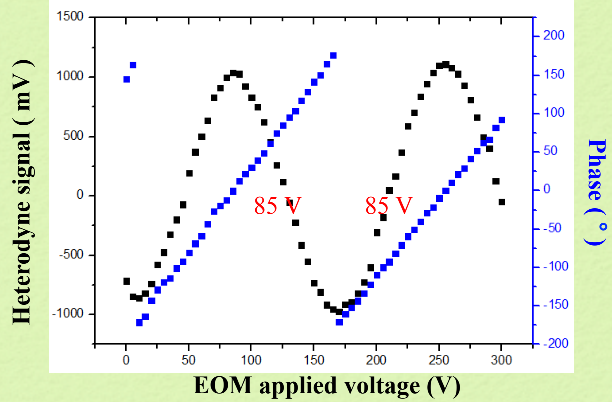


$$S(\Omega) = S_0 e^{-\alpha d} \cos\left[2\pi\left(\frac{\Delta l}{\lambda_1}\right) - \left(\frac{\omega_1}{c}\right)(n-1)d - \Omega t\right]$$

$\Delta l \rightarrow 0$

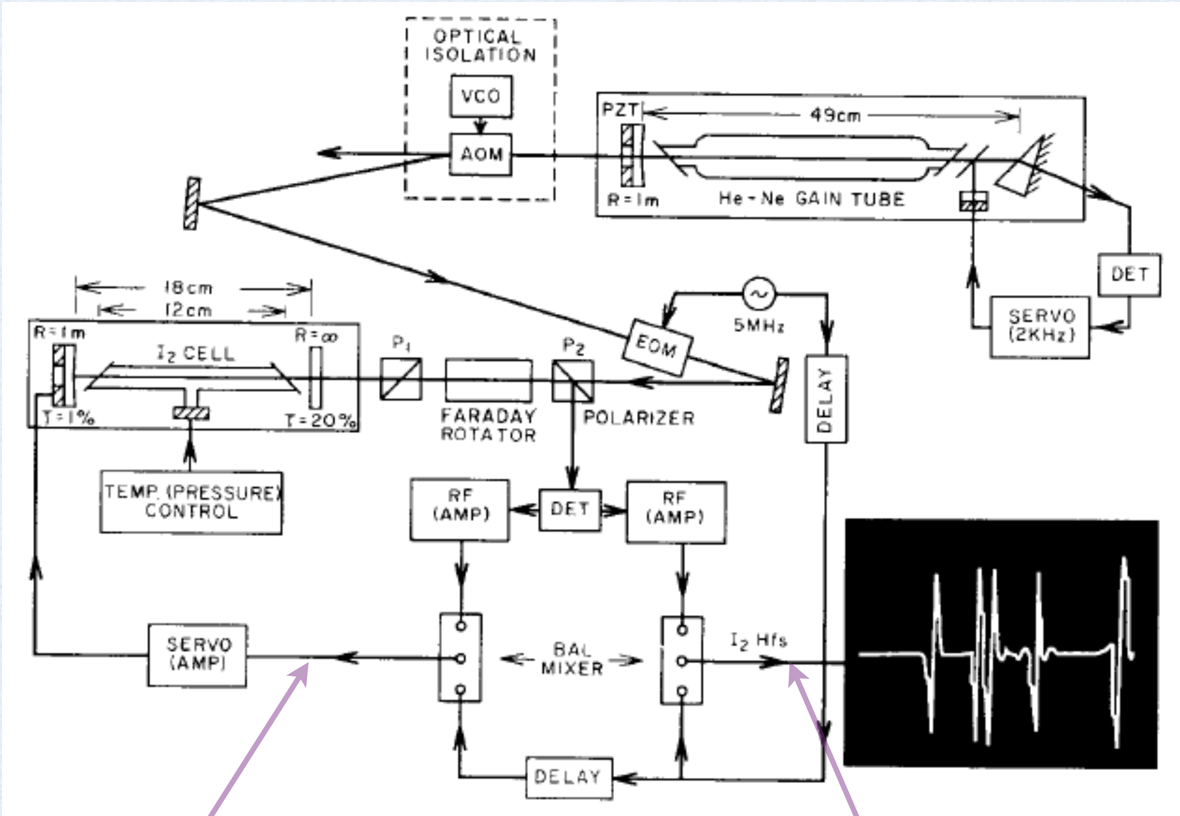
Dispersion Measurement





Optical Heterodyne Spectroscopy Using EOM

L. S. Ma, and J. L. Hall, "Optical Heterodyne Spectroscopy Enhanced by an External Optical Cavity: Toward Improved Working Standards," *IEEE J. Quantum Electron.*, vol. 26, 2006-2012 (1990).

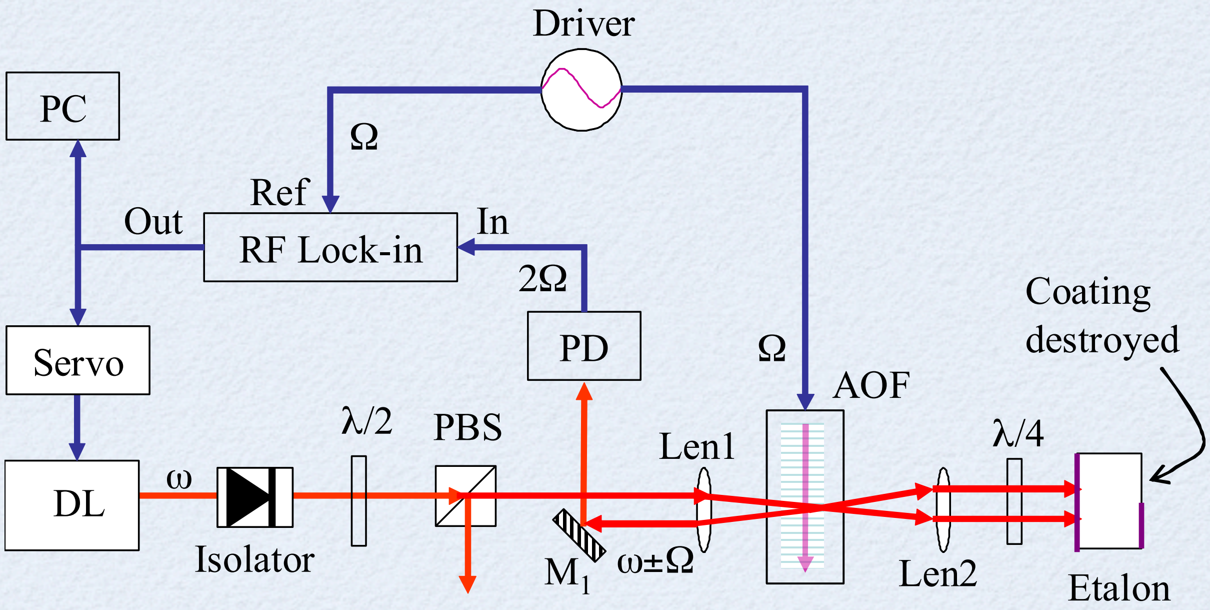


$\propto A_1\left\{\cos(\phi_0-\phi_1)-\cos(\phi_{-1}-\phi_0)\right\}\cos\delta t$

$\propto A_1\left\{\sin(\phi_0-\phi_1)-\sin(\phi_{-1}-\phi_0)\right\}\sin\delta t$

Optical Heterodyne Spectroscopy Using AOM : Etalon Frequency Locking

Che-Chung Chou, Chien-Hou Chang, and Tyson Lin, "Laser Phase Stabilization Using Optical Heterodyne Detection Based on Single Acousto-Optic Shifter," *19th International Conference on Laser Spectroscopy*, V-2 (2009).



- Single AOM in double-pass configuration
- Nearly equal-arm interferometer
- Heterodyne frequency at second harmonic of AOM driven frequency

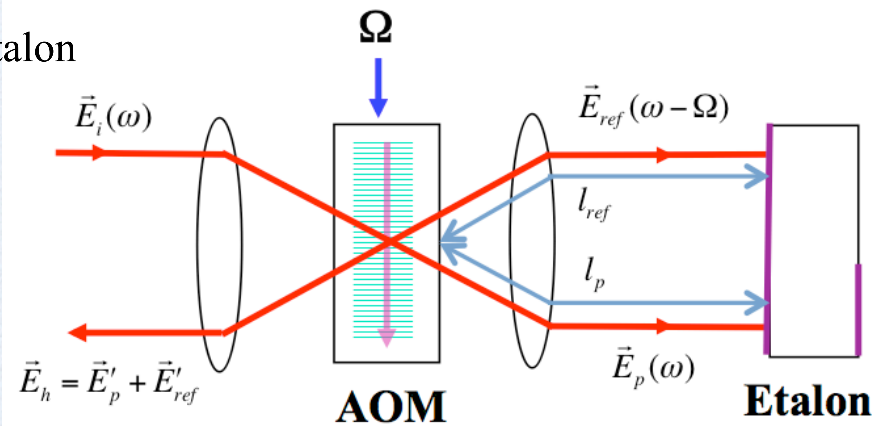
$F(\omega)=|F(\omega)|e^{i\delta(\omega)}$: reflection coefficient of etalon

$\vec{E}_i(\omega)=Ae^{i\omega t}\hat{e}_h$: incident field

nd : optical thickness of AOM

η : diffraction efficiency of AOM

R : reflectivity of Etalon coating



l : distance between AOM and detector for the interference beams

The optical heterodyne signal is given by

$$S_h=-2G_p\eta(1-\eta)|A|^2\sqrt{R}|F(\omega)|\cos\left\{2\Omega t+\delta(\omega)-\frac{\omega}{c}(2\Delta l)-(\frac{\Omega}{c})nd+(\frac{2\Omega}{c})(l-l_{ref})\right\}$$

Therefore, the output of RF Lock-in amplifier at phase angle θ can be expressed as

$$V=-2G_lG_p\eta(1-\eta)|A|^2\sqrt{R}|F(\omega)|\cos\{\delta(\omega)+\Phi-\theta\}$$

where $\Phi\equiv-\frac{\omega}{c}(2\Delta l)-(\frac{\Omega}{c})nd+(\frac{2\Omega}{c})(l-l_{ref})\approx$ constant

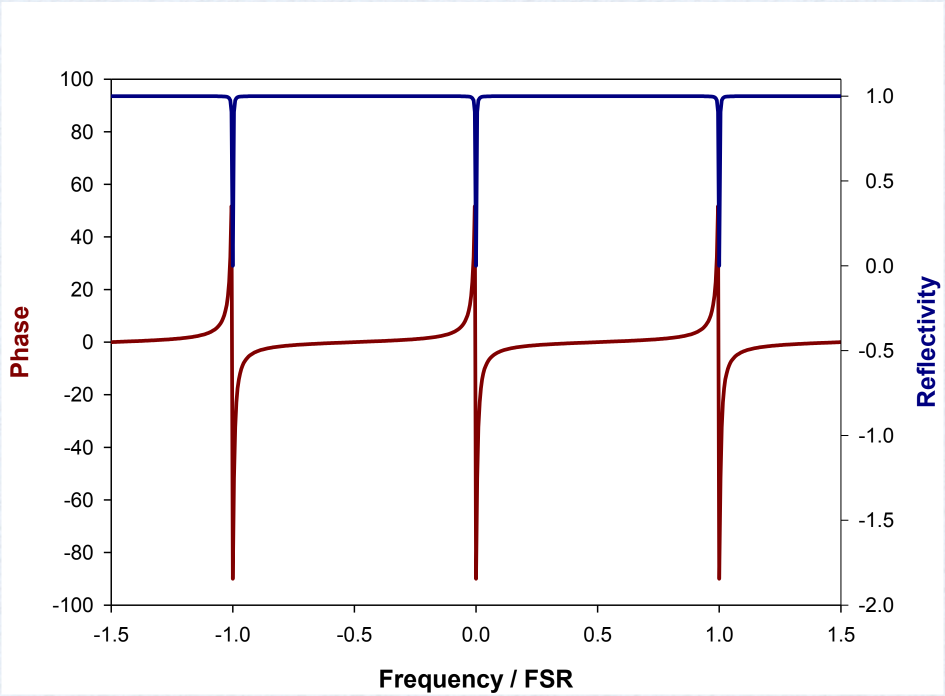
0

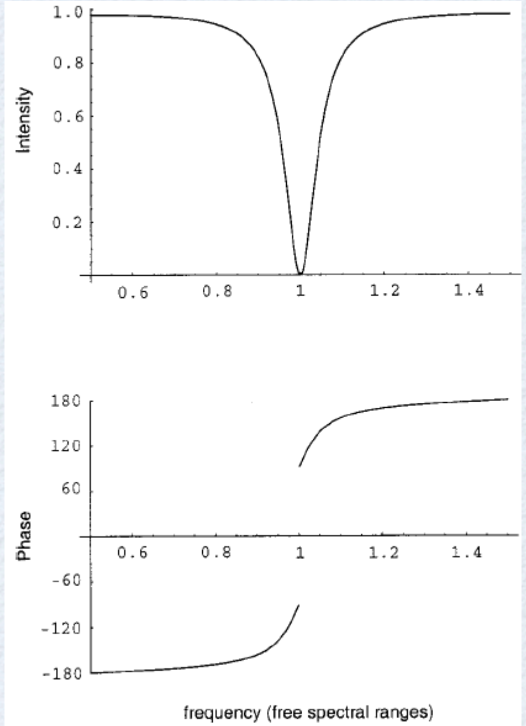
Absorption-like signal:

$$\Phi - \theta = 0 \Rightarrow V = -2G_l G_p \eta(1-\eta)|A|^2 \sqrt{R}\,|F(\omega)|\cos\{\delta(\omega)\}$$

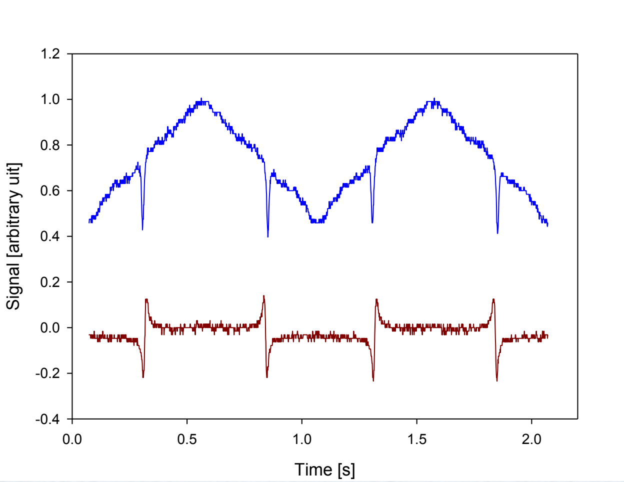
Dispersion-like signal:

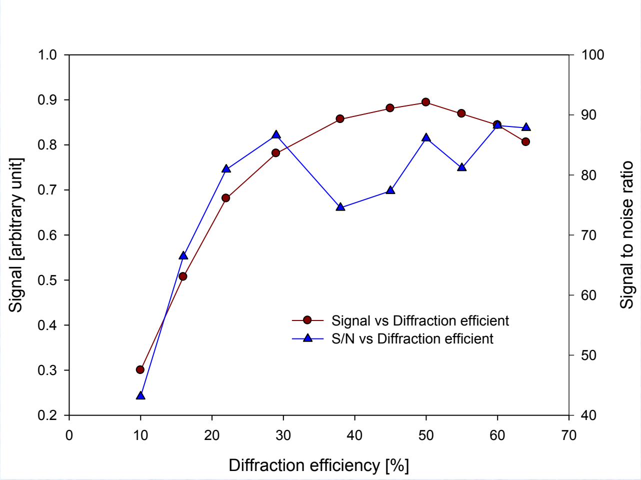
$$\Phi - \theta = \frac{\pi}{2} \Rightarrow V = 2G_l G_p \eta(1-\eta)|A|^2 \sqrt{R}\,|F(\omega)|\sin\{\delta(\omega)\}$$

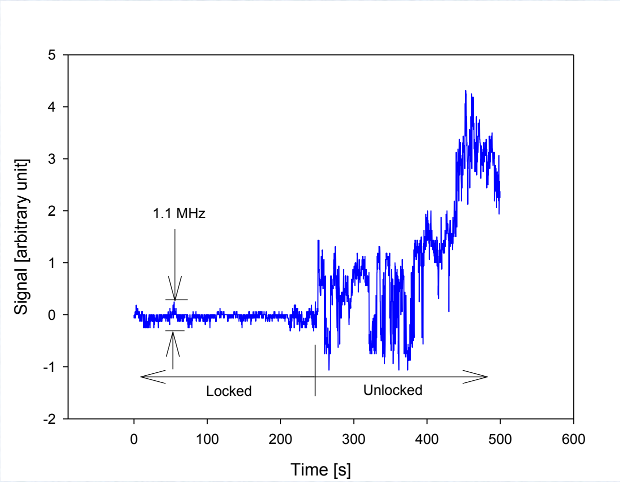




$$F(\omega) = \frac{\sqrt{R}\left[\exp\left(i\frac{\omega}{\Delta\nu_{fsr}}\right) - 1\right]}{1 - R\exp\left(i\frac{\omega}{\Delta\nu_{fsr}}\right)} = |F(\omega)|e^{i\delta}$$







$\lambda = 780$ nm $\Omega/2\pi = 40$ MHz

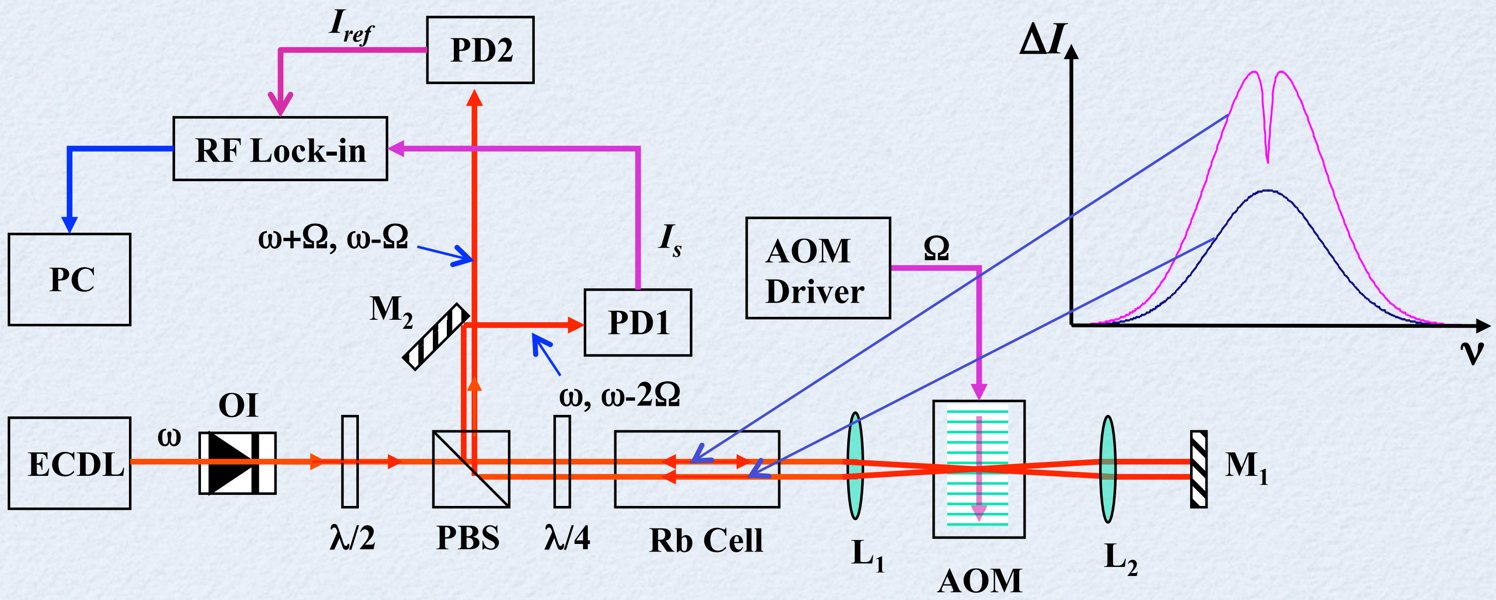
$R = 98.9\%$ FSR = 19.61 GHz

FWHM = 225 MHz

Laser frequency stability:

$$\frac{\Delta\nu}{\nu} \approx 2\times10^{-9}$$

Optical Heterodyne Spectroscopy Using AOM
: Rb Saturation Spectroscopy



- Single AOM in double-pass configuration
- Exactly equal-arm interferometer
- Probe beams doubly pass the Rb cell while the reference beam pass the Rb cell once only.

$\vec{E}_i(\omega) = Ae^{i[\omega t - k(\omega) l_c]}\hat{e}_R$: incident field

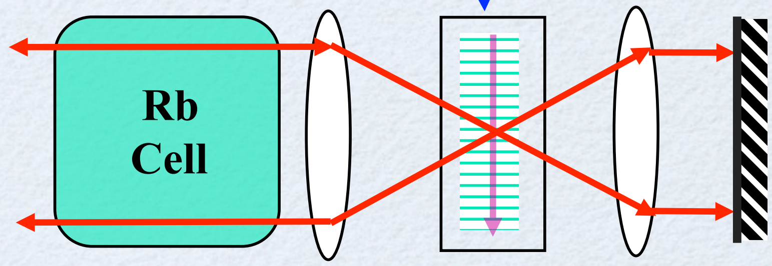
nd : optical thickness of AOM

η : diffraction efficiency of AOM

l_c: length of Rb cell

$k(\omega)$: unsaturated complex wave constant

$k_s(\omega)$: saturated complex wave constant



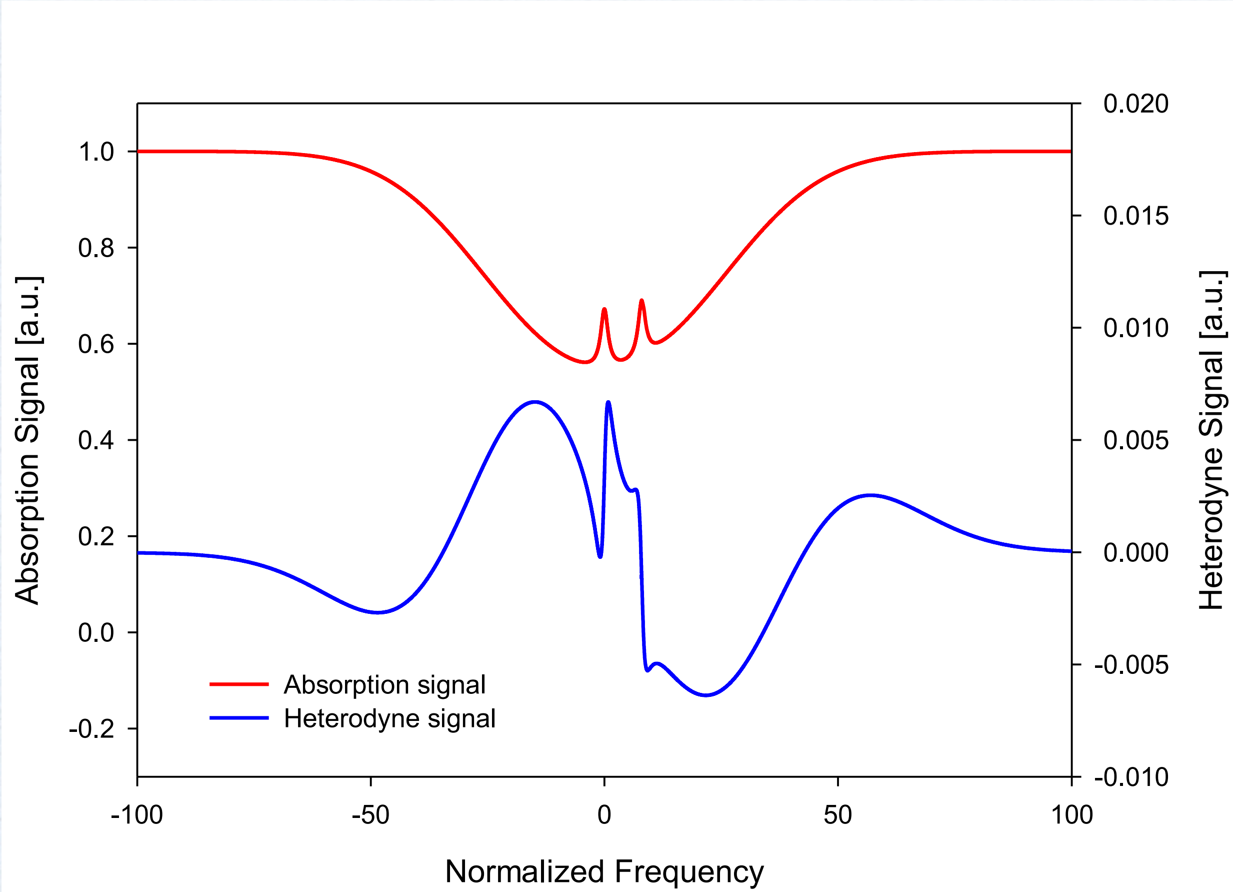
The complex wave constant can be expressed as $k(\omega) = n(\omega)\frac{\omega}{c} - i\frac{\alpha(\omega)}{2} = \beta(\omega) - i\frac{\alpha(\omega)}{2}$

where $n(\omega)$ is the refractive index and $\alpha(\omega)$ is the absorption coefficient.

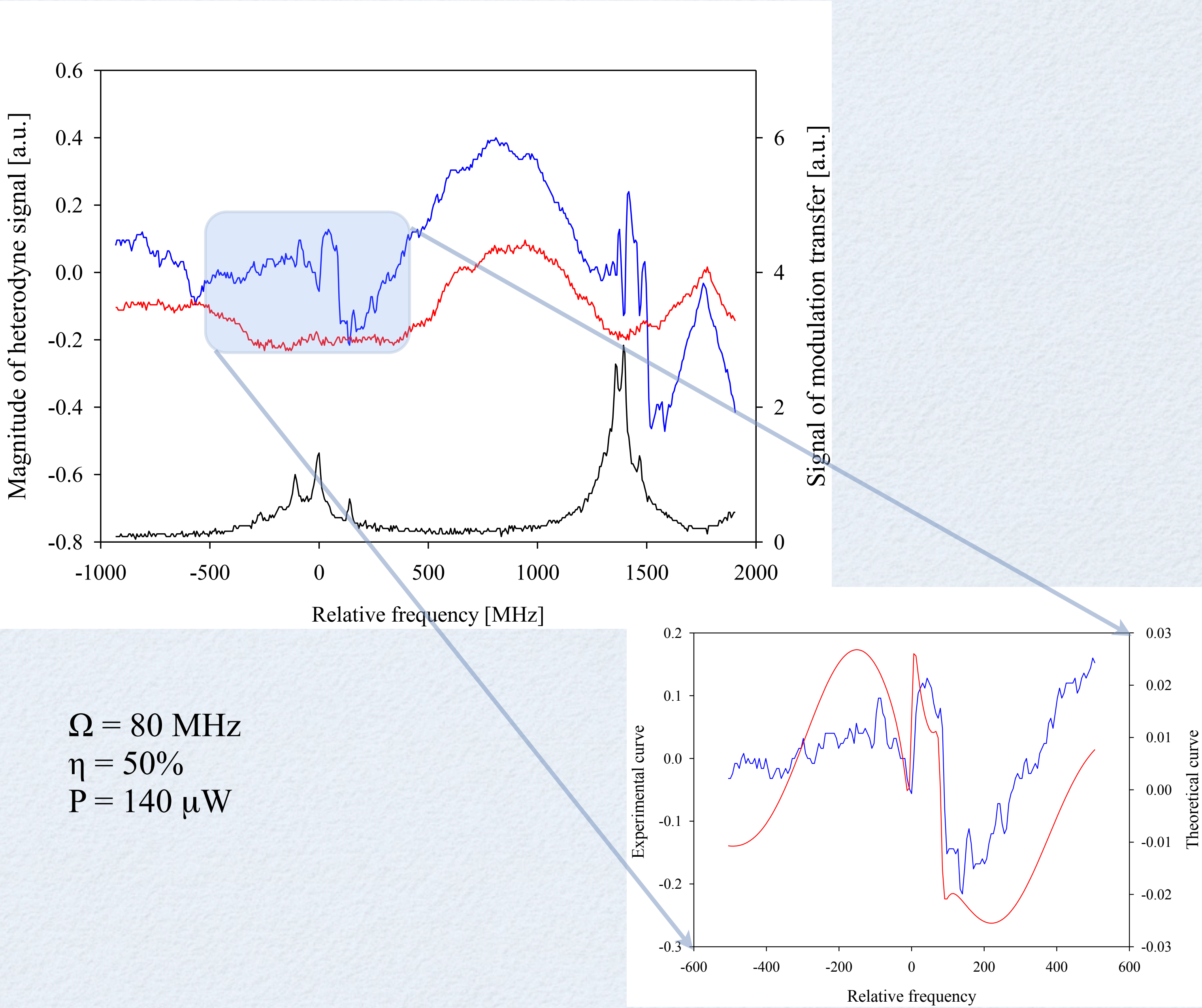
$$\beta(\omega) = \frac{\omega}{c}n(\omega) \approx \frac{\omega}{c} + s\cdot\frac{\omega-\omega_0}{\Delta\omega}\alpha(\omega), \quad s = \begin{cases} 1, & \text{Lorentzian} \\ 4\sqrt{\ln 2/\pi}, & \text{Gaussian} \end{cases}$$

Therefore, the output of RF Lock-in amplifier at phase angle θ can be expressed as

$$V = G_{\text{LIA}} G_1 \eta(1-\eta)|A|^2 e^{-[\alpha_s(\omega)+\alpha_s(\omega-2\Omega)]/2}$$
$$\cdot\cos\left\{\left[\beta_s(\omega) - \beta_s(\omega-2\Omega)\right]l_c - \left[\beta(\omega+\Omega) - \beta(\omega-\Omega)\right]l_c - \theta\right\}$$



$$\frac{\omega}{c} n_s(\omega) - \frac{\omega - 2\Omega}{c} n_s(\omega - 2\Omega) - \frac{\omega + \Omega}{c} n(\omega + \Omega) + \frac{\omega - \Omega}{c} n(\omega - \Omega)$$

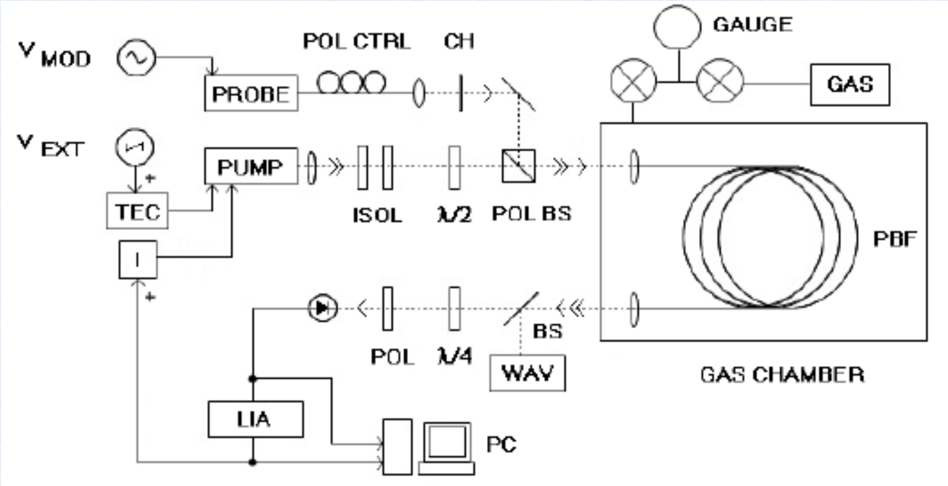


$\Omega = 80$ MHz
$\eta = 50\%$
$P = 140\ \mu W$

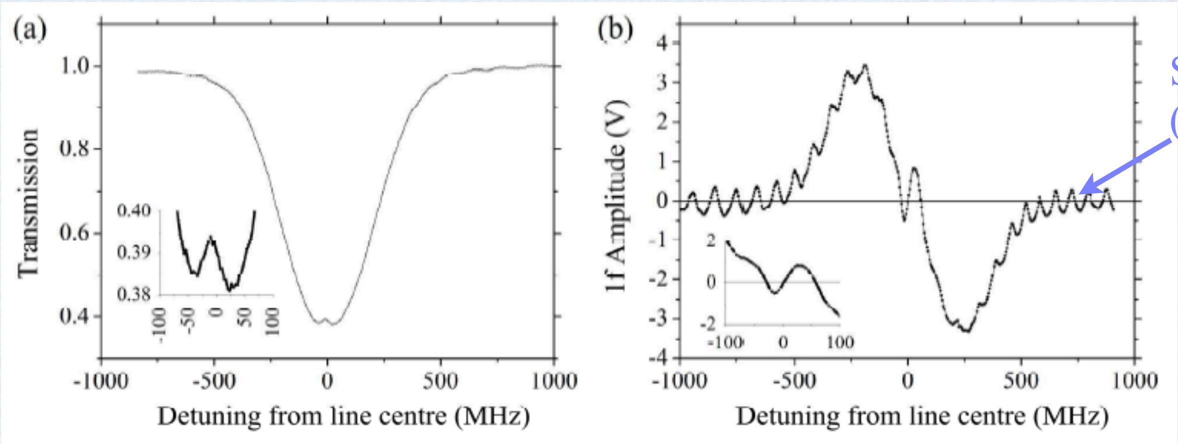
Summary of AOM-based Laser Heterodyne Spectroscopy

- Optical heterodyne spectroscopy using single AOM was demonstrated and applied to:
  - a diode laser locked to an etalon with typical stability about 10^{-9}.
  - detecting the dispersion of Rb saturation absorption was also successfully demonstrated.
- Better stability and clean profile can be obtained by using Fabry-Perot cavity.

Acetylene saturation absorption in HC-PCF

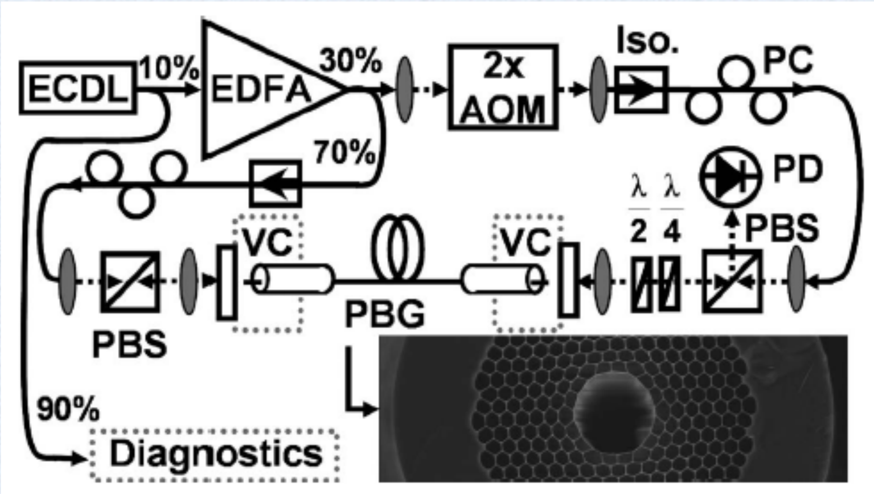


P. Pineda-Vadillo, M. Lynch, C. Charlton, J. F. Donegan and V. Weldon, "Non-resonant wavelength modulation saturation spectroscopy in acetylene-filled hollow-core photonic bandgap fibres applied to modulation free laser diode stabilization," *Opt. Express*, vol. 17, 23309-23315 (2009).

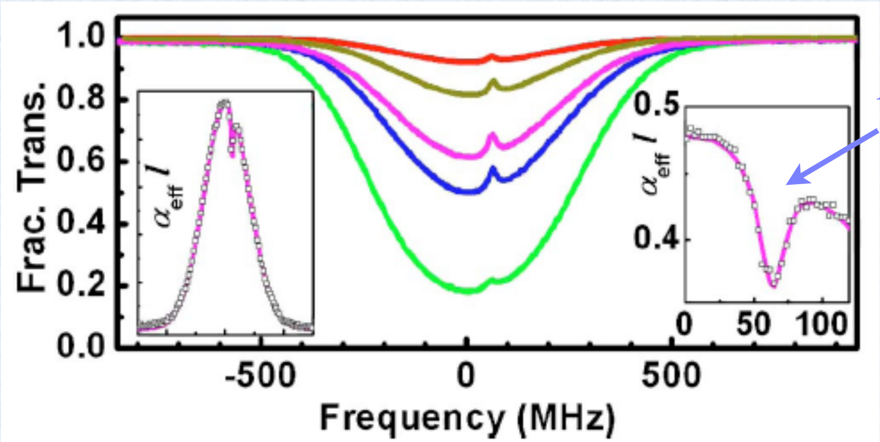


Surface-mode interference (multimode propagation)

Acetylene saturation absorption in HC-PCF

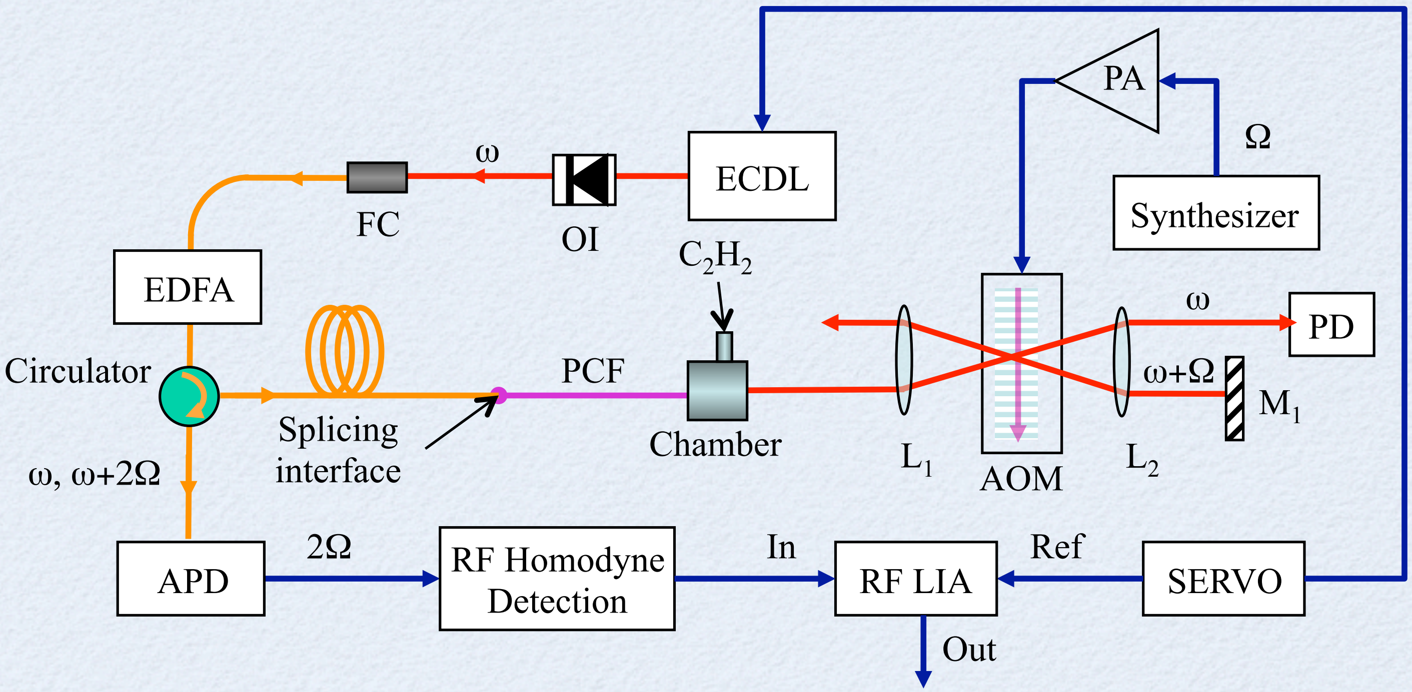


R. Thapa, K. Knabe, M. Faheem, A. Naweed, O. L. Weaver, and K. L. Corwin, "Saturated absorption spectroscopy of acetylene gas inside large-core photonic bandgap fiber," *Opt. Lett.*, vol. 31, 2489-2491 (2006).

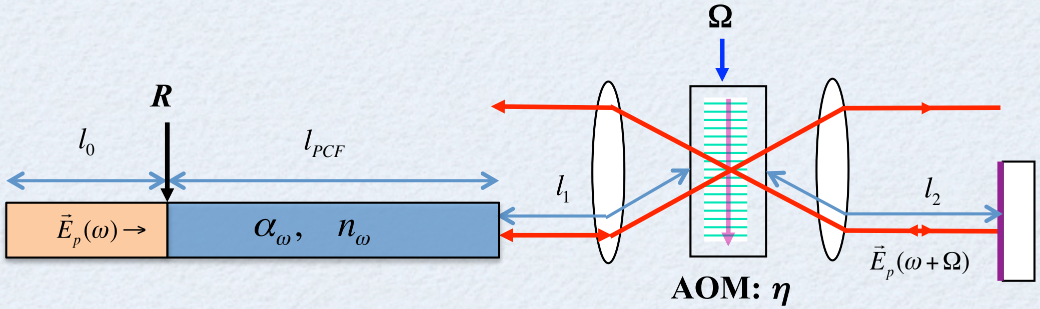


Asymmetric line profile

Optical Heterodyne Spectroscopy Using AOM :Acetylene saturation absorption in HC-PCF



- Nonlinear absorption in HC-PCF
- Single AOM in double-pass configuration
- Surface-mode interference free
- Symmetric line profile



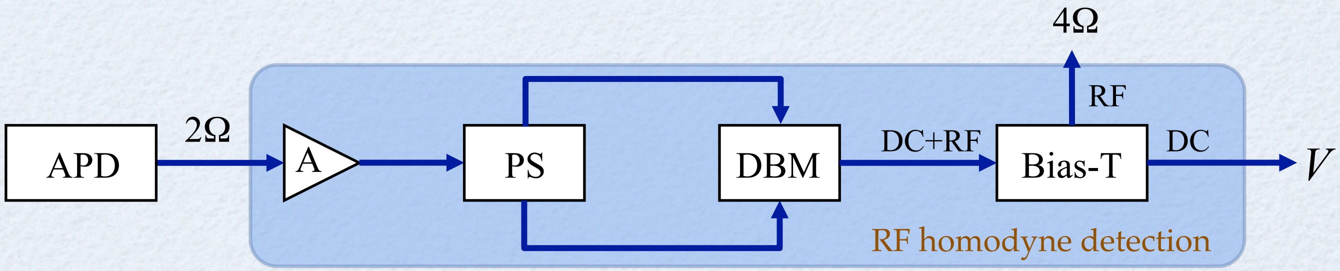
$$S_h = G_{APD}\eta(1-R)\sqrt{R}\exp\left[-\frac{1}{2}(\alpha_{\omega+2\Omega}+\alpha_\omega)l_{PCF}\right]\cos\left[2\Omega t-\Phi(\omega)-(\frac{\omega+2\Omega}{c}n_{\omega+2\Omega}+\frac{\omega}{c}n_\omega)l_{PCF}\right]$$

where $\Phi(\omega)=\frac{2\omega}{c}(nd+l_1+l_2)+\underbrace{\frac{\Omega}{c}[3nd+2(l_1+l_2-l_{APD}-l_0)]}_{\text{constant}}$

Note that $nd + l_1 + l_2 \approx 1$ m ⇒ FSR ≈ 150 MHz

⇒ order of magnitude same as line width

- Dispersion (phase) spectrum seriously disturbed by path interference
- Absorption (amplitude) spectrum still available



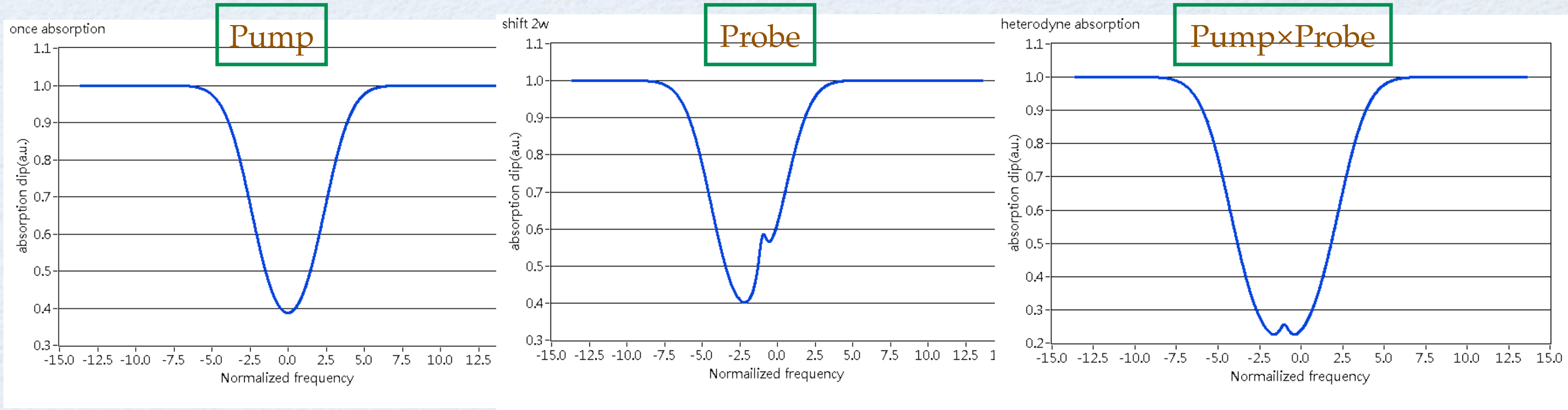
$$V = KG_{APD}^{2}(1-R)^{2}\eta^{2}R\exp\left[-(\alpha_{\omega+2\Omega}+\alpha_{\omega})l_{PCF}\right]$$

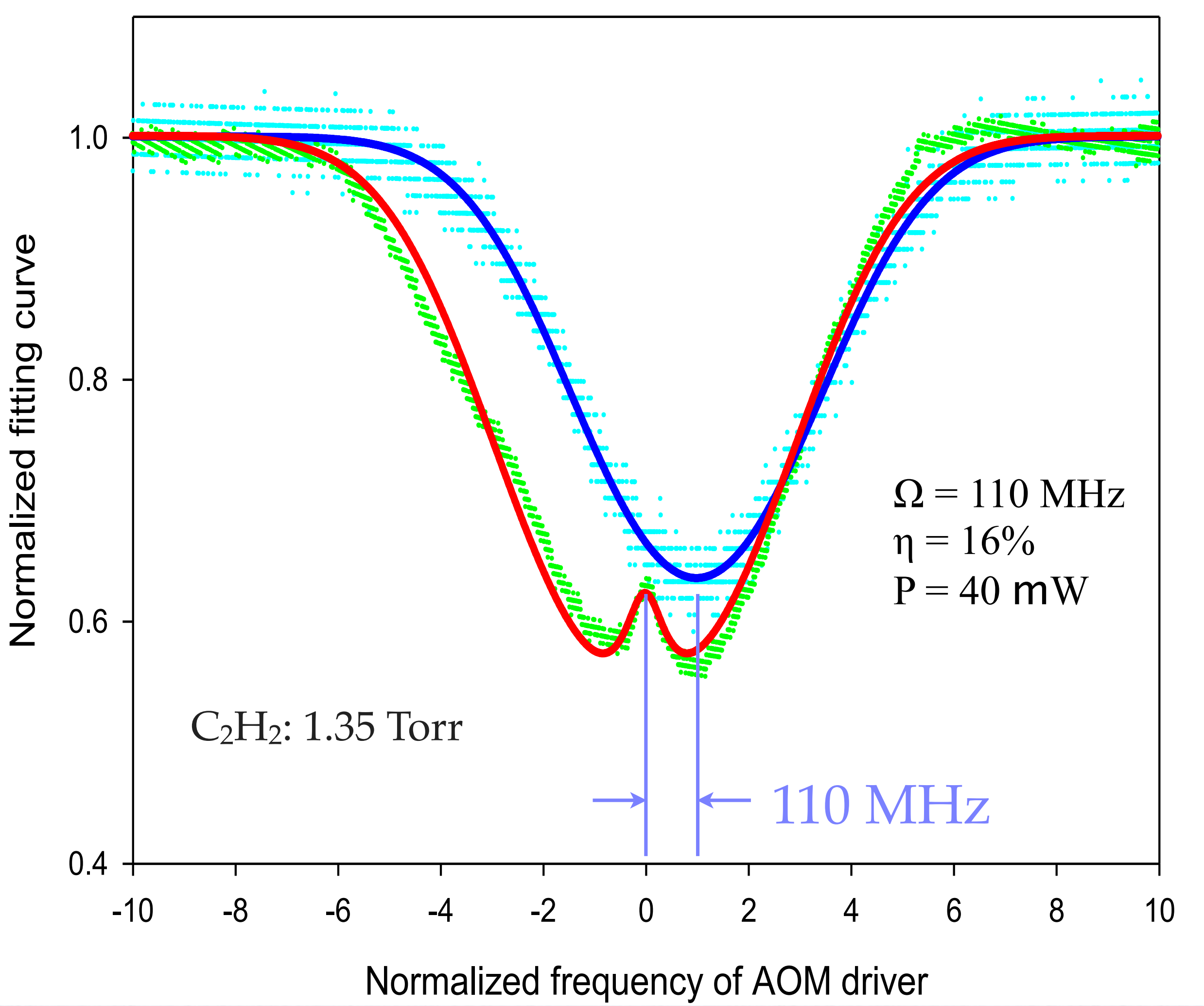
$$\because \quad \alpha(\omega+2\Omega)=G(\omega+2\Omega)-L(\omega+\Omega): \quad \text{Probe}$$

$$\alpha(\omega)=G(\omega): \quad \text{Pump}$$

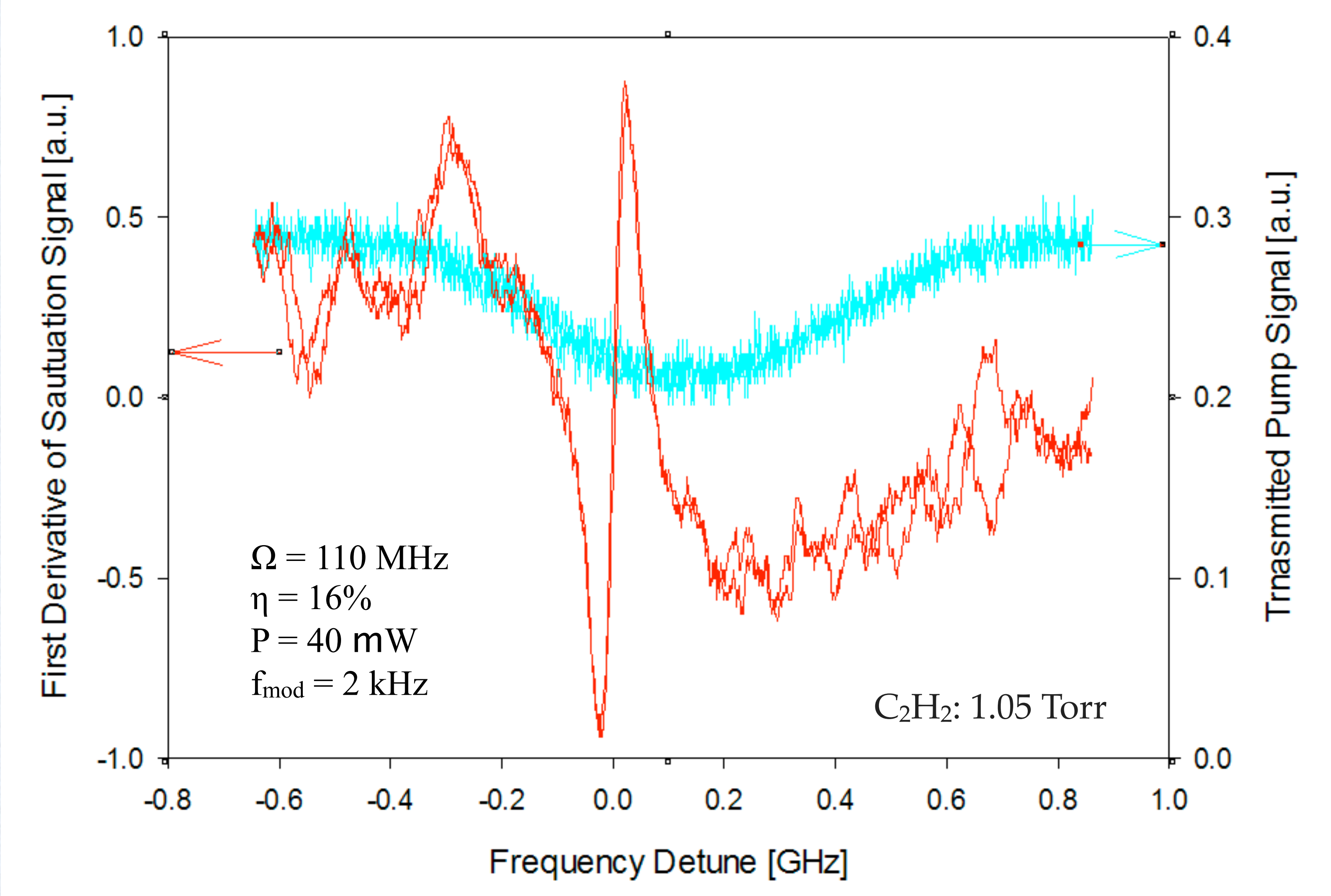
Let $\omega'=\omega+\Omega \Rightarrow \quad V \propto \exp\left\{-\left[G(\omega'+\Omega)+G(\omega'-\Omega)-L(\omega')\right]l_{PCF}\right\}$

Line profile is symmetric with respect to $\omega_0 - \Omega$





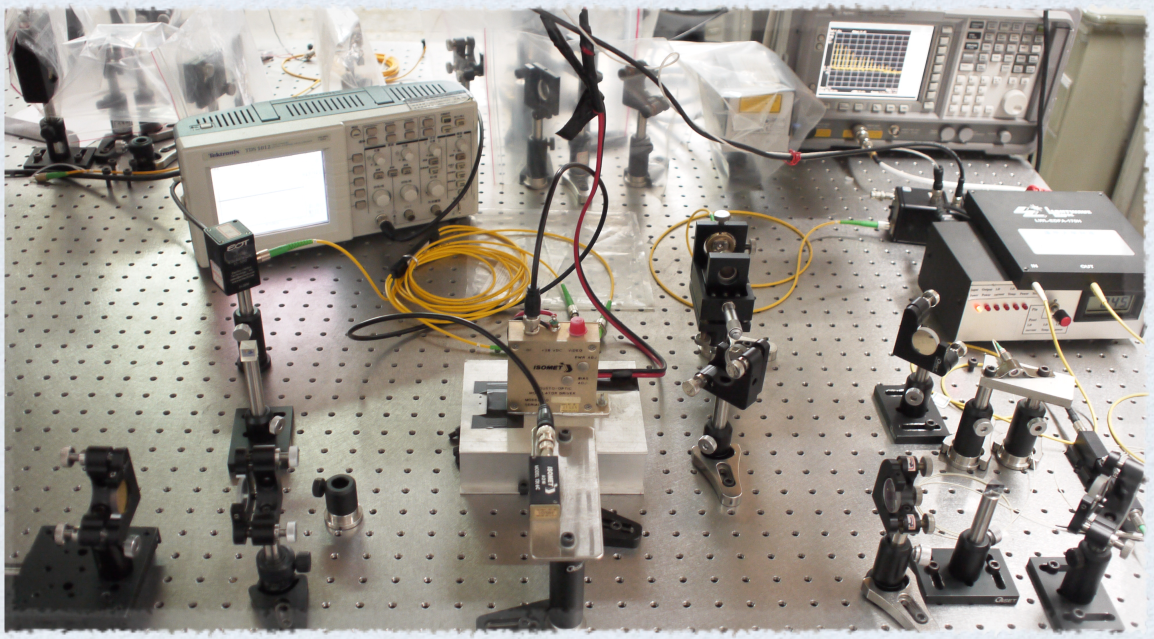
Normalized fitting curve
1.0
0.8
0.6
0.4
-10
-8
-6
-4
-2
0
2
4
6
8
10
Normalized frequency of AOM driver
Ω = 110 MHz
η = 16%
P = 40 mW
C2H2: 1.35 Torr
110 MHz



1.0
0.5
0.0
-0.5
-1.0
0.4
0.3
0.2
0.1
0.0
-0.8
-0.6
-0.4
-0.2
0.0
0.2
0.4
0.6
0.8
1.0
First Derivative of Sautuation Signal [a.u.]
Trnasmitted Pump Signal [a.u.]
Frequency Detune [GHz]
Ω = 110 MHz
η = 16%
P = 40 mW
fmod = 2 kHz
C2H2: 1.05 Torr

Summary of AOM-based Acetylene saturation absorption in HC-PCF

- Optical heterodyne spectroscopy using single AOM applied to Acetylene saturation absorption in HC-PCF was demonstrated.
  - surface-mode interference free
  - symmetric line profile with dip shifted by one AOM frequency



Thanks for your attention!