NICT Workshop on the Optical Frequency Standard (Feb. 7-8,2013, NICT, Tokyo, Japan)

Laser Phase and Frequency Stabilization Using Atomic Coherence

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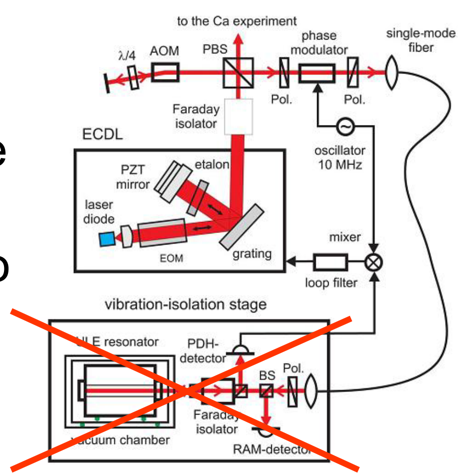
Motivation of this work

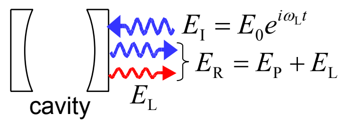
Can we reduce the laser linewidths without resorting to ULE cavities ?



Optics Letter, **31**, 736 (2006)

Reflectance of an undercoupled cavity

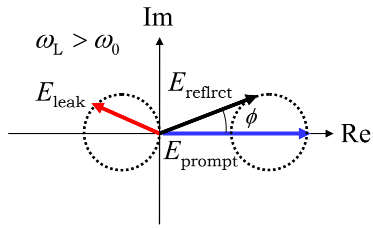
$$\delta = -k \cdot 2L = -\frac{\omega_L}{\nu_{FSR}}$$



Amplitude reflectivity:

$$r_1 = \sqrt{R_1} \quad r_2 = \sqrt{R_2} \quad R \equiv r_1 r_2$$

$$E_{\text{prompt}} = r_1 E_0 \quad T_1 \equiv 1 - r_1^2$$



$$E_{\text{leakage}} = -E_0 \frac{t_1^2 r_2 e^{i\delta}}{1 - r_1 r_2 e^{i\delta}}$$

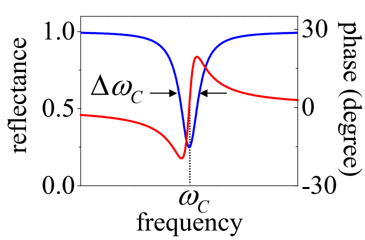
$$= -E_0 \frac{T_1}{r_1} \frac{Re^{i\delta}}{1 - Re^{i\delta}} = -E_0 \frac{T_1 R}{r_1} \frac{\cos\delta - R + i\sin\delta}{(1-R)^2 + 4R\sin^2(\delta/2)}$$

$$E_{\text{reflect}} = E_{\text{prompt}} + E_{\text{leakage}} = E_0 \frac{r_1 - r_2 e^{i\delta}}{1 - r_1 r_2 e^{i\delta}} = E_0 \frac{1}{r_1} \frac{R_1 - Re^{i\delta}}{1 - Re^{i\delta}}$$

High finesse limit of the undercoupled cavity

$$E_{\text{leakage}} = -E_0 \frac{T_1}{r_1} \frac{Re^{i\delta}}{1 - Re^{i\delta}} = -E_0 \frac{T_1 R}{r_1} \frac{\cos\delta - R + i\sin\delta}{(1-R)^2 + 4R\sin^2(\delta/2)}$$

$$\cong -E_0 \boxed{\frac{T_1}{1-R} \frac{1-ix}{1+x^2}} \quad (R \approx 1, \delta << 1)$$



$$\delta = -\frac{\omega_{laser}}{\nu_{FSR}} = -2\pi \frac{\omega_{laser}}{\omega_{FSR}}$$

$$x \equiv -\frac{\sqrt{R}}{1-R}\delta = \frac{\omega_{laser} - \omega_{cavity}}{\Delta\omega/2} \quad F \equiv \frac{\pi\sqrt{R}}{1-R} \quad \Delta\omega \equiv \frac{\omega_{FSR}}{F}$$

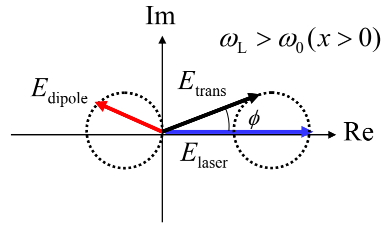
Transmittance of an atomic vapor

We assume that the sample of the atomic vapor is thin and the amplitude of the incident laser field is constant over the sample length of dx

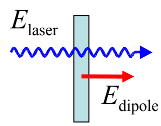
$$E_{\text{laser}} = E_0$$

$$E_{\text{dipole}} = -\frac{1}{2} ik(\chi' + i\chi'')dxE_0$$

$$\delta \equiv \omega_{laser} - \omega_{atom}, \quad x \equiv \frac{\delta}{\gamma} = \frac{\delta}{\Gamma/2}$$

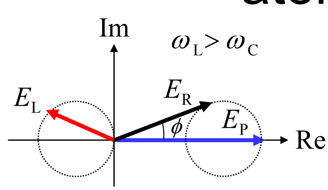


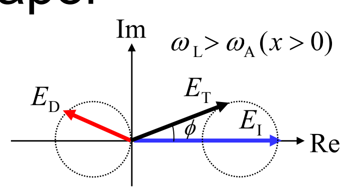
$$\begin{cases} \chi'(\omega) = -\chi''_{\max} \dfrac{\delta\gamma}{\delta^2 + \gamma^2} = -\chi''_{\max} \dfrac{x}{1+x^2} \\ \chi''(\omega) = -\chi''_{\max} \dfrac{\gamma^2}{\delta^2 + \gamma^2} = -\chi''_{\max} \dfrac{1}{1+x^2} \end{cases}$$

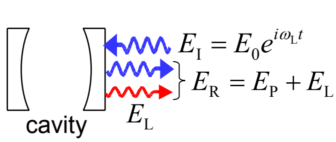


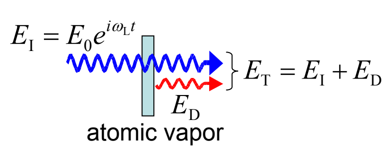
$$E_{\text{trans}} = E_{\text{laser}} + E_{\text{dipole}} = E_0 \left[1 - \alpha \frac{1 - ix}{1 + x^2} \right] \qquad \alpha \equiv \frac{1}{2} k\chi''_{\max} dx$$

Analogy between the cavity and the atomic vapor









$$E_R = E_0 \left[1 - \alpha \frac{1 - ix}{1 + x^2} \right]$$

Same form

$$E_T = E_0 \left[1 - \frac{\alpha}{2} \frac{1 - ix}{1 + x^2} \right]$$

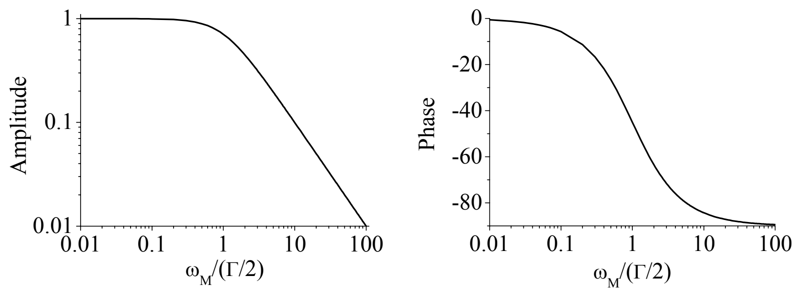
$$x \equiv \frac{\omega_L - \omega_C}{\Delta\omega / 2} \qquad \alpha \equiv \frac{1 - R_I}{1 - R}$$

$$x \equiv \frac{\omega_L - \omega_A}{\Gamma / 2} \qquad \alpha = k\chi''_{\max} dx$$

Transfer function of the frequency discriminator based on polarization spectroscopy

$$G(\omega_M) = \frac{G_0}{1 + i\omega_M / (\Gamma/2)}$$

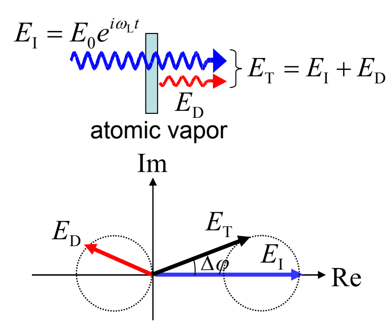
Same as the PDH method !

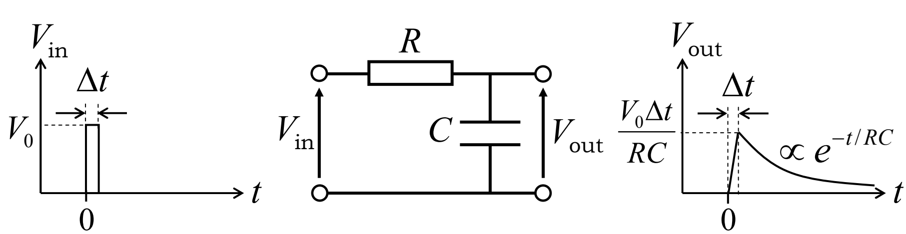


Y. Torii, et.al., PRA 86, 033805 (2012)

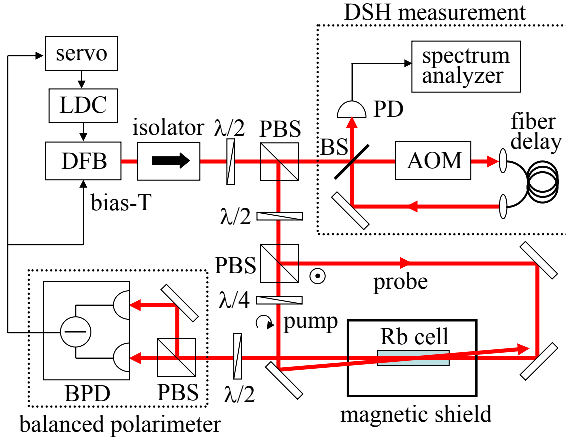
Response to a sudden phase jump

$$V_0 = \Delta\omega = \frac{\Delta\phi}{\Delta t}$$

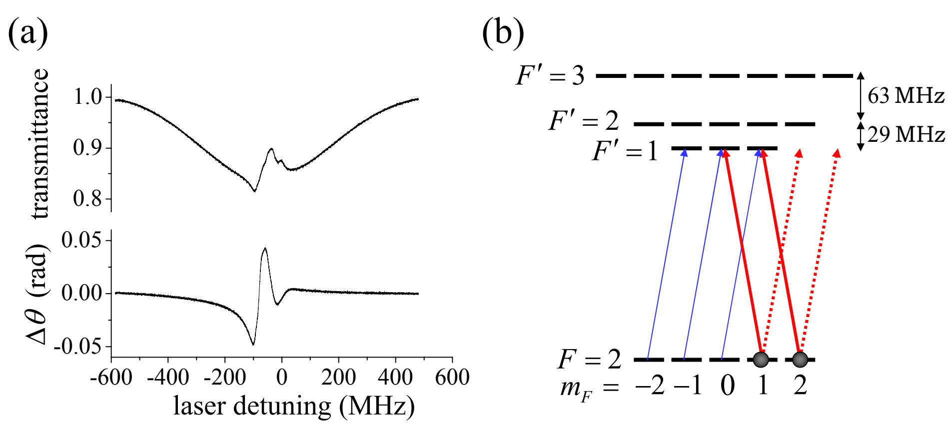




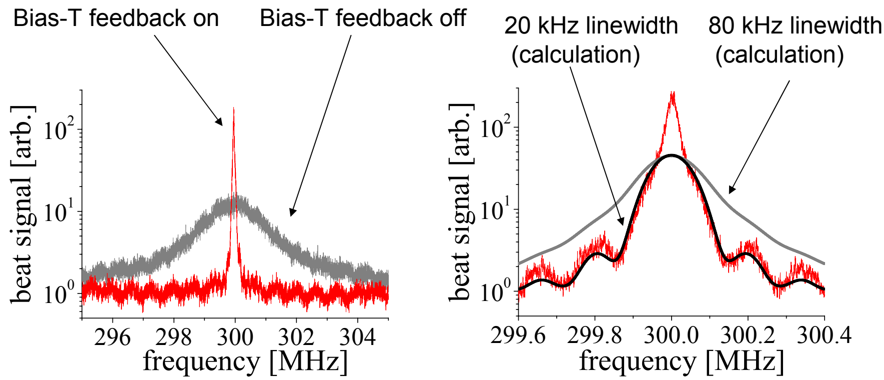
Experimental Setup



Polarization Spectroscopy of Rb85



Linewidth reduction of the DFB laser



Y. Torii, et.al., PRA 86, 033805 (2012)

Summary

- The respons of the polarization spectroscopy signal, in the thin vapor limit, has the same transfer function as the PDH method, and thus offers efficient laser linewidth reduction
- A preliminary experiment using a Rb vapor demonstrates a shot-noise-limited laser linewidth reduction (from 2 MHz to 20 kHz).