Temperature Sensitivity of an Atomic Vapor Cell-Based Dispersion-Enhanced Optical Cavity

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Abstract: Enhancement of the response of an optical cavity to a change in optical path length, through the use of an intracavity fast-light medium, has previously been demonstrated experimentally and described theoretically for an atomic vapor cell as the intracavity resonant absorber. This phenomenon may be used to enhance both the scale factor and sensitivity of an optical cavity mode to the change in path length, e.g. in gyroscopic applications. We study the temperature sensitivity of the on-resonant scale factor enhancement, S_0, due to the thermal sensitivity of the lower-level atom density in an atomic vapor cell, specifically for the case of the ^{87}Rb D_2 transition. A semi-empirical model of the temperature-dependence of the absorption profile, characterized by two parameters, $\alpha_0(T)$ and $\Gamma_\alpha(T)$ allows the temperature-dependence of the cavity response, $S_0(T)$ and dS_0/dT to be predicted over a range of temperature. We compare the predictions to experiment. Our model will be useful in determining the useful range for S_0, given the practical constraints on temperature stability for an atomic vapor cell.

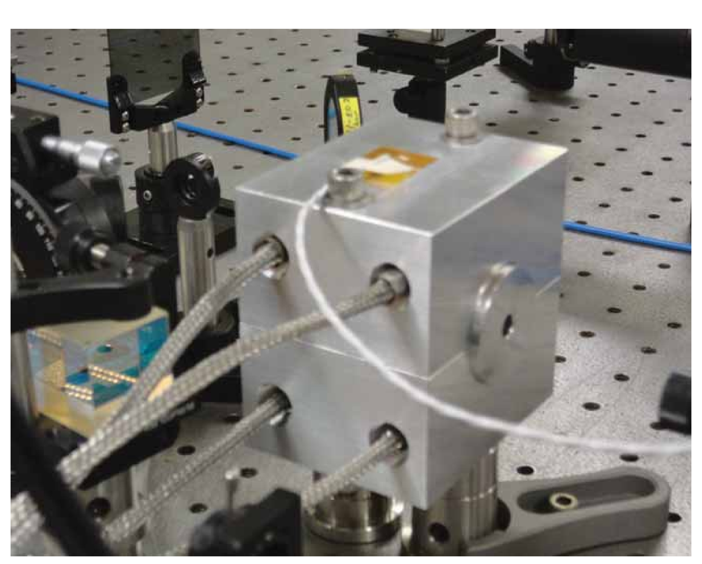
Introduction

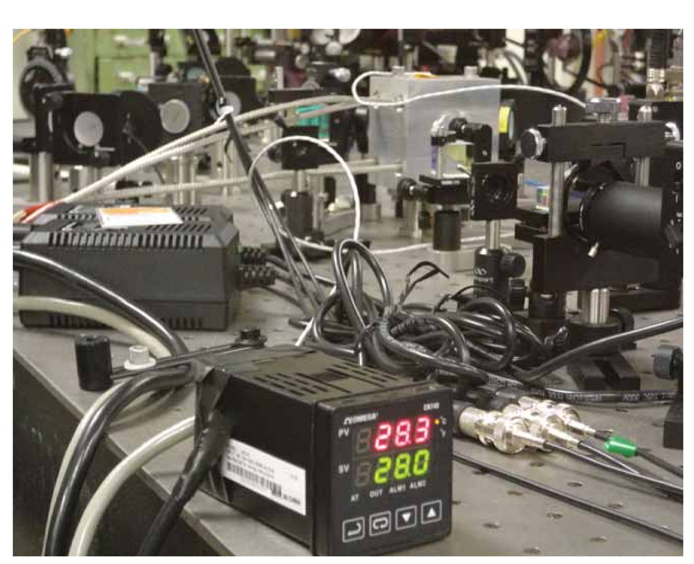
A resonant optical cavity containing an intracavity medium which provides anomalous dispersion at the resonant mode frequency has enhanced response to a change in cavity length[1]. This phenomenon has been demonstrated [2] and may be used to develop enhanced sensors, such as ring gyroscopes. An absorption resonance of the intracavity medium can provide the anomalous dispersion if the resonance is stable in frequency, peak absorption coefficient, and resonance width. While the atomic resonance has high intrinsic frequency stability, variations in the ambient temperature can cause significant variations in the peak absorption coefficient and the resonance width.

Our experimental system is a ring cavity containing a temperature-stabilized atomic vapor cell of ^{87}Rb, with the cavity and laser resonant with the Doppler-broadened D_2 line at 780.2 nm. Without the cavity, we measure the single pass variation of the resonance parameters in the laboratory and compare them to a semi-empirical model for the absorption coefficient profile vs. temperature for the D_2 line. Using the ring cavity, we measure the scale factor enhancement S_0 of the ring cavity as a function of temperature. A model of S_0 vs T, based solely on the two absorption resonance parameters $\alpha_0(T)$ and $\Gamma_\alpha(T)$, is compared with the data.

Temperature-Controlled Atomic Vapor Cell

A temperature-controlled oven, based on a published design[3], was adapted for use with a 2.5 cm quartz atomic vapor cell, containing isotopically pure ^{87}Rb.





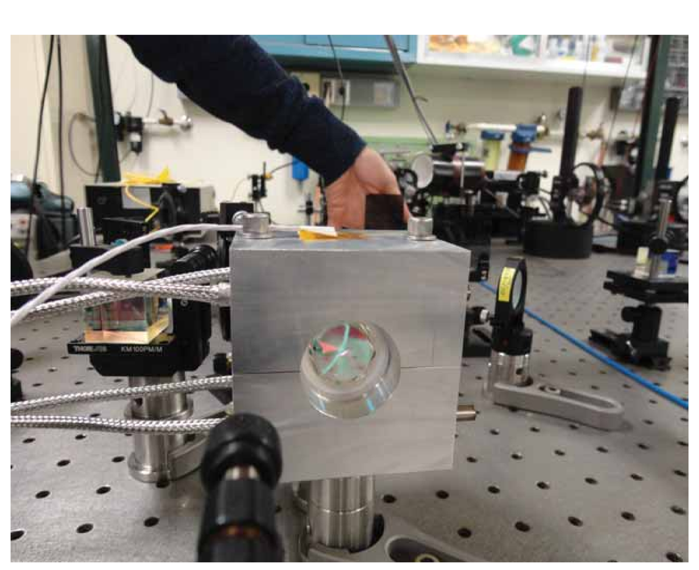


Fig. 1 a) Top Left: Rb atomic vapor cell in temperature stabilized mount. End caps with beam apertures reduce heat loss. b) Top Right: Temperature controller, c) Bottom Left: Temp. stabilized mount without end caps, showing the 2.5 cm atomic vapor cell inside.

Acknowledgments

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Resonance Model

$$\Gamma_\alpha^{(1)}(T) = \frac{\omega}{c}\left(\frac{8\,k_B T \ln(2)}{m}\right)^{1/2}$$

$$\alpha_0(T) = N_l(T) F_l(T) \sigma_0^{F_g,F_e} \qquad N_l(T) = \left(\frac{2F_g+1}{\sum_{F_g} 2F_g+1}\right) N(T)$$

$$\sigma_0^{F_g,F_e} = \frac{2\omega|\mu_{F_g,F_e}|^2}{c\,\epsilon_0 \hbar \gamma} \qquad N(T) = \frac{133}{k_B T}\times 10^{2.881+4.312-4040/T}$$

Single Pass Beam Measurements of $\alpha_0(T)$ and $\Gamma_\alpha(T)$

Transmittance spectra of the D_2 line were obtained at different vapor temperatures, using a highly attenuated tunable laser to avoid saturation and optical pumping effects. The beam intensity was less than 15 μW/cm^2. From a fit of the D_2 transmittance spectrum with the three hyperfine components of the line, the peak absorption coefficient and resonance full width at half max (FWHM) were obtained, and compared against the semi-empirical model, as shown below.

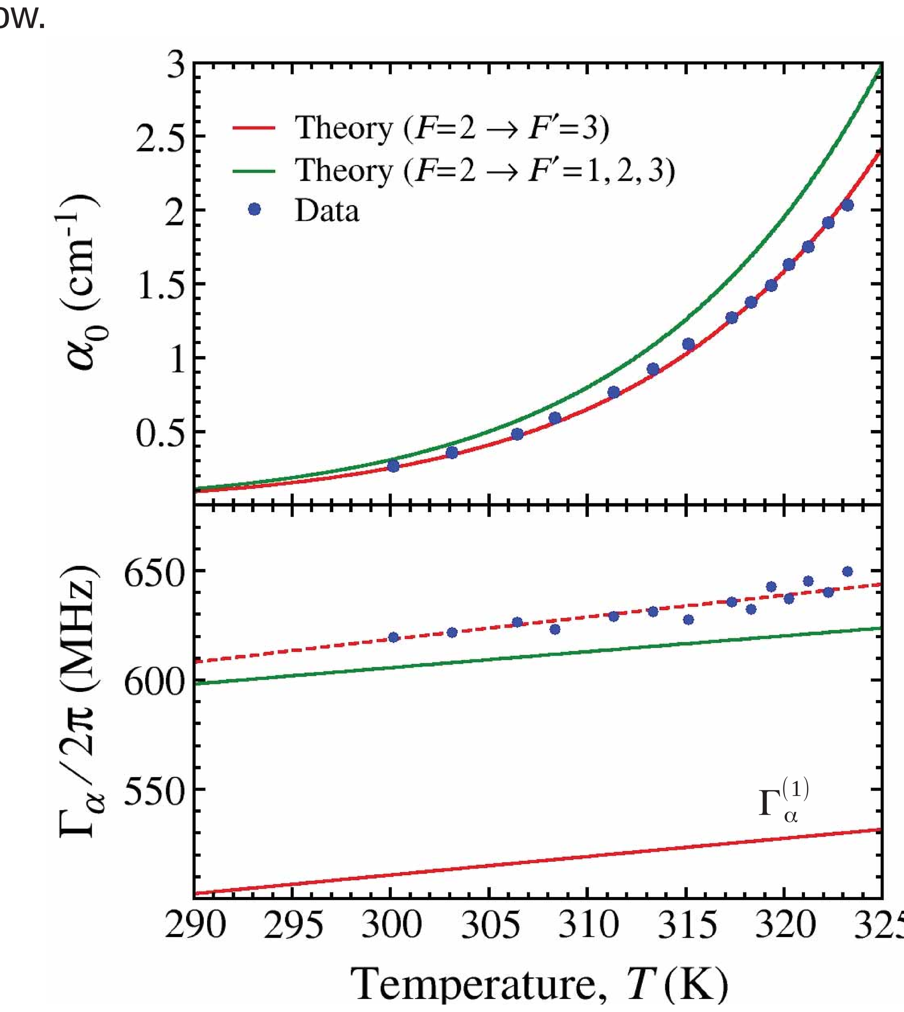

Fig. 2 Peak absorption coefficient (top) and FWHM resonance width (bottom) vs temperature. Solid curves are computed from a semi-empirical model with no adjustable parameters, using only the F = 2 ⟶ F' = 3 transition (red) and using all three F = 2 ⟶ F' transitions (green). Dashed curve is the single transition Γ_α scaled to match the resonance width.

References

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Scale Factor Enhancement Theory

For a dispersive medium in a resonant cavity, the on-resonance scale factor enhancement, S_0, is given by [4],

$$S_0(T) = \left(\hat{n}_g(T) + \frac{1}{t_c}\left|dF(\Delta,T)/d\Delta\right|_{\Delta=0}\right)^{-1}$$

For a Gaussian resonance, these terms may be evaluated analytically to give,

$$S_0(T) = \left(\hat{n}_g(T) + \frac{1}{(L/c)^2}\,\frac{4L\ln(2)}{\hat{n}_g(T)}\left(\frac{1-g_0^2(T)}{2g_0(T)}\right)\frac{\hat{\alpha}_0(T)}{\Gamma_\alpha(T)^2}\right)^{-1}$$

with

$$\hat{n}_g(T) = 1 - 2c\sqrt{\frac{\ln(2)}{\pi}}\,\frac{\hat{\alpha}_0(T)}{\Gamma_\alpha(T)} \qquad g_0(T) = ra\exp(-\hat{\alpha}_0(T)L/2)$$

$$\hat{\alpha}_0(T) = \alpha_0 l/L$$

Ring Cavity Measurements of $S_0(T)$

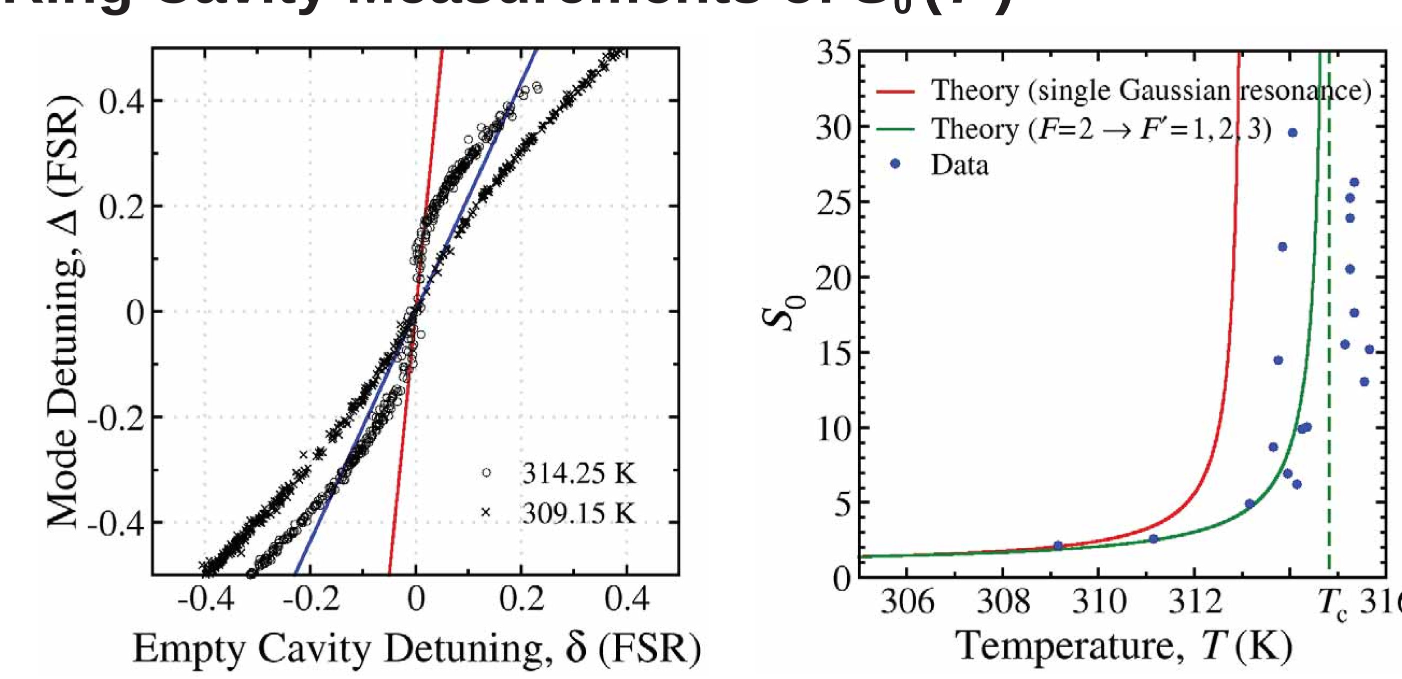

Fig. 3 a) Scale factor enhancement near and far from the critical temperature, T_c. Cavity mode is pushed by the ^{87}Rb D_2 F = 2 resonance resulting in an increased slope. b) Comparison of experiment vs theory for the scale factor enhancement, S_0. The critical temperature for S_0 is within 2 K of that predicted by the single Gaussian resonance theory (red). For comparison the theory including all three F = 2 ⟶ F' transitions is shown (green).

Conclusions

The single Gaussian resonance model is useful for determining the behavior of the scale factor as a function of the temperature, from which the temperature sensitivity can be readily determined. The predicted critical temperature was within 2 K of the full three transition model for the D_2 F_g = 2 resonance. For an assumed atomic vapor temperature variation of 10 mK, S_0^{max} is 530 for a variation of S_0^{max}. For any medium with a Gaussian absorption resonance and with known $\alpha_0(T)$ and $\Gamma_\alpha(T)$ we can use the model to predict its temperature-dependent cavity scale factor enhancement $S_0(T)$ and determine S_0^{max} for the desired scale factor stability.