Laser frequency stabilization using The Pound-Dever-Hall detector setup

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Abstract

A highly stable laser in both power and frequency is crucial for quantum atom systems in quantum computing. Instabilities affect atomic excitation accuracy, necessitating an efficient laser locking system. This project implements the Pound-Drever-Hall (PDH) technique, a widely used method for stabilizing laser frequency. The experiment ensures laser mode selection (TEM_{00}) and precise optical focusing into an ULE cavity with a beam waist radius of 248.2 µm. Key components include an electro-optical modulator(EOM), convex lenses for focusing beam, and a feedback system to stabilize the laser frequency. The study successfully obtained the TEM00 mods, the optimal focused beam into cavity and the cavity refection signal.

Introduction

This project focuses on developing a stable laser locking system for quantum atom system in quantum computing research. Pound-Drever-Hall (PDH) technique stabilizes the laser frequency using an error signal produced from the ultra-low extension cavity (ULE) setup. Laser polarization is modulated using an electro-optic modulator (EOM) driven at 20 MHz before the laser beam enters the ULE cavity. The interfered reflection from the cavity together with the modulation signal are processed to produce the error signal, which is then feedback to laser controller allowing for frequency stabilization.

Theory

- **ULE cavity**

It is a device that amplifies the light signal or increases the number of photons by allowing the light to travel back and forth multiple times. This device consists of two highly reflective mirrors arranged in parallel. When laser light enters, it reflects repeatedly between the two mirrors, undergoing interference until it reaches sufficient intensity and equilibrium. At this point, a portion of the light signal passes through and exits the ULE cavity.

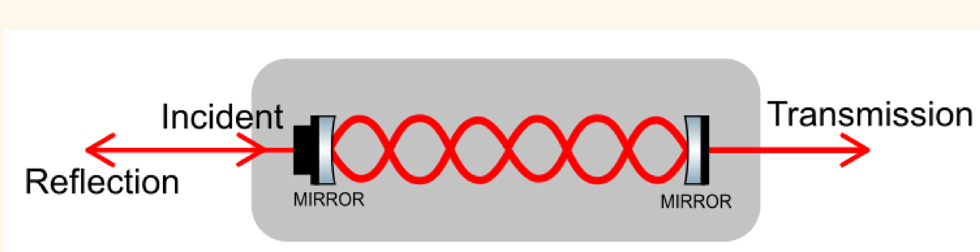


Figure1 ULE cavity Diagram

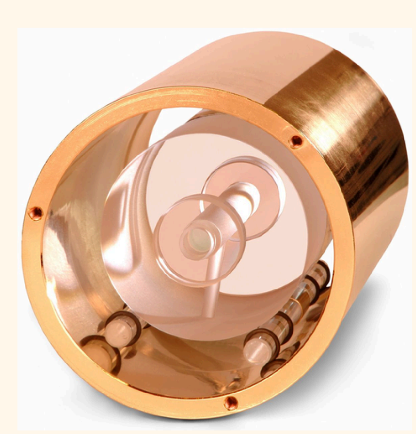


Figure2 ULE cavity without chamber

Experiment

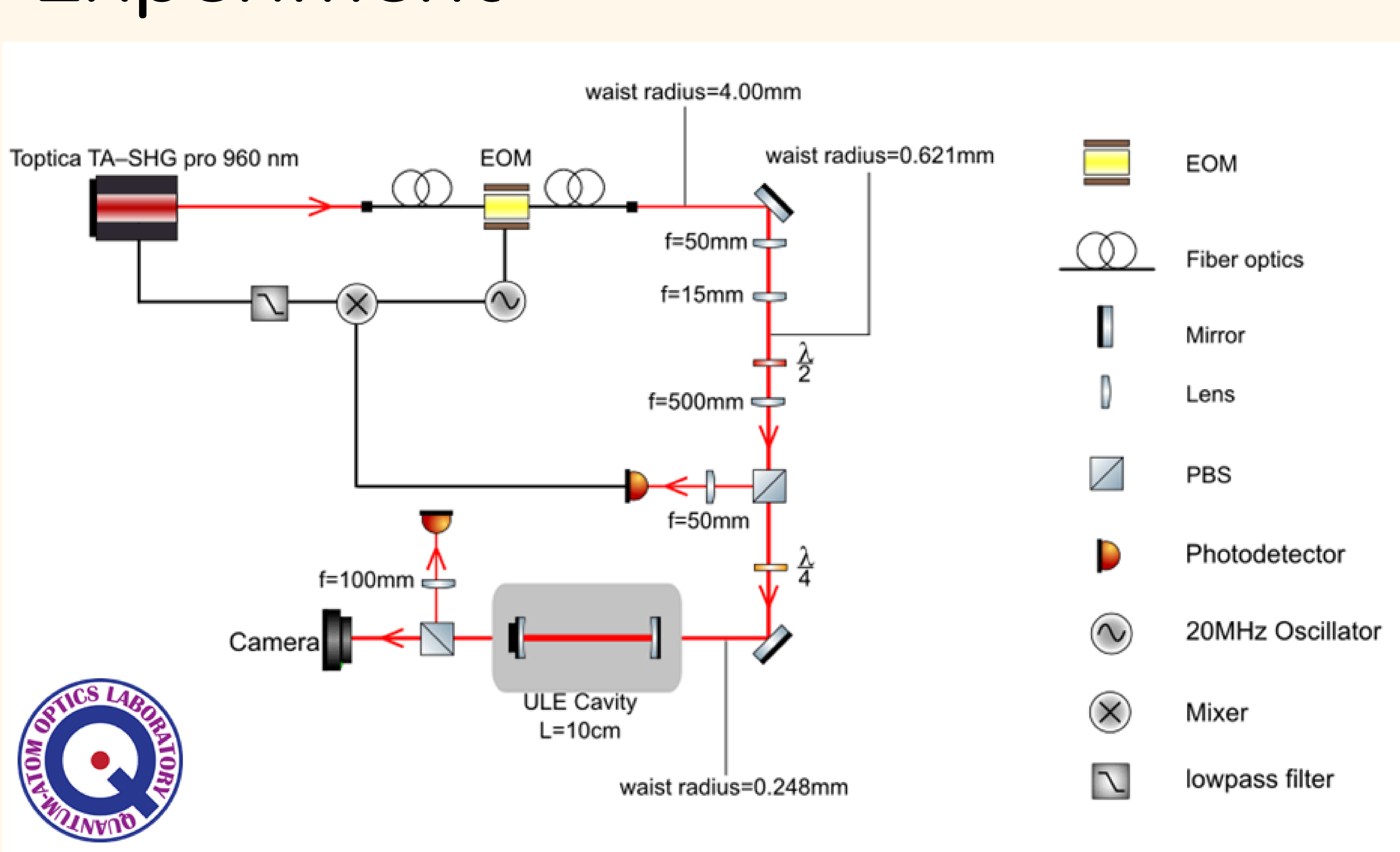


Figure3 Device installation diagram

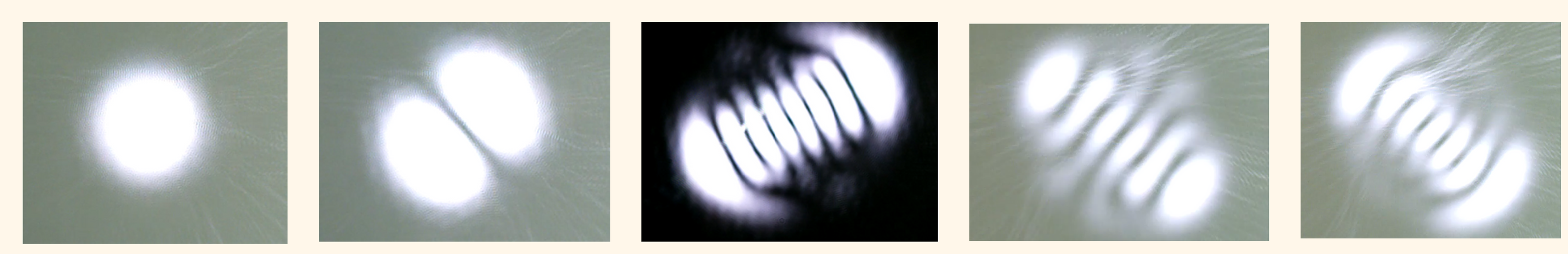
In this experiment, convex lenses with focal 50mm, focal 15mm, and focal 500mm were installed to focus the radius down to 248.2 µm.

Results & Conclusion

In the analysis of Gaussian beam modes, the following equation can be used to simulate the pattern of TEM modes in laser systems.

$$E_{mn(x,y,z)} = E_0 \frac{\omega_0}{\omega(z)} H_m\left(\sqrt{2}\frac{x}{\omega(z)}\right) H_n\left(\sqrt{2}\frac{y}{\omega(z)}\right) exp\left(-\frac{x^2+y^2}{\omega\left(z\right)^2}\right) exp\left(-i\xi\left(x,y,z\right)\right)$$

when $\xi = \left[kz - (1+m+n)arctan\frac{z}{z_R} + \frac{k\left(x^2+y^2\right)}{2R\left(z\right)}\right]$ and Hm, Hn = Hermite Polynomial



TEM_{00} TEM_{01} TEM_{09} TEM_{70} TEM_{80}

Figure4 TEM found in experiments

The laser passing through the ULE cavity exhibits multiple transverse electric field patterns, characterized by integer indices (m, n). The TEM_{00} mode has the highest intensity at the center, providing greater energy and symmetry compared to other TEM modes.

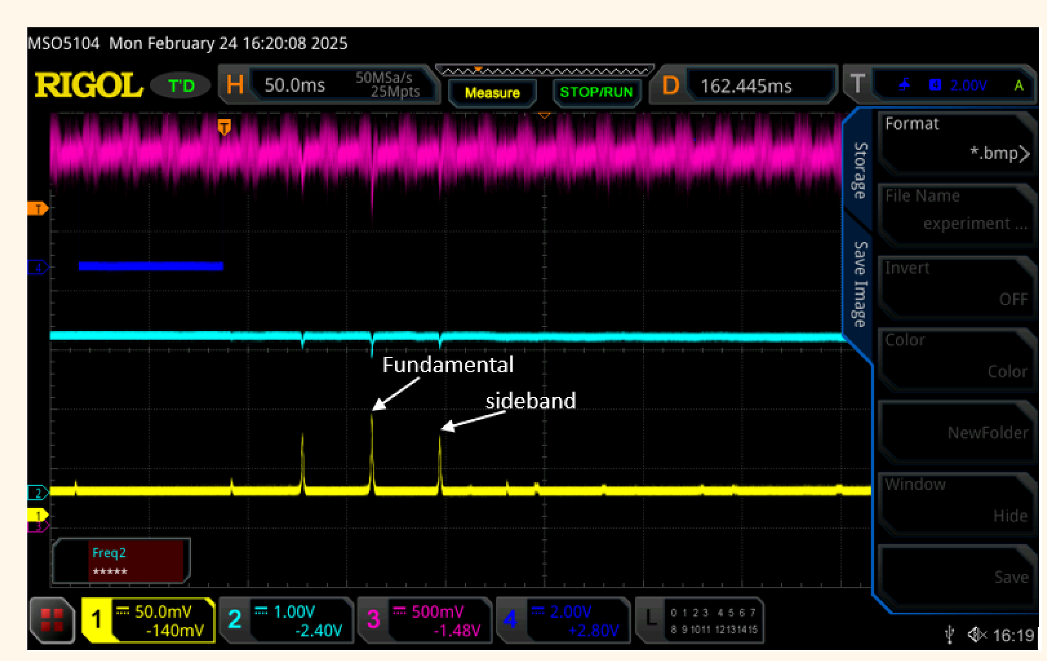


Figure5 Light signals observed from the ULE cavity.

- Yellow signal is the light signal transmitted through the ULE cavity.
- Blue signal is the light reflected from the ULE cavity, which is a high-impedance output signal.
- Pink signal is an amplification of the Blue signal using a non-inverting Op-Amp, this produces a 50Ohm impedance output signal which is impedance matched to the mixer.

x axis is directly proportional to time and y axis is directly proportional to Intensity

It can be observed that the reflected signal is too weak to be utilized, necessitating signal amplification. However, despite the increased signal , a significant amount of noise is also introduced.

Finesse can be derived by calculating the ratio of the FSR to FWHM from the obtained signal

$$Finesse = \frac{FSR}{FWHM} = \frac{0.642335s}{0.002660s} = 241.479 \pm 0.027$$

and The cavity has an FSR 1.5 GHz. By calculate linewidth of this cavity as 6.212 MHz

$$FWHM = \frac{FSR}{Finess} = \frac{1.5\times10^9Hz}{241.479} = 6.212\times10^6Hz \pm 702.43Hz$$

Results obtained from the experiment

- The coupling of laser TEM modes into the ULE cavity was investigated to ensure efficient mode matching.
- The beam cross-sectional size was adjusted to optimize the coupling into the TEM_{00} mode.
- A 50Ohm impedance reflection signal was generated before evaluating the error signal.
- The cavity's fundamental properties, including FSR, FWHM, and finesse, were analyzed.

Reference

[1] Eric D. Black, 3 January 2000. An introduction to Pound–Drever–Hall laser frequency stabilization

[2] M Nickerson, A review of Pound-Drever-Hall laser frequency locking