Undergraduate Research Projects – Summer 2026

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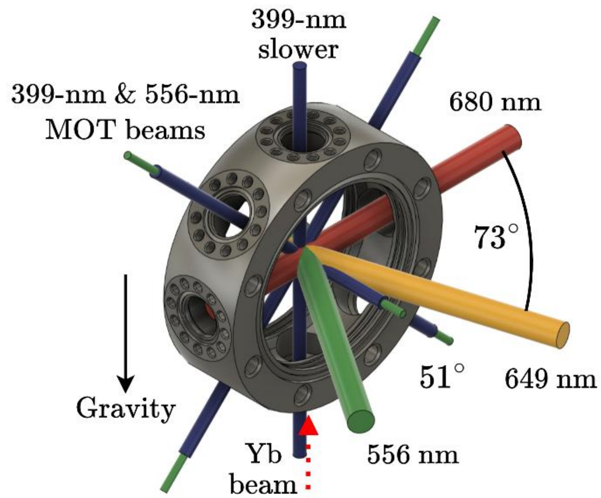
Laser Cooling and Spectroscopy of Ultracold Ytterbium



This project aims to develop a new type of optical atomic clock.

Optical atomic clocks are among the most precise and accurate devices ever developed, operating by stabilizing the frequency of a laser to an atomic resonance. State of the art clocks are now operating with systematic uncertainties of less than 1 part in 10^{18}. This performance is enabled by probing atomic quantum levels with extremely high Q-factors and low sensitivity to environmental noise. For example, the optical clock transition in ytterbium (Z=70) has a wavelength of 578 nm and a Q-factor of over 10^{17}. In order to measure the atomic resonances with such high levels of accuracy, the atoms must first be laser-cooled to ultracold temperatures, typically on the order of tens of microkelvin.

We are currently constructing a new atomic clock apparatus using ensembles of ytterbium atoms. In contrast to previous clocks, we will use a three-photon Doppler-free probing scheme [1], enabling high performance in a simplified setup with fewer sources of systematic uncertainty. Furthermore, we have recently devised a new, magnetic field-free approach for laser cooling of atoms, which we expect will unlock unique functionalities both for clocks and other atomic physics experiments.

In this project, the student will participate in the design and construction of a cutting-edge ultracold laser cooling and atomic clock apparatus. Responsibilities may vary depending on student interest and ongoing work in the lab, but could include alignment of optical systems, design and construction of optical and electronics modules for light modulation and detection, and stabilization of laser frequencies to atomic and cavity references.

[1] T. Hong, C. Cramer, W. Nagourney, and E. N. Fortson., Optical Clocks Based on Ultranarrow Three-Photon Resonances in Alkaline Earth Atoms. Phys. Rev. Lett. **94**, 050801 (2005)

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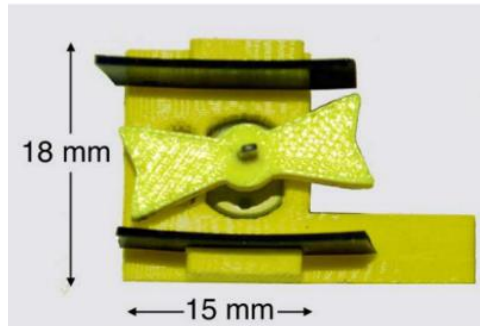
High-Performance Custom Laser Shutters



This project aims to surpass the performance achieved by the 3D-printed optical shutter introduced in [1].

Mechanical optical shutters are an essential component in quantum optics experiments, due to their unique combination of perfect transmission when opened and perfect optical attenuation when closed.

This advantage often outweighs the shutters' much slower response speed as compared to alternative technologies for blocking and unblocking light, such as electro-optical, acousto-optical, and MEMS-based modulators. Commercial solutions for mechanical optical shutters are typically large, slow, expensive, and/or noisy. In a previous project [1], we demonstrated a simple and compact 3D-printed optical shutter with 1 ms response time and a volume footprint below 5 cm^3. The CAD files for producing this shutter design were shared in an open-source manner to maximize utilization by other laboratories. Since then, we have identified several improvements to both the mechanical and optical aspects of the shutter design, including:

- Fabricating the shutter body out of metal to improve thermal dissipation properties.
- Fabricating the shutter blade out of metal or carbon fiber to increase laser power handling and shutter switching speed.
- Using high-torque and increasingly compact DC motors developed for drone applications.
- Using a digitally controlled circuit to increase shutter speed and reduce mechanical noise.
- Simplifying the customization of the shutter for high speed or high laser power applications by introducing a semi-standard library of shutter blade designs.

In this project, the student will realize the above goals by designing and building a new optical shutter and driver system. The student will quantitatively test the shutter's speed, repeatability, reliability, and low level of mechanical and electrical noise to confirm its suitability for usage in a state-of-the-art quantum optics laboratory. The student will also investigate the fundamental and technical limitations to optical shutter performance at different laser beam sizes and powers.

[1] G.H. Zhang, B. Braverman, A. Kawasaki, and V. Vuletić, Note: Fast compact laser shutter using a direct current motor and three-dimensional printing. Review of Scientific Instruments **86**, 126105 (2015)

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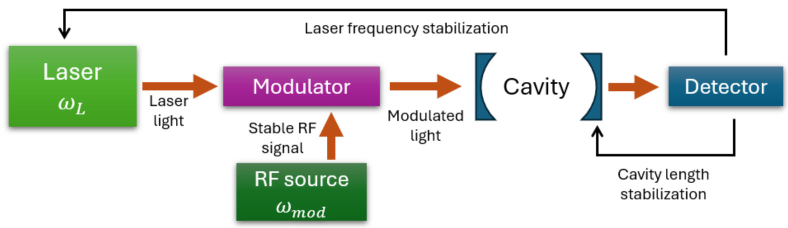
Dual Laser-Cavity Frequency Stabilization



This project aims to lock the laser frequency ω_L to a cavity resonance, while simultaneously stabilizing the cavity length to a stable microwave signal at ω_{mod}.

Fabry-Perot cavities are commonly used for laser stabilization, by locking the laser frequency to the resonance frequency of one of the modes of the cavity. In state-of-the-art systems, this approach can achieve laser linewidths of 1 Hz or below. However, the measured signal is only sensitive to the frequency difference between the cavity and laser. As a result, any drifts in the length of the cavity translate directly into a drift of the laser frequency.

Changes in the absolute length of the cavity can be monitored and stabilized by generating additional laser frequency sidebands using an electro-optic modulator (EOM) and simultaneously probing multiple resonances of the cavity. The phase difference between light transmitted through the cavity at these different resonances provides information about the length of the cavity relative to the wavelength of microwaves used to drive the EOM. As a result, frequency stability is transferred between the optical and microwave domain, which we will use to perform long-term absolute frequency stabilization of a laser to an atomic clock microwave reference.

In this project, the student will assist in performing simulations, constructing the apparatus, and implementing the locking scheme to simultaneously stabilize the frequency of the laser and the length of the cavity.