Summer 2025 Projects

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Precision measurement using disorder

Optical cavities comprised of mirrors with low absorption and scattering loss are key building blocks for precision laser stabilization and cavity quantum electrodynamics (QED) experiments. In the context of laser stabilization, Fabry-Perot cavities with a finesse of 100,000 or higher are used to measure and lock laser frequencies down to a linewidth of 1 Hz or below. Despite this exceptional performance, locking a laser to a Fabry-Perot cavity comes with drawbacks. The measurement sensitivity to changes in laser frequency is only high near the (narrow) cavity resonance, requiring the laser to already be close to the resonance in order for the laser lock to be engaged. In addition, the Fabry-Perot cavity has many identical-appearing resonances typically spaced by 1 GHz, requiring additional instrumentation to unambiguously determine the laser frequency.

A contrasting approach to laser frequency measurement and locking is to use a multipath interferometer to produce multiple intensity signals, which can be computationally inverted to extract the laser frequency. A “photon box”, consisting of an enclosed space coated with low-loss optical mirrors with localized input and output ports, could in principle achieve similar precision as a Fabry-Perot cavity, but without the dynamic range and signal ambiguity limitations outlined above.

In this project, the student will study the spectral response of multipath optical interferometers, including the limit of long-duration confinement in a low-loss optical cavity. Building on current work in the research group, the student will simulate the optical response of highly multipath interferometers and measure the response of these devices in the laboratory.

High-Performance Custom Laser Shutters

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, 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 aspect 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.

Optimal filtering of spatial modes of light

A common challenge in laser physics is mode cleaning: increasing the coherence of a beam of light by suppressing or eliminating higher-order modes. An ideal mode filter would transmit 100% of the desired mode, and completely block all remaining modes. In the spatial domain, such an ideal filter exists: a single-mode fiber (SMF). Over a propagation distance of only a few cm, all higher-order modes can be efficiently radiated away. However, a conventional single-mode fiber is not always an option: when the target modes are higher-order transverse modes, when filtering high-intensity lasers that would damage an SMF, when working with wavelengths for which SMFs are unavailable, or when filtering temporal rather than spatial modes of light. A simple, albeit imperfect, alternative to an SMF for mode cleaning is a "spatial filter" consisting of a single aperture between a pair of lenses. More generally, one can construct a mode filter out of a sequence of arbitrarily shaped masks separated by lenses and free space.

In this project, the student will simulate the generalized version of the spatial filter and optimize its performance by varying the positions and shapes of the constituent lenses and masks to maximize the transmission of the mode of interest while suppressing all others. The student will then experimentally verify the performance of the spatial filter they designed.