Compact ultrastable lasers supporting fundamental physics in space

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Abstract: Potential scientific discoveries utilizing high precision optical clocks in space include dark matter searches, local Lorentz invariance tests, and tests of general relativity. In addition to the atoms themselves, optical atomic clocks require ultrastable lasers to perform spectroscopy on the clock transition, and whose electric field oscillations serve as the readout "ticks" of the clock. The narrowness of the clock transition requires pre-stabilization of the spectroscopy laser, best performed by locking the laser to a passive reference cavity. Here we propose to use newly developed microfabrication techniques and advanced cavity design to create compact, rugged, and low noise micro-Fabry-Perot cavities integrable with space optical atomic clocks. With these optical frequency reference cavities, state-of-the-art performance can be achieved within a cavity volume of 10 mL and mass less than 25 g.

Overview and science goals

Lasers locked to passive reference cavities are now the most frequency-stable sources of electromagnetic radiation. The scientific and technical utilization of such ultra-stable optical frequency sources continues to grow, with applications in optical clocks and the redefinition of the SI second [1, 2]; constraints on dark matter [3]; quantum information processing [4]; earthquake detection [5]; and, when used in conjunction with an optical frequency comb, low noise microwave generation for communications, radar and spectroscopy [6, 7]. Fundamental physical science applications of ultra-stable lasers are extended when they are integrated on space-based platforms. An important example is the successful laser ranging interferometry experiment of the GRACE Follow-On mission [8]. Not only did this provide an order of magnitude improvement over microwave ranging, but proved the viability of ultra-stable lasers in space for LISA and other future missions. An exciting mission prospect is the Fundamental Physics with an Optical Clock Orbiting in Space (FOCOS) proposal to place state-of-the-art optical atomic clocks in space for fundamental science research in dark matter, local Lorentz invariance, and tests of general relativity. Importantly, optical atomic clocks require an ultra-stable laser to perform spectroscopy on the clock transition and readout of the clock frequency. This application places some of the most stringent demands on the frequency stability of a laser. Indeed, the most stable lasers demonstrated to date have been targeted towards use in optical atomic clocks [9].

At the heart of every ultra-stable laser is a high quality-factor optical resonator cavity, typically comprised of high reflectivity mirrors bonded to a glass spacer. Locking a laser's frequency to this reference cavity transfers the length stability of the cavity to the laser frequency, resulting in laser linewidths below 1 Hz and fractional frequency instabilities below $\Delta f/f = 10^{-16}$. A state-of-the-art optical resonator used in conjunction with an optical clock typically occupies a volume exceeding 1 m^3, is held in high vacuum with multiple layers of thermal isolation, and free-space lenses and mirrors are used to efficiently couple light into the optical cavity. The large size and weight of these systems, as well as their delicate optical alignment, has largely relegated their use to staid laboratory environments. The goal of this project is to leverage recent innovations at NIST and Yale University to create compact optical reference cavities for space applications that are fiber-coupled, amenable to mass manufacture, mass less than 25 g and a volume of < 10 mL, all while exhibiting a fractional frequency instability below 10^{-14}. When the ultimate in stability is required, instabilities as low as 10^{-16} can be achieved at the expense of slightly larger cavity weight and volume. This cavity development is critical for optical clock operation in space, and successfully achieving the associated science goals.

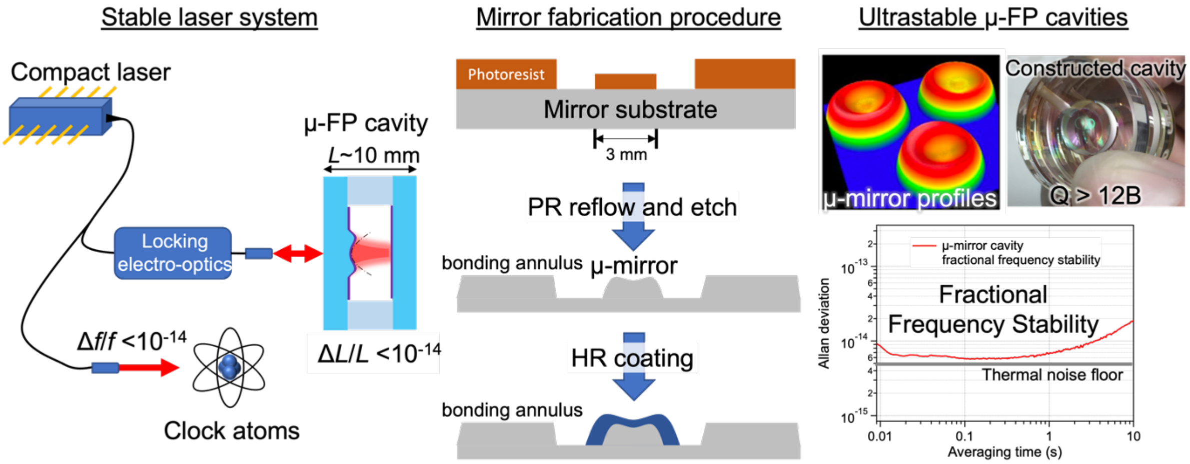

Fig. 1. Microfabricated mirrors and μ-FP performance. **Left**: Laser stabilized to a μ-FP is used to interrogate the clock transition of an optical clock. **Center**: Mirror and bonding annulus fabrication. Photoresist (PR) reflow of the central PR island creates a concave mirror shape that is transferred to the substrate upon reactive ion etch. Thicker PR on the edge of the substrate protects a pre-defined bonding annulus during the etch. **Right**: Micrograph of mirror substrate with three μ-mirrors, photograph of a constructed μ-FP cavity with the same substrate, and measured fractional frequency stability of a 10 mm long μ-FP.

Meeting optical cavity requirements with micro-Fabry Perot cavities

Frequency stability requirements of an optical atomic clock on a space-based platform necessitate a cavity design with low thermal noise, extremely high optical quality factor, and low environmental sensitivity. Recently developed vacuum-gap cavities constructed with microfabricated mirrors [10, 11], or micro-Fabry-Perot (μ-FP) cavities, offer a compelling path to realize ultra-stable frequency performance in space-borne optical atomic clocks. Figure 1 shows how these mirrors are fabricated, as well as showing demonstrated mirror profiles and μ-FP cavity performance. In the paragraphs below, we discuss the required properties and performance of cavities for space-borne optical atomic clocks, and how μ-FP cavities are well-positioned to meet these requirements.

The fractional frequency stability of a laser locked to a reference cavity is ultimately limited by cavity thermal noise [12]. Cavity thermal noise primarily arises from the optical beam sampling the thermally driven fluctuations of the mirror surface. Its impact on the frequency stability is reduced by increasing the cavity length and by averaging over a larger portion of the mirror surface with a large optical spot size. We are able to fabricate mirrors with a radius of curvature > 1 m, resulting in large optical spot sizes and low thermal noise in compact cavities. Figure 1 shows a fractional frequency instability that reaches 6×10^{-15} for a μ-FP cavity length of only 10 mm. We note that this stability is more than 10x better than lasers stabilized to solid-state reference cavities [13]. The higher instability in solid-state resonators is due to thermally driven refractive index fluctuations experienced by the optical mode. Thus the vacuum-gap of a μ-FP offers a compelling advantage for high performance optical clocks.

A high optical quality factor provides a narrow cavity resonance required for high-fidelity laser locking, and is key to the laser's frequency instability reaching the cavity's thermal noise limit. High cavity Q is achieved with high reflectivity (R > 99.999%), low loss mirrors. Our analysis shows the Q should be at least 5 billion, with even higher Q easing the low noise requirements in the locking electronics. For a given mirror reflectivity, the Q increases linearly with cavity length; thus compact cavities generally benefit from a higher mirror reflectivity. Importantly, the mirror reflectance in the highest finesse cavities is limited by the roughness of the mirror substrate. Our team's mirrors have demonstrated angstrom-level roughness, yielding reflectivity of 99.9997%, and cavity Q > 12 billion on a 10mm long cavity.

We achieve low environmental sensitivity through a combination of low thermal expansion materials and utilizing cavity geometries with a high degree of mechanical symmetry. Cavities composed of ULE glass can operate with a thermal coefficient of expansion of less than 10^{-8}/K. Such low temperature sensitivity is critical for providing sub-10^{-14} fractional frequency instability. Cavity vibrations will distort the cavity shape, but are mitigated when the cavity has a high degree of mechanical symmetry. The smaller volume of a compact μ-FP cavity volume also reduces flexing of the cavity shape in a high vibration environment, leading to lower vibration sensitivity. An optical cavity on a space-based platform will also need to be rigidly held. Some level of change to the holding forces are unavoidable (due to, for example, temperature changes), and a properly designed holding structure limits resultant changes to the cavity length. We have designed and implemented structures that rigidly hold a cavity with first-order insensitivity to holding force variations [14]. This holding architecture is directly applicable to μ-FP cavities.

An important technical consideration that impacts both the cavity volume and environmental sensitivity is how the mirrors are bonded to the spacer. Standard mirrors are fabricated by lapping and polishing a curved surface on a glass substrate, then polishing a flat annulus on the outer rim of the mirror for bonding onto the cavity spacer. With large ROC mirrors, the sag in the center of the mirror is typically only a few microns, with smaller mirror diameters yielding smaller sag for a given ROC. This puts a lower limit on the diameter of the mirror, since otherwise the annulus polishing will damage the pristine surface at the mirror's center. For example, the minimum diameter substrate for a mirror with 1 m ROC and a contact annulus is 12.7 mm (with a cavity spacer diameter at least as large). However, for a 10 mm long optical cavity with this ROC, only the central 1 mm is illuminated by the optical beam. Thus a large reduction in the mirror and spacer diameter can be achieved if the link between ROC and mirror diameter can be broken. Moreover, the required low surface roughness requirement on the annulus itself leads to large variability in the size of the contact annulus – polishing stops whenever the desired roughness is reached. This in turn leads to variability in the response of the cavity to the externally applied stresses of a rigid holding structure, making it extremely difficult to design for minimum cavity length distortions due to holding structure forces.

Microfabricated mirrors obviate the difficulties in polishing a contact annulus, allowing large ROC in a smaller diameter mirror, and a highly repeatable contact annulus. The mirror and annulus fabrication method is illustrated in Fig. 1. Photoresist is spun onto a superpolished flat substrate in lithographically defined areas at the mirror center and the outer rim. When placed in a vapor environment, the PR becomes mobile and undergoes reflow. At the mirror center, the PR edges gradually move inward and form a near-parabolic surface around the center. This pattern is transferred to the substrate via reactive ion etch. A thicker layer of PR on the outer rim of the mirror substrate protects this surface during etch, leaving the superpolished annulus available for bonding to the cavity spacer.

Proposed Research

With demonstrated fractional frequency instability of 6×10^{-15} for a cavity volume of 8 mL, Q > 12 billion, and lithographically controlled mirror centering and bonding, we believe μ-FP cavities are the best path to meet the stringent requirements of space-based optical atomic clocks and oscillators. Here we briefly outline a research program that will transition these cavities from laboratory demonstrations to integration within space clocks.

- *Grey-scale lithography for larger ROC*. Preliminary measurements and analysis indicate ROCs approaching 10 m are possible using grey-scale lithography techniques. This would provide nearly a factor 2 improvement in fractional frequency stability for a given cavity length, or, conversely, a halving of the cavity length needed to achieve a given level of performance.
- *High Q cavities at optical clock wavelengths.* Have been demonstrated at a wavelength of 1550 nm. While we foresee no major roadblocks, similar performance needs to be demonstrated at optical clock wavelengths.
- *Reduce sensitivities to acceleration, holding force and temperature*. Through finite element modeling and testing, we will reduce the environmental sensitivity of μ-FP cavities. Tasks include: increase the mechanical symmetry of the cavity to reach acceleration sensitivity < 10^{-11}/g; reduce holding force sensitivity to < 10^{-10} $\Delta f/f$ per N; operating with 0.5 C of the cavity's thermal coefficient of expansion zero-crossing temperature.
- *Direct fiber coupling*. To date, free-space lenses and mirrors have been employed in μ-FP cavity experiments. In order to reduce optical alignment complexity, we will design and implement ruggedized fiber coupling to the cavity.
- *Hydroxide bonding*. Optical reference cavities employ optical contact bonding to join the mirror substrates to the cavity spacer. We will explore hydroxide bonding [15] as a way to increase bonding strength. Cavities will be tested to ensure fractional frequency stability is maintained.
- *Demonstrate microfabricated mirrors with high reflectivity on silicon*. The highest stability cavities are currently constructed with single-crystal silicon spacers and mirrors, and operate at cryogenic temperatures [16]. This task will transfer advantages of lithographic mirror production to these systems, providing a path for fractional frequency performance near 1×10^{-16} in a cavity volume < 30 mL.

Research outcomes: With the successful completion of this research program, we will have demonstrated a mass-producible, rugged, and compact reference cavity system with state-of-the-art ($\Delta f/f = 10^{-16}$) performance necessary to enable wide-spread deployment compact atomic clock systems for space-based and terrestrial applications.

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