High-stability laser using Ramsey-Bordé Interferometry

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***Abstract*—We describe a system for high-performance laser stabilization using Ramsey-Borde interferometry with calcium.**

Keywords—optical clock, optical frequency standard, atomic clock, calcium, stabilized laser

I. Introduction

The conventional approach for state-of-the-art laser stabilization utilizes high-Q Fabry-Perot cavities. By frequency locking a laser to the optical mode of a carefully-designed and highly-isolated cavity, 10^{-16} laser frequency stability has been achieved over short timescales, making these stabilized oscillators very-well-suited to a wide range of applications, from optical clocks to low-noise-microwave generation. Present research efforts explore cryogenically-cooled optical cavities, as a way to reduce the thermal-mechanical fluctuations that typically limit the obtainable frequency stability. Here we report on a fundamentally distinct approach for realizing state-of-the-art laser stabilization, using high resolution spectroscopy of calcium in a Ramsey-Borde interferometer.

II. Laser Stabilization

Ramsey-Borde (RB) interferometry [1] is a powerful-spectroscopic tool that allows narrowband atomic and molecular resonances to be measured with high resolution in a Doppler-free configuration. Significantly, this technique can be applied to large atom samples with even a broad velocity distribution. RB spectroscopy on atomic calcium has a rich history spanning several decades of research on both thermal and laser-cooled systems (e.g. [2-5]). Here we employ RB spectroscopy to measure the frequency of the low-lying $^1S_0$-$^3P_1$ intercombination transition in a high-flux, collimated beam of thermal atomic calcium.

RB interferometry requires four laser-atom interaction zones, two each from opposing directions. High spectral resolution relies on sizeable distances between interaction zones, in order to achieve long Ramsey free-evolution-times. To realize this laser configuration with the strict angular tolerances required by RB interferometry, we utilize a monolithic, ultra-low-expansion (ULE) glass assembly which shares the same vacuum housing as the atomic beam. The ULE assembly includes optically contacted mirrors to generate the four laser interaction zones from a single input laser source. The resulting RB zones offer a ~1.5 kHz spectral linewidth for the thermal calcium beam utilized.

Measurement of the RB spectroscopic fringes can be made by monitoring photon fluorescence from natural decay out of the excited $^3P_1$ state. However, to reduce photon-shot-noise limitations in the fringe measurement, we employ a variant on electron-shelving detection with a 431nm cycling transition from the $^3P_1$ excited state to a doubly-excited $^3P_0$ state. This laser-induced-fluorescence offers orders-of-magnitude improved photon flux compared to natural decay from $^3P_1$, thus enhancing the measurement signal-to-noise.

Even though RB interferometry is a Doppler-free technique, it is known to suffer from residual first-order Doppler effects due to, for example, imperfect interferometer alignment. These residual first-order shifts can be large, and can thus compromise the achievable frequency stability at all timescales derived from a RB system. To mitigate these effects, our system employs dual, counter-propagating calcium beams, as well as independent detection of each atomic beam. Both atomic beams traverse the same laser-interaction zones, so that key residual Doppler shifts are equal and opposite for the opposing atomic beams. By stabilizing the laser frequency simultaneously to RB fringes from both atomic beams, residual first-order Doppler effects can thus be suppressed.

With a 657 nm laser stabilized to the RB calcium interferometer described above, we have observed laser frequency instability of 2×10^{-16} at 10 seconds. The frequency stability remains at or below the 5×10^{-16} level at all times from 1 to 1000 seconds. We are currently exploring ways to improve the resulting frequency stability towards the shot-noise limit, experimentally assessed to be in the 10^{-17} decade at just one second. This includes a detailed study of systematic drifts in the system which can impact frequency instability on both short and long timescales.

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