Optical frequency measurements at $1x10^{-18}$ uncertainty with ytterbium optical lattice clocks

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***Abstract* — We describe ytterbium optical lattice clocks under development at NIST. This includes the characterization of optical frequency stability and uncertainty, as well as measurements between two independent clocks, at the 10^{-18} level. We also report on optical frequency ratio measurements with other optical clocks at NIST.**

***Index Terms* — optical clock, optical lattice, ytterbium, optical frequency ratio, optical frequency standard, precision measurement, uncertainty.**

I. Introduction

Optical lattice clocks have long promised performance beyond the best primary standards of time and frequency. Indeed, in recent years such clocks have reported frequency (in)stability [1] and uncertainty [2] approaching the 10^{-18} fractional level, and have demonstrated the potential for making valuable contribution to international atomic time (e.g. [3,4,5]). Here we report on recent progress in the development of ytterbium optical lattice clocks, reaching state-of-the-art levels in each of the three most important figures of merit for such a standard: stability, uncertainty, and reproducibility.

II. Uncertainty, Stability, and Reproducibility

We recently completed a full evaluation of the systematic uncertainty of two Yb optical lattice clocks at NIST. These clocks benefit from the use of an in-vacuum atomic enclosure, which provides two important features: a highly-characterized blackbody radiation environment bathing the lattice trapped atoms [6], and a Faraday shield isolating the atoms from stray electric fields. Furthermore, our recent study of optical-lattice-induced Stark effects characterizes important atomic-temperature-dependent light shifts, including both scalar and hyper-polarizability contributions [7]. In addition to these and other systematic effects that are typically considered in an uncertainty evaluation of lattice clocks, we experimentally investigate shifts resulting from background gas collisions, residual Doppler effects, and imperfect atomic polarization. In all, we find a total systematic uncertainty for each clock of $<2x10^{-18}$ (fractional frequency).

Stability sets the statistical precision of any frequency measurement, and we have previously demonstrated optical clock stability reaching the $\sim1.5x10^{-18}$ level [1]. Benefiting from the added environmental control afforded by the blackbody enclosure, we have now observed clock stability reliably reaching $<1x10^{-18}$ level at long times, the first time this has been observed in an atomic clock.

As optical clocks mature, another important figure of merit is the frequency reproducibility between one standard to the next [8]. After all, the clock uncertainty only includes those systematic effects that a researcher has actively considered, and thus represents only a best-effort estimate of the actual uncertainty in realizing the unperturbed atomic clock transition frequency. Making direct frequency measurements between two similar but independent systems always has the potential to reveal discrepancies beyond the characterized uncertainty. We carry out a series of frequency comparisons between two Yb lattice clocks at NIST, reaching a measurement uncertainty of $\sim1x10^{-18}$ level, and indicating agreement between the two standards.

VI. Conclusion

In addition to describing recent developments in operation and performance of the ytterbium clocks at NIST, we highlight initial results in the measurements of optical frequency ratios with other optical clocks at NIST. We also mention efforts towards an improved optical local oscillator and a portable Yb standard.

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