# Precision metrology and interferometry with ultracold calcium atoms

**E.A. Curtis, C.W. Oates, and L. Hollberg**
*National Institute of Science and Technology, 325 Broadway, Boulder, Colorado 80305*
*Phone: (303) 497-7969, Fax: (303) 497-7845, curtisa@boulder.nist.gov*

**Abstract**: Advances in laser cooling of alkaline earth atoms have reduced trapped atom temperatures from the millikelvin to the microkelvin regime. Using such atoms, our optical atomic clock should have a fractional frequency uncertainty approaching $1\times10^{-15}$. Sub-recoil cooling and two-pulse atom interferometry are also discussed.

**OCIS codes:** (140.3320) Laser cooling; (300.6320) High resolution spectroscopy

At NIST we have developed an optical frequency standard based on laser-cooled neutral Ca atoms that uses four-pulse optical Bordé-Ramsey spectroscopy to interrogate the narrow (400 Hz) intercombination line at 657 nm. Our previous measurement of the absolute optical frequency had a systematic frequency uncertainty of 26 Hz on the 456 THz transition, giving a fractional frequency uncertainty of $5.7\times10^{-14}$ [1]. Since the dominant systematic uncertainties resulted from residual Doppler effects, we have implemented a second cooling stage that greatly reduces the temperature of the atomic sample. Using the technique of 3-D quenched narrow-line laser cooling, we have cooled the atom cloud from 2 mK to less than 10 μK [2-4]. With this colder atomic sample, we expect the frequency uncertainty of the Ca 456 THz transition to be < 1 Hz, making it competitive with the best primary atomic standards.

In Figure 1 we show a Fourier-transform-limited Bordé-Ramsey lineshape derived from 10 μK atoms. Figure 2 shows Bordé-Ramsey fringes at the resolution of the natural linewidth of the clock transition.

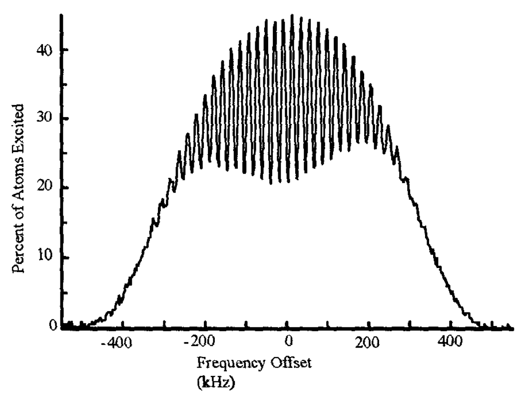


Fig. 1. Bordé-Ramsey fringes at a resolution of 11.55 kHz taken after 4 ms second-stage cooling with an atom temperature of ~10 μK. A single 100-second frequency sweep gives high contrast, Fourier-transform-limited fringes.

The high signal-to-noise ratio achievable with this system clearly reveals an asymmetry in the fringe envelope (see Figure 1) that is a result of atomic recoil effects and consistent with a theoretical formulation [5]. Furthermore, this large signal-to-noise ratio (in combination with the high line Q) yields one of the highest stabilities demonstrated by an atomic standard (fractional frequency uncertainty < $1\text{x}10^{-14}$ in 1 second), which enables rapid evaluation of systematic shifts. The latest systematic uncertainties and measurements of the Ca clock frequency relative to a cesium-fountain will be presented at the conference.

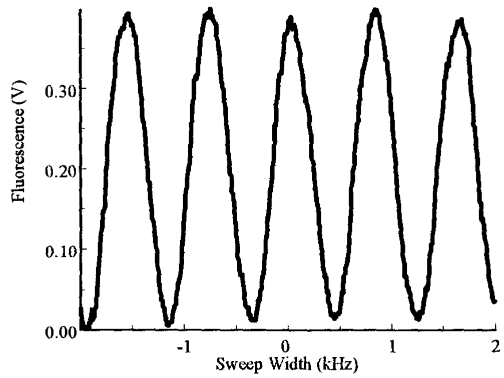


Figure 2. Bordé-Ramsey fringes based on 10 μK Ca atoms taken at the natural linewidth of the transition (400 Hz resolution). Data averaging time was < 30 seconds.

Ultracold Ca atoms present other experimental possibilities including atomic interferometry and further cooling towards quantum degeneracy. With an additional third stage of 1-D cooling, we have achieved atom temperatures as low as 300 nK and have shown that two-pulse Ramsey interferometry is possible with sub-microkelvin Ca atoms [4].


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