Atom interferometric method for eliminating Doppler effects in precision measurements

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Abstract: We present a method to reduce the residual Doppler effect by almost two orders of magnitude in our optical frequency standard. The approach combines atom interferometry and launching of microkelvin neutral atoms.

OCIS codes: (120.3940) Metrology

1. Introduction

State of the art optical frequency standards with neutral atoms are highly competitive in both accuracy (relative uncertainty $2\cdot10^{-14}$ [1]) and stability (relative instability of $7\cdot10^{-15}$ in 1 s of averaging [2]). Nevertheless, the free expansion of the atoms during the measurement in combination with non-perfect wave fronts [3] has thus far been limiting the accuracy [4]. In this work we combine laser cooling and atomic interferometry with launched atoms to reduce the relative uncertainty due to the Doppler effect in a microkelvin ensemble to $2\cdot10^{-16}$. With subsequent improvements we anticipate reaching a level of $1\cdot10^{-17}$ and beyond. The other known uncertainty contributions do not appear to limit the overall uncertainty at this level. The method has the potential to push the relative uncertainty of free neutral atom frequency standards into the regime anticipated for future single ion [5] and neutral atom frequency standards that use optical lattices to localize the atoms and avoid the Doppler effect [6]. This will allow one to maintain the simplicity and high signal-to-noise ratio one enjoys with freely expanding atoms in an external field-free zone. Furthermore, the method could find application in precision atom interferometric measurements, e. g. of gravity [7].

2. Method

The implementation of a new cooling scheme [8,9] in our Ca optical frequency standard allows us to perform measurements at atomic ensembles of 10^6 atoms at a temperature of 10 μK. Applying purely phase-dependent atom interferometry in the time domain with three parallel laser pulses separated by a time T we measure the fraction of excited atoms as function of a laser phase shift $\Delta\phi$ in the last pulse (see Fig. 1a).

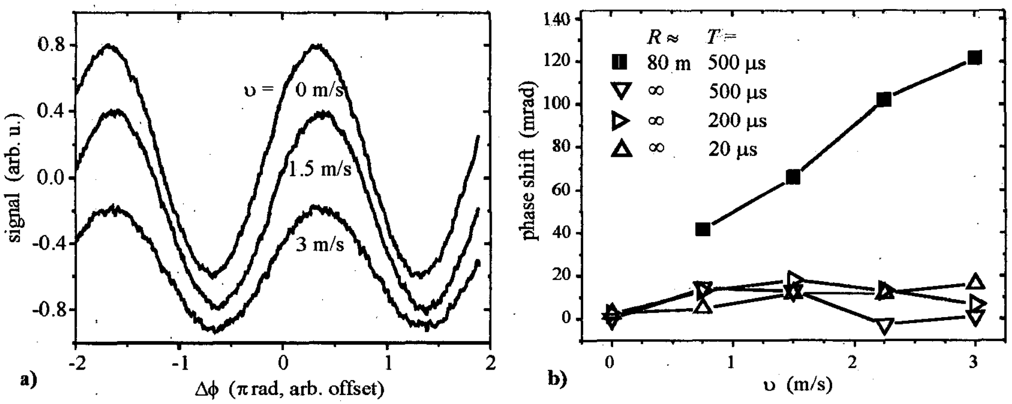

Fig. 1. a) Spectra of a phase dependent atom interferometer in the time-domain with 3 laser pulses separated by $T = 500$ μs applied to atomic ensembles launched by different velocities υ perpendicular to the laser beams. b) Velocity dependent phase shifts deduced from spectra as shown in a) for either a high radius of curvature and $T = 500$ μs with a strong shift and for a plane wave front with low phase shifts for a wide range of settings of T.

If we launch the atoms up to $\upsilon = 3$ m/s perpendicular to the spectroscopy beam the phase offset of the spectroscopic signal changes as function of the velocity ($\sim\upsilon^2$) and radius of curvature ($\sim 1/R$). Fig. 1b shows the measured phase shifts for different settings of the wave-front curvature. The three overlapping lines close to zero show the phase shift for minimized wave-front curvature for three different settings of T. Though the sensitivity of the phase shift scales with υ^2 and T^2 the curves overlap within 25 mrad peak to peak.

After reducing the wave front curvature we can then use a frequency dependent atom interferometer comprising four pulses from two counterpropagating laser beams in combination with launching of atoms to reduce the mutual beam tilt. In a last step we can then use this interferometer to reduce the angle of the laser beams to gravity. With the present resolution of 5 Hz ($1\cdot10^{-14}$) for the frequency dependent atom interferometer and 5 mrad for the phase dependence we can measure the radii of curvature to better than 480 m and the mutual beam tilt to 12 µrad resulting in a total relative frequency uncertainty for the residual Doppler effect of $2\cdot10^{-16}$.

3. References

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