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Frequency comb atom interferometry

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Abstract. We have implemented of a light pulse atom interferometer based on the diffraction of free-falling atoms of Rubidium by a picosecond frequency-comb laser. We have studied the impact of the pulses' length as well as of the interrogation time on the contrast of the fringes. Our data are well reproduce by a theoretical model based on the effective coupling which depend on the overlap between the pulses and the atoms. This technique, which we demonstrated in the visible spectrum on Rb atoms, paves the way for extending light-pulse interferometry to other spectral regions (deep-UV to X-UV) and therefore to new species, since one can benefit from the high peak intensity of the ultrashort pulses which makes nonlinear frequency conversion in crystals and gas targets more efficient.

1 Introduction

Frequency combs have revolutionized optical frequency metrology at the turn of the century: they allow having a graduated ruler against which it is possible to measure by beating the frequency of a laser. It is also possible to make measurements directly using a frequency comb to interrogate atoms. This interrogation is favored when a two-photon transition is performed, as many pair of teeth are resonants and their amplitudes can be added[1–3]. Using a comb, it is possible to make measurements of two-photon transitions without Doppler effect. It is also possible to realize Raman transitions without Doppler effect, where the use of the comb is particularly interesting in the case where the separation of the two levels is too important to use the usual techniques. In this context, we wanted to explore the possibility to use directly frequency combs (FC) in light-pulse atom interferometry. Indeed, the use of FC could allow extending atom interferometry to other spectral regions and therefore to new species by taking advantages of their high peak intensity.

2 Counter propagating Raman transition and atom interferometry

To perform light pulse atom interferometer it is essential that the transition be driven by two counter-propagating beams, allowing for a large separations between the two paths of the interferometer. To drive Raman transitions with a FC and thus to perform atom interferometry, we need two counter propagating pulses overlapping on the atomic cloud. The full apparatus of the experiment is described in [4].

This condition impose a pulse duration on the order of the picosecond so that every atom in the atomic cloud perform the transition. Furthermore, because the atomic cloud is freely falling, we can interrogate the atoms only during a finite duration given by $\sqrt{2c\tau/g} \sim 10$ ms. In order to create the overlap zone, we use a delay line (as depicted in 1) where the total length is adjusted to match the distance between the initial atoms position and the bottom mirror (distance denoted as d). The acousto-optic modulator (AOM-2) is used to compensate for the Doppler shift.

Because of the finite size of the pulses, the Raman Rabi frequency can be written as

$$\Omega(z,\tau) = \frac{\Gamma^2}{4\Delta}\frac{I}{2I_s} e^{-(\frac{z}{c\sigma_\tau})^2} e^{-(\frac{(\omega_0-\omega)\sigma_\tau}{2})^2} \quad (1)$$

here Γ, Δ and I_s are the natural linewidth, the 1-photon detuning and the saturation intensity of the $5s\ ^2S_{1/2} - 5p\ ^2P_{1/2}$ transition, respectively. Here, $I = I_0\sqrt{\pi}\sigma_\tau f_{\text{rep}}$ is the combined average intensity of the two trains of picosecond pulses, which intensity envelops are here considered to be Gaussian (with peak intensity $I_0/2$). This equation shows that the Raman Rabi frequency with a FC is the same as the one for a CW laser of similar average intensity modulated by a geometrical part $e^{-(\frac{z}{c\sigma_\tau})^2}$ and a term that is the impact condition resulting from the Fourier transform of the pulse shape when integrating the Hamiltonian for one pulse.

3 Results

In Figure 2, we have plotted the interference pattern in a gravimeter configuration where we scan the slope of the frequency sweep used to compensate gravity. The contrast of the interferometer can be well understood by precisely calculating a position-dependent effective Raman coupling. One of the main limitations of this interferometer is to maintain the overlap between the pulses and the

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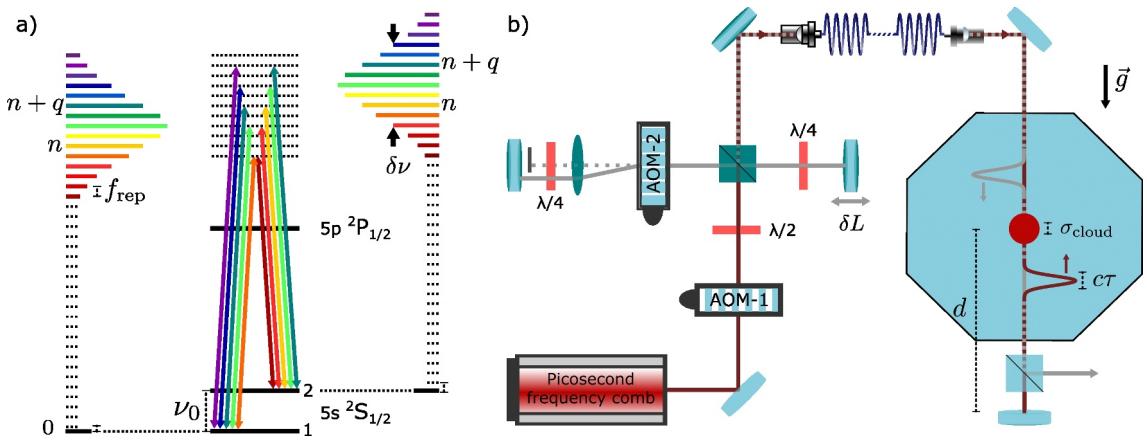

Figure 1. a) Principle of frequency-comb-driven Raman transitions between two hyperfine levels in the electronic ground state of ^{87}Rb. b) Schematic overview of our experimental setup. The overlap position of the counter-propagating pulses is adjusted precisely by translating one of the mirrors in the delay line. The Doppler effect due to free fall is compensated by chirping the frequency of an acousto-optic modulator (AOM-2).

atoms. Due to the free-fall of the atoms, we are limited to 10ms of interrogation time. In order to increase our sensitivity, we are currently implementing an adjustable delay line to follow the free fall acceleration of the atoms. This will allow us to improve the contrast of the fringes and to increase the total duration of the interferometer (and therefore its sensitivity).

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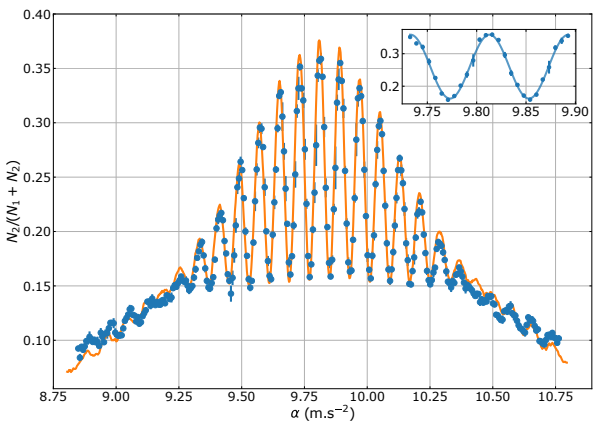

Figure 2. Interferences fringes for a Ramsey-Bordé configuration with a delay between pulses of 1.5 ms. (See [4])