Application of Velocity Grating Spectrum in Calcium-beam Optical Clock

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Abstract—**We apply the velocity grating optical spectrum to the calcium-beam optical clock with Rabi interrogation, in order to take full use of the large amount of atoms with non-zero velocities in the thermal atomic beam. Thus the signal-to-noise ratio and the stability index of calcium optical clock can be improved.**

Keywords—velocity grating spectrum; atomic utilization efficiency; calcium optical lock; frequency stability.

I. INTRODUCTION

Transportable optical frequency standards have been under research in the last two decades [1–6], which can potentially supports applications like optical clock networks [7], space optical clocks or commercial requirements.

Calcium atomic beam is an excellent candidate for transportable optical clocks. Because of the pivotal application of spatially electronic-shelving detection [8], the thermal calcium beam optical clock has shown much reduced frequency stabilities both with Rabi and Ramsey excitations. [9-11]. The instability of calcium-beam optical clocks is closely related to the atomic utilization efficiency, namely the signal to noise ration (SNR) of the detected clock transition spectrum. Despite the significantly improvement of the SNR through application of electronic-shelving detection, the calcium-beam optical clock still suffers from the fact that large amount of atoms with non-zero velocities are wasted.

In this paper, we apply the velocity grating optical spectrum to the calcium-beam optical clock with Rabi interrogation, in order to take full use of the large amount of atoms with non-zero velocities in the thermal atomic beam. Thus the signal-to-noise ratio and the stability index of calcium optical clock can be improved.

II. EXPERIMENTAL SETUP

The experimental setup is shown in Fig. 1. The narrow linewidth 657nm laser is divided into two beams by a polarizing beam splitting prism. One beam is frequency stabilized to a reference cavity and the other beam is used as the interrogation laser after frequency shifting. The interrogation laser is transformed by a group of electro-optical modulators (EOMs) into a multi-frequency laser with numbers of narrow-linewidth sidebands separated by the modulation frequency v_m. Hence the multi-frequency interrogation laser can interact with atoms with equal transverse velocity intervals, shown as Fig. 2. The opposing-propagated beams compose a saturated absorption spectrum. A beam of readout laser pre-stabilized to the calcium 423 nm ($^1S_0$-$^1P_1$) or 431 nm ($^3P_1$-$^3P_0$) transition interact with the calcium atoms, and the fluorescence spectrum is detected by a photodetector. Finally, the spectrum is modulated and demodulated by the servo feedback system, which controls the RF driver of AOM and provides the frequency standard of the calcium-beam clock. In the process of phase modulation, it is necessary to introduce the ”flat top” electro-optic comb technology [12–15] to obtain uniform power distribution among the frequency components, so as to ensure that atoms with different transverse velocities have approximately the same Rabi frequency.

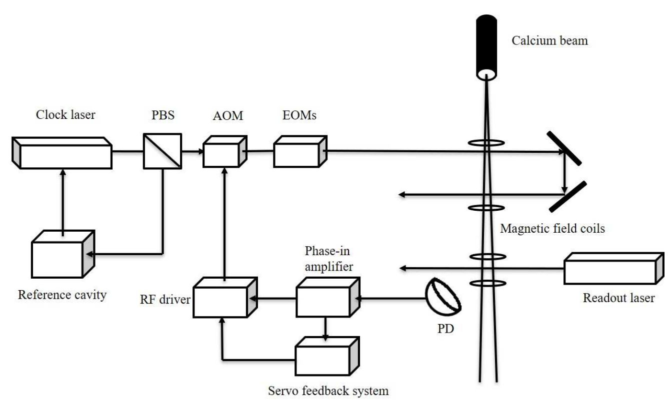

Fig. 1. Experimental setup for velocity-grating spectrum based calcium-beam optical clock. The interrogation laser is transformed by a group of electro-optical modulators (EOMs) into a multi-frequency laser with numbers of narrow-linewidth sidebands separated by the modulation frequency v_m. Hence the multi-frequency interrogation laser can interact with atoms with equal transverse velocity intervals.

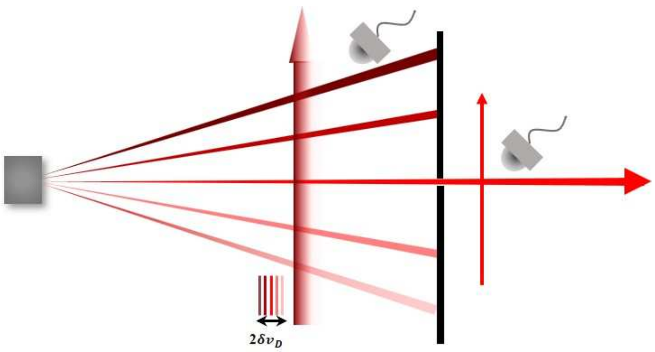

Fig. 2. The Rabi excitation in thermal beams generally encounters the challenges of taking full advantage of atoms with nonzero transverse velocities. In our scheme the multi-frequency interrogation laser can interact with atoms with equal transverse velocity intervals.

III. RESULTS

According to the theoretical calculation and simulation results, the utilization efficiency of calcium atoms can be improved by two orders of magnitude with appropriate modulation frequency and intensity of the interrogation laser. Specially, the simulated lineshape with numbers of modulated spectral lines being 251 and 3 are shown in Fig 3.

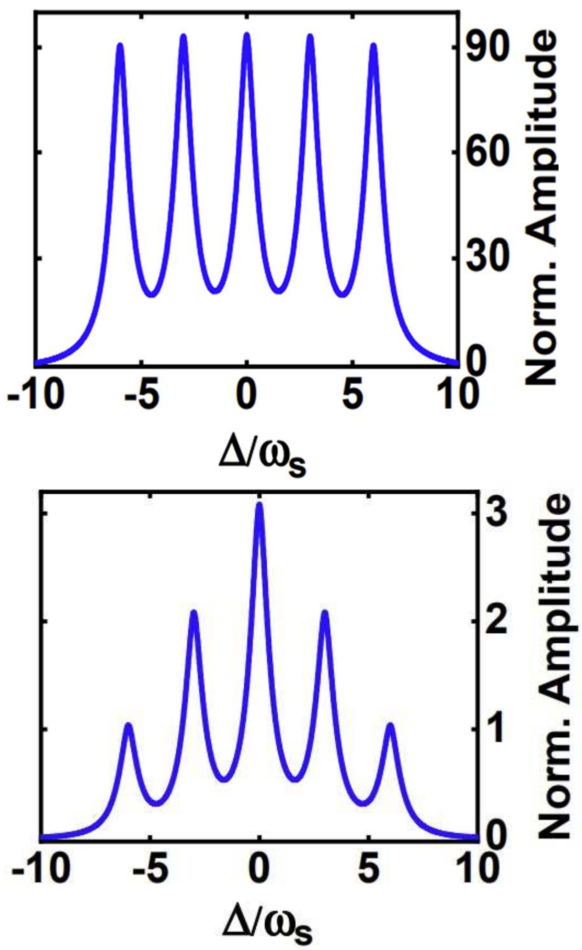

Fig. 3. Spectrum with numbers of spectral lines being 251 (up) and 3 (down).

According to the calculation, the amplitude enhanced ratio R of the central line decreases as the modulation frequency ν_m increases, because of fewer atoms contributing to the lineshape, the results are presented in Fig. 4. Furthermore, the R would saturate with the increased number of modulated spectral lines since the transverse velocity distribution of the atoms is finite. In the condition of $\delta\nu_D$=100 MHz and $\nu_m = 6\nu_s$, a maximum R of 90 can be acquired for the Ca system, meaning that the utilization efficiency of calcium atoms are improved by 90 times.

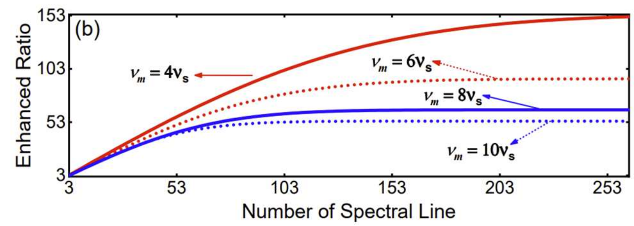

Fig. 4 Amplitude-enhanced ratio R of the spectroscopy vs the number of spectral lines and the modulation frequency ν_m.

For optical clocks, the limitations deteriorating the frequency stability typically include quantum-projection noise (QPN) and technical noise. Considering that continuous efforts are aimed at reaching the QPN, the thermal systems are similarly assumed to be not limited by the technical noise eventually. Under this assumption, the frequency instability can be decreased by nearly an order of magnitude with the utilization of the velocity-grating spectrum.

IV. CONCLUSIONS

In this paper, we apply the velocity grating optical spectrum to the calcium-beam optical clock with Rabi interrogation, in order to take full use of the large amount of atoms with non-zero velocities in the thermal atomic beam. Thus the signal-to-noise ratio and the stability index of calcium optical clock can be improved.

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