Interleaved Atom Interferometry for High Sensitivity Inertial Measurements

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Abstract—We report on interleaved operation of a cold-atom inertial sensor, where three atomic clouds are simultaneously probed in an atom interferometer featuring 4 Hz sampling rate and interrogation time of 801 ms. Interleaving improves the inertial sensitivity by efficiently averaging vibration noise and allows us to perform dynamic rotation measurements in a so far unexplored range. We demonstrate sensitivity of $30 \text{ nrad. s}^{-1} \text{Hz}^{-1/2}$ and reach the long-term stability of $3 \times 10^{-18}$ rad s$^{-2}$, which competes with the best stability levels obtained with fiber-optic gyroscopes. Our work validated interleaving as a key concept for future atom-interferometry sensors probing time-varying signals, as in on-board navigation and gravity gradiometry, searches for dark matter, or gravitational wave detection.

Keywords—atom interferometry; inertial sensor; interleaving; long-term stability; vibration noise

I. INTRODUCTION

Inertial sensors based on cold atoms address various applications in geoscience, navigation, civil engineering and fundamental physics tests. These sensors operate sequentially, with rather long cycling time that is necessary to perform high-sensitivity inertial measurements. As a result, the reduced sampling rate of the cold-atoms-based inertial sensors limits their ability to efficiently measure time-varying signals.

Here we present the interleaved operation of a cold-atom-based inertial sensor [1], allowing for about 4 Hz sampling frequency and featuring a high inertial sensitivity due to the 801-ms-long interrogation time of the atoms during the interferometric cycle. We employ the method of interleaving to acquire static and dynamic rotation rate signals and demonstrate its versatility. This method may be generalized to atom interferometers of other architectures as, for example, accelerometers and gradiometers. Our work thus opens new perspectives for the future development of high-bandwidth and high-sensitivity inertial sensors based on cold atoms.

II. METHODS/RESULTS

The experimental apparatus used in this work has been described in detail elsewhere [2]. In Figure 1 we sketch the core of the setup and illustrate the main operational principles. We laser-cool atoms of $^{133}\text{Cs}$ to a typical temperature of 1.2 µK. We then vertically launch the atoms with a velocity of about 5 m/s in a fountain-like configuration and select the atoms in $m_s=0$ magnetic sub-level by means of Stern-Gerlach separation. We interrogate the atoms in the interferometer with four subsequent light pulses thus realizing a symmetric folded geometry (see Fig 1b) in space [3]. Due to this symmetry, our sequence has zero sensitivity to dc-acceleration, while being very sensitive to rotation signals as constituted by the 11 cm$^2$ Sagnac area of the interferometer. Atom optics elements of our gyroscope rely on two-photon stimulated Raman transitions with counter-propagating laser beams, coupling the $|F=3, m_s=0\rangle$ and $|F=4, m_s=0\rangle$ clock states of the $^{133}\text{Cs}$ atom. We detect the final state at the output of the interferometer on the descending path of the atoms by means of fluorescence detection. In Figure 1c we demonstrate the key concept of interleaving the measurements, with a symmetrized combination of several chain-like joint sequences, such as there are three atomic clouds inside the interferometer at any given moment in time.
III. DISCUSSION/INTERPRETATION

In cold-atom-based inertial sensors with large interferometric area (i.e., using long interrogation time and/or large-momentum transfer techniques [4]), vibration noise represents the dominating source of sensitivity degradation. This noise manifests in random phase shifts due to the displacement of the retro-reflecting Raman mirrors in the reference frame of free-falling atoms. Efficient vibration isolation at low frequencies (below a few hertz) is technically challenging [5] and not suitable for field applications. The approach of interleaving enables for significant reduction of the impact of this key noise source on the measurement.

Correlation of vibration noise

We analyze the influence of inertial noise on our sensor by considering a rotation center to be located at the top Raman mirror: In this case, inertial noise may be decomposed into linear acceleration noise of both mirrors and rotation noise of the bottom mirror.

In order to account for the contribution of the common acceleration noise, we permanently acquire acceleration time traces with auxiliary classical sensors (seismometers) in two locations in our apparatus. We then apply dedicated real-time correction protocol allowing us to suppress the linear acceleration noise by about a factor of 7 [1], and correlate the measured phase shift with the best-guessed values of the noise contribution.

Rotation noise is represented by random variations of the angle $\theta_B(t)$ of the Raman beam with respect to a geostationary reference frame [6], adding terms $[\theta_B(2T) - \theta_B(0)]$ to the resulting interferometer phase. While averaging $N$ successive measurements of the joint type with shared $\pi/2$-pulses, the contribution of rotation noise of the previous sequence at $t=2T$ (last pulse) is exactly canceled by the one of the next sequence at $t=0$ (first pulse). In other words, the rotation noise of successive joint sequences becomes correlated, suggesting that

$$\text{the gyroscopic sensitivity should improve as } r^{-1}; \text{ where } r = 2NT$$

is the total integration time. This time dependence should contrast $r^{-1/2}$-behavior, obtained in the case of uncorrelated measurements affected by rotation noise.

In addition, the increased sampling rate due to interleaving is responsible for over-sampling of the residual uncorrected acceleration noise, thus effectively introducing shot-to-shot correlations and efficient averaging in the frequency range below ~ 4 Hz.

Gyroscope sensitivity and stability

In Figure 2 we show the Allan standard deviation of the gyroscope stability for an 11.3-hour data. The sensitivity clearly improves as $r^{-1}$ for integration times up to $\approx 7$ s. The stability then gradually enters the $r^{-1/2}$ regime characteristic of uncorrelated white noise, corresponding to a sensitivity of $3\times10^{-8}$ rad $s^{-1}$ Hz$^{-1/2}$. This level of sensitivity represents an improvement by more than a factor of 3 over our previous result [3] and establishes the new record for cold-atom gyroscopes, for the first time favorably competing with the best fiber-optic gyroscopes. This high sensitivity opens the possibility to perform systematic studies of the biases (shifts) in a cold-atom gyroscope for the first time in the range of low $10^{-9}$ rad $s^{-1}$.

Dynamic rotation rate measurements

In a proof-of-principle experiment, we employ the unprecedented sampling rate and inertial sensitivity of our gyroscope in order to perform measurements of small dynamic rotation rates. We periodically modulate the sensor’s orientation around the y-axis by applying a force on the bottom plate that connects the experimental frame to the vibration isolation platform, with the voice-coil actuator that controls the tilt of the apparatus in the x-z plane. The modulation is parameterized as $\theta(t) = \theta_0 \sin(\omega t)$ with $2\pi/\omega$ being a period and $\theta_0$ - an amplitude (typically few $10^{-7}$ rad).

The resulting rotation rate along y-axis is $\Omega(t) = \Omega_0 \cos(\omega t)$, with $\Omega_0 = \omega \theta_0$. In Fig. 4 we show the measurements for modulation periods of 5 s and 10 s, which correspond to the

![Figure 2](image1.png)

**Figure 2.** Sensitivity of the gyroscope. Stability analysis of an 11.3-hour portion of rotation rate measurements acquired during the night. The error bars represent the 68% confidence intervals on the estimation of the Allan deviation. Dashed black line, $3.3\times10^{-7}$ rad s$^{-1}$r$^{-1/2}$; green dashed line, $r^{-1/2}$ scaling from the one-shot Allan deviation; red dotted-dashed line, $r^{-1}$ scaling from the one-shot Allan deviation; orange dotted line, detection noise limit corresponding to $8\times10^{-4}$ rad s$^{-1}$r$^{-1/2}$.

![Figure 3](image2.png)

**Figure 3.** Measurement of dynamic rotation rates. Atom interferometer phase deduced from the transition probability, for rotation rate modulations of 5 s period (A) and 10 s period (B). Plain line: sinusoidal fit to guide the eye. (C): Fourier analysis of the total rotation rate signal, with a frequency resolution of 0.37 mHz.
modulation amplitudes for the rotation rate of $2.3 \times 10^{-7}$ rad and $3.4 \times 10^{-7}$ rad, respectively.

We clearly detect a small sinusoidal modulation in rotation rate, on top of the large constant signal produced by the rotation rate of the Earth (about 100 times larger), as extracted from the variation of atomic phase proportional to the transition probability $P(t)$ (see Fig. 4A and 4B). In Fig. 4C, we show the Fourier analysis of the total detected rotational signal which is the sum of atomic phase and the real-time-corrected phase (as discussed above). Within our frequency resolution, we find the amplitude of the reconstructed rotation rate to match with 5% relative uncertainty the expected values. These experiments, performed with so-far unexplored time resolution and inertial sensitivity for a cold-atom sensor, demonstrate the potential of interleaved atom interferometry for measurements of rapidly-varying small inertial signals.

IV. CONCLUSIONS

We have demonstrated the method of interleaving in a large-area cold-atom-based atomic gyroscope, allowing us to simultaneously operate with high inertial sensitivity and fast sampling rate of the sensor. Interleaving enables us to efficiently average vibration noise – the major limiting factor for atom-interferometry-based inertial sensors – and manifests a promising way of reaching the quantum projection noise limit, a necessary condition before increasing the atom flux or implementing schemes for quantum-enhanced metrology. As a result, we have attained record short-term sensitivities for a cold-atom gyroscope enabling characterization of systematic effects in a so far unexplored range. Our results thus demonstrate interleaving as a key concept for future applications of cold-atom inertial sensors and pave the way for a change of technology in future high-precision inertial navigation systems.

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