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The Sagnac effect: 100 years later / L'effet Sagnac 100 ans après

Large-area Sagnac atom interferometer with robust phase read out

Interféromètre Sagnac atomique avec une acquisition de signal robuste

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ABSTRACT

We report on recent progress on our matter-wave Sagnac interferometer capable of resolving ultra-slow rotations below the μrad s^{-1} level with a 1-s measurement time and a repetition rate of 2 Hz. Two Raman interferometers are employed that are susceptible to rotation and acceleration. We demonstrate two read-out schemes exploiting the strict phase correlation of the dual interferometer, the first one locking the interferometer to the mid-fringe position, and the second relying on phase modulation combined with ellipse fitting. In both, the sensitivity to gravity acceleration is employed for controlling the differential interferometer phase without influencing the rotation signal. Furthermore, we discuss errors in the rotation signal arising from atom source instabilities combined with a residual misalignment of the three pulsed light gratings used for atomic diffraction. Monitoring the source position fluctuations allows us to suppress this spurious signal. We achieve stable operation with a sensitivity of 850 nrad s^{-1} Hz$^{-1/2}$ for a 1-s measurement time, and 20 nrad s^{-1} after 4000 s of averaging.

RÉSUMÉ

Nous présentons ici les progrès réalisés avec notre interféromètre Sagnac à ondes de matière capable de résoudre des rotations ultra-lentes de l'ordre du μrad s^{-1} avec un temps de mesure de 1 s et un taux de répétition de 2 Hz. Deux interféromètres Raman, sensibles aux rotations et aux accélérations, ont été utilisés. Nous avons développé deux techniques d'acquisition de signal qui exploitent la corrélation de phase du double interféromètre, la première en stabilisant l'interféromètre sur la position à mi-frange, la deuxième se basant sur la modulation de phase en combinaison avec la méthode dite *ellipse fitting*. Les deux techniques reposent sur la sensibilité à l'accélération gravitationnelle qui est utilisée pour contrôler la phase différentielle sans perturber la phase de rotation. De plus, nous discutons dans cet article des erreurs dans la mesure de la rotation engendrées par des instabilités des sources atomiques croisées, avec un non-alignement résiduel des trois réseaux optiques qui sont utilisés pour la diffraction atomique. L'enregistrement des fluctuations de la position des sources nous permet de réduire ce signal parasite. Nous atteignons ainsi une

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sensibilité d'opération stable de 850 nrad s^{-1} $Hz^{-1/2}$ à une seconde de temps de mesure et 20 nrad s^{-1} après 4000 s d'intégration.

1. Introduction

Since the discovery of the rotation-induced phase shift in an interferometer with area-inclining paths, the Sagnac effect [1] has become the basis for high-precision rotation measurements [2]. The first observation of this effect, demonstrated by Georges Sagnac in 1913, was realized with a spectrally refined light field emitted from an electric lamp. Over the last century, the technological advances, in particular the invention of the laser, boosted the sensitivity of light-based Sagnac interferometers. Moreover, the possibility of coherently manipulating neutral atoms with laser light enabled the development of matter-wave-based Sagnac interferometers, subject of this article. In both, light and atom interferometers rotation measurements rely on the Sagnac phase:

$$\Phi_{\text{Sagnac}} = \frac{2E}{\hbar c^2}\mathbf{\Omega} \cdot \mathbf{A} \tag{1}$$

where E is the particle energy of the interfering photons or atoms, respectively. Furthermore, $\hbar$ is the reduced Planck constant, c the speed of light, $\mathbf{\Omega}$ the rotation, and $\mathbf{A}$ the area enclosed by the interferometer paths. This yields an advantage in the interferometer scaling factor for atoms featuring much higher particle energy. Comparing the energy $E = \hbar\omega$ of photons at the helium–neon laser wavelength of $\lambda_{\text{HeNe}} = 2\pi c\omega^{-1} \approx 633$ nm with the energy of rubidium-87 atoms at low velocities $E = m_{^{87}\text{Rb}}c^2$ yields an increase factor of 1.2×10^{11} in the Sagnac phase for given area and rotation rate. This huge factor is put into perspective by the fact that typical sources for matter-waves have relatively low particle flux leading to high shot-noise [3], and the realization of areas as large as several square centimetres or even many square meters has yet to be demonstrated with matter-waves. Nevertheless, the tremendous boost in the Sagnac scale factor allows the realization of highly compact devices capable of reaching sensitivities comparable with state-of-the-art laser gyroscopes. Furthermore, the absolute value of the area enclosed by a matter-wave Sagnac interferometer is well-controlled through the well-known atomic mass and, in case of atom interferometers involving light gratings for atomic diffraction, the photon-induced atomic recoil velocity, yielding a high accuracy and stability in the rotation measurement.

The most sensitive atom interferometer gyroscopes employ light gratings for atomic beam splitting. Atom interferometers based on this technique have rapidly evolved to high-precision tools for measurements of fundamental physical constants [4–7], electromagnetic fields [8], and inertial forces [9] within the last two decades. The cornerstone for these interferometers is the coherent manipulation of the internal and external atomic degrees of freedom using laser light. Precision gyroscopes based on this concept have been pioneered by groups at Stanford University and at SYRTE ("Systèmes de référence temps espaces") in Paris. The work in Stanford led to the first development of a dual atom interferometer gyroscope [10] using two thermal beams of neutral cesium atoms. It reached sensitivities of down to 0.6 nrad s^{-1} $Hz^{-1/2}$ inferred from the instrument's signal-to-noise ratio [11], only one order of magnitude less than today's best ring–laser gyroscopes [12]. The group at SYRTE realized a dual atom interferometer capable of measuring all six axes of inertia using two laser-cooled atomic clouds counter-propagating on superimposed trajectories and a single-light grating that was pulsed in time [9]. These works yielded a much more compact and highly sensitive cold-atom gyroscope with a demonstrated sensitivity of 240 nrad s^{-1} $Hz^{-1/2}$ and 10 nrad s^{-1} after integration [13].

In this article, we present advances on our atomic dual Sagnac interferometer, which uses three spatially separated light gratings that are pulsed in time for splitting, redirecting, and recombining the interferometer paths enabling large interferometer areas and therefore high rotation sensitivity. We present two different robust rotation signal read out techniques exploiting the correlation of the two interferometers. The use of three single light gratings sets high demands on the relative alignment of the employed laser beams as well as on the control of the atomic sources position and launch velocities. These demands and their impact on the gyroscope measurement stability are discussed in detail in this article, which is organized as follows: Section 2 describes the operation principle of Raman light-pulse atom interferometers and, in particular, of our atomic gyroscope. In Section 3, the gyroscope measurement procedure and technical setup are described. Section 4 introduces the obtained interferometer signals and derives the sensitivity of a rotation measurement using the dual Raman interferometer. The robust read-out techniques are introduced in Section 5, and the long-term stability of the rotation measurement as well as the major source for slow fluctuations are discussed in Section 6, before concluding on the achieved results in Section 7.

2. Measuring rotation with atom interferometry

The functional principle of our light-pulse–atom-interferometer-based inertial sensor relies on matter-wave diffraction on light gratings formed by counter-propagating laser beams transferring two photon momenta to the atoms [14,15]. The thereby induced Rabi oscillations occurring between different atomic momentum states enable the realization of coherent