

Multiloop and multiaxis atomtronic Sagnac interferometry

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We report the experimental realization of a large-area and multiaxis atomtronic interferometer in an optical waveguide for rotation sensing. A large enclosed area is achieved through multiloop operation in a guided-atom interferometer using Bose-Einstein condensates. We demonstrate a three-loop interferometer with a total interrogation time of ~ 0.4 s and an enclosed area of 8.7 mm^2 —the largest reported in a fully guided or one-dimensional setup. High-contrast interference fringes are observed for up to five Sagnac orbits in a smaller loop-area configuration. Our approach enables interleaved rotation measurements about multiple arbitrary axes within the same experimental setup. We present results for area-enclosing interferometers in both horizontal and vertical planes, demonstrating that the interferometer contrast remains comparable across orthogonal orientations of the enclosed area vectors.

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The interference of matter waves is fundamental to quantum mechanics. The development of laser cooling, magnetic and optical trapping, and evaporation techniques has powered the field of atom interferometry to rapid growth. Atom interferometry is typically done by coherently splitting a cloud of cold (ultracold) atoms into separate paths using light pulses, propagating them along different trajectories, and finally recombining them to generate interference fringes [1–5]. The phase of the fringe pattern is a direct measure of the phase difference accumulated by the wave packets along their respective paths. The interferometer space-time geometry can be configured to perform precise measurements of inertial forces, fundamental constants, dark energy searches, gravitational wave detection, general relativity tests, and more [6–14].

Atom interferometry is implemented in two main settings: with freely falling cold and ultracold atoms [5,15–19], or with ultracold atoms that are fully trapped [20–26] or guided [24,27–33] in smooth optical and/or magnetic potentials. The latter, also known as the atomtronics approach, aims at developing tools to manipulate atomic matter waves in controlled environments such as waveguides [11]. The advantage of this approach is that trapping the matter waves makes possible long interrogation times, and hence high sensitivity, in a physics package that can be much smaller than a system that must be large enough to accommodate atoms falling freely under gravity. Our atomtronic Sagnac interferometer

operates by splitting, reflecting, and recombining a Bose-Einstein condensate (BEC) using Bragg diffraction from a pulsed standing wave, with the BEC being guided within a linear optical waveguide throughout the process [34]. To enclose an area, the guide is moved outward and back between the first and the last beam splitter (BS) pulse. A key distinction from other guided schemes is that we work with a delta-kick collimated [35–37] large-size BEC containing only a few thousand atoms resulting in significantly decreased mean-field interactions. This enables us to push the interferometer interrogation time to hundreds of milliseconds while maintaining high fringe contrast. A practical approach to enclosing a larger geometrical area is working with multiple smaller loops. Area-enclosing multiloop guided-atom interferometers have been proposed [28,38] and experimentally studied with freely falling atoms [39,40]. With access to a longer interrogation time thanks to the delta-kick cooling, small BECs, and fringe phase correction using a classical accelerometer, we are able to increase the number of loops beyond one and extend the Sagnac area by more than one order compared to our previous generation interferometer [34]. In a two-dimensional magnetic trap (time-orbiting potential trap), Beydler *et al.* have recently achieved a two orbit BEC interferometer enclosing 8 mm^2 Sagnac area [41]. A unique and powerful feature of our scheme is that by moving the guide in different planes (keeping the waveguide's propagation direction normal to gravity), it is easily possible to sense rotation rates about multiple axes without the issue of wave packet trajectories being impacted by gravity. This is not straightforward to implement in other guided schemes, where gravity compensation would be needed when the loop plane is tilted away from horizontal [41].

In this Letter, we present a large-area, multiloop waveguide atom interferometer designed for rotation sensing about multiple axes. The largest enclosed area achieved in our experiments is 8.7 mm^2 with three Sagnac orbits with an orbit time of 124 ms per loop. Additionally, we demonstrate a

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five-loop interferometer enclosing a smaller area of 0.13 mm^2 with a shorter orbit time of 22 ms per loop. To demonstrate multiaxis rotating sensing, we explore two configurations: one with the waveguide oriented in the vertical plane (large-area, multiloop results) and another in the horizontal plane. Both configurations produced comparable fringe contrasts for similar enclosed areas, demonstrating the capability to sense in orthogonal orientations.

The experimental setup is a more recent version of the one described in Ref. [34]. We generate a BEC of approximately 1000 ^{87}Rb atoms in the $|1, -1\rangle$ state using a crossed optical dipole trap with 1064 nm beams. The horizontal and vertical beams have waists of 17 and $88 \mu\text{m}$, respectively. The atoms are then transferred to the first-order magnetically insensitive $|1, 0\rangle$ state via a Landau-Zener rf sweep followed by a magnetic gradient kick to remove unwanted $F = 1$ states (see S1 of the Supplemental Material [42]). The BEC is adiabatically loaded into another crossed dipole trap formed by a horizontally oriented guide beam (waist $67 \mu\text{m}$) and the same vertical beam. The guide trap frequencies are measured as $(\omega_x, \omega_y, \omega_z) \approx 2\pi \times (140, 140, 0.5)$ Hz, while the vertical beam has a transverse trap frequency of 20.3 Hz. The BEC is loaded into the guide by ramping down the vertical beam power and expanded along the guide at 1.54 mm/s. After a 60 ms expansion, we apply a delta-kick “lens” to collimate the wave packet, achieving a final effective temperature of 1.1 nK and an axial size of $120 \mu\text{m}$ (Thomas-Fermi FWHM) in the guide. To enable this collimation, the vertical beam is time averaged (painted) at 10 kHz to create a large harmonic lens of FWHM size $180 \mu\text{m}$. This painted lens is also utilized to focus the wave packets at the interferometer readout (see Fig. 1). The measured trap frequency of the painted lens is 19.7 Hz. The delta-kick collimation and focusing lens durations are 0.9 and 2 ms, respectively.

The interferometer sequence begins right after the delta-kick pulse prepares a collimated wave packet. Figure 1 explains the sequence of our moving guide interferometer [34]. The guide translation is performed by a one-axis acousto-optic deflector (AOD, IntraAction ATD-274HD6), placed one focal length (f) behind an $f = 20 \text{ cm}$ plano-convex lens. The focus of this lens is aligned with the trap inside the science cell. By changing the rf frequency to the AOD, the beam after the lens is translated by $338 \mu\text{m}$ for 1 MHz change in the rf frequency. The beam splitters and mirrors of the atom interferometer are implemented through Bragg scattering off a near-resonant standing wave formed by retroreflection from a dichroic mirror placed in the guide beam [34]. A double-square intensity pulse is used as a symmetric beam splitter [43] and a Gaussian pulse for the mirror operation on BECs [44]. We measure nearly 100% splitting and reflection pulse efficiency. We employ $\pm 2\hbar k$ (or 1.2 cm/s for ^{87}Rb with D2 line) momentum transfer, where $k = 2\pi/780 \text{ nm}$. The beam splitter pulse is composed of two square pulses of 22.3 and $21.2 \mu\text{s}$ with a no-light gap of $37.9 \mu\text{s}$ in between. The Gaussian reflection pulse has an FWHM duration of $44.3 \mu\text{s}$. The Bragg laser is $\approx 12.6 \text{ GHz}$ blue detuned from the $5S_{1/2}, F_g = 1 \rightarrow 5P_{3/2}$, and F' transition (see S2 of the Supplemental Material [42] on Bragg setup). The one-loop interferometer uses a Bragg pulse sequence of beam splitter-mirror-mirror-beam splitter. To scan the interferometer phase,

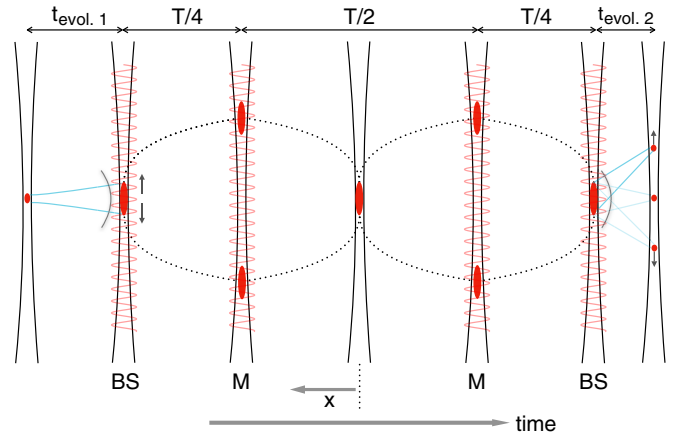


FIG. 1. One-loop moving waveguide unfolded interferometer scheme. The sequence starts by releasing a BEC from a crossed dipole trap into the guide. After an expansion duration of $t_{\text{evol.1}}$, a delta-kick collimation lens is applied, and right after that a BS pulse is shone on a collimated wave packet. After a guide moving time of $T/4$, a mirror (M) pulse is shone that reverses the sign of the atomic momentum. At the midpoint of the interferometer at $T/2$, the guide motion is reversed. A second M pulse is applied at $3T/4$. The wave packets are recombined at T with a second BS at their starting position. Right after the final BS, a delta-kick focusing lens is applied that tightly focuses all three momentum states in $t_{\text{evol.2}}$, and the three states separate spatially. The dotted curves show the trajectory of the atoms (see main text).

the Bragg laser frequency is varied by applying a voltage to the piezo of the laser at the recombination stage (more details in S3 of the Supplemental Material [42]). Right after the recombination pulse, a strong delta-kick pulse is applied that focuses all three momentum states to a tight spot in 20 ms, at which point the states are separated by $260 \mu\text{m}$. This final lens drastically improves the signal to noise ratio, which is particularly important given the low atom number and large size of the BECs. We use absorption imaging to count the number of atoms in the three peaks with no time of flight. Final analysis is performed on the absorption images after applying a fringe-removal algorithm [45,46].

We can easily switch between static and moving guide interferometers in the experiment by either keeping the rf frequency to the AOD fixed (static beam) or ramped (moving case). A static guide interferometer does not enclose any area, but its performance gives us a reference point for the moving guide case. The guide is moved using the shortcuts to adiabaticity (STA) protocol [47]. The enclosed area is approximately 25% larger with the STA trajectory compared to moving the guide at a constant velocity (see S4 of the Supplemental Material [42]). This is because the guide, starting from rest, moves more slowly at the beginning, turning point(s), and end of the loop. The parameters that define the rf frequency ramp to move the guide include the transverse trap frequency, the desired guide translation, and the time required to traverse the interferometer. To enable fast transport, the transverse confinement is kept strong, typically operate above 100 Hz. Meanwhile, the static guide can be operated at much lower power, providing just enough confinement to prevent atoms from free fall.

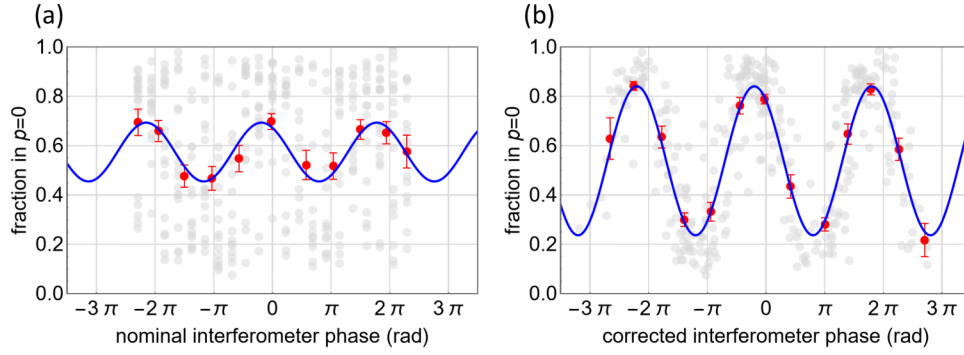


FIG. 2. Accelerometer phase correction. Improvement in the average fringe contrast after applying the phase correction to the individual runs of a 121 ms one-loop static guide interferometer. (a) Without phase correction and (b) phase corrected fringe. The gray dots are individual experimental data points, the red points are binned averages of those measurements, and the blue curves are least-squares fit of a cosine function to the average points.

A challenge associated with interferometers that use a mirror to retroreflect a laser beam to create the Bragg pulses for the splitting and mirror operation on atoms is the vibration of the mirror itself. This makes the phase of the standing wave light pulses different than programmed and injects noise into the interferometer. We use a classical accelerometer to measure the mirror acceleration during the interferometer sequence and postcorrect each run's phase to remove this effect [48–50]. The change in the interferometer phase due to the mirror motion is calculated by multiplying the measured mirror acceleration $a(t)$ by the double triangle like response function $f(t)$ and integrating the product over the interferometer cycle, $\Delta\Phi = 4nk \int f(t)a(t)dt$, where integer n is the diffraction order ($n = 1$ for $2\hbar k$).

We have installed two navigation grade accelerometers (InnaLabs AI-Q-2110) in the experiment to compute the phase correction. The first one is attached to the retroreflection mirror mount and the second to the experiment breadboard to which all the optic posts are mounted. The phase correction given by the two accelerometers agrees well. There is a factor of roughly two times average contrast improvement after applying the phase correction. This method of accelerometer correction works equally well for a static or moving guide interferometer and depends only on T . Figure 2 shows $T = 121$ ms one-loop static guide fringes, without [panel (a)] and with [panel (b)] the accelerometer phase correction. The peak-to-peak fitted fringe contrast increased from 0.23 to 0.6 by applying the correction. Here, the guide axial confinement is weaker ($\omega_z/2\pi \approx 0.4$ Hz) than the moving guide cases in the results below.

We quantify the fringes by least squares fitting the $p = 0$ fraction data, $N_{0\hbar k}/(N_{-2\hbar k} + N_{0\hbar k} + N_{+2\hbar k})$, to the function $P(\phi) = O + C/2 \cos(\phi + \phi_0)$, where O is the fringe offset, C is the fringe contrast, and ϕ and ϕ_0 are the interferometer and reference phase, respectively. We obtain an interference fringe by scanning ϕ_0 (more details in S3 of the Supplemental Material [42]).

In our configuration, each wave packet completes an integer number of full orbits around the Sagnac loop, with the final beam splitter readout occurring at the same point as the initial splitting. As a result, the interferometer is sensitive to rotation but not to constant acceleration. The interferometer phase shift from the rotation of the apparatus (or Earth) is

$\Phi_S = 4\pi \mathbf{\Omega} \cdot \mathbf{A}/(h/m)$, where $\mathbf{A}$ is the loop area, $\mathbf{\Omega}$ is the rotation angular velocity, and m is the atomic mass. It is of course critical to identify and minimize any systematic phase errors.

A typical calibration of the interferometer sequence involves a scan of the mirror to mirror pulse time to maximize the fringe contrast by maximizing the overlap of the wave packets when the recombination pulse is applied. The width of the overlap time window depends on the size of the wave packets and the potential curvature. We typically measure a FWHM of about 0.3 ms. It is worth noting that a higher axial guide curvature or interferometer T both shorten the time wave packets take to overlap again at the end [51,52]. The deviation in $T/2$ (mirror to mirror time) in a harmonic potential from being in a flat potential for the overlap condition is $\omega^2 T^3/32$, where ω is the axial trapping frequency of the guide. The experiment follows this dependence very well (see S5 of the Supplemental Material [42]).

To increase the number of loops, we turn off the last beam splitter pulse, allow the wave packets to go through each other, and repeat the guide motion and mirror pulse sequence. The second beam splitter pulse is applied when the atoms come back to the starting position after an additional even number of mirror pulses. Due to a restriction of the optical system on how far the guide beam can be moved, we have slightly modified the loop geometry (single and multiple) to further increase the enclosed area. This is done by keeping the guide static for a short time in the beginning, at the guide turning points, and at the end. In these regions, the guide is at rest or moves slowly. This allows the wave packets to move farther along the guide, enlarging the loop area. This t_{hold} is placed symmetrically, $t_{\text{hold}}/4$ at the beginning, $t_{\text{hold}}/2$ in the middle, and $t_{\text{hold}}/4$ at the end of the interferometer. This short hold in the static guide increases the Sagnac area for any number of loops, for example, from 2.7 to 2.9 mm² for a one-loop interferometer shown in Fig. 3(a).

Figure 3 shows our multiloop and large-area interferometer experiment results. In all the fringes discussed below, the radial trapping of the guide was 140 Hz. In the first three fringes of Figs. 3(a)–3(c), the guide was moved by 2.7 mm in 50 ms vertically downward and then brought back to the starting position in 50 ms. The inclusion of hold intervals where the guide position was held fixed increased the single-loop time to the values given below. All the fringes presented below are

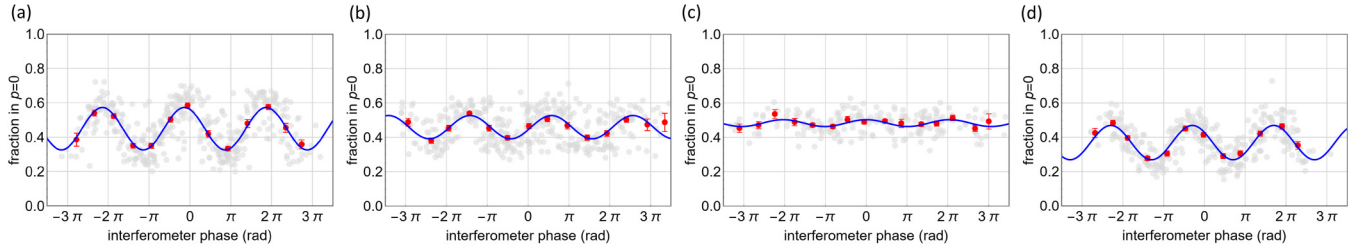


FIG. 3. Multiloop moving guide interferometry. (a) One-loop fringe for $T = 124$ ms and 2.9 mm^2 enclosed area. (b) Two-loop fringe for a total $T = 246$ ms and 5.8 mm^2 enclosed area. (c) 371 ms total T three-loop fringe with of 8.7 mm^2 enclosed area. (d) A five-loop fringe for a total T of 108 ms and 0.13 mm^2 enclosed area. The guide was moved vertically in all these interferometers. The red (gray) points show the bin-average (raw) fringe data. The blue curve is the cosine fit.

phase corrected from the accelerometer. Figure 3(a) shows a contrast $C = 0.26$ fringe for one-loop moving guide interferometer with $T = 124$ ms and enclosed area of 2.9 mm^2 . The guide was static for 24 ms and moved for 100 ms in total. For the two- and three-loop fringes, the guide was static for 22 ms and moved for 100 ms in each loop. Figure 3(b) shows a two-loop contrast $C = 0.13$ fringe with $T = 246$ ms and 5.8 mm^2 enclosed area. The three-loop interferometer experiment was a direct extension of the two-loop one [see Fig. 3(c)]. We set $T = 371$ ms and the computed enclosed area is 8.7 mm^2 . The fitted fringe contrast is $C = 0.05$. Figure 3(d) is a five-loop fringe (contrast $C = 0.2$) of total interrogation time of 108 ms. t_{hold} was set to zero for this five-loop configuration. The guide translation here was smaller, 0.17 mm.

Our interferometer scheme has the potential to sense rotation rates about multiple arbitrary axes without any hardware changes in the experiment. We currently use a one-axis AOD that deflects the guide only in the vertical plane. All the fringes shown in Fig. 3 are with the vertically moving guide. By rotating the AOD by 90° , we performed interferometry where the guide carrying atoms moves in the horizontal plane. Figure 4 shows a fringe in this configuration for an interrogation time of 160 ms. The total hold in the static guide was 80 ms, moved for 80 ms, and the guide translation was 2 mm. The wave packets enclose an area of 3.2 mm^2 and the fitted fringe contrast is $C = 0.12$. We measure similar fringe contrast for the vertically and horizontally moving guide interferometers when the guide translation and interrogation time are kept the same. A comparison can be drawn between the

vertical loop interferometer with area 2.9 mm^2 [Fig. 3(a)] and the horizontal loop enclosing 3.2 mm^2 area [Fig. 4(b)].

We now discuss the factors that can limit the performance of our interferometer. The fringe underlying contrast is affected by factors such as overlap of the wave packets at the end, nonoptimal Bragg pulse intensity, imperfect overlap of the Bragg and guide beams, experiment table floating condition, the Zeeman state of the atoms, the axial curvature of the guide, and the starting position of the wave packets with respect to the waist of the guide beam. We do measure a significantly lower underlying fringe contrast when the interferometer is operated with the initial location of the wave packet located away from the guide waist and/or with high axial curvature [51,53]. The axial trap frequency sets the size of the collimated BEC (to be the ground state size) that should ideally be used in the interferometer. Otherwise, the long-axis size after the collimation lens oscillates and degrades the interferometer contrast.

For long interrogation times, a small amplitude and slow oscillation of the table can be picked up by the atoms as an initial velocity and can result in population imbalance between the two interferometer arms and improper overlap at the end. We noticed this for $T = 120$ ms and longer. We are currently investigating the initial velocity fluctuation of the condensate, which should ideally be much smaller compared to $\pm 2\hbar k$ or 11.8 mm/s . Overall, we believe that an improved condensate collimation and initial velocity stability should result in a higher underlying and averaged fringe contrast, respectively.

We noticed that the waveguide waist moved for a duration of a few seconds due to the thermal lensing caused by the AOD. Since the total duration of the longest interferometer we ran is 400 ms, it is a factor that can affect the wave-packet dynamics. A better solution will be to use a piezo-based fast-tip/tilt mirror. A piezo mirror also offers a large deflection range and will not cause any disturbance to the waveguide profile.

Finally, the phase diffusion time due to the atomic interactions is estimated to be about 1 s for our system (for the phase noise to be π) [54]. It is not a leading cause of the reduced average contrast here.

Overcoming the loss of fringe contrast at longer interrogation times and using a larger deflection two-axis AOD or piezo-based tip/tilt mirror would allow us to study bigger Sagnac loops. Routing the vertically deflected guide beam back to the trap location would be a straightforward way to realize an interleaved three orthogonal Sagnac atom

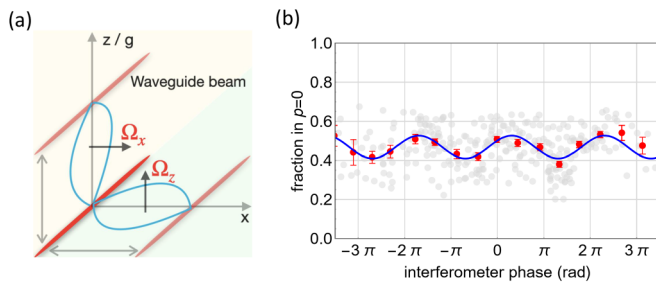


FIG. 4. Multiaxis interferometry. (a) Waveguide moving in the horizontal and vertical plane forming two Sagnac loops with orthogonal area vectors for sensing Ω_x and Ω_z . (b) One-loop interferometer fringe for the guide moving in the horizontal plane. The interrogation time and enclosed area are 160 ms and 3.2 mm^2 , respectively.

interferometers. Another promising direction to increase the loop area is working with higher momentum wave packets [55–58]. We are currently investigating higher momentum guided-atom interferometers using novel pulse shapes to realize high fidelity and intensity-robust beam splitters [59].

Angle random walk (ARW, in $\text{deg}/\sqrt{\text{h}}$) and bias stability (in deg/h) are the two most important parameters of a gyroscope. ARW depends on the noise in the fringe phase (represents sensitivity), and bias stability is related to drift in the averaged phase (any offset from the true rotation). With the largest Sagnac area reported above, 8.7 mm^2 , our interferometer has a scale factor ($\Phi_S/\Omega = 2 \text{ mA}/\hbar$) of $2.4 \times 10^4 \text{ rad}/(\text{rad/s})$. With the fit phase uncertainty of 0.24 rad , we estimate a rotation error (phase uncertainty/scale factor) of $20 \text{ } \mu\text{rad/s}$. With a total measurement time of 1.35 h , we estimate an ARW of $2.4 \text{ deg}/\sqrt{\text{h}}$, comparable to a recent demonstration in a two-dimensional waveguide atom interferometer [41]. We would like to emphasize that currently, with an increase in the number of loops or Sagnac area, contrast goes down due to technical (not fundamental) issues, and ARW remains of that order as mentioned above.

We have observed high underlying but poor average contrast in a one-loop static guide interferometer for T up to 400 ms . For 1 cm guide translation and $6\hbar k$ splitting, a 400 ms one-loop interferometer will give an area of 1 cm^2 translating to an order higher scale factor of $\sim 3 \times 10^5 \text{ rad}/(\text{rad/s})$. A sub-Hz BEC producing machine would be desirable to further improve the performance [60]. We measured the Allan De-

viation of the interferometer phase, and it follows the $1/\sqrt{\tau}$ scaling up to 10^4 s [34]. Since gyro's bias stability is one of the most important parameters together with the sensitivity, we believe our approach has potential to meet the navigation level performance.

In summary, we have experimentally realized a multiloop and multiaxis guided-atom interferometer. The Sagnac area reported here is the largest realized in a waveguide so far. To further validate the promise of a multiloop approach, we presented a high-contrast five-loop moving waveguide interferometer for a smaller loop area. In addition, we offer a solution to the challenging and important problem of multiaxis guided-atom interferometry. We presented similar performance interferometers with Sagnac loops oriented in the horizontal and vertical planes. Our results on guided-atom interferometry are an important step toward realizing a compact atomic gyroscope for applications such as inertial navigation.

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The authors declare no competing interests.

Data availability. The data that support the findings of this article are not publicly available. The data are available from the authors upon reasonable request.

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