Atom Interferometry with Top-Hat Laser Beams

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(Dated: August 13, 2018)

The uniformity of the intensity and phase of laser beams is crucial to high-performance atom interferometers. Inhomogeneities in the laser intensity profile cause contrast reductions and systematic effects in interferometers operated with atom sources at micro-Kelvin temperatures, and detrimental diffraction phase shifts in interferometers using large momentum transfer beam splitters. We report on the implementation of a so-called top-hat laser beam in a long-interrogation-time cold-atom interferometer to overcome the issue of the inhomogeneous laser intensity encountered when using Gaussian laser beams. We characterize the intensity and relative phase profiles of the top-hat beam and demonstrate the associated gain in atom interferometer contrast, in agreement with numerical simulations. We discuss the application of top-hat beams to improve the performance of different architectures of atom interferometers.

Inertial sensors based on light-pulse atom interferometry address various applications ranging from inertial navigation \cite{1–3}, metrology \cite{4–6}, gravimetry \cite{7–11} and gradiometry \cite{12, 13}, tests of fundamental physics \cite{14–17}, or gravitational wave astronomy \cite{18, 19}. Light-pulse atom interferometers rely on the coherent transfer of momentum from the photons of counter-propagating laser beams to free falling atoms in order to split, deflect and recombine the matter-waves. The sensitivity and accuracy of the instruments thus crucially depend on the relative phase uniformity of the laser beams realizing these atom-optics functionalities. State-of-the-art cold-atom sensors typically use sources at few \(\mu\)K temperatures, interrogation times of several hundreds of milliseconds, and two-photon transitions \cite{5, 8, 20}. Inhomogeneities in the laser intensity across the atom cloud degrade the atom optics efficiency, which causes a decrease of interferometer contrast and hence a lower signal to noise ratio, as well as systematic effects \cite{21}. Such detrimental effects are amplified in interferometers employing large momentum transfer (LMT) techniques (in which several momenta are transferred to the atoms) \cite{17, 22}, in particular because of diffraction phase shifts \cite{23}. The problem of intensity inhomogeneity can be mitigated by employing Gaussian beams with a size much larger than that of the atom cloud, at the cost of a reduced peak intensity.

In this work, we report on the implementation of a collimated top-hat laser beam (i.e. with a uniform intensity distribution in the central part \cite{24}) as a solution to circumvent the problems encountered in atom interferometers employing Gaussian beams.

Beamshaping is a topic of intense development, with applications ranging from micro-lithography, optical data storage, or optical tweezers, where different approaches are followed to produce structured light patterns. For application to atom interferometry, the requirement on the relative phase homogeneity motivates a scheme where the counter-propagating beam pair is obtained by retro-reflection (the retro-distance typically lying in the ten-centimeters-to-meter scale). The interrogation laser beams are thus required to be well collimated over such distances. This requirement on the beam shaping technique amounts to achieving a flat phase profile.

The simplest form of shaping the intensity distribution of a laser beam, apodization, results in significant loss of optical power (for example, the optimal transformation of a Gaussian beam into a beam with a flat intensity profile sacrifices 64\% of the power). More efficient techniques involve diffractive optical elements, such as spatial light modulators (SLMs), or collimated structured beams when multiple SLMs are cascaded \cite{26}. However, the bulkiness of the optical setup, the potential drift of the beam-shaping performance linked to the use of an active material, and the limited incident peak intensity make such solutions cumbersome for atom interferometry experiment. Instead, passive refractive techniques based on aspheric optical elements \cite{27} seem favorable, owing to their compactness, stability, and efficiency.

Our passive top-hat collimator solution is based on a recently released commercial beamshaper from the Asphericon company (model TSM-25-10-S-B), see Fig. 1a). The beamshaper shall receive at its input a Gaussian beam of 10 mm 1/e\(^2\)-diameter and produce a top-hat beam of 15 mm full width at half maximum (FWHM), with a region of about 14 mm where the intensity varies by less than 10\% (Ref. \cite{28}). The beamshaping is done with multiple aspheric optics, based on principles similar to those of Ref. \cite{27}. The advertised uniformity of intensity plateau is 0.056 rms, with a phase inhomogeneity of \(\lambda/3\) peak-valley (PV) and \(\sim\lambda/20\) rms, allowing the beam to propagate without deformation on distances of several meters \cite{28}. We inject the beamshaper with a home-made fiber collimator made of 3 simple lenses, to produce a Gaussian beam of 9.95 \(\pm\) 0.05 mm 1/e\(^2\) diameter. At the output of the beamshaper, the top-hat beam...
is magnified by a factor of two with two achronatic doublets, in order to reach a useful region of 28 mm. This size was calculated to be optimal for the interrogation of the atom cloud in our cold-atom interferometer [20]. The optical system can be mounted conveniently on an experiment. The power transmission of the input collimator plus the beamshaper is 91%, while that of the full system is 85%. The quality of the generated top-hat beam mainly depends on the input beam size (which must fall within the 10 mm diameter specification at the 10% level [28]), and of its collimation.

To align the top-hat collimator, we image the beam on a paper screen, and optimize the intensity profile by moving the input fiber placed on a 5-axis mount. We target a flat circular intensity profile maintained over a propagation distance of at least 150 cm. Fig 1b) shows the beam imaged on the paper screen at the output of the expander. While this method is convenient for the alignment procedure, it is not suited for a precise measurement of the intensity uniformity of the beam because of the speckle produced on the paper screen. We use a large-area beamprofiler (11.3 × 6.0 mm²) to measure the uniformity of the plateau. Fig 1c) shows the stitched images acquired by scanning the beamprofiler in front of the beam after 40 cm of propagation. The beam exhibits a qualitatively flat plateau. Large diameter rings concentric to the beam are attributed to the beamshaper. The uniformity of the plateau over a diameter of 28 mm is 0.11 rms, and the FWHM is 31.7 ± 0.2 mm. Fig 1d) shows a profile of the vertical cut through the middle of the beam (along the blue line). The orange line is a moving average over 1 mm of the profile, shown here to illustrate lower frequency inhomogeneities. For comparison, the green line shows a Gaussian beam with 40 mm diameter at 1/e² (as used in Ref. [20]) and same peak intensity as the top-hat beam.

In an atom interferometer, the relative phase between two counter-propagating laser beams is imprinted on the atomic wave-function during the light pulses. This relative phase contains a term associated with the free propagation, \( \varphi(x, y, 0) - \varphi(x, y, 2L) \), where \( L \) the distance between the atom cloud and the retro-mirror [29]. We measured such relative phase field for our top-hat beam using an asymmetric Michelson interferometer with the difference of its arms set to 2L. At the output, the interference pattern carries the 2D relative phase map, which we recover using a Fourier analysis [30]. A lower bound on the accuracy is set by the planeity of the mirrors and of the beamsplitter used in the interferometer, specified to be \( \lambda/10 \) peak-valley (PV). The relative phase map in a pupil of 28 mm diameter corresponding to the useful part of the beam is shown Fig 1e), for a difference in propagation distance 2L = 70 cm. We find relative phase inhomogeneities of \( \lambda/5 \) PV and a \( \lambda/28 \) rms. Additional phase maps for further propagation distances are given in the supplemental material [31]. Our characterizations show that the top-hat beam is suitable for high-precision atom interferometry, where relative wavefront inhomogeneities are an issue [11, 21, 29, 32].

We implemented the top-hat beam on a cold-atom gyroscope-accelerometer experiment. The setup has been described in previous works [20, 33] and we recall here the main features which are relevant for this study. Laser-cooled Cesium atoms (temperature of 1.2 \( \mu \)K) are launched vertically with a velocity of up to 5.0 m.s⁻¹. After a selection step of the \( m_F = 0 \) magnetic sublevel, we realize the atom interferometer by means of two-photon stimulated Raman transitions from counter-propagating laser beams, which couple the \( |F = 3, m_F = 0 \rangle \) and \( |F = 4, m_F = 0 \rangle \) clock states. The direction of the Raman beams is nearly horizontal. We use two beams separated vertically by a distance of 211 mm. The top-hat collimator was set up at the position of the top beam, while the bottom beam is a Gaussian beam of 40 mm diameter at 1/e² (Fig. 2a)). The state of the atoms at the output of the interferometer is finally read out using fluorescence detection.

We first probe the intensity profile of the top-hat beam
by applying a Raman pulse of fixed duration $\tau$ at different times as the atoms travel on their way up. The atoms are launched with velocity of $4.7 \text{ m.s}^{-1}$, and their mean trajectory intersects the center of the beam after a time of flight (TOF) of $170 \text{ ms}$. After this relatively short TOF, the size of the cloud is still close to that of the initially launched atoms ($\approx 1.5 \text{ mm rms radius}$) and much smaller than the beam size. The transition probability, $P \propto \sin^2(\Omega(z)\tau/2)$, is determined by the local value of the two-photon Rabi frequency, $\Omega(z)$, and can thus be used as a probe of the local intensity of the beam (here $z$ denotes the direction parallel to gravity). Fig. 2b) shows the transition probability versus the relative position of the cloud inside the beam. We observe a qualitatively flat intensity profile in the center, with a width consistent with the optical characterization reported in Fig. 1.

![Fig. 2](image)

\textbf{FIG. 2.} a) Sketch of the experiment. b) Measurement of the local Raman lasers intensity with a cold atom cloud, by recording the transition probability versus time-of-flight. The duration of the Raman pulse is fixed ($\tau = 9\mu s$) and set close to that of a $\pi/2$ pulse, where the sensitivity to intensity fluctuations on the plateau is maximum. The horizontal axis ($z$) is obtained by multiplying the TOF with the mean velocity of the atoms in the beam (3.0 $\text{m.s}^{-1}$).

To demonstrate the potential gain in efficiency of the atom-optics offered by the top-hat beam, we recorded Rabi oscillations after various TOF, when the atom cloud crosses the beam on its way up and its way down. We compared these results with the similar ones obtained for the lower Gaussian beam. For a quantitative comparison, the difference in height between the two beams (211 mm) was matched by the respective change in launch velocity, in order to obtain nearly the same TOFs when crossing the Gaussian and top-hat beams.

Fig 3a) shows the Rabi oscillations on the way up after a TOF of $170 \text{ ms}$ and on the way down after TOF of $855 \text{ ms}$ for the top-hat and Gaussian beams. On the way up, the cloud size is smaller than the beam sizes, and the Rabi oscillations have a similar shape for the Gaussian and top-hat beams, as expected. The transfer efficiency of $\approx 70\%$ is limited by the velocity selectivity of the two-photon transition, given by the finite Rabi frequency (i.e. laser power) and velocity spread of the atoms in the direction of the beams. On the contrary, on the way down, the Rabi oscillation in the top-hat beam (green) is significantly improved with respect to that in the Gaussian beam (red), owing to the homogeneity of the two-photon Rabi frequency experienced by the atoms in the top-hat beam.

To model the Rabi oscillations, we employ a Monte-Carlo simulation where we generate an ensemble of atoms with individual velocities following the distribution measured with the Doppler-sensitive Raman transitions (corresponding to a 3D temperature of $1.2\mu K$). The individual transition probabilities are calculated according to

$$P(\vec{r}, v) = \frac{\Omega(\vec{r})^2}{\Omega(\vec{r})^2 + \delta_D^2} \sin^2 \left[ \frac{\tau}{2} \sqrt{\Omega(\vec{r})^2 + \delta_D^2} \right],$$

where $\Omega(\vec{r})/2\pi$ is the two-photon Rabi frequency, proportional to the local intensity of the beam at the position $\vec{r}$ of the atom, $\tau$ the pulse duration, and $\delta_D = k_{eff} v$ the two-photon detuning, with $k_{eff} = 4\pi/\lambda$ the two-photon wave-vector and $v$ the velocity of the atom in the direction of the beam. Damping of the Rabi oscillations results from the average of many sinusoids with different Rabi frequencies and/or detunings. The simulation accounts for the finite detection region of the atoms (modeled as a rectangle of 30 mm by 30 mm in the plane transverse to gravity), and for spontaneous emission. The peak intensity is fitted on the upwards Rabi oscillation and fixed to this value for the downward oscillations. The model reproduces well the data, and allows to assess the intensity homogeneity of the top-hat beam. Fig. 3b) shows the measured Rabi oscillation confronted to a simulation where intensity noise of various levels is added on the top-hat profile [34]. The data match best the numerical simulation assuming an inhomogeneity of 8.3$\%$ rms, consistent with the optical characterization of the intensity inhomogeneities of 11$\%$ reported in Fig. 1.

Finally, we demonstrate that the top-hat beam is beneficial to high-sensitivity atom interferometry, by running a 3-pulse atom interferometer sequence with a pulse separation time $T = 147 \text{ ms}$. The first $\pi/2$ pulse is realized in the Gaussian beam (on the way up, TOF = $170 \text{ ms}$), while the second and third pulses are realized in the top-hat beam (TOF = $317$ and $464 \text{ ms}$). For such long interrogation time, the interferometer is highly sensitive to vibration noise producing at its output a typical rms phase shift of more than $\pi$ rad. Running the interferometer results in a random sampling of the fringe pattern by vibration noise, which appears blurred without additional knowledge on vibration noise at each run. To extract the contrast, we follow the method of Ref. [2] and compute the histogram of the transition probability data (Fig. 4a), from which we extract a contrast of $35\%$. Furthermore, we recover the interference fringes by correlating the atom interferometer output with the phase calculated from vibration data acquired with two broadband seismometers [20, 35], see Fig. 4b). The uncertainty (1$\sigma$)
on the fitted phase is 80 mrad, corresponding to an horizontal acceleration uncertainty of $2.5 \times 10^{-7}$ m.s$^{-2}$. Although the measurement sensitivity is limited by residual vibration noise, this experiment shows that the top-hat beam is compatible with high-sensitivity inertial measurements based on long-interrogation-time cold-atom interferometry.

We have set up and characterized a large collimated top-hat laser beam and illustrated its benefit over Gaussian beam for atom interferometry experiments. We expect that the use of top-hat beams will be beneficial to various atom interferometer geometries.

The intensity homogeneity of the interrogation beams will allow reducing or canceling important systematic effects in cold-atom interferometers, such as the two photon light shift [36]. It can also be used to improve the efficiency and stability of atom launching techniques based on the coherent transfer of photon momenta, such as in Bloch oscillations [4, 6, 17]. Moreover, this beamshaping solution could be adapted for atom interferometers with baselines of several meters as in Ref. [17].

Employing a single top-hat beam can be used to build compact, yet precise, cold-atom inertial sensors. For example, a $D = 28$ mm wide homogeneous intensity profile should allow to run a fountain interferometer with a total interferometer time $2T \simeq 2 \times \sqrt{2D/g} = 151$ ms if the atoms are launched from the bottom of the beam. Moreover, the design of gyroscopes, where the atoms travel through successive laser beams with a velocity transverse to the momentum transfers [21, 37, 38], could be simplified with a single top-hat beam.

Homogeneity of the intensity profile should reduce the diffraction phase shifts encountered in LMT Bragg diffraction [39–41]. For example, a variation of 1% of laser intensity in $4k$ Bragg diffraction amounts to a variation in diffraction phase of about 84 mrad [23]. The intensity uniformity of our top-hat beam is 11% over a region of 28 mm (Fig. 1c). Keeping a 11% rms intensity variation within a Gaussian beam of 20 mm waist (which yields the same velocity selectivity as our current top-hat) requires to work within a radius of 7.8 mm around the center, which translates in using only 25% of the total power. This suggests that the efficiency and accuracy of LMT beam splitters should be significantly improved by employing top-hat beams.

We thank Josiane Firminy and Faouzi Boussaha for their realization of engraved aspheric phase plates in an early design of beamshaper conducted in the beginning of this project. This work was supported by Ville de Paris (project HSENS-MWGRAV), FIRST-TF (ANR-10-LABX-48-01), Centre National d’Etudes Saptiales (CNES), Sorbonne Universités (project LORINVACC), Action Spécifique du CNRS Gravitation, Références, Astronomie et Métrologie (GRAM), and by the European Union’s Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 660081.
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FIG. 5. Cut of the intensity profile for various propagation distances. Left: 0 cm. Center: 40 cm (Fig. 1 d) of the main text). Right: 130 cm.

RELATIVE PHASE

We show in Fig. 6 the relative phase maps extracted from the measurement with the asymmetric Michelson interferometer for different distances of propagation (i.e. various differences in arm length between the two arms of the interferometer). The first column shows the measurement for zero propagation distance and allows to assess the limit of the method given by the quality of the optics.
FIG. 6. Relative phase maps for various distances of propagation and pupil diameters. From top to bottom, the pupil diameter is 15 mm, 20 mm and 28 mm. From left to right, the propagation distances are 0 cm, 30 cm, 70 cm (Fig. 1e) of the main text), and 110 cm.