Robust quantum inertial sensors with optical beam shaping

Ulrike Fuchs[1], Henrike Schlutow[1], Joel Gomes Baptista[2], Leonid A. Sidorenkov[2] and Camille Janvier[3]

1 asphericon GmbH, Stockholmer Str. 9, 07747 Jena, Germany
2 LNE-SYRTE, Observatoire de Paris, Université PSL, CNRS, Sorbonne Université, 61 Avenue de l'Observatoire, 75014 Paris, France
3 Exail Quantum Systems, 1 rue François Mitterrand, 33400 Talence, France

Introduction

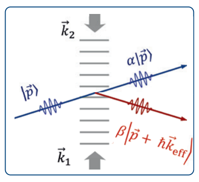
ABSTRACT/SUMMARY

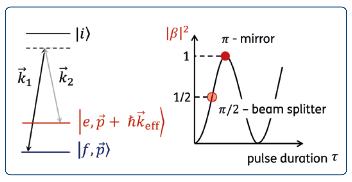
Inertial sensors based on atom interferometry benefit from laser beams of homogeneous intensity and wavefront. Here we present a fiber-coupled athermalized beam shaper retaining these properties over an extended temperature range, developed for a field-deployed quantum gravimetry within the FIQUgS project. With optimally matched thermal properties of lens and housing materials, we obtain a top-hat collimator design with an RMS wavefront error of less than 6mλ over the entire temperature range and less than 3% intensity variation over the entire propagation range. Our results open perspectives for extending application of top-hat collimators towards different architectures of atomic inertial sensors demanding enhanced robustness, optical powers and laser beam propagation distances.

Atom interferometry with top-hat beams

BUILDING BLOCKS OF ATOM INTERFEROMETER ANALOGY WITH OPTICS

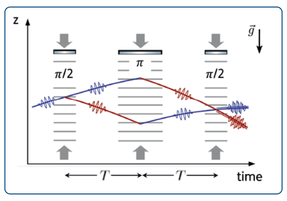
	Optics	Matter waves
Coherent source	Plane wave/ laser field	De Broglie matter waves: λ = h / p "monochromatic" source → laser cooling
Optics elements	Beam splitters, mirrors	"Atom optics" = Diffraction of atomic wave packets with lasers = Coherent interaction between laser field & an atom (e.g. Raman transition)





How does inertial sensitivity appear?

= Interferometric sequence (example of Mach-Zehnder)



- Interferometric pattern:

$$P_{|\vec{p}\rangle \to |\vec{p}+\hbar\vec{k}_{eff}\rangle} = \frac{1}{2}(1 - C\cos\Delta\Phi)$$

= Classical equation of motion along the two paths

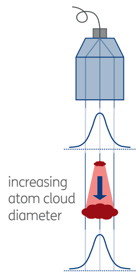
= Laser phase "imprinted" on diffracted wave function:

$$\phi(t) = \vec{k}_{eff}.\vec{r}(t)$$

= Acceleration and rotation contributions

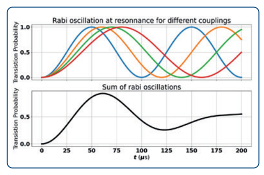
$$\Delta\Phi = \vec{a}.\vec{k}_{eff}T^2 - 2\vec{k}_{eff}(\vec{\Omega} \times \vec{v})T^2$$

BENEFITS OF ATOM INTERFEROMETRY WITH TOP-HAT BEAMS



Non-homogeneous atom-light coupling across the laser beam:

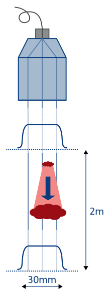
$$P(x) = \sin^2(|\Omega_{eff}(x)|\tau/2)$$



Degraded efficiency of the atom-optics!

Gaussian beam

= Non-uniform transition probability + expansion of atomic cloud → loss of interferometric contrast
= Spurious contributions to measured acceleration → loss of measurement accuracy



Fiber-coupled collimator with beam shaping optics

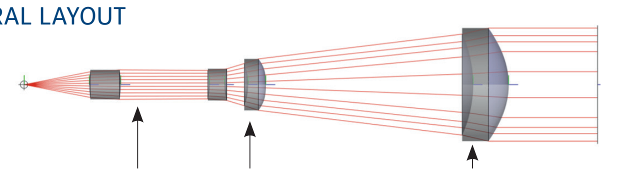
= Wavelength 780 nm
= Top-hat output profile 30 mm FWHM
= Beam uniformity 0.1
= RMS wavefront error < λ/10
= Propagation length 2m
= Passive athermalization 0-50°C
= Housing titanium alloy

Top-hat beam

= Uniform transition probability
= Elimination of spurious contributions

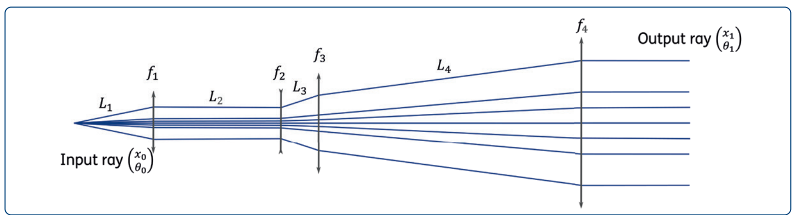
Athermalization of fiber coupled beam shaper

GENERAL LAYOUT



Space for phase plates, polarizing filters, LCVR, ... | Aspherical lens for energy redistribution | Aspherical phase flattener for collimation

CLASSICAL ATHERMALIZATION CONDITION



Collimation condition: $\theta_1 = F(f_i(T_0), L_i(T_0)) = 0$ (1)

Athermalization condition: $\frac{dF}{dT}|_{T=T_0} = 0$ (2)

From (2): $F'(f_i(T_0), L_i(T_0)) * \left(\alpha_H + \frac{dn/dT}{n-1} - \alpha_G\right) = 0$

Matching thermal properties of housing and glass

Thermal power $\gamma = \frac{dn/dT}{n-1} - \alpha_G$

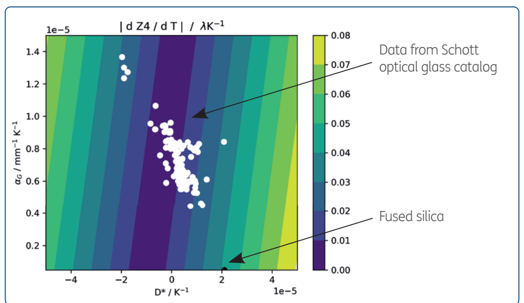
Titanium: α_H = 8.2e-6 K^{-1}
Fused silica: γ = 17.2e-6 K^{-1}
N-LAK21: γ = -8.3e-6 K^{-1}
N-KF9: γ = -10.1e-6 K^{-1}

Best matching glass: N-LAK21

ATHERMALIZATION OF BEAM SHAPING SYSTEMS

= Temperature change mainly introduces wavefront defocus (Z4)
= Optimization parameter $\frac{dZ_4}{dT} = 0$
= Variation of glass properties $D^* = D_0 + \frac{E_0}{\lambda^2 - \lambda_k^2} \propto \frac{dn}{dT}$

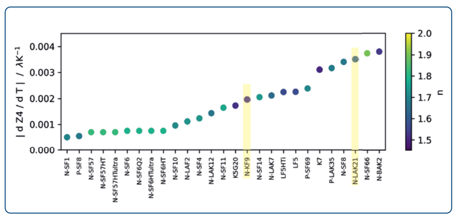
α_G while keeping constant refractive index



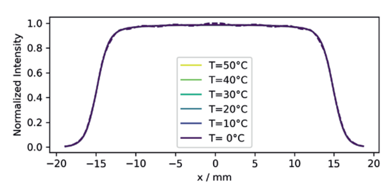
Interpolation of | d Z4 / dT | to real glass data for selection of optimum glass with low refractive index and for titanium housing

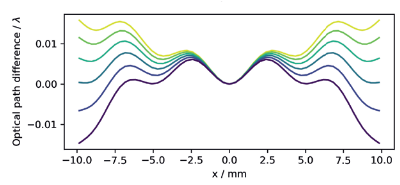
Best matching glass with low refractive index: N-KF9 better athermalization than N-LAK21

| d Z4 / dT | N-KF9 = 1.9mλ/K
| d Z4 / dT | N-LAK21 = 3.5mλ/K



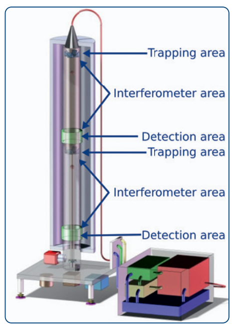
Simulated performance of athermalized top-hat collimator with N-KF9





Expected Gravimeter performance (FIQUgS project)

THE DIFFERENTIAL QUANTUM GRAVIMETER IN DEVELOPMENT BY EXAIL



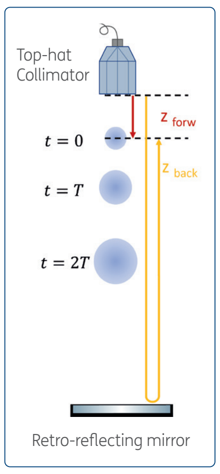
= Differential Quantum Gravimeter (DQG) is a dual interferometer quantum gravimeter
= Using a double tracking scheme, we are able to measure both gravity and vertical gravity gradient simultaneously
= Using the same laser for both interferometers ensures maximum common mode rejection on gradient
= Leverage the experience acquired in developing the AQG
= Gaussian beam collimator → top-hat collimator possible in future

Gravimeter: $\bar{g} = \frac{z_2 g_1 - z_1 g_2}{(z_2 - z_1)}$

Gradiometer: $\Gamma_{zz} = \frac{g_1 - g_2}{L}$

Perspective:
FIQUgS project aims deploying the dedicated version of DQG + spectral ground penetrating radar on the robotized platform for semi-autonomous geophysical surveys on the field

SIMULATED TOP-HAT PROFILES AND INTERFEROMETRIC SEQUENCE

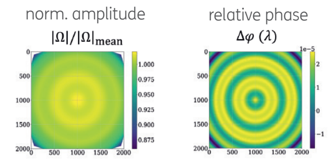


Simulation details:

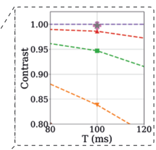
= Atomic source rms expansion at 10 mm/s
= T = 100 ms
= Top-hat profiles @ exact distances
= Consider no diffraction on apertures
= Counter-propagating pair of beams
= Raman coupling is given by:

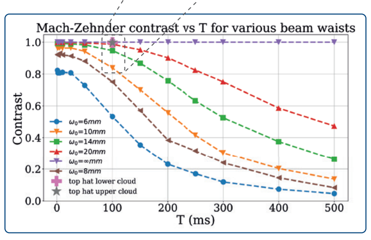
$$\Omega \propto E_{forw} * E^*_{back} = \sqrt{I_{forw}} * \sqrt{I_{back}}\, e^{\Delta\varphi}$$

Coupling for the 1st laser pulse (t=0):



Preliminary conclusion:
No significant contrast loss from residual inhomogeneity of top-hat laser beam profile





FIQUgS is a project initiated by the European Commission under the „Horizon Europe" programme, a key EU programme for funding scientific research and innovation. The project has received funding from the European Union's Horizon Europe under Grant Agreement n°101080144.
More: www.fiqugs.eu