Ring-Lasers
seismic rotational sensing
Angela Di Virgilio-INFN-Pisa

The Sagnac effect
G-Pisa sensitivity and some data taken at VIRGO in 2010-2011
GP2 GINGERino G-Las
The Sagnac Effect and the ring-laser

\[ f_{\text{Sagnac}} = |f_{\text{CW}} - f_{\text{CCW}}| = \frac{4\mathbf{A} \cdot \mathbf{\Omega}}{\lambda p} \]
Angular Rotation Inertial Sensor - No moving parts

**Advantages**

- No moving masses
- No signal for a linearly accelerating reference-frame
- $L > 1 \text{ m} \rightarrow$ Earth rotation is the bias

**Quantum limit**

$$\delta \Omega_{\text{shot}} = \frac{c P}{4 A Q} \left( \frac{h \nu T}{2 P_{\text{out}} t} \right)^{1/2}$$

- Low cavity losses
- High power
- Large size
Mechanical, fiber optic, and ring laser gyroscopes
Status of the Art of ring-laser

- Ring laser have a large application in navigation
- Few large frame rings have been developed for geodetic and geophysical application

New Zealand
J. Stedman 1997

- Prototype: C-II (1997)
- Perimeter 4 m
- He-Ne (632.8 nm)
- Cavity in Neutral Plane
- UHV-Compatibility
- RF-Excitation
- $\Delta \Omega/\Omega < 10^{-6} @ 1000 s$

Feasibility of Concept shown
OUR INFN PROTOTYPES

• Hetero-lithic mechanical design
• Stable by control

LONG TERM STABILITY IS OUR MAIN CONCERN

Since 2008, in collaboration with U. Schreiber of the GrossRing G of the Geodetic observatory of Wettzell
What ‘long term’ stability means for us:

Courtesy U. Schreiber
Ringlaser/Seismology

- Colocate one ring-laser+seismometer
- The simultaneous measurement of ground translation and rotation
- dispersion curve of Love waves over a broad frequency range, from which a local shear-wave velocity profile can be inferred with resolutions on the order of 100 m and penetration depths up to several tens of kilometers.
Several INFN experiments, from 2008 G-Pisa/ G-GranSasso-DS/ G-GranSasso-RD

At present G-GranSasso-RD (CommII):
Pisa: J. Belfi, N. Beverini, G. Carelli, A. Di Virgilio, U. Giacomelli, E. Maccioni, A. Simonelli
LNL: A. Ortolan
Padova-DEI: A. Beghi, D. Cuccato, A. Donazzan, G. Naletto, M. Pelizzo
Napoli: C. Altucci, A. Porzio, R. Velotta
Torino: ML Ruggiero, A. Tartaglia General Relativity theory

26/05/16 Angela Di Virgilio, GWADW2016
G-Pisa during the installation in Virgo
Getters pumps avoid the aging of the gas
Ring Lasers are Shot-Noise Limited

- Sensitivity improves quadratically with L (Q & p/A)

- $P_{out}$, typically 10-20 nW, but should be possible go up to 500mW-1mW

- Typical wavelength 633nm, but infrared and green are feasible

- Squeezing in principle feasible, but no experience so far
Sensitivity depends on several parameters

- Wavelength, losses and transmission of the mirrors, side length, output power
Example: 4.5 total losses, 633nm (other wavelength feasible-infrared and green)

<table>
<thead>
<tr>
<th>Side/power</th>
<th>$1. m$, PSD rad/s 1 s</th>
<th>2m</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 nW</td>
<td>$3.8 \times 10^{-10}$</td>
<td>$1.9 \times 10^{-10}$</td>
</tr>
<tr>
<td>50 nW</td>
<td>$1.7 \times 10^{-10}$</td>
<td>$8.5 \times 10^{-10}$</td>
</tr>
<tr>
<td>500 nW</td>
<td>$5 \times 10^{-11}$</td>
<td>$2.7 \times 10^{-11}$</td>
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Bandwidth depends on the ringdown time of the cavity

- Size of the ring and quality of the mirrors
- Typical value in our prototypes (meter size): from 80µs up to 660µs

\[ \sim 1 \text{kHz bandwidth} \]

They can run continuously un-attended
Transportable

Our first prototype G-Pisa:

• assembled in Pisa, and has taken data in Pisa
• moved to the VIRGO central area
• has taken data for several months during last Virgo run (data stored in the raw data)
• Has been moved to S.Piero, and has taken data there
• Has been moved to the GranSasso national lab. And has taken data there
• In 2015 it has been disassembled and the mechanical parts are now user for the new prototype GINGERino
Horizontal and vertical gyrolaser operation
G-Pisa in the Virgo Central Area
G-Pisa RLG

\[ \Delta f \approx 106 \text{ Hz} \]
A 1.82 m² ring laser gyroscope for nano-rotational motion sensing

Low frequency sensitivity limited by backscattering.

This noise can be canceled.

![Graph](image)

**Fig. 10** Tilt sensitivity in a very quiet period, the requirements of AdVirgo are $10^{-26} \text{rad}/\sqrt{\text{Hz}}$ in the range 5 – 500 mHz.
On month of continuous Data Taking with perimeter locked.
Comparison with the Wind Monitor
Virgo was not affected by this
Shock, no evidence of jitter of the output beam or in the accelerometers
But the DarkFring has seen it

More on G-Pisa@VIRGO, 2011
Coherence with Dark Fringe

Coherence between our signal and the DarkFringe has not been done extensively, but there is evidence of coherence.

G-Pisa bandwidth at the moment is 1kHz
There is coherence at low frequency between the gyrolaser and LVDT signals.
Backscatter noise dominates below 0.1 Hz, it can be subtracted

Earth Rot. Rate \((7.2921150 \pm 0.0000001) \times 10^{-5}\) radians

Expected Sagnac Freq. 155.519 Hz
Allan Deviation, G-Pisa in a ‘standard laboratory’ 2014 implementable on-line

Figure 19: Allan deviations of AR(2) (upper curve) and EKF (lower curve) rotational frequency estimates. The straight line represents the shot noise level of G-PISA for a cavity quality factor of $5.4 \times 10^{11}$ and an output power of 4 nW.
GP2- 1.6m in side
GEOMETRY CONTROL STUDY
necessary for the long term stability
**Problem**
The magnitude of the *relativistic frame dragging* term is of 1 part in $10^9$ of the Earth rotation

- scale factor $k_s$ stabilization better than $10^{10}$
- accuracy on mirror position better than 1 nm

**Approach used in the past**

*Observable*: RL optical frequency (cavity perimeter control)

*Stabilization methods*: comparison with reference laser; by tuning the environmental pressure; by locking to a frequency comb

*Limitation*: variations of mirror inter-distances remain uncontrolled

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**Our original approach**

*Observables*: distance between opposite mirrors (& perimeter)

*Stabilization methods*: lock of diagonal cavities respect to a frequency standard

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Interferometric length metrology for the dimensional control of ultra-stable ring laser gyroscopes, Class. Quantum Grav. 31 (22), 225003, (2014)

Angela Di virgilio, GWADW2016
GP2: Optical setup
Mirrors position actuators

- #3 1-axial PZT; #1 3-axial PZT
- dynamic range (measured): 80 μm
- control bandwidth (measured): few tens of Hz

Frequency–response of the mirror–holder actuator (diagonal direction)
2 diagonals stabilization

Closed-loop correction to the opposite mirrors (digital PI controller)

Mires displacement (um)

Difference

GINGERino, the ring laser inside LNGS, 3.6m in side
GINGERino, angular velocity - average value, 50Hz DAQ, May 24, 0 UTC, RAW DATA
GINGERino, Power Spectrum, Raw Data, no filters

backscattering not subtracted raw data
G-LAS, Gyro-Laser Angle Standard under assembling, 0.5 m in side

Transportable Goniometer for metrology
INRIM/INFN
Accuracy 5 $10^{-9}$ rad

Angela Di Virgilio, GWADW2016
Two papers with the analysis of tele-seismic events: both Love and Rayleigh waves

References


Summary

• Ringlaser with ~ 1m in side are robust, bandwidth ~ 1kHz
• Triangular rings feasible
• the independent components of the angular rotation vector can be measured changing the orientation of the ring (ROMY 4 rings array in construction in Baviera, ERC Heiner Igel)
• They are suitable for ‘observatory’, they run un-attended
• Sensitivity depends on mirror and size, easily better than $10^{-9}\text{rad/s}/\sqrt{\text{Hz}}$