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Ring Laser gyroscopes and Gravitational waves research

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Abstract. The INFN research for the development of top sensitivity ring laser gyroscope began about 15 years ago. At that time the aim was to develop top sensitivity tilt-meter for the Virgo suspensions, and the CSN5 in 2009 has financed a first project to learn the technique, later the project passed to CSN2 as an R&D project to develop ring laser gyroscopes for fundamental physics investigation, in particular for general relativity tests. This long time work has proposed the GINGER experiment, based on an array of ring lasers, under construction inside the underground laboratory of Gran Sasso. The ring laser structure plays a big role, and the design developed for GINGER can be scaled down to approximately 1-1.5m side square structure. A prototype, called TRIO, has been built in Pisa and is in the commissioning phase. The feasible sensitivity and the possible utilization of RLG for third generation gravitationa waves detection will be discussed.

Ring laser gyroscopes (RL or RLG)[1] are based on a closed path interferometer, usually a square defined by 4 mirrors at the vertices of the square, and defining a high finesse optical cavity. An active medium is contained in the square ring cavity, two counter-propagating laser beams are generated. The interference of the beams transmitted by each mirror brings information on the non reciprocal effects experienced by the two counter-propagating beams. Since the two beams share the same path, the differences due to these non reciprocity effects are extremely small. However, if the optical cavity is rotating, an asymmetry is generated between the two propagation directions, producing a difference between the beams proportional to the rotational rate, a well known effect since more than 100 years, called Sagnac effect, which largely dominates all other effects and is generally exploited in devices for inertial navigation[2–4]. The active large frame Sagnac interferometer is by far the most sensitive instrument; prad/s sensitivity and continuous operation have been extensively demonstrated[1, 5, 6]. However, there are other non reciprocal effects related to the space time structure or to fundamental asymmetries, and so RLGs are suitable for fundamental physics investigations[7–9]. The optical cavity structure plays a big role, since the response depends on the geometry and it is necessary to avoid spurious rotation of the apparatus induced by environmental disturbances[10]. The first working RLGs were based on monolithic structures made of very low thermal expansion ceramic materials, and most of the small size gyroscopes are monolithic. However, for high sensitivity large apparatus are required, at that purpose RLGs with hetero-lithic (HL) cavity, composed of different mechanical components[11, 12]. Two HL prototypes have been built and extensively studied by our group: G-Pisa, the first prototype which has been operating in 2010-2011 at the Virgo central area to measure local rotations and tilts, GINGERINO [13], placed in the Gran Sasso under-

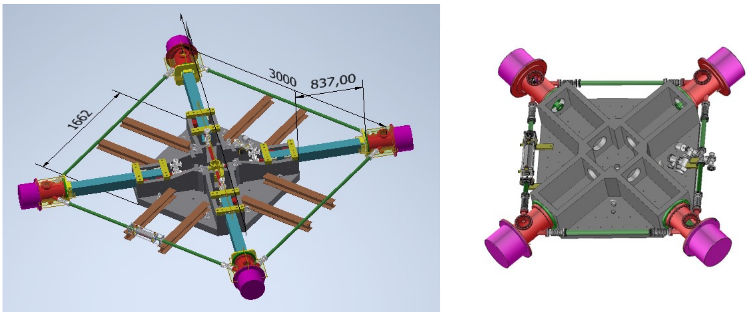


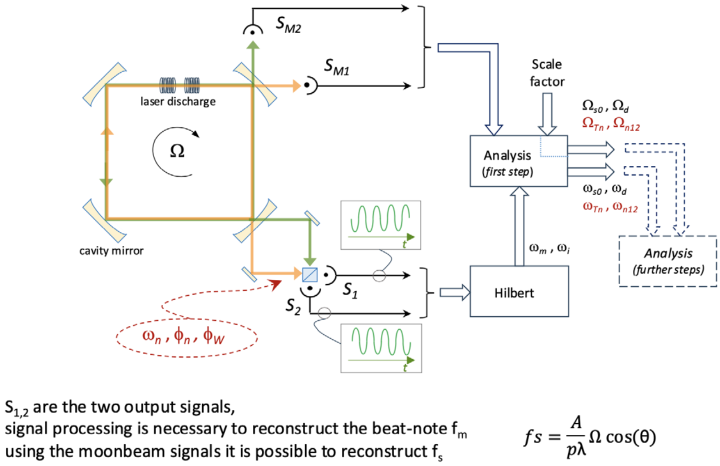
Figure 1. ON THE LEFT: The HL RLG developed for GINGER, 3m side. Four vacuum tank boxes are located at the corner of a square. The boxes host the four super-mirrors that are aligned in order to define a square optical cavity. The boxes are connected by pipes, vacuum tight, and filled with a mixture of Helium Neon gases. In the middle of one of the side is located the pyrex capillary with external electrodes, used to power the laser by radio frequency excitation. The laser emission has wavelength 633nm. The mirrors are equipped with piezoelectric actuators, used to control the geometry, but in general the RLG can be operated uncontrolled. ON THE RIGHT: the transportable RLG TRIO, based on the GINGER design, but with 1.5m side without spacers.

ground INFN laboratories, and GP2 [11], located in Pisa INFN laboratories. At present a third prototype is in the commissioning phase. Unattended continuous operation for months, a typical sub-nrad/s sensitivity in 1 second of measurement time, large bandwidth, fast response, in principle as fast as milliseconds, have been proven in the experiments carried out so far. At present large ring lasers are the top sensitivity device to measure angular rotations. The GINGER experiment, an array of large HL RLGs, is presently under construction at the underground Gran Sasso laboratory. It will be useful to geophysics, geodesy and fundamental physics investigation [7]. The GINGER HL design, called GP3, can be scaled to make cavities of 1 m, up to 5-6m side. The reduced size open the way to applications for inertial platform development in general, and other applications, Fig. 1 shows the drawing we have developed for GINGER. It is composed of a granite central part, the mirrors, contained in the red boxes, are connected to the granite structure through spacers, changing the length of the spacers the size of the cavity can be changed from 1.5m op to 5-6m side. The whole structure can be oriented at will, to record rotations around the 3 Cartesian axis. So far we have successfully operated prototypes with different orientations: horizontal, vertical and inclined at the maximum signal. In the following we shortly discuss the advantages of RLG and a list of possible implementations for third generation GW detectors.

An RLG senses the component of the angular velocity vector $\vec{\Omega}$ along the axis of the closed polygonal cavity, defined by the area vector. The relationship between the Sagnac frequency f_s and the angular rotation rate Ω reads:

$$f_s = 4\frac{A}{\lambda p}\Omega\cos\theta \tag{1}$$

where A is the area enclosed by the optical path, L is its perimeter, λ is the wavelength of the light, and θ is the angle between the area vector $\vec{A}$ and $\vec{\Omega}$. RLGs are certainly extremely powerful instruments, however their diffusion has been limited by the fact that the result is affected by systematics induced by laser dynamics. We have developed an original data analysis scheme in order to remove such systematics from the data and provide a proper reconstruction of the true Sagnac frequency[14]. In general mechanical devices are used to



$S_{1,2}$ are the two output signals,
signal processing is necessary to reconstruct the beat-note f_m
using the moonbeam signals it is possible to reconstruct f_s

$$fs = \frac{A}{p\lambda} \Omega \cos(\theta)$$

Figure 2. RLG scheme containing the device, the read-out and the scheme of the procediure to reconstruct the frequency and remove the systematics of the laser. On the bottom left mirrors the transmitter light beams are over–imposed at a cube beam-splitter, the interference is the beat–note recorded by the photodiodes and stored to be analysed. On the top left corner the two output beams (called monobeams, S_{M1} and S_{M2}) are recorded by photodiodes. The relationship between the Sagnac frequency f_s and the angular rotation Ω is shown. The Sagnac frequency is reconstructed using the beat note signal and the mono–beams, in order to correct the typical systematics of the laser: back–scatter and null–shift.

measure tilts and angular rotations, RLG uses the light, and this poses several advantages: Advantages with respect to standard mechanical gyroscopes:

- No moving part i.e. no contribution from other degrees of freedom
- Continuous operation with high duty cycle
- Signal based on frequency reconstruction, i.e. huge dynamical range, free running operation feasible
- Frequency high stability and input source not required

RLG use for inertial platforms in general is straightforward, here implementations for GW research are listed:

- Environmental monitor: G-Pisa prototype has been operating for one year in the Virgo central area and has benn able to provide the measure of the local tilt induced by strong wind.
- Earth based GW interferometers use special suspensions for the mirrors in order to filter out seismic noise above a certain frequency. Usually suspensions are multi-pendulum, and the RLG could be integrated as an active element of the multi-pendulum (see for example Virgo Note VIR-0019E)
- The mirror suspensions takes care as well of interferometer alignment, and RLGs could be used in order to control the relative orientations of the different mirrors, one with respect to the other, using as reference the Earth angular rotation axis, avoiding the use of reference on ground.

- presently under investigation the RLG to improve by a factor 100 satellites AOCS (Attitude and Orbit Control). This could be relevant for space based GW interferometers.

In the last 10 years it has been demonstrated that large frame RLG, square devices witn 3-4m side, can be operated with a few prad/s sensitivity in a continuous basis and large bandwidth. The design can be scaled and large square RL with 1m side are feasible with reduced cost, further scaling is not recommended because the two beams will be locked, making the instrument blind. The sensitivity depends on side, but 1 m side devices should guarantee 10prad/s sensitivity in 1 second. Possible use for future generation gravitational waves interferometers is outlined.

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