G-Pisa gyrolaser

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***Abstract*—G-Pisa is an experiment which is investigating the possibility to operate a laser-gyro with area less than 1 m^2 and high sensitivity in order to improve the performances of the mirrors suspension of the gravitational wave antenna Virgo. The experimental set-up consists of a 4 mirrors square cavity, the mechanical drawing allows us to scale the area from 2 down to 0.81 m^2. G-Pisa is working since July 2008, in the following the results so far obtained are reported. At low frequency, below 1 Hz, the sensitivity is typically in the range of 10^{-8} rad/s/$\sqrt{\text{Hz}}$, it has been checked that G-Pisa is working properly in single mode and multimode good stable operation has been observed up to 4 mode**

I. Introduction

Laser-gyros are devices sensitive to inertial angular motion. They are based on the Sagnac effect: in a closed cavity rotating at angular velocity Ω the two counter propagating beams complete the path at different times. Different kinds of such devices have been developed mainly for aircraft, ship and submarine navigation. They are only sensitive to angular velocity and entirely insensitive to translational velocity. We distinguish between passive (fiber optic gyros) and active (ring lasers) Sagnac interferometers. Passive devices measure the phase shift between the two beams, while the active ones measure the frequency difference, an inherently more accurate measure. Small fiber gyros typically used for navigation have a resolution of 10^{-8} rad/s, while the large ring laser gyros used in geophysics and geodesy have a sensitivity at the level of 10^{-12} rad/s. In the following we will focus on active ring lasers and will call them simply gyros. One application of large gyros is the monitoring of the variations of Earth rotation speed. Up to now the reached resolution is 10^{-8} of the Earth rotation, integrating the signal for several hours [1], [2], [3], [4], [5]. Mode locking between the two counter-propagating modes of the laser is the major problem of small ring lasers; technical tricks, like rate biasing or dithering, have to be applied to overcome this issue. In large gyros the rate bias induced by the Earth rotation is enough to avoid mode locking. The orientation with respect to the Earth axis is important since the induced signal is proportional to the scalar product between the normal of the gyro area and Earth axis, see equation 1. For horizontal gyros the signal is zero at the equator and maximum at the pole; at intermediate latitudes, horizontal and vertical cavities work fine. The Sagnac frequency i.e. the beat signal between the two output beams is:

$$\delta\phi = 4A\,\vec{n}\cdot\vec{\Omega}/(\lambda P) + \phi_\rho \qquad (1)$$

where A and P are the area and the perimeter of the cavity respectively, λ is the wavelength of the laser beam, $\vec{n}$ is the normal vector of the plane of the ring cavity and $\vec{\Omega}$ is the induced vector of rotation, with Earth rotation being at least one contributor, ϕ_ρ is denoting additional, usually very small, contributions to the Sagnac frequency due to non-reciprocal effects in the laser cavity, such as Fresnel drag [6]. A laser gyro can monitor with high accuracy the orientation of the laboratory reference frame, but our main interest is in extending the use for improvements of the gravitational waves interferometeric antennas of Virgo [8], [7]. This suspension (Super Attenuator, SA [9]) is basically passive and is a multi pendulum, composed of a cascade of several stages, each of them acting as an oscillator in all the 6 degrees of freedom, with resonance frequency below 1 Hz. In the following, the first paragraph describes the performances and the fundamental limits of gyros; the second describes our prototype its first experimental set up, the typical sensitivity and the characterization of the laser; at the end the conclusions come.

II. Large G-gyros

The large ring laser gyros built by the joint ring laser working group in New Zealand and Germany have sides of the

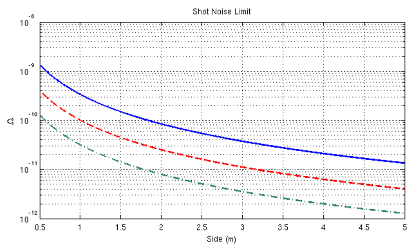

Fig. 1. Shot noise limits as a function of the mirrors reflectivity ($R = 99.9999\%, 99.9995\% and 99.999\%$).

order of several meters. "G" [10] located at at the Geodetic Observatory inWettzell (Germany) iss a monolithic square with 4 m sides, "UG2", a rectangle with 40m by20 m sides, is the largest ring. In principle the larger the area the better the sensitivity, but the best gyro so far, is "G". This ring consists of a 4 mirror cavity made from a single block of Zerodur, the super-mirrors have a reflectivity of 0.999995. The entire beam path is inside a vacuum tight enclosure, filled with a mixture of Helium and Neon. A very small portion of this gas mixture is excited with a radio frequency (RF) oscillator in order to provide the necessary laser gain. "G" is operating very close to the quantum limit (just a factor 3 higher), and the measured power spectrum noise is of the order of 10^{-11} rad/s/$\sqrt{\text{Hz}}$, with a duty cycle close to 100%. The Allan deviation has not shown any systematic effects on a time scale of about 3 hours, and the sensor drift is normally below 1.5 parts in 10^8 of the Earth rotation ($1.1 \cdot 10^{-12}$ rad/s). The Allan deviation goes down as the square root of time up to 2.7 hours of averaging time, then goes up for a while before it resumes the theoretically expected downward trend. It is very important to stress out the fact that these ring lasers have a very high duty cicle, close to 100%. In large gyros the shot noise of light gives the fundamental limit to sensitivity:

$$\Omega_{sn} = \frac{c}{2\pi K L} \sqrt{h \nu \mu \frac{T t}{2P}} \qquad (2)$$

where c is the speed of light, L the side of the square ring, h the Plank Constant, ν the frequency of the light, μ the total absorptions, T the transmittance, P the total transmitted power, t the observation time, and K is the scale factor of the instrument. In figure 1 the shot noise is shown for various values of the parameters μ, T and P.

For the continuous line $\mu = 40$ ppm, $T = 0.2$ ppm and $P = 10^{-8}$ W, for the dotted line absorption have been reduced to 4 ppm, and for the point-dotted line the transmitted power has been increased to 10^{-7} W. In short a device with L below 1 m could reach a sensitivity of 10^{-9} rad/s/$\sqrt{\text{Hz}}$, a device with $L = 1$ m could have $3 \cdot 10^{-10}$ rad/s/$\sqrt{\text{Hz}}$, but to reach 10^{-11} rad/s/$\sqrt{\text{Hz}}$ devices larger than 2 m are required. The lower limit to the size of the gyro are the laser frequency pulling and the mode locking, which have to be avoided. As a rule, for a given set of mirrors, it is always possible to build a ring large enough that the bias induced by the Earth rotation is large enough to avoid mode locking. The parameter

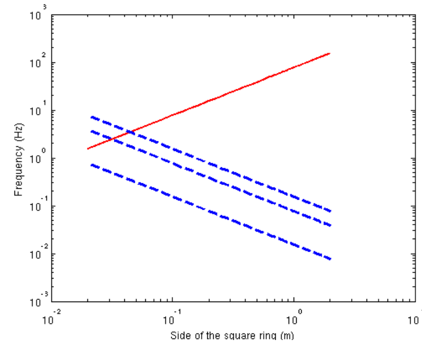

Fig. 2. Continuous (red) line shows the Sagnac frequency, the three dotted lines show the threshold frequency for three different set of mirrors (R=99.9999%, 99.9995% and 99.999%).

which sets the magnitude of the mode pulling is the locking threshold frequency l, where $l \approx c s \lambda/(p d P)$, where c is the speed of light, s is (1-R), where R is the reflectivity of the mirrors, λ is the laser wavelength, d is the beam waist and P is the ring perimeter. The above formula is rather pessimistic since it assumes that the light is backscattered uniformly and the non reflected light is all backscattered. In figure 2 the dotted lines show the mode locking limit as a function of the side of a square ring, for different sets of mirror (R 99.9999%, 99.9995% and 99.999%), the beam waist is assumed to be 1 mm. The continuous line shows the Sagnac frequency given by the Earth rotation for a device horizontally located at the latitude of Pisa (43 degrees) as a function of the ring size. In the following the sensitivity is discussed and the characterization of the device is given.

III. Experimental apparatus, sensitivity and characterization

The gyro installed in Pisa operates in a squared cavity 5.6 m in perimeter, fig. 3. The whole cavity is contained in a vacuum chamber, about $5 \cdot 10^{-3}$ m^3 in volume, which is entirely filled with a mixture of He and an 50% isotopic mixture of ^{20}Ne and ^{22}Ne. The total pressure of the gas mixture is set to 560 Pa with a partial pressure of Neon of 20 Pa. Four spherical mirrors 6 m in radius were chosen for the resonator, and two micrometric lever arm acting on the tilt of each mirror, make it possible a fine tuning of the cavity alignment. Mirrors reflectivity is optimized for the emission line around 633 nm. In the table below are summarized the main parameters of the optical apparatus.

The cavity losses and then the finesse were estimated from a direct measurement of the intracavity ring-down time, $4.8 \cdot 10^{-4}$ s. The laser pumping system consists of a capacitive radio frequency discharge obtained by coupling the gas to a couple of semi-cylindrical electrodes fitting the cylindrical glass tube located in the middle of one side of the square. This kind of discharge provides a very good passive stability and made possible to regulate the laser output power very close to the laser threshold since the first runs.

TABLE I
OPTICAL PARAMETERS

Parameter	
Free Spectral Range	53.6 MHz
Finesse	1.610^5
Horizontal beam waist	0.36 mm
Sagittal beam waist	0.29 mm
Total cavity losses per round trip	3.810^{-5}

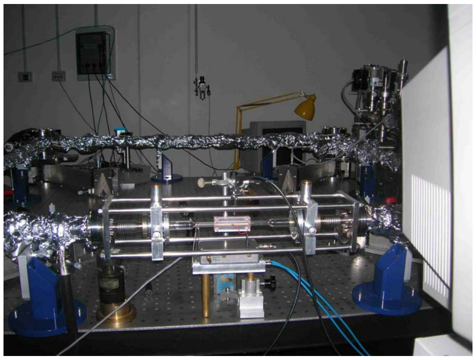

Fig. 3. The G-Pisa apparatus, the discharge is shown.

By taking into account the latitude of our laboratory and the orientation of the plane of the laser, one gets for the Sagnac frequency Ω_s an approximated estimation of 111.4 Hz. The laser has an output power not higher than few tens nW and only one longitudinal mode (TEM_00) in both sense of propagation is above the laser threshold. The beat note at the expected Sagnac frequency can be observed both in the interference between the two counter-rotating beams and in the single. The two outputs (clockwise and counter-clockwise sense of circulation) from one cavity mirror are combined by means of a 50% intensity beam splitter and detected by a photodiode. The photododiode current is voltage converted by a trans impedance stage with a gain of 10^9 and a 1 msec of rise time. The two single beam outputs are also monitored by means of two fibre-coupled photomultipliers The signal is acquired and analyzed off-line. It is important to see the low frequency sensitivity (0.001-1 Hz), which is obtained reconstructing the phase of the beat note, and differentiating it, in order to obtain the angular speed. The mean of this signal gives the Earth rotational speed, which is usually subtracted. The power spectrum of the signal obtained as said before gives the upper limit of the low frequency sensitivity, which is very important for applications for the improvement of the gravitational waves interferometer suspension, a typical spectrum is reported in fig. 4.

Several measurements have been done to learn the behavior of the ring laser in function of power and to investigate multimodal operation of the cavity. The presence of mode have been detected injecting the output beams in a high finesse linear cavity. Stable operation has been checked to be possible from a mono mode operation up to 4 modes, with an increase in output power by a factor 3. The first parameter is the contrast of the output signal, Fig. 5 shows the contrast in function of the tension given to the capacitance which excite the laser, in order to compare measurements done in different condition, the voltage has been normalized by the threshold voltage, which has been constantly monitored.

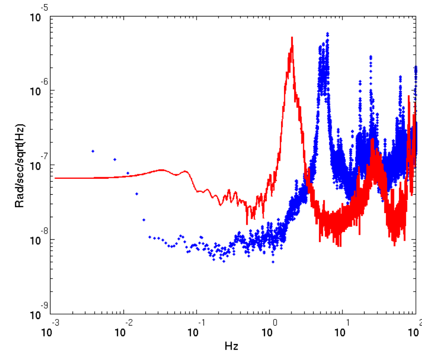

Fig. 4. Comparison among the best low frequency measurement with a typical spectrum taken.

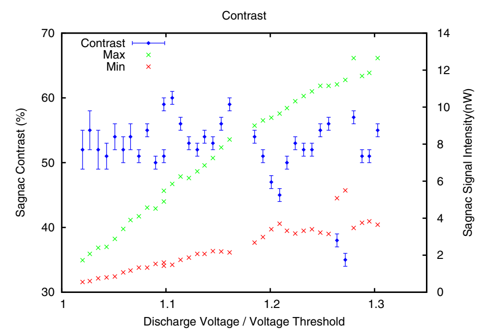

Fig. 5. Blue points, left scale: contrast in function of the normalized discharge voltage. Green and red are the Maximum and minimum intensity of the signal.

The contrast is $\approx$ 55%, and from 1 up to 1.1 normalized voltage it has been checked that the laser operate in monomode. The multimodal operation in general looks good, i.e. the different modes are locked in phase and the instrument gives a reliable Sagnc frequency, but when there are several modes quite often the operation is not stable, and sometime the output exhibits bad contrast. Fig. 6 shows the behavior of the intensity of clock wise and anti-clock wise beams, measured increasing (up) and decreasing (down) the voltage of the discharge.

It is possible to see that the two modes have different threshold and different slops. Some hysteresis is as well evident, but the measurements is not jet good enough to well show the hysteresis, this point will be investigated more deeply in the future. Hydrogen contamination is matter of concern, since when the level is too high the gyrolaser stops lasing. Fig. 7 shows the concentration of Hydrogen increasing in function of the time. This measurement refers to the vacuum tank not jet backed. After backing and adding getter pumps, this level of contamination will be highly reduced.

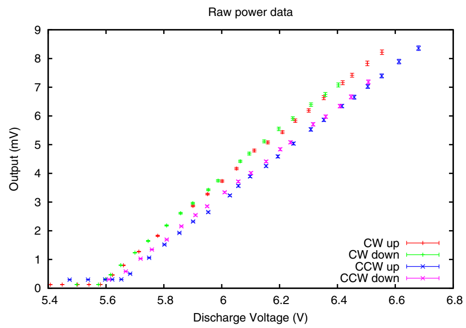

Fig. 6. Clockwise and CounterClockwise beams in function of the voltage applied to the discharge

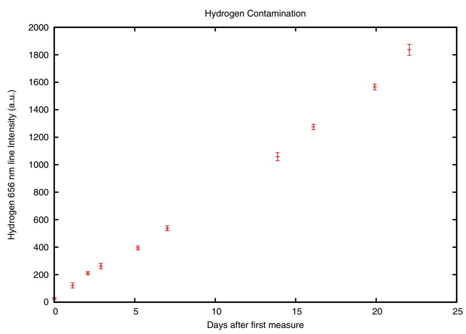

Fig. 7. Hydrogen contamination as a function of time

IV. Conclusion

The laser gyroscopes developed by the Germany-New Zealand collaboration have shown a remarkably high sensitivity demonstrating their possible employment as tilt meters in the control system of the mirror motion in large gravitational wave antennas such as VIRGO and LIGO. The existing best performer ring laser gyros are referred as“large ring laser” because their area is not less than several m^2. Such large dimensions represent a strong limitation to their employment in monitoring the tilt of meter-sized objects. The performances of a gyro-laser 0.6-0.7 m in size, mounted on the top of the bottom ring in the VIRGO super-attenuator have been considered in this paper. Assuming a quantum limited sensitivity of $3 \cdot 10^{-11}$ rad/s/$\sqrt{\text{Hz}}$ we show that G-Pisa started with the construction of a 1.4 m sized uni-axial ring laser gyro, the very first operation of which are briefly presented in this text. This system will be the experimental “training setup”, for the optimization work leading to the development of a multi-axial device to be applied to a gravitational wave antenna. The sensitivity so far obtained is in the range of 10^{-8} rad/s/$\sqrt{\text{Hz}}$ below 1 Hz, limited by the experimental set up, which is located in the campus of the Pisa Physics Departement. It has been checked that stable operation of the Sagnac is not limited to a single mode configuration of the laser, but stable operation has been observed up to 4 modes in the cavity.

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