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Solid-state ring laser gyro for aerospace applications

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***Abstract*—We report on the development of a prototype solid-state ring laser gyro based on a diode-pumped neodymium-doped yttrium aluminum garnet crystal as the gain medium. We describe in this paper how we circumvent mode competition between the counter-propagating modes using a feedback loop acting on the differential losses. We then show how the non-linear frequency response can be significantly improved by vibrating the gain medium along the laser axis, leading to a behavior similar as a typical Helium-Neon ring laser gyro. We finally discuss the undergoing improvements for achieving high inertial performance with this device, with significant potential benefits in terms of cost and robustness as compared to other high-performance gyro technologies.**

***Index Terms*—solid state, laser gyro, rotation sensing.**

I. Introduction

The ring laser gyro, first demonstrated in 1963 [1], is now used routinely in the field of inertial navigation, including satellites and launchers. It is based on Sagnac effect, which requires the coexistence of two counter-propagating modes sharing the same path in a ring laser cavity to be detected. In its most common form, it uses a mixture of Helium and Neon as the gain medium. This leads, thanks to Doppler inhomogeneous gain broadening, to a very low level of mode competition between the counter-propagating modes, hence stable bidirectional operation [2]. From the industrial point of view, it could be a great advantage in terms of lifetime, cost and reliability to use a solid-state gain medium rather than the Helium-Neon mixture, for example a diode-pumped neodymium-doped yttrium aluminum garnet crystal (Nd-YAG) which is a very robust and mature solid-state laser technology. However in this case mode competition usually hinders bidirectional emission, and the usual trick based on Doppler effect cannot be employed. One possibility to circumvent this problem, early suggested and implemented in [3], is to introduce inside the laser cavity differential losses which are kept proportional to the intensity difference between the counter-propagating modes using an electronic feedback loop. To ensure stability, the sign of the feedback loop gain is chosen such that at any time the more intense laser mode gets the higher losses.

In this paper, we will describe how we have applied this technique to demonstrate rotation sensing on a diode-pumped solid-state ring laser. We will then show how crystal vibration along the laser axis [4] can strongly reduce the nonlinearities of the frequency response curve of such a device, making it behave similarly as its Helium-Neon counterpart. Finally, we will investigate the main identified potential sources of drift, and describe the improvements currently being implemented on our prototype, with a view to reaching navigation-grade performances on this device.

II. Control of differential losses for bidirectional operation

The basic experimental setup of a solid-state ring laser gyro is sketched on Figure 1. A neodymium-doped yttrium aluminum garnet (Nd:YAG) crystal is placed inside a four-mirror ring cavity. Light from a 808-nm laser diode is focused on one end of the crystal to create population inversion. The rotation signal is detected, as usual for a ring laser gyro, through the beat note between the two counter-propagating modes.

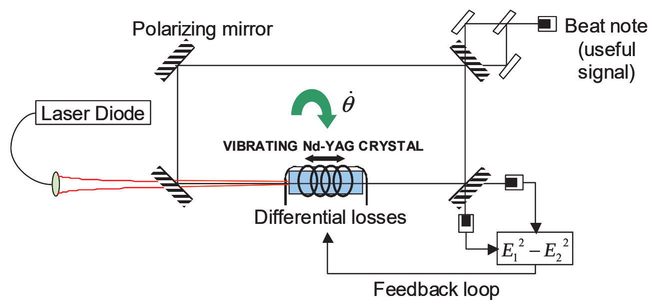

Figure 1 : Basic experimental setup of a solid-state ring laser gyro

Differential losses can be created in the laser cavity thanks to the combination of three optical functions, namely a polarization effect (induced by one cavity mirror with appropriate coating), a reciprocal rotation (induced by a slightly non-planar geometrical configuration of the ring cavity, not shown on Figure 1) and a non-reciprocal rotation (induced by Faraday effect in the gain crystal which has been placed in the center of a magnetic coil). In order to ensure stable bidirectional emission, the intensity of the two counter-propagating modes are monitored on two independent photodiodes, and the computed difference between the two measured intensity values is used as the input signal of an electronic feedback loop, which will maintain the current in the magnetic coil (hence the differential losses) proportional to the intensity difference. Of course, the feedback loop gain must have the correct sign such that the most intense mode gets the highest losses.

Thanks to this stabilizing device, we were able to achieve rotation sensing on a diode-pumped solid-state ring laser. The resulting frequency response curve is shown on Figure 2 (triangle marks). This curve is non-linear, and deviates upwards from the ideal Sagnac line, with no rotation sensitivity (scale factor equals to zero) at null rotation rate.

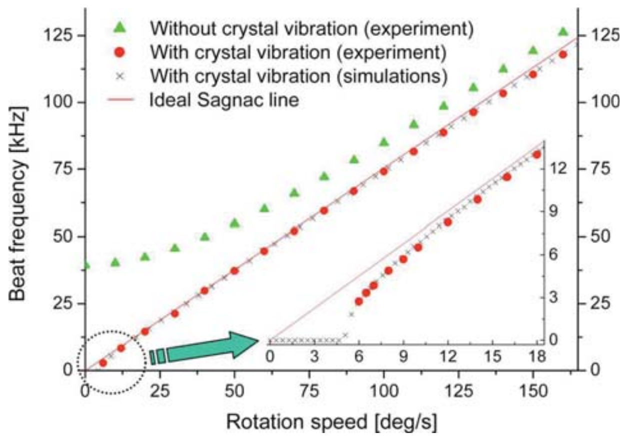

Figure 2 : Experimental frequency response curve of our prototype solid-state ring laser gyro with (circle marks) and without (triangle marks) crystal vibration. Also shown (crosses) is the result of numerical simulations in the vibrating crystal case.

III. Improvement of the linearity of the frequency response curve using crystal vibration

Two main sources of coupling between the counter-propagating modes are responsible for the important non-linearity and upwards deviation of the frequency response curve of the solid-state ring laser gyro. The first one is linear coupling due to backscattering, which is much stronger than in the Helium-Neon case because diffusion comes not only from the cavity mirrors but also from the solid-state gain medium itself. The second source of coupling comes from spatial inhomogeneity of the gain. As a matter of fact, the optical standing wave will induce more gain saturation where light is more intense (bright fringes), and less gain saturation where light is less intense (dark fringes). Light diffraction on the resulting population inversion grating will create, in return, a non-linear coupling between the two counter-propagating modes.

In order to reduce the influence of these two coupling sources, we have mounted the Nd-YAG crystal on a mechanical device creating a vibration movement along the laser longitudinal axis (see Figure 1). Such a vibration movement can benefit the solid-state ring laser gyro in two ways. First, it can wash out the population inversion grating. For this, the vibration amplitude must be such that each atom is no longer confined into a dark or a bright fringe of the optical standing wave, but rather sees on average the same optical intensity as all others. Furthermore, the vibration frequency must be fast enough for the atoms to be sensitive to the average (rather than instantaneous) optical intensity. The typical frequency above which this occurs is on the order of one over the population inversion lifetime, around 4.3 kHz for the Nd-YAG laser transition at 1064.1 nm considered here. The second positive effect of crystal vibration on the solid-state ring laser gyro is to Doppler-shift light diffused by the moving gain medium. Thanks to this effect, light from one mode backscattered on the crystal into the counter-propagating mode will be no longer resonant with the latter, resulting in a strong reduction of crystal-induced linear coupling.

The experimental frequency response curve of the solid-state ring laser gyro with crystal vibration at a frequency of about 168 kHz is shown on Figure 2 (circle marks). As can be seen, the non-linearity is strongly reduced in comparison to the non-vibrating case, and the curve has a typical downwards deviation similar to the Helium-Neon ring laser gyro case. This result can be interpreted as follows: since the two previously mentioned couplings (population inversion grating and crystal-induced diffusion) have been suppressed by crystal vibration, we are left only with the coupling resulting from mirror-induced diffusion (scattering), as it is the case of a Helium-Neon ring laser gyro. The size of the lock-in zone that can be deduced from Figure 2 is typically two orders of magnitude bigger than what can be found on a high-performance Helium-Neon ring laser gyro, which we attribute to the quality of our mirrors.

IV. Numerical simulations of the solid-state ring laser gyro with high-quality mirrors

We have shown in this section how crystal vibration could result in a frequency response curve for the solid-state ring laser gyro similar to the frequency response curve of its Helium-Neon counterpart. As it is the case for the latter, one can wonder if the lock-in zone of the solid-state ring laser gyro is determined solely by the mirror quality since all other sources of coupling are supposed to vanish. In particular, the question is whether or not a solid-state ring laser gyro equipped with mirrors of the same quality as high-performance Helium-Neon ring laser gyro will achieve, under mechanical dithering, the same level of angular random walk performance. We have checked this numerically, using semi-classical equations for the solid-state ring laser gyro with crystal vibration.

Although the solid-state ring laser gyro is very different, in terms of laser dynamics, from the Helium-Neon ring laser gyro, it can be seen on Figure 3 that when the crystal is properly vibrated they have the same dead zone size, determined only by the backscattering coefficient of the non-vibrating scattering part, i.e. the mirrors.

Moreover, we have implemented numerically a statistical study of the angular random walk for the solid-state ring laser gyro with crystal vibration under the usual dithering process that is typically used for Helium-Neon ring laser gyros (including random changes in the dithering amplitude to avoid dynamical lock-in). We have performed the same simulations for the Helium-Neon ring laser gyro with equivalent (high-quality) mirrors. The result (reported on Figure 4) shows no significant difference between the two cases.

In conclusion, we expect, considering the results of our numerical simulations, that the solid-state ring laser gyro will have the same behavior as the Helium-Neon ring laser gyro in terms of angular random walk. In both cases, the ultimate limit will be determined by the diffusion rate of the cavity mirrors. We will now consider, in what follows, the other possible factors that are expected to affect the performances of the solid-state ring laser gyro and describe the ongoing improvements implemented on our prototype to reach inertial performances.

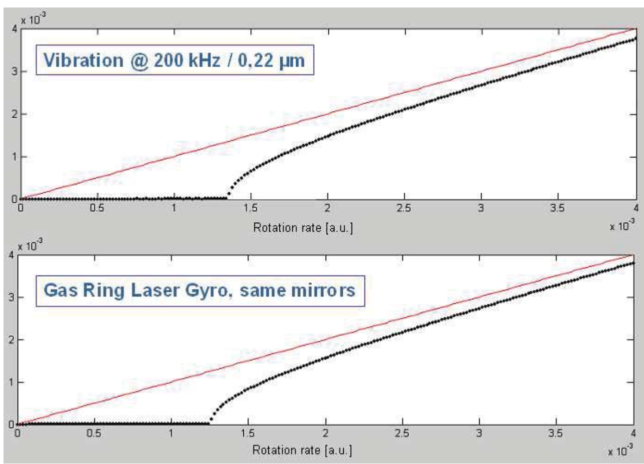

Figure 3 : Comparison of the frequency responses of the solid-state ring laser gyro with vibrating crystal (above) and of the Helium-Neon ring laser gyro (below) with identical values of the mirror-induced backscattering coefficient (numerical simulations).

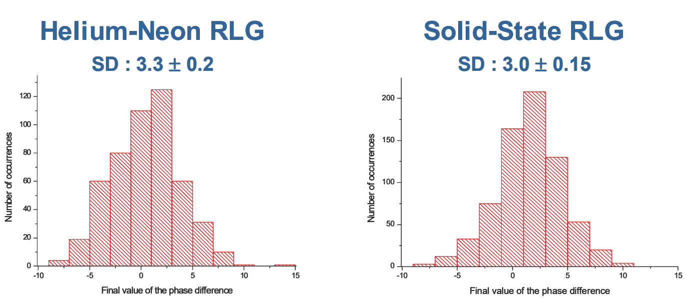

Figure 4 : Comparison of the frequency responses of the solid-state ring laser gyro with vibrating crystal (above) and of the Helium-Neon ring laser gyro (below) with identical values of the mirror-induced backscattering coefficient (numerical simulations

V. Towards a High-Performance Solid-State Ring Laser Gyro

According to the results described in the previous section, it is mandatory to have high-quality mirrors on the solid-state ring laser gyro if we want to reach the same level of angular random walk as for a high-performance Helium-Neon device. This is currently being implemented on our next generation prototype.

Another thing being implemented on our prototype is the stabilization of the overall laser intensity. As a matter of fact, if crystal vibration makes the frequency response curve much more linear at low rotation rates, it also creates a small non-linearity for higher rotation rates (all the more important than the Sagnac frequency is close to the crystal vibration frequency), the latter being dependent on the intensity. It can be shown that the intensity has to be stabilized at the 0.1% level to bring the associated residual scale factor stability below 10ppm.

Finally, we are building a numerical control of the differential losses to replace the analogical scheme described in section II. In particular, it is important to monitor precisely the current flowing inside the solenoid around the gain medium at any time, to compensate for the bias resulting from the (small but nonzero) nonreciprocal rotation of the states of polarization used for creating the differential losses. The required precision on this current measurement is on the order of 0.1%, in order to reach a bias stability at the 0.01deg/hour level.

VI. Conclusion

The experiments and simulations described in this paper show the feasibility of rotation sensing with a solid-state ring laser gyro. Moreover, we have derived some specifications that we are currently implementing on our prototype. This could lead to a new kind of high-performance ring laser gyro with all the industrial assets associated with the solid-state laser technology, including cost, lifetime, reliability and space qualification.

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