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# Solid-state ring laser gyro behaving like its Helium-Neon counterpart at low rotation rates

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Nonlinear couplings induced by crystal diffusion and spatial inhomogeneities of the gain have been suppressed over a broad range of angular velocities in a solid-state ring laser gyro, by vibrating the gain crystal at 168 kHz and 0.4 $\mu$m along the laser cavity axis. This device behaves in the same way as a typical Helium-Neon ring laser gyro, with a zone of frequency lock-in (or 'dead band') resulting from the backscattering of light on the cavity mirrors. Furthermore, it is shown that the level of angular random walk noise in the presence of mechanical dithering only depends on the quality of the cavity mirrors, as is the case with typical Helium-Neon ring laser gyros. © 2009 Optical Society of America

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The ring laser gyro (RLG), first demonstrated in 1963 [1], is now routinely used as a rotation sensor in the field of inertial navigation. It typically employs, as a gain medium, a mixture of Helium and Neon, resulting in the absence of mode competition thanks to Doppler inhomogeneous gain broadening [2]. From the industrial point of view (especially as regards lifetime, reliability, cost of components and fabrication process), one major improvement on this device could be the use of a solid-state gain medium instead of a gaseous mixture. A step has been made in this direction with the demonstration of a diode-pumped Nd:YAG RLG [3], where mode competition in the solid-state gain medium has been circumvented by the use of an electronic feedback loop controlling differential losses of the counterpropagating modes [4]. However, the resulting frequency response curve is significantly nonlinear, with a typical upward deviation from the ideal Sagnac line [3] as sketched in Fig. 1. This nonlinearity, which is mostly induced by couplings between counterpropagating modes in the Nd:YAG crystal (due to diffusion and spatial inhomogeneities of the gain), depends on the pumping rate and is much more important than what is typically observed with high-performance commercial Helium-Neon (He-Ne) RLGs (see Fig. 1). In the latter case, the main source of nonlinearity is backscattering of light on the cavity mirrors, which is pump independent and can be made very low. This major difference between the two devices is the main reason why solid-state RLGs have not found any practical high-performance application so far.

In this Letter, we will show how the frequency response of the solid-state RLG has been significantly improved by vibrating the gain medium fast enough along the laser cavity axis. To this end, we will first provide a short description of our experimental device, and derive some requirements on the amplitude and frequency of the gain medium's vibration. We will then present experimental data obtained using a high frequency device ($\simeq$168 kHz), and highlight the similarity with typical He-Ne RLGs. Finally, we will theoretically compare the performances of the solid-state and He-Ne RLGs (in terms of angular random walk), and show that equivalent results can be obtained if mirrors of equivalent quality are used.



The solid-state RLG used in our experiment is sketched in Fig 2. It is made of a 22-cm-long ring cavity containing a 3-mm-long diode-pumped Nd:YAG crystal. In keeping with the technique described in [3] for the stabilization of bidirectional emission, we use a slightly non-planar cavity, a polarizing mirror and a solenoid around the gain crystal with an electronic feedback loop controlling the current within it, in order to create differential losses proportional to the difference between the counterpropagating modes' intensities. This typically results in a stable beat signal whose frequency is monitored on a dedicated photodiode (the use of an additional photodiode, not shown in Fig. 2, furthermore allows to measure the sign of angular velocity, as is the case for commercial He-Ne RLGs). Finally, the Nd:YAG crystal is mounted on a piezoelectric vibration device, inducing a translatory movement along the axis of the laser cavity at a frequency of about 168 kHz. The overall crystal displacement can be linearly tuned between 0 and almost 0.5 $\mu$m by changing the amplitude of the sinusoidal voltage applied to the piezoelectric transducer.

The optimum value for the crystal displacement $d$ corresponds to the situation where the average intensity is the same for all the atoms of the gain medium (which is obviously not the case when the crystal remains still because the optical field has a standing wave structure). In the case of the non-rotating laser, this can be expressed as $J_0(2\pi d/\lambda) = 0$ [5], where $\lambda = 1.064$ $\mu$m is the laser wavelength in vacuum and $J_0$ is the Bessel function of the first kind and order zero. The smallest displacement for which the above condition is obeyed is $d \simeq 0.407$ $\mu$m, which is within the reach of our experimental device. As regards the choice of the vibration frequency $f$, it is driven by two distinct conditions. First, the movement has to be fast enough for the atoms to be sensitive to the average (rather than instantaneous) intensity, which reads $f \gg 1/T_1$ where $T_1 \simeq 230$ $\mu$s is the population inversion lifetime. This condition is easily fulfilled by typical mechanical vibration devices in the 0.5 $\mu$m range. Second, the phenomenon of parametric resonance which arises when Sagnac frequency equals crystal vibration frequency [6] must be avoided all over the RLG's operation range. For example, if the RLG has to be operated between -150 deg/s and +150 deg/s then, considering our typical scale factor value of $\simeq 0.754$ kHz/(deg/s), the crystal vibration frequency has to be higher than $\simeq 113$ kHz to avoid parametric resonance. Our experimental device achieves 168 kHz, resulting in more than 200 deg/s of operation range. By comparison, our previous version at $\simeq 40$ kHz, described in reference [6], was limited to $\simeq 50$ deg/s of operation range, which was not enough for many practical applications.

The experimental frequency response curve of the solid-state RLG with crystal vibration at 168 kHz and 0.407 $\mu$m is shown in Fig. 3. The effect of crystal vibration can be seen by comparison with the case (also shown in Fig. 3) of the solid-state RLG with its gain medium remaining still. Moreover, the insert of Fig. 3 shows how the frequency response curve goes downwards for low angular velocities, similarly to the case of He-Ne RLGs. The measured dead band is about 5 deg/s, which is typically two orders of magnitude above typical high-performance He-Ne RLGs. Considering Fig. 3, it could be tempting to stick to the non-vibrating case for rotation sensing with a solid-state RLG, as described in [7]. There are two major drawbacks however, making the latter technique virtually useless for all high-performance practical applications. The first one is the strong dependence of the beat frequency on the pumping rate [3]. The second one is the fact that the sensitivity vanishes at low angular velocities [7].

A more quantitative understanding of our experimental observations is brought by numerical modeling. To this end, we used the basic equations for the solid-state RLG with crystal vibration as derived in [6]. Most of the relevant parameters of the numerical model have been measured independently, following the methods described in [8]. As can be seen in Fig. 3, there is a good agreement between the resulting numerical simulations and experimental data. Interestingly, those simulations show that the size of the lock-in zone depends only on the backscattering coefficients of the cavity mirrors. In particular, it is independent of crystal diffusion and pumping rate. Physically, this is due to the conjunction of two independent effects of the crystal vibration. First, it washes out the population inversion grating by making all atoms exposed to the same average intensity as described previously. Second, it creates a Doppler shift for crystal-backscattered light, ensuring it is no longer resonant with the counterpropagating modes. As a result, all couplings due to the presence of the gain crystal in the laser cavity vanish. The only efficient coupling in this case comes from backscattering on the cavity mirrors, as is the case for the He-Ne RLG. Because of the high gain available with Nd:YAG, standard quality mirrors have been used for this experiment, which explains why the measured dead-zone (5 deg/s) is typically two orders of magnitude bigger than in the case of a commercial He-Ne RLG. However, our simulations predict that both devices will have lock-in zones of the same size if mirrors of equivalent quality are used.

It should be reminded at this point that the size of the lock-in zone in the He-Ne RLG is not a measure of the minimum measurable rotation rate, but rather a measure of the level of angular random walk noise [9]. As a matter of fact, the lock-in phenomenon is typically circumvented by the technique of mechanical dithering [10], which consists in adding a sinusoidal bias by rotating the cavity alternately in one direction and the opposite. The amplitude of this bias is furthermore changed randomly in time to avoid the phenomenon of dynamic lock-in [9]. This technique allows the measurement of any rotation rate, at the cost of an additional angular random walk noise, whose amplitude depends on the size of the lock-in zone $\Omega_L$. More precisely, assuming a sinusoidal bias of the form $\Omega_D \sin(\omega t)$ results in a phase diffusion coefficient proportional to $\Omega_L/\sqrt{\Omega_D}$ [9].



Our numerical simulations tend to show that this theory is applicable to the case of the solid-state RLG with crystal vibration, provided the frequency and amplitude of the vibration movement are set properly (as described previously). In particular, we have observed a phenomenon of dynamic lock-in similar to the one described in [9]. We have also observed that the angular random walk noise in the presence of mechanical dithering was proportional to the size of the lock-in zone. This is illustrated by the result of the numerical simulations shown in Fig. 4. Those simulations include a sinusoidal bias of the form $\Omega_D \sin(\omega t)$, with the following parameters (typical of commercial He-Ne RLGs) : $\omega/(2\pi) = 320$ Hz and $\Omega_D/(2\pi) = 140$ kHz. A random variation of a few percent on $\Omega_D$ every three mechanical cycles is furthermore implemented to avoid dynamic lock-in. We have calculated for 500 successive runs the final value of the phase difference between the counterpropagating modes after one second of operation in the absence of external rotation, and this for two distinct situations. The first case corresponds to the He-Ne RLG with mirrors of reasonably good quality, namely corresponding to a lock-in zone size of $\Omega_L/(2\pi) = 200$ Hz (or equivalently 0.27 deg/s). The second case is the Nd:YAG RLG with crystal vibration as described previously, that would be equipped with mirrors of the same quality (corresponding to the same lock-in zone size of $\Omega_L/(2\pi) = 200$ Hz). As can be seen in Fig. 4, similar standard deviations are observed for both cases, corresponding to a phase diffusion coefficient approximately equal to $\Omega_L/\sqrt{2\Omega_D}$. This is in keeping with previous theories about mechanical dithering of He-Ne RLG [9].

To conclude, we have shown experimentally that high-frequency crystal vibration could suppress all crystal-induced couplings in the solid-state RLG, making the latter behave exactly like a He-Ne RLG over a broad range of rotation rates. In particular, a typical downward deviation of the frequency response curve and a lock-in phenomenon at low rotation rates have been observed. We have additionally shown with numerical simulations that the size of the lock-in zone and the related level of angular random-walk noise were only dependent on the quality of the cavity mirrors. In other words, the solid-state RLG with crystal vibration could have the same random walk noise performance as a commercial He-Ne RLG, provided it is equipped with equivalent high-quality mirrors. This could be an important step toward the achievement of a new generation of high-performance solid-state RLG.

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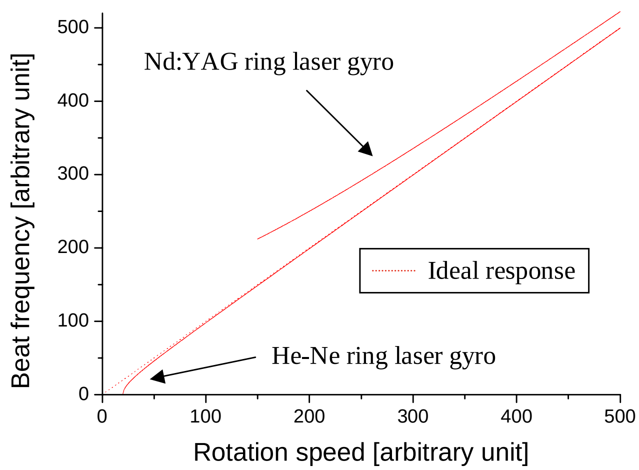


Fig. 1. Typical frequency response curves (not to scale) of a He-Ne ring laser gyroscope (as derived for example in [2]) on the one hand and of an Nd:YAG RLG (as reported for example in [3]) on the other hand.

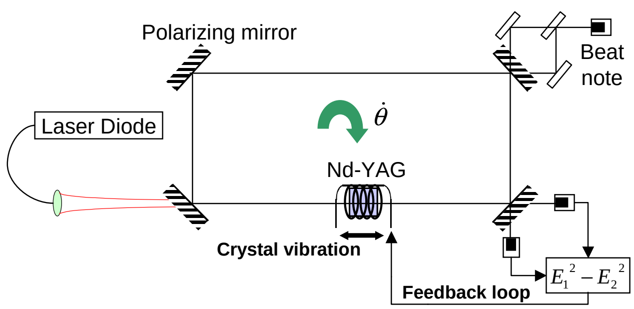


Fig. 2. Schematic drawing of our experimental setup (see text for full description).

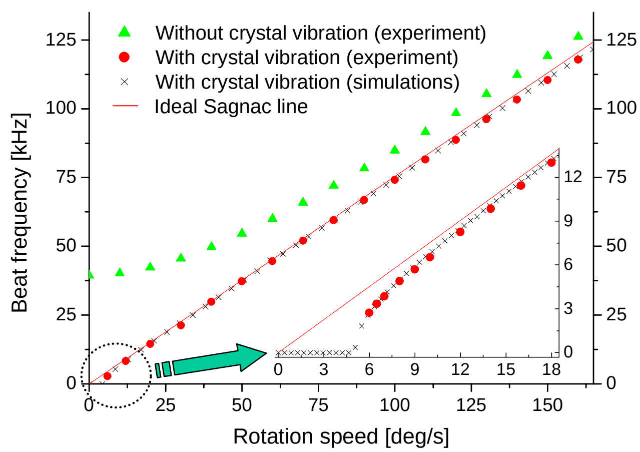


Fig. 3. Frequency response curves of the solid-state RLG with and without crystal vibration. The relaxation frequency in this case is $\simeq 17$ kHz. The insert is a magnification around lower angular velocities. Also shown is the result of numerical simulations, with experimentally measured laser parameters (see text).

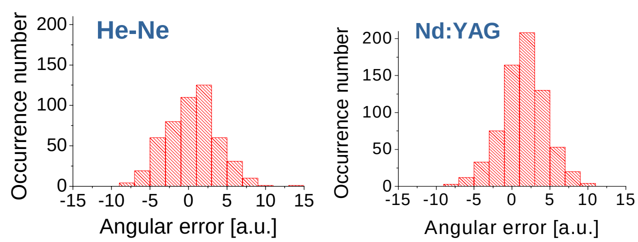


Fig. 4. Angular error after 1 second for 500 successive runs of the same numerical simulation (see text). The measured standard deviation is $3.3 \pm 0.2$ in the He-Ne case, and $3.0 \pm 0.15$ in the Nd:YAG case.