THE FIBER-OPTIC GYROSCOPE:
AN ULTIMATE-PERFORMANCE SENSOR

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ABSTRACT:

The fiber-optic gyroscope started to be investigated in the mid-70s with the advent of fiber-optic communications, taking advantage of their solid-state-component technologies: low-attenuation optical fiber, semiconductor laser-diode, integrated optics and optical amplifier. Today, it reaches ultimate theoretical performance and surpasses its well-established competitor, the ring laser gyroscope, with applications ranging from underwater robotics to satellite.

1. INTRODUCTION

Both optical gyroscopes, the ring-laser gyro (RLG) and the fiber-optic gyro (FOG), are based on the same Sagnac effect (Post, 1967), which shows that light travelling along a closed ring path in opposite directions allows one to detect rotation with respect to inertial space [Figure 1]. Over one turn, as in the original experiment, the effect is extremely weak, but it can be increased with recirculation in the resonant cavity of a ring laser or using the numerous loops of a fiber coil.

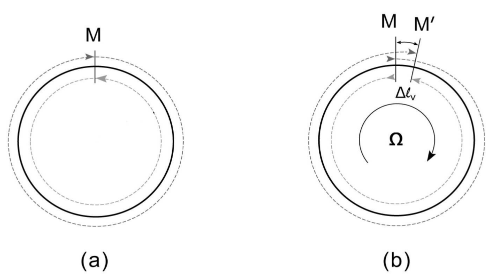

Figure 1. Principle of Sagnac effect:
(a) at rest, both opposite paths have equal length
(b) rotating at rate Ω, M moves to M' during the transit time, then the corotating path is more than one turn while the counterrotating path is less, yielding a path difference $2\Delta l_v$

The RLG was demonstrated only a few years after the invention of the laser in 1960, and it is based on helium-neon (He-Ne) technology (Aronowitz, 1999). It became very successful in the 80s and has since overcome classical spinning-wheel mechanical gyroscopes because of its improved life time and reliability. It was clear progress but gas lasers still have several drawbacks such as high-voltage discharge electrodes which tend to wear out over the long term or the need for perfect sealing of the gas enclosure.

The advent of low-attenuation optical fiber and efficient semiconductor light source in the 70s opened the way for a fully solid-state device. Then, however, the FOG was seen as an approach limited to medium performance, but unable to compete with the RLG for top-grade applications. As we shall see, this is not the case today, with the FOG now surpassing its well-established competitor.

2. WHAT ARE WE LOOKING FOR? RECIPROCITY IS KEY!

Gyroscopes are used with accelerometers in so-called inertial measurement units (IMUs). A gyroscope triad is needed to measure the three components of rotation rate vector $\vec{\Omega}$ with respect to inertial space, as well as three accelerometers. Note that accelerometers do not measure only acceleration vector $\vec{a}$, but its difference with gravity vector $\vec{g}$.

With medium performance sensors (1 to 10°/h gyros), one measures attitude, i.e. the vertical which is the direction of $\vec{g}$. With higher performance (0.1 to 0.01°/h gyros) it becomes possible to measure accurately the direction of Earth rotation rate vector (its module being 15°/h), and then the direction of true geographical North, with the technique of gyrocompassing. Finally with top performance (0.01°/h and below) inertial navigation techniques allow one to get the trajectory without any external reference.

Despite their difference of principle, RLGs and FOGs have similar theoretical noise for the same single-turn enclosed area and the same number of recirculations. Typical RLG perimeter is 20 to 30 cm with on the order of 10^4 recirculations in the cavity. A FOG coil of 10^4 loops of 10 cm diameter (i.e. 3 km long) has the same potential.

Today RLGs are in the 0.01 to 0.001°/h range while highest-performance FOGs are better than 0.001°/h. Translated in path length difference induced by the Sagnac effect, it means a relative change on the order of 10^{-18} or below! This incredible number may look unrealistic, but there is the fundamental principle of reciprocity of light propagation which acts as a perfect common-mode rejection between both counter-propagating waves. Because of reciprocity the transit time of both counterpropagating waves can be perfectly balanced leaving only the Sagnac effect. The quality of the residual bias instability (zero instability) depends on the residual lack of reciprocity.

RLGs have naturally a "quasi-reciprocity" because the propagation takes place in a low-density gaseous plasma which does not have any birefringence in particular, but its reciprocity is not perfect. The electrical discharge creates an ionic flow, and because of the Fresnel-Fizeau drag effect, this matter flow yields a velocity difference between counterpropagating waves (Aronowitz, 1999). This creates a spurious effect equivalent to about 1°/h. It is counter-balanced by using a common cathode and two symmetrical electrodes [Figure 2], but this balancing cannot be perfect and there is a residual bias instability on the order of several thousandths of degree per hour.

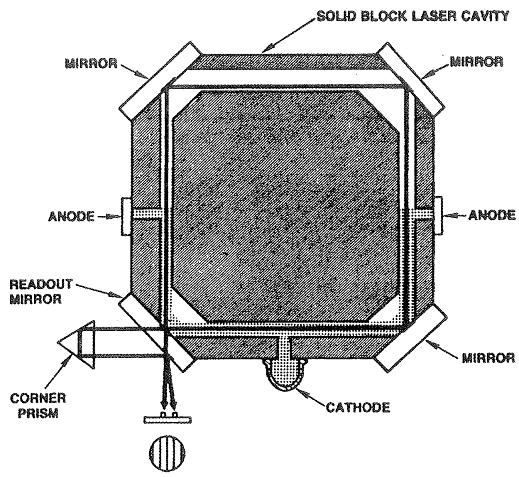

Figure 2. Configuration of an RLG, after [2]
(note one cathode and two symmetrical anodes)

In the case of FOG, reciprocity was much more difficult to get, mainly because of the residual birefringence of the fiber but, today, the problem is eliminated with the progress of components. Proton-exchanged lithium niobate ($LiNbO_3$) waveguide provides excellent polarization rejection that eliminates these birefringence–induced non-reciprocities, and one also takes advantage of polarization-preserving fibers and unpolarized ASE (amplified spontaneous emission) broadband source based on telecom diode-pumped EDFA (erbium-doped fiber amplifier) technology (Lefèvre, 1993).

Now, light travelling in a dense medium and with high-power density because of the guidance, one could have faced nonlinear effect destroying reciprocity which is based on the linearity of propagation equation, but "magically" the power fluctuation statistics of broadband source happens to balance this effect perfectly (Lefèvre, 1993). Today, the FOG appears as a unique sensor just limited by its theoretical photon noise without sources of long term drift.

However, gyroscopes have to operate over a large dynamical range, and this requires signal processing techniques that will not degrade this intrinsic stability.

3. THE OTHER KEY ISSUE: SIGNAL PROCESSING TECHNIQUES

Among the advantages of RLG is its very simple read-out mechanism. As in any laser, there is an integral number of wavelengths along the cavity path. Path length difference created by the Sagnac effect induces a wavelength difference between both counterpropagating resonant beams, and therefore a frequency difference. Output beams are recombined to interfere [Figure 2] and yield a frequency beating that is proportional to the rotation rate. A simple counting electronics provides a linear read-out of the rate over a very large dynamical range.

Note however, that at low rate there is the so-called lock-in effect. Both laser beams have very close frequencies: 1 Hz difference for 1°/h, when light frequency is 500 THz at HeNe operating wavelength of 633 nm. Despite impressive technological progress, there is still residual mirror backscattering yields coupling that locks them on the same frequency. This is eliminated by a mechanical dithering but it increases the measurement noise by an order of magnitude (Aronowitz, 1999).

The FOG is not an active resonator anymore but a passive interferometer with an external light source. There is no lock-in, so no need for dithering which avoids its related noise degradation. However the raw response is a non-linear raised cosine. This has been overcome by a very efficient phase modulation technique associated to a phase feedback [3]. This so-called digital phase ramp combines square-wave biasing modulation and synchronized phase steps generated and demodulated digitally [Figure 3].

This sophisticated processing approach is conceptually much more complicated that the simple frequency readout of an RLG, but it can be easily implemented with present digital electronics. It does not yield any degradation of the basic noise nor the reciprocity of the interferometer, and works without quantification noise despite a limited number of bits because of averaging effects.

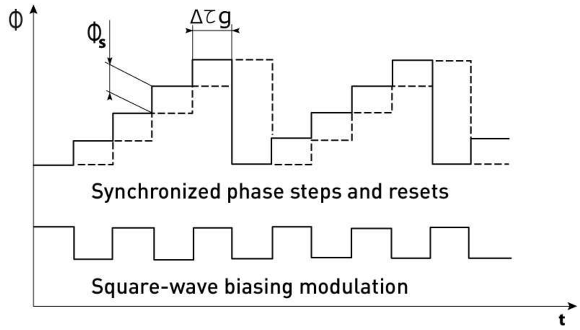

Figure 3. Principle of digital phase ramp feedback, with Δt_g being the transit time through the coil (5 µs/km)

Bias noise and drift are calculated with Allan variance (IEEE Std 952, 1997), and a high-performance FOG yields the theoretical -1/2 power reduction slope of a white noise over days of measurement without any visible bias drift limitation.

4. CONFIGURATION OF A FOG

Based on optical telecom solid-state technologies the FOG yields in addition a very long life time. It is composed of [Figure 4]:

- A broadband source based, for high grade, on EDFA technology at a wavelength of 1550 nm.
- A polarization-preserving fiber coil (a few hundred meters for medium grade and a few kilometers for high grade).
- $LiNbO_3$ integrated-optic circuit with electrodes to generate phase modulation and that provides excellent polarisation selectivity with proton-exchanged waveguide.
- A fiber coupler to send to a detector light returning from the common input-output port of the interferometer.
- A digital logic electronics that generates the phase modulation and the phase feed-back through a digital-analog (D/A) convertor.
- An analog-digital (A/D) convertor to sample the detector signal.

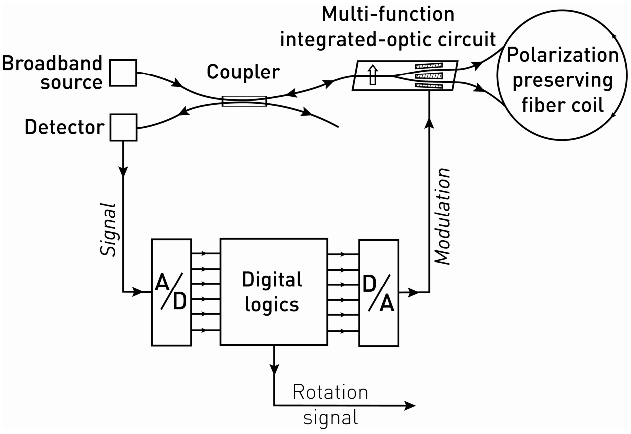

Figure 4. Configuration of a FOG with a Y junction as the splitter and recombiner of the interferometer, a polarizer and a pair of electro-optic phase modulators on the multi-function $LiNbO_3$ integrated-optic circuit.

Testament to the quality, accuracy and reliability of the fiber-optic gyro is its growing use for positioning and navigation instruments in space applications. Examples in the last few years include the French space agency, CNES, which opted to use the technology on board its *Pleiades* Earth observation satellite; the EADS company Astrium has adopted the technology in its latest generation of Earth-observation satellites; and the European Space Agency has chosen fiber-optic gyroscopes for the *Planck* space observatory.

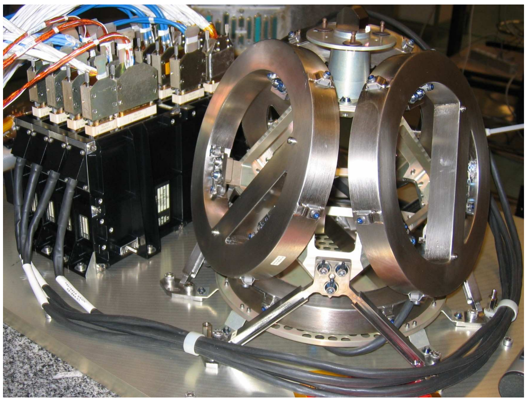

Figure 5. 4-axis FOG developed by iXSea and iXSpace (iXBlue companies) in cooperation with EADS-Astrium

5. CONCLUSION

Entering production in the 80s, the RLG has revolutionized inertial techniques, and it is clearly the technology of reference today. However its limited lifetime and its need for dithering have motivated the development of FOG technology based on a fully solid-state approach.

Theoretical performance is similar for both technologies, but it has been more difficult for FOG to obtain it. It started as a product in the 90s (OFS 18, 2006) for medium grade applications. However, with the development of fiber-optic communications components and digital signal processing techniques, it was shown that the FOG not only brings the expected improvement of lifetime, but does not face the performance limitation of the RLG in terms of noise and bias stability.

Today there is a clear change of mind, and the FOG is not seen anymore as limited to medium grade, but on the contrary as the ultimate performance gyro that can surpass by at least one order of magnitude RLG technology.

6. REFERENCES

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