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Invited Paper

The fiber-optic gyroscope: Challenges to become the ultimate rotation-sensing technology

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ABSTRACT

Taking advantage of the development of optical-fiber communication technologies, the fiber-optic gyroscope started to be investigated in the mid 1970s, opening the way for a fully solid-state rotation sensor. It was firstly seen as dedicated to medium-grade applications, but today, it reaches strategic-grade performance and surpasses its well-established competitor, the ring-laser gyroscope, in terms of bias noise and long-term stability. Further progresses remain possible, the challenge being the ultimate inertial navigation performance of one nautical mile per month corresponding to a long-term bias stability of 10^{-5}°/h.

1. Introduction

Both optical gyroscopes, the ring-laser gyro (RLG) and the fiber-optic gyro (FOG), are based on the same Sagnac effect [1,2], which shows that light traveling along a closed ring path in opposite directions allows one to detect rotation with respect to inertial space (Fig. 1). Over one turn as in the original experiment 100 years ago [3], 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. 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. It became very successful in the 1980s and has since overcome classical spinning-wheel mechanical gyroscopes because of its improved life time and reliability. It also provided excellent scale factor, making strap-down navigation systems possible. It was clear progress over mechanical gyroscopes 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 1970s opened the way for a fully solid-state device. Then, however, the FOG was seen as an approach dedicated to medium performance, and unable to compete with the RLG for top-grade applications. As we shall see, this is not the case anymore.

2. What are we looking for? Single-mode reciprocity is key

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 [4]. Typical RLG perimeter is 20–30 cm with on the order of 10^4 recirculations in the high-Q mirror cavity (Fig. 2). A FOG coil of 10^4 loops of 10 cm diameter (i.e. 3 km long and typically 3 dB of attenuation) has the same potential. Today, RLGs are in the so-called navigation-grade performance range, i.e. below 10^{-2} °/h in term of long-term bias stability, while highest-performance FOGs are in the strategic-grade performance range, i.e. at least ten times better, below 10^{-3} °/h. Translated in path length difference induced by the Sagnac effect, it means a relative change on the order of 10^{-18} for RLG, and 10^{-19} to 10^{-20} for FOG! These incredible numbers 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-rotating waves, when there is single-mode propagation. Because of single-mode reciprocity the transit time of both counterpropagating waves, can be perfectly balanced leaving out only the Sagnac effect. The quality of the residual bias instability (zero instability) depends on the residual lack of reciprocity.

A detailed analysis of the principle of RLG can be found in Ref. [5] by Aronowitz, one of the pioneers of this technology. The RLG has naturally "quasi-reciprocity" because it operates in a single transverse laser mode as well as a single longitudinal mode and 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 [5]. It is only on the order of 10^{-15} in terms of relative velocity value but it creates a spurious non-reciprocal effect equivalent to about 1°/h. It is counter-balanced by using a common cathode and two symmetrical anodes (Fig. 3), but this balancing cannot be perfect and there is a residual bias instability on the order of few thousandths of degree per hour.

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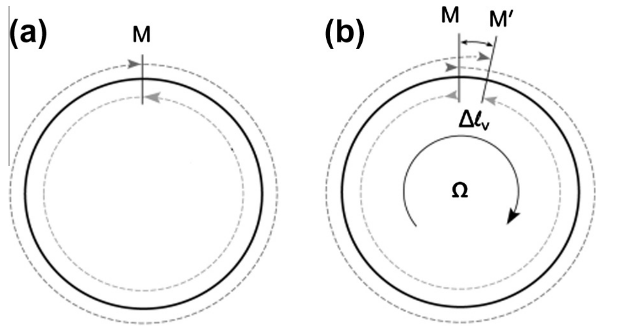

Fig. 1. Principle of Sagnac effect: (a) at rest, both opposite paths have equal length and (b) rotating at rate Ω, M moves to M′ during the transit time, then the corotating path is more than one turn while the counterrotating path is less, yielding a path difference $2\Delta l_v$.

One could think why does one not use a solid-state laser to avoid this drag effect? After all, since the early sixties when the He–Ne laser gyro was invented, numerous kinds of laser have been developed, but there is a key problem in laser behavior: mode competition! In principle, a CW ring laser should not work because both directions have the same lasing conditions and they "compete", i.e. it is unstable. He–Ne ring lasers work because of a very subtle effect: with the flow, the moving amplifying ions see different frequencies for both opposite directions because of Doppler effect, and the use of Ne^{20} and Ne^{22} isotopes with gain curves shifted in frequency, allows one to get two "superimposed" lasers: one isotope amplifying one direction and the other one the opposite one, which avoids mode competition. "Magic"… but within the limit of the Fresnel–Fizeau drag-induced non-reciprocity!

In the case of FOG, reciprocity was much more difficult to get, mainly because of the residual birefringence of the fiber. As it is well known a single-mode fiber has actually two orthogonal polarization modes which propagate with slightly different velocities because of fiber birefringence. One understands that if one direction uses one mode and the opposite one uses the crossed mode, there is a non-reciprocal phase difference. It was shown very early [6] that reciprocity does not require true single-mode propagation along the entire interferometer and that a single-spatial mode/single-polarization mode filter at the common input–output of the ring interferometer is sufficient. However, the requirement on

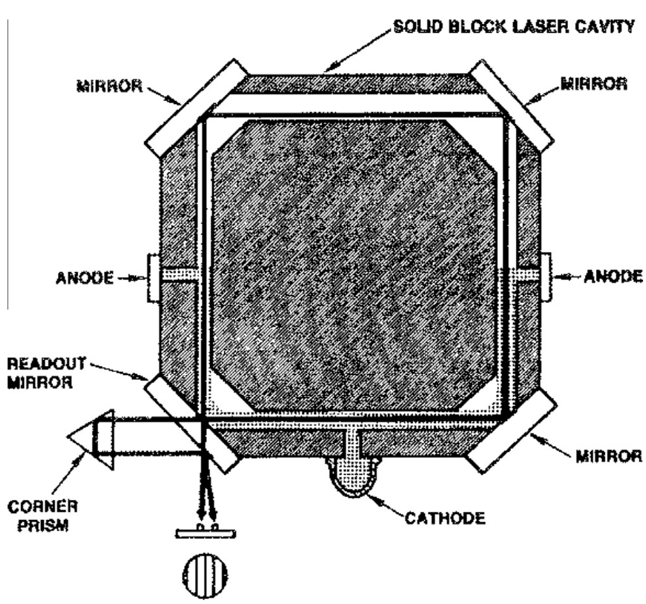

Fig. 2. Configuration of an RLG, after Ref. [5].

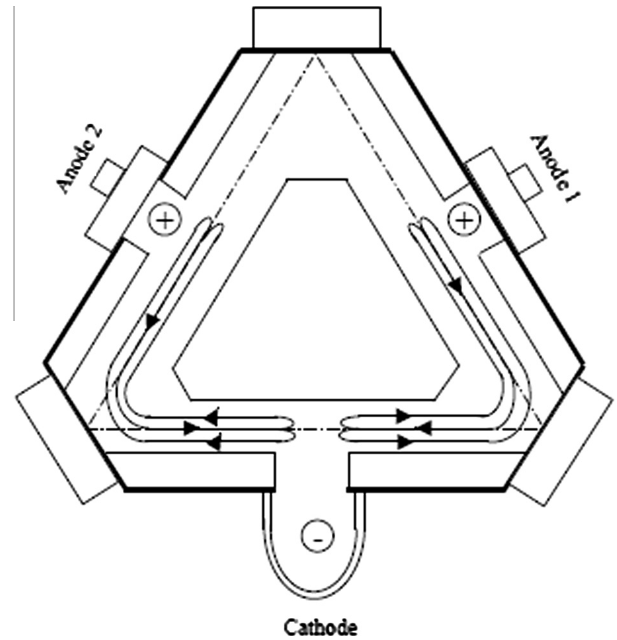

Fig. 3. Symmetrical discharge to balance. Fresnel–Fizeau drag effect due to the ionic flow in this electrical discharge

polarizer rejection to fully suppress the problem can be very stringent. Because of coherence effects, the residual phase non-reciprocity in radian may be equal to the amplitude rejection of the polarizer [7], i.e. a very good rejection of −80 dB may yield a phase non-reciprocity as high as 10^{-4} radian but, today, the problem is solved with the progress of components and the use of decoherence [8]. Proton-exchanged lithium niobate ($LiNbO_3$) integrated-optics yields single-polarization waveguide that provides excellent polarization rejection (as good as −80/−90 dB) and polarization-maintaining (PM) fiber, also called polarization-preserving fiber, limits the amount of light in the crossed polarization mode, but it would not be sufficient by far. One has also to take advantage of decoherence/depolarization effects with the use of a broadband source which has a short coherence time. Because of the birefringence of PM fiber and $LiNbO_3$ crystal, the spurious crossed polarization propagates at a different speed from the main signal and loses its coherence with respect to this main signal, which drastically reduces the parasitic effect. To further reduce defects, one can also take advantage of the natural unpolarization of ASE (Amplified Spontaneous Emission) sources based on telecom diode-pumped EDFA (erbium-doped fiber amplifier) technology. The crossed component of the input unpolarized light (the component orthogonal to the polarizer axis) compensates for the residual non-reciprocity of the main component [8]. Because of the residual polarization dependent loss of the components, the actual input unpolarization is not perfect but in practice the degree of polarization of the input ASE light is only few percents and this brings an additional 30-fold reduction of polarization non-reciprocities.

Now, light traveling in a dense medium and with high-power density because of the guidance, one could have faced non-linear effect destroying reciprocity [9] which is based on the linearity of propagation equation, but the power fluctuation statistics of broadband source happens to balance this effect perfectly [8]. Today, the FOG appears as a unique sensor that could be just limited by its theoretical white photon shot noise without any source of long-term drift.

Note that the use of a low-temporal-coherence source, brings excess relative intensity noise (excess RIN) because of the random intensity beating of all its spectral components. With an erbium