C. R. Physique 15 (2014) 841–850

Contents lists available at ScienceDirect

Comptes Rendus Physique

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The Sagnac effect: 100 years later / L'effet Sagnac : 100 ans après

Towards a solid-state ring laser gyroscope

Vers un gyrolaser à état solide

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ARTICLE INFO

Article history:
Available online 30 October 2014

Keywords:
Ring laser gyroscope
Solid-state laser
Sagnac effect

ABSTRACT

In this paper, we report our recent progress towards a solid-state ring laser gyroscope (RLG), where mode competition is circumvented by active control of differential losses, and nonlinear effects are mitigated by longitudinal vibration of the gain medium. The resulting dynamics is significantly different from that of a classical helium–neon RLG, owing in particular to parametric resonances that occur when the Sagnac frequency is an integer multiple of the crystal vibration frequency. We describe the main experimental and theoretical results obtained so far, and the prospects of practical applications in the near future.

RÉSUMÉ

Nous décrivons dans cet article nos récents progrès vers la réalisation d'un gyrolaser à état solide. Dans ce dispositif, le problème de la compétition entre modes est résolu par un contrôle actif des pertes différentielles, et les effets non linéaires sont fortement atténués par la mise en vibration du milieu à gain. La dynamique d'un tel système est significativement différente de celle d'un gyrolaser à hélium–néon classique, en particulier à cause des résonances paramétriques qui surviennent lorsque la fréquence Sagnac est un multiple entier de la fréquence de vibration du cristal. Nous décrivons les principaux résultats expérimentaux et théoriques obtenus jusqu'ici et discutons les perspectives d'applications pratiques à court et moyen termes.

1. Introduction

A century after Sagnac pioneering experiments [1,2] and more than fifty years after the first demonstration of a ring laser gyroscope by Macek and Davis [3], optical rotation sensing is still a remarkably active field of research. It includes integrated

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http://dx.doi.org/10.1016/j.crhy.2014.10.008
1631-0705/Published by Elsevier Masson SAS on behalf of Académie des sciences.

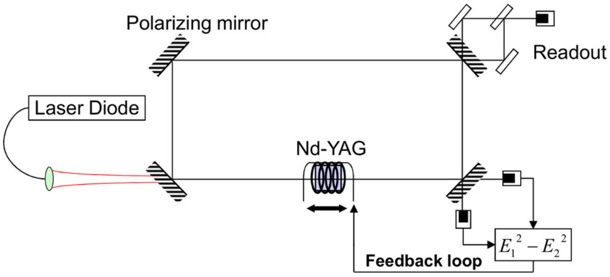

Fig. 1. Basic principle of the solid-state ring laser gyroscope. The double arrow relates to the vibration of the Nd–YAG crystal, which will be discussed in Sections 3 and 4. (Color online.)

optics [4–6], slow and fast light [7–14], hollow core fibers [15–17] and large instruments for fundamental science [18–21]. From an industry perspective, two solutions have emerged and are routinely used for guidance, navigation and control: the ring laser gyroscope (RLG) [22] and the interferometric fiber-optic gyroscope (IFOG) [23]. Although the two devices can be shown to be equivalent in theory (in the sense that they have the same shot-noise limit for equal size and optical power, under the additional hypothesis that the number of fiber turns in the IFOG is equal to the finesse of the cavity in the RLG [24,14]), they differ by their practical implementation: the IFOG is shot-noise limited, but more sensitive to external perturbations (especially time-dependent temperature gradients [25]), while the RLG is more robust to its environment, but has an additional source of noise resulting from mechanical dither (which is the best known solution so far to circumvent the lock-in phenomenon [26,27]).

A key requirement common to all kinds of optical gyroscopes is reciprocity, which means that the two counter-propagating beams must share the same optical path, in order to make the variations of the latter common-mode. For the RLG, which is an active device, this implies that the two counter-propagating modes must also share the same gain medium, and are thus subject to mode competition, which tends to hinder bidirectional emission. This problem is classically solved by using a gaseous gain medium for the RLG, typically a helium–neon mixture. The trick is to tune the cavity out of resonance with the atoms at rest, such that the two counter-propagating modes are resonant, owing to the Doppler effect, with two different classes of atoms (corresponding to opposite classes of velocity), ensuring stable bidirectional emission. From a practical point of view, it would be a strong asset to be able to replace the gaseous mixture with a solid-state component, taking advantage of the recent progress in cost reduction, lifetime and reliability driven by markets much bigger than inertial sensing. In this case, however, the Doppler trick cannot be used anymore, and one has to implement new techniques to circumvent mode competition and nonlinear couplings.

In this manuscript, we report our recent progress towards the achievement of a diode-pumped neodymium-doped yttrium aluminium garnet (Nd–YAG) RLG. We will first describe the technique of active control of the differential losses that we have implemented on this device, enabling bidirectional emission and rotation sensing. We will then discuss the nonlinearity of the resulting frequency response curve, which is mostly due to the existence of a population inversion grating in the amplifying medium. Based on theoretical predictions from a semiclassical model and on experimental results, we will show how the grating can be washed out by vibrating the gain crystal along the laser axis, significantly improving the linearity of the frequency response. We will also describe the residual nonlinearities, due for the most part to a parametric resonance between the Sagnac frequency and the crystal vibration frequency. Finally, we will discuss the expected performance of this novel rotation sensor, and prospects for future applications.

2. Circumventing mode competition in the solid-state ring laser

Our basic setup is sketched in Fig. 1. It is made of a four-mirror ring cavity, containing a diode-pumped Nd–YAG crystal as the gain medium. The readout system combines the beams emitted from the two counter-propagating modes to form a beat signal on a photodiode.

The issue of mode competition is addressed by an active control of the differential losses between the counter-propagating modes [28–30]. The basic idea is to measure independently the intensity of the two beams, and to make the differential losses proportional to the intensity difference using a feedback loop, with the appropriate sign such that the more intense mode gets the higher losses at any time. In practice, the differential losses are created by polarization effects, based on the combination of a nonreciprocal rotation (obtained by Faraday effect in the YAG crystal placed inside a solenoid), a reciprocal rotation (obtained by a slight non-planarity of the cavity) and a polarizing effect (obtained by an appropriate coating on one of the mirrors). The amount of differential losses is proportional (in the limit of small rotations) to the current flowing in the solenoid, which is controlled by the feedback loop as described above.

The experimental frequency response curve of the solid-state ring laser with active stabilization of the differential losses is shown in Fig. 2. Below a critical rotation rate on the order of 10 deg/s, nonlinear couplings in the gain medium dominate and no stable signal is observed. Above this critical rotation rate, the feedback loop becomes efficient and a stable beat signal is obtained. As can be seen in Fig. 2, the frequency response curve of the solid-state RLG is nonlinear, with an upwards deviation from the ideal Sagnac line. The main reason for this nonlinearity is the presence of a population inversion grating