Optics Communications 407 (2018) 208–216

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

The effect of broadened linewidth induced by dispersion on the performance of resonant optical gyroscope

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ARTICLE INFO

Keywords:
Dispersion
Gyroscopes
Optical resonators
Sagnac effect

ABSTRACT

Anomalous dispersion enhancement physical mechanism for Sagnac effect is described by special relativity derivation, and three kinds of definitions of minimum detectable angular rate of resonance optical gyroscope (ROG) are compared and the relations among them are investigated. The effect of linewidth broadening induced by anomalous dispersion on the sensitivity of ROG is discussed in this paper. Material dispersion-broadened resonance linewidth deteriorates the performance of a passive ROG and dispersion enhancement effect, while the sensitivity of a structural dispersion ROG is enhanced by two orders of magnitude even considering the dispersion-broadened resonance linewidth.

1. Introduction

Optical inertial rotation sensors based on Sagnac effect [1], without moving parts in the design, have almost replaced mechanical gyroscopes for aerospace guidance and navigation applications. Physically, the optical path difference between two counter-propagating beams will induce a frequency or phase shift, which is proportional to the mechanical rotation that changes the optical path traveled by light propagating clockwise (CW) and counterclockwise (CCW) with respect to rotation axis, due to the Sagnac effect. Ring laser gyro (RLG) and interferometric fiber optic gyro (IFOG) are the two most widely used devices for both civilian and military applications. In past years, the replacement of the He–Ne gain medium with a solid-state one in the RLG and the use of air-core photonic bandgap fibers in the IFOG were proposed to enhance the performance of these devices [2,3]. More importantly, in order to make rotation sensors more sensitive, it is necessary to obtain more frequency shift or phase shift with an angular velocity rate. Although extending loop area of a gyroscope is a direct and effective way, the physical size and weight of an optical gyroscope are limited on the applications, such as orbital launch vehicles or spacecraft. Any reduction in size or weight is essential to the capabilities and cost of such systems. Moreover, civilian applications like vehicles and smart phones require gyros with compact size, low power consumption and cost, thus new propagating medium, such as silicon based waveguide instead of fiber, needs to be considered for integrated devices [4,5]. Integrated optoelectronics for angular rate sensing may solve some open issues in gyro technology [2,6–17].

In order to make a miniaturized optical gyroscope more sensitive to rotation angular rate, various coupled-cavity structures such as coupled resonator optical waveguides (CROWs) and side-coupled integrated spaced sequence of resonators (SCISSOR) were proposed and normal dispersion accompanying slow light effect in those structures has to be considered [15–22]. Physically, slow light is a resultant property of the highly dispersive structure and has no direct link with the enhancement of gyro's sensitivity [16]. Optical propagation loss ultimately limits the achievable sensitivity in CROW structures. The reported lowest propagation loss of silica-based planar waveguide is less than 0.1 dB/m [23], which is still three orders of magnitude higher than that in fiber at the wavelength of 1550 nm. Thus, the performance of chip-sized resonant gyroscope is not as good as a RLG or IFOG with an equal loop area due to both compact size and high propagation loss [24,25]. Digonnet et al. compared the sensitivity of a resonant optic gyro (ROG) with CROW gyros and showed that even after optimizing the CROW gyro structural

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http://dx.doi.org/10.1016/j.optcom.2017.09.044
Received 27 April 2017; Received in revised form 10 September 2017; Accepted 11 September 2017
0030-4018/

parameters, the CROW gyros had the same sensitivity as a ROG under the equal loop loss and footprint [26–29] conditions.

In addition, a resonator-based optical gyroscope's sensitivity can be enhanced by using anomalous dispersion accompanied with the characteristic of superluminal light propagation. The experimental schemes of achieving anomalous dispersion, including using the alkali metal vapors and optical coupled resonators, have been studied by [30–50]. Experimental investigation of controllable anomalous dispersion was presented by using bi-frequency Raman lights in a rubidium (Rb) vapor as the anomalous dispersion medium [34–36]. Two pump beams with slightly different frequencies are used to generate closely spaced gain doublet in which the anomalous dispersion lies in between the two gain peaks. However, the intensity of probe light in gain doublet method is weak and it is not appropriate for using high power signal light in the rotation sensing application. A simpler method using gain depletion would allow a high power beam to experience anomalous dispersion. The lasing frequency will experience anomalous dispersion if a narrow dip in the middle of the unsaturated gain profile is introduced [37–40]. However, whether bi-frequency Raman gain or gain depletion in a Rb vapor, it is a rather complex experimental system and is not appropriate for reduction of gyro's size and weight.

Optical coupled microresonators with a miniaturized area can provide anomalous dispersion only using passive elements, while avoiding the complexities of tailoring the dispersion in stimulated transitions of alkali metals. An fast-light enhanced on-chip structure of RLG was proposed in [49,50], in which the physical effect responsible for the increased rotational sensitivity is the anomalous dispersion achieved by passive coupled resonators.

Anomalous dispersion properties in an atomic vapor or optical coupled resonators enable enhancement the sensitivity of resonant gyros, but it should not neglect the issue that broadened linewidth of resonance spectrum induced by anomalous dispersion medium in a resonator deteriorates the performance of gyros and may counteract the enhancement sensitivity due to mode broadening. Hence, the influence of linewidth broadening induced by anomalous dispersion on the sensitivity of resonant gyros is discussed in this paper. The rest of this paper is organized as follows. In Section 2, the anomalous dispersion enhancement physical mechanism for Sagnac effect is described by special relativity derivation. In Section 3, three kinds of definitions of minimum detectable angular rate of ROG are compared and the relations among them are investigated. In Section 4, two typical methods to generate dispersion, material dispersion (MD) and structural dispersion (SD), are showed. In Section 5, the influence of dispersion-broadened resonance linewidth on minimum detectable angular rate of passive ROG is discussed.

2. Physical mechanisms for dispersion enhanced Sagnac effect

The principle of optical gyroscope is based on Sagnac effect, and the equivalence between interferometric and passive ROG is clarified by Schwartz [51]. The two gyros have the same shot-noise limit for the equal dimensions and number of photons if the number of fiber turns in interferometric gyro is equal to the finesse of the cavity of resonant gyro, which is the average number of turns made by light during the decay time. Thus, we firstly deduce the Sagnac effect in a passive resonator containing a dispersion cell and assume that the resonator is filled with linear dispersive medium around the center frequency υ_0.

The elementary derivation of for the enhanced Sagnac effect by anomalous dispersion medium in the nonrelativistic case is described by Eliseev [52]. As shown in Fig. 1, two counter-propagating traveling waves, satisfied the resonance condition (the length of the cavity be an integer multiple of the wavelength), propagate in the ring resonator and the resonant order m is

$$m = \upsilon_0 \frac{n_0 L}{c} = \upsilon_0 T_0 = \upsilon^+ T^+ = \upsilon^- T^- \tag{1}$$

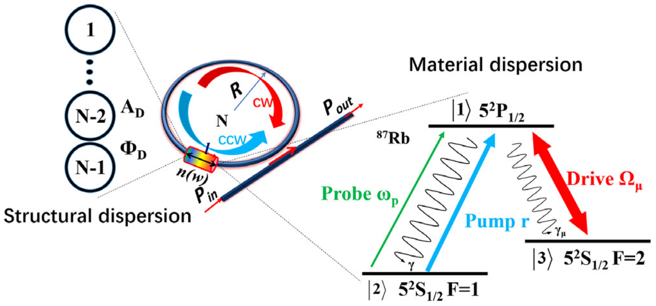

Fig. 1. Schematic diagram showing Sagnac effect in a ring resonator inserting a dispersion cell (optical resonators or Rb vapors).

where υ_0 and T_0 are the degenerate resonant frequency of the counterpropagating waves and the one round-trip transit time in an ideal non-rotation ring cavity, respectively. Here, n_0 is the refractive index at the center frequency υ_0, L is the perimeter length of the ring cavity, c is the speed of light in vacuum. The superscripts (±) denote the two directions, clockwise CW (+) and counter-clockwise CCW (−). Note that the resonant order m is unchanged in both directions whether the ring cavity is rotating or not. Two counterpropagating modes are expected to exhibit the same resonant frequency attributed to identical optical path, due to non-rotation angular velocity in the resonator. As long as the system rotates at an angular frequency, nonreciprocity of the counterpropagating waves results in an optical path or phase difference between them and as a consequence, the two initially degenerate resonant frequencies split correlated linearly with rotation rate. It results in a red shift of resonance wavelength when the light propagates in the same direction with angular velocity. On the other hand, there is a blue shift of resonance wavelength, having the same magnitude of the red shift, when the light propagates in the opposite direction with angular velocity.

Here we taking into account the rules of special theory of relativity (STR) in a ring cavity with a dispersion medium inside it. Actually, the STR works when two coordinate frames move at constant velocity relative to each other, which is just the case happening for light propagating in a rotating cavity. The expressions for the Sagnac effect in the STR framework can be derived by taking advantage of the invariance of the interval $x^2+y^2+z^2 = c^2t^2$ (where x, y, z are the wave front coordinates, and t is the time) [44]. Considering a ring resonator filled with dispersion materials and the effective length, phase velocity and round-trip time for the two counterpropagating lights are

$$\begin{aligned} L^{\pm} &= 2\pi R \pm \Omega R T^{\pm} \\ V_R^{\pm} &= \frac{\frac{c}{n_0} \pm \Omega R}{1 \pm \frac{\Omega R}{c n_0}} \\ T^{\pm} &= \frac{L^{\pm}}{V_R^{\pm}} = \frac{2\pi R}{V_R^{\pm} \mp \Omega R} \end{aligned} \tag{2}$$

where V_R is the relativistic velocity of the phase front. The resonance condition could be described as

$$L_{res}^{\pm} = \frac{2\pi mc}{n(\omega^{\pm})\,\omega^{\pm}} \tag{3}$$

By taking into account the first-order dispersion and neglecting high-order dispersion, we can obtain

$$\frac{c}{n^-} - \frac{c}{n^+} \approx -\frac{c}{n_0^2}\left(\upsilon^- - \upsilon^+\right)\frac{dn}{d\upsilon} \tag{4}$$

Thus, using Eqs. (1)–(3), one can write the splitting frequency difference between CW and CCW beams,

$$\Delta\upsilon = \upsilon^- - \upsilon^+ = \frac{4An_0^2\Omega}{L\lambda}\left[n_0\left(1+\frac{w_0}{n_0}\frac{dn}{dw}\right)\right]^{-1} = \frac{4An_0^2\Omega}{L\lambda n_g} = \frac{2R\Omega}{\lambda_0 n_g} \tag{5}$$