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Effects of gain medium parameters on the sensitivity of semiconductor ring laser gyroscope

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ABSTRACT

The semiconductor gain medium has rich non-linear dynamics and several internal parameters influence the generation and propagation of light through it. With the gain medium being an integral part of semiconductor ring laser gyroscope (SRLG) cavity, its parameters affect the overall performance of the gyro. The effect is further elevated in integrated SRLG due to stronger confinement of charge carriers and photons leading to a more intense interaction between them. In this paper, we evaluate the influence of semiconductor gain medium parameters such as gain saturation coefficient, linewidth, internal quantum efficiency etc. on the sensitivity of bulk fiber-optic SRLG. Ways of controlling these parameters and optimizing their values to enhance the performance of SRLG are also discussed.

1. Introduction

Optical gyroscopes are inertial rotation sensors working mostly on the Sagnac effect to sense the angular velocity [1]. Novel optical gyroscopes based on rotation induced evolution of far-field emission patterns [2] and transmission response of coupled resonators have been proposed, but majority of optical gyroscopes still rely on Sagnac interferometer for inertial rotation sensing [3–6]. Sagnac effect states that two light waves traveling different optical paths inside the same closed cavity, accumulate different phase shifts [7]. When the non-degeneracy in path length is brought about by rotating the cavity externally, the difference in phase accumulated by counter-traveling waves is proportional to the velocity of rotation. Thus, the angle of rotation, its rate and direction can be estimated by measuring the phase difference between the waves through interferometry. This technique is used in Interferometric Fiber Optic Gyros (IFOG) which are passive devices because the light waves counter-traveling inside the cavity are generated by a source which is external to the cavity [8].

Apart from phase shifts, inertial rotation also splits resonance frequencies of the ring resonator. Thus, on rotation, resonance frequency in the clockwise (CW) direction is different from that in the counter-clockwise (CCW) direction, with the difference proportional to the inertial rotation velocity [9]. Measurement of this frequency difference is inherently more sensitive than measuring the phase difference. In Resonant Fiber Optic Gyros (RFOG), the resonance frequency difference is measured by exciting the resonator from an external light source. Generally, acousto-optic modulators or tunable laser sources are required for accurate measurement of rotation rates by RFOG [10].

However, if the counter-traveling waves are generated by a laser source present inside the ring resonator itself, the rotation induced resonance frequency difference can be measured by simple interferometric techniques [11]. Thus, interference of the CW and CCW waves results in a beat signal whose frequency is equal to the resonance frequency difference. Such gyroscopes are called active ring resonator gyros or Ring Laser Gyros (RLG) [12]. In all the RLGs, the presence of light source or gain medium inside the closed cavity influences the dynamics of the device [13]. Because of the phase amplitude coupling, magnitude and linearity of the rotation induced Sagnac beat frequency depends upon various gain medium parameters like gain coefficient, linewidth, self and cross saturation coefficients, internal quantum efficiency etc. These parameters also affect the gyro performance metrics such as quantum limit, angle random walk and bias stability.

In Semiconductor RLG (SRLG), the gain medium is highly non-linear as compared to the gaseous gain medium of He-Ne RLG because of strong interaction between charge carriers and optical signal [14–16]. It has also been shown that the dynamics of semiconductor lasers subjected to optical feedback is affected by the phase-amplitude coupling, which further complicates the dependency of gyro performance on the gain medium parameters [17,18]. Thus, an analysis of

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SRLG performance considering the effect of gain medium parameters is important to increase its sensitivity by parameter optimization. The inherent description of Sagnac effect quantifies the beat frequency in terms of only passive cavity parameters as the amplitude and phase rate equations are de-coupled from each other. Including the gain medium dynamics in the calculation of Sagnac beat frequency is essential to study the effects of amplitude-phase coupling on the gyro output, as reported by us in [19].

In this paper, we model the bulk fiber-optic SRLG by the rate equations of electric field inside the cavity, with an aim to incorporate the phase and amplitude affecting parameters in the same equation. An experimental SRLG setup is also tested by manually rotating the optical table. The close agreement between theoretical and experimental beat signal output confirms the feasibility of the proposed model. The gain medium parameters such as gain coefficient, linewidth, internal quantum efficiency etc. are then varied to analyze their effect on the output sensitivity. Solutions to optimize these parameters and improve the bulk-optic SRLG performance is also discussed. A similar analysis for the on-chip integrated SRLG was also performed by us and reported elsewhere [20].

2. Experimental results

The basic configuration of bulk fiber optic SRLG consisting of a semiconductor optical amplifier (SOA) as the gain medium and an external optical fiber as the ring cavity is shown in Fig. 1(a). The gain medium used is an InP buried heterostructure (BH) type linear SOA, which is a low confinement factor device. The typical wafer structure used to fabricate the gain medium is a multiple quantum well (MQW) Aluminium quaternary i.e. $Al_{0.44}Ga_{0.07}In_{0.49}As$. Here, the strained QWs and barriers are sandwiched between two InAlGaAs graded index separate confinement (GRINSC) layers and two additional $Al_{0.423}\mathrm{l}rmGa_{0.047}In_{0.53}As$ layers to decrease the leakage of carriers. In the fiber ring, an optical filter is used to limit the number of longitudinal modes oscillating simultaneously and a fiber-optic coupler is used to tap the useful power out of the ring cavity. Polarization controllers (PC) are used to maintain the CW and CCW modes in same state of polarization. A photodiode (PD) converts the optical signal to equivalent electrical signal which is analyzed on a RF spectrum analyzer (SA). A similar setup was built in our lab as shown in Fig. 1(b) with external fiber cavity length of 7.3 m, filter bandwidth of 0.8 nm, and photodiode with responsivity 0.9 A/W The whole set up enclosing an area of 200 cm^2, was rotated at 45 deg/s.

Fig. 2 shows the output of the RF spectrum analyzer, where circled line shows the output after rotation while solid line is the output without rotation. The beat frequency output obtained without rotation shows the presence of inherent bias in the gyro. This error occurs primarily due to the frequency splitting caused by sudden changes in the index of refraction along the ring cavity. The most favorable site for such scattering to occur is the connection between the semiconductor gain medium and the external fiber ring. It is necessary to calculate the magnitude of the frequency bias and calibrate the gyro output accordingly. In our case, the peak bias occurred at the frequency of 2.05 kHz.

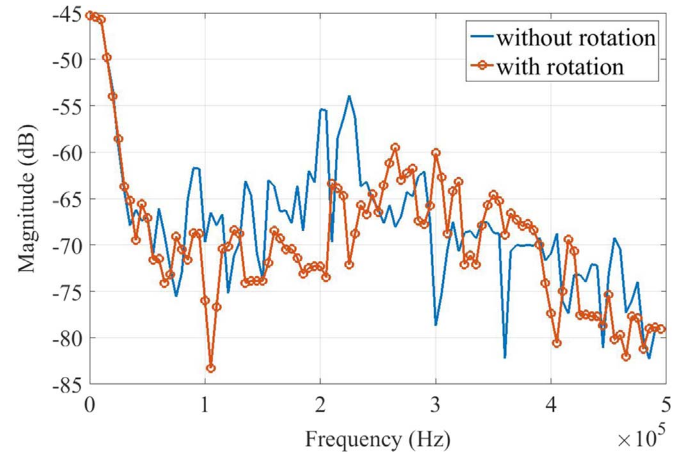


Fig. 2. Output of spectrum analyzer showing the frequency response with and without rotating the SRLG setup. The presence of output without rotation shows the existence of a bias or null shift error.

The output signal obtained on rotating the setup shows a shift in the peak relative to frequency axis. The corresponding beat signal is thus obtained by the difference in the frequency peaks of signals before and after rotation and is as shown in Fig. 3(a). As can be seen, the beat frequency (Δf) is about 100 kHz. Now, the change in the optical path length due to rotation can be calculated from the Sagnac formula as

$$\Delta L = \frac{4A\Omega_r}{c} = 2.095 \times 10^{-9}\, m \tag{1}$$

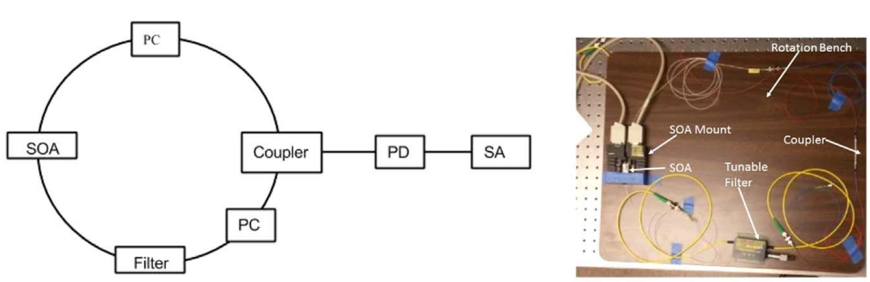
where A is the area enclosed by the gyro and Ω_r is the magnitude of angular rotation velocity.

We define the scale factor as the ratio of frequency difference to the path length change and its experimental value is given as

$$\frac{\Delta f}{\Delta L} = \frac{100 \times 10^3}{2.095 \times 10^{-9}} = 4.77 \times 10^{13}\, Hz/m \tag{2}$$

3. Theoretical analysis

The semiconductor ring laser gyro of the above experimental setup can be modeled by using coupled-cavity rate equations [21]. This approach consists of using the rate equations to model the electric field in both the gain medium (active) cavity and the external fiber ring (passive) cavity, and a coupling coefficient to effectively couple the fields between them. The effect of external rotation can be modeled by varying the external cavity resonance frequency. Thus, both the CW and CCW modes will have different resonance frequencies as per the Sagnac effect. The corresponding rate equations for an externally rotated semiconductor ring laser gyro are given as follows



(a) (b)

Fig. 1. (a) Basic configuration of a bulk fiber-optic Semiconductor RLG and (b) The assembled configuration used for experimental verification in the lab at SIU, Carbondale. The readout circuitry consisting of a photodetector and spectrum analyzer is not shown in the setup.