International Conference on Space Optics—ICSO 2004

Toulouse, France

30 March–2 April 2004

Edited by Josiane Costeraste and Errico Armandillo

Quantum effects in new integrated optical angular velocity sensors

M. N. Armenise, C. Ciminelli, F. De Leonardis, V. M. N. Passaro

International Conference on Space Optics — ICSO 2004, edited by Errico Armandillo, Josiane Costeraste, Proc. of SPIE Vol. 10568, 1056815 · © 2004 ESA and CNES
CCC code: 0277-786X/17/$18 · doi: 10.1117/12.2308032

QUANTUM EFFECTS IN NEW INTEGRATED OPTICAL ANGULAR VELOCITY SENSORS

M. N. Armenise, C. Ciminelli, F. De Leonardis, V. M. N. Passaro

Optoelectronics Laboratory, Dipartimento di Elettrotecnica ed Elettronica, Politecnico di Bari
Via Orabona n.4, 70125 Bari, Italy, e-mail: armenise@poliba.it

ABSTRACT

The paper describes the quantum effects to be considered in the model of new integrated optical angular velocity sensors. Integrated optics provides a promising approach to low-cost, light weight, and high performance devices. Some preliminary results are also reported.

1. INTRODUCTION

Very compact and low-cost rotation sensors are important devices for any moving system, from automotive to satellite applications.

Currently, fiber optic gyros represent the most widely used gyro technologies while gyros based on MEMS (Micro Electro Mechanical Systems) are the most studied. However both technologies show some limitations in high-performance applications, e.g. in satellite attitude control. For these last applications, new integrated optical angular velocity sensors [1] seem to be very promising providing the potential of satisfying the requirements of low cost, very compact, light weight and high – performance.
The integrated optical gyroscopes are based on the Sagnac effect, which occurs as a non-reciprocal phenomenon when two light beams counter-propagating in an optical resonant cavity suffer from a rotation. The Sagnac effect leads to a frequency difference proportional to the angular velocity. The Sagnac effect has been demonstrated in semiconductor ring laser having different configuration, such as triangular, squared or circular. The integrated optical gyroscope proposed in [2] has an architecture similar to the fiber optic gyro because it is a passive ring-based device where the sensing element is a circular waveguide ring to which the counter-propagating beams are coupled by means of two directional couplers diametrically positioned.
The fully integrated optical gyro configuration proposed in Ref. [1] includes a multi-quantum well (MQW) ring laser, a circular directional coupler, an electrooptic phase modulator, an optical combiner and a photodetector.
We have developed the mathematical model of the ring based on the semiclassical theory of the laser to study the dynamic evolution of the two beams in the ring, by taking into account the non linear quantum effect involved in the laser operation.

2. QUANTUM EFFECTS

The performance of a gyro based on an active ring laser is mainly limited by the quantum limit, lock-in and mode competition effects. Quantum limit constitutes the physical limit to the measurement uncertainty and depends on the laser spontaneous emission. Since the spontaneous emission occurs randomly, the phase of the electric field in the cavity is no longer well determined, but becomes a stochastic quantity. This produces an error in the frequency difference between the two counter-propagating beams and, therefore, an error in the determination of the rotation velocity.

$$\delta\Omega = \frac{\lambda}{2R_{eff}} \frac{\Delta f}{\sqrt{\tau P_c/(hc/\lambda)}} \qquad (1)$$

where R_{eff} is the effective ring radius (i.e. the radial distance of the electric field from the ring center), P_c is the beam power, τ is the measure time and Δf is the ring passive resonator linewidth at half maximum.
To reduce the quantum limit it needs to increase the ring radius and decrease the ring losses.
Lock-in effect is caused by the backscattering due to the roughness of the ring sidewall and leads to a frequency difference equal to zero even if the angular velocity is very low. This, in turn, limits the minimum detectable angular velocity. The lock-in effect, in fact, generates a range of the angular velocity [0 - $\Omega_{loch-in}$] where the output signal of the sensor is always zero.

$$\Omega_{lock-in} = \frac{1}{2\pi F} \frac{b_k c}{\pi n_v R_{eff}} \qquad (2)$$

where n_v is the laser mode effective index, R_{eff} is the ring radius, b_k is the backscattering coefficient in the cavity and F is the sensor scale factor.The conventional techniques to cancel the lock-in effect involve the introduction of either a constant-frequency or alternating-frequency bias between the two counter-propagating beams (dithering).

Mode competition is caused by nonlinear effects generated in the gain medium, such as self-saturation and cross-saturation [3]. It induces the suppression of one of the two counter-propagating beams, which makes impossible to extract the information on the angular velocity.

The active medium gain and the laser polarization are calculated by using the density matrix formalism. Electron transition mechanisms are considered under the momentum conservation condition. The time dynamics of the intensities I_1 and I_2 of the two counter-propagating beams are determined by means of the following equations:

$$\frac{dI_1}{dt} = 2I_1\left(\alpha_1 - \tilde{\beta}_1 I_1 - \tilde{\theta}_{12} I_2\right) - 2\sqrt{I_1 I_2}\left(\xi_1 I_1 + \eta_{12} I_2\right) \quad (3)$$

$$\frac{dI_2}{dt} = 2I_2\left(\alpha_2 - \tilde{\beta}_2 I_1 - \tilde{\theta}_{21} I_1\right) - 2\sqrt{I_1 I_2}\left(\xi_2 I_2 + \eta_{21} I_1\right) \quad (4)$$

where $\tilde{\beta}_n$ e $\tilde{\theta}_{nm}$(n, m = 1,2; n≠m) are the self-saturation and cross-saturation coefficients, respectively, and α_n is the net gain of the two beams.

We have demonstrated that the bi-directional operation of the laser is achieved by imposing appropriate conditions on the coupling coefficient *C* and on the gain coefficients $\tilde{g}_1$ and $\tilde{g}_2$, obtained by considering both the linear and non linear contributions to the mode gain. The coupling coefficient *C* and the gain coefficients $\tilde{g}_1$, $\tilde{g}_2$, are given by:

$$C = \frac{\tilde{\theta}_{12}\tilde{\theta}_{21}}{\tilde{\beta}_1\tilde{\beta}_2} \quad (5)$$

$$\tilde{g}_1 = \alpha_1 - \tilde{\theta}_{12}\frac{\alpha_2}{\tilde{\beta}_2}$$
$$\tilde{g}_2 = \alpha_2 - \tilde{\theta}_{21}\frac{\alpha_1}{\tilde{\beta}_1} \quad (6)$$

In Fig. 1 the electric field intensities of the two resonant modes in the ring laser are reported as a function of the time t, assuming C = 4, the carrier density N equal to $3\cdot10^{24}$ m^{-3}, and the frequency difference between the two modes $\Delta\omega = 0$.

As it can be seen, the two intensities are distinguishable for t > 50 psec, where the effect of mode competition is well apparent after 0.1 nsec, resulting in an unstable bi-directional operation of the sensor.

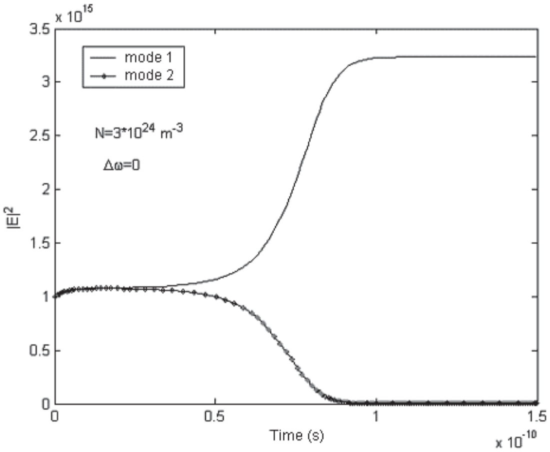

Fig. 1. Field intensities versus time for Δω = 0

We have also calculated the intensities of the two modes in the cavity at different values of Δω.

In Fig. 2 we have considered $\Delta\omega = 5.5\cdot10^{-12}$. In this case we obtain C < 1, $\tilde{g}_1 > 0$ and $\tilde{g}_2 < 0$. As it is clear from the figure, also in this case the bidirectional operation is unstable.

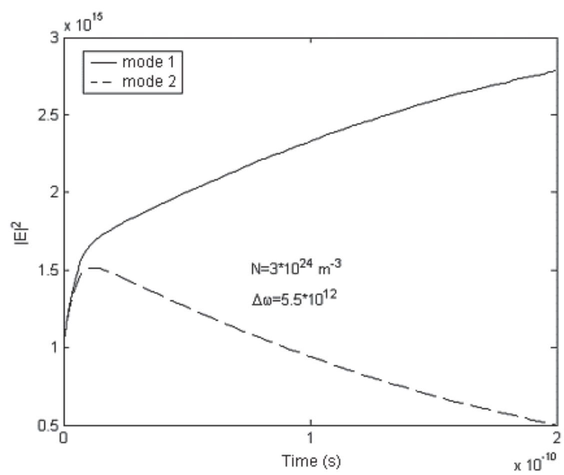

Fig. 2. Field intensities versus time for $\Delta\omega = 5.5\cdot10^{-12}$

However, an optimisation procedure involving the carrier density and frequency difference parameters can be pointed out to achieve a stable bi-directional operation condition.

3. CONCLUSIONS

In this paper, the study of the nonlinear quantum effects in MQW ring laser has been carried out. We have confirmed that the quantum limit depends on the spontaneous emission and on the scattering in the structure, and the lock-in effect is related to the backscattering noise. We have also found, for the first time, that a stable bi-directional operation can be achieved by optimizing the geometrical and physical parameters of the MQW ring laser structure in relation with the non linear quantum effects. This result should allow preventing mode competition also in relatively large structures, where appropriate solutions should be required.

This work has been supported by ESA Reference Contract DEE-MI /IOLG N. 16783/02/NL/PA.

4. REFERENCES

[1] M. N. Armenise, V. M. N. Passaro, F. De Leonardis, M. Armenise, “Modelling and Design of a novel miniaturized integrated optical sensor for gyroscopes systems”, IEEE J. Lightwave Technol., vol. 19, n. 10, October 2001, pp. 1476-1494.

[2] C.Monovoukas, A.K. Swiecki, F. Maseeh, “Integrated optical gyroscopes offering low cost, small size and vibration immunity”, IntelliSense Corporation.

[3] M. Yamada, Y. Suematsu, “Analysis of gain suppression in undoped injection lasers”, J. Appl. Phys. 52 (4), April 1981, pp.2653-2664.