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Fiber-Optic Laser Gyroscope with Current Modulation of the Optical Power*

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Abstract. In this article we investigate a Fiber-Optic Laser Gyroscope. Phase modulation is the most frequently used method for modulation of the optical radiation, realized in this paper as well. Along with it is proposed the other alternative method, amplitude modulation of optical power in laser diode. It gives better results (for our experimental setup). Both cases are presented experimentally for comparison.

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1 Introduction

Navigation is one of the oldest skills and techniques known to man. In this connection the gyroscope, which works in the principle of conservation of angular momentum, is an important instrument for measuring and maintaining the orientation. Because of its precision, it is used nowadays in navigation in every commercial flying and sailing apparatus.

The discovery of lasers in 1960 brought development of the gyroscope. Undoubted advantage of a laser gyroscopes is the fact that such systems do not contain any rotating mass, and hence are insensitive to linear accelerations as compared to the mechanical one. The laser gyroscope was first demonstrated in 1963 by Macek and Davis [1], showing high precision in registration of very small angular velocities. The first laser gyroscope in Bulgaria is constructed ten years later in 1973 at the Institute of Solid State Physics, [2, 3] with angular velocity of $\omega = 0.4$ mrad/s. Further improvement was made with the introduction

*This paper has been presented at the International Workshop on Laser and Plasma Matter Interaction, 18-20 November, 2015, Plovdiv, Bulgaria of fiber optics [4–7]. This made possible to design smaller and low cost products. The fiber-optic gyroscope (FOG) uses optical fiber as a medium of the laser light propagation. The sensitivity of gyroscope could be enhanced by using long low loss single-mode optical fibers (of the order of kilometer or even more).

In the present article we investigate and compare different methods of modulation of fiber-optic gyroscope with a purpose to improve its sensitivity. Here we suggest a new method of modulation of optical power, propagating in a single-mode fiber, which leads to more than two times greater sensitivity. Transition characteristics are defined for laser amplitude modulation and both theoretical and experimental results are compared.

2 Sagnac Effect

The Fiber-Optic laser gyroscope represents Sagnac interferometer, Figure 1. Optical gyros are based on the Sagnac effect [8, 9], explanation of which is shown with the figure below.

Let us consider square path. Light, from laser source with angular frequency ω, entering the path is split by a beam-splitter (BS) into two beams: one propagating clockwise and the other one propagating counterclockwise. When the interferometer is at rest, both light waves travel through the same optical path and return in phase to their origin. The propagation time T is given by $T = 4a/c$ (a is the side of the square, c is the light velocity). Now, let us assume that the entire system is rotating counterclockwise in angular velocity Ω. In that case a difference in the optical path between the two beams will occur. This corre-

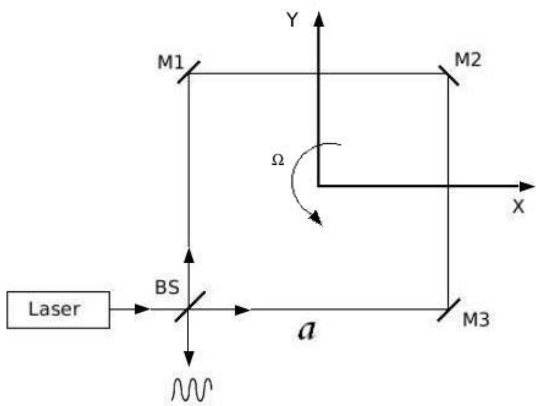

Figure 1. Sagnac interferometer

sponds to a phase shift

$$\Delta\varphi = \frac{4A\omega}{c^2}\,\Omega, \tag{1}$$

where A is the area, covered by interferometer ($A = a^2$). In the interferometric fiber-optic gyroscope, the two beams are again propagating through the fiber in opposite directions. When we have an optical fiber with total length L, refractive index n, N loops, and radius R for each loop – formula (1) transforms into

$$\Delta\varphi = 4\pi\frac{LR}{\lambda c}\Omega; \qquad L = 2N\pi R. \tag{2}$$

3 Experimental Setup

Laser diode LPS-830-FC – THORLABS, working in CW regime is coupled with fiber by directional coupler FC830-50B – THORLABS. Our experimental setup is presented in Figure 2. We investigate two different methods of modulation of optical power: first classical and well known method – phase modulation with piezoceramics and second – direct modulation of the laser current.

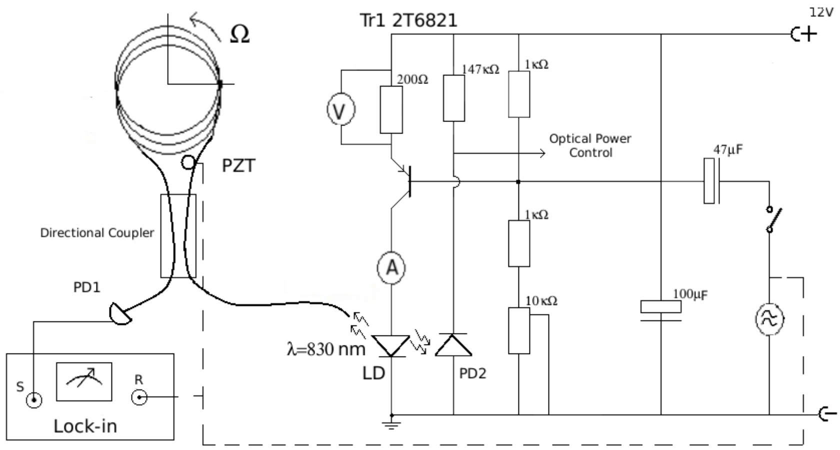

Figure 2. Electrical scheme. Here LD stands for laser diode and PD – photodiode, PZT – cylindrical piezo-transducer, respectively.

First case – phase modulation with cylindrical piezo-transducer – PZT. The light from laser diode passes through the directional coupler, where the signal is divided in half. Than it passes through the optical fiber of length 450 m and, traveling in opposite directions, it is detected by the photo detector PD_1. The signal from the detector enters in a lock-in amplifier, where it is registered. At the one end of the fiber loop we have cylindrical piezo-ceramic PZT with several turns of the optical fiber around it, serving as a phase modulator. A mechanical stress is caused on the fiber when a sinusoidal signal is applied to the piezo-ceramic modulator. As a result of the piezoelectrical effect, the refractive index of the fiber is changed. This change leads to different optical path and to appearance of phase difference. The response of the photo detector I_D is proportional to the square of the absolute value of the electric field. It is presented as a superposition of both (clockwise and counterclockwise) waves reaching the detector. The result is given by the following formula [10], (for detailed derivation see Appendix, formula (15)):

$$I_D = \frac{1}{2} I_0 \left(1 + \cos(\Delta\varphi_{NR})\right), \tag{3}$$

where I_0 is the initial intensity. Rotating the gyroscope with a constant velocity $\Omega = 0.17$ rad/s causes Sagnac effect leading to a phase difference $\Delta\varphi_{NR}$. It is calculate by formula (2), and for our experimental case is

$$\Delta\varphi_{NR} = 4\pi \frac{L\,R}{\lambda\,c}\Omega = 4\pi \frac{450 \times 0.085}{830 \times 10^{-9} \times 3 \times 10^{8}} 0.17 = 0.328 \quad \text{rad.} \tag{4}$$

Taking into account eq. (20) from Appendix, the signal is

$$I_D = 2 I_0 J_1 \left(2\varphi_{m0} \sin\left(\frac{\omega_m T}{2}\right)\right) \sin(\Delta\varphi_{NR}) \sin(\omega_m t), \tag{5}$$

ω_m is the modulating frequency, φ_{m0} is the amplitude of the modulating sinusoidal signal, J_1 is the first order Bessel function. The maximum of the signal reaches when the Bessel function has maximum, which takes place when the argument is 1.8. This allows us to evaluate the appropriate modulation frequency ω_m at which the optical system will work in optimal conditions, and for our experimental setup it is

$$f_m = \frac{\omega_m}{2\pi} = \frac{c}{2nL} = \frac{3 \times 10^8}{2 \times 1.467 \times 450} \approx 227\,\text{kHz}, \tag{6}$$

where n is the refractive index of the fiber core.

Second case – amplitude modulation of the laser optical power. We apply a *sinusoidal signal* (the graph at the bottom left side in Figure 3) together with a constant voltage to modulate the laser current

$$u(t) = u_c + u_0 \sin(\omega_m t). \tag{7}$$

The sinusoidal signal with amplitude u_0 is applied, switching the generator directly to the input of the electrical scheme. The constant voltage u_c is defined by the operating point of the transistor Tr1. From the technical characteristics of our specific laser given by THORLABS, we plot the *current-voltage characteristic* (the graph at the middle left side in Figure 3). By the RMS we define the analytical expression of the *laser current* (Table 1, case **a**, second formula),

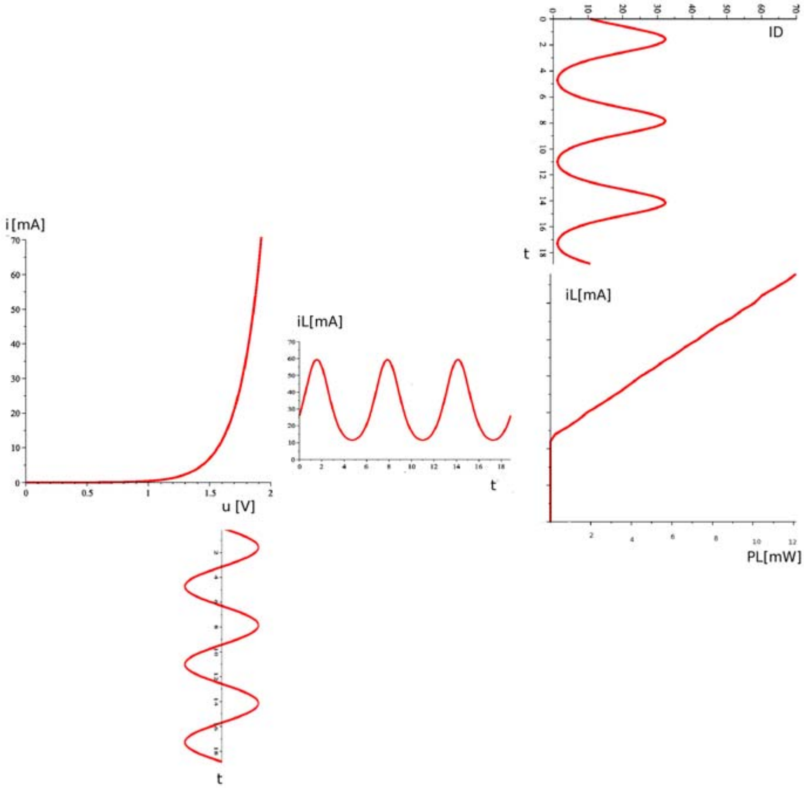

Figure 3. From bottom left to top right are presented the following graphs: 1. Sinusoidal signal (t – a.u.); 2. Current-voltage characteristic; 3. Laser current; 4. Laser optical power vs. laser current; 5. Detected intensity. The 2nd and 4th graphs serve as a “mirrors”‘ to transfer the signals.

shown as a graph at the middle in Figure 3. We see that after the transition of IU-curve, the signal is no more sinusoidal. This is not a problem, because the lock-in amplifier operates only at frequency ω_m and non-linearity is not essential for the setup (even this non-linearity could be removed with special electronic schemes).

In similar way we project the laser current curve $i_L(t)$ (the graph at the middle right side in 3) through *optical power* characteristics (Table 1, case **b**). The final result for laser optical power and for the component of *detected intensity* (the graph at the top right side in Figure 3) between interfering waves (3) and Sagnac effect (2) is

$$I_D = \frac{1}{2}[c_2 i_0 \exp(c_1(u_c + u_0 \sin(\omega_m t))) + c_3](1 + \cos(\Delta\varphi_{NR})). \quad (8)$$

All constants in the eqs. (7) and (8) are shown in Table 1.

Table 1. Transfer functions and their coefficients for (**a**) current-voltage and (**b**) laser optical power characteristics

	Function	Coefficients
	$u(t) = u_c + u_0 \sin(\omega_m t)$	$u_c = 1.74$ V $u_0 = 0.15$ V
a	$i(u) = i_0 \exp(c_1 u)$	$i_0 = 0.186$ mA $c_1 = 5.487$ V^{-1}
	$i_L(t) = i_0 \exp[c_1(u_c + u_0 \sin(\omega_m t))]$	$u_c = 1.74$ V $u_0 = 0.15$ V
b	only the slope-line of P_L $P_L = c_2 i_L(t) + c_3$	$c_2 = 0.121$ mW/mA $c_3 = -23$ mW
	$I_0(t) \sim P_0(t)$ $P_0(t) = c_2 i_0 \exp(c_1(u_c + u_0 \sin(\omega_m t))) + c_3$	

4 Results

We investigate the dependence between the received signals, when the gyroscope is rotating two times (clockwise and counterclockwise) with a constant velocity $\Omega = 0.17$ rad/s at different modulating frequencies. The graphics are shown in Figures 4 and 5. Each graph represents both methods (phase and current modulation) and compares them in respect to sensitivity [mV/(rad/s)]. The comparison shows that the new method gives better signal. On other side, our method has a disadvantage – the signal does not give information about the direction of rotation. Our proposal to overcome this problem is to combine both methods together, so the sign of sinus function will determine the direction of rotation. An explanation of this fact is that we have non-symmetrical transition of the light through the directional coupler, leading to additional phase $\pi/2$, moving through the operating point of gyroscope in dark regime.

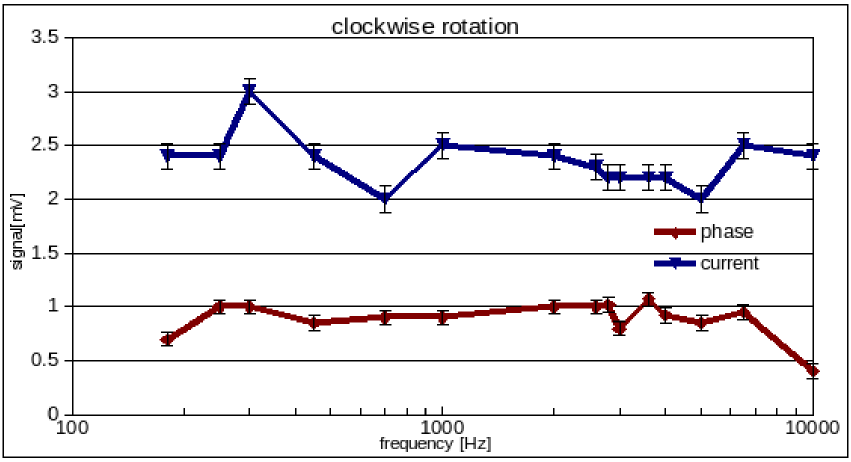

Figure 4. Detected signal vs applied frequency for phase and current modulation - clockwise rotation.

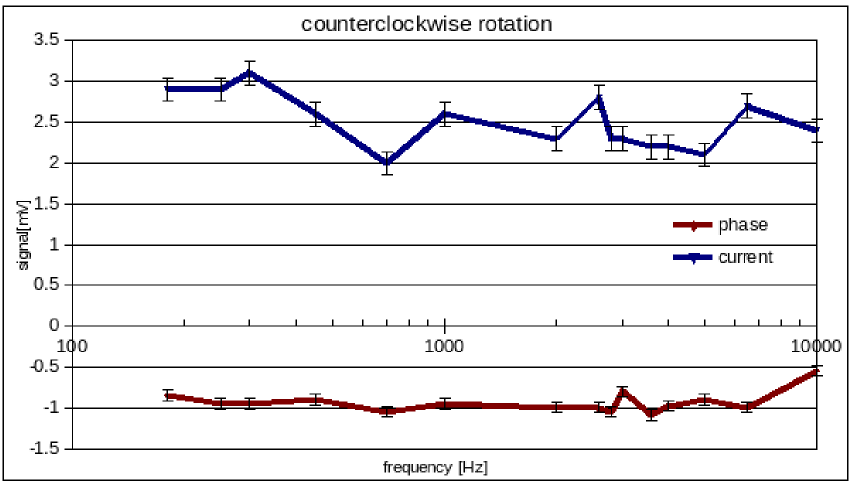

Figure 5. Detected signal vs applied frequency for phase and current modulation - counterclockiwise rotation.

5 Conclusion

In the present article we investigate and compare two different methods of modulation of fiber-optic gyroscope with the purpose to improve their sensitivity. A new method of modulation of optical power is proposed, which leads to more than two times greater sensitivity. The theoretical and experimental results for both methods are compared. For the new case an explicit formula for laser intensity I_D is shown in adiabatic approximation.

Acknowledgments

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Appendix

Here we will show the derivations of formulae (5) and (8). Let us first consider the Sagnac interferometer represented in Figure 1. It is advantageous to calculate only the electrical fields since the light intensity is

$$I = |\langle S\rangle_t| = \frac{\varepsilon c}{2}|\vec{E}|^2. \tag{9}$$

Here $|\langle S\rangle_t|$ is the time–mean value of the Poynting vector. In this case, the speed of light is c in the respective medium and ε is the corresponding dielectric constant. Considering horizontal polarization for the electric field, we will present the propagating waves in clockwise and counterclockwise direction as

$$E_1 = E_0 \cos(\omega t + kz + \varphi 1); \qquad E_2 = E_0 \cos(\omega t + kz + \varphi 2), \tag{10}$$

where $\varphi 1$ and $\varphi 2$ are the phases of waves 1 and 2, respectively, incident on the detector. The superpose electric field is

$$E = E_1 + E_2 = E_0 \cos(\omega t + kz + \varphi 1) + E_0 \cos(\omega t + kz + \varphi 2) \tag{11}$$

and for intensity, one has

$$I_D = I_1 + I_2 + 2\sqrt{I_1 I_2}(\langle \cos(2\omega t + 2kz + \varphi 1 + \varphi 2)\rangle_t + \cos(\varphi 1 - \varphi 2)) \tag{12}$$

The term with integration on time vanishes. In an ideal Sagnac interferometer, the intensities and the phases are equal, simplifying more the above relation.

For an ideal beam splitter (50%/50%, without losses) each pass decreases the power twice, so after two passes the intensity is one forth of the initial I_0. Following the work [10] and notations therein, we receive for the intensities

$$I_1 = \frac{1}{4}I_0 + \frac{1}{2}\Delta I_{NR}; \qquad I_2 = \frac{1}{4}I_0 - \frac{1}{2}\Delta I_{NR}, \tag{13}$$

and for the phases

$$\Delta\varphi_1 = \Delta\varphi_0 + \frac{1}{2}\Delta\varphi_{NR}; \qquad \Delta\varphi_2 = \Delta\varphi_0 - \frac{1}{2}\Delta\varphi_{NR}, \tag{14}$$

where ΔI_{NR} and $\Delta\varphi_{NR}$ represent the intensity and the phase change due to Sagnac effect, eq. (2). Applying eqs. (13) and (14) in (12) and neglecting the terms of second order in $\frac{\Delta I_{NR}}{I_0}$, we receive the well-known formula for the intensity I_D on the photo detector

$$I_D = \frac{1}{2} I_0 (1 + \cos(\Delta\varphi_{NR})). \tag{15}$$

This general formula is valid for both cases – standard Sagnac interferometer (Figure 1) and Fiber-Optic Sagnac interferometer (Figure 2).

First case – phase modulation with cylindrical Piezo-Transducer – PZT. We have cylindrical piezo-ceramic with several turns around it, placed at one end of the fiber loop, where we applied sinusoidal signal $\varphi_m(t) = \varphi_{m0}\sin(\omega_m t)$ with frequency ω_m. The phase difference is [10–12]

$$\Delta\varphi(t) = \Delta\varphi_{NR} + \varphi_m(t) - \varphi_m(t-\tau). \tag{16}$$

where $\varphi_m(t) = \varphi_{m0}\sin(\omega_m t)$ is the applied sinusoidal modulation, and τ is the group delay time between the phase modulator and the symmetrical point on the other side of the fiber loop. Applying the Jones matrix method as in [13] for the detected signal, we receive

$$I_D = \frac{I_0}{2}(1 + \cos(\Delta\varphi_{NR} - \eta\sin(\omega_m t))) \tag{17}$$

where $\eta = 2\varphi_{m0} sin(\frac{\omega_m T}{2})$. Applying some formulae from trigonometry, we receive

$$I_D = \frac{I_0}{2}(1 + \cos(\Delta\varphi_{NR}) cos(\eta\sin(\omega_m t)) + \sin(\Delta\varphi_{NR})\sin(\eta\sin(\omega_m t))). \tag{18}$$

For the terms $\cos(\eta\sin(\omega_m t))$ and $sin(\eta\sin(\omega_m t))$, we apply Bessel generating functions (9.1.42) and (9.1.43) from [14], and the result is

$$I_D = \frac{I_0}{2}(1 + \cos(\Delta\varphi_{NR}) J_0(\eta) + \sin(\Delta\varphi_{NR}) 2 J_1(\eta)\sin(\omega_m t)). \tag{19}$$

Since detected signal is demodulated at the reference frequency ω_{m0} in a lock-in amplifier, we removed higher-order Bessel functions. And the same argument is valid for the first two terms, so the final result is

$$I_D = I_0 J_1(\eta)\sin(\Delta\varphi_{NR})\sin(\omega_m t). \tag{20}$$

Second case – amplitude modulation of the laser power. Now we will consider what happens if we modulate the current of the semiconductor laser with sinusoidal frequency ω_m, in other word we should precise the time dependence of I_0

$$I_D = \frac{1}{2} I_0(t)(1 + \cos(\Delta\varphi_{NR})). \tag{21}$$

It is worth noting that the time dependence $I_0(t)$ is an adiabatic process, since the frequency of the light $\omega \gg \omega_m$. For this purpose we will consider the *current–voltage* and *optical power* characteristics of the semiconductor laser shown in Figure 3. The modulation of the current is realized with a special scheme, shown in Figure 2, which supports the necessary threshold of the laser.

We apply sinusoidal signal together with constant voltage u_c to modulate the laser current. The current is projected through current–voltage characteristic, and it is shown at the middle of the figure (it is no more sinusoidal because of non-linear IU-curve). The next step is to project this current through optical power characteristic. The optical power is shown at the top of the figure, and it is no more sinusoidal either. The modulated initial intensity $I_0(t)$ is proportional to optical power. The operating point of transistor Tr_1, Figure 2, defines the laser current in the case of absent ($u_0 = 0$) input signal, i.e. $i(u_c) = i_0$. Here u_c is the voltage, which ensures laser optical power over the threshold.

So the final result for the component of detected intensity between interfering waves (3) and Sagnac effect (2) is given by

$$I_D = \frac{1}{2}[c_2 i_0 \exp(c_1(u_c + u_0 \sin(\omega_m t))) + c_3](1 + \cos(\Delta\varphi_{NR})). \tag{22}$$

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