Application study of ultra high frequency modulation of laser radiation for fiber-optic gyroscope noise reduction

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Abstract. Microwave photonics is implemented in many applications, including the area of inertial navigation systems based on high-precision fiber-optic gyroscopes. Microwave photonic technologies allow increasing the fiber-optic gyroscope accuracy. This paper investigates and evaluates the effect of ultra high frequency modulation of laser radiation on the closed-loop fiber-optic gyroscope output signal. Research results show that ultra high frequency modulation makes it possible to broaden spectrum width due to redistribution to modulation harmonics of the laser radiation. This approach allows to reduce the standard deviation of the laser-driven fiber-optic gyroscope output signal more than 2.5 times compared to using a laser-driven fiber-optic gyroscope without modulation. In order to achieve the noise level of a laser-driven fiber-optic gyroscope the same as the noise level of a fiber-optic gyroscope with a broadband source, it is necessary to use a broadband noise source with a constant power spectral density and higher output power. This study is useful for understanding how application of microwave photonic technologies can impact on the fiber-optic gyroscope output signal. The obtained results can be used for researchers in this area of study and can facilitate the rapid development of this field.

1. Introduction
Microwave photonics (MP) is a new scientific and technical area of research. MP technologies can be used for creating devices with unique characteristics. The working principle of MP devices is based on the interaction between electrical and light waves [1]. In recent years, MP is implemented in many applications, including the area of inertial navigation systems based on high-precision fiber-optic gyroscopes (FOGs). In these papers [2, 3] authors use phase modulation for FOG noise reduction. The main idea of this article [3] is to use a Gaussian-noise phase modulation of a laser-driven FOG, the frequency band of a noise source from 10 MHz to 11 GHz. This approach [3] makes it possible to reduce angular random walk noise and drift of the laser-driven FOG output signal to a level of a FOG driven by a broadband source. A broadband light source can minimize Rayleigh backscattering because its very short coherent length allows suppression of the spurious interference effects [4]. However, the central wavelength stability of a broadband source is lower than the stability of the laser [3, 4]. This technique can potentially improve scale-factor stability, reduce excess noise, cost and complexity. Thus, the latest achievements in this field [2, 3] show that the application of MP is a possible way of improving the FOG accuracy.
2. Measurements and evaluation

2.1. Experimental setup
Since the application of MP in the field of FOG is a modern research trend, it is necessary to investigate the effect of ultra high frequency modulation on the output signal in detail. This paper deals with the closed-loop FOG, which working principle is described in many scientific papers [5, 6]. Schematic diagram of the experimental setup is shown in figure 1.

![Figure 1. Schematic diagram of the experimental setup.](image)

A radiofrequency (RF) signal generator (R&S SMA100B), a ferrite isolator (FVK3-28), a laser (FiTel FRL15TCWx-D86-xxxxxA) were used for this setup. The phase modulator was fabricated at A.F. Ioffe Physical-Technical Institute. The operating parameters of the modulator: $V\pi = 5$ V, bandwidth is up to 20 GHz, the maximum power dissipation at the terminator is 0.5 W, the terminator resistor is 30 Ohm. The laser diode power is about 5.5 mW.

2.2. Measurements
The output FOG signal was recorded for each experimental condition. The basic criteria were the Allan variance, standard deviation, and spectrum of the FOG signal. The optical spectra of the FOG input signal measured with and without modulation are shown in figure 2. The optical signal was attenuated by 30 dB.

![Figure 2. Optical spectra measured with and without modulation.](image)
The ultra high frequency modulation was at 2 GHz because ferrite isolator operating frequency range is from 1 GHz to 2 GHz. Figure 2 shows how the optical spectrum changes with modulation. Unfortunately, due to the low modulation frequency and limited resolution of the USB Interrogation Monitor (Ibsen I-MON 512 USB), it is impossible to analyze the spectrum in detail. Even so, the reduction of power at the optical carrier frequency due to redistribution to modulation harmonics and the spectrum broadening are observed.

Dependence of the standard deviation of the laser-driven FOG output signal on the modulation signal power is presented in figure 3. The standard deviation of the FOG signal is calculated in the frequency band below 50 Hz. Also, the dependence of the standard deviation of the FOG signal driven by a broadband source on the modulation signal power is shown in this figure.

Figure 3 shows that the standard deviation of the laser-driven FOG signal decreases with the increasing power of the RF signal. This is because the phase shift of the modulator depends on the applied signal voltage. The standard deviation of the FOG signal driven by a broadband source has not changed with RF signal modulation, because the spectrum width of a broadband source is about 2.5 THz. Also, the standard deviation of the laser-driven FOG with sawtooth frequency modulation (from 2 GHz to 2.020 GHz) was evaluated. The RF signal power was set at 28 dBm. In this case, the standard deviation of the FOG output signal was the same as at 2 GHz. Thus, the lowest standard deviation of the FOG output signal was achieved at modulation frequency 2 GHz and RF signal power 28 dBm.

In figure 4 the Allan variance is presented that shows the effect of RF signal power and frequency on the FOG noise level. The lowest noise level of the laser-driven FOG is achieved by using sawtooth frequency modulation. In view of the fact that the record length of the FOG signal was 15 minutes, it is taken that reliable data is limited by the 10 seconds averaging window.
Figure 4. Allan variance of the FOG signal driven by the laser or by the broadband source.

Thus, the noise level of the laser-driven FOG can be reduced using ultra high frequency modulation. Also, it is evident that the noise level of the FOG signal driven by a broadband source is much less. This is because the laser spectrum was broadened by using an ultra high frequency modulation that minimized Rayleigh backscattering and suppressed spurious interference effects [4]. Likewise, as the spectrum width of the broadband light source is much broader, spurious interference effects are much less. It is important to emphasize that a noise level has a greater dependence on the RF signal power than on modulation frequency.

The spectra of the FOG output signal were analyzed too. The spectrum of the laser-driven FOG without modulation and the spectrum of the FOG driven by a broadband source without modulation are shown in figure 5 (a). In figure 5 (b) the spectrum of the laser-driven FOG with sawtooth frequency modulation and the spectrum of the laser-driven FOG without modulation are presented.

Figure 5. Spectra of the FOG output signal.
Figure 5 shows that the noise floor of the laser-driven FOG output signal can be reduced using ultra high frequency modulation. The noise floor of the FOG spectrum decreases as well as the standard deviation of the FOG output signal.

3. Results and discussions

The dependencies of the parameters of the FOG output signal on the frequency and on the RF signal power are evaluated in the experiment.

Research shows that ultra high frequency modulation of laser radiation made it possible to increase spectrum width due to redistribution to modulation harmonics of the laser radiation. This approach allows to reduce the standard deviation of the laser-driven FOG signal more than 2.5 times (according to Allan variation in the region of averaging windows up to 10 seconds) compared to using laser-driven FOG without modulation. Nevertheless, to achieve the noise level of a laser-driven FOG the same as the noise level of a FOG driven by a broadband source, it is necessary to use a broadband noise source with a constant power spectral density and higher output power. In this research, the broadband light source gives better results, however technique of ultra-high frequency modulation of the laser radiation shows comparable results with other RF signal generators [2, 3]. This technique has a significant advantage that the central wavelength of a laser has better stability comparing with a broadband source [6]. Also, this approach allows to improve scale-factor stability and reduce excess noise. Besides, this method can be very useful to reduce the cost and complexity of the FOG. The application of MP is a possible way of improving the FOG accuracy.

The researchers plan to perform additional experiments to study the effect of the ultra high frequency modulation of laser radiation on the FOG scale factor. The results of these studies will be published in the following papers.

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References

[1] Vostrikov E V, Litvinov E V, Volkovskii S A, Aleinik A S and Polte G A 2020 Application of microwave photonics in fiber optical sensors *Scientific and Technical Journal of Information Technologies, Mechanics and Optics* **20** 1–23

[2] Chamoun J and Digonnet M J F 2016 Pseudo-random-bit-sequence phase modulation for reduced errors in a fiber optic gyroscope *Optics Letters* **41** 5664–67

[3] Chamoun J and Digonnet M J F 2017 Aircraft-navigation-grade laser-driven FOG with Gaussian-noise phase modulation *Optics Letters* **42** 1600–03

[4] Ciminelli C, Dell'Olio F and Armenise M N 2016 *Photonics in space: Advanced photonic devices and systems* (Singapore: World Scientific Publishing Co. Pte. Ltd.) pp 236

[5] Lefevre H C 2013 The fiber-optic gyroscope: challenges to become the ultimate rotation-sensing technology *Opt. Fiber Technol.* **19** 828–35

[6] Lefevre H C 2014 *The Fiber-Optic Gyroscope 2nd edition* (Norwood: Artech House Publishers) pp 416