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Research Article

1030 nm All-Fiber Closed-Loop Fiber Optic Gyroscope with High Sensitivity

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Angle random walk (ARW) is a critical noise component of a typical gyroscope alongside with bias instability noise. ARW has dominant effects especially in short-term accuracy. The measurement uncertainty degrades with the deterioration in ARW resulting in the lowered overall gyroscope accuracy. Many inertial navigation applications such as satellite control and gyrocompassing require low ARW. For an interferometric fiber optic gyroscope, lowest detectable rotation is proportional to scale factor of sensor and inversely proportional to optical bandwidth of light source used in the gyroscope. In this study, using a novel pump laser control closed-loop method, gyroscope performance is able to significantly enhance including signal-to-noise ratio (SNR). Fiber optic gyroscope includes an Yb-doped amplified spontaneous emission (ASE) source with broad emission spectra of 15 nm bandwidth used as light source in order to improve gyroscope sensitivity. The final ARW performance is about $0.008^\circ/\sqrt{hr}$ for a fiber coil of 150 m length.

1. Introduction

In case of loss of navigation information of an exterior source such as global navigation satellite systems (GNSS), scientist and engineers seek methods that can facilitate self-navigation. While high accuracy is paramount in inertial navigation systems (INS), the demand for low power consumption is just as important. Applications, such as unmanned air vehicle (UAV), unmanned underwater vehicle (UUV), satellite control system, and gyrocompass, require compact, highly accurate, robust INS in order to increase operation time and performance of the system [1, 2]. Accelerometers and gyroscopes are the main inertial sensors used in INS for each orthogonal axis. For many years, ring laser gyroscopes (RLGs) had been leading the gyroscope technology due to its accuracy and temperature stability. Today, the fiber optic gyroscope (FOG) technology reaches ultimate theoretical performance and surpasses the RLGs and has gained an important role in the market thanks to their compact and robust structure that does not include moving parts [3, 4]. Additionally, its low production complexity and widely available fiber optic components thanks to telecommunication industry make them ideal for low cost and mass production. Although new FOG technologies such as Brillouin or resonant FOG have been developed over the past few decades, they have not replaced the well-established interferometric FOG technology [5]. The need for more accurate and compact INS pushed researchers to improve performance of interferometric fiber optic gyroscope (IFOG). Different modulation techniques and calibration techniques are implemented in this regard [6–8].

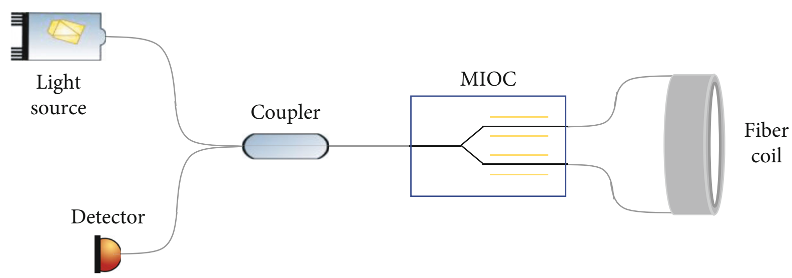


Figure 1: Basic IFOG schematic.

Furthermore, lower wavelength IFOGs are developed. Scale factor (SF) of FOG is a parameter that determines the relation between the input rotation rate and output. This relation is given in [3]

$$\Delta\phi_R = \frac{2\pi \bullet L \bullet D}{\lambda \bullet c}\Omega_R, \quad (1)$$

where $\Delta\phi_R$ is the phase difference due rotation rate, Ω_R; L and D are total fiber coil length and diameter, respectively; c is the speed of light; and λ is the central wavelength of the light source.

Wavelength and sensitivity are inversely proportional, as can be seen in (1). Therefore, designing an IFOG with a shorter wavelength increases sensitivity. Typically, open-loop modulation technique is implemented in these applications [9, 10].

Mainly, ARW of IFOG is limited by relative intensity noise (RIN), and this noise is inversely proportional to the bandwidth of the optical source. This characteristic of RIN is one of the main factors for the light source selection. Superluminescent laser diodes (SLDs) with their broad spectrum are commonly used as light source for the FOG; however, its central wavelength sensitivity to the temperature changes limits their application to a narrow operating temperature range [11].

Amplified spontaneous emission (ASE) sources have many excellent features such as broadband spectrum, low coherence, high optical power, and good mean-wavelength stability which are essential for fiber optic gyroscopes [12]. Most common rare earth elements that are used in ASE source as active medium are erbium (Er) and ytterbium (Yb). Er-doped ASE sources produce light around a center wavelength of 1550 nm, whereas Yb-doped ASE source produces around 1030 nm. Er-doped fiber ASE sources have been thoroughly investigated over the years where various new techniques were developed in order to broaden their spectral width and increase the wavelength stability [13, 14]. Mainly, Er-doped ASE sources are used in IFOG as light sources. However, IFOG with Er-doped ASE sources reached limits in their performance. Therefore, new techniques and sources are mandatory in order to further improve the gyroscope performance. For example, IFOG driven by 1550 nm laser source broadened by phase modulation used as new light source was developed in order to minimize ARW by 3 dB [15, 16]. This technique has some drawbacks such as requirement for additional component that increase size and complexity in IFOG architecture. On the other hand, Yb-doped fiber has many attractive characteristics such as broad gain spectrum and higher efficiency compared to Er-doped ASE sources [17]. Broad gain spectrum creates wide bandwidth, while higher efficiency enables to drive laser diode of ASE source with lower current. These advantages provide lower power consumption. Moreover, radiation resistance makes Yb ASE source suitable for space missions [18]. Additionally, sensitivity and noise performance increase as the central wavelength of gyroscope decreases. Considering all these features, Yb-doped ASE source is suitable for lower power consumption, lower ARW, and higher wavelength stability.

A basic IFOG consists of a light source, a coupler, a phase modulator including Y-junction, a fiber coil, and a detector as shown in Figure 1. In this study, Yb-doped ASE source is used as light source. Multifunctional integrated optical circuit (MIOC) is used as Y-junction coupler, polarizer, and phase modulator. Detector is a positive intrinsic negative field effect transistor (PINFET) device.

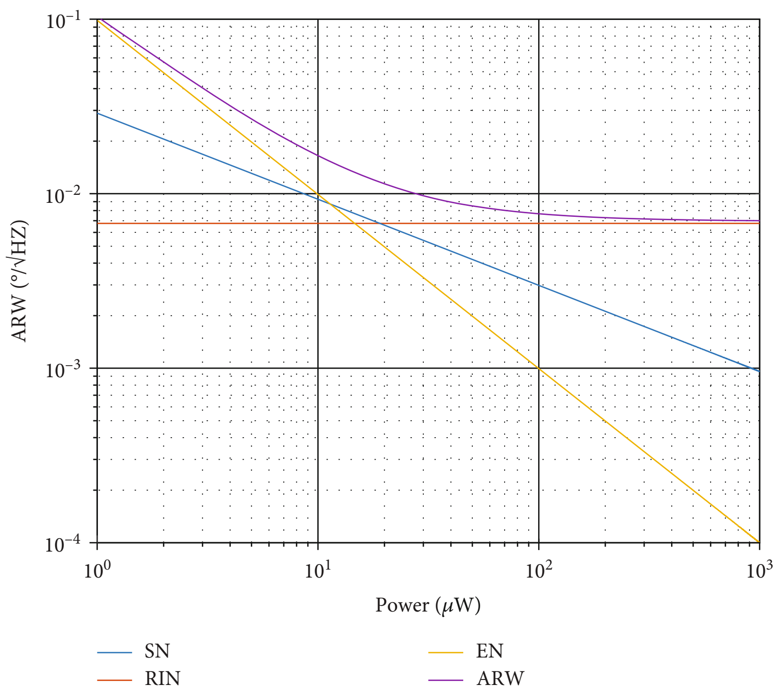
ARW sources of IFOG consist of electrical noises (EN), such as Johnson noise, dark current noise, shot noise (SN), and optical noise (i.e., relative intensity noise (RIN)), respectively, as shown in (2). ARW at typical modulation depth of $\pi/2$ can be theoretically calculated as [19]

$$\mathrm{ARW} = \frac{\sqrt{2}\lambda \bullet c}{2\pi \bullet L \bullet D}\sqrt{\frac{4k_b T}{R\eta^2 P^2} + \frac{e i_d}{\eta^2 P^2} + \frac{e}{\eta P} + \frac{\lambda^2}{4c\Delta\lambda}}, \quad (2)$$

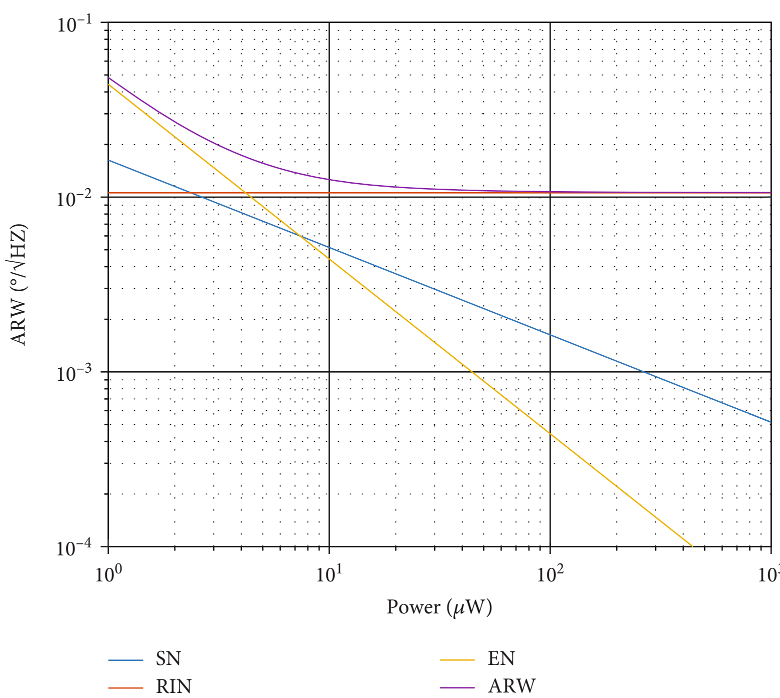
where k_b is the Boltzmann's constant, T is the temperature in Kelvin, R is the resistance of the transimpedance amplifier, η is the photodiode efficiency, P is the optical power at photodiode, e is the elementary charge, i_d the is dark photodiode current, λ the is central wavelength, and $\Delta\lambda$ is bandwidth the of optical source.

Using (2), dominant noise can be identified [19]. By decreasing central wavelength of IFOG, SF and RIN can be reduced. Hence, ARW performance can be improved by using Yb-doped ASE instead of Er-doped ASE source. In Figure 2, this theoretical improvement is displayed. Here, horizontal axis is the optical power at photodiode.

EN is the dominant noise source type if there is low optical power at photodetector. RIN limits ARW if the optical power is over 10 μW. In case of constant optical bandwidth for both configurations, only using 1030 nm



(a)



(b)

FIGURE 2: Noise analysis of (a) 1030 nm and (b) 1550 nm FOG.

ASE source will improve ARW about 2-fold for around 100 μW optical power output at PINFET theoretically. This value can be further improved by increasing the optical power because ARW of IFOG using Er-doped ASE source is limited around 100 μW optical power, while 200 μW optical power results in better ARW values for IFOG using Yb-doped ASE source.

According to the Sagnac effect, a fiber optic gyroscope is a sensing element of rotation that creates phase difference between counterpropagating waves inside fiber coil. This phase change ($\Delta\Phi_R$) can be calculated using [3]

$$\Delta I = 2I_0[\sin\Delta\Phi_R \sin \Phi_m] + 2\sigma_i, \tag{3}$$

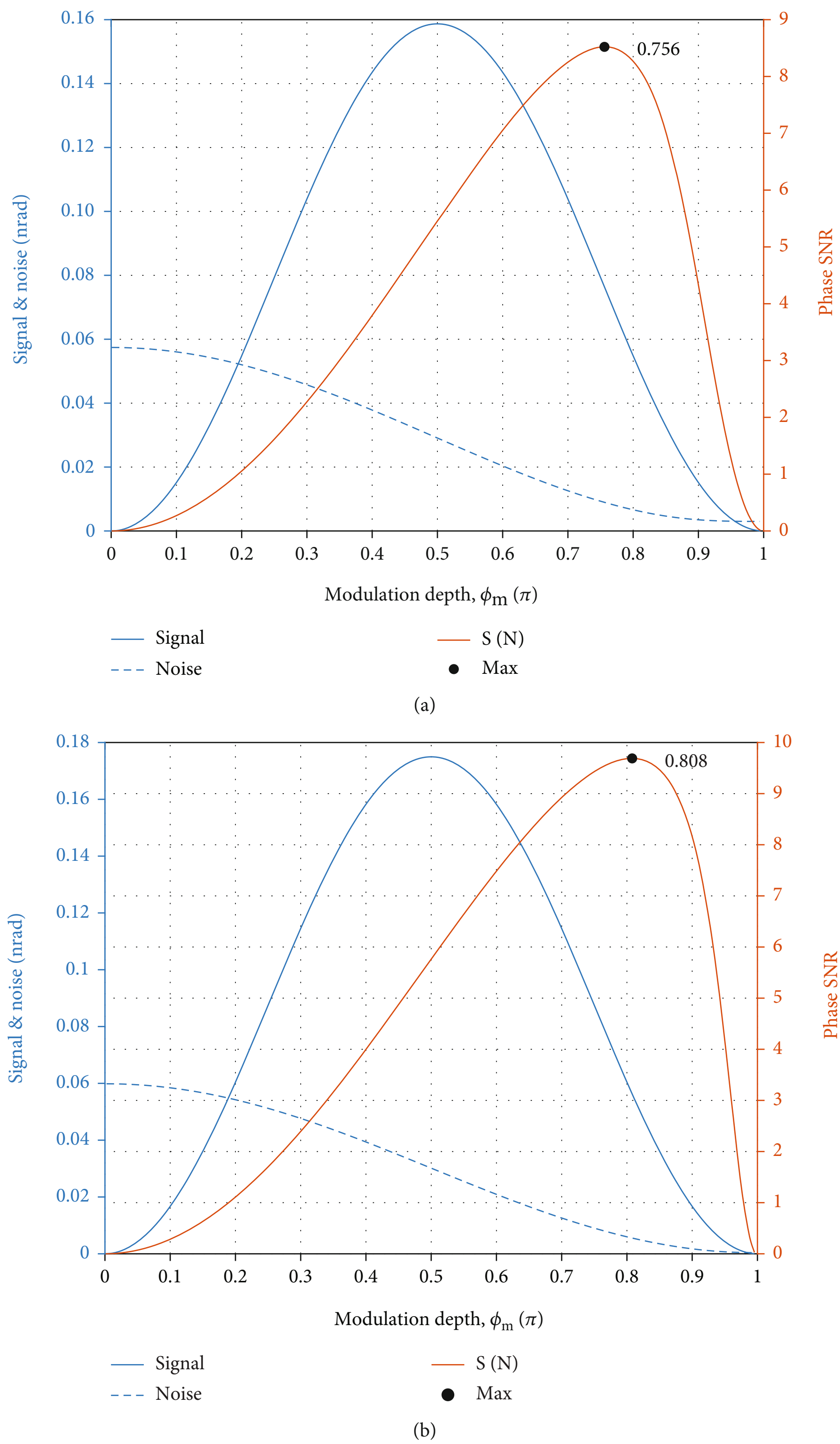


Figure 3: SNR analysis of 1030 nm FOG (a) 100 μW and (b) 105 μW optical power.

where ΔI is the signal difference between modulation levels, I_0 is the maximum signal level, Φ_m is the phase modulation depth, and σ_i is the uncorrelated noise at i^{th} modulation level.

Phase difference due to rotation can be calculated using small angle approximation.

$$\Delta\Phi_R \approx \frac{\Delta I}{2I_0 \sin \Phi_m} - \frac{\sigma_i}{I_0 \sin \Phi_m}. \quad (4)$$

The first term in (4) is defined as phase signal, and the second term is noise in phase due to rotation. After simplifying, phase SNR can be calculated using

$$\mathrm{SNR} = \frac{\Delta I}{2\sigma_i}. \quad (5)$$

The noise (σ_i) at photodetector corresponds to a specific phase noise level. This noise level limits the minimum detectable rotation rate. Noise component at detector is highly dependent on optical power of light source. Hence, ratio between phase difference due to rotation and phase noise level can be optimized by controlling and optimizing optical power. Figure 3 shows phase signal which is optimal at $\Phi_m = \pi/2$, noise and SNR values corresponding 100 μW and 105 μW optical at PINFET for 1030 nm. Phase signal level is calculated for Earth rotation rate at latitude of 39.93°.

5% change in optical power shifts the optimal SNR and modulation value. Similarly, phase SNR value for a fixed modulation depth of 0.8π changes about 8.3 to 9.8. These results state that optical power should be optimized and controlled for improved SNR value for a fixed modulation depth.

Mainly, four fundamental ASE source configurations are developed in literature including single pass forward (SPF) and backward (SPB) and double pass forward (DPF) and backward (DPB) [20]. Each design has its benefits in terms for optical power, central wavelength stability, and optical bandwidth. Hence, SPB configuration with broadest bandwidth is implemented to reduce ARW, which is the main aim of this study. ASE design consists of a pump laser diode (LD) operating at 976 nm, a wavelength division multiplexer (WDM) to combine pump and emission wavelength, Yb-doped fiber with high concentration, and in-line isolator to block back reflections resulting from fiber outputs. The design is shown in Figure 4.

As shown in Figure 3, optical power should be optimized and controlled for improved SNR. The proposed system includes a closed-loop control system that optimizes output optical power at ideal value for optimal SNR as shown in Figure 4. Back faced (BF) output of LD which is correlated with power output of the system is monitored. The monitored value is controlled and optimized using and signal processing unit that drives laser current. Phase SNR can be enhanced by over 10 percent for 5 percent change of optical power using closed-loop control of ASE source.

In this study, a novel IFOG is proposed including a closed-loop operation of laser diode inside Yb-doped ASE source. Such operation significantly enhances the SNR. Additionally, all the advantages of IFOG such as high sensitivity with shorter wavelength, stable light source such as amplified spontaneous emission source robust structure with all-fiber design, low power consumption, higher stability, and closed-loop operation were combined in order to achieve a high-performance system.

2. Experimental Results

For SPB configuration, Yb-doped fiber pumped in forward direction. Output is observed either through the second input of WDM. Angled-physical contact (APC) is used to block back reflections from active fiber end.

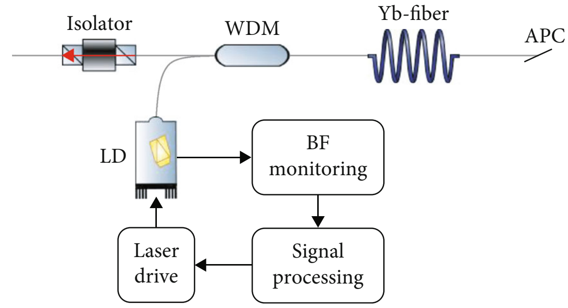


Figure 4: Single pass backward configuration.

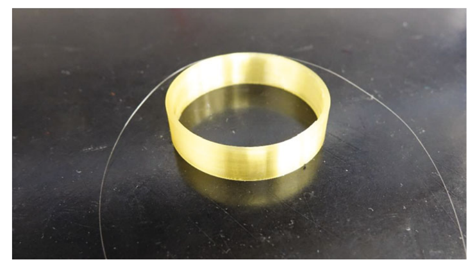


Figure 5: PM fiber for 1030 nm, 150 m length.

A special PM fiber operating at around 1 μm wavelength was used as heart of IFOG. PM type fiber has a reduced coating diameter which is 165 μm. Thus, smaller volume can be obtained compared to fibers with standard 250 μm coating. PM fiber is wound about 150 m using quadrupole winding technique to create a symmetrical structure that minimizes the effect of temperature change [3, 21]. Diameter of coil is about 45 mm. The photo of the fiber coil is shown in Figure 5.

1030 nm IFOG mainly consists of Yb-doped ASE source, heart of gyroscope sensor, detection part, and reading electronics as shown in Figure 6 [22]. Output light from ASE source is directed to MIOC and PM fiber coil. Here, PM fiber coil is sensing element, and MIOC has role of phase coupling, polarizing, and modulation. Additionally, closed-loop signal is directed to MIOC. Optical signal output of sensing element of FOG is detected using PINFET. Current output of PINFET is converted to voltage signal via an analog to digital converter (ADC). A main electronic card including processing unit (CPU) is responsible for data acquisition, signal processing, sensor control, and input/output communication management. Mathematical calculations of the closed-loop FOG are implemented in digital signal processing (DSP) module. Modulation signal is the sum of biasing modulation which sets interferometer to working point and rate control loop feedback modulation that nulls the phase shift due to the Sagnac effect at the interferometer.

3. Results

The output of Yb-doped ASE source is characterized in terms of optical power and optical spectrum. Central

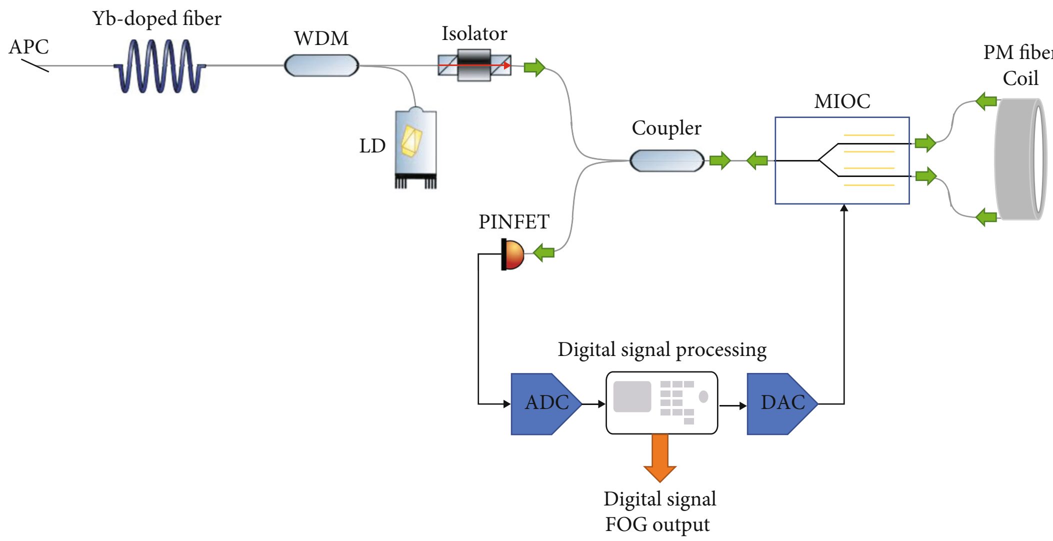


Figure 6: Functional scheme of Yb ASE IFOG.

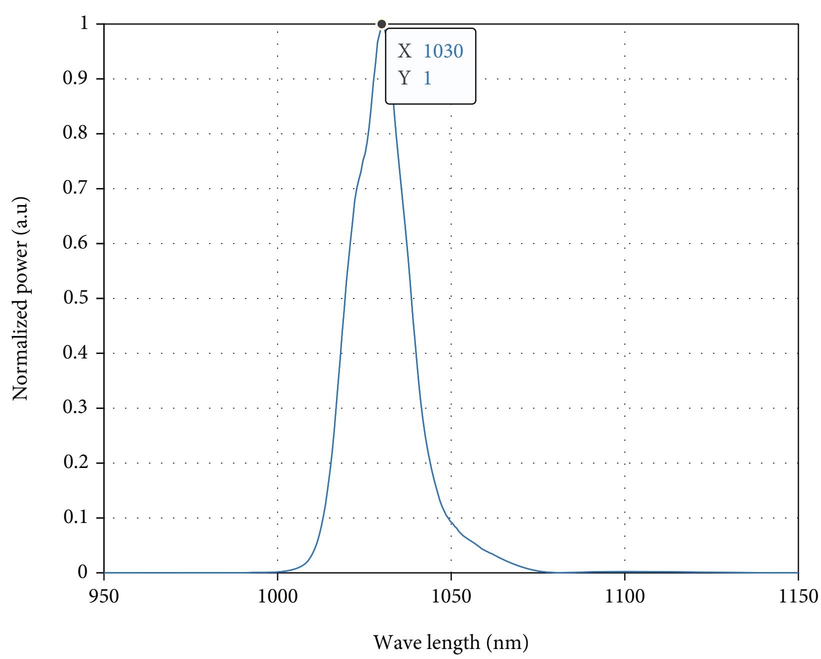


Figure 7: Spectrum output of Yb-doped ASE source.

wavelength of ASE source 1030.0 nm and optical bandwidth is about 15 nm. Optical spectrum analyzer is used for spectral measurements. Spectrum output of ASE emission is shown in Figure 7.

Optical power measurements of Yb-doped ASE source power were carried using optical power meter. The results are displayed in Figure 8.

In order to achieve similar power levels with Er-doped ASE source, laser diode current should be almost doubled. For about 0.5 A laser diode current and 5 V operation voltage, 2.5 W power is gained. Additionally, lowering laser diode current increases the laser diode lifetime (i.e., mean time between failure (MTBF)) [23].

Angle random walk (ARW) is an uncorrelated and high-frequency noise component for fiber optic gyroscopes. ARW of fiber optic gyroscope is the main noise source in short-term performance. ARW parameters for various optical power at PINFET are determined using Allan variance analysis. The ARW results are displayed in Figure 9. Straight lines are the tangential lines with the slope of -1/2 to Allan deviation curves for 10, 110, and 120 μW (blue, red, and green, respectively). The intersection of $\tau = 1$ hr and extrapolated line determines the ARW parameter in the Allan variance graphic.

The ARW value of 1030 nm FOG has good agreement with theoretical analysis. For 110 μW and 120 μW, ARW

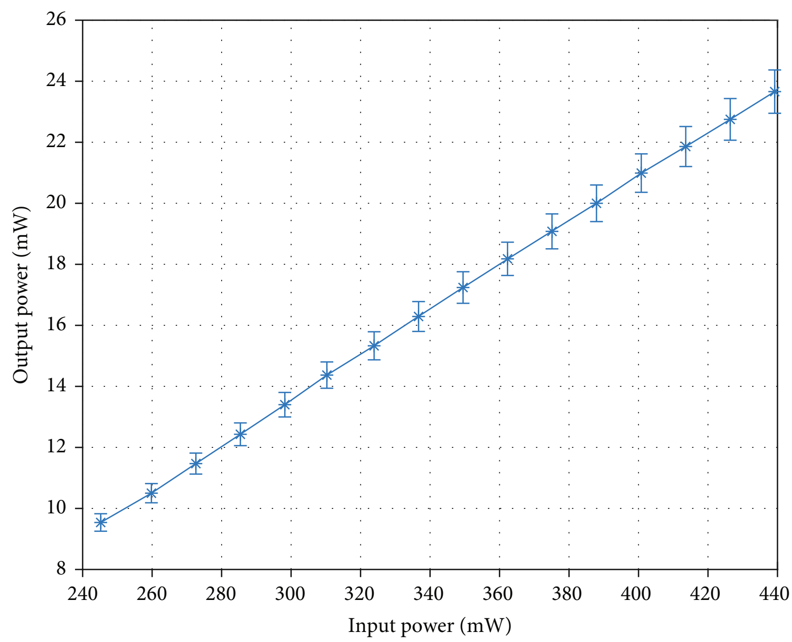


Figure 8: Optical power output of Yb-doped ASE source.

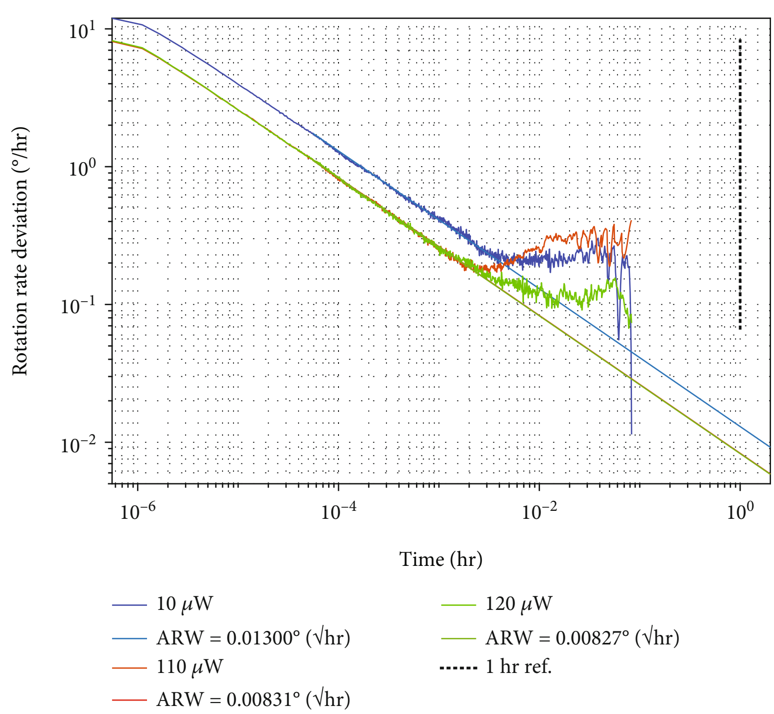


Figure 9: Allan variance analysis results for various optical power.

values are about $0.00831^\circ/\sqrt{\text{hr}}$ and $0.00827^\circ/\sqrt{\text{hr}}$ which states that optical dependency of ARW is still observable. This dependency is also displayed with 10 μW optical power measurement which has ARW value of $0.0130^\circ/\sqrt{\text{hr}}$. The system is optimized in terms of ARW performance. Bias stability is not considered. The heat dissipation of electronics and mechanics creates in drift in long term. Therefore, further improvement in mechanical design and temperature calibration can enhance bias stability performance.

4. Conclusion

In this study, a novel closed-loop operation of laser diode inside ASE source is implemented in IFOG. New technique increases SNR by controlling power output of light source at optimal power level. Phase SNR can be enhanced by over 10 percent for 5 percent change of optical power. An all-fiber closed-loop 1030 nm fiber optic gyroscope is demonstrated. For the first time, Yb-doped ASE source with broad bandwidth is developed to reduce dominant source of ARW which is dominated by relative intensity noise and increase scale factor of gyroscope. All-fiber structure allows operating a robust system. High efficiency in gain medium allow to operate low operating current resulting in low power consumption which is very crucial for space applications. Rotation rate sensitivity is increased by about 2-fold with the increase in scale factor when compared to common ASE source of 1550 nm. Alongside with the increase in sensitivity, ARW performance is also improved. This improvement results in better gyroscope performance compared similar gyroscope operating at 1550 nm. Different techniques such as a laser broadened by phase modulation are used to enhance ARW performance. In literature, 3 dB performance increase is demonstrated. Yb-doped ASE source can be combined with phase broadening method to achieve 4-fold ARW performance. Moreover, one can decrease the device volume by designing smaller gyroscope coil with shorter fiber length for a desired ARW value. Addition to low power consumption and low volume, radiation resistant of Yb-doped ASE source makes such design suitable for space missions. Finally, SNR is optimized by monitoring and controlling power output of the ASE source.

Data Availability

Data is available upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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