

**HYBRID ASE LIGHT SOURCE OPTIMIZATION USING UNPUMPED
EDF: IMPACT ON SPECTRAL PROPERTIES AND BIAS INSTABILITY IN
FIBER OPTIC GYROSCOPES**

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NİGAR BUSE BOZKUŞ

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EDF: IMPACT ON SPECTRAL PROPERTIES AND BIAS INSTABILITY IN
FIBER OPTIC GYROSCOPES**

submitted by **NİGAR BUSE BOZKUŞ** in partial fulfillment of the requirements for
the degree of **Master of Science in Physics, Middle East Technical University** by,

Prof. Dr. Naci Emre Altun
Dean, **Graduate School of Natural and Applied Sciences**

Prof. Dr. Seçkin Kürkçüoğlu
Head of the Department, **Physics Dept., METU**

Assist. Prof. Dr. Ihor Pavlov
Supervisor, **Physics Dept., METU**

Examining Committee Members:

Prof. Dr. Alpan Bek
Physics Dept., METU

Assist. Prof. Dr. Ihor Pavlov
Supervisor, **Physics Dept., METU**

Prof. Dr. Ahmet Bingöl
Physics Engineering Dept., Gaziantep University

Date: 21.08.2025



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Name Last Name: Nigar Buse Bozkuş

Signature:

ABSTRACT

HYBRID ASE LIGHT SOURCE OPTIMIZATION USING UNPUMPED EDF: IMPACT ON SPECTRAL PROPERTIES AND BIAS INSTABILITY IN FIBER OPTIC GYROSCOPES

Bozkuş, Nigar Buse
Master of Science, Physics
Supervisor: Assist. Prof. Dr. Ihor Pavlov

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Amplified Spontaneous Emission (ASE) light sources with erbium-doped fiber (EDF) are commonly used in sensor technologies due to their high power, incoherent nature, wide bandwidth, and high wavelength stability. Improvements in the ASE light source directly enhance the gyroscope outputs, including bias instability.

In this study, double-pass forward and double-pass backward configurations are combined and optimized by adding an unpumped erbium-doped fiber as a filter. The integration of a spectral filter into the configuration decreased the wavelength stability of the light source from approximately 14 ppm to nearly 6 ppm. Thermal tests at -25°C and $+60^{\circ}\text{C}$ revealed enhanced wavelength stability for the configuration with an EDF filter under extreme conditions. Furthermore, the average bias instability value is improved by 36% using the filtering technique in a single-axis tactical-grade gyroscope. These results demonstrate the significant role of the EDF filter in ASE performance and sensor outputs, providing valuable insights for optimizing light sources in IFOG systems to meet the system's specific needs.

Keywords: Amplified Spontaneous Emission (ASE) Light Source, Erbium-Doped Fiber, Fiber Optic Gyroscope (FOG), Bias Instability

ÖZ

POMPALANMAMIŞ EDF KULLANILARAK HİBRİT ASE IŞIK KAYNAĞININ OPTİMİZASYONU: SPEKTRAL ÖZELLİKLER VE FİBER OPTİK DÖNÜÖLÇERLERDEKİ SAPMA KARARSIZLIĞINA ETKİSİ

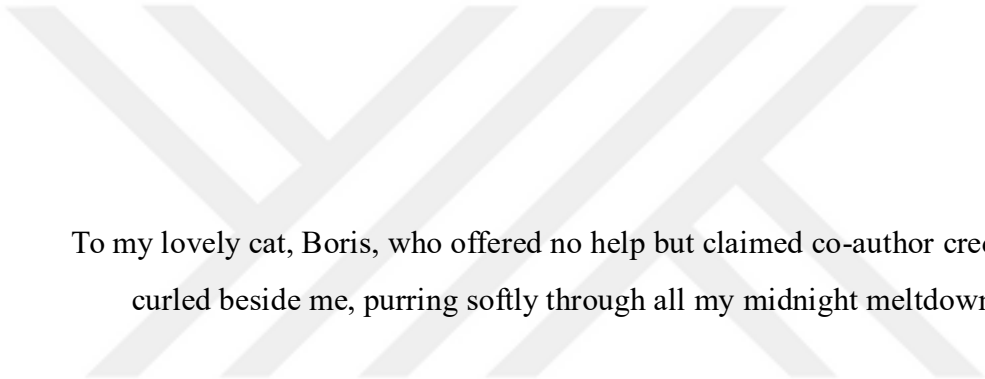
Bozkuş, Nigar Buse
Yüksek Lisans, Fizik
Tez Yöneticisi: Dr. Öğr. Üy. Ihor Pavlov

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Erbiyum katkılı fiber (EDF) içeren Yükseltgenmiş Kendiliğinden Emisyon (ASE) ışık kaynakları, yüksek güçleri, incoherent yapıları, geniş bant genişlikleri ve yüksek dalga boyu kararlılıkları nedeniyle sensör teknolojilerinde yaygın olarak kullanılmaktadır. ASE ışık kaynağındaki iyileştirmeler, sapma kararsızlığı gibi dönüölçer çıktılarını doğrudan iyileştirir.

Bu çalışmada, çift geçişli ileri ve çift geçişli geri konfigürasyonlar birleştirilmiş ve filtre olarak pompalanmamış erbiyum katkılı fiber eklenerek optimize edilmiştir. Konfigürasyona bir spektral filtrenin entegre edilmesi, ışık kaynağının dalga boyu kararlılığını yaklaşık 14 ppm'den neredeyse 6 ppm'ye düşürdü. -25°C ve $+60^{\circ}\text{C}$ 'deki termal testler, zorlu çevresel koşullar altında EDF filtreli konfigürasyon için gelişmiş dalga boyu kararlılığını ortaya koydu. Dahası, ortalama sapma kararsızlığı değeri, tek eksenli taktik seviye bir dönüölçerde filtreleme tekniği kullanılarak %36 oranında iyileştirildi. Bu sonuçlar, EDF filtrenin ASE performansında ve sensör çıktılarında önemli rolünü göstererek, sistemlerdeki ışık kaynaklarını sistemin özel ihtiyaçlarını karşılayacak şekilde optimize etmek için değerli çıkarımlar sağlıyor.

Anahtar Kelimeler: Yükseltgenmiş Kendiliğinden Emisyon (ASE) Işık Kaynağı, Erbiyum Katkılı Fiber, Fiber Optik Dönüölçer, Sapma Kararsızlığı



To my lovely cat, Boris, who offered no help but claimed co-author credit, and
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LIST OF ABBREVIATIONS

ABBREVIATIONS

APE	Annealed Proton Exchange
ARW	Angle Random Walk
ASE	Amplified Spontaneous Emission
CCW	Counter-Clockwise
CW	Clockwise
DPB	Double Pass Backward
DPF	Double Pass Forward
DTG	Dynamically Tuned Gyroscopes
EDF	Erbium-Doped Fiber
EDFA	Erbium-Doped Fiber Amplifier
FBG	Fiber Bragg Grating
FC	Fiber Channel
FOG	Fiber Optic Gyroscope
FRM	Faraday Mirror
FWHM	Full Width at Half Maximum
GPS	Global Positioning System
IFOG	Interferometric Fiber Optic Gyroscope
IMU	Inertial Measurement Unit
INS	Inertial Navigation System
LD	Laser Diode
LDC	Laser Diode Controller
LED	Light Emitting Diode
MEMS	Micro Electro-Mechanical System
MIOC	Multifunction Integrated-Optic Circuit
MM	Multimode
OSA	Optical Spectrum Analyzer

PD	Photodetector
PIN	Positive-Intrinsic-Negative
PINFET	Positive-Intrinsic-Negative Field Effect Transistor
PM	Polarization Maintaining
PMF	Polarization Maintaining Fiber
ppm	parts per million
PSD	Power Spectral Density
RLG	Ring Laser Gyroscope
SAP	Stress Applying Parts
SF	Scale Factor
SLD	Super-Luminescent Diode
SM	Single Mode
SMF	Single Mode Fiber
SPB	Single Pass Backward
SPF	Single Pass Forward
TIR	Total Internal Reflection
YDFA	Ytterbium-Doped Fiber Amplifier
WDM	Wavelength Division Multiplexer

LIST OF SYMBOLS

SYMBOLS

A	Area of fiber coil
B	Bias instability coefficient
c	Velocity of light in a vacuum
D	Diameter of fiber coil
f_0	Cut-off frequency
h	h -parameter of a polarization-maintaining fiber
L	Length
M	Number of layers in a fiber coil
N	Number of turns in a fiber coil
N	Number of data points
N	Angle random walk coefficient
n	Index of refraction
n_1	Index of refraction of the core in a fiber
n_2	Index of refraction of the cladding in a fiber
n_{cladding}	Index of refraction of the cladding in a fiber
n_{core}	Index of refraction of the core in a fiber
P	Power
P_{max}	Maximum power
$\frac{P_{\text{max}}}{2}$	Half of the maximum power
P_{in}	Incoming power
P_{out}	Outgoing power
$P_{\perp}$	Power of the light propagating along the vertical axis
$P_{//\text{in}}$	Power of the light propagating along the horizontal axis
R	Radius of fiber coil
R_{in}	Inner radius of fiber coil
R_{out}	Outer radius of fiber coil

$S_{\Omega}(f)$	Rate power spectral density
t	Time
t_{ccw}	Transit time for counter-clockwise beam
t_{cw}	Transit time for the clockwise beam
v	Velocity of light in a medium
x	Distance
ΔL	Phase difference length of circular path
ΔL_{CW}	The path that CW light propagates
ΔL_{CCW}	The path that CCW light propagates
Δt	Transit time difference
$\Delta \phi$	Difference of phase
θ	Angle
λ	Wavelength
λ_1	The wavelength value at half of the max power in left side
λ_2	The wavelength value at half of the max power in right side
$\bar{\lambda}$	Mean wavelength
λ_c	Central wavelength
$\lambda_{stability}$	Wavelength stability
π	3.14159...
$\sigma(\tau)$	Allan deviation with respect to cluster time
$\sigma^2(\tau)$	Allan variation with respect to cluster time
τ	Cluster time
Ω	Rotation rate
$\Omega(t)$	Instantaneous Output Rate of Inertial Sensor
ω	Angular frequency
$\langle \rangle$	Temporal averaging

CHAPTER 1. INTRODUCTION

1.1. Gyroscope Technologies

1.1.1. What is a Gyroscope?

A gyroscope is a device that measures the angular velocity of a rotating frame with high accuracy (Lefevre, 2022). Since gyroscopes enable motion detection and precise navigation without the need for external references, such as the Global Positioning System (GPS), they are widely used in various sectors, including industrial, automotive, marine, and aerospace applications. There are several classes of gyroscopes, categorized by their operating principles and technologies. They can be utilized in many systems, including the Inertial Measurement Unit (IMU) and Inertial Navigation System (INS) (Passaro et al., 2017). The classes of gyroscopes can be divided into three basic categories, as shown in Figure 1.1.

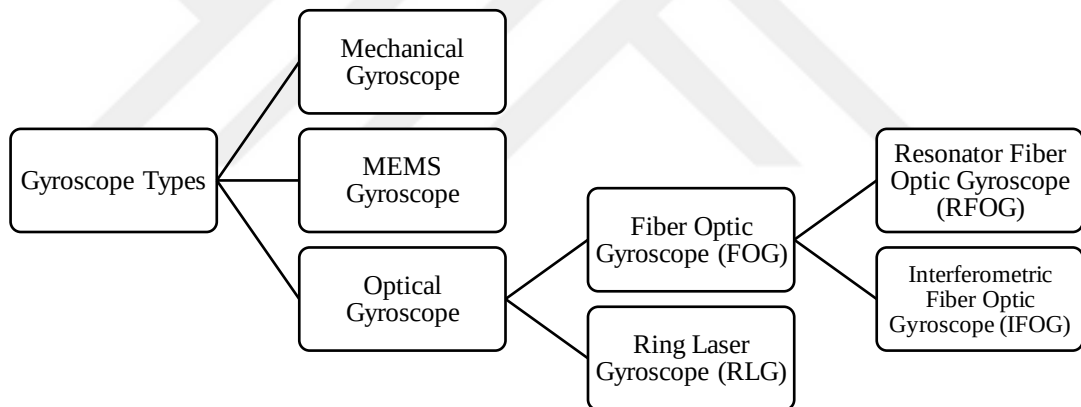


Figure 1.1. Gyroscope types (Shalaby & Elghandour, 2024).

1.1.2. Types of Gyroscopes

As mentioned, there are several types of gyroscopes, each with different operating principles and technologies:

Mechanical Gyroscopes:

In 1982, Leon Foucault developed the mechanical gyroscopes as part of his investigation into the Earth's rotation. The conservation of angular momentum represents what mechanical gyroscopes offer. As shown in Figure 1.2,

mechanical gyroscopes primarily utilize a rotating rotor to detect angular motion. The rotating component spins freely in any direction. The system tends to resist motion and stay parallel to itself if an external force is applied in any direction.

Classical inertial navigation systems are frequently utilized. Modern mechanical gyroscopes are significantly smaller and more compact than the large, heavy mechanical gyroscopes of the past. However, the moving elements on this gyroscope cause friction when it rotates, which is a major disadvantage (Kahveci, 2022).

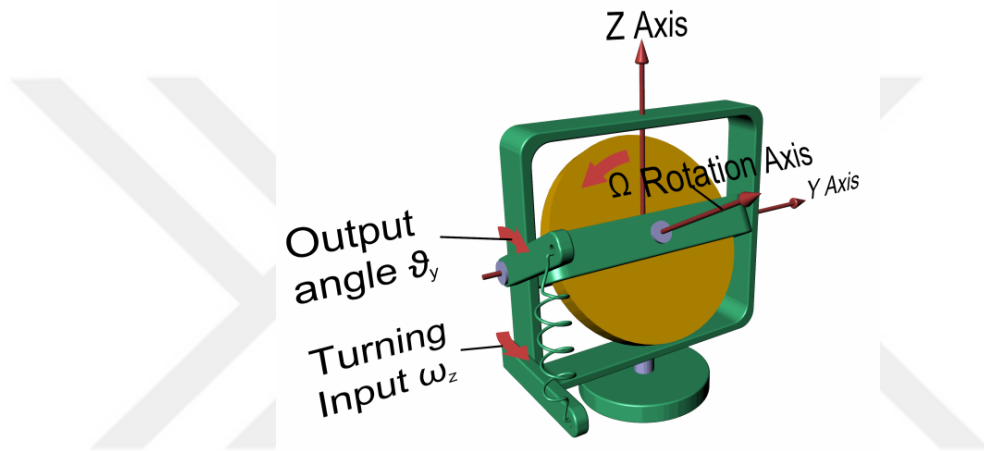


Figure 1.2. Parts of a mechanical gyroscope (Passaro et al., 2017).

MEMS Gyroscopes:

A MEMS gyroscope, which utilizes Coriolis force, is a type of gyroscope that is built using micro-electromechanical systems technology. They measure the angular velocity of moving objects. Unlike traditional gyroscopes, MEMS devices utilize a vibrating element instead of rotating parts with bearings, which simplifies miniaturization and enables production using standard MEMS manufacturing methods (Zhanshe et al., 2015). These gyroscopes have an advantage due to their smaller size, lower weight and lower costs compared to other gyroscopes (Shalaby & Elghandour, 2024).

Optical Gyroscopes:

An optical gyroscope is a type of gyroscope that uses the interference of light to measure rotation. The optical gyroscopes detect angular velocity using the Sagnac effect, a fundamental principle of physics based on the behavior of light in rotating reference frames.

The Sagnac effect, which will be discussed in detail in the following chapters, is a phenomenon observed when two beams of light travel in opposite directions around a closed loop on a rotating platform. Since the platform is rotating, one of the beams has a slightly longer path to travel than the other. This results in a measurable phase shift between the two counter-propagating beams. This phase difference is directly related to the angular velocity of the rotation. There are simply two types of optical gyroscopes that use this operating principle;

- i. Ring Laser Gyroscopes (RLGs): These gyroscopes use counter-propagating laser beams in a closed-loop cavity to detect phase shifts induced by rotation. When this closed-loop laser cavity is in rotation, the frequency shift is observed.

RLG is essentially a triangular glass block with the cavity inside filled with a helium-neon gas mixture. There are three air channels in the glass block and three mirrors in the corners, which produce a triangular optical resonator as shown in Figure 1.3. All three tubes are filled with Helium-Neon gas at low pressure. By using the two anodes and the cathode, a high-voltage electrical discharge is applied to pump the cavity electrically. As a consequence of this pumping, two counterpropagating beams with equal resonant frequencies are obtained in the cavity. By incorporating a partially reflective mirror into the system, one can measure the angular velocity by observing the shift in the resonant frequency of the device (Passaro et al., 2017).

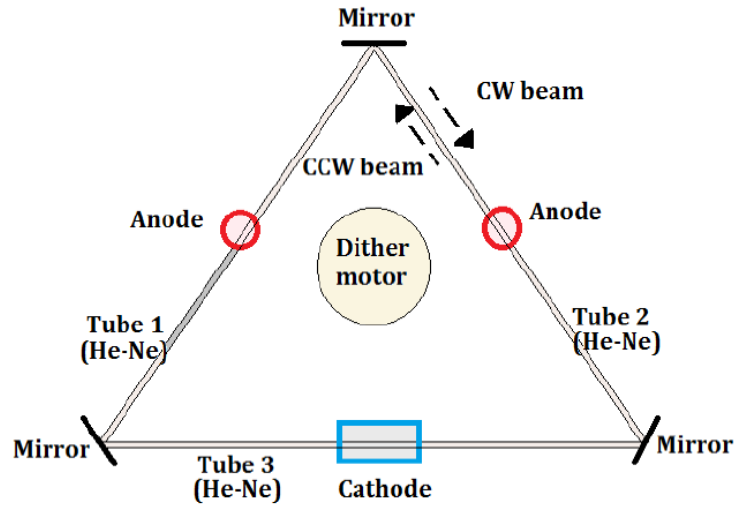


Figure 1.3. RLG diagram (Passaro et al., 2017).

Like all gyroscopes, Ring laser gyroscopes come with notable drawbacks to their performance and production. Their construction requires extremely precise cavity geometries and high-quality mirrors, often demanding assembly in clean-room conditions, which drives up costs and limits their economic use in lower-performance applications. In addition, their large size and weight hinder portability, and efforts to reduce these dimensions have frequently led to decreased reliability, with smaller units operating for much shorter durations (Juang & Radharamanan, 2009).

- ii. **Fiber Optic Gyroscopes (FOGs):** These gyroscopes utilize a fiber-optic coil to measure rotation by detecting the interference of counter-propagating light waves in a fiber loop, thereby providing high precision and reliability. There are two types of FOGs namely Resonator Fiber Optic Gyroscopes (RFOGs) and Interferometric Fiber Optic Gyroscopes (IFOGs).

An interferometric fiber optic gyroscope (IFOG), to be the main subject of this thesis, is an advanced optical sensor that utilizes the Sagnac effect to measure rotation. It works by using a laser source to split a beam into two separate wavelengths that travel in opposite directions through a fiber-optic coil. When these light beams reconvene at the

detector, any phase differences caused by rotation are measured to determine the rotation rate. The design and winding technique of fiber coil decide the performance of a FOG. The length, diameter, winding technique, and adhesive used for winding directly affect the coil performance, which in turn affects the overall sensor output. It is known that the sensitivity of a gyroscope increases with the length of the fiber coil. In contrast to RLGs, FOGs are a very cost-effective fiber-optic technology (Passaro et al., 2017).

1.1.3. Performances of Gyroscopes

The primary challenges associated with all gyroscope categories are related to measurement inaccuracies. The stability of the scale factor, therefore, serves as one of the most significant performance variables, where the scale factor indicates the optical gyroscope's sensitivity. A minimum scale-factor stability results in minor sensor errors and necessitates greater precision, while also increasing the system's cost. As a result, the application requirements have a direct impact on gyroscope performance and prices (Passaro et al., 2017).

Figure 1.4 presents gyroscope types with different performance levels and technologies. They differ from each other based on scale factor stability, which is on the y-axis, and bias stability, which is on the x-axis. The graph categorizes gyroscopes into different performance grades, illustrating their applications.

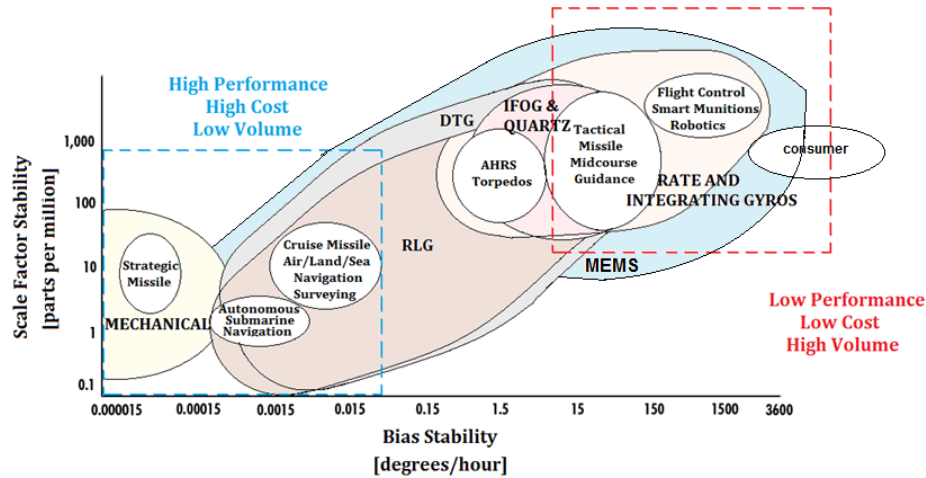


Figure 1.4. Comparison graph of scale factor stability vs. bias stability in gyroscopes (Passaro et al., 2017).

As seen in Figure 1.4, the performance zones are divided into three categories: high-performance, high-cost, and low-volume gyroscope; low-performance, low-cost, and high-volume gyroscope; and the middle region, which encompasses the gyroscope between these two categories. The high-performance, high-cost, and low-volume gyroscopes offer better scale factor stability and bias stability. Compared to this, the gyroscopes in the low-performance, low-cost, and high-volume section provide poorer scale factor stability and bias stability than those in the high-performance, high-cost, and low-volume section.

Table 1.1. compares Mechanical, Optical (RLG & FOG), and MEMS gyroscopes across key performance parameters, including size, weight, power consumption, precision, drift stability, environmental sensitivity, lifetime, and cost. Each gyroscope type has strengths and weaknesses, making them suitable for different applications.

Table 1.1. Comparison of Mechanical, Optical (RLG & FOG), and MEMS Gyroscopes Across Key Performance Parameters

Feature	Mechanical Gyroscope	Optical Gyroscope (RLG & FOG)	MEMS Gyroscope
Operating Principle	Uses a spinning rotor to detect angular motion	Exploits the physics of the Sagnac effect	Measures the Coriolis effect in vibrating structures
Technology Type	Classical, macroscopic	Laser-based (RLG) or fiber-based (FOG)	Silicon microfabrication
Size	Large and bulky	Medium (FOG) to large (RLG)	Very small, chip-scale
Weight	Heavy	Lighter than mechanical gyros	Extremely lightweight
Power Consumption	High	Moderate to high	Low

Precision	High, but degrades over time	Very high (FOG > RLG)	Moderate to low
Drift & Bias Stability	Moderate (due to mechanical wear)	Very low drift (FOG is the best)	High drift due to small-scale fabrication defects
Environmental Sensitivity	Sensitive to shocks and vibrations	Resistant to mechanical shocks	Highly sensitive to temperature, shock, and bias
Lifetime	Shorter due to moving parts	Long (no moving parts)	Long, but may degrade with aging effects
Cost	Expensive (due to precision mechanics)	High (RLG is more expensive than FOG)	Very low (mass production)
Common Applications	Aerospace, navigation, stabilization	Navigation, inertial guidance, fiber optic gyros	Consumer electronics, automotive, wearables

1.2. Objectives and Scope of The Study

The primary objective of this study is to design, implement, and evaluate a hybrid amplified spontaneous emission (ASE) light source configuration intended for use in interferometric fiber optic gyroscopes (IFOGs).

For this purpose, a general introduction to gyroscope technologies is discussed in the first chapter to reinforce and advance knowledge about gyroscopes. Moreover, various types of gyroscopes and their performances are compared with one another.

Then, the chapter delves into detail, discussing types, grade levels, and components in depth to gain a better understanding of IFOG. Lastly, the common error sources and their mitigation methods are summarized for a general perspective. Since this study focuses on the light source, specifically the ASE light source and its performance, the ASE light source configurations in the literature are investigated. First, the common configurations are described in detail, including their construction: single-pass backward, single-pass forward, double-pass backward, and double-pass forward configurations. Second, the spectral performance of single-pass backward, single-pass forward, double-pass backward, and double-pass forward sources is discussed, drawing on relevant literature. Then, the combination of double-pass configurations is analyzed. A specific method for improving performance is investigated and discussed in the following. Finally, the impact of IFOG on bias instability, achieved by enhancing the ASE light source, is discussed.

In Chapter 3, we construct the hybrid ASE light source, providing details about its configuration and the production steps involved. Most literature sources utilize two pumping wavelengths of 980 nm and 1480 nm. However, this study uses only one pumping wavelength at 980 nm. Power measurements and spectral test results are detailed and discussed. The key parameters of the light source are examined, including output power, central wavelength, full width at half-maximum (FWHM), spectral shape, spectral symmetry, and wavelength stability.

Additionally, the configuration improves with the addition of extra components: first, isolator, and then unpumped EDF. Since unpumped erbium-doped

fiber acts as a filter, significantly enhancing the output, we compare the light source results with and without the filter. While previous studies have utilized longer unpumped EDF lengths, such as 2.5 m, this study examines the effects of using lengths of only 1 m or 0.5 m.

With the recent addition, the ASE light source results have improved. To see if this improvement is reflected in gyro outcomes, we constructed and tested a single-axis gyroscope with a tactical-grade fiber coil. We discuss and compare the bias instability values and angle random walk values using Allan deviation, leading to an improvement in bias instability of approximately 36%.

Finally, we discuss and summarize the findings in Chapter 5, which serves as the conclusion. Overall, this study constructs and tests the hybrid ASE light source with new configurations, including IFOG tests. This research contributes to the ongoing development of high-performance, low-noise optical sources for inertial navigation systems, offering a practical approach to enhancing IFOG precision by optimizing ASE source design.

CHAPTER 2. LITERATURE REVIEW

2.1. Interferometric Fiber Optic Gyroscope (IFOG)

An Interferometric Fiber Optic Gyroscope (IFOG) is a high-precision gyroscope that utilizes the Sagnac effect to measure angular velocity. In an IFOG, light from a broadband source is split into two beams that travel in opposite directions through a long fiber-optic coil. When the gyroscope rotates, a phase shift occurs between the two beams due to the Sagnac effect, which is detected through an interferometric process to determine the gyroscope's orientation.

2.1.1. Working Principle of IFOG: Sagnac Effect

The fundamental principle behind nearly all optical gyroscopes is the Sagnac effect, discovered by George Sagnac in 1913, which induces a phase difference $\Delta\Phi$ within a ring interferometer configuration due to a rotation rate Ω . In Sagnac's original experiment, a collimated light source and a beam-splitting plate were used to divide the incoming beam into two counter-propagating waves that traveled along a closed-loop path defined by mirrors (Lefevre, 2022).

In Figure 2.1, a fiber coil with two counterpropagating beams is illustrated, based on the Sagnac principle. One of the beams travels in the clockwise direction, indicated by red arrows, while the other beam propagates in the counterclockwise direction, marked with blue arrows.

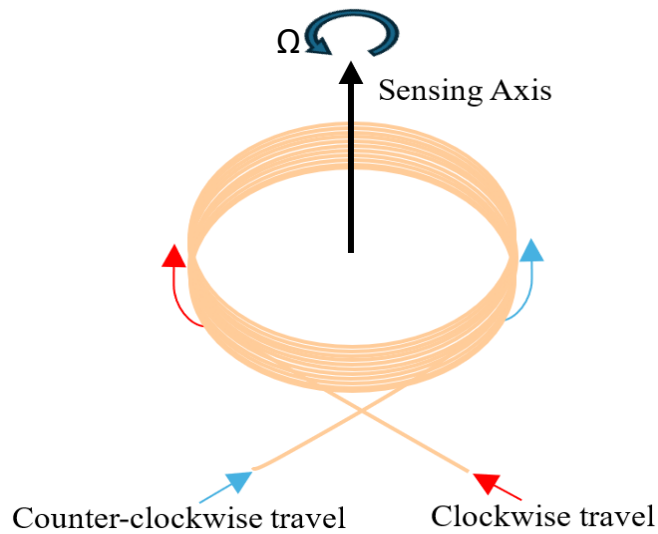


Figure 2.1. Light propagation on fiber coil.

Suppose two light beams are sent through the fiber coil from opposite directions. In that case, they reach the same point at the same time, i.e., with equal transit times, due to the symmetrical circular path, as illustrated in Figure 2.2.a, if the system is stationary. However, if there is a rotation in the system, a phase difference will occur because the transition times of the two counter-propagating beams will differ from each other.

According to the Sagnac effect, when two light beams travel in opposite directions around a circular path, a phase difference occurs between them if the system is rotating, as illustrated in Figure 2.2.b. This phase difference can then be used to determine the angular velocity of the rotating system (Lefevre, 2022). As shown in the figure, the beam in the clockwise direction will move more than the counter-clockwise direction beam by ΔL .

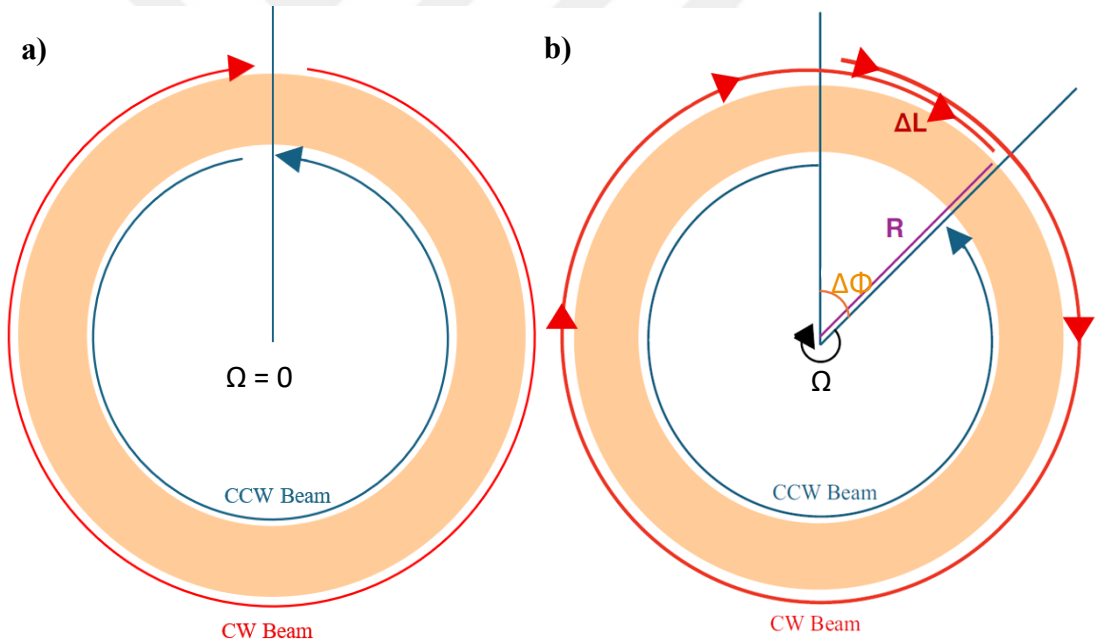


Figure 2.2. Sagnac effect representation: (a) stationary system, (b) rotating system.

The parameters will be used in the following equations:

- $\Omega \equiv$ angular velocity, rotation rate, where $\Omega = 2\pi\nu$
- $\Delta\Phi \equiv$ phase difference
- $R \equiv$ radius of fiber coil
- $\Delta L \equiv$ phase difference length of circular path
- $c \equiv$ speed of light in vacuum

- $\lambda \equiv$ working wavelength
- $v \equiv$ speed of light in medium with refractive index n where $v = c/n$
- $\nu \equiv$ frequency where $\nu = c/\lambda$

It is known that the basic velocity formula is $x = v \times t$. In this case, this becomes $\Delta L = R \times \Omega \times t$ where $R \times \Omega$ It is the tangential angular speed. Therefore, the total length of the path in clockwise and counter-clockwise directions can be calculated as follows:

$$L_{CW} = 2\pi R + R\Omega t_{CW} = ct_{CW} \quad 2.1$$

$$L_{CCW} = 2\pi R - R\Omega t_{CCW} = ct_{CCW} \quad 2.2$$

If equations 2.1 and 2.2 are arranged, one can obtain the transit time for two opposite directions. Thus, the transition time with N turns in the clockwise direction becomes:

$$2\pi RN = ct_{CW} - R\Omega t_{CW} \quad 2.3$$

$$2\pi RN = t_{CW}(c - R\Omega) \quad 2.4$$

$$t_{CW} = \frac{2\pi RN}{c - R\Omega} \quad 2.5$$

Similarly, transit time in the counter-clockwise direction is becoming:

$$t_{CCW} = \frac{2\pi RN}{c + R\Omega} \quad 2.6$$

By using Equations 2.5 and 2.6, one can calculate the transit time difference, Δt , as follows:

$$\Delta t = t_{CW} - t_{CCW} = \frac{2\pi RN}{c - R\Omega} - \frac{2\pi RN}{c + R\Omega} \quad 2.7$$

$$\Delta t = \frac{4\pi R^2 N \Omega}{c^2 - R^2 \Omega^2} \quad 2.8$$

Since $c^2 \ll R^2 \Omega^2$, one can deduce Equation 2.8 to the following

$$\Delta t \cong \frac{4\pi R^2 N \Omega}{c^2} \quad 2.9$$

Since the diameter is $D = 2R$ and the total perimeter of the loop is $L = 2\pi R N$, Equation 2.9 becomes

$$\Delta t \cong \frac{LD\Omega}{c^2} \quad 2.10$$

Finally, one can determine the phase difference $\Delta\Phi$ induced by rotation rate Ω as follows:

$$\Delta\Phi = \Omega \times t = 2\pi\nu \times \Delta t = 2\pi \frac{c}{\lambda} \Delta t \quad 2.11$$

One can place Equation 2.10 into Equation 2.11.

$$\Delta\Phi = 2\pi \frac{c}{\lambda} \frac{LD\Omega}{c^2} \quad 2.12$$

Therefore, the phase difference in vacuum becomes

$$\Delta\Phi = \frac{2\pi LD}{\lambda c} \Omega \quad 2.13$$

Since the light is propagating in a medium, one can use v , which is the speed of light in the medium with refractive index n , where $v = c/n$. Therefore, the phase difference in a medium is

$$\Delta\Phi = \frac{2\pi LD}{\lambda v} \Omega \quad 2.14$$

Since the total fiber length L , the mean diameter D , and the working wavelength λ and the speed of light in a medium v are constants, the phase difference is directly proportional to the rotation rate Ω . This constant includes L , D , λ and v . It is called the Scale Factor (SF), which is a proportionality constant that defines how precisely the FOG works. Its formula can be shown as follows

$$SF = \frac{\Delta\Phi}{\Omega} \quad 2.15$$

Therefore, the scale factor formula is

$$SF = \frac{2\pi LD}{\lambda v} \quad 2.16$$

2.1.2. Grade Levels of Fiber Optic Gyroscopes

The scale factor stability, bias instability, and angle random walk are the most commonly used criteria when ranking gyroscope performance. Based on these criteria, gyroscopes' grade levels are commonly classified into four categories: strategic-grade, navigation-grade, tactical-grade, and commercial-grade (Lin et al., 2019). In Table 2.1, fiber optic gyroscopes are categorized based on their scale factor stability, bias stability, angular random walk (ARW), and typical application areas:

Table 2.1. Grade Levels of IFOG (Lin et al., 2019)

Grade	Scale Factor Stability (ppm)	Bias Stability (°/h)	ARW (°/√h)	Typical Applications
Strategic Grade	1-10	0.0001-0.001	< 0.01	Spacecraft and precision military systems
Navigation Grade	10-100	< 0.01	< 0.002	Aircraft, missiles, naval systems, space
Tactical Grade	100-1000	1-10	0.05-0.02	Guided missiles, drones, and automotive navigation systems
Commercial Grade	> 1000	360	Several	Automotive, platform stabilization, agriculture

2.2. General Perspective on IFOG Operation and Design

A fiber optic gyroscope consists of several key components that determine its performance. When constructing a fiber optic gyroscope, various schemes can be employed with different components. However, Figure 2.3 illustrates the basic

configuration of a single-axis fiber optic gyroscope. All the optical components in the IFOG configuration have fiber pig-tails. As defined in Figure 2.3, the fibers are single-mode fibers (SMF) up to MIOC's first pigtail. MIOC and fiber coil have polarization-maintaining single-mode fiber (PMF).

To combine all these components, we need to fuse these fibers using a splice procedure called a fusion splice, as demonstrated in Figure 2.3 as X. Fusion splicing is defined as heating the glass core of two different fibers and combining them by applying an electric arc. For this process, specialized splice machines and distinct modes are used for SMF and PMF splices. A fiber optic gyroscope consists of the following:

- ✓ **light source** to supply light,
- ✓ **coupler** to divide light into two,
- ✓ **photodetector** to convert the light signal to an electrical signal,
- ✓ **MIOC** to modulate, polarize, and couple the light, and
- ✓ **fiber coil** to obtain the Sagnac effect to measure the rotation rate.

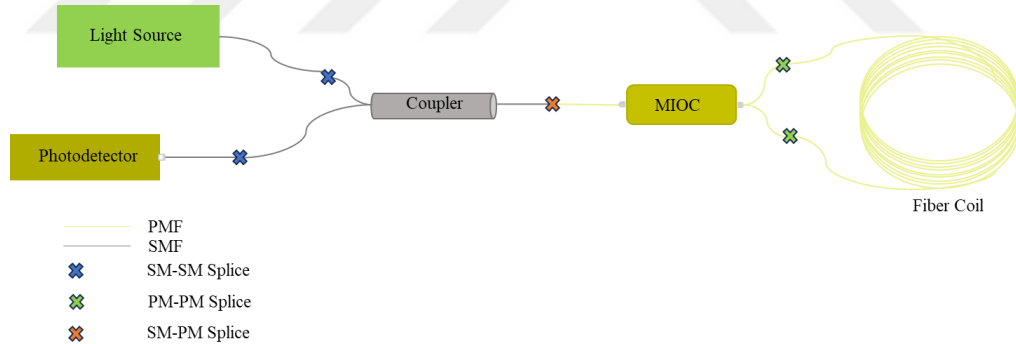


Figure 2.3. Basic configuration of a single-axis fiber optic gyroscope.

According to demand, two-axis and three-axis fiber optic gyroscopes may be produced by adding more couplers to the system. Each component will be analyzed in detail in the following pages.

The principle of reciprocity in a linear optical medium implies that for every optical wave, there exists a counterpart wave traveling in the opposite direction with the same accumulated phase and identical attenuation. The lack of reciprocal configuration may result in an error in the IFOG. Thus, using reciprocal configuration in IFOG is crucial to protect the IFOG from any other phase difference

source other than the rotation. In other words, a reciprocal configuration is employed to ensure that the phase difference between the clockwise (CW) and counterclockwise (CCW) waves arises solely from rotation. To achieve this, both beams are constrained to follow the same optical path (Öğüt, 2013).

In Figure 2.4, the opposite paths followed by the CW and CCW beams are illustrated, showing the reciprocal configuration, which is also the minimum configuration. Half of the light passes through the first beam splitter and, after polarization, enters the second splitter. The CW wave passes through the fiber coil and then the phase modulator, while the CCW wave takes the reverse order. Both beams return and interfere at the photodetector (Öğüt, 2013).

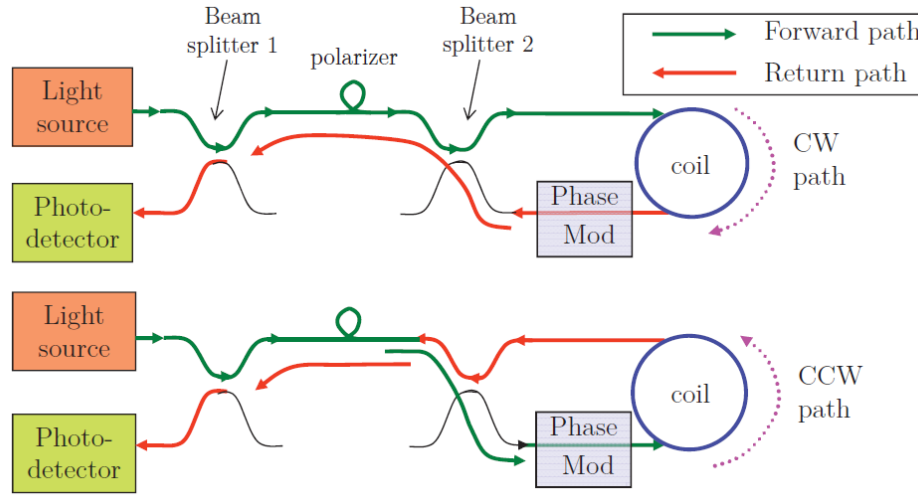


Figure 2.4. Reciprocity configuration (Öğüt, 2013).

The nonreciprocal phase shift refers to the relative phase difference between the clockwise (CW) and counterclockwise (CCW) waves. For high-performance IFOG, only the Sagnac effect must create a phase difference in the system. To obtain a symmetric system, one must minimize other sources of nonreciprocity, which are summarized in Figure 2.5 (Öğüt, 2013).

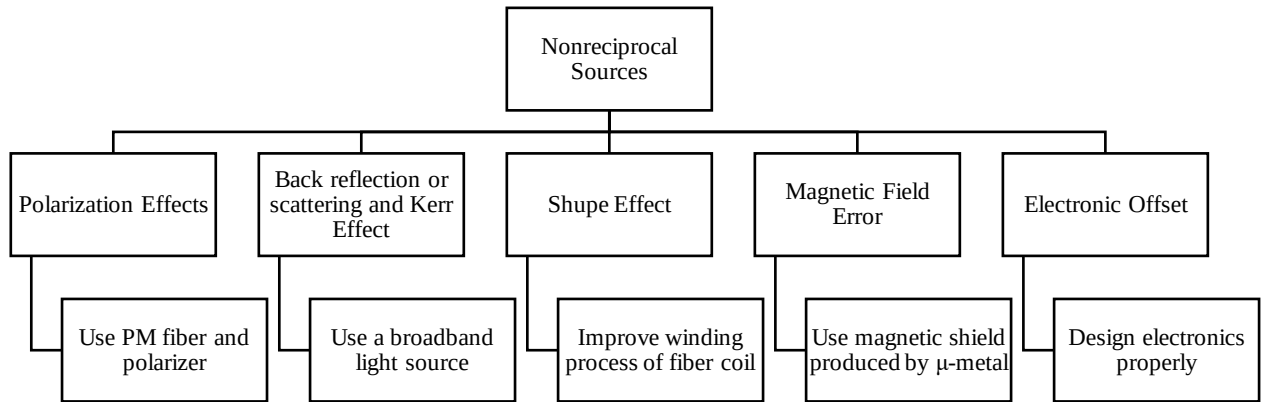


Figure 2.5. Nonreciprocal errors and solutions.

2.2.1. Optical Components of IFOG

☆ *Fiber Coil*

◇ *Fiber*

An optical fiber, that is illustrated in Figure 2.6, consists of a core with a refractive index n_1 (n_{core}) that is slightly greater than the refractive index n_2 (n_{cladding}) of the surrounding cladding. This refractive index difference causes light to propagate within the core through the mechanism of total internal reflection (TIR) at the interface between the core and cladding (Lefevre, 2022).

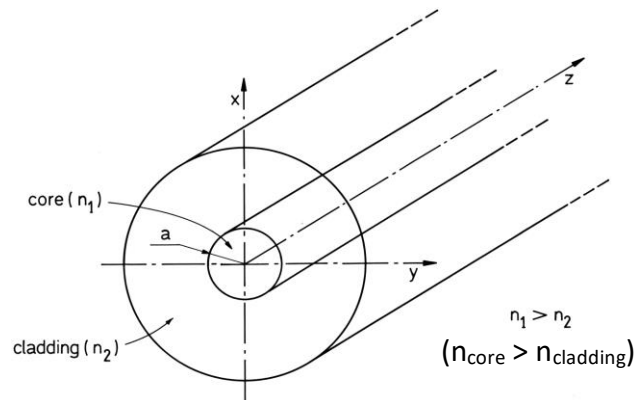


Figure 2.6. Optical fiber representation with its core and surrounding cladding (Lefevre, 2022).

Silica (SiO_2) is the preferred material for low-attenuation optical fibers due to its glassy structure. Silica fibers are coated with two polymer layers as shown in Figure 2.7: a soft inner layer to reduce stress and a harder outer layer for handling (Lefevre, 2022).

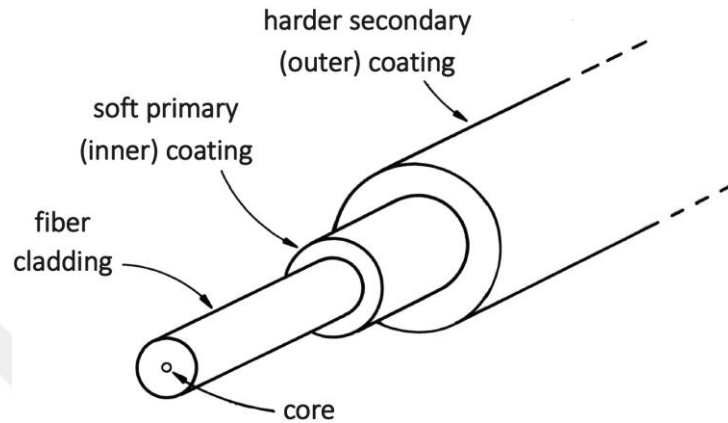


Figure 2.7. Optical fiber structure (Lefevre, 2022).

To sum up, the core allows light to travel through the fiber; the cladding, inseparable from the core, helps keep the light confined within it, and the coating serves as a protective layer for the delicate glass structure (Sunderwirth, 2017). There are several types of optical fibers with varying diameters. Typically, in interferometric fiber optic gyroscopes (IFOG), we use single-mode (SM) and polarization-maintaining (PM) fibers. The core diameter is generally around $9\text{ }\mu\text{m}$. For PM fibers, the cladding diameter is usually $80\text{ }\mu\text{m}$, with coating diameters of $135\text{ }\mu\text{m}$ or $180\text{ }\mu\text{m}$. In contrast, SM fibers typically have a cladding diameter of $125\text{ }\mu\text{m}$ and a coating diameter of $250\text{ }\mu\text{m}$.

◇ Fiber Types

Based on the number of modes, there are two kinds of fibers: Single-mode (SM) and multimode (MM) fibers differ primarily in core size and the number of light paths they support. In this thesis, the SM fibers are utilized. SM fibers have a narrow core, approximately $9\text{ }\mu\text{m}$ in diameter, allowing only a single light mode to propagate. This results in minimal dispersion and is ideal for long-distance, high-precision applications, such as fiber optic

gyroscopes (Sunderwirth, 2017). They are favored for their affordability and ease of integration into various systems. Commercially available SM fibers such as *SMF-28e+* and *H11060* are among the most commonly used due to their cost-effectiveness and wide availability (Keskin, 2023).

Although single-mode fibers guide only one spatial mode, they can still support two polarization modes due to residual birefringence, resulting in a slight difference in propagation speeds between the two orthogonal polarization states. In fiber optic gyroscopes, polarization-maintaining (PM) fibers are used to preserve the polarization state of light. This is achieved by introducing high birefringence into the fiber. A widely adopted method involves stress-induced birefringence, created by embedding two stress-applying parts (SAPs) made of materials with higher thermal expansion coefficients than silica on either side of the fiber core. During the fiber drawing and cooling process, these SAPs experience tensile stress due to differential thermal contraction, which in turn induces controlled stress in the core, resulting in strong birefringence (Lefevre, 2022). The shape of these stress regions determines the fiber type, as shown in Figure 2.8.

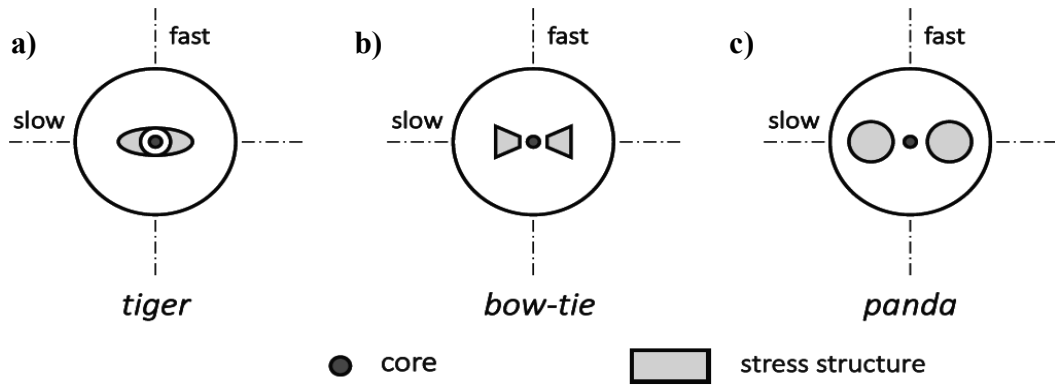


Figure 2.8. Stress structure of PM fibers (a) tiger-eye fiber, (b) bow-tie fiber, (c) panda fiber (Lefevre, 2022).

◇ Fiber Coil Winding

The fiber coil is often referred to as the "heart" of the Sagnac interferometer, much like a vital organ in the human body. It is not only the core component responsible for generating the phase difference due to rotation but also the primary determinant of the gyroscope's sensitivity (Öğüt, 2013). The Sagnac effect is observed within the fiber coil, and one of the most critical parameters, the scale factor, is directly influenced by the coil's performance.

The length and diameter of the fiber coil significantly affect the overall performance of the gyroscope, even determining its classification within performance grade levels. As shown in Table 2.2, increasing the length of the fiber coil proportionally enhances the accuracy of the Interferometric Fiber Optic Gyroscope (IFOG) (Lefevre, 2022). Similarly, the diameter of the coil and the area of the coil are also rising. The winding pattern, which will be discussed, is also improved, as accuracy increases, as shown in Table 2.2. Each axis in a fiber optic gyroscope (FOG) has its fiber coil; therefore, a three-axis IFOG contains three separate fiber coils, while a single-axis IFOG uses only one.

Table 2.2. Fiber Coil Specifications by IFOG Performance Grade

Grade	Length of Fiber Coil (m)	Diameter of Fiber Coil (cm)	Area of Fiber Coil (m²) ($A = LD/4$)	Common Winding Pattern
Strategic Grade	> 1500	~ 30	750	Octupole/Hexadecapole
Navigation Grade	700-1000	~ 10	25	Quadrupole/Octupole
Tactical Grade	100-300	~ 3	0.75	Quadrupole

In addition to the physical properties of the fiber optical coil, the fiber type and coil winding pattern play a crucial role in determining the effectiveness of a fiber coil. To achieve a high-grade gyroscope, polarization-maintaining (PM) fibers are being used in the industry. With advances in technology, various winding patterns have been developed, and symmetrical winding is one of the most popular, as illustrated in Figure 2.9. These winding techniques are designed to improve the thermal performance, reduce mechanical stress within the fiber, and minimize non-reciprocal effects. The related error mechanisms and their impact on performance will be discussed in detail in the following sections.

This means that the dipole winding pattern follows the sequence AB, the quadrupole pattern uses ABBA, the octupole pattern follows ABBABAAB, and the hexadecapole pattern uses ABBABAABBAABABBA. These sequences are repeated throughout the entire length of the fiber. Therefore, each turn and layer must be pre-calculated based on the product spool's dimensions before the winding process begins. As the winding pattern goes from dipole to hexadecapole, the sensitivity of the sensing coil improves.

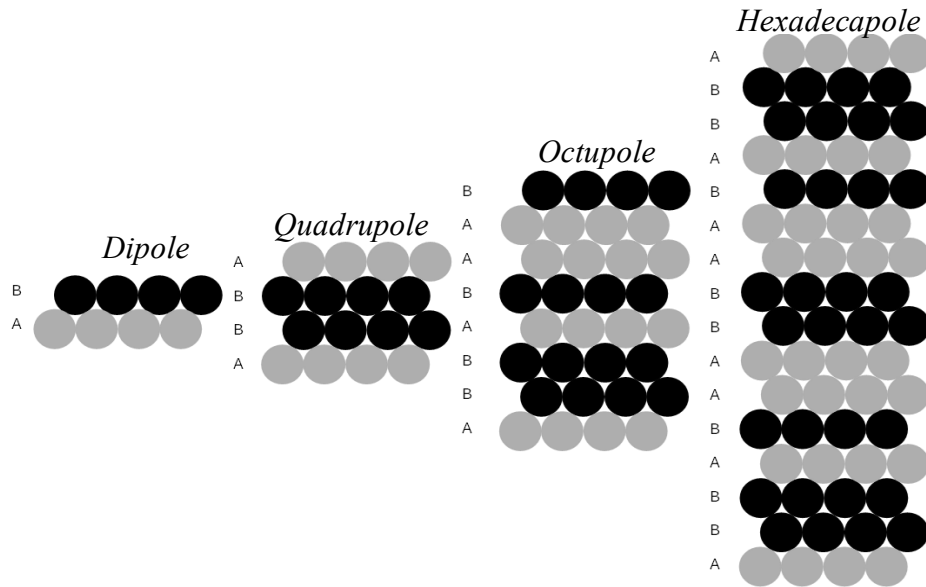


Figure 2.9. Winding pattern representation.

The winding process begins by carefully placing the midpoint of the fiber at the starting point of the product spool. Supply spools A and B correspond to the layers illustrated in Figure 2.10 and are used to create the desired winding pattern. To enable various winding configurations, the machine must be designed so that either supply spool can be positioned on either side of the product spool. One supply spool rotates together with the product spool, while the other dispenses the fiber (Andre & Lin, 2001).

With technological advancements and increasing demand, various brands have developed winding devices using different technologies. Traditional winding machines require manual labor and continuous supervision throughout the winding process. However, recent innovations have led to the development of fully automatic fiber winding machines, allowing a single operator to manage multiple devices simultaneously.

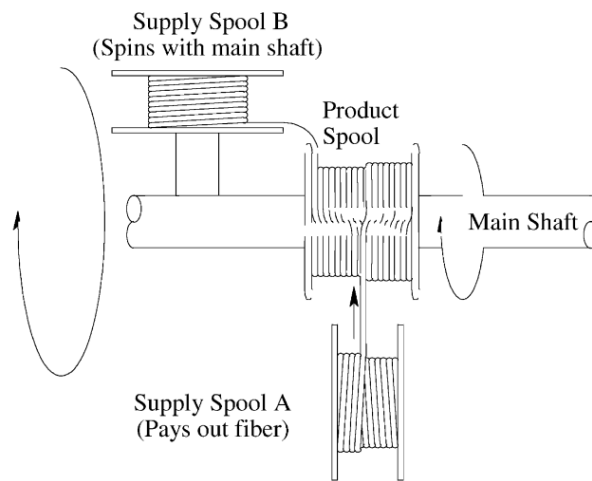


Figure 2.10. Winding process representation (Sharon & Lin, 2001).

Figure 2.11 presents a schematic illustration of a fiber coil, where M indicates the number of fiber layers and N represents the total number of turns. R_{out} and R_{in} refer to the outer and inner radii of the coil, respectively (Wang et al., 2022). As the length of the fiber coil increases, the number of layers and turns will also change accordingly.

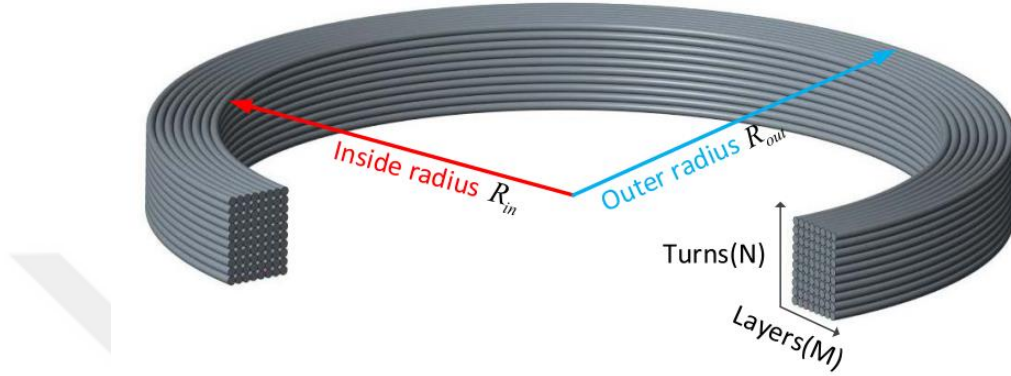


Figure 2.11. Schematic view of the fiber coil in three dimensions (Wang et al., 2022).

The completed fiber coil, representing the final stage of the winding process, is illustrated in Figure 2.12.



Figure 2.12. Fiber coil representation (Wang et al., 2022).

☆ *Multi-Integrated Optic Chip (MIOC)*

The Multifunction Integrated Optic Chip (MIOC) plays a crucial role in Fiber Optic Gyroscopes (FOG), which are widely utilized in inertial navigation systems. This chip integrates a 3 dB splitter, phase modulator, and polarizer onto a single substrate. Lithium niobate (LiNbO_3) is selected as the

material for MIOC fabrication due to its outstanding electro-optic properties (Tripathi et al., 2007).

Integrated optics is founded on the principle of using microlithography to construct optical components, such as waveguides, on a flat substrate. The core component is the channel waveguide, formed by locally modifying the refractive index beneath the substrate's surface through doping, confined within precisely defined narrow regions (Lefevre, 2022).

Production of MIOC is commonly achieved using one of two techniques: titanium-indiffused waveguides with absorbing overlays, or annealed proton-exchanged waveguides that support single-polarization propagation (Lefevre, 2022). Due to the polarization advantage offered by the Annealed Proton Exchange (APE) method, the MIOC fabricated using this technique will be utilized in this thesis.

☆ *Broadband Light Source*

One of the core and indispensable components of an Interferometric Fiber Optic Gyroscope (IFOG) is the light source. The use of a broadband optical source mitigates many environmental and system-related disadvantages that degrade the accuracy and sensitivity of the gyroscope, as will be discussed in the following sections. Preferred broadband light sources include semiconductor superluminescent diodes (SLDs) and erbium-doped fiber amplified spontaneous emission (ASE) sources (Lefevre, 2022). Each has its advantages and limitations; however, SLDs are typically used in medium-grade systems, whereas ASE sources are favored for higher-grade applications.

◇ Superluminescent Diode (SLD) Sources

At the beginning of the 1980s, semiconductor-emitting diodes were developed as light sources, namely laser diodes (LDs) and light-emitting diodes (LEDs). Both utilize III-V semiconductors, which refer to materials composed of group III elements (Al, Ga, In) combined with group V elements (N, P, As, Sb) (Xie et al., 2018). Different compositions are used to generate different

wavelength ranges. For example, AlGaAs-GaAs junctions are used for the 800 nm to 850 nm range, and InGaAsP-InP junctions for the 1300 nm to 1550 nm range. LEDs are based on spontaneous emission, while LDs rely on stimulated emission. Due to their broad emission area, LEDs cannot be efficiently coupled to single-mode fibers, whereas LDs naturally emit from a narrow stripe, allowing efficient coupling. Although LEDs offer a broad spectrum, LDs exhibit narrow emission peaks and high spatial coherence (Lefevre, 2022).

Considering these limitations, a brand new light source is needed, which enables the development of superluminescent diodes (SLDs). This modification enables the light source to combine excellent spatial coherence with low temporal coherence, outperforming both laser diodes (LDs) and light-emitting diodes (LEDs) in certain applications. In SLDs, the absorbing region is minimized to suppress lasing effects. Since SLDs are modified and combined versions of LDs and LEDs, spontaneous emission is dominant, but stimulated emission also occurs. The full width at half maximum (FWHM) of the SLD spectrum is relatively broad, typically ranging from 30 to 70 nm in width. However, because SLDs produce partially polarized light, polarization-maintaining (PM) fibers are required in the system. Among these disadvantages, the most significant is the low spectral stability of SLDs. SLDs typically exhibit a wavelength stability of around 400 ppm (Lefevre, 2022). Since fiber optic gyroscopes require high wavelength stability and unpolarized light, SLDs fall short in meeting the demands of high-accuracy IFOG technology.

◇ Amplified Spontaneous Emission (ASE) Sources

Amplified Spontaneous Emission (ASE) occurs when spontaneously emitted photons are further amplified by stimulated emission as they propagate through a gain medium (Lei et al., 2022). In optics, gain media refer to materials used to amplify light in laser systems. Rare-earth-doped laser gain media are specifically those infused with rare-earth ions to enable this amplification. Rare earth elements comprise a group of transition metals, primarily consisting of the lanthanide series, as shown in Figure 2.13, along with scandium and yttrium. They play a crucial role in various materials and technologies, such as superconductors and lasers (Helmenstine, 2015). Among the most widely used laser-active ions are neodymium, ytterbium, and erbium.

Rare Earth Elements

H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	*	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra	**	Rf	Db	Sg	Bh	Hs	Mt	Ds	Rg	Cn	Uut	Fl	Uup	Lv	Uus	Uuo
*			La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
**			Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr

Light Rare Earth Element

Heavy Rare Earth Element

Figure 2.13. Rare Earth elements on the periodic table (Helmenstine, 2015).

Rare-earth doping enables light sources to achieve high amplification gain, broadband high-power emission, and stable energy levels (Tanabe, 2022). Among the most widely used laser-active ions are neodymium (Nd), ytterbium (Yb), and erbium (Er). In Erbium-Doped Fiber Amplifiers (EDFAs), trivalent erbium ions are incorporated into the core of a silica fiber. These amplifiers are effectively pumped at wavelengths of 980 nm or 1480 nm, resulting in optical gain in the 1550 nm spectral range (Tanvi & Gupta, 2014). Erbium-doped fiber emits green light when it is pumped with 980 nm which explained in Appendix A.

The absorption characteristics of silica-based optical fibers vary significantly with wavelength. The attenuation spectrum reveals three key transmission windows widely used in telecommunications, which are shown in Figure 2.14: approximately 850 nm, 1300 nm, and 1550 nm (Peters & Inaudi, 2014). At shorter wavelengths, Rayleigh scattering caused by microscopic inhomogeneities becomes a major loss mechanism (Wang, 2019).

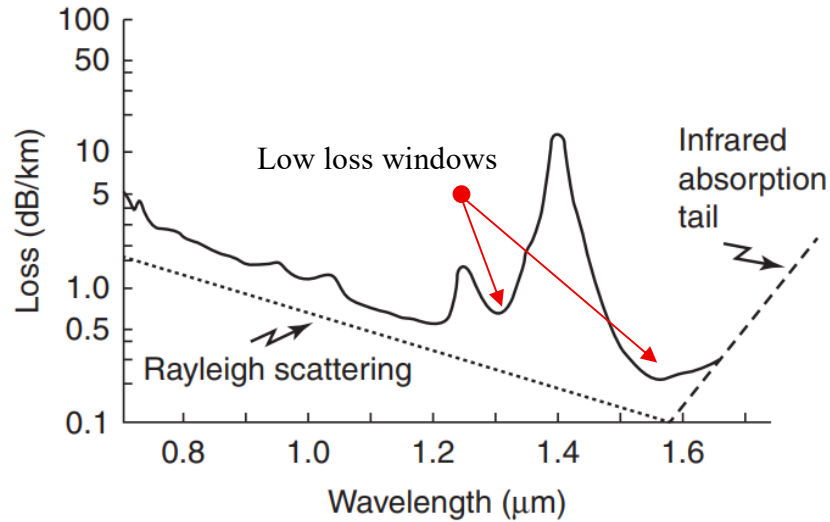


Figure 2.14. The attenuation coefficient of fused silica glass as a function of wavelength (Peters & Inaudi, 2014).

The light around 1550 nm is advantageous because it exhibits negligible chromatic dispersion and has minimal Rayleigh scattering. Consequently, erbium-doped fiber becomes the most efficient choice for ASE light sources. It is naturally suitable for single-mode fibers, and it also emits unpolarized light, which helps reduce polarization-induced nonreciprocity in interferometric sensing applications.

Before explaining amplified spontaneous emission (ASE), it is essential to understand the fundamental mechanisms of light–matter interactions, as illustrated in Figure 2.15. These interactions include absorption, stimulated emission, and spontaneous emission. In absorption, an electron in a lower energy state absorbs an incoming photon. As a result, the electron transitions to a higher energy state. Spontaneous emission occurs when an electron in an excited state returns to a lower energy level without any external influence, emitting a photon in the process. This random emission is a primary source of naturally occurring light. In contrast, stimulated emission happens when an incoming photon interacts with an already excited electron. This causes the electron to fall to a lower energy state and emit a second photon (Pollnau, 2019). Stimulated emission occurs only when the gain medium is sufficiently pumped to achieve population inversion, a state in which more atoms occupy the excited energy level than the lower one. In contrast, spontaneous emission happens regardless of whether population inversion is present. Therefore, achieving population inversion is a necessary condition for laser amplification (Zhu et al., 2007). Understanding these three processes is crucial for analyzing how ASE light sources function in optical systems.

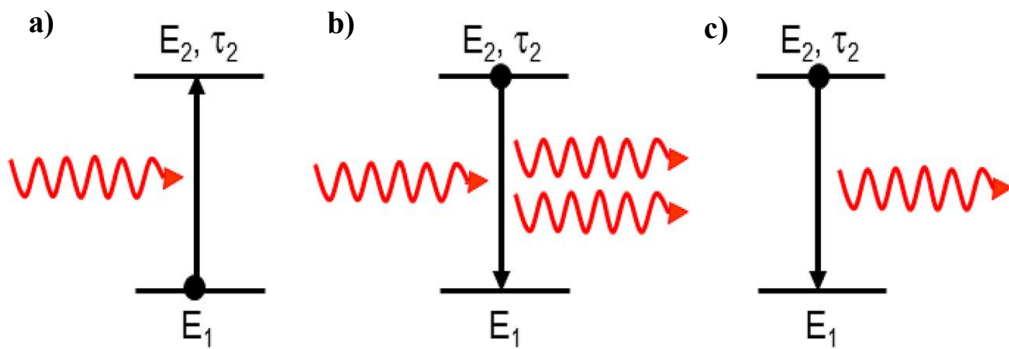


Figure 2.15. Representation of (a) absorption, (b) stimulated emission, and (c) spontaneous emission (Pollnau, 2019).

In Figure 2.16, the energy levels of a trivalent erbium ion (Er^{3+}), a rare-earth element, are represented. Due to the Stark effect, the energy levels are bands, resulting in a relatively wide emission spectrum. When a 980 nm pump laser is applied, erbium ions are excited from the ground state to a higher energy level, then quickly decay non-radiatively to a metastable state. From this state,

they return to the ground level by spontaneous emission, generating photons in the 1550 nm. As these photons propagate through the fiber, they are further amplified, especially under stronger pumping, producing amplified spontaneous emission (ASE) (Zhu et al., 2007).

In Erbium-doped fiber, pumping is possible at both 980 nm and 1480 nm. The 980 nm band features a higher absorption cross-section, making it ideal for applications that require low-noise performance. However, due to its narrow absorption range, it requires wavelength-stabilized laser sources. In contrast, the 1480 nm band has a broader but lower absorption cross-section, making it more suitable for high-power amplification (Tanvi & Gupta, 2014).

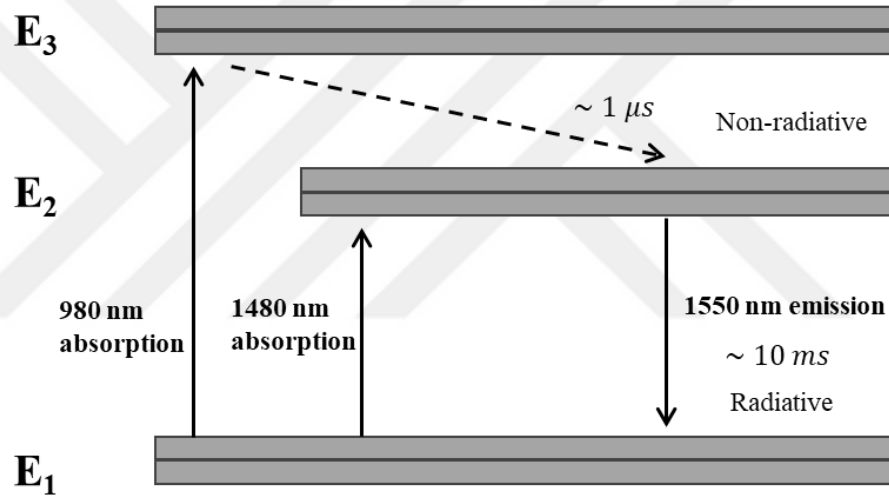


Figure 2.16. Energy level diagram of erbium.

EDFAs offer high optical gain within the 1530–1560 nm wavelength range, where erbium ions emit more energy than they absorb. In this region, the gain bandwidth is relatively narrow. As shown in Figure 2.17, the peak gain occurs around 1550 nm, confirming that the optimal operating wavelength for EDFA systems is centered at 1550 nm (Tanvi & Gupta, 2014).

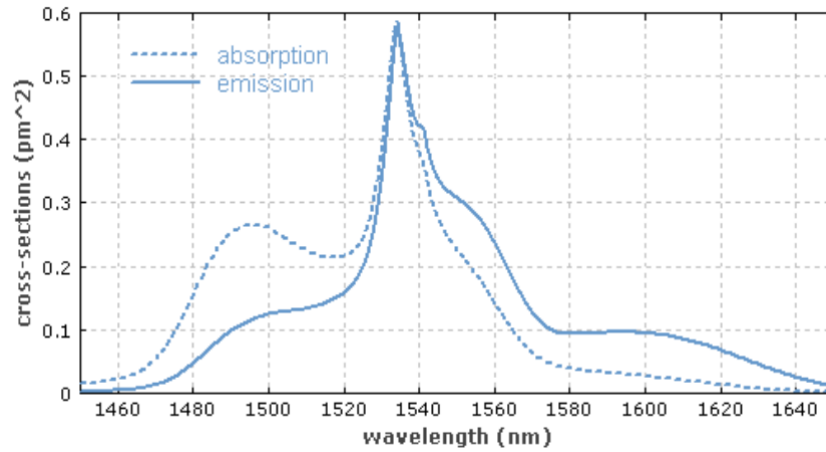


Figure 2.17. Absorption and emission of erbium (Tanvi & Gupta, 2014).

As previously discussed, the erbium-doped fiber is the core component of an ASE light source. In addition to the fiber, the laser diode pump and wavelength division multiplexer (WDM) are also essential elements. Within the light source, the erbium-doped fiber is excited by the pump laser diode, while the WDM fiber coupler is used to filter out the pump wavelength from the output (Ögüt, 2013). WDM is used to multiplex, combine, and separate the wavelengths. In other words, WDM takes 980 nm light and conveys it in a different wavelength range. These wavelength ranges are named differently, as shown in Table 2.3. Since we are using an EDF that operates approximately at 1550 nm, we utilize C-band WDM in the 1530-1565 nm range. Moreover, to prevent back-reflection, isolators are also integrated into most ASE light sources. Using these components and many others, various configurations of ASE light sources can be constructed, which will be explored in the following chapter.

Table 2.3. WDM Wavelength Bands (FiberLabs, 2023)

Band Name	Wavelength Range (nm)
O-band (Original)	1260-1360
E-band (Extended)	1360-1460
S-band (Short)	1460-1530
C-band (Conventional)	1530-1565
L-band (Long)	1565-1625

☆ *Passive Components*

◇ Coupler

At the output of the ASE light source, a component is required to combine the generated light and distribute it efficiently to the subsequent components in the system. Optical couplers are used for this purpose to either split or combine light signals traveling within a system. They allow two light beams to be directed along different paths or to be merged into a single path from separate inputs (Alaçakır, 2019). There are several types of couplers used in industry, each serving distinct needs, including X-couplers and Y-couplers (Lefevre, 2022).

◇ Photodetector (PD)

If data cannot be used and processed, the tests become meaningless, since the ultimate goal is to generate a usable and interpretable output. In this manner, the photodetector serves as a crucial feedback mechanism in the IFOG. It converts optical signals into electrical signals. It is therefore positioned at the end of the optical path, where it transmits the electrical signal to the electronic processing unit. To enhance performance, Positive-Intrinsic-Negative Field Effect Transistor (PINFET) diodes are employed in modern IFOG systems (Alaçakır, 2019). These devices combine a PIN photodiode with a field-effect transistor-based amplifier circuit, enabling high-sensitivity and low-noise signal detection in advanced optoelectronic applications (Keskin, 2023).

For processing data, the electronic components of the IFOG are equally crucial, as they transform the detected signals into meaningful and usable information.

2.2.2. Error Types in IFOG and Their Mitigation

Several error sources can impact the precision and sensitivity of a fiber optic gyroscope (FOG). These errors, along with their corresponding mitigation strategies, can be categorized as follows:

Table 2.4. FOG Error Sources and Mitigation Techniques

Error Source	Origin	Effect on FOG	Mitigation Strategies
Bias Instability	Temperature fluctuations affecting the modulator, fiber coil, and electronics	Leads to slow-changing output offset	Precise temperature control and digital bias compensation
Polarization Non-Reciprocity	Birefringence in the fiber coil and imperfections	Causes phase errors due to unequal polarization states	Use of PM fiber
Scale Factor Nonlinearity	Variation in modulation depth or detector nonlinearity	Distorts the proportionality between the rotation rate and output	- Precision control of modulation voltage
Shupe Effect	Temperature-related changes across the fiber coil	Limits the accuracy of IFOG	Use of symmetrical coil winding patterns
Kerr Effect	Intensity-dependent refractive index in the fiber core	Causes a phase shift due to optical power variations	Use of broadband light source and better MIOC
Backscattering	Imperfections and Rayleigh scattering in the fiber coil	Produces false interference	- Use of spun fibers- Coil design optimization- Optical isolators
Wavelength Instability	Temperature-induced drift in the light source	Causes bias errors due to dispersion effects	Use of erbium-doped fiber for high stability
Vibration	Mechanical stress on the coil or loose screw	Introduces bias errors	Use of rigid coil and IFOG mounting
Faraday Effect	External magnetic fields interacting with the fiber coil	Induces phase shifts due to magneto-optic effects	Use of PM fiber and magnetic shielding with μ -metal
Photodetector Noise	Electronic noise in the PINFET	Limits sensitivity and increases ARW	Use low-noise detector circuits

In an inertial navigation system (INS), there are both deterministic errors and stochastic random errors. Bias, scale factor error and misalignment are examples for deterministic errors which are systematic and predictable errors. In contrast, the bias instability, angle random walk (ARW), rate random walk and quantization errors are random errors which make them stochastic errors. In this thesis, main subject to investigate will be bias instability and angle random walk. Since these are random errors, they cannot be minimized with mathematical models, but can be modeled with Allan variance which explained in Appendix B.

Takei et. al showed ARW relationship as seen in Equation 2.17 in 2022.

$$ARW \approx \sqrt{\sigma_{TPN}^2 + \sigma_{RIN}^2 + \sigma_{SN}^2 + \sigma_{DN}^2} \quad 2.17$$

Where σ_{TPN} , σ_{RIN} , σ_{SN} and σ_{DN} are the demodulated current noises for thermal phase noise (TPN), relative intensity noise (RIN), shot noise (SN) and detection noise (DN), respectively (Takei et. al, 2022). Also, the RIN is inversely proportional to square root of spectrum bandwidth, i.e. full width at half maximum, as seen in Equation 2.18.

$$\sigma_{RIN} \approx \frac{1}{\sqrt{\Delta f_{FWHM}}} \quad 2.18$$

2.3. ASE Light Source Configurations

There are several types of ASE light source configurations. The most basic ones include single-pass forward (SPF), single-pass backward (SPB), double-pass forward (DPF), and double-pass backward (DPB) configurations. Single-pass configurations are more commonly preferred in gyro technologies due to their simple construction and moderate performance. However, double-pass configurations offer a wider linewidth, excellent mean wavelength stability, and an efficient pump. Moreover, compared to single-pass systems, double-pass schemes require a short erbium-doped fiber length to achieve good performance results (Huang et al., 2009). Even these configurations can vary further by incorporating additional optical components into the system. The fundamental structure and working principles of these configurations will be presented in the following section:

2.3.1. Single Pass ASE Light Source Configuration

As the minimum configuration of IFOG is suggested, one can demonstrate the minimum configuration for the light sources. The single-pass ASE light sources are basic and generally require fewer elements in the system (Huang, 2009). They are divided into two: the first is single pass backward (SPB) and the second is single pass forward (SPF).

Single Pass Backward (SPB) ASE Light Source Basic Configuration

Single-pass backward ASE light source configuration is represented in Figure 2.18. The path of pump light is represented in orange arrows, while yellow arrows represent the ASE light. As shown, the pump light moves in the forward direction when the ASE light is moving in the opposite direction. That is why this configuration is called a single-pass backward configuration, because the ASE light only passes once in the backward direction (Tsai et al., 2002). As shown, the end of the EDF is terminated to absorb the light and prevent back reflection. There are many methods to terminate this pigtail, such as splicing an APC connector, which has an angled end, or cleaving the fiber end at an angle, etc.

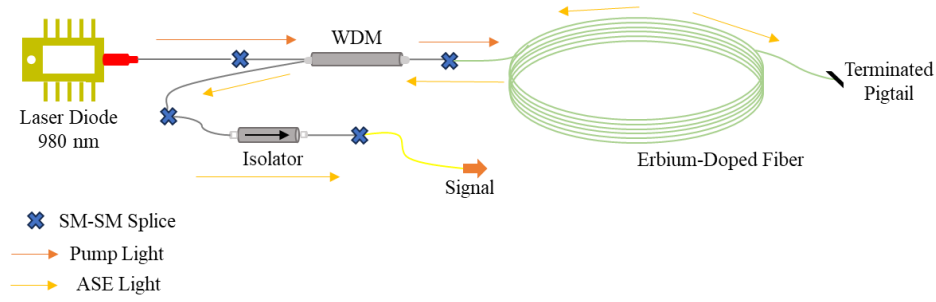


Figure 2.18. SPB ASE light source configuration.

Single Pass Forward (SPF) ASE Light Source Basic Configuration

The major difference between the SPB and SPF is where the terminated pigtail is placed and where the output signal is. Single-pass forward ASE light source configuration is represented in Figure 2.19. In contrast to SPB, the pump light and ASE light propagate in the same direction (Tsai et al., 2002), as shown by the paths drawn with orange and yellow arrows, respectively. Single-pass forward ASE light source configuration is represented in Figure 2.19. Since the ASE light is traveling forward, this configuration is referred to as single-pass forward. As shown, the second pigtail, namely the common one, is terminated to absorb the light and prevent back reflection.

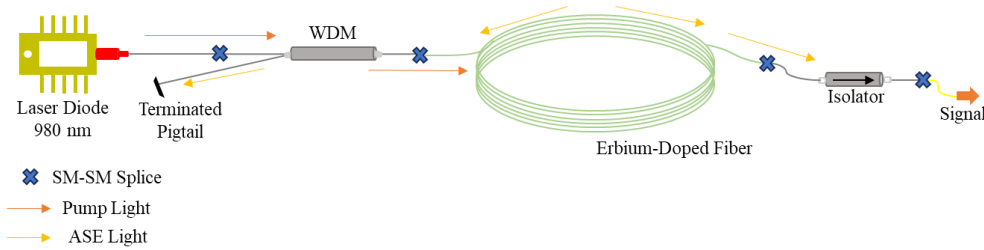


Figure 2.19. SPF ASE light source configuration.

2.3.2. Double Pass ASE Light Source Configurations

Double-pass configurations differ from single-pass configurations by the addition of a mirror to the system. While SPB and SPF configurations are distinguished by the location of the terminated pigtail, DPF and DPB configurations differ based on the placement of the fiber mirror within the setup. In other words, the fiber mirror is placed where the pigtails are terminated in the single-pass configurations. The fiber mirror is used to reflect the ASE light, enabling it to pass

through the system a second time and thus forming a double-pass configuration (Tsai et al., 2002).

Double Pass Backward (DPB) ASE Light Source Basic Configuration

The double-pass backward ASE light source configuration is represented in Figure 2.20. The pump light, orange arrows, travels in the forward direction while the ASE light, yellow arrows, moves in backward direction. To achieve the second amplification to make the system double pass, the reflective mirror is placed to end of the EDF to reflect the forward ASE light to the system (Tsai, et al., 2002). Therefore, the light moves twice through the gain medium in backward direction.

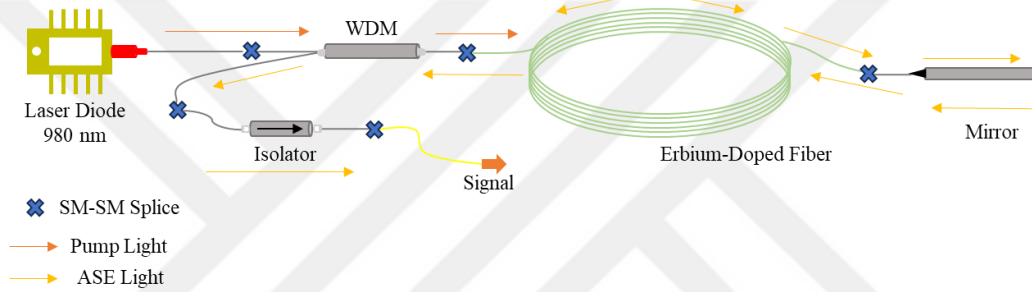


Figure 2.20. DPB ASE light source configuration.

Double Pass Forward (DPF) ASE Light Source Basic Configuration

Double pass forward ASE light source configuration is represented in Figure 2.21. The pump light with orange arrows and ASE light with yellow arrows are illustrated. As seen, both of them travel in the forward direction. To amplify the gain medium, EDF, twice, the fiber mirror is positioned to redirect the backward ASE light source back into the system (Tsai et al., 2002). Therefore, the light moves twice through the gain medium in the backward direction.

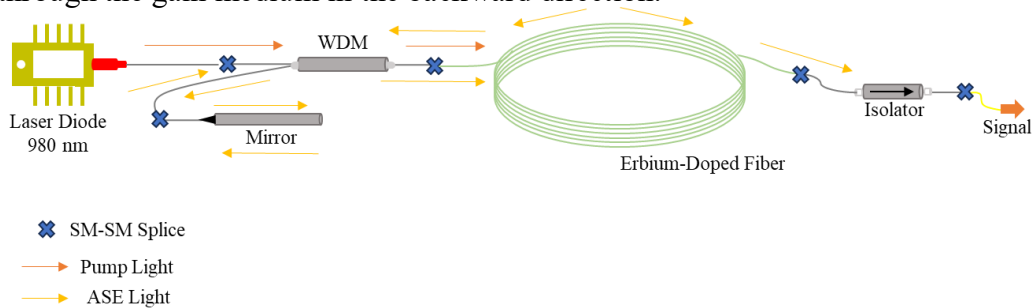


Figure 2.21. DPF ASE light source configuration.

2.4. Comparison of Single Pass Backward and Double Pass Backward ASE Light Source

Several experiments and articles reveal the performance results of the various configurations. In 2009, Huang and other scientists constructed both SPB and DPB configurations to compare the performance outcomes of two diverse light sources. The configurations of the light sources are shown in Figure 2.22.a and Figure 2.22.b, which represent the SPB and DPB, respectively. As shown, the study used two basic schemes for the tests.

To decrease the radiation sensitivity, EDF with low Al concentration is used in this study. In the SPB configuration, they utilized a 16-meter erbium-doped fiber, whereas they used only 7 meters in the DPB.

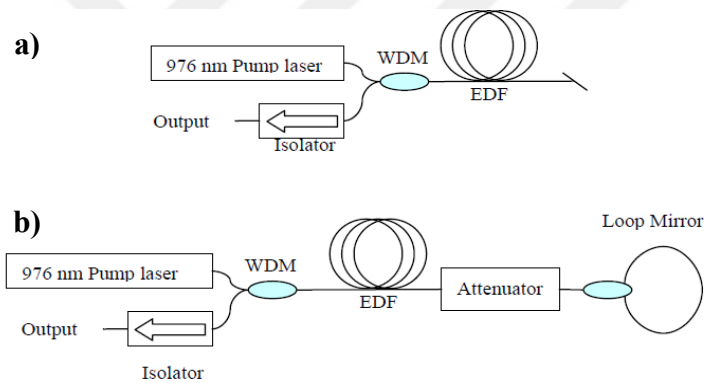


Figure 2.22. ASE configurations (a) SPB (b) DPB (Huang et al., 2009).

As seen from Figure 2.23.a, SPB had a smaller linewidth compared to a DPB configuration independent of the pump power. To be more specific, when the pump power was 290 mW, the linewidth values were approximately 16 nm and 20 nm for SPB and DPB, respectively. Similarly, it is clear from the graph that the mean wavelength of DPB is higher than the mean wavelength of SPB. Moreover, Huang et al. stated that the output power of SPB was 32 mW when the DPB had 47 mW output power with 290 mW output power. In addition, it is seen in Figure 2.23.b. that the DPB configuration is concentrated on longer wavelengths while SPB is concentrated on shorter wavelengths. Also, the writers claimed that the angle random walk of DPB could be better than the angle random walk of SPB due to its high power and linewidth values.

After the light source tests were completed, they constructed a single-axis fiber optic gyroscope to analyze the rotation rates of configurations. They had performed the tests on a vibration-free table where the fiber coil is placed perpendicular to the earth, where the vertical earth rotation was about 6.3 deg/h at the location. As showed in Figure 2.23.c and d, the rotation rate is better and there is less noise in DPB configuration. It can be explained that due to the higher linewidth, the coherence and polarization errors are minimized in the DPB configuration.

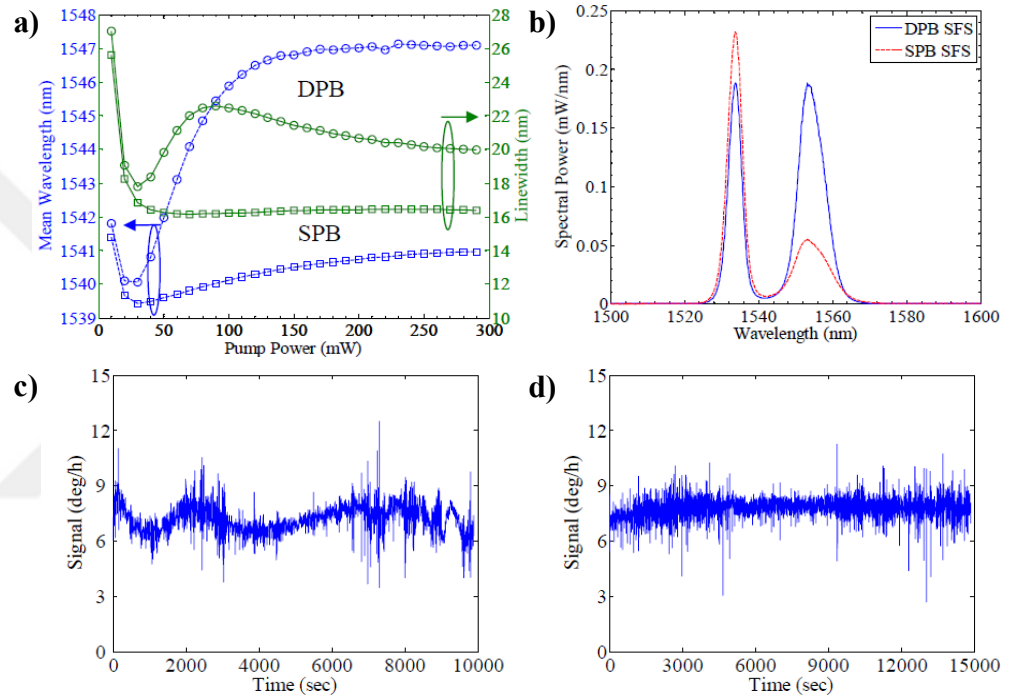


Figure 2.23. (a) Comparison of SPB and DPB optical parameters, (b) spectrum comparison of SPB and DPB configurations, (c) Earth rotation rate graph of SPB, (d) Earth rotation rate graph of DPB (Huang et al., 2009).

In Figure 2.24, the Allan variance of two systems was illustrated. The angle random walk of SPB and DPB were found as $0.023 \text{ deg}/\sqrt{h}$ and $0.019 \text{ deg}/\sqrt{h}$ respectively. Similarly, the bias drifts of SPB and DPB were reported as 0.47 deg/h and 0.18 deg/h , respectively (Huang et al., 2009).

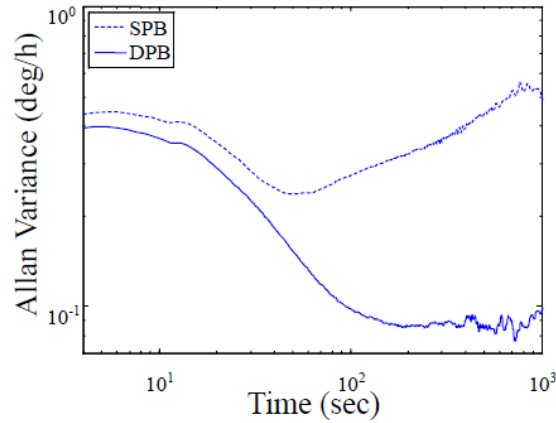


Figure 2.24. The Alan variance graph of SPB and SPB (Huang et al., 2009).

Overall, the DPB configuration demonstrates superior optical and bias performance compared to the SPB system. As a result, the choice between these configurations can be made based on the required level of accuracy.

2.5. Comparison of Double Pass Backward and Double Pass Forward ASE Light Source

In 1997, Wang and Chen compared the performance results of DPB and DPF configurations. They have constructed their setups as shown in Figure 2.25.

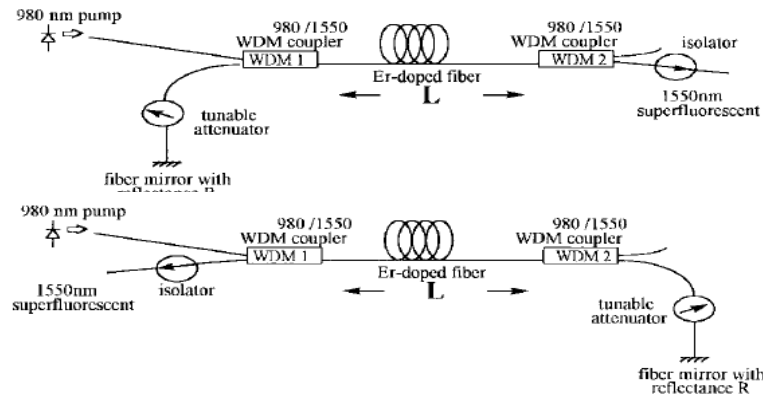


Figure 2.25. DPF and DPB configurations (Wang & Chen, 1997).

This study demonstrates that when the pump power is 80 mW for both configurations, the optimum erbium-doped fiber lengths are 6 meters and 7 meters for DPF and DPB, respectively. Moreover, the output power of DPB exhibited better consistency in output power compared to DPF, even though both decayed due to reabsorption (Wang & Chen, 1997).

They had showed that the DPB has a more stable mean wavelength than the DPF configuration. Moreover, the linewidth in DPB systems is higher than the DPF setup (Wang & Chen, 1997). Therefore, one it can be seen that although there are no major differences, DPB configurations have slightly better performance than DPF configurations for high accuracy IFOG.

2.6. Comparison of Single Pass Backward, Single Pass Forward, Double Pass Backward, and Double Pass Forward ASE Light Sources

Hsu and others attempted to investigate the L-band, in the range of 1570-1610 nm, using ASE light sources in several configurations, including SPB, SPF, DPB, and DPF, theoretically. They have used erbium-doped fiber, but they pumped the sources with 1480 nm in the simulations. The configurations are shown in Figure 2.26.

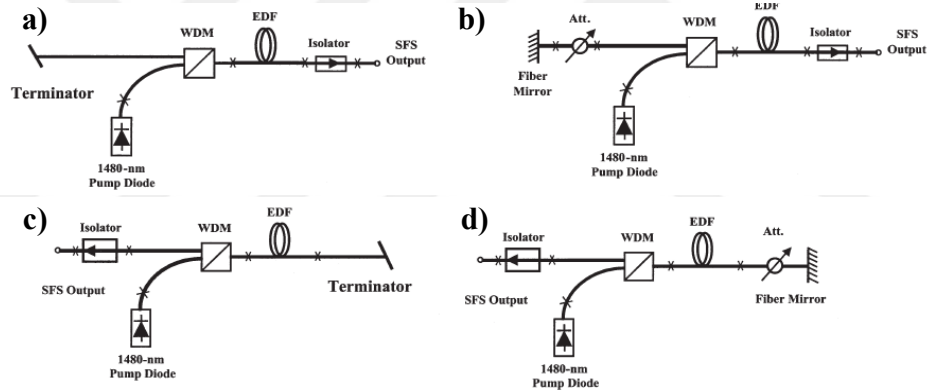


Figure 2.26. ASE with (a) SPF (b)DPF (c) SPB (d) DPB (Hsu et al., 2002).

In this study, the results of the configurations are quite different according to the band. It is stated that when the light source is in the C-band, all configurations are usable. However, due to its high output power and stable spectrum, the double-pass backward configuration is advantageous. However, in L-band, the results had changed. It is shown that SPB and DPB failed to achieve L-band ranges because the mean wavelength remained steady at 1560 nm, even though the erbium-doped fiber length was changed. SPF configuration had a good spectrum for band applications; however, the output power was extremely low. In contrast to these conditions, DPF had an excellent performance in L-band. The mean wavelength stability, output

power, and linewidth were high enough. Moreover, the spectrum was flat as required in L-band (Hsu et al., 2002).

2.7. Combination of Double Pass Backward and Double Pass Forward ASE Light Sources

After many years of work and advancements, Jinlong and Manqing constructed a hybrid ASE light source, which consisted of DPF and DPB configurations, in 2011. The aim was to have a highly accurate and precise IFOG. Since the work of Hsu and others has shown that DPF configuration is suitable for longer wavelengths, while DPB is suitable for shorter wavelengths. Therefore, combining these two configurations will produce both long and short wavelengths, i.e., combine C-band and L-band (Jinlong & Manqing, 2011). The setup is constructed using only one pump laser, and two configurations are combined by the coupler, as shown in Figure 2.27.

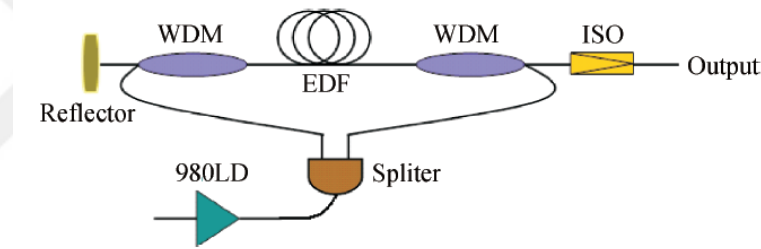


Figure 2.27. DPF and DPB combination (Jinlong & Manqing, 2011).

Generally, the light source is pumped from only one direction. In such a configuration, absorption is higher near the pump source and lower at the far end of the gain medium. This results in uneven absorption along the fiber as light propagates, leading to poor wavelength stability and inefficient use of the erbium-doped fiber (EDF). To address this issue, the study suggests uniform pumping from both ends of the EDF. This approach enhances wavelength stability and improves the quality of the output light (Jinlong & Manqing, 2011).

Figure 2.28.a shows the central wavelength change as laser diode current is changed in variable lengths. As shown, the central wavelength becomes more stable as the length of the EDF decreases with variable current. This means that the stability of the light source is better when the EDF length is 11 meters.

It is a fact that the output spectrum of ASE light source generally has two humps as shown in Figure 2.28.b. The first hump is located at approximately 1530 nm, while the second one is approximately 1560 nm. Because different wavelengths are amplified differently depending on the number of erbium ions excited, the ASE spectrum's shape varies with pump power. Lower reabsorption causes the spectrum to peak around 1560 nm at low pump power, whereas higher population inversion favors 1530 nm at high pump power, moving the spectrum peak. As seen in the figure, the 11 m EDF has a flatter spectrum shape compared to the others.

Jinlong and Manqing (2011) showed that as the length of EDF increases, the pump power decreases. However, at 11 m, the pump power is starting to decay. Thus, they have shown that the length of EDF is ideal between 11 m and 12 m to take advantage of efficient pump power.

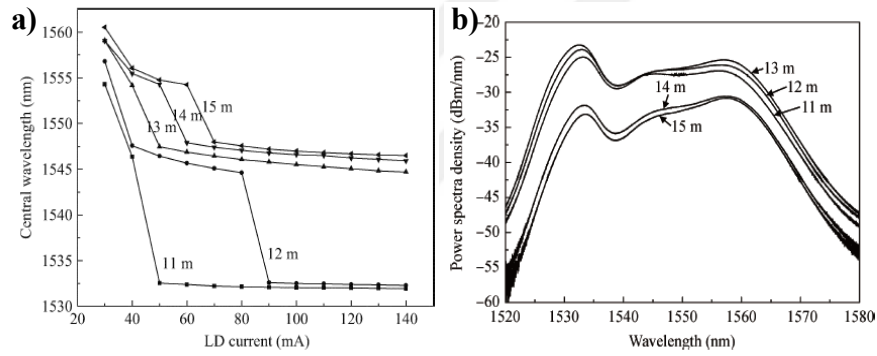


Figure 2.28. (a) Central wavelength and LD current comparison (b) Spectrum of light source at different EDF lengths (Jinlong & Manqing, 2011).

2.8. Enhancing ASE Light Source Performance through Unpumped Erbium-Doped Fiber Integration

There are several important characteristics of ASE light sources, including mean wavelength stability, output power, and spectral shape. These characteristics directly influence the overall performance of IFOG. That is, the mean wavelength of ASE is the mean wavelength value of IFOG. The broadband light source enables IFOG to have less shot noise, back reflections, and the Kerr effect (Kikilich et al., 2021). Moreover, high stability during temperature change is a vital feature for a broadband source. Therefore, improving these parameters is quite significant, so scientists are continuously trying to advance them.

In this study, a single-pass backward ASE light source has been constructed. According to their claim, adding an unpumped erbium-doped fiber and a Faraday mirror to the configuration, which creates a double-pass backward configuration, would improve the performance of the ASE light source. A 2.5 m unpumped EDF is used as a filter, and a Faraday mirror (FRM) is used to reflect the light, making the configuration a double pass (Li et al., 2013). The EDF filter, which is unpumped, is used to shift the spectrum to longer wavelengths, i.e., the L-band, because it can absorb ASE light from the gain erbium and transfer it to longer wavelengths (Kikilich et al., 2021).

The double-pass backward ASE light source with EDF filter configuration is shown in Figure 2.29. To prove the claim, they have tested all versions of the configuration: SPB without unpumped EDF, SPB with unpumped EDF, DPB without unpumped EDF, and DPB with unpumped EDF. Li and others tested all the systems and compared the results.

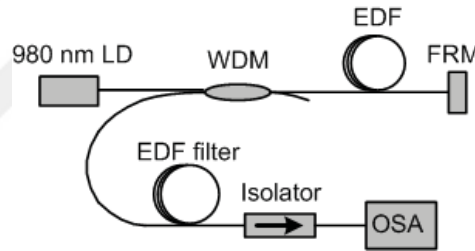


Figure 2.29. Configuration of double-pass backward ASE with unpumped EDF (Li et al., 2013).

The light sources are constructed with a 5 m EDF, and the spectra for all of them are presented in Figure 2.30. As shown, the spectra of these four configurations are distinct from one another. Since unpumped EDF acted as an absorber of the 1530 nm peak, the power spectral density decreased when it was inserted. Peak wavelength about 1530 nm had -36.9 dB in DPB without unpumped EDF configuration, and it diminished to -62.7 dB. Similarly, in SPB configurations, the peak emission declined from -27.5 dB to -42.7 dB when a non-optically pumped erbium-doped fiber (EDF) was added.

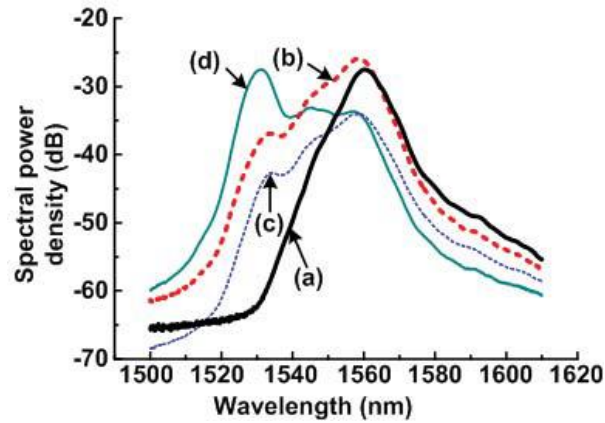


Figure 2.30. Spectra of (a) DPB with unpumped EDF, (b) DPB without unpumped EDF, (c) SDPB with unpumped EDF, (d) SPB without unpumped EDF (Li et al., 2013).

As discussed earlier, the output power of double-pass configurations is greater than that of single-pass configurations. As seen in Table 2.5, the DPB ASE without filtered EDF had an output power of 14.7 mW, while the SPB ASE without filtered EDF had an output power of 10.85 mW. Even though DPB ASE had a higher output power when the EDF filter was added, the output powers decreased due to the addition of 7.8 mW and 2.84 mW for DPB and SPB ASE, respectively, with the filtered EDF.

For the full width at half maximum (FWHM) values, which is the width of a peak measured at the point where its intensity is half of the maximum value, the opposite is valid. As shown in Table 2.5, the FWHM values for SPB setups and DPB without an EDF filter are higher than those of DPB with unpumped EDF values because peak emissions at 1530 nm exist distinctly in SPB setups and DPB without an EDF filter (Li et al., 2013). Moreover, adding unpumped EDF decreases the FWHM values for both. Additionally, the implementation of a non-optically pumped EDF in the system increased the central wavelength. For instance, the central wavelength is increased from 1555.32 nm to 1561.59 nm. In addition, Li and others demonstrated that the addition of filtered EDF enhances the mean wavelength stability at distinct temperatures.

Table 2.5. ASE Light Source Parameters (Li et al., 2013)

Configuration Name	Central Wavelength (nm)	FWHM (nm)	Output Power (mW)
DPB ASE with unpumped EDF	1561.59	15.84	7.80
DPB ASE without unpumped EDF	1555.32	21.91	14.70
SPB ASE with unpumped EDF	1555.26	23.40	2.84
SPB ASE without unpumped EDF	1538.18	26.26	10.85

2.9. Effect of Enhancing ASE Light Source Performance on Bias Stability in Fiber Optic Gyroscopes

Broadband ASE light sources play a crucial role in mitigating noise sources in IFOG, which include the Kerr effect and Rayleigh scattering, and in improving the scale factor by flattening the spectrum (Zuo et al., 2023).

In 2023, Zuo and others constructed a broadband light source, which is a two-stage two-pump erbium-doped fiber ASE light source and it generates a broad C+L band spectrum. This configuration is shown in Figure 2.31 and they used two 980 nm pump lasers. The first stage is forward-pumped from both ends to produce C-band ASE, which then enters the second stage. The second stage is backward-pumped and uses both pump light and the incoming C-band ASE to generate additional ASE. In the front section of the second stage, more C-band ASE is produced, while in the rear section, the C-band ASE acts as a secondary pump to excite L-band emission.

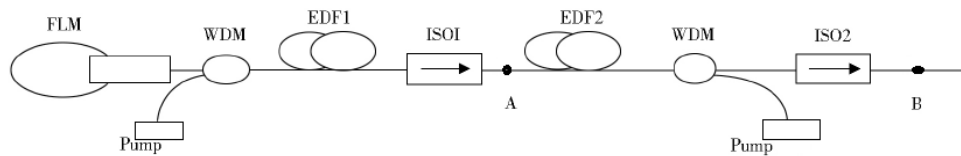


Figure 2.31. C+L band ASE light source configuration (Zuo, et al., 2023).

Since L-band generation is less efficient, due to lower emission and absorption in that range, the second fiber must be longer and more heavily doped with Er^{3+} ions (Zuo, et al., 2023). For this reason, they have used 9.5 m EDF1 and 45 m EDF2 in their configuration. It is obvious from the spectrum that the output that combines both C-band and L-band ASE with high spectral flatness.

To identify the gyro performance, they used two standard ASE light sources with an output power of about 10 mW and tested them. Also, they tested the configuration that they proposed. These results are summarized in Table 2.6. The output power of an ordinary ASE light source is approximately 10 mW, while the proposed method achieves around 21 mW of output power. Moreover, the central wavelength of standard light sources is lower than that of the proposed configuration.

Table 2.6. Performance Results (Zuo et al., 2023)

Sample	Output Power (mW)	FWHM (nm)	Central Wavelength (nm)	Scale Factor (ppm)	Bias Stability (°/h)
Standard ASE 1	-	38	1545.0	1.5	0.00025
Standard ASE 2	-	38	1545.0	2.0	0.0003
C+L Band ASE 1	21.2	78.76	1566.3	1.6	0.00018
C+L Band ASE 2	21.5	78.76	1566.4	2.2	0.00022

When they tested the gyroscopes with those ASE light sources, they demonstrated that the proposed method exhibits better bias stability compared to standard ASE light sources. For example, the average bias stability in the 100s is decreased from 0.00025 °/h to 0.00018 °/h, from standard ASE to proposed ASE. In contrast, scale factor values have remained almost steady, even though the light source's performance has improved.

In conclusion, this study reveals that advancements in ASE light source performance can dramatically improve gyroscope performance parameters.

CHAPTER 3. DESIGN AND OPTIMIZATION OF HYBRID ASE LIGHT SOURCE

3.1. Construction of Hybrid ASE Light Source

For this thesis, the hybrid DPB and DPF ASE light source is constructed. For the integration of components, the following actions are taken.

1) *Integration of Laser Diode*

In most hybrid or two-stage configurations, researchers typically employ two laser diodes, either both at 980 nm, both at 1480 nm, or a combination of 980 nm and 1480 nm wavelengths. However, in this study, a single 980 nm laser diode is used as the sole pump source to investigate the performance efficiency when operating with only one pump.

Firstly, the 980 nm laser diode is taken, whose scheme is shown in Figure 3.1. It includes a 10-pin mini-butterfly, SM fiber pigtail, and Fiber Bragg Grating (FBG) inserted into the SM fiber. This FBG is used to improve wavelength stability. The pump laser operates properly within a temperature range of -20°C to $+75^{\circ}\text{C}$.

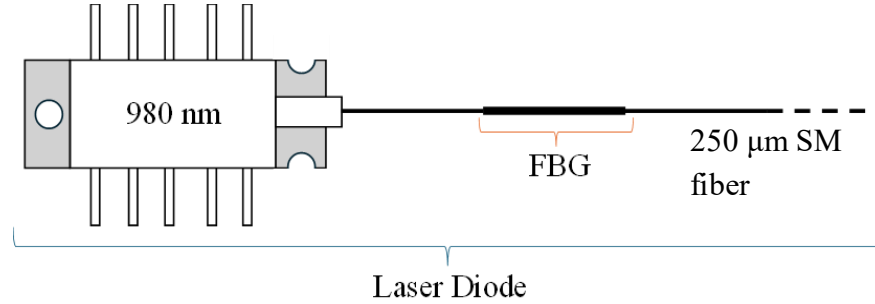


Figure 3.1. Laser diode scheme.

The output power of the laser diode was measured at various laser current levels using a laser diode controller (LDC), laser diode mount, and power meter. As shown in Table 3.1, the laser diode output power increases with rising laser current, as expected.

Table 3.1. Applied Laser Current Values (mA) vs. LD Output Power (mW)

Applied Laser Current (mA)	Output Power (mW)
100	26.8
150	61.9
200	96.9
250	132.0
300	167.0

2) Integration of 1x2 Coupler

Since this study used only one laser diode, the light had to be divided into two to feed the DPB and DPF stages of the configuration. In IFOG, one needs to have a 1x2 coupler with an operating wavelength of 1550 nm. However, for the purpose of this study, the 980 nm operation wavelength is used because the incoming light is 980 nm. The coupler's splitting ratio is 50:50, which means the two pigtails have equal power. The pigtails are single-mode fiber, and the basic scheme of a 1x2 coupler is given in Figure 3.2.a, and an example of a commercial 1x2 is given in Figure 3.2.b.

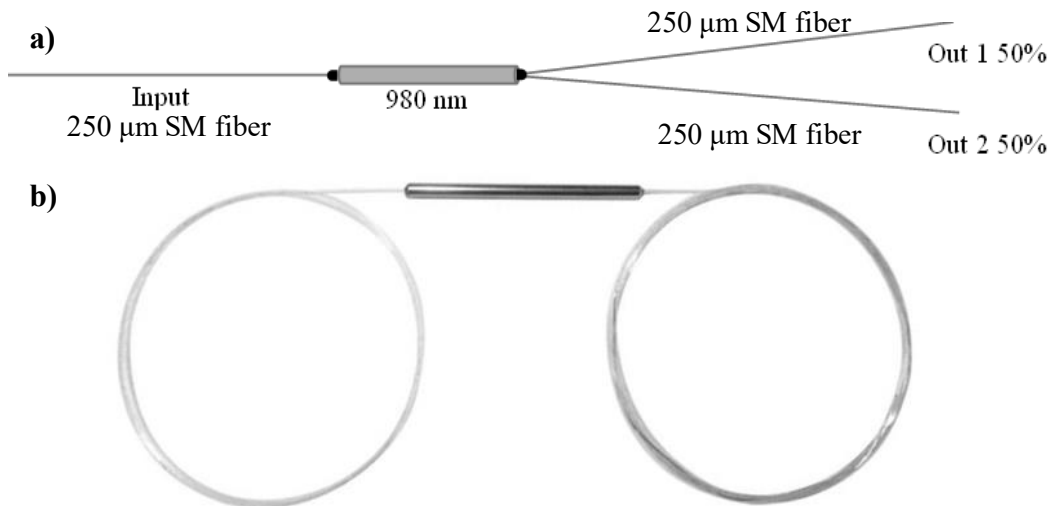


Figure 3.2. (a) Basic scheme of 1x2 coupler (b) example of 1x2 coupler (Seagnol Photonics Co., Ltd., n.d.)

At the time this study was initiated, commercially available 1×2 fused fiber couplers specifically designed for operation at 980 nm were not available in the lab. Consequently, a 2×2 coupler specified for 980 nm operation was employed as the closest alternative. To simulate a 1×2 configuration, one of the output pigtails was properly terminated. The functional schematic of the 2×2 coupler used is illustrated in Figure 3.3.

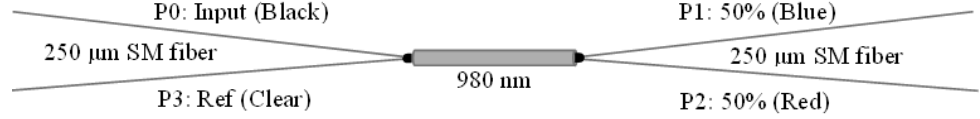


Figure 3.3. Basic scheme of 2×2 coupler.

To combine the laser diode and black input pigtail of a 2×2 coupler, the SM splicer with SM-SM mode, SM cleaver, and stripper are used. The splice procedure is followed.

The clear pigtail of the 2×2 coupler is terminated by cleaving it with an angled cleaver. The angle is chosen as 8° , and after cleaving, it is approved by the splicer.

The scheme is presented in Figure 3.4.

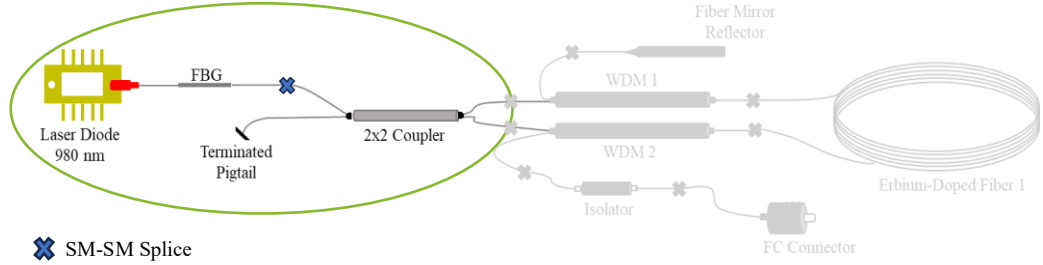


Figure 3.4. Representation of scheme when the laser diode and 2×2 coupler is combined.

3) Integration of WDM

The wavelength division multiplexer (WDM) is designed to combine/split the pumped light with signal light. Basically, it takes 980 nm light and transmits 1550 nm light. The basic scheme of WDM is shown in Figure 3.5. Pump pigtail is connected to pump source and conveys 980 nm pumped light to other pigtails. SM signal pigtail carries 1550 nm signal

through WDM while SM common pigtail is the output of both 980 nm and 1550 nm.



Figure 3.5. Basic scheme of WDM.

Since it is needed to pump the light through the WDM, the SM pump pigtails of two WDM are spliced to 2x2 coupler's two out pigtails as shown in Figure 3.6. Therefore, the 980 nm light enters to WDM's 980 nm port.

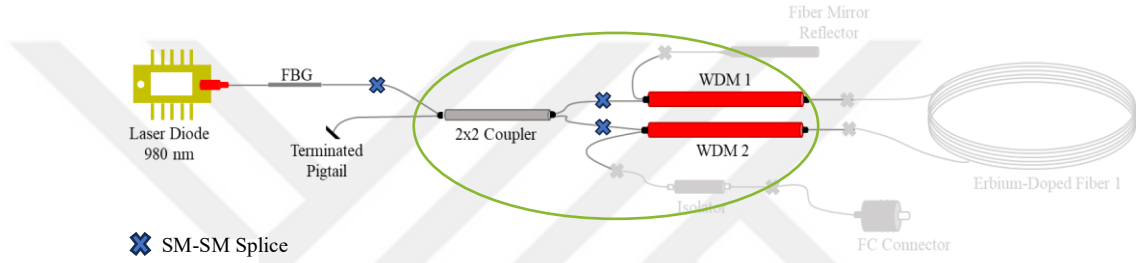


Figure 3.6. Representation of integration of WDMs.

4) Integration of EDF

As a gain medium, the M-12 (980/125) type EDF, which has a peak absorption wavelength of 1530 nm and a coating diameter of 250 μm , is used. The length of the EDF fiber is decided to be 11 meters without any special reason. The erbium-doped fiber's two pigtails are connected with signal ports of WDM 1 and WDM 2 to obtain hybrid double-pass forward and backward configurations as illustrated in Figure 3.7.

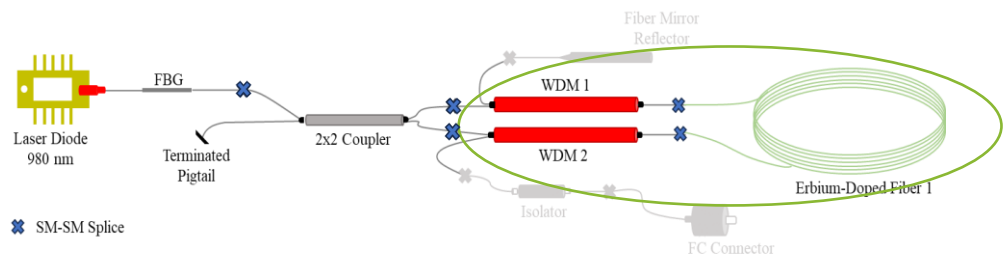


Figure 3.7. Representation of the integration of an 11-meter erbium-doped fiber.

5) Integration of Fiber Mirror

Fiber mirrors are designed to reflect light propagating through the fiber back along its original path. Thus, in this configuration, it is used to obtain a double-pass system. The representation of fiber mirror is given in Figure 3.8.a while Figure 3.8.b. shows the real-life example of mirror.



Figure 3.8. (a) Representation of fiber mirror (b) Example of fiber mirror reflector (DK Photonics Technology Limited, n.d.).

The fiber pigtail is SM fiber with a 250 μm coating diameter, and it is spliced to the common pigtail of WDM 1 as shown in Figure 3.9.

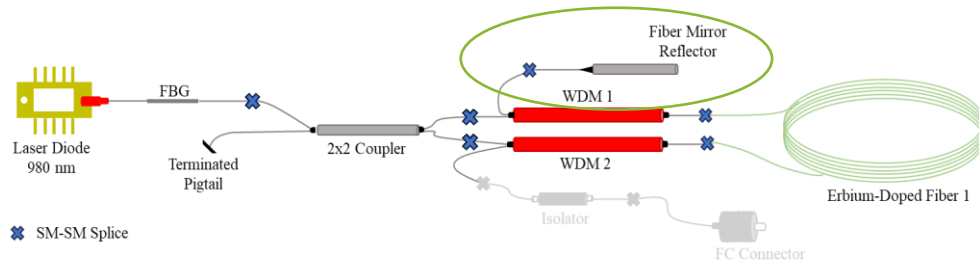


Figure 3.9. Representation of the integration of the fiber mirror.

6) Integration of Isolator

The isolator functions as a blockage to the returning light directed toward the ASE. Thanks to the filters inside, it operates in only one direction, as indicated by an arrow on the outer casing, as shown in Figure 3.10.a. It has one input and one output SM fiber with a 250 μm coating diameter, and its operating wavelength is 1550 nm, similar to the other ASE components. The real-life isolator looks like as in Figure 3.10.b.



Figure 3.10. (a) Representation of isolator (b) Example of isolator (DK Photonics Technology Limited, n.d.).

It integrates the common pigtail of WDM 2 as the ASE light source configuration is almost completed, which is illustrated in Figure 3.11.

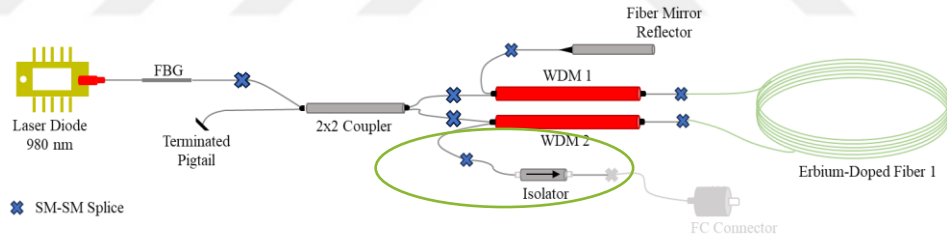


Figure 3.11. Representation of the integration of the isolator.

For the connection of ASE light source and Optical Spectrum Analyzer or power meter, FC connector is implemented in the system. The final scheme of ASE configuration is given in Figure 3.12.

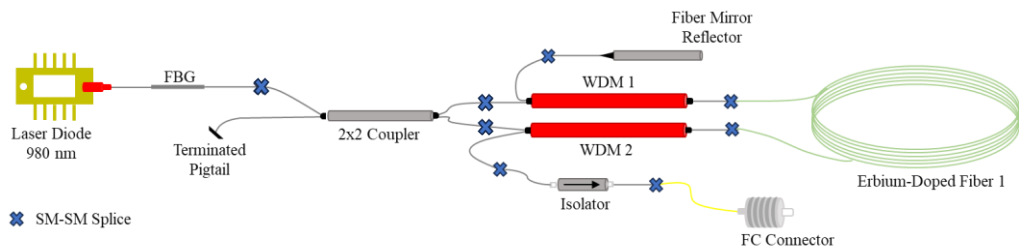


Figure 3.12. Final scheme of ASE light source configuration.

The constructed hybrid ASE light source is illustrated in Figure 3.13, with the names of its components labeled.

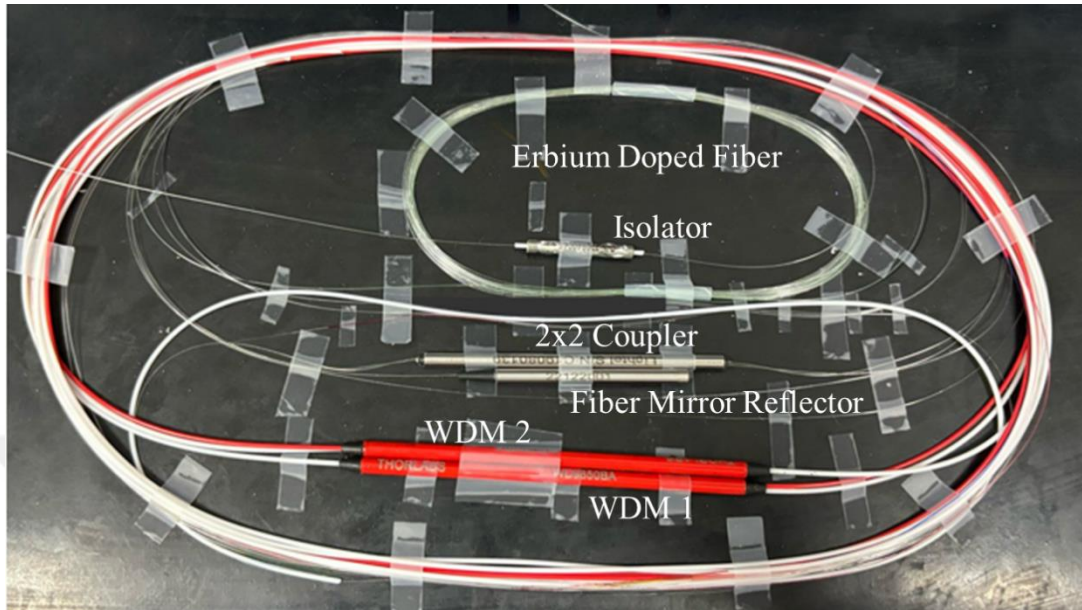


Figure 3.13. The hybrid ASE light source when the power is off.

When the light source is connected to the laser diode controller (LDC) and the laser diode is pumped, the EDF fiber begins to emit green light. If the room is dark, the emission of green light is clearly visible, as shown in Figure 3.14.

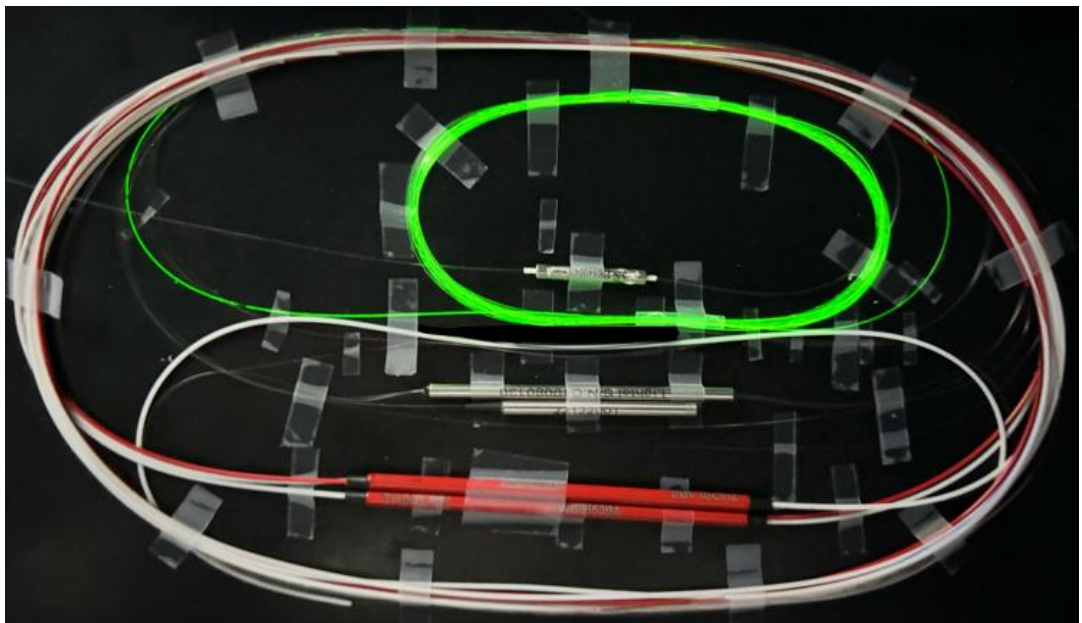


Figure 3.14. The hybrid ASE light source is on.

3.2. Testing of the Hybrid ASE Light Source

I. Measurement of Output Power

While constructing the ASE light source, splice losses were minimized to achieve the highest possible output power. To measure the output power for different applied current values, a laser diode controller (LDC) that maintains the temperature of the laser diode at room temperature, a power meter, and a laser mount are used to place the laser diode, as shown in Figure 3.15.

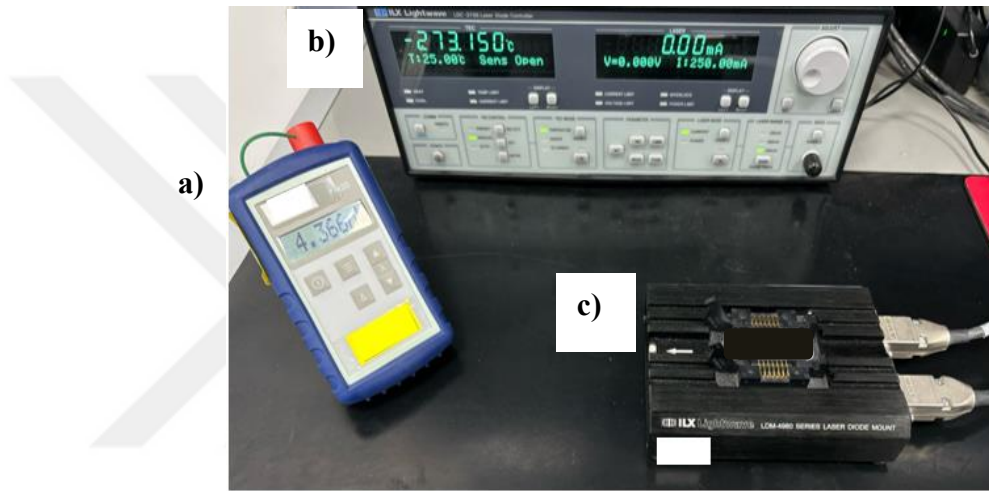


Figure 3.15. Power measurement setup: (a) power meter, (b) LDC, (c) LD mount.

The output light of the ASE light source is measured at various laser current values, as shown in Table 3.2. As seen as the laser current is increased from 100 mA to 300 mA, the output power of broadband source is increased from 2.24 mW to 26.20 mW. For the ASE optical tests, the laser diode will be pumped with 250 mA of current.

Table 3.2. Laser Current (mA) vs Output Power (mW) Values for Hybrid ASE Light

Laser Current (mA)	Output Power (mW)
100	2.24
150	7.41
200	13.54

250	19.80
300	26.20

II. Measurement of Optical Performance

To measure the optical performance of a light source, the following components are required: a laser diode controller, a computer, a measuring interface, an optical spectrum analyzer (OSA), and a laser diode mount. The measurement setup is demonstrated in Figure 3.16.

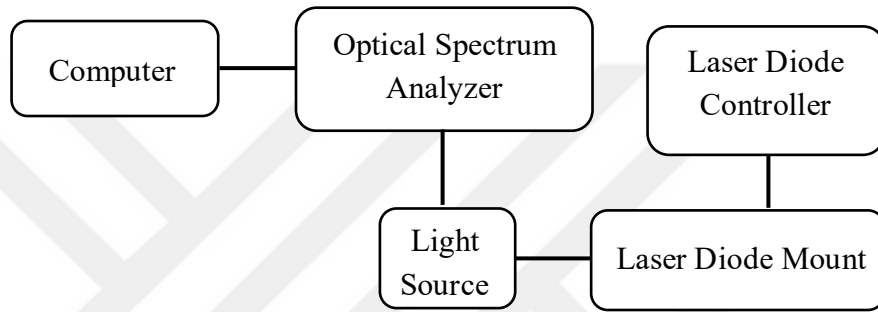


Figure 3.16. OSA measurement setup demonstration.

Light source is connected to OSA via FC connector and the laser diode is placed to laser diode mount. Laser diode controller used to pump the laser and control the temperature. Computer and OSA is connected with each other with ethernet cable to communicate. The optical spectrum analyzer (OSA) collects the data from the light source and transfers it to the computer. By taking data from the OSA, one can obtain the light source's parameters.

Ultimately, one can obtain the spectrum of a light source with wavelength stability values. From the ASE spectrum, one can determine the maximum wavelength, central wavelength, maximum power, full width at half maximum (FWHM), and spectrum symmetry.

The maximum wavelength is essentially the wavelength value at which the maximum power is obtained. For example, the maximum wavelength value is 1562.59 nm, where the maximum power is -11.24 dBm, as shown in Figure 3.21, which is the spectrum of the constructed ASE light source.

Full width at half maximum is the width of a peak measured at the point where its intensity is half of the maximum value. Therefore, the FWHM is the difference between the wavelength value at half of the max power on the right side, λ_2 , and the wavelength value at half of the max power on the left side, λ_1 , as shown in Equation 3.1 and Figure 3.17.

$$FWHM = \lambda_2 - \lambda_1 \quad 3.1$$

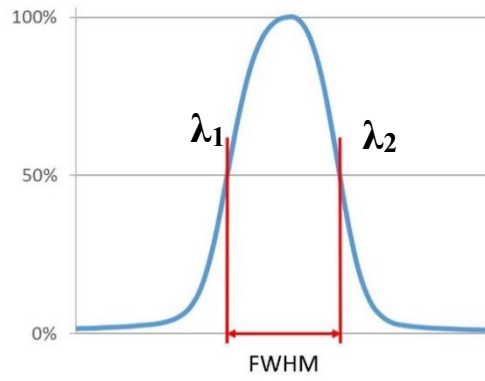


Figure 3.17. FWHM demonstration (Light Source Tech., n.d.).

To calculate the FWHM value in Figure 3.21, one needs to determine the half-power value. The values are in dBm, so on the logarithmic scale, half means a -3 dBm change. Thus, the half-power value is

$$P_{\frac{max}{2}} = P_{max} - 3 \text{ dBm} \quad 3.2$$

$$P_{\frac{max}{2}} = -11.25 \text{ dBm} - 3 \text{ dBm} = -14.25 \text{ dBm} \quad 3.3$$

$$P_{\frac{max}{2}} = -14.25 \text{ dBm} \quad 3.4$$

In Figure 3.18, the wavelength values corresponding to -14.25 dBm are 1557.60 nm and 1567.99 nm for the right and left sides of the graph, respectively. Therefore, FWHM is

$$FWHM = 1567.99 \text{ nm} - 1557.60 \text{ nm} = 10.39 \text{ nm} \quad 3.5$$

$$FWHM = 10.39 \text{ nm} \quad 3.6$$

Therefore, FWHM is 10.39 nm for the constructed ASE light source.

The spectrum symmetry is an indication of how symmetric the spectrum is around the maximum wavelength value. It is dimensionless, and the values must be between 0 and 1.

The central wavelength is calculated as the integration of the weighted mean of a spectral function (Wan et al., 2023).

$$\lambda_c = \frac{\int \lambda \cdot P(\lambda) d\lambda}{\int P(\lambda) d\lambda} \quad 3.7$$

Equation 3.7 can also be expressed as follows (Wysocki et al., 1994).

$$\lambda_c = \frac{\sum_{i=1}^n \lambda_i P(\lambda_i)}{\sum_{i=1}^n P(\lambda_i)} \quad 3.8$$

The wavelength stability is the difference between the maximum central wavelength and the minimum central wavelength that is

$$\lambda_{stability} = \lambda_{c,max} - \lambda_{c,min} \quad 3.9$$

It can also be calculated in ppm as following equation where $\bar{\lambda}_c$ is the average of the central wavelength (Kikilich et al., 2022).

$$\lambda_{stability} = \frac{\lambda_{c,max} - \lambda_{c,min}}{\bar{\lambda}_c} \cdot 10^6 \quad 3.10$$

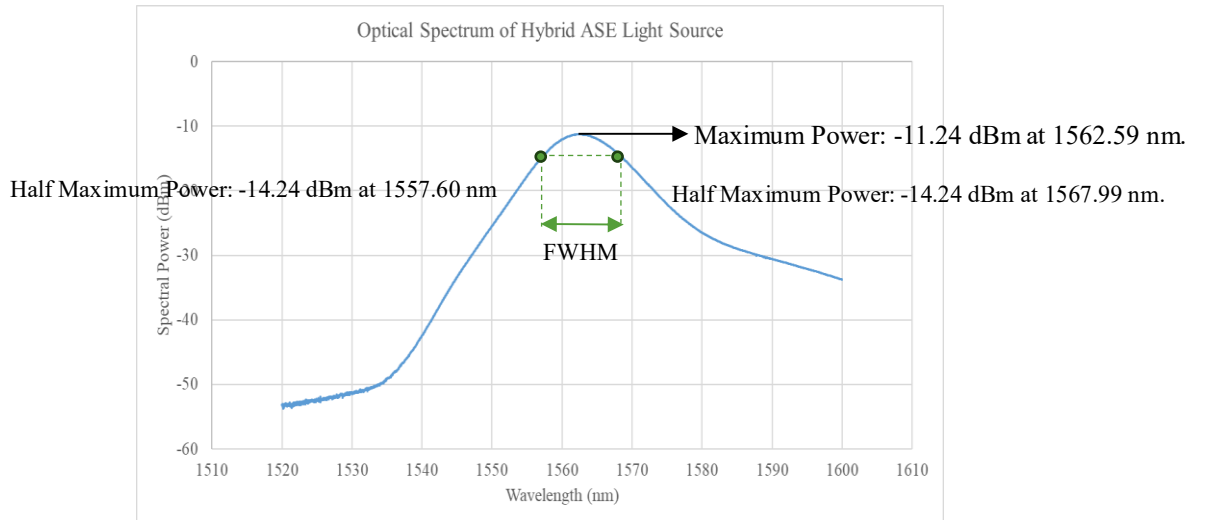


Figure 3.18. Optical spectrum and parameters of the demonstration of a hybrid ASE light source.

Figure 3.19 presents the spectrum graph of the hybrid ASE light source for different laser currents applied to the light source. As shown, each graph has only one peak, while the spectrum, pumped with 150 mA, exhibits two peaks due to inefficient power absorption at 1530 nm. As expected, the spectral power also rises as the laser current increases.

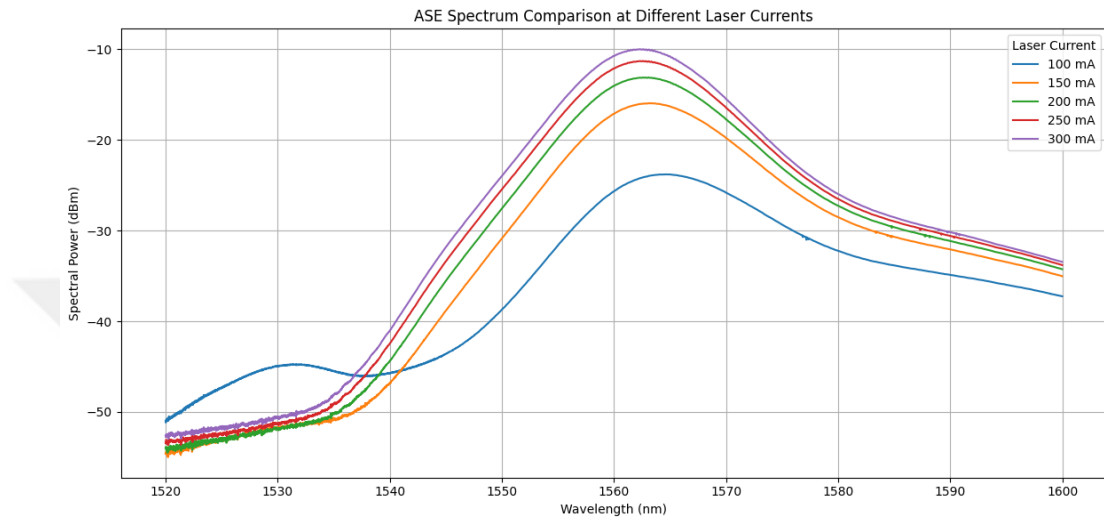


Figure 3.19. Hybrid ASE light source spectrum for distinct laser currents.

In Table 3.3, the numerical results for the spectrum parameters are summarized, which are consistent with the outcomes of the spectrum analysis. FWHM values decrease as the laser current increases. In contrast, the spectrum symmetry is climbing up with the rising laser current.

Table 3.3. Optical Parameters for ASE Light Source

Laser Current (mA)	Max Power (dBm)	Max Wavelength (nm)	Central Wavelength (nm)	FWHM (nm)	Spectrum Symmetry
100	-23.79	1564.75	1567.47	41.21	0.76
150	-15.94	1563.07	1564.89	10.99	0.023
200	-13.06	1563.09	1564.04	10.64	0.023
250	-11.27	1562.59	1563.58	10.36	0.018
300	-9.95	1562.32	1563.26	10.18	0.013

The completed teste above took two minutes for each one because it required only one data. However, to achieve wavelength stability, the OSA test is conducted for 20 minutes at room temperature. The laser current was 250 mA, so the spectrum is the same as in Figure 3.19. However, the values are changing over time. In addition, the parameters shown in Table 3.3 also remain the same.

The wavelength stability of the hybrid ASE light source is changing over time, as seen in Figure 3.20. The last value was 19.2 ppm, indicating a good wavelength stability. However, this value could be better with some arrangements in the light source's configuration, which is discussed in the next section.

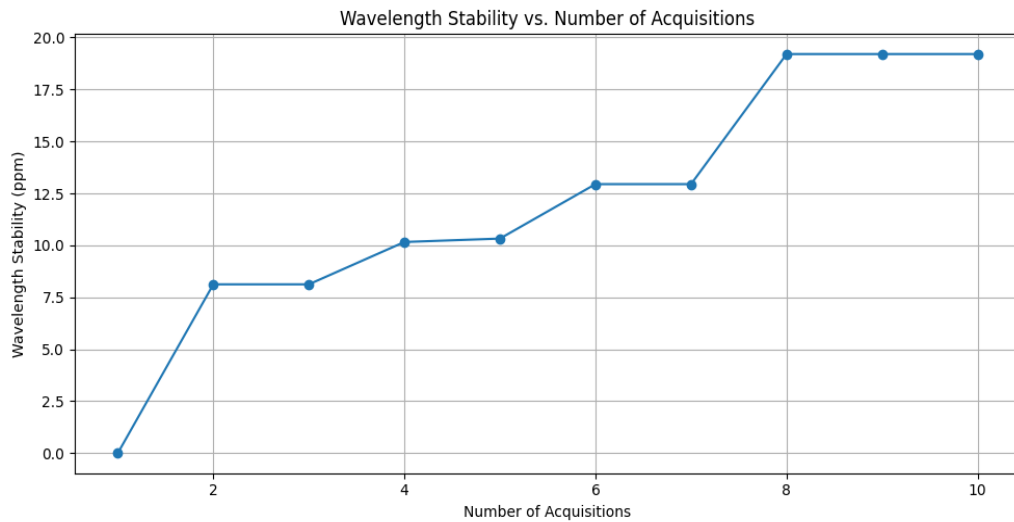


Figure 3.20. Wavelength stability of the hybrid ASE light source.

3.3. Arrangement in Configuration of Hybrid ASE Light Source

Isolator is a device specifically produced to filter specific wavelength by blocking light reflected back as shown in Figure 3.21. For this reason, it is integrated into the configuration to improve ASE light source performance.



Figure 3.21. Example of isolator (DK Photonics Technology Limited, n.d.).

It is spliced between the laser diode and a 2×2 coupler, as shown in Figure 3.22. It's input pigtail is spliced to the laser diode, while the output pigtail is connected to the input of the 2×2 coupler.

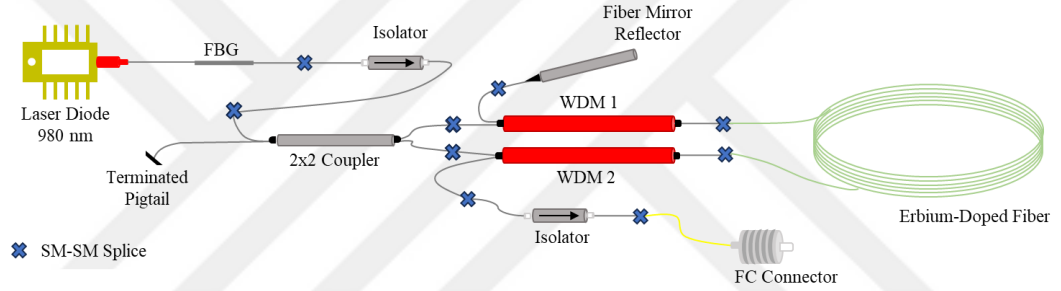


Figure 3.22. Addition of second isolator to the ASE light source configuration.

3.4. Testing of the Hybrid ASE Light Source with Isolator

I. Measurement of Output Power

The output power of the ASE light source is measured at various laser current values, as shown in Table 3.4, as before. As seen as the laser current is increased from 100 mA to 300 mA, the output power of broadband source is increased. Compared to the previous configuration without isolator, the output power decreases due to the addition of the optical component. However, still, the output power is relatively high that is 18.22 mW at 250 mA pump compared to the ordinary light sources whose output power is about 10 mW.

Table 3.4. Laser Current (mA) vs Output Power (mW) Values for Hybrid ASE Light

Laser Current (mA)	Output Power (mW)
100	2.21
150	7.35
200	12.73
250	18.22
300	23.80

II. Measurement of Optical Performance

Figure 3.23 presents the spectrum graph of the hybrid ASE light source for different laser currents applied to the light source when isolator is included. As expected, spectral power increases with increasing laser current.

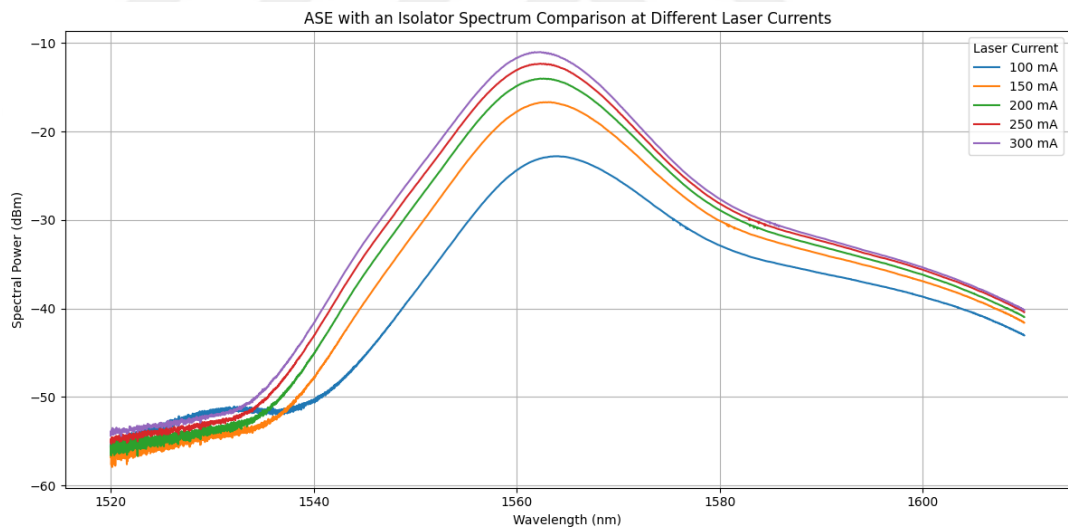


Figure 3.23. Spectrum of hybrid ASE light source with isolator at distinct laser currents.

In Table 3.5, the results for spectrum parameters are presented. FWHM values decrease as the laser current increases. In contrast, the spectrum symmetry is climbing up with the rising laser current.

Table 3.5. Optical Parameters for Hybrid ASE Light Source with Isolator

Laser Current (mA)	Max Power (dBm)	Max Wavelength (nm)	Central Wavelength (nm)	FWHM (nm)	Spectrum Symmetry
100	-22.09	1563.35	1565.85	12.08	0.026
150	-16.30	1563.37	1563.85	11.03	0.019
200	-13.74	1562.21	1563.11	10.68	0.015
250	-12.02	1561.74	1562.70	10.39	0.013
300	-10.77	1561.73	1562.39	10.27	0.012

The wavelength stability of the hybrid ASE light source with isolator is shown in Figure 3.24. The last value was 14.31 ppm, which is an excellent wavelength stability value. Moreover, it is stable because, even though the time changes, the wavelength stability remains steady at approximately 14 ppm.

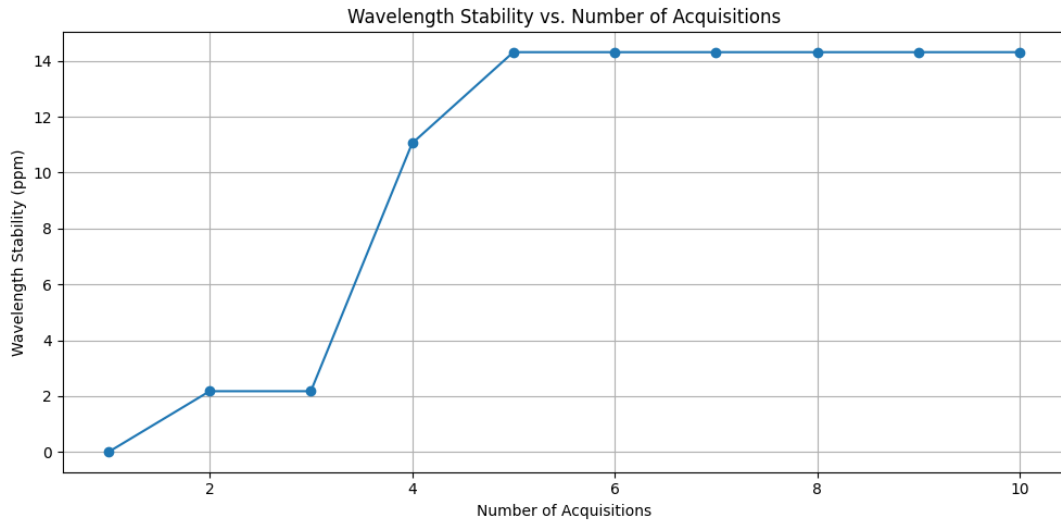


Figure 3.24. Wavelength stability of a hybrid ASE light source with isolator.

3.5. Performance Evaluation of Hybrid ASE Light Sources: With vs. Without Isolator

It is time to compare the performance of the two distinct ASE light source configurations. The spectra of these sources are quite similar to one another, as shown in Figure 3.25. However, the noises around 1520-1530 nm and 1585 nm appear to decrease with isolator.

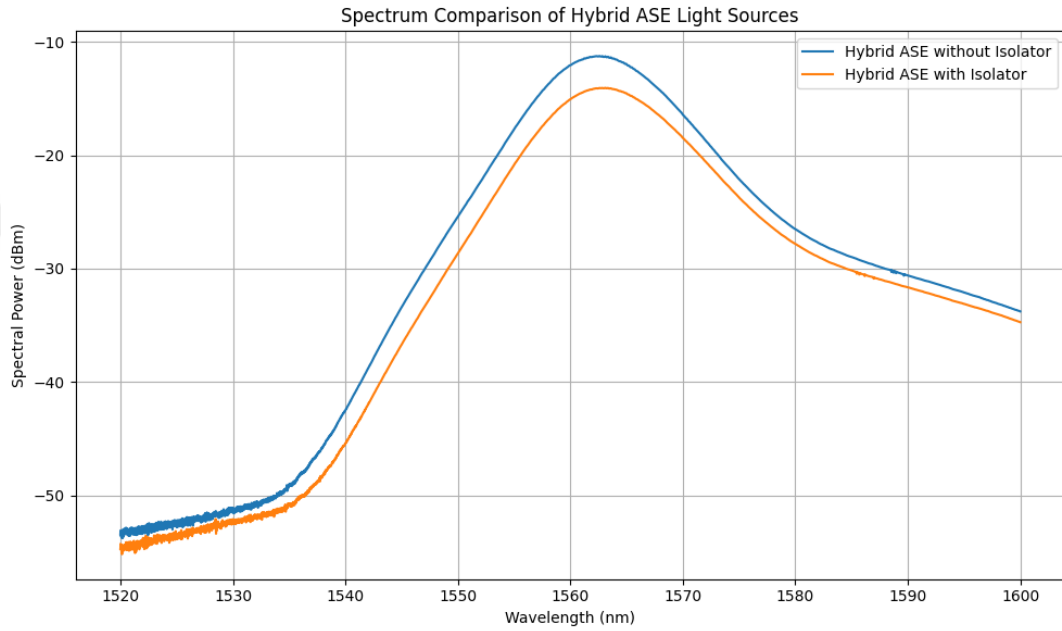


Figure 3.25. Spectrum comparison of light sources without isolator and with isolator.

Even though the spectral shapes are similar to each other, the parameters are slightly different from each other. The addition of isolator to the setup decreased the output power from 19.80 mW to 18.22 mW. The maximum power, maximum wavelength, FWHM, and central wavelength values are almost the same, as summarized in Table 3.6.

However, the average spectrum symmetry value is higher in the setup with isolator. The average spectrum symmetry value of the setup without isolator is 0.019, while it decreases to 0.011 with the integration of isolator. Likewise, the wavelength stability values are dramatically decreased from 19.20 ppm to 14.31 ppm.

Table 3.6. Optical Parameters of Hybrid ASE Sources without and with Isolator at 250 mA

Parameters	Without Isolator	With Isolator
Output Power (mW)	19.80	18.22
Max Power (dBm)	-11.27	-12.02
Max Wavelength (nm)	1562.59	1561.74
Central Wavelength (nm)	1563.58	1562.70
FWHM (nm)	10.36	10.39
Average Spectrum Symmetry	0.019	0.011
Wavelength Stability (ppm)	19.20	14.31

Along with the improved wavelength stability value, the consistency of the wavelength stability is also enhanced by including the isolator, as shown in Figure 3.26. To further improve the performance of ASE, a new addition has been made to the configuration discussed in the next section.

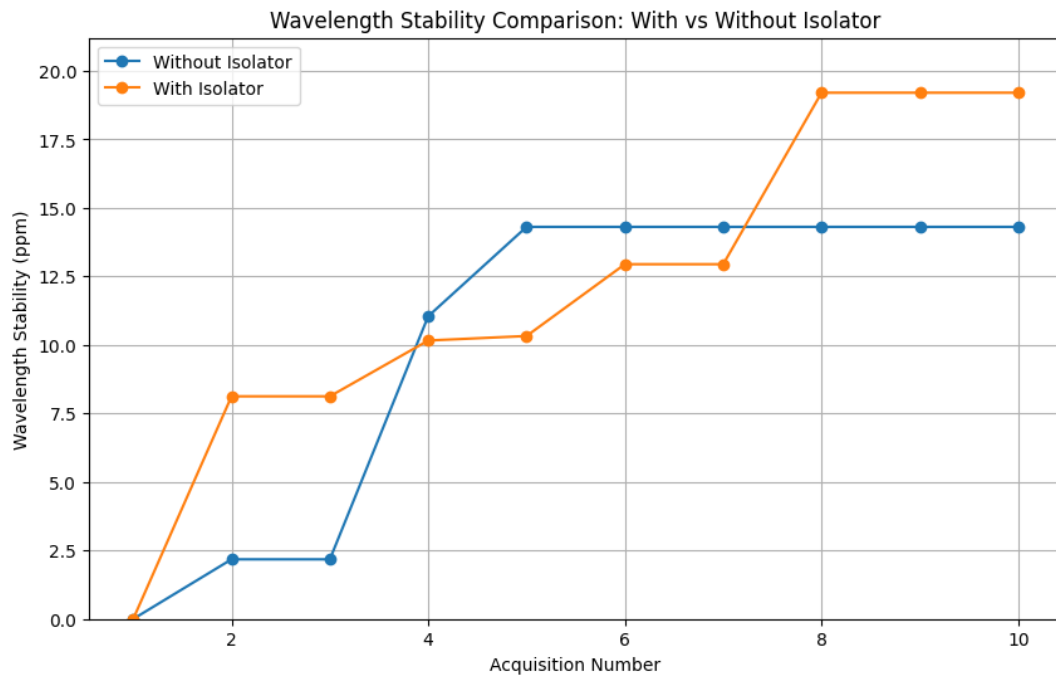


Figure 3.26. Wavelength stability comparison of light sources without isolator and with isolator.

3.6. Performance Optimization of a Hybrid ASE Light Source Through Unpumped EDF Integration

As discussed earlier, the unpumped EDF is used to shift the spectrum toward longer wavelengths by absorbing the 1530 nm component (Kikilich et al., 2021). Moreover, Li et al. (2013) demonstrated that integrating an EDF as a filter improves ASE performance. Considering these factors, the unpumped EDF is integrated into the constructed ASE light source to analyze its performance. Unlike the others, only 0.5 meters and 1 meter are added to the system to see how a short filter affects the performance. Unpumped erbium-doped fiber, namely Erbium-doped fiber 2, is spliced between the fiber mirror and WDM 1 as shown in Figure 3.27. The broadband light source is tested with 0.5 m and 1 m unpumped EDF, respectively.

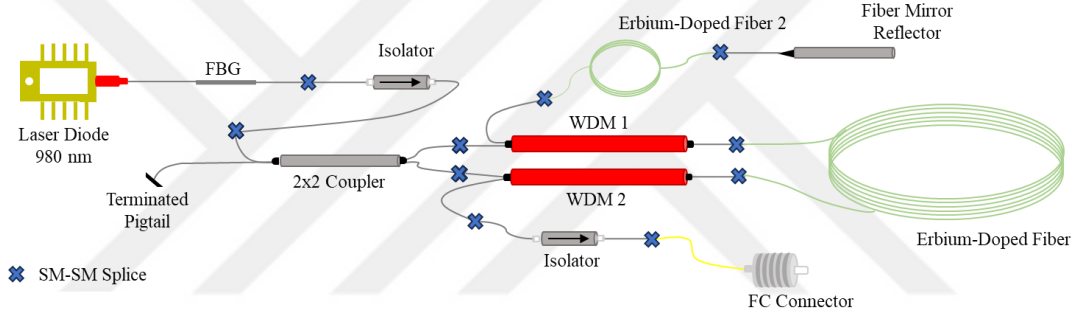


Figure 3.27. Hybrid ASE light source configuration with unpumped EDF.

3.7. Testing of the Hybrid ASE Light Source with Isolator

I. Measurement of Output Power

After splicing the 0.5-meter and 1-meter EDF filters separately, the output power of the ASE light source is measured at various laser current values, as shown in Table 3.7. Since the fiber is inserted into the setup and new splice points are created, the optical power of the light source decreases. The output power was 18.22 mW when the laser current was 250 mA. However, it decreases to 17.96 mW and 17.60 mW for the 0.5-meter filtered EDF and 1-meter filtered EDF, respectively. In a similar manner to the previous measurements, as the laser current is increased from 100 mA to 300 mA, the output power of the broadband source is also increased.

Table 3.7. Laser Current (mA) vs Output Power (mW) Values for Hybrid ASE
Light with Filtered EDF

Laser Current (mA)	Output Power of ASE with 0.5-meter Filter EDF (mW)	Output Power of ASE with 1-meter Filter EDF (mW)
100	1.98	1.96
150	7.09	6.94
200	12.53	12.22
250	17.96	17.60
300	23.76	23.12

II. Measurement of Optical Performance

Figure 3.28 illustrates the spectrum graph of a hybrid ASE light source with a 1-meter filtered EDF for different laser currents. The measurement with different laser currents is not yet completed using a 0.5 m unpumped EDF. As expected, spectral power increases with increasing laser current, and the spectral shape remains unchanged with filtered EDF.

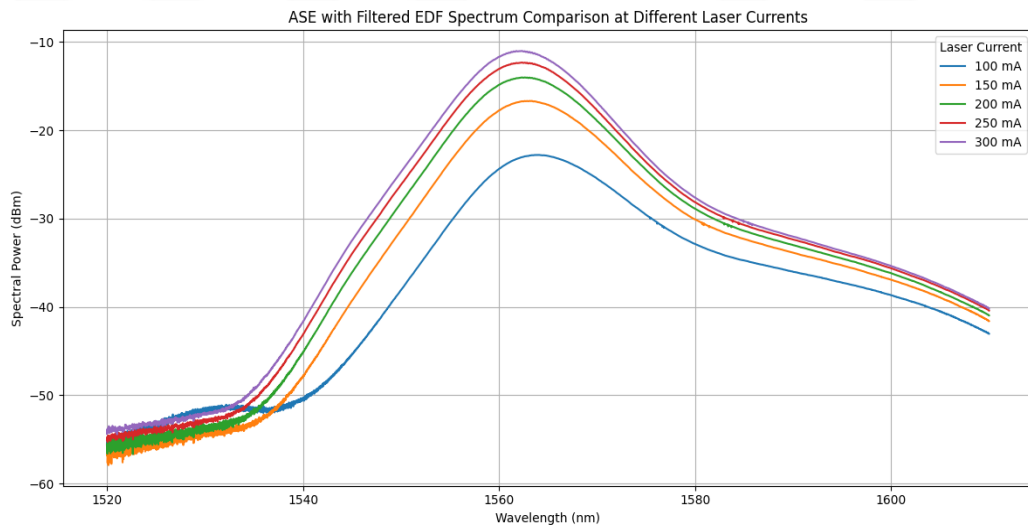


Figure 3.28. Spectrum of hybrid ASE light source with 1 m EDF filter at distinct laser currents.

The optical spectrum of the light source shifted downward as the length of the filtered EDF increased, as seen in Figure 3.29. Since the filter is used to absorb 1530 nm, it can be seen that the 1 m filter is a better absorber compared to the 0.5 m filter.

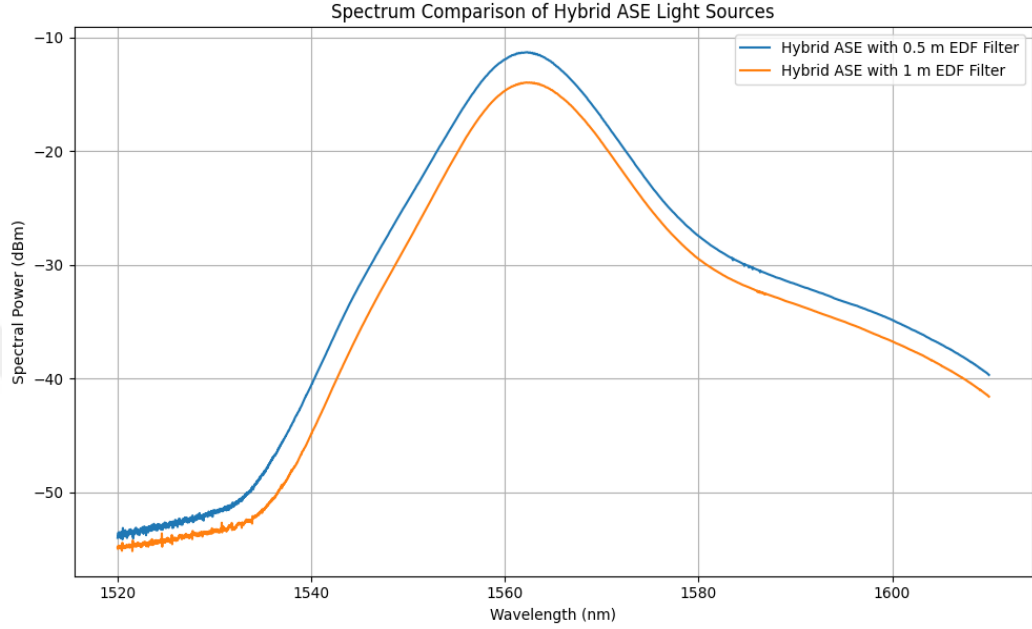


Figure 3.29. Spectrum comparison of a hybrid ASE light source with 0.5 m and 1 m EDF filter at 250 mA.

In Table 3.8, the results for spectrum parameters are presented for a 1 m unpumped EDF. As in the other measurements, the FWHM values decrease as the laser current increases. In contrast to previous results, the spectrum symmetry is climbing up with the rising laser current until 250 mA. From 250 mA to 300 mA, the spectrum symmetry is increased from 0.015 to 0.019. This is a good reason to make the performance tests while applying 250 mA.

Table 3.8. Optical Parameters for Hybrid ASE Light Source with Isolator

Laser Current (mA)	Max Power (dBm)	Max Wavelength (nm)	Central Wavelength (nm)	FWHM (nm)	Spectrum Symmetry
100	-20.65	1610.00	1566.90	48.97	0.86
150	-16.67	1563.10	1564.65	10.81	0.021
200	-14.01	1562.61	1563.84	10.51	0.019
250	-12.32	1562.35	1563.39	10.31	0.015
300	-11.01	1562.35	1563.08	10.08	0.019

In Table 3.9, the comparison of optical parameters is given for two different filter EDF lengths. As seen, even though the output power, maximum power, and maximum wavelengths values are slightly decreased, the wavelength stability is improved by almost 52%. In contrast, the FWHM and average spectrum symmetry are decreased slightly.

Table 3.9. Optical Parameters of Hybrid ASE Sources without and with 0.5 m and 1 m EDF Filter at 250 mA

Parameters	With a 0.5 m EDF Filter	With a 1 m EDF Filter
Output Power (mW)	17.96	17.60
Max Power (dBm)	-11.30	-13.98
Max Wavelength (nm)	1562.31	1562.19
Central Wavelength (nm)	1563.05	1563.52
FWHM (nm)	10.25	10.48
Average Spectrum Symmetry	0.015	0.017
Wavelength Stability (ppm)	12.67	5.98

The wavelength stability of the hybrid ASE light source was improved from 19.20 ppm to 14.31 ppm with the use of isolator. Now, it has decreased even more with the filter. By adding a 0.5-meter filter, the stability decreased from 14.31 ppm to 12.67 ppm slowly, as seen in Figure 3.30. However, a 1-meter erbium-doped fiber dramatically decreased the stability value to 5.98 ppm, which is an extremely good performance value.

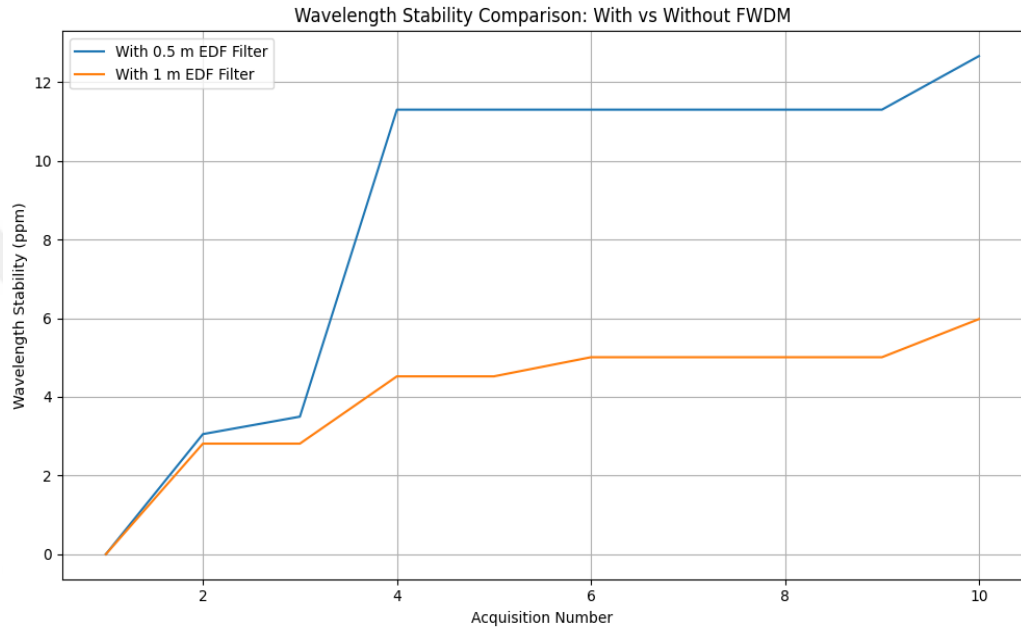


Figure 3.30. Wavelength stability of the hybrid ASE light source with 0.5 m and 1 m filters.

3.8. Performance Evaluation of Hybrid ASE Light Sources: With and Without Unpumped EDF

When the spectra are compared, it can be seen that they are almost the same, regardless of whether the source is filtered with EDF or not, and whether the EDF is filtered with 0.5 m or not. However, the spectrum of the source with 1 m filtered EDF is shifted as seen in Figure 3.31.

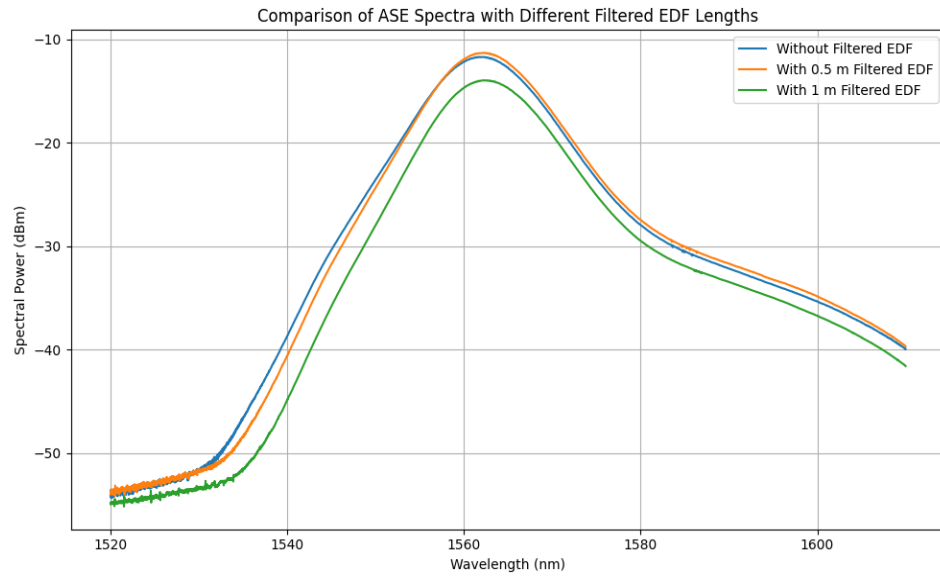


Figure 3.31. Comparison of ASE light source spectrum with different filtered EDF at 250 mA.

In Table 3.10, the results for optical parameters are summarized for three configurations. The output power declines as the EDF filter length increases. Unlike output power, the central wavelength value increases with the length of the filter. The average spectrum symmetry is deteriorating as the filtered erbium-doped fiber is added and its length is increased. However, the wavelength stability has been significantly improved.

Table 3.10. Comparison of Optical Parameters of Hybrid ASE Sources at 250 mA

Parameters	Without EDF Filter	With a 0.5 m EDF Filter	With a 1 m EDF Filter
Output Power (mW)	18.22	17.96	17.60
Max Power (dBm)	-12.02	-11.30	-13.98
Max Wavelength (nm)	1561.74	1562.31	1562.19
Central Wavelength (nm)	1562.70	1563.05	1563.52
FWHM (nm)	10.39	10.25	10.48
Average Spectrum Symmetry	0.011	0.015	0.017
Wavelength Stability (ppm)	14.31	12.67	5.98

The data was collected over 20 minutes with 2-minute intervals, resulting in 10 acquisitions. As seen in Figure 3.32, the wavelength stability is highly improved with the filter EDF.

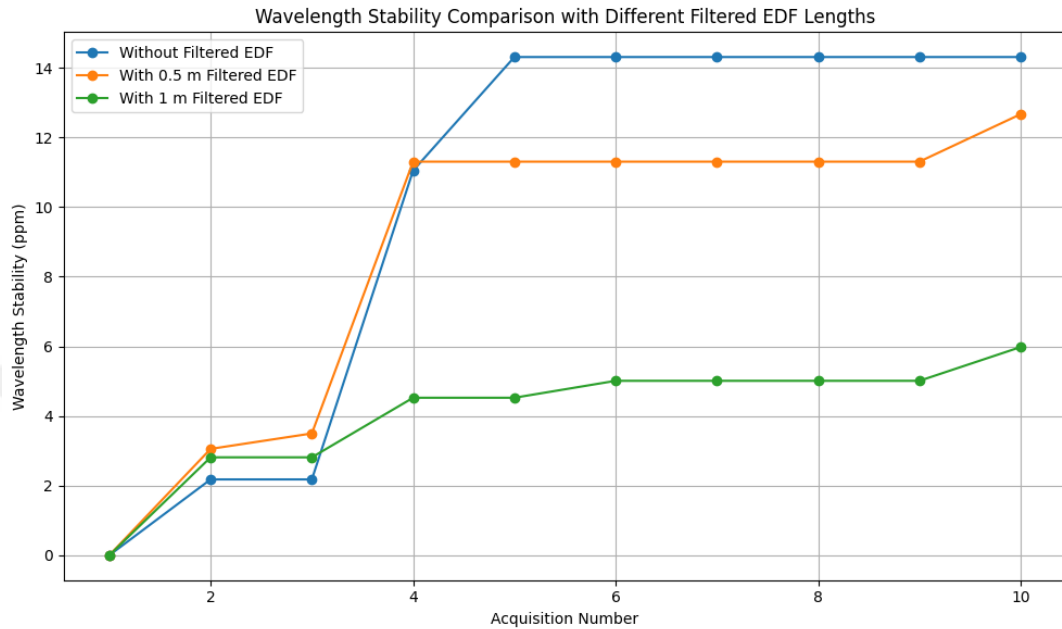


Figure 3.32. Wavelength stability comparison for different lengths of filter EDF.

The wavelength stability graph is linearly fitted, and the slope is calculated as seen in Figure 3.363 The slope of the linear fit for the hybrid ASE light source is found as 1.72. After the erbium filter is integrated, the slope decreases to 1.28 and 0.50 for the 0.5 m filter and the 1 m filter, respectively. This proves that even though time changes and the components' temperature increase similarly across all configurations, the stability and consistency of the configuration with a 1-meter filter EDF are better than those of all the others.

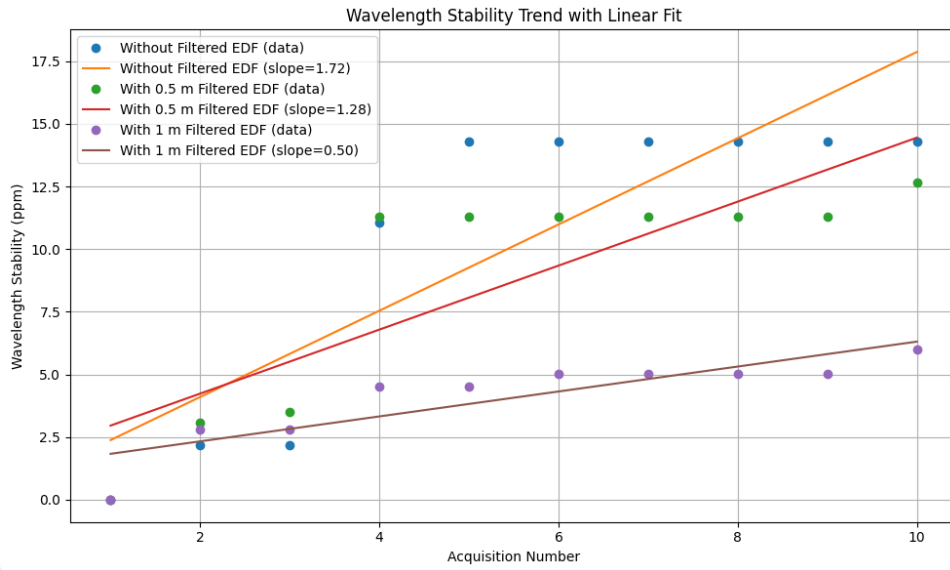


Figure 3.33. Wavelength stability trend with linear fit.

Since the performance parameters are better for a 1-meter EDF filter, the following performance tests, which are temperature tests and bias tests, will be done for ASE light without an EDF filter and with a 1-meter EDF filter.

3.9. Thermal Performance of Hybrid ASE Light Sources: Comparison with and without 1 m Unpumped EDF

To analyze the durability of the light source under extreme conditions, temperature tests were conducted on the hybrid ASE light source, both with and without a 1 m unpumped EDF filter. Since a temperature-controlled chamber was not available, the light source was conditioned at +60°C in an oven for 30 minutes and then immediately tested at room temperature. Similarly, it was conditioned for 30 minutes at -25°C in the fridge and immediately tested afterward. As the optical tests were performed at room temperature following thermal conditioning, these are referred to as worst-case scenario tests. However, the results were quite satisfactory, despite the poor conditions for this type of analysis.

The spectral shape of the ASE light source remained unchanged when it was conditioned at extreme temperatures, as shown in Figure 3.34. However, the cooled and heated versions of the spectrum are shifted downward compared to the room temperature graph.

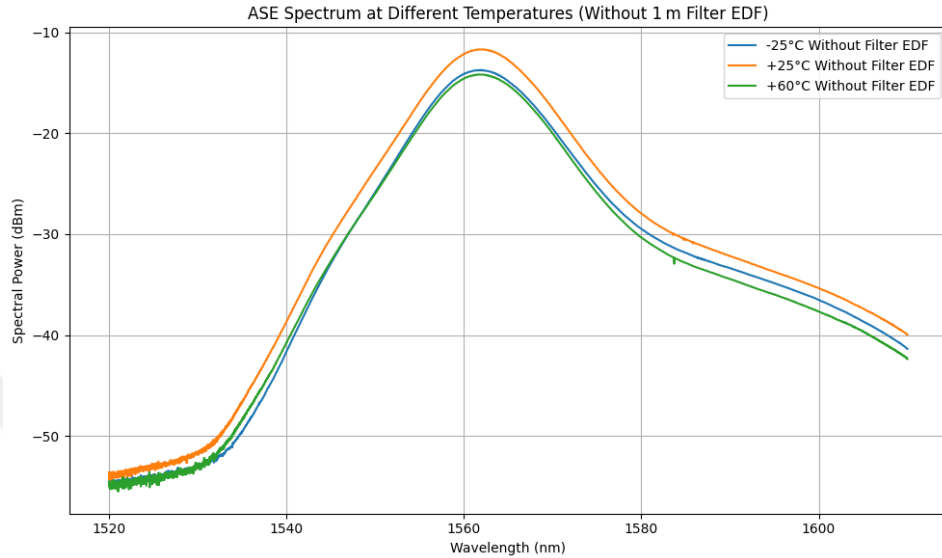


Figure 3.34. Spectrum at different temperatures for the configuration without the EDF filter.

Similarly, the spectral shape generally remains the same for the system with unpumped erbium-doped fiber as seen in Figure 3.35. However, in contrast to ASE without an EDF filter, the spectrum of -25°C did not shift.

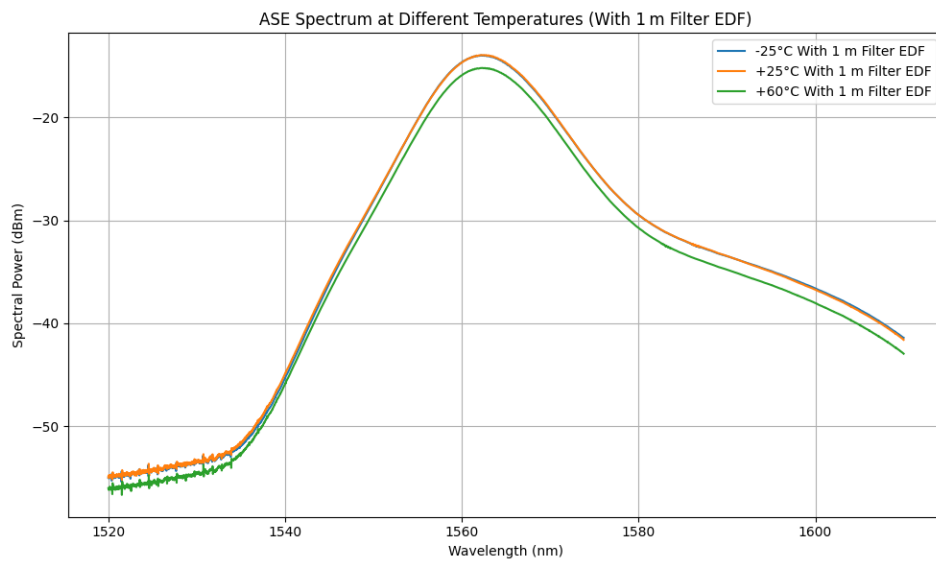


Figure 3.35. Spectrum at different temperatures for configuration with 1 m EDF filter.

For a better visualization, all graphs are combined in one graph in Figure 3.36.

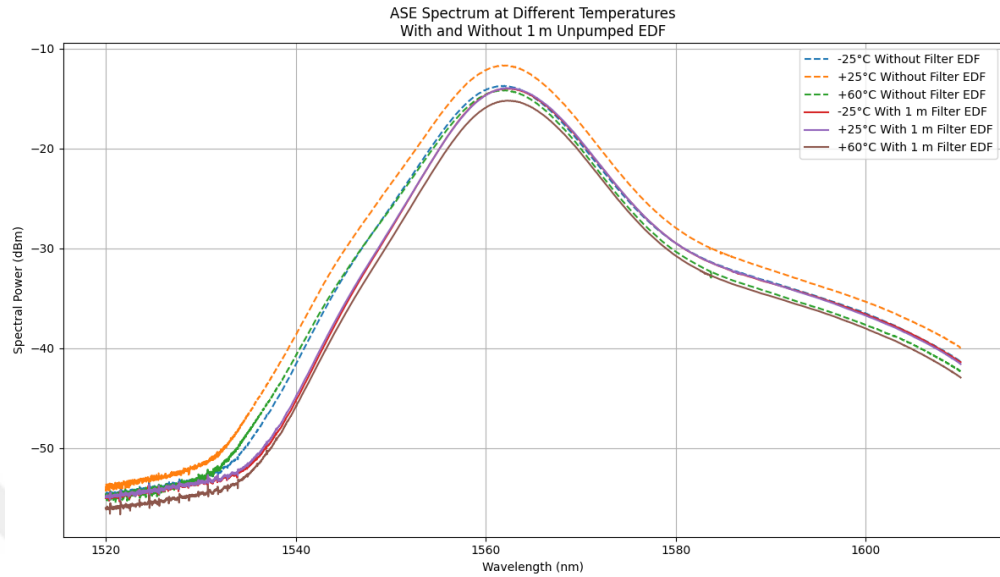


Figure 3.36. Comparison of the spectrum for the configuration with and without a 1 m EDF filter.

The test results are summarized in Table 3.11. The maximum wavelength remained almost the same for the configurations as the temperature changed. However, the max power and FWHM values are fluctuating slightly. The central wavelength values remain constant for temperature changes. The average spectrum symmetry of the configuration without filtered EDF is increased as the temperature changes from 0.011 to about 0.015 for extreme temperatures. However, it remained almost the same for the setup with unpumped EDF, at about 0.017.

A significant difference is observable when reviewing the wavelength stability values. It is discussed that the stability has dramatically declined from 14.31 ppm to 5.98 ppm with the integration of one meter of unpumped erbium-doped fiber. The same trend is seen at different temperatures.

Table 3.11. Comparison of Parameters for Two Configurations at Several Temperatures

Parameters Configuration	P_{max} (dBm)	λ_{max} (nm)	λ_{central} (nm)	FWHM (nm)	SS_{ave}	λ_{stability} (ppm)
Without the EDF Filter at +25°C	-12.05	1561.74	1562.70	10.39	0.011	14.31
Without EDF Filter at -25°C	-13.70	1561.59	1562.78	10.58	0.016	52.63
Without the EDF Filter at +60°C	-14.09	1561.71	1562.68	10.56	0.014	26.63
With 1m EDF Filter at +25°C	-13.98	1562.19	1563.52	10.48	0.017	5.98
With 1m EDF Filter at -25°C	-13.95	1562.77	1563.54	10.49	0.018	42.16
With 1m EDF Filter at +60°C	-15.22	1562.26	1563.49	10.39	0.017	16.89

As shown in Figure 3.37, the wavelength stability values of the improved configuration with the EDF filter remain below those of the normal configuration. In a setup without a filter, the wavelength stability increases from 14.31 ppm to 52.63 ppm as the system is conditioned at -25 °C with a refrigerator. In other words, there was an approximately 3.5-fold increase, while the increase for the EDF filtered version was 7-fold. Although the improved configuration shows a higher order of magnitude increase, the wavelength stability value is still lower than 52.63 ppm, at 42.16 ppm. As the light source is conditioned at +60°C, the wavelength stability increased to 26.63 ppm for the setup without a filter and to 16.89 ppm for the setup with a filter.

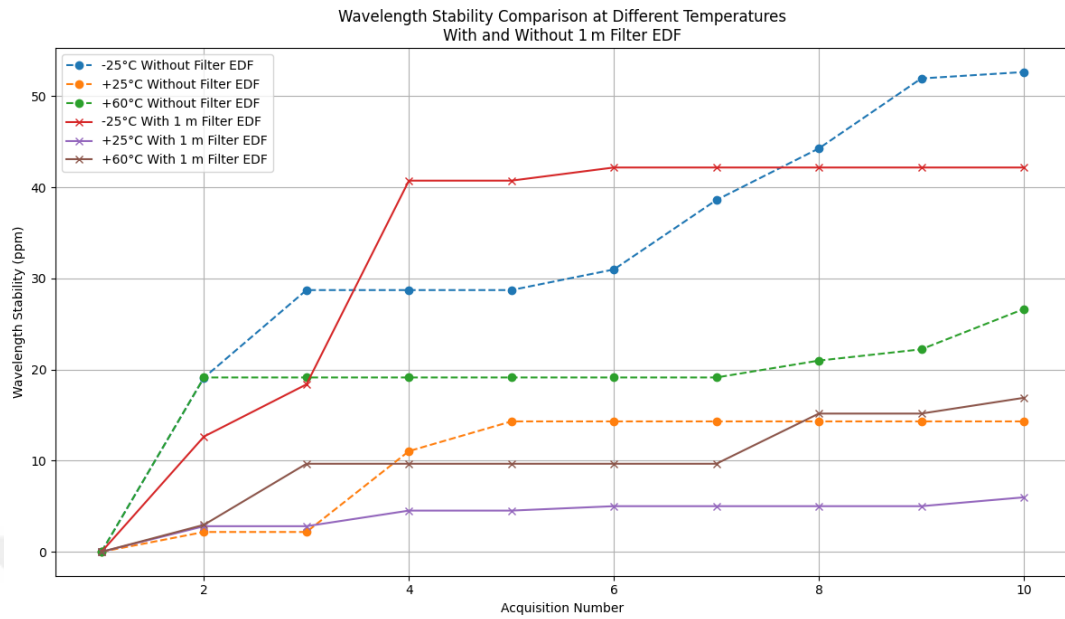


Figure 3.37. Comparison graph for wavelength stability of configurations at different temperatures.

In conclusion, the filtered erbium-doped fiber improves the ASE light source's performance parameters, not significantly, but considerably. It is now important to determine if these improvements are also evident in the bias measurements.

CHAPTER 4. CONSTRUCTION AND EVALUATION OF AN IFOG WITH A HYBRID ASE LIGHT SOURCE

4.1. Construction of Single-Axis IFOG with a Hybrid ASE Light Source

To measure and compare the bias performance of two configurations, a single-axis fiber optic gyroscope is constructed. The FC connector is removed from the end of the isolator. For the construction, the following actions are made:

1. An isolator and one pigtail of a 1x2 coupler are spliced as shown in Figure 4.1.

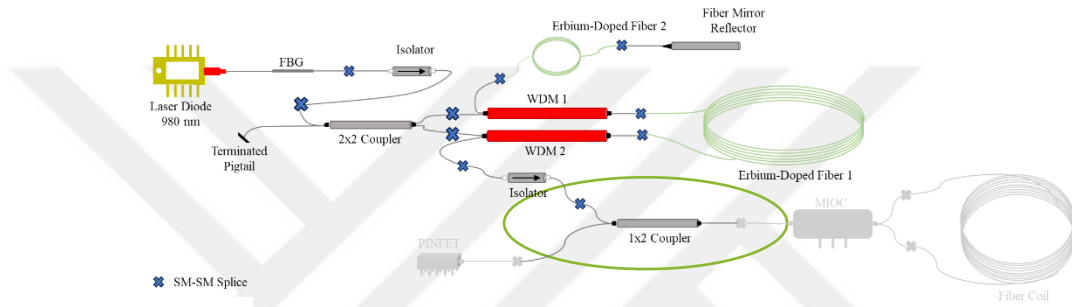


Figure 4.1. Integration of 1x2 coupler.

2. The other pigtail of the 1x2 coupler is spliced with a PINFET to convert the optical signal to an electrical signal as seen in Figure 4.2.

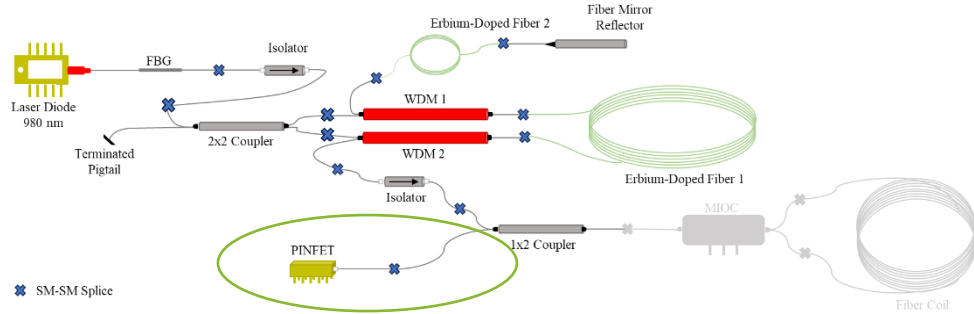


Figure 4.2. Integration of PINFET.

APE MIOC is used as a modulator which is shown in Figure 4.3.

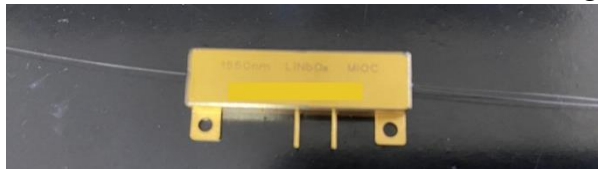


Figure 4.3. MIOC representation.

3. Single pigtail side of 1x2 is spliced to MIOC's input pigtail by splicing SM-PM fibers as shown in Figure 4.4.

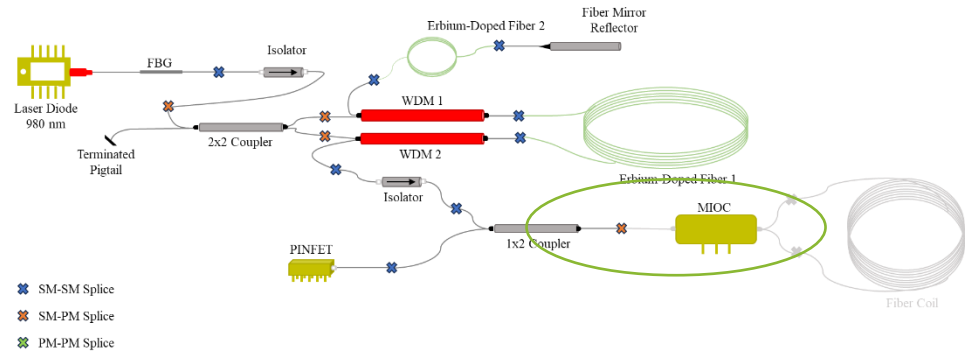


Figure 4.4. Integration of MIOC.

For this thesis, the tactical grade fiber optic coil is used as shown in Figure 4.5. The length of coil is about 200 meters. The winding method is quadrupole.

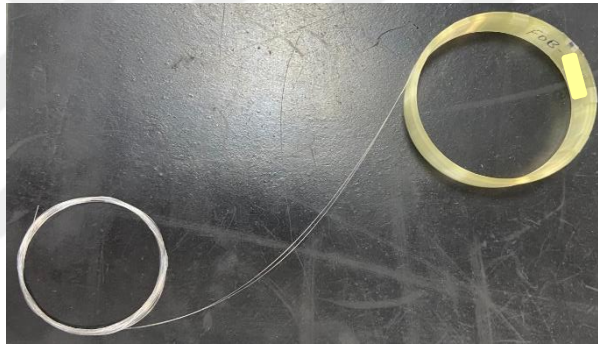


Figure 4.5. Representation of fiber coil.

4. Two pigtails of MIOC are spliced with a fiber coil and the coil and MIOC assembly is shown in Figure 4.6.

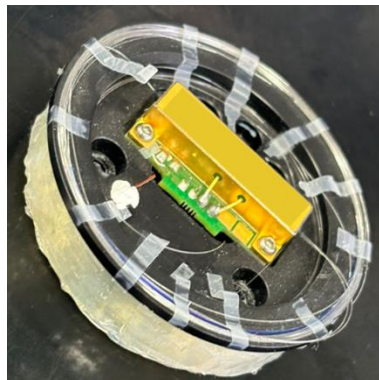


Figure 4.6. Representation of fiber coil and MIOC assembly.

The final configuration is shown in Figure 4.7.

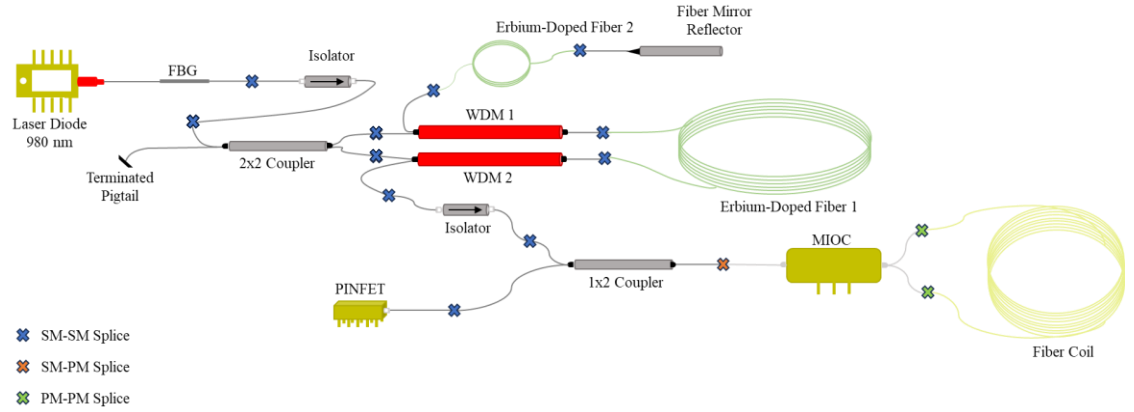


Figure 4.7. Configuration of single-axis IFOG with a hybrid ASE light source.

5. Laser diode and PINFET are connected to the electronic board.
6. The electronic board drives the LD and PINFET, which are connected to the main board and power board.
7. The cable is connected to the electrical boards to transfer the signal.

The IFOG is tested in both configurations under the same environmental conditions. Since the ASE light source is not designed for any specific optical tray, it cannot be fit into the case. Therefore, the upper cover of the optical case is not closed as seen in Figure 4.8, and the fiber of the laser diode passes through the gap between the case and cover.

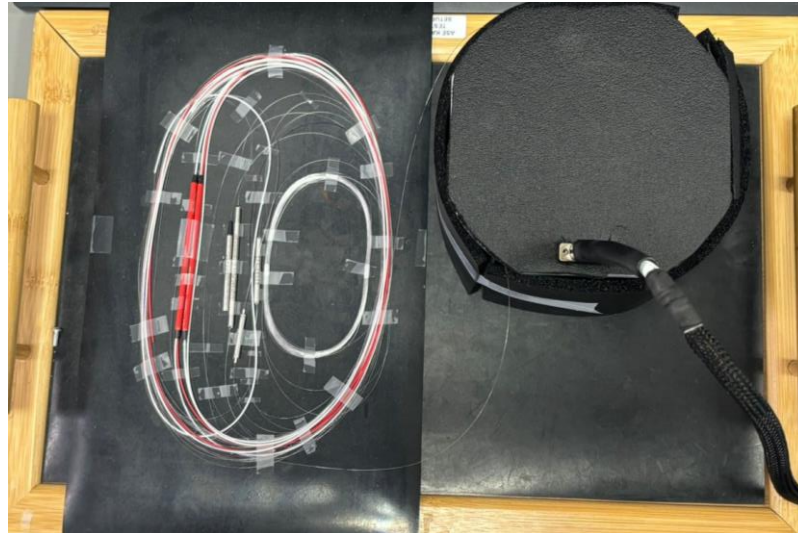


Figure 4.8. Representation of single-axis gyroscope.

4.2. Performance Tests of Single-Axis IFOG

The test setup consists of a single-axis gyroscope, a power supply, a computer equipped with a test interface, and the necessary connection cables. The single-axis gyroscope is placed on a seismic ground platform in an isolated laboratory to prevent any external noise. All tests are conducted at room temperature for 30 minutes of data collection; however, the temperature of the electronic cards increases over time. Thus, each test is repeated after a waiting period to allow the gyroscope and electronic cards to reach thermal equilibrium.

Since the upper cover of the case is left open, proper thermal isolation could not be achieved. Nevertheless, because the test conditions remained the same for all repetitions, the results are still considered valid.

In Figure 4.9, the temperature graphs for the main board and power board of the two configurations are presented. When the temperature values are compared, it is evident that the two configurations were tested under the same conditions. It is obvious that the temperature change is almost the same for both configurations at the two cards.

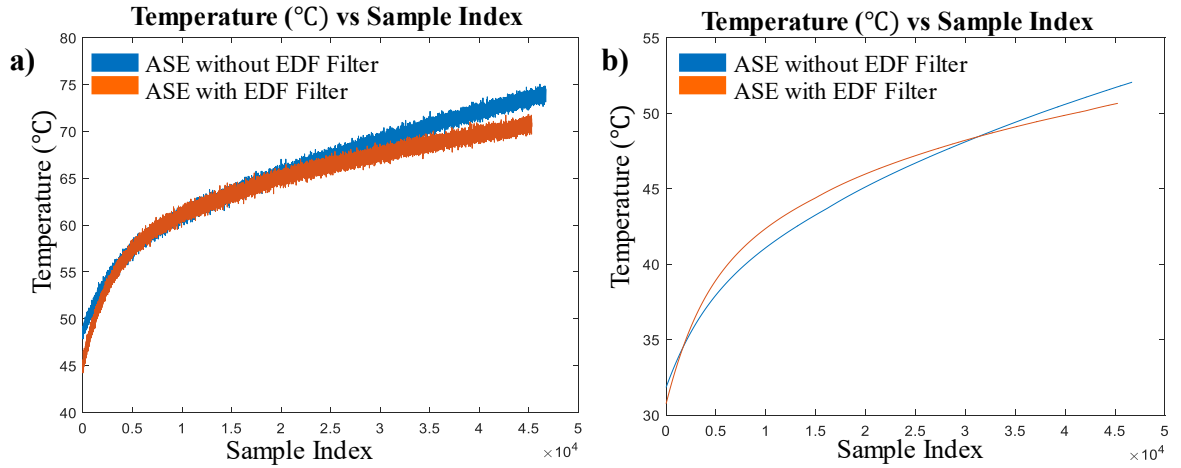


Figure 4.9. Temperature graphs of (a) the main board and (b) the power board for two configurations.

After the electronic cards, the temperature of the fiber optic coil, i.e., the axis, which is the combination of MIOC and fiber coil, is significant. As seen in Figure 4.10, the temperature of the axis is almost the same for both configurations. The temperature at the beginning of the ASE test without a filter is almost 22°C and increases to 38°C by the end. Similarly, the temperature of the axis is rising from 20°C to 36°C in the ASE light source with 1 meter of erbium-doped fiber.

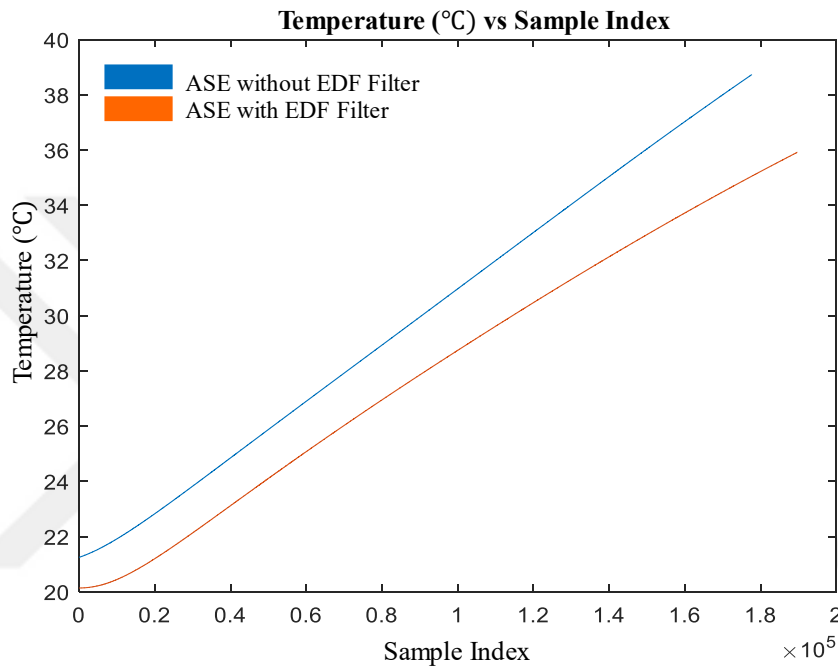


Figure 4.10. Temperature comparison of the axis for the two configurations.

4.3. Analyzing the Bias Performance of Single-Axis IFOG With and Without Filter EDF

As discussed earlier, the bias instability values for the tactical-grade gyroscope are between $0.15^\circ/\text{h}$ and $15^\circ/\text{h}$. If it is lower than $0.15^\circ/\text{h}$, the bias instability performance is closer to the navigation grade. The ARW values for tactical grade are between $0.05\%/\sqrt{h}$ and $0.5\%/\sqrt{h}$. When it is between $0.01\%/\sqrt{h}$ and $0.05\%/\sqrt{h}$, it is the navigation grade performance.

The bias performance test was conducted for 30 minutes for each repeat, and the test was repeated five times for each configuration: hybrid ASE light sources without a 1 m EDF filter and with a 1 m EDF filter.

In Figure 4.11, the first test for the hybrid ASE light source, without an unpumped EDF, is presented. In Figure 4.11.a, the rotation rate graph is demonstrated which includes some random peaks due to environmental effect. The Allan deviation graph is given in Figure 4.11.b. As shown, the plot matches the fitted line, indicating that this sensor exhibits Gaussian white noise. The ARW value of the light source is about $0.010\%/\sqrt{h}$ which is a good value in the range of navigation-grade sensors. On the other hand, the bias instability value is approximately $0.15^\circ/\text{h}$, indicating a tactical-grade performance.

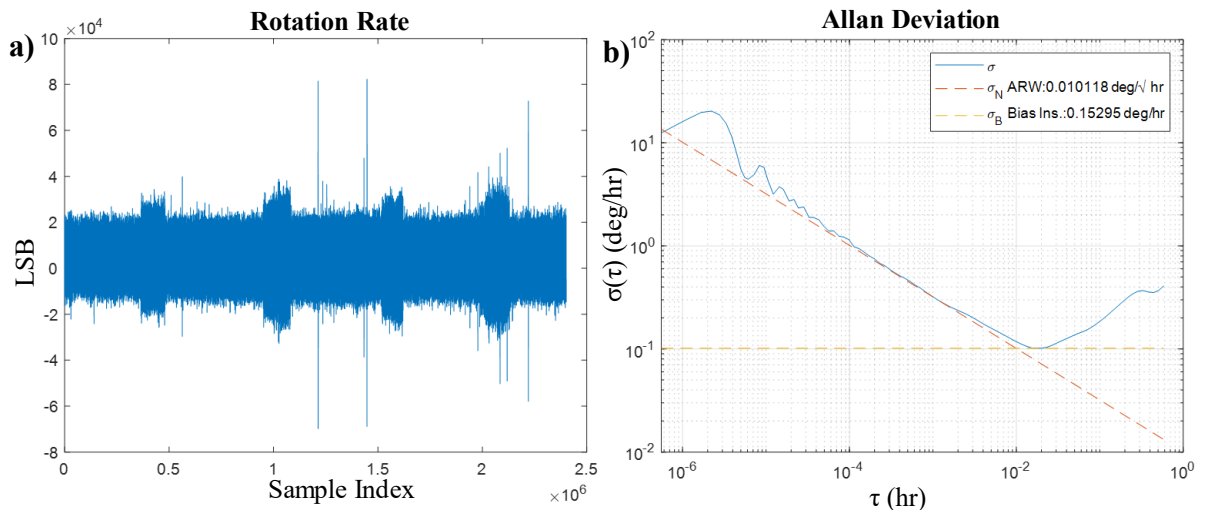


Figure 4.11. (a) Rotation rate graph (b) Allan deviation graph for hybrid ASE without unpumped EDF (Test 1).

In the second test, the number of peaks and noise in the rotation rate graph is decreased, but still exists, as seen in Figure 4.12.a. The Allan deviation is shown in Figure 4.12.b. The bias instability value is the same as before, but the ARW is slightly decreased to $0.009\%\sqrt{h}$.

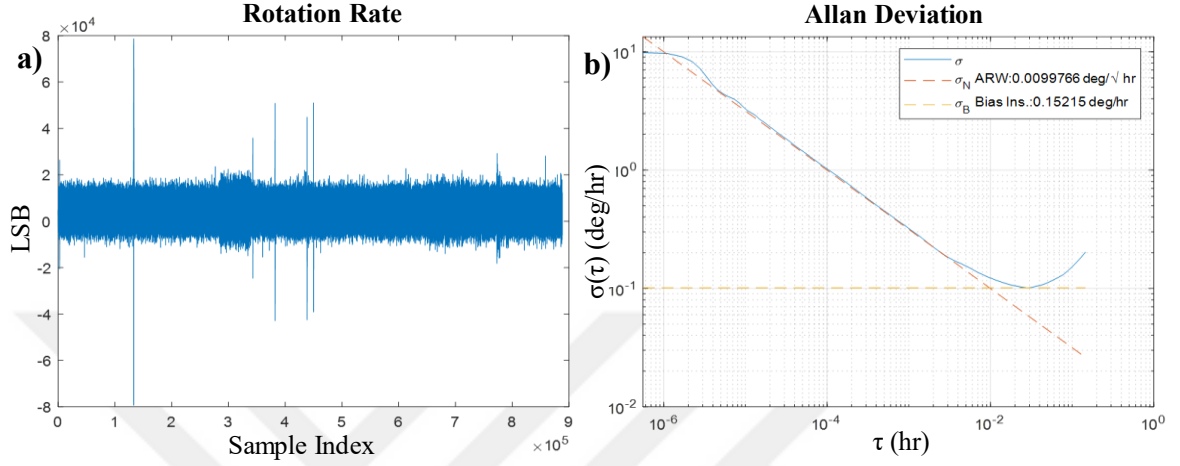


Figure 4.12. (a) Rotation rate graph (b) Allan deviation graph for hybrid ASE without unpumped EDF (Test 2).

In the rotation rate graph, the number of peaks and noise is decreased as seen in Figure 4.13.a in the third test. The ARW value remains almost the same as before, but the bias instability value has gradually declined to 0.14 $^{\circ}/h$, as shown in Figure 4.13.b.

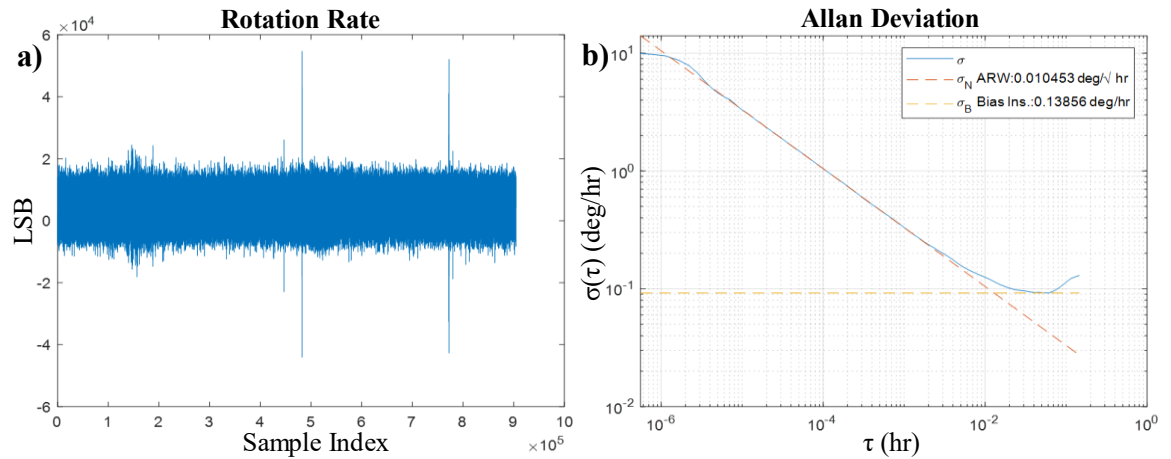


Figure 4.13. (a) Rotation rate graph (b) Allan deviation graph for hybrid ASE without unpumped EDF (Test 3).

The rotation rate graph seems almost the same as illustrated in Figure 4.14.a. Similar to the third test, the ARW value continues to be about $0.010\%/\sqrt{h}$. The bias stability value fluctuates with an increase to $0.16\%/h$ as presented in Figure 4.14.b.

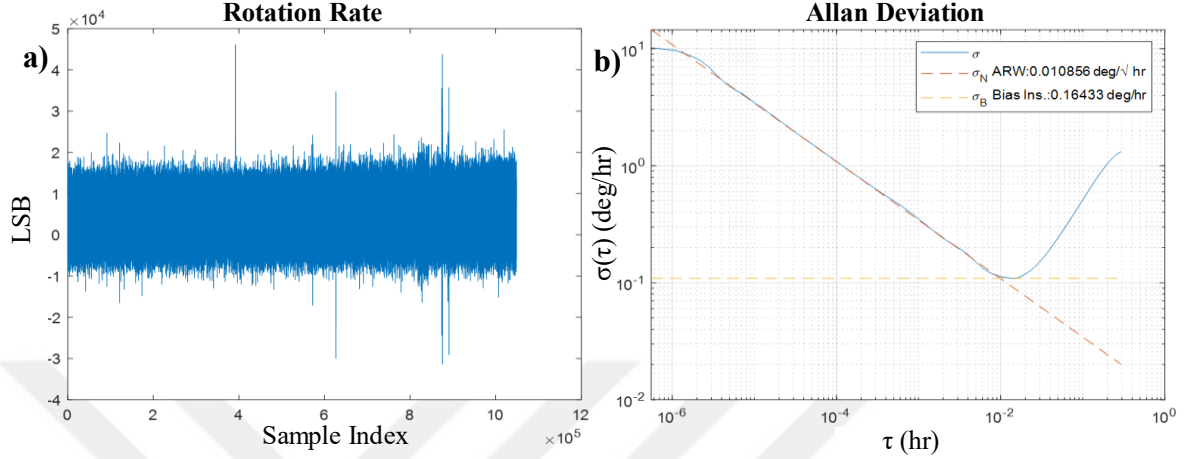


Figure 4.14. (a) Rotation rate graph (b) Allan deviation graph for hybrid ASE without unpumped EDF (Test 4).

Finally, in Figure 4.15.a and 4.15.b, the rotation rate and Allan deviation for the fifth test for the unpumped ASE source. The rotation rate graph is smoother than the previous ones, and the ARW is almost the same. However, the bias instability value is decreased to $0.14\%/h$.

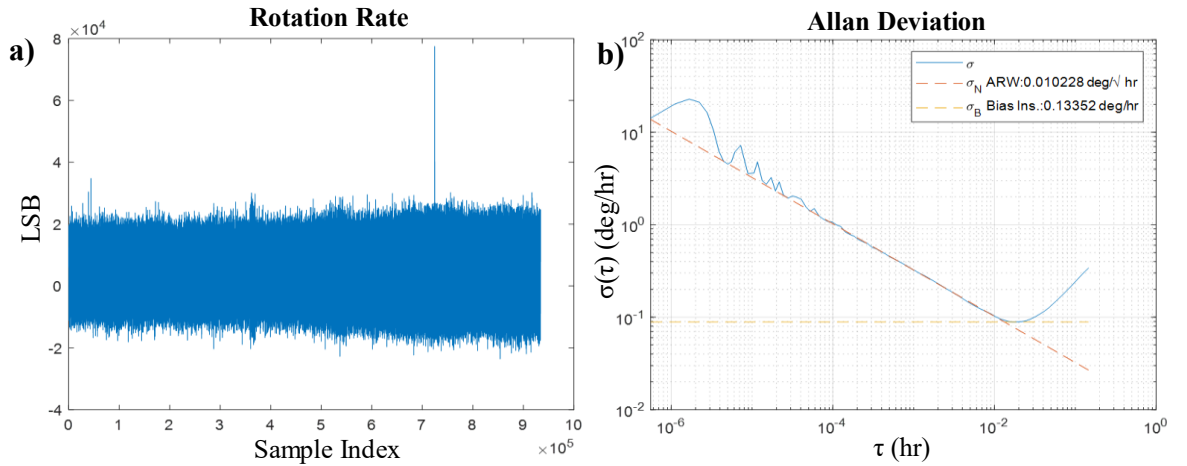


Figure 4.15. (a) Rotation rate graph (b) Allan deviation graph for hybrid ASE without unpumped EDF (Test 5).

As seen from the test results, the rotation rate graphs of ASE without unpumped EDF have peaks and noise. ARW values are about $0.010\%/\sqrt{h}$ while bias instability is around $0.15\%/h$. After bias tests are completed, a 1-meter erbium-doped fiber is included in the light source's configuration. The test results regarding the improved ASE configuration are as follows.

The first test results are given in Figure 4.16. In Figure 4.16.a, the rotation rate graph for the new configuration is shown, which has no random peaks and noise compared to the previous configuration. Although the ARW value is almost the same as the previous configuration without filtered EDF, the bias instability is slightly improved. The bias instability value is approximately $0.12\%/h$, which is lower than $0.15\%/h$.

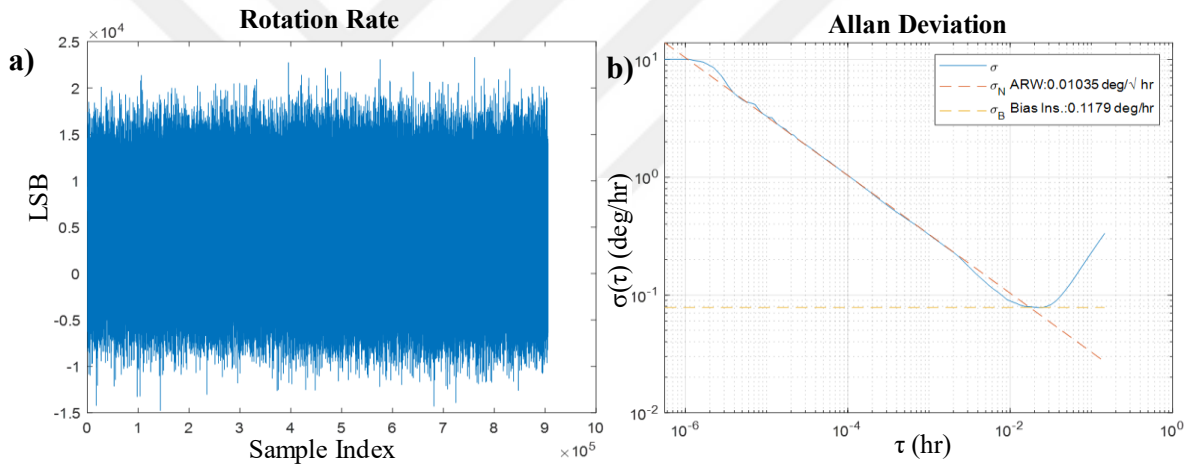


Figure 4.16. (a) Rotation rate graph (b) Allan deviation graph for hybrid ASE with unpumped EDF (Test 1).

When the second test is conducted, the rotation rate protects the trend from peaks and noise, as shown in Figure 4.17.a. The angle random walk value is found as $0.010\%/\sqrt{h}$ which is consistent for both of the configurations so far. However, the bias instability value is significantly improved. The bias instability value is decreased from $0.12\%/h$ to $0.087\%/h$. This means that the bias instability value is shifted to a more accurate gyro grade from the lower one. Moreover, the Allan deviation plot matches with the slope fit, which demonstrates the gyroscope has Gaussian white noise as expected and preferred, as seen in Figure 4.17.b.

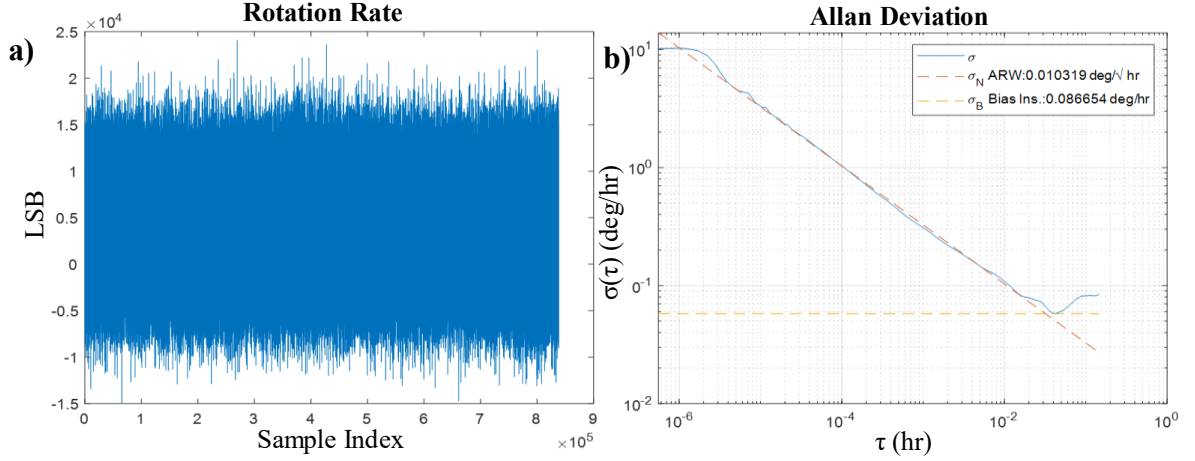


Figure 4.17. (a) Rotation rate graph (b) Allan deviation graph for hybrid ASE with unpumped EDF (Test 2).

In the third test shown in Figure 4.18.a, the rotation rate trend is still consistent with its perfect trend, which does not include peaks and noise. Also, the linear fit matches the Allan deviation. ARW value is remaining still at $0.010^\circ/\sqrt{h}$. Furthermore, the bias instability value is decreased even further to $0.056^\circ/h$, as seen in Figure 4.18.b.

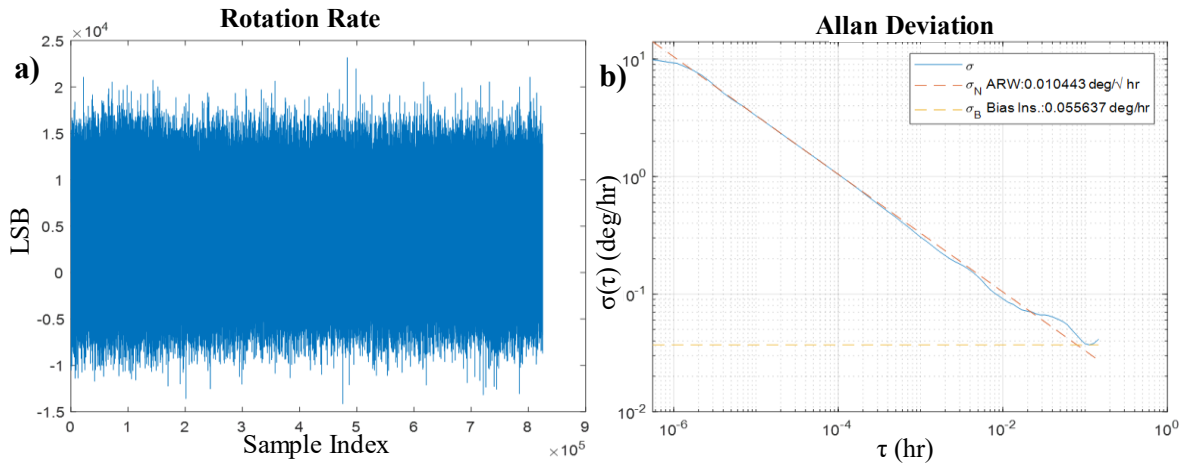


Figure 4.18. (a) Rotation rate graph (b) Allan deviation graph for hybrid ASE with unpumped EDF (Test 3).

The fourth test reveals a slight increase in bias instability, with the value rising from 0.056 °/h to 0.11 °/h. ARW value is almost remaining constant at $0.010\sqrt{h}$. The trend of the rotation rate graph exhibits no abnormal peaks or noise, while the linear fit and Allan deviation continue to match as before.

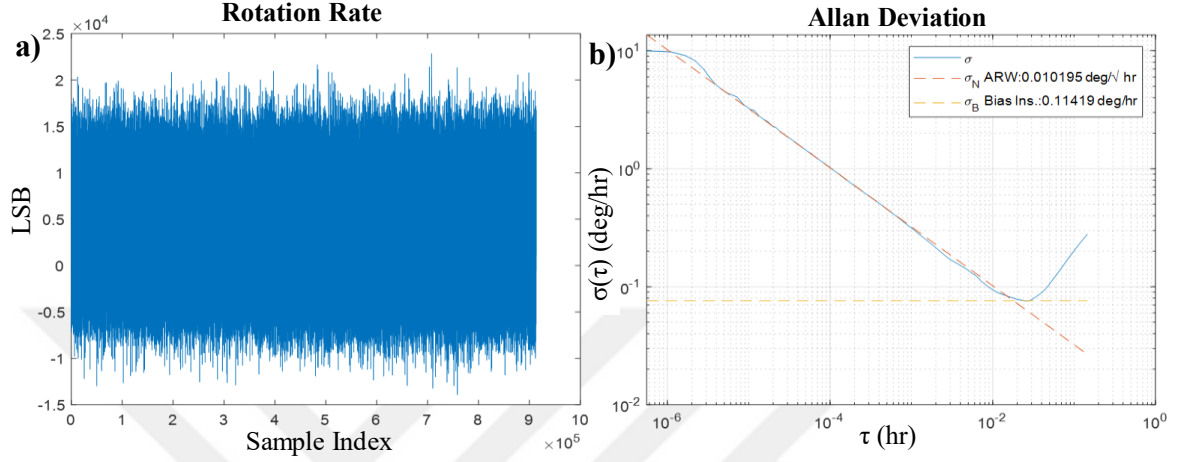


Figure 4.19. (a) Rotation rate graph (b) Allan deviation graph for hybrid ASE with unpumped EDF (Test 4).

In the fifth and final test, all variables are almost the same, except for the bias instability value. The bias instability value is found to be 0.082 °/h, which is better than the fourth result. Therefore, the bias test results are presented.

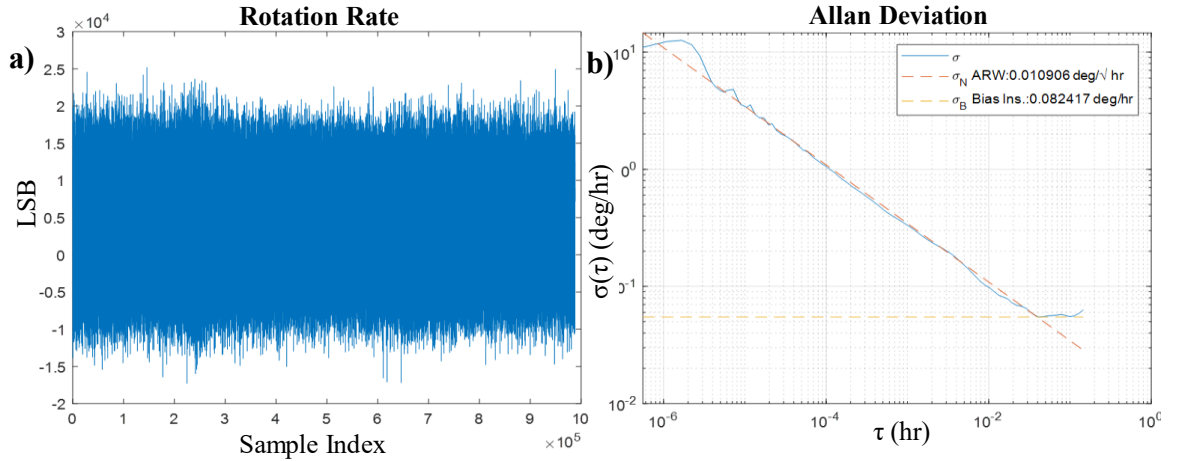


Figure 4.20. (a) Rotation rate graph (b) Allan deviation graph for hybrid ASE with unpumped EDF (Test 5).

4.4. Comparison of the Bias Performance of Single-Axis IFOG with and without Filter EDF

As discussed earlier, the rotation rate graphs of IFOG without an EDF filter include noise and peaks, compared to those of IFOG with an EDF filter, as shown in Figure 4.21.a and 4.21.b. Therefore, one can conclude that the EDF filter improved the behavior of the rotation rate in response to environmental movements.

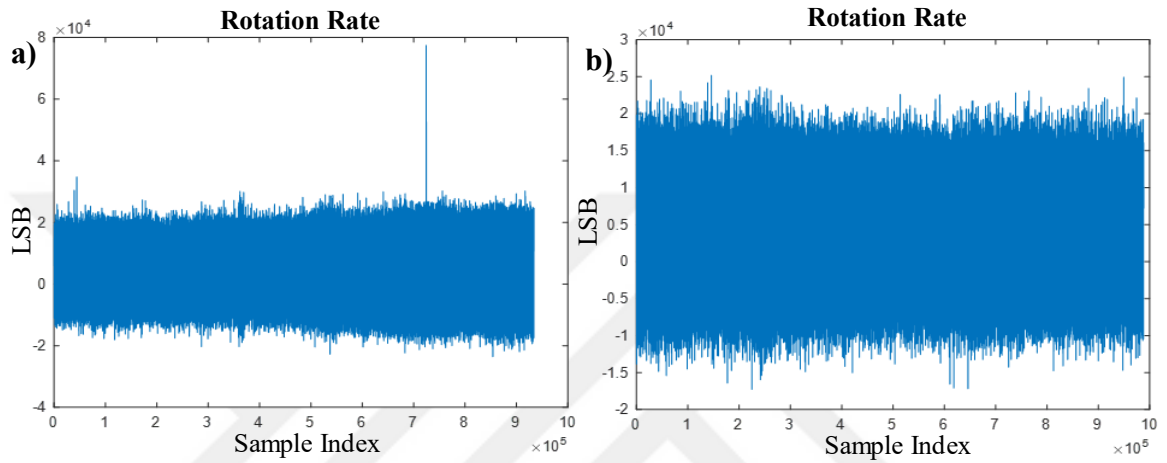


Figure 4.21. (a) Rotation rate graph for hybrid ASE without unpumped EDF **(b)** rotation rate graph for hybrid ASE with unpumped EDF (Test 5).

In Table 4.1, ARW values are summarized to compare the values properly. Since ARW is a type of stochastic error, it is normal to fluctuate randomly. However, the general results from these values indicate that integrating a filter-erbium-doped fiber did not affect the ARW performance of the gyroscope.

As seen, the average value of ARW for IFOG without EDF filter is $0.010228\%/\sqrt{h}$ while it is $0.010906\%/\sqrt{h}$ for IFOG with EDF filter. It is obvious that even though the ARW value is slightly decreased with filtered EDF, the change in ARW is in the fourth decimal place, which is not a significant change and can be ignored.

Therefore, it is concluded that the filtered EDF did not affect the ARW performance in the tactical-grade fiber optic gyroscope constructed with a hybrid ASE light source.

Table 4.1. Comparison of ARW Values for IFOG without and with EDF Filter

Test Number	ARW of IFOG without EDF Filter ($^{\circ}/\sqrt{h}$)	ARW of IFOG with EDF Filter ($^{\circ}/\sqrt{h}$)
1	0.010118	0.010350
2	0.009977	0.010319
3	0.010453	0.010443
4	0.010856	0.010195
5	0.010228	0.010906
Average	0.010326	0.010443

Although ARW values have remained constant, a 36% decrease in average bias instability is observed. Bias instability values for each measurement are given in Table 4.2. When the bias instability values are analyzed for IFOG without filtered EDF, it is evident that the values fluctuate between $0.13^{\circ}/h$ and $0.16^{\circ}/h$. A similar fluctuation is observable for IFOG with the EDF filter, as its values also change between $0.056^{\circ}/h$ and $0.1113^{\circ}/h$. Despite fluctuations in values, the bias instability values of IFOG with the EDF filter are always smaller than those of IFOG without the EDF filter.

It is known that bias instability is a stochastic error, similar to ARW. For this reason, this kind of change in bias instability is normal, but the improvement in values is permanent. For example, the worst bias instability value for IFOG without filter EDF is $0.16433^{\circ}/h$, while the worst bias instability value for IFOG with filter EDF is $0.11790^{\circ}/h$. The decrease between these values is almost 28%, which is still a significant improvement.

Similarly, let us compare the best and worst in IFOG, both with and without a filter. The values are $0.13352^{\circ}/h$ and $0.11790^{\circ}/h$, respectively, and there is still a decrease of approximately 12% in the bias instability value.

If we check the opposite value, i.e., the worst in IFOG without filter, 0.16433 %/h, and best in IFOG with filter, 0.05564 %/h. The improvement in the bias instability value is becoming 66%, which is incredibly high.

In conclusion, it can be stated that even though the values change randomly due to the stochastic nature of bias instability, the unpumped erbium-doped fiber significantly improves the sensor's bias instability values.

Table 4.2. Comparison of Bias Instability Values for IFOG without and with EDF Filter

Test Number	Bias Instability of IFOG without EDF Filter (°/h)	Bias Instability of IFOG with EDF Filter (°/h)
1	0.15295	0.11790
2	0.15215	0.08665
3	0.13856	0.05564
4	0.16433	0.11419
5	0.13352	0.08242
Average	0.14302	0.09136

CHAPTER 5. CONCLUSION and DISCUSSION

This research studied spectral stability and its impact on bias instability of a hybrid ASE light source in interferometric fiber-optic gyroscopes through its design and optimization. For this purpose, the hybrid double-pass backward and forward configuration is constructed and improved by addition of the isolator. With this enhancement, the wavelength stability improved from 19.20 ppm to 14.31 ppm, while the other parameters remained unchanged. Furthermore, the effect of filtering on the hybrid ASE light source's parameters is investigated. Thus, this research utilized both 1 meter and 0.5 meters of unpumped erbium-doped fiber as a filter. The addition of a 0.5 meters EDF filter decreased wavelength stability from 14.31 ppm to 12.67 ppm, while the 1 meter filter reduced it further to 5.98 ppm. Therefore, contrary to similar studies, our study revealed that the implementation of an erbium-doped fiber filter enhanced wavelength stability in an ASE light source.

To evaluate thermal performance, the light source was tested at different temperatures, that are +60 °C, and -25 °C. While the spectral shape remained constant, the wavelength stability varied significantly. Without a filter, the wavelength stability increased from 14.31 ppm at room temperature to 52.63 ppm at -25 °C and 26.63 ppm at +60 °C. With a filter, stability was better at room temperature, that is 5.98 ppm, but it increased sharply to 42.16 ppm and 16.89 ppm at -25 °C and +60 °C respectively. Across all conditions, the filtered source showed better overall stability.

After construction of single-axis fiber optic gyroscope, the bias tests are completed in a seismic ground with an isolated laboratory. The results showed that the rotation rate graph of ASE without a filter has higher noise and peaks, while the rotation rate graph of ASE with a filter is much smoother in comparison. This indicates that the noise in the rotation rate is decreased with the EDF filter.

Furthermore, the Allan deviation graphs are analyzed for each case, and each of them shows that the linear fit and the Allan deviation graphs match with each other. Therefore, it is evident that the sensor exhibits Gaussian white noise. While the average ARW value of IFOG without a filter is about $0.010326\% \sqrt{h}$, the ARW

value with a filter is $0.010443\%/h$. Hence, it can be stated that the filtering did not change the ARW values. The reason is that ARW is directly proportional to relative intensity noise which is inversely proportional to FWHM. Since FWHM is remained constant in the hybrid ASE light source, one can understand why ARW values did not change significantly even though the light source configuration is changed. On the other hand, the bias instability values changed significantly. The average bias instability value of IFOG without a filter was around $0.14\%/h$, while it decreased to $0.091\%/h$ with the filter integrated. Thus, the bias instability values improved by 36% overall.

The scale factor error may be measured to compare for both of the configurations. However, this measurement could not be done due to lack of rotating system in the laboratory. Since the wavelength stability is enhanced in the modified configuration, the scale factor error may be improved proportionally. Moreover, the random error in tactical grade fiber optic gyroscope is improved with the hybrid ASE light source. However, this ASE light source is more suitable to the higher-grade levels such as navigation grade and strategic grade fiber optic gyroscopes. For the further investigation, one can construct a fiber optic gyroscope with more sensitive and longer fiber coil to explore the hybrid ASE light source's effect on gyroscope. Since the navigation and strategic grade gyroscopes are more sensitive, the impact on bias instability may be more significant compared to tactical grade single axis gyroscope results.

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APPENDIX A

Erbium-doped fiber only emits green light when pumped with 980 nm. This occurs due to the two-step upconversion of erbium, as shown in Figure A.1.a. Even though erbium ions in $^4I_{11/2}$ is in a higher state compared to $^4I_{13/2}$. It can absorb 980 nm light, unlike $^4I_{13/2}$. This happens when the light transits from $^4I_{11/2}$ to $^4F_{7/2}$ level. Ions in $^4F_{7/2}$ level starts to decay non-radiatively to the lower state, namely $^4S_{3/2}$. The green light emission occurs due to the two-step upconversion process in this state, as shown in Figure A.1.a (Quimby, et al., 1992). When the light transitions from this state to the ground state, it produces 547 nm light, which is a green light from the visible light spectrum, as shown in Figure A.1.b. It is known that EDF can be pumped by both 980 nm and 1480 nm, but this glowing occurs only at 980 nm due to upconversion at this wavelength.

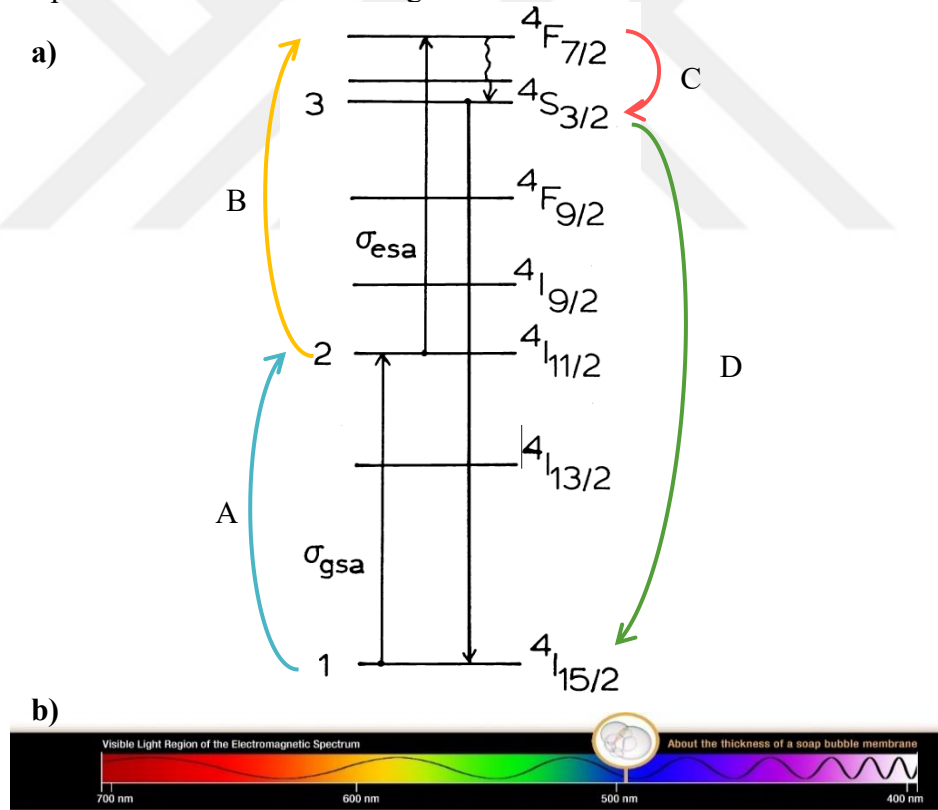


Figure A. 1. a) Energy level diagram of erbium illustrating the two-step upconversion mechanism employed to measure the excited-state absorption spectrum at 980 nm (Quimby, et al., 1992) (b) electromagnetic spectrum of visible light (NASA Science, n.d.).

APPENDIX B

Derivation of Allan Variance

In a system, there are two basic types of error: deterministic errors and stochastic errors. Deterministic errors are predictable and systematic, in contrast to stochastic errors, which are random and not systematic. Since they are random errors, they cannot be minimized with mathematical models. Bias instability, angular random walk (ARW), and rate random walk (RRW) are examples of stochastic errors in gyroscopes that can be modeled using Allan variance (Miao et al., 2015). The test results for this study will provide the Allan variance. Before evaluating the results, it is necessary to examine the Allan variance.

In Figure A.2, consider a sequence of N data points, each sampled at time intervals of τ_0 is showed. By selecting groups of n consecutive points, each group forms a cluster, that is, a time τ , where $\tau = n \cdot \tau_0$, $n=1, 2, 3, \dots, N$. (Hou, 2004).

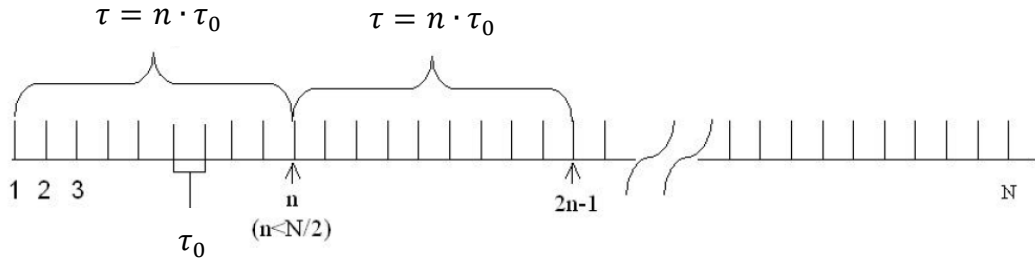


Figure A. 2. Data points representation (Hou, 2004).

Allan variance is a function of the cluster time, expressed based on either the output rate or the output angle, as shown in Equation A.1 (IEEE Std 952-1997, 1998).

$$\theta(t) = \int^t \Omega(t) dt \quad \text{A.1}$$

Then, the average of the cluster can be written as the following equation for the k^{th} data point.

$$\overline{\Omega}_k(\tau) = \frac{1}{\tau} \int_{t_k}^{t_k+\tau} \Omega(t) dt \quad \text{A.2}$$

Then, the following average of the cluster is the following where $t_{k+1} = t_k + \tau$.

$$\overline{\Omega_{k+1}}(\tau) = \frac{1}{\tau} \int_{t_{k+1}}^{t_{k+1}+\tau} \Omega(t) dt \quad \text{A.3}$$

The Allan variance for τ is given as in IEEE Std 952-1997 as following.

$$\sigma^2(\tau) = \frac{1}{2} \langle [\overline{\Omega_{k+1}}(\tau) - \overline{\Omega_k}(\tau)]^2 \rangle \quad \text{A.4}$$

This Equation A.4 can be written as Equation A.5.

$$\sigma^2(\tau) = \frac{1}{2} \langle \overline{\Omega_{k+1}^2}(\tau) \rangle + \frac{1}{2} \langle \overline{\Omega_k^2}(\tau) \rangle - \langle \overline{\Omega_k}(\tau) \cdot \overline{\Omega_{k+1}}(\tau) \rangle \quad \text{A.5}$$

To write Equation A.5 explicitly, drive the terms step by step.

$$\begin{aligned} \langle \overline{\Omega_k^2}(\tau) \rangle &= \langle \left(\frac{1}{\tau} \int_{t_k}^{t_k+\tau} \Omega(t) dt \right)^2 \rangle = \frac{1}{\tau^2} \langle \left(\int_{t_k}^{t_k+\tau} \Omega(t) dt \right)^2 \rangle = \\ &= \frac{1}{\tau^2} \langle \int_{t_k}^{t_k+\tau} \int_{t_k}^{t_k+\tau} \Omega(t) dt \Omega(t') dt' \rangle \end{aligned} \quad \text{A.6}$$

Where $\langle \Omega(t) \cdot \Omega(t') \rangle$ is a rate correlation function and equals to $R(t', t) = R(t' - t)$. The Fourier transform of this function gives the rate power spectral density (Hou, 2004).

$$S_\Omega(f) = \int_{-\infty}^{\infty} R(t' - t) e^{-2\pi i f(t' - t)} d(t' - t) \quad \text{A.7}$$

$$R(t' - t) = \int_{-\infty}^{\infty} S_\Omega(f) e^{-2\pi i f(t' - t)} df \quad \text{A.8}$$

Therefore, Equation A.6 becomes

$$\langle \overline{\Omega_k^2}(\tau) \rangle = \frac{1}{\tau^2} \int_{-\infty}^{\infty} S_\Omega(f) df \int_{t_k}^{t_k+\tau} \int_{t_k}^{t_k+\tau} e^{-2\pi i f(t' - t)} dt dt' \quad \text{A.9}$$

From Fourier transform

$$\int_{t_k}^{t_k+\tau} \int_{t_k}^{t_k+\tau} e^{-2\pi i f(t' - t)} dt dt' = \frac{\sin^2(\pi f \tau)}{(\pi f)^2} \quad \text{A.10}$$

Thus, Equation A.9 is becoming

$$\langle \overline{\Omega_k^2}(\tau) \rangle = \int_{-\infty}^{\infty} S_\Omega(f) \frac{\sin^2(\pi f \tau)}{(\pi f)^2} df \quad \text{A.11}$$

Since this equation does not depend on t_k , the same equation is valid for the following average cluster (Hou, 2004).

$$\langle \overline{\Omega_{k+1}^2(\tau)} \rangle = \int_{-\infty}^{\infty} S_{\Omega}(f) \frac{\sin^2(\pi f \tau)}{(\pi f \tau)^2} df \quad \text{A.12}$$

To evaluate $\sigma^2(\tau)$, one needs to obtain $\langle \overline{\Omega_k(\tau)} \cdot \overline{\Omega_{k+1}(\tau)} \rangle$.

$$\langle \overline{\Omega_k(\tau)} \cdot \overline{\Omega_{k+1}(\tau)} \rangle = \frac{1}{\tau^2} \langle \int_{t_k}^{t_k+\tau} \int_{t_{k+1}}^{t_k+\tau} \Omega(t) dt \Omega(t') dt' \rangle \quad \text{A.13}$$

Since $t_{k+1} = t_k + \tau$,

$$\langle \overline{\Omega_k(\tau)} \cdot \overline{\Omega_{k+1}(\tau)} \rangle = \frac{1}{\tau^2} \langle \int_{t_k}^{t_k+\tau} \int_{t_k+\tau}^{t_k+2\tau} \Omega(t) dt \Omega(t') dt' \rangle \quad \text{A.14}$$

By using Equation A.8 again, one can find the following (Hou, 2004).

$$\langle \overline{\Omega_k(\tau)} \cdot \overline{\Omega_{k+1}(\tau)} \rangle = \frac{1}{\tau^2} \int_{-\infty}^{\infty} S_{\Omega}(f) df \int_{t_k}^{t_k+\tau} \int_{t_k+\tau}^{t_k+2\tau} e^{-2\pi i f(t'-t)} dt dt' \quad \text{A.15}$$

From Fourier transform, the real parts become

$$\int_{t_k}^{t_k+\tau} \int_{t_k+\tau}^{t_k+2\tau} e^{-2\pi i f(t'-t)} dt dt' = \frac{\sin^2(\pi f \tau)}{(\pi f)^2} \cos(2\pi f \tau) \quad \text{A.16}$$

Thus, Equation A.15 is becoming

$$\langle \overline{\Omega_k(\tau)} \cdot \overline{\Omega_{k+1}(\tau)} \rangle = \int_{-\infty}^{\infty} S_{\Omega}(f) \frac{\sin^2(\pi f \tau)}{(\pi f \tau)^2} \cos(2\pi f \tau) df \quad \text{A.17}$$

Therefore, Equation A.5 can be written as

$$\begin{aligned} \sigma^2(\tau) &= \frac{1}{2} \int_{-\infty}^{\infty} S_{\Omega}(f) \frac{\sin^2(\pi f \tau)}{(\pi f \tau)^2} df + \frac{1}{2} \int_{-\infty}^{\infty} S_{\Omega}(f) \frac{\sin^2(\pi f \tau)}{(\pi f \tau)^2} df \\ &\quad - \int_{-\infty}^{\infty} S_{\Omega}(f) \frac{\sin^2(\pi f \tau)}{(\pi f \tau)^2} \cos(2\pi f \tau) df \end{aligned} \quad \text{A.18}$$

$$\sigma^2(\tau) = \int_{-\infty}^{\infty} S_{\Omega}(f) \frac{\sin^2(\pi f \tau)}{(\pi f \tau)^2} df - \int_{-\infty}^{\infty} S_{\Omega}(f) \frac{\sin^2(\pi f \tau)}{(\pi f \tau)^2} \cos(2\pi f \tau) df \quad \text{A.19}$$

$$\sigma^2(\tau) = \int_{-\infty}^{\infty} (1 - \cos(2\pi f \tau)) S_{\Omega}(f) \frac{\sin^2(\pi f \tau)}{(\pi f \tau)^2} df \quad \text{A.20}$$

By using the trigonometric equation, one can write

$$(1 - \cos(2\pi f \tau)) = 2\sin^2(\pi f \tau) \quad \text{A.21}$$

By integrating Equation A.21 into A.20,

$$\sigma^2(\tau) = \int_{-\infty}^{\infty} S_{\Omega}(f) \frac{\sin^4(\pi f \tau)}{(\pi f \tau)^2} df \quad \text{A.22}$$

This equation can also be written as

$$\sigma^2(\tau) = 4 \int_0^\infty S_\Omega(f) \frac{\sin^4(\pi f \tau)}{(\pi f \tau)^2} df \quad \text{A.23}$$

Therefore, Equation A.23 reveals the relationship between the Allan variance and the rate noise power spectral density (PSD) (IEEE Std 925-1997, 1998). By using Equation A.23, one can derive the equations for angle random walk, bias instability, and rate random walk, among others. Since the test results of this study show the ARW and bias instability, their derivations are summarized in the following equations.

The presence of spontaneously emitted photonics in the output of the source is the major cause of ARW. Other noise sources can be easily canceled with the efficient design. To establish the relationship between Allan variance and rate noise PSD, the angle random walk coefficient is defined (IEEE Std 952-1997, 1998).

$$S_\Omega(f) = N^2 \quad \text{A.24}$$

The variable of integration in Equation A.23 is changed with $u = \pi f \tau$ and $df = du/\pi \tau$ and the new equation with Equation A.24 becomes the following.

$$\sigma^2(\tau) = \frac{4}{\pi \tau} \int_0^\infty N^2 \frac{\sin^4(u)}{(u)^2} du \quad \text{A.25}$$

It is known that

$$\int_0^\infty \frac{\sin^4(u)}{(u)^2} du = \frac{\pi}{4} \quad \text{A.26}$$

Therefore,

$$\sigma^2(\tau) = \frac{N^2}{\tau} \quad \text{A.27}$$

Thus, the Allan deviation for ARW is

$$\sigma(\tau) = \frac{N}{\sqrt{\tau}} \quad \text{A.28}$$

Overall, Equation A.27 represents the Allan variance for ARW, while Equation A.28 shows the deviation of Allan variance. The log-log plot of $\sigma(\tau)$ with respect to τ has a -1/2 slope that is shown in Figure A.3. Moreover, the slope line where τ equals to 1, gives the numerical value of N (Hou, 2004).

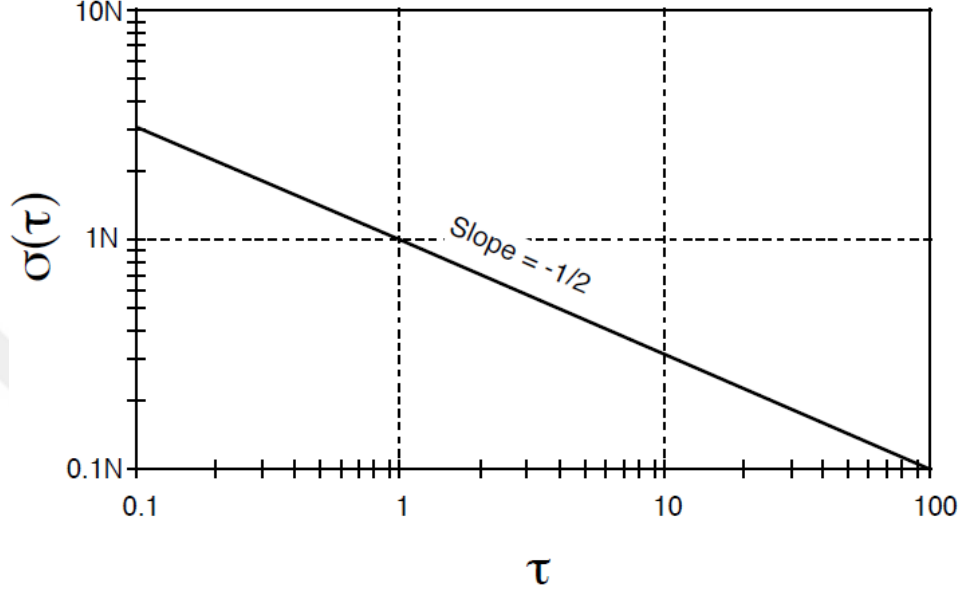


Figure A. 3. The plot of $\sigma(\tau)$ with respect to τ for ARW (IEEE Std 952-1997, 1998).

The major source of bias instability is the noise in electronics and other components, which are sensitive to any random flickering. To obtain the relationship between Allan variance and rate noise PSD, the bias instability coefficient is defined, B (IEEE Std 952-1997, 1998).

$$S_{\Omega}(f) = \begin{cases} \left(\frac{B^2}{2\pi}\right) \frac{1}{f} & \text{for } f \leq f_0 \\ 0 & \text{for } f > f_0 \end{cases} \quad \text{A.29}$$

Where f_0 is the cutoff frequency (IEEE Std 952-1997, 1998). By similar variable change and calculation one can calculate the $\sigma^2(\tau)$ value for bias instability which is given in Equation A.30 ((IEEE Std 952-1997, 1998).

$$\sigma^2(\tau) = \frac{2B^2}{\pi} \left[\ln 2 - \frac{\sin^3(\pi f_0 \tau)}{2(\pi f_0 \tau)^2} (\sin(\pi f_0 \tau) + 4(\pi f_0 \tau) \cos(\pi f_0 \tau)) + Ci(2\pi f_0 \tau) - Ci(4\pi f_0 \tau) \right] \quad A.30$$

It is approximated as

$$\sigma^2(\tau) = \begin{cases} 0 & \text{for } \tau \ll f_0 \\ \frac{2B^2}{\pi} \ln 2 & \text{for } \tau \gg \frac{1}{f_0} \end{cases} \quad A.31$$

Therefore, the Allan deviation for bias instability is

$$\sigma(\tau) = \sqrt{\frac{2 \ln 2}{\pi}} B \cong 0.664B \text{ for } \tau \gg \frac{1}{f_0} \quad A.32$$

Overall, Equation A.31 represents the Allan variance for bias instability, while Equation A.32 illustrates a log-log plot of $\sigma(\tau)$ with respect to τ that is shown in Figure A.4. As seen in Figure A.4, for low frequencies, the slope is +1, while it levels off to 0.664B as the slope approaches 0 when the frequency increases beyond the cutoff frequency. That region is used to determine the bias instability (Hou, 2004).

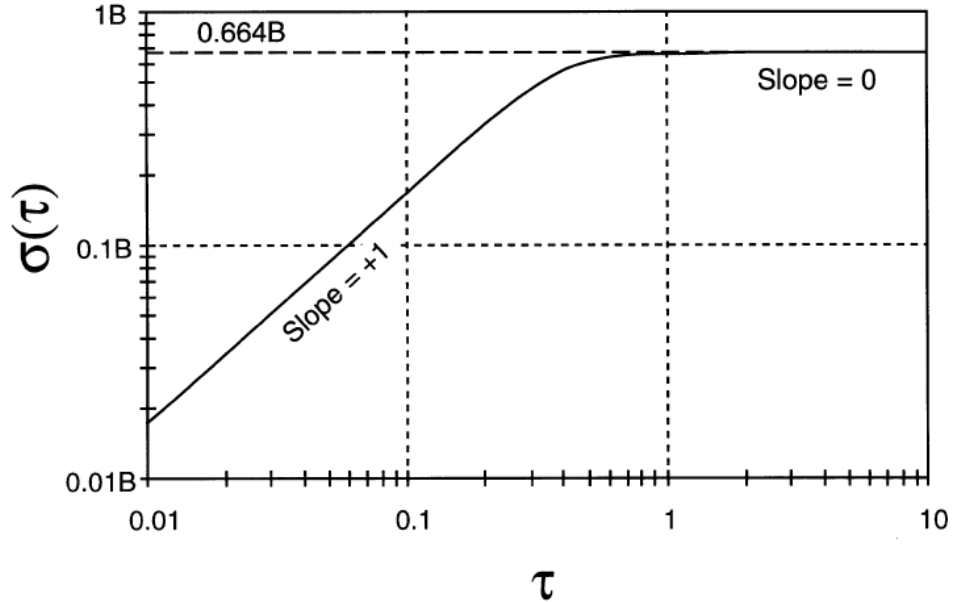


Figure A. 4. The plot of $\sigma(\tau)$ with respect to τ for bias instability (IEEE Std 952-1997, 1998).

The curve of Allan variance is given in Figure A.5. The slope of $-1/2$ gives ARW with $\%/\sqrt{h}$, and the flat region gives the bias instability with the unit $\%/h$ (Lefevre, 2022).

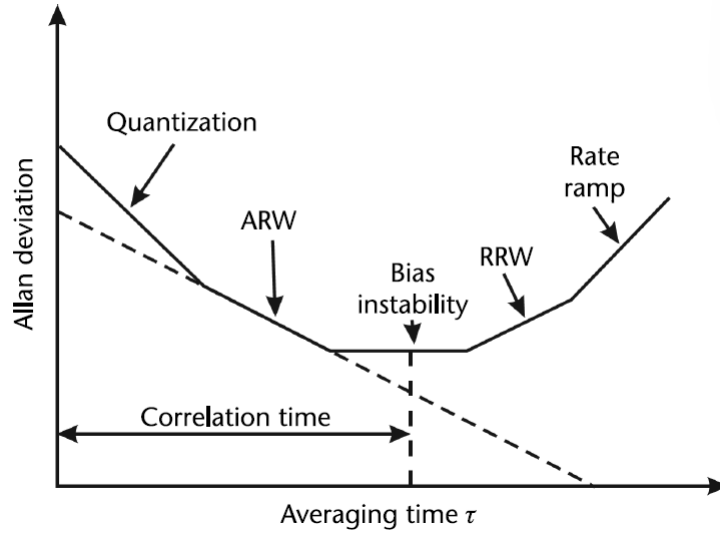


Figure A. 5. Modes of Allan variance (Lefevre, 2022).

By using the Allan deviation graph, one can determine whether the gyro exhibits Gaussian white noise or not. If $-1/2$ slope matches with the result of the deviation, it means that Gaussian white noise exists in the gyroscope. As shown in Figure A.6, the plot aligns with the fit; therefore, the noise is assumed to be Gaussian white noise. It is essential to have Gaussian white noise because most sensor fusion algorithms assume the state measurements have it (Wrona, 2021).

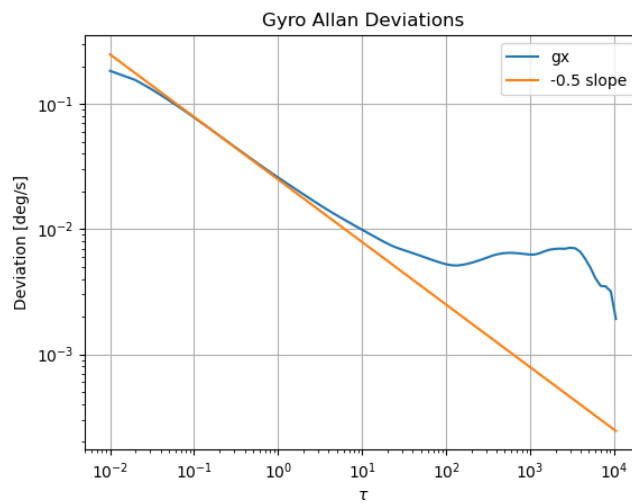


Figure A. 6. Allan deviation graph for gyro x and linear fit (Wrona, 2021).