Contributing International Traveling Summer School 2007, Pforzheim:

The Fiber Optic Gyroscope – a SAGNAC Interferometer for Inertial Sensor Applications

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12th July 2007

0. Outline

1. Scope of the Presentation
2. From Interferometer to FOG
3. Fiber Optic and Optoelectronic Modules of FOG
4. FOG in Inertial Sensor Applications
5. Summary
6. Abbreviations
7. References

1. Scope of the Presentation

- The Fiber Optic Gyroscope shall be described within this presentation, at first focusing on the interferometric roots according to SAGNAC’s effect.

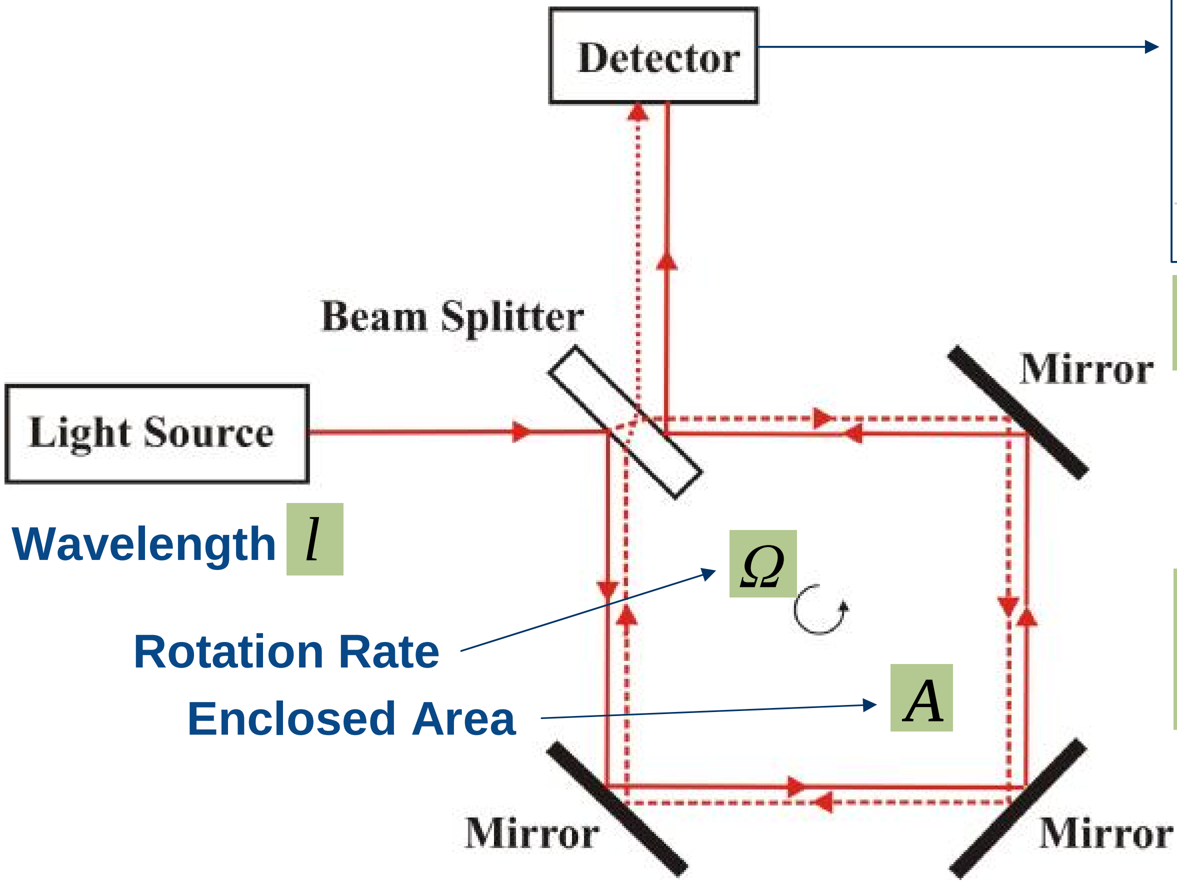
- A second chapter shall demonstrate the main optical modules of a FOG, incorporating many modern fiber optic and optoelectronic principles and components.

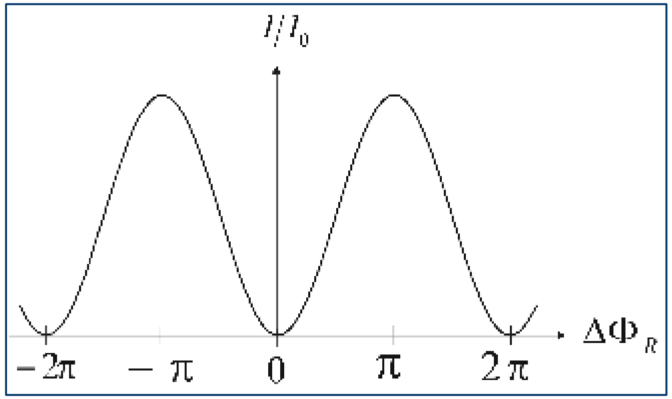
- A third part shall explain how FOG technology can be implemented by designing sensors and equipment for inertial measurement applications.

0. Outline

2.1. SAGNAC Effect (1#2)

4 **Interference of two coherent, phase correlated, counter propagating waves**





$$I(\Omega) = I_0\{1 + \cos(\Delta\Phi_R + p)\}$$

Wavelength l

Rotation Rate Ω

Enclosed Area A

$$\Delta\Phi_R = \frac{8p}{l\,c}\,\vec{A}\cdot\vec{\Omega}.$$

Ccw- wave is reflected twice!

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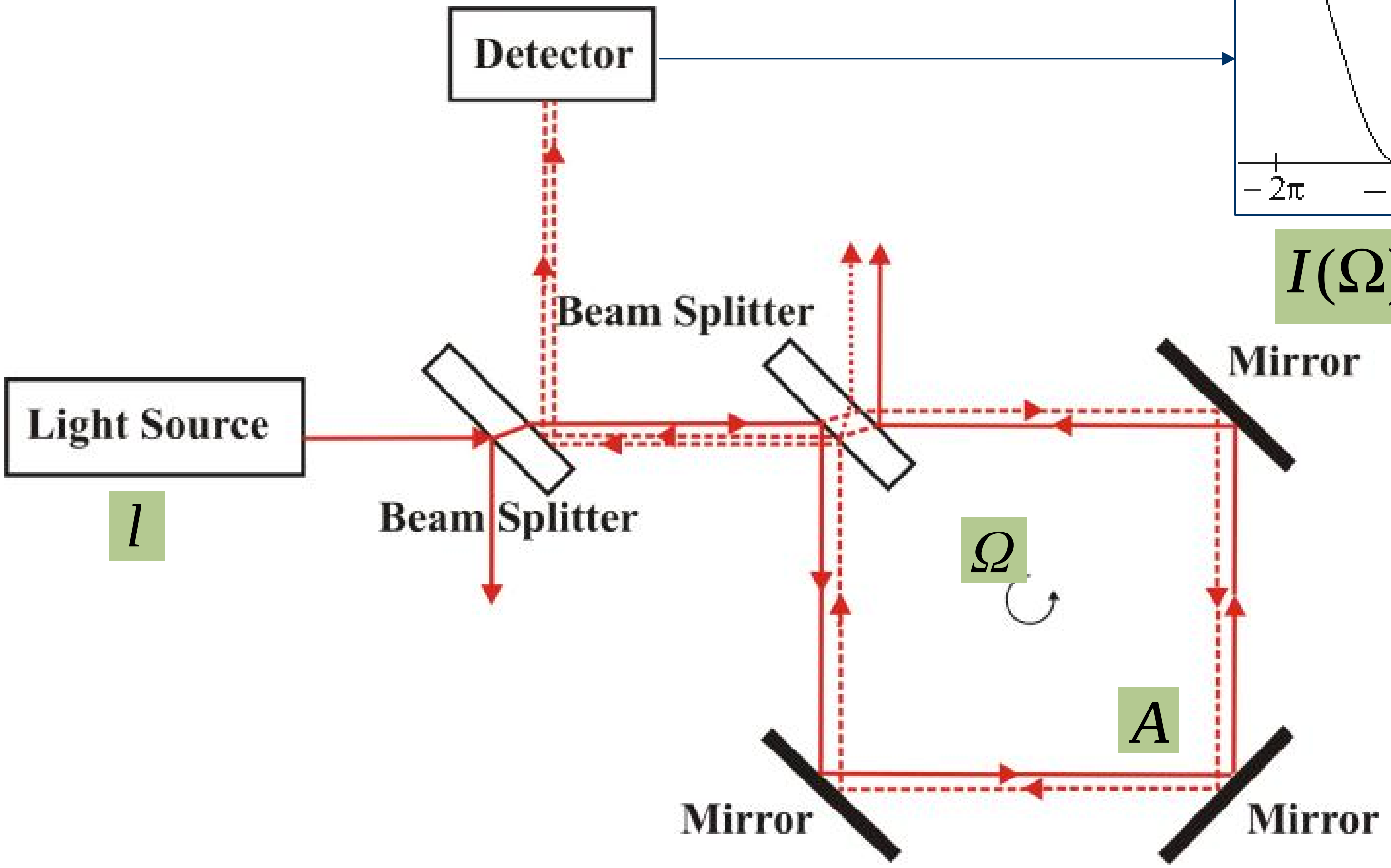
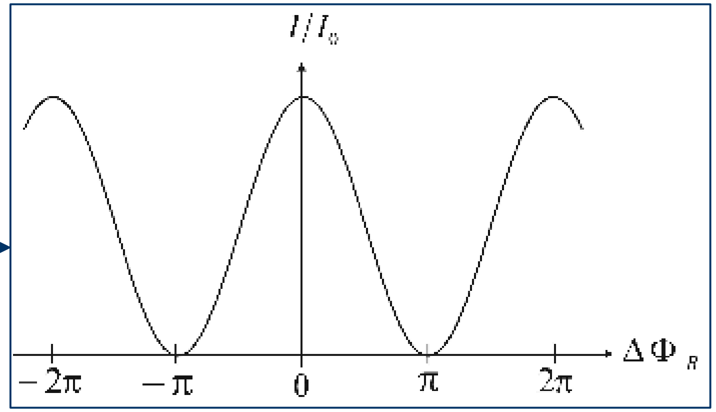
2.1. SAGNAC Effect (2#2)

- Interference of coherent, phase correlated, counter propagating waves
- But: Reciprocal configuration





$$I(\Omega) = I_0\{1 + \cos(\Delta\Phi_R)\}$$

$$\Delta\Phi_R = \frac{8\pi}{\lambda c}\vec{\mathbf{A}} \cdot \vec{\mathbf{\Omega}}.$$

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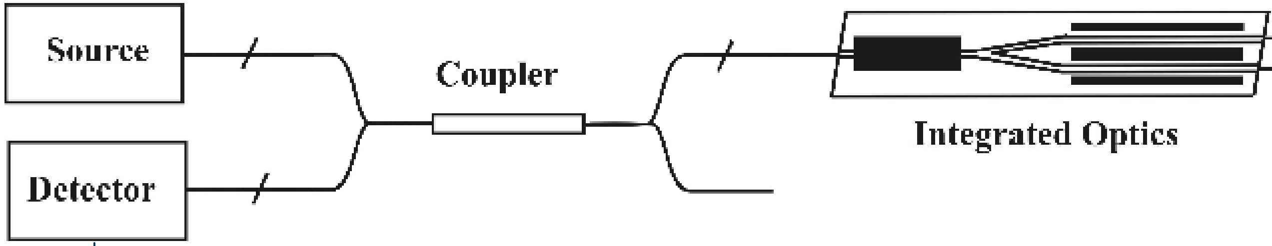
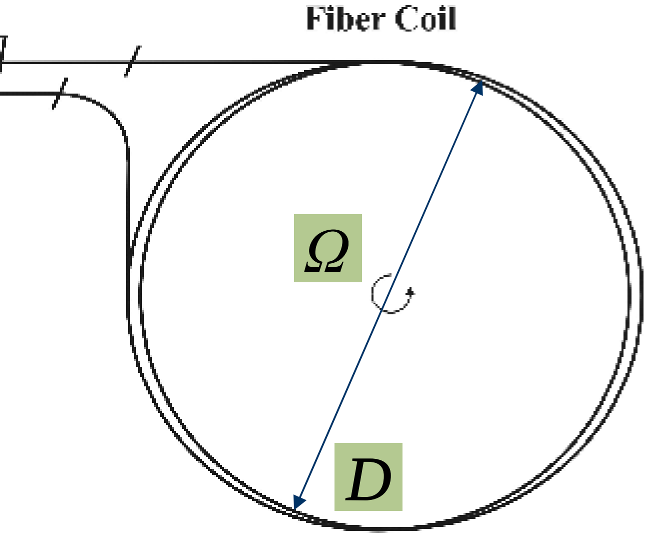
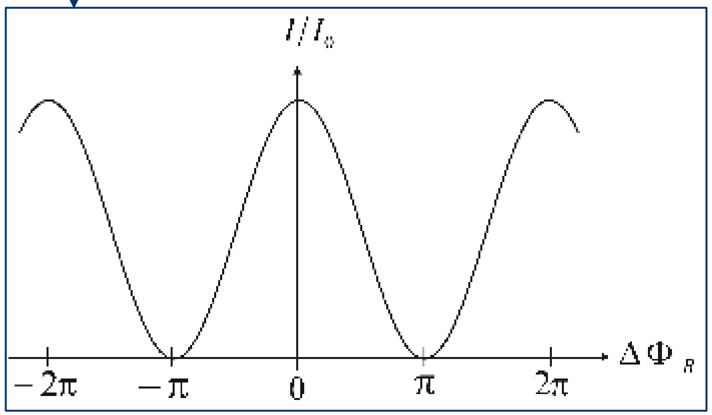
2.2. FOG Principle (Phase Modulated)

- Beam splitting and combination realized by Fiber Coupler and Integrated Optics
- Counter propagating Waves guided by optical fiber







$$\Delta\Phi_R = \frac{2p}{l} \cdot \frac{LD}{c}\,\Omega$$

Length of Fiber L

$$I(\Omega) = I_0\left\{1 + \cos(\Delta\Phi_R)\right\}$$

2.3. Propagation of Guided Light

- Wave equation based on MAXWELL's equations:

$$\Delta E - \left(\frac{n}{c}\right)^2 \frac{\partial^2}{\partial t^2} E = 0 \longleftarrow E(r,t) = E(x,y) \cdot e^{i(kz - wt)}$$

Plane wave propagating along z-direction

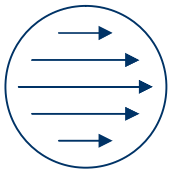
- Adapt basis according symmetry of tube (fiber):

$$x, y, z, t \rightarrow r, f, z, t$$

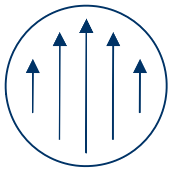
- Wave equation solved by BESSEL functions:

$$E_l(r) = \sum_{a=0}^{\infty} \frac{(-1)^a}{a!(l+a)!} \left(\frac{r}{2}\right)^{(l+2a)} \qquad l = 0, 1, 2, \ldots$$

$$\downarrow \; l = 0$$

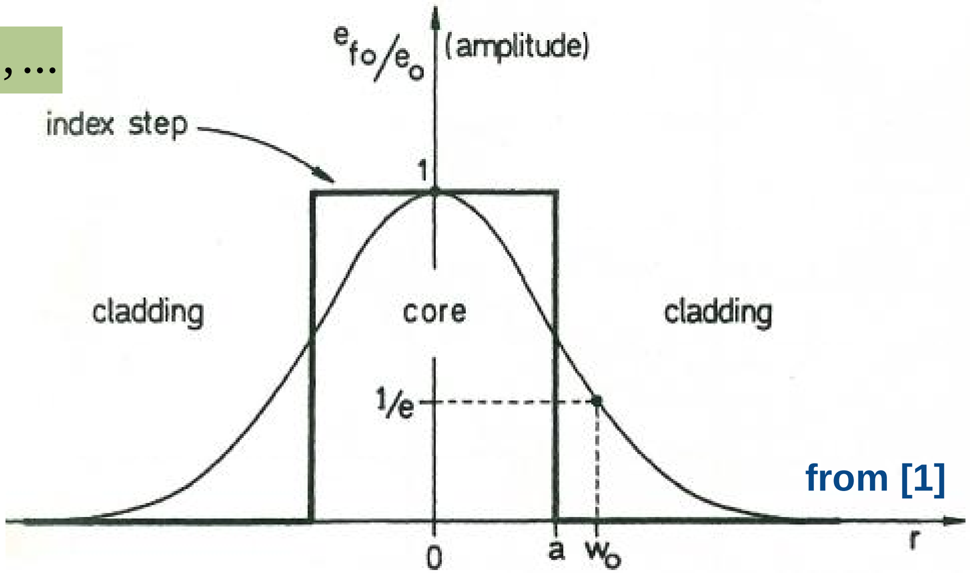


$E \parallel$



$E \perp$

Horizontal and vertical polarization



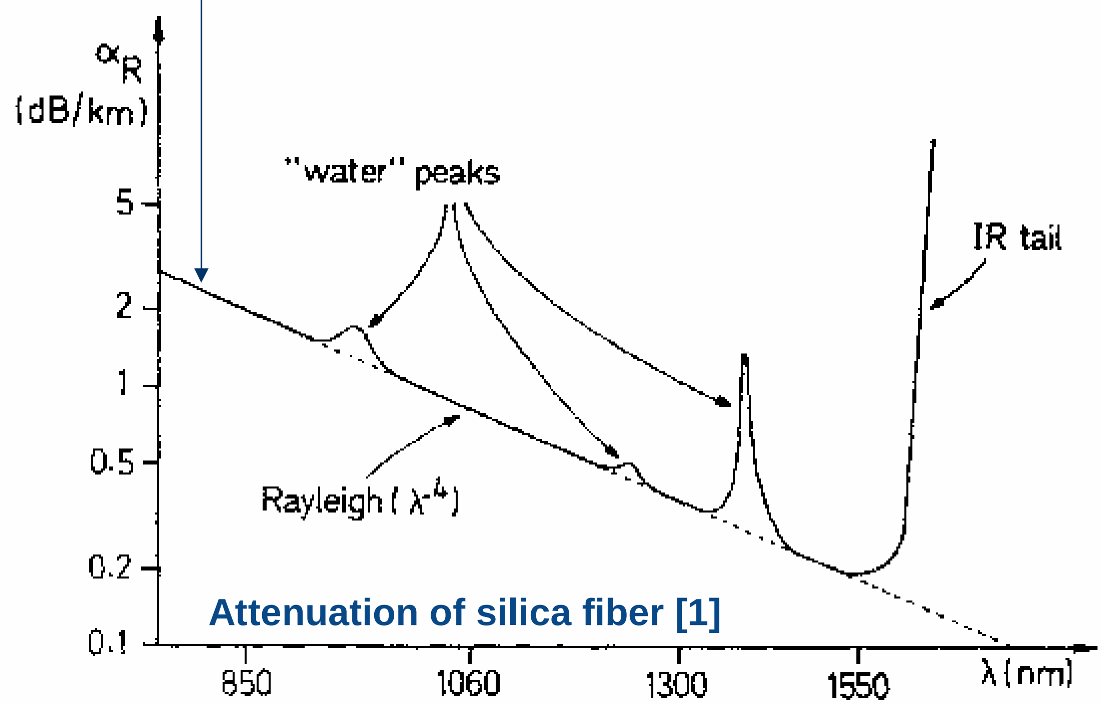
from [1]

2.4. Appropriate Wavelength for FOG

Trade-Off between

Transmission window in silica fiber

$$l = 820nm$$



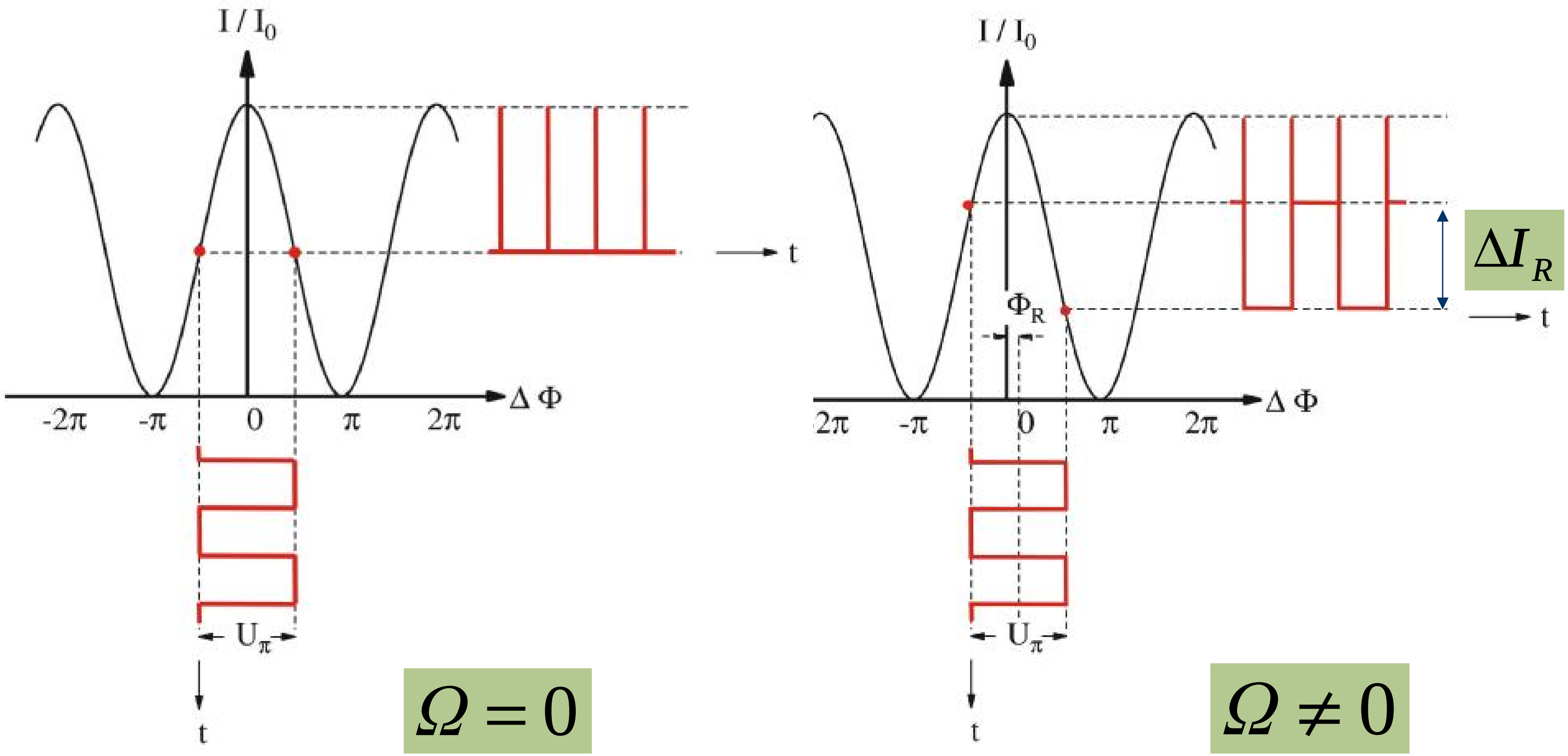
Attenuation of silica fiber [1]

Scale factor maximization

$$SF = \frac{\Delta\Phi_R}{\Omega} = \frac{2p}{l} \cdot \frac{LD}{c}$$

Near IR wavelength supports maximum Scale Factor, and therefore maximum resolution!

2.5. FOG Transfer Function – Bias Modulation



0. Outline

1. Scope of the Presentation
2. From Interferometer to FOG
3. **Fiber Optic and Optoelectronic Modules of FOG**
    1. **Source Module**
    2. **Fiber Coupler, Depolarizer**
    3. **Integrated Optic Module**
    4. **Fiber Coil**
    5. **Detector Module**
4. FOG in Inertial Sensor Applications
5. Summary
6. Abbreviations
7. References

3.1. Source Module (1#2)

- Due to back-reflection and backscattering as noise sources, the appropriate FOG light source shall have limited coherence.
- Potential high order coherences must not fit to high order reflected or backscattered wave trains.
- As a consequence, Super luminescent Laser Diodes (SLD) or MM Laser are more useful for FOG instead of SM Lasers.

Spectral Distribution

$$P(l) \longrightarrow P(k) \xrightarrow{\text{FFT}} g(x)$$

$$l_{\text{FWHM}} \longrightarrow k_{\text{FWHM}} \xrightarrow{\text{FFT}} L_{\text{coh}} = \frac{1}{2p} \cdot \frac{l_0^2}{l_{\text{FWHM}}}$$

λ → k

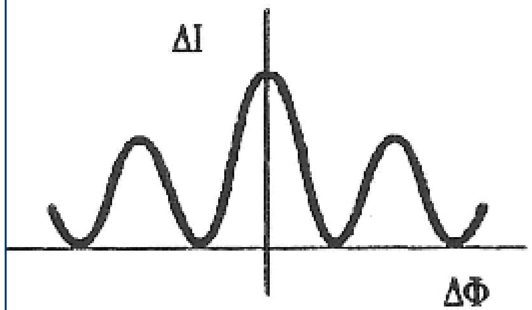
FFT

Coherence Function

Coherence Length

Transfer function at limited coherence

$$I(\Omega) = I_0\{1 + g(\Delta L_R) \cdot \cos(k \cdot \Delta L_R)\}$$



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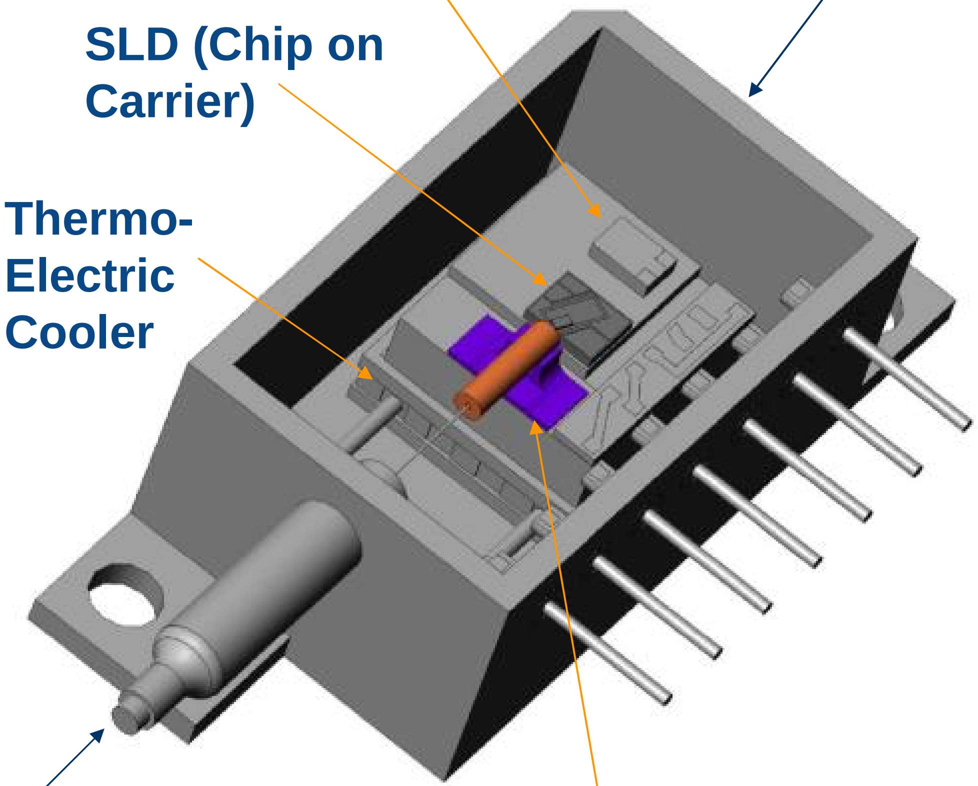
$$\Delta\Phi_R = \frac{2p}{l} \cdot \frac{LD}{c} \Omega$$

3.1. Source Module (2#2)

- Common SLD technology is based on edge emitting diode type.
- To ensure wavelength and scale factor stability, SLD is temperature controlled using T-sensor and thermo-electric cooler.
- Main light source characteristics are Optical Power, Wavelength, Laser Current, Temperature, etc.



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3.2. Fiber Coupler

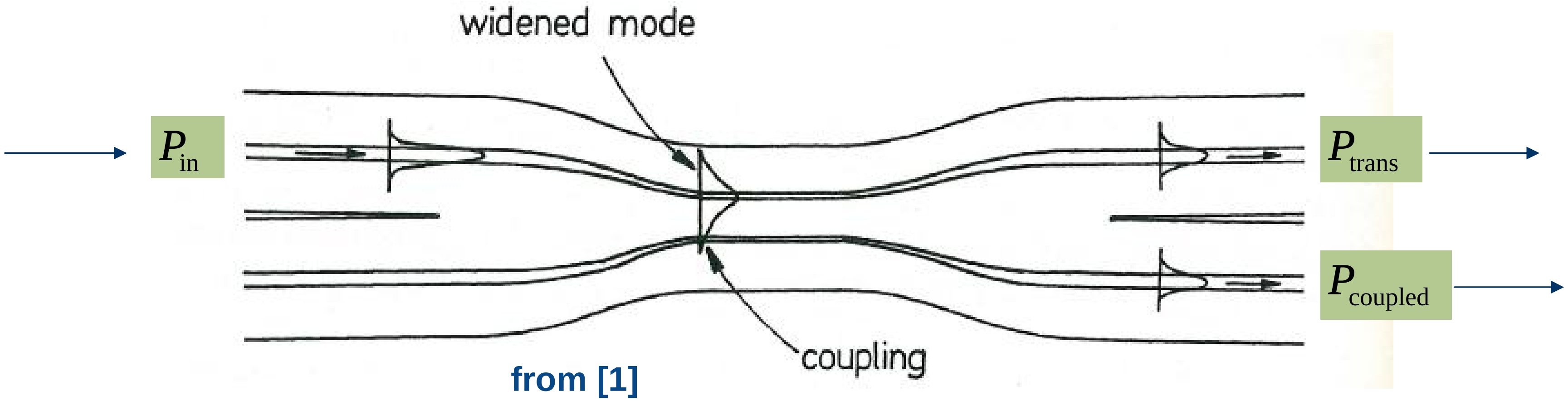
- Fused fiber coupler made of single mode fiber
- Coupling by evanescent field
- 2x2 configuration for (single axis) FOG

- Coupling Ratio

$$:= \frac{P_{coupled}}{P_{coupled} + P_{trans}}$$

- Insertion Loss (dB)

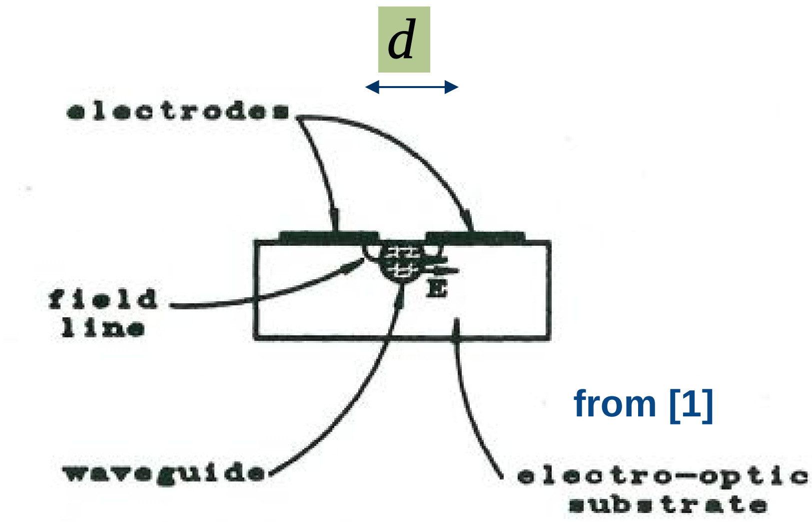
$$:= 10 \cdot \log\left[\frac{P_{in}}{P_{coupled}}\right]$$



from [1]

3.4. Integrated Optics Module

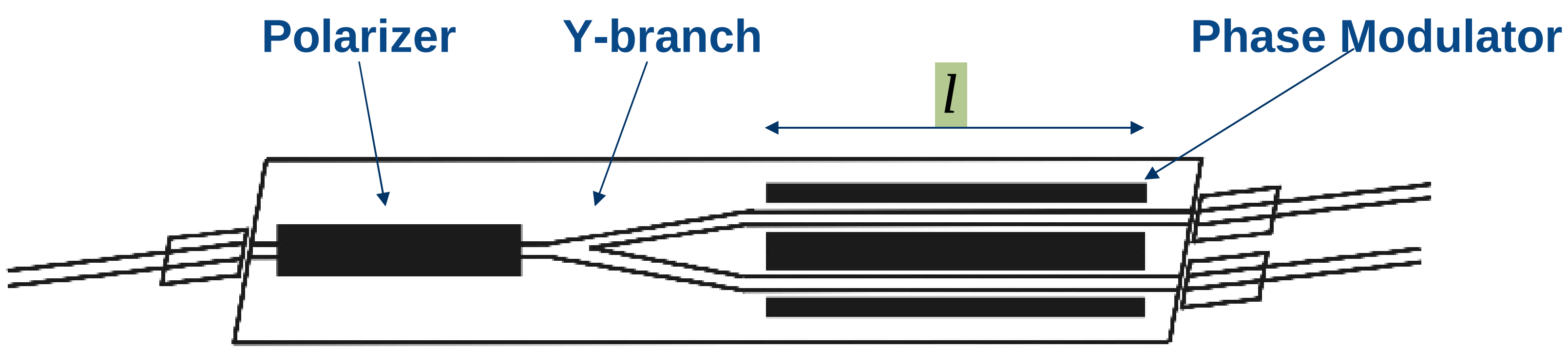
- $LiNbO_3$ based waveguide, where
- Incoming wave is polarized,
- Then split by a Y-branch,
- Both waves are phase modulated, and
- cw and ccw waves after coil transit are superposed.



from [1]

$$\Delta\left(\frac{1}{n^2}\right)_i = \sum_{j=1}^{3} r_{ij} E_j$$

$$U_p = -\frac{2d}{l} \cdot \frac{l}{n_j^3 r_{jj}}$$



3.5. Fiber Coil

- Fiber coil represents the sensing element of FOG
- Only one (of two) polarization axis illuminated (extinction)
- Quadrupolar coil winding of PM-fiber to reduce transient effects
- Transit time through coil

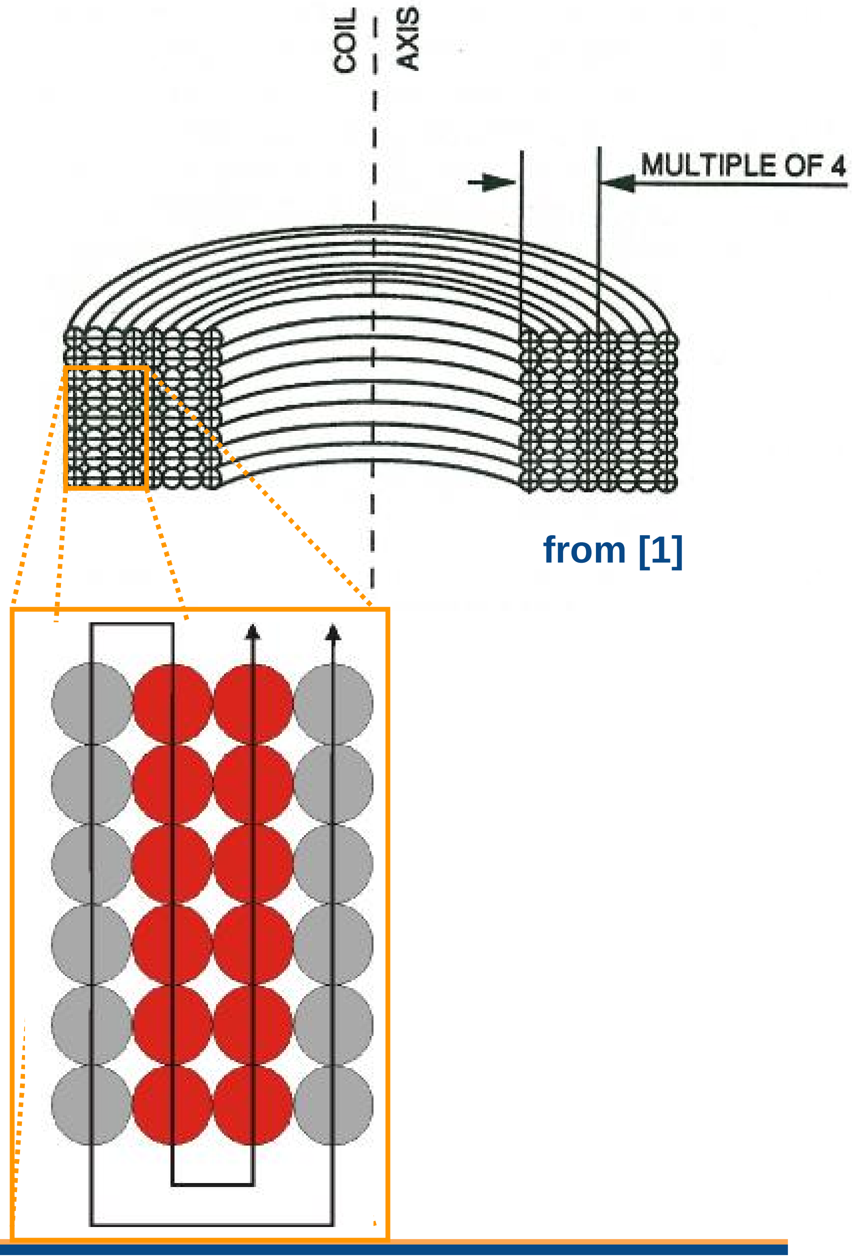
$$t_{\text{coil}} = \frac{nL}{c}$$

determines Eigen frequency

$$f_{\text{coil}} = \frac{c}{nL}$$

and therefore optimal modulation frequency

$$f_{\text{mod}} = \frac{1}{2} f_{\text{coil}}$$

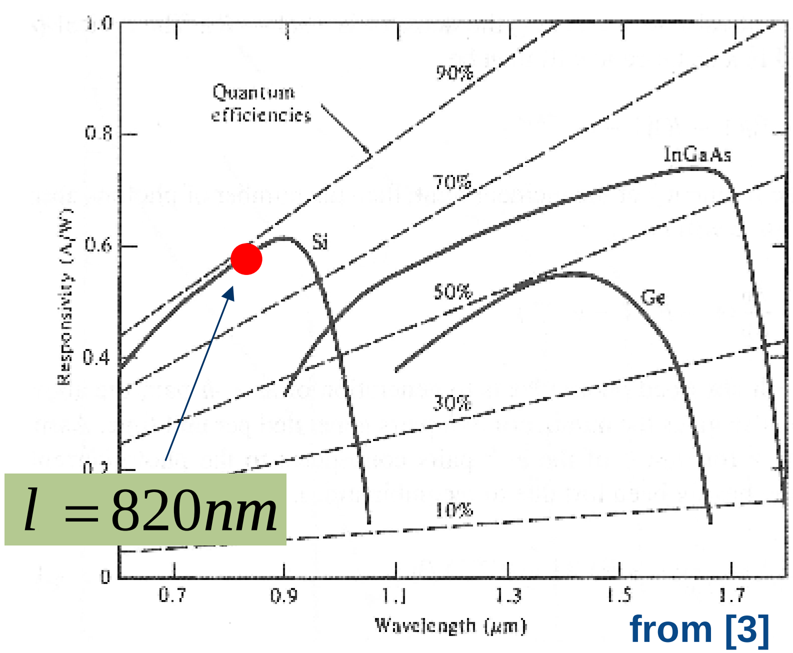


from [1]

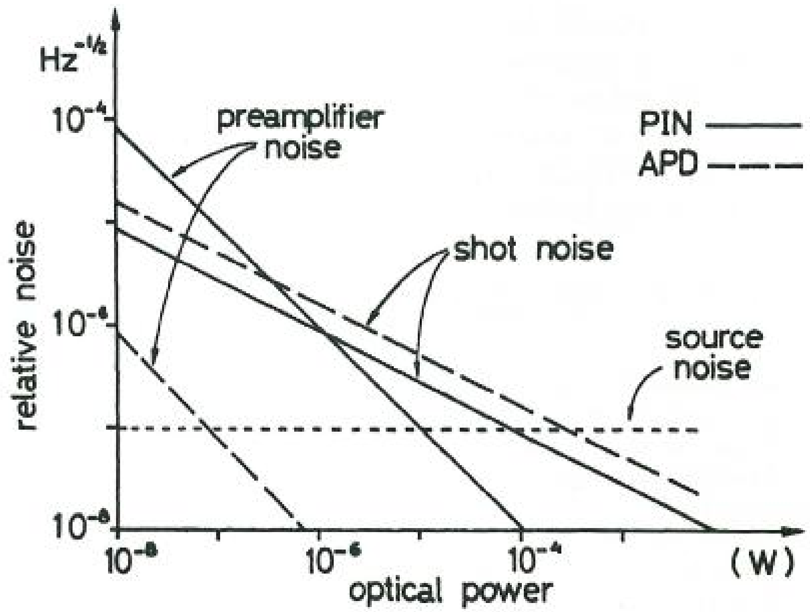
3.3. Detector Module

- Photo diode detects light intensity variations due to rotation induced phase shifts
- Transimpedance preamplifier converts photo current into voltage
- Main detector characteristics are:

Responsivity $\text{Resp.} = \frac{I_{\text{Photo}}}{P_{\text{Opt}}}$, Noise equivalent power $\text{NEP} = \frac{I_{\text{Noise}}}{\text{Resp.}}$



from [3]



Noise to Signal Ratio for Silicon Diode from [1]

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4. **FOG in Inertial Sensor Applications**
   1. FOG Electronics
   2. Closed Loop Operation of FOG
   3. Scales and Substantiation of Rotation
   4. Limiting and Parasitic Effects in FOG
   5. Inertial Sensors
   6. Application of Gyroscopic Sensors
   7. Typical FOG Applications
   8. Environmental Requirements
   9. FOG Based Products
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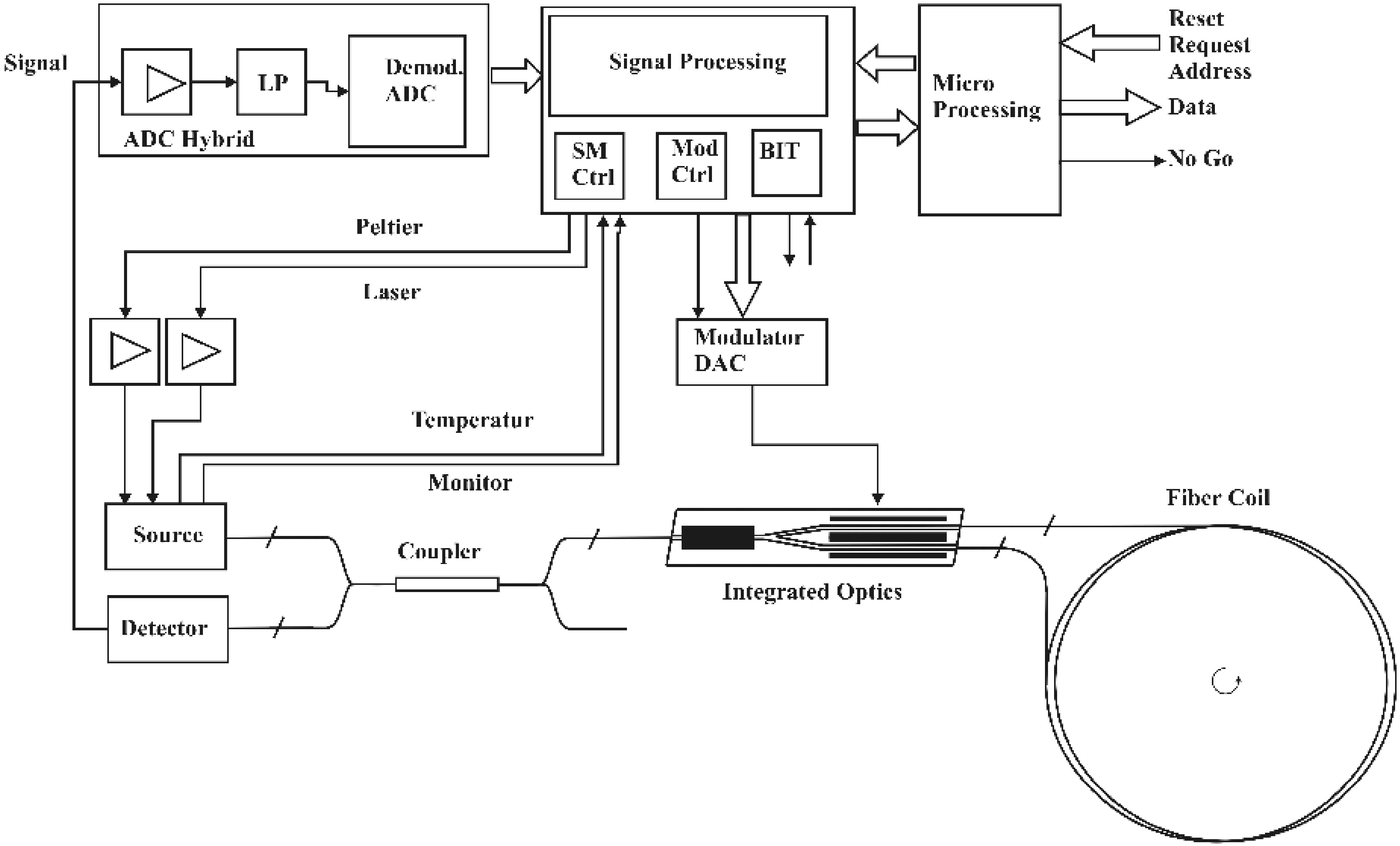
4.1. FOG Electronics

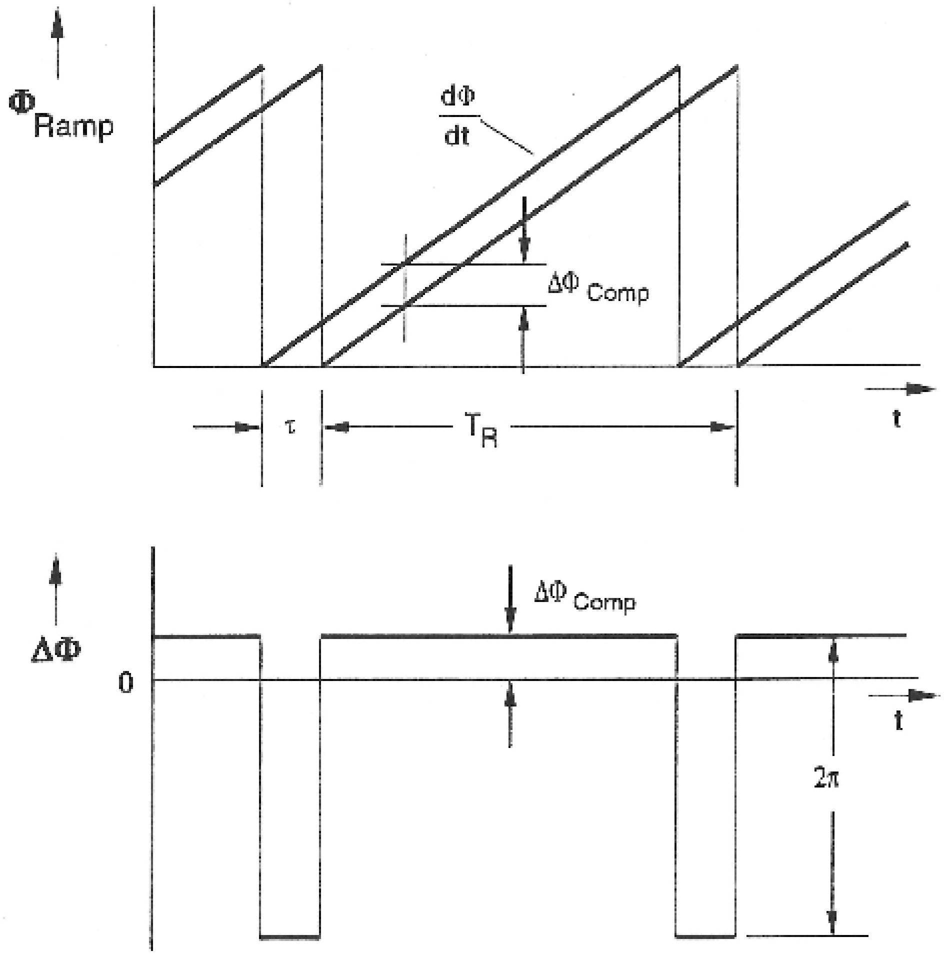


4.2. Closed Loop Operation of FOG (1#2)

- **"Closed Loop": If rotation applies, SAGNAC phase is compensated by controlled feedback phase**

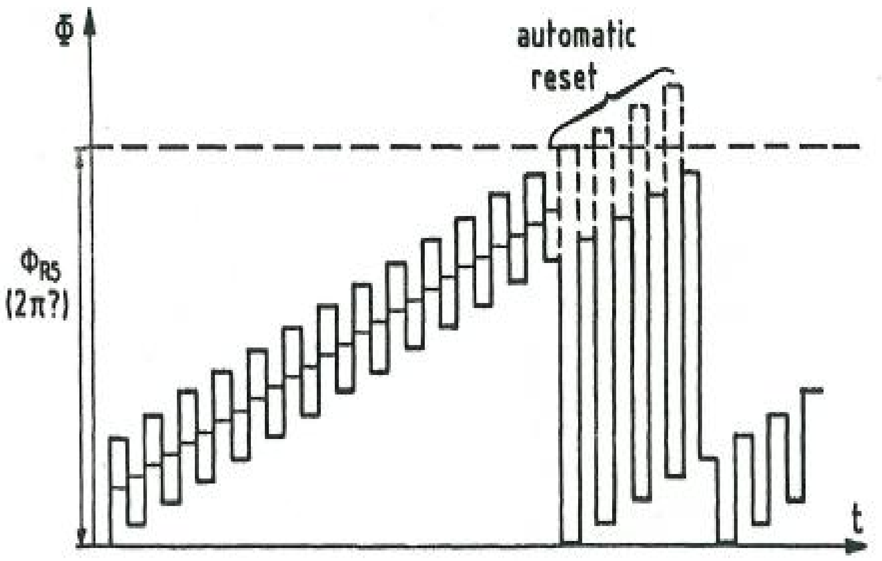
$$\Delta f_{FB} = \Delta f_R$$

- **"Closed Loop" operates the FOG in high-resolution regime, i.e. slope 1 in the FOG response curve**
- **"Closed Loop" operation preserves optimal scale factor linearity**



4.2. Closed Loop Operation of FOG (2#2)

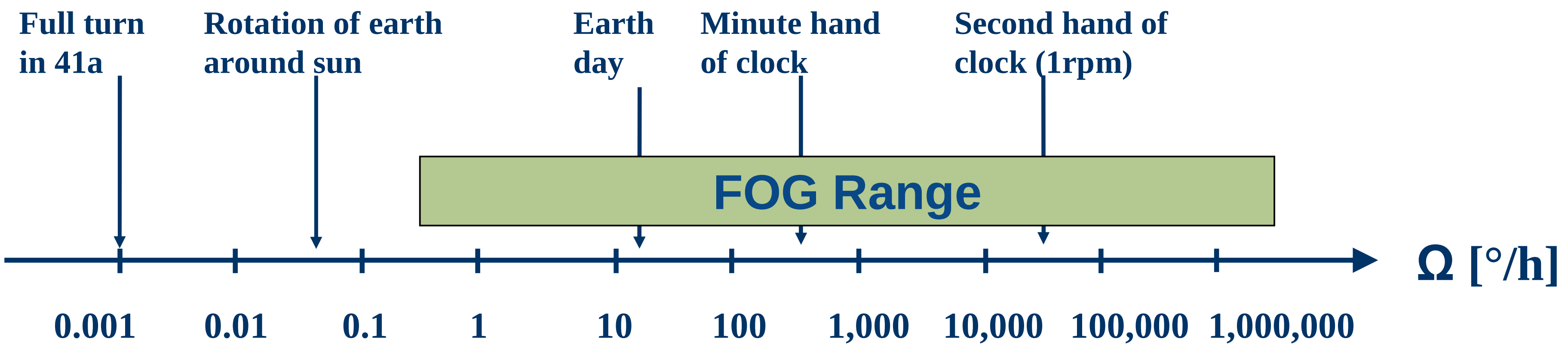
4 **“Closed Loop” implemented by staircase digital phase ramp**



from [1]

4.3. Scales and Substantiation of Rotation

- **Range (typical):** Ω = 800°/s … 0.0001°/s (3x10^6 °/h … 0,3°/h)
- **Angular Resolution (max.):** φ = 0.1 µrad (6x10^{-6}°)
- **Corresponding Path Length (after passage of > 100m fiber): <10^{-14}m**



4.4. Limiting and Parasitic Effects in FOG

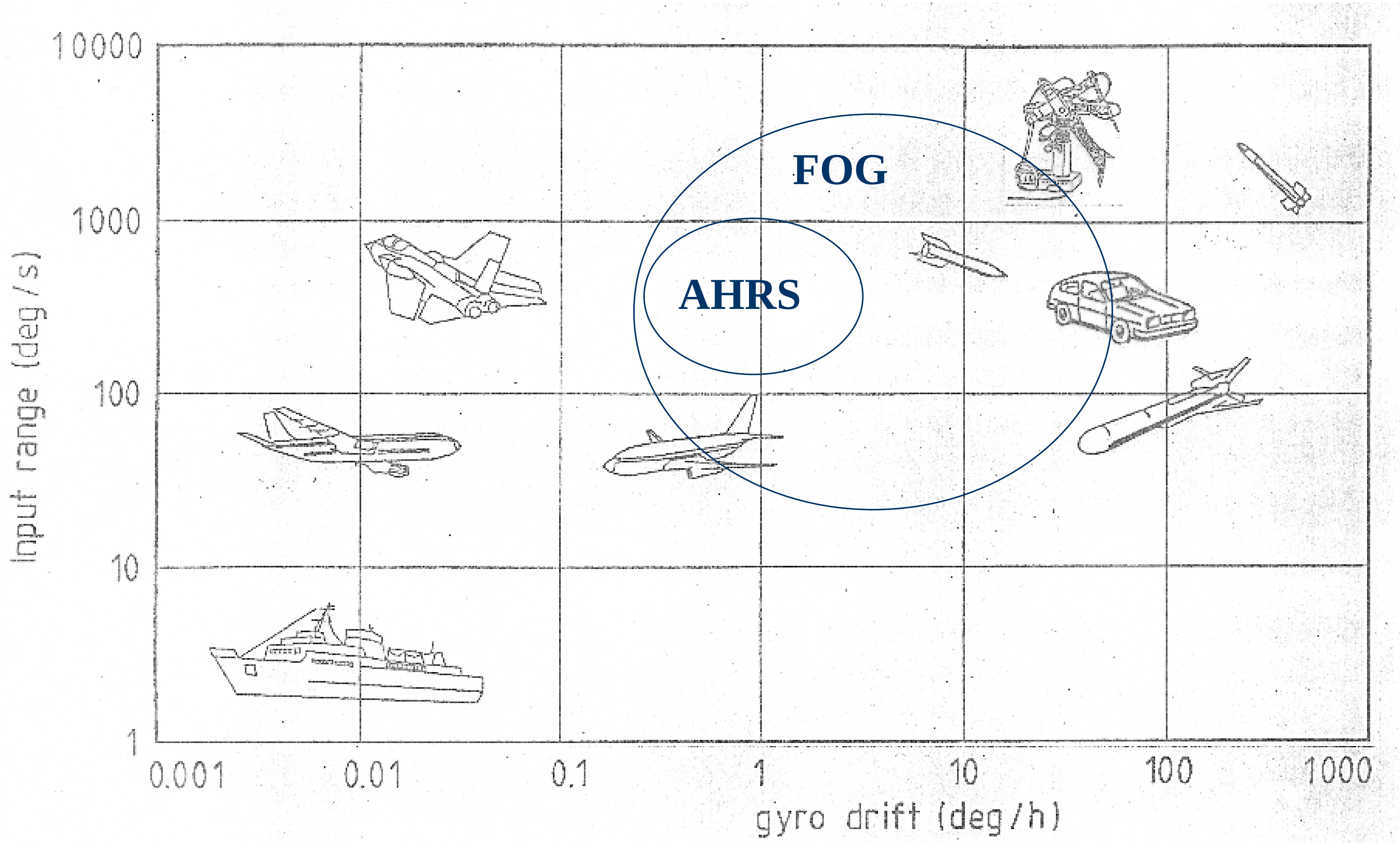
Effect	Compensation, Correction
Noise due to back-reflection and backscattering	Low coherence, broadband optical sources
Non-reciprocities due to birefringence	Polarization maintaining fiber, broadband optical sources
Temperature transience and vibrations (Shupe-effect)	Quadrupolar coil winding, coil potting
Faraday effect	Polarization maintaining fiber, magnetic shielding
Kerr effect	broadband optical sources
Scale factor non ambiguity, non-linearity	Closed loop operating using phase ramp modulation

4.5. Inertial Sensors

- An inertial sensor determines accelerated movements, i.e.
  - In case of linear accelerations by accelerometers and,
  - In case of rotation by gyroscopes.
  - Note: Acceleration is defined by time variation of amount or direction of the velocity vector.
- An inertial measurement unit typically consists of
  - A 3 axis triad of gyroscopes, plus
  - A 3 axis triad of accelerometers.
- A body moves inertially, if there is absolutely no acceleration and rotation in any space direction.

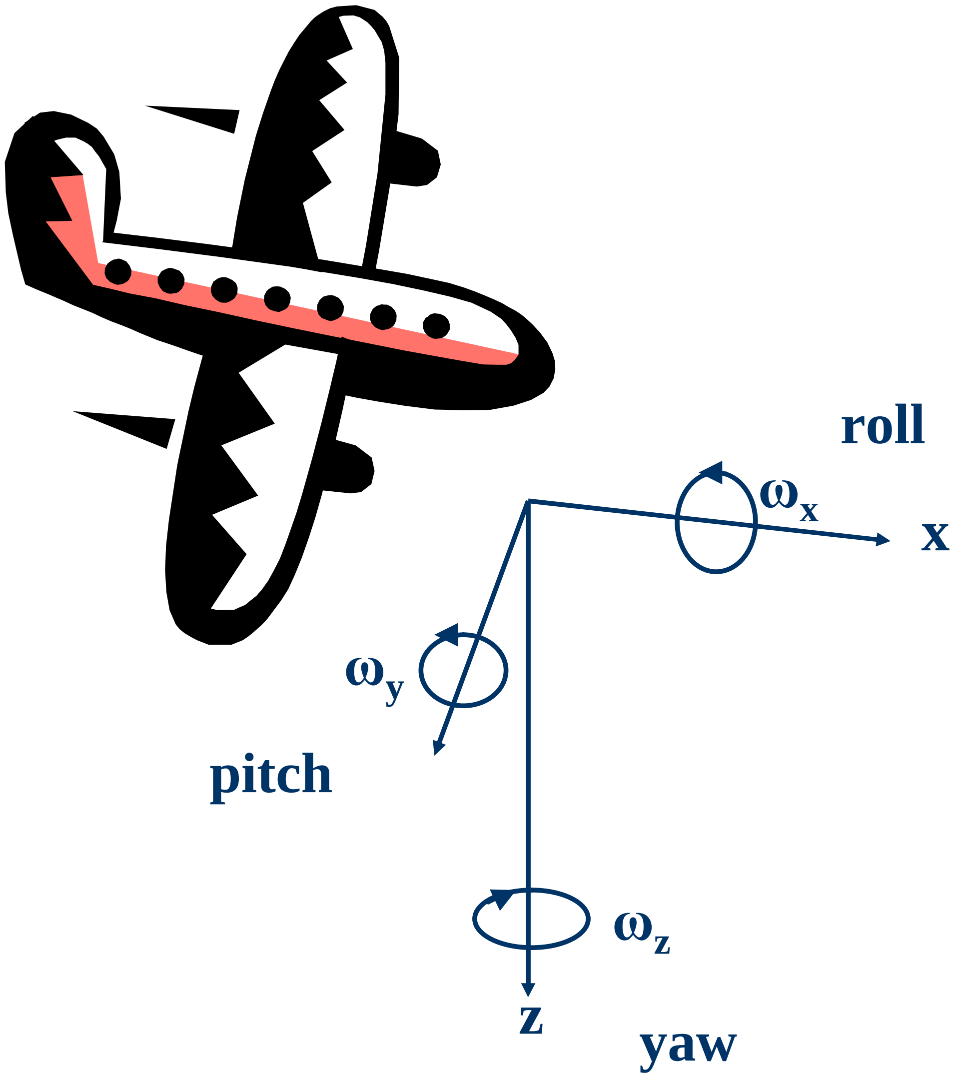
  Note: Due to its spin (15°/h) the earth is not an inertial system!

4.6. Application of Gyroscopic Sensors



4.7. Typical FOG Applications

- **Avionic / Space:**
  - **Attitude Heading Reference Systems (AHRS),**
  - **stability augmentation systems,**
  - **rudder control, etc.**
- **Naval:**
  - **Navigation,**
  - **stabilization control, e.g. submarine periscopes**
- **Mining, drilling, pipeline inspection**
- **Industrial Robotics**
- **Military:**
  - **Alignment,**
  - **Stabilization**
- **Etc.**



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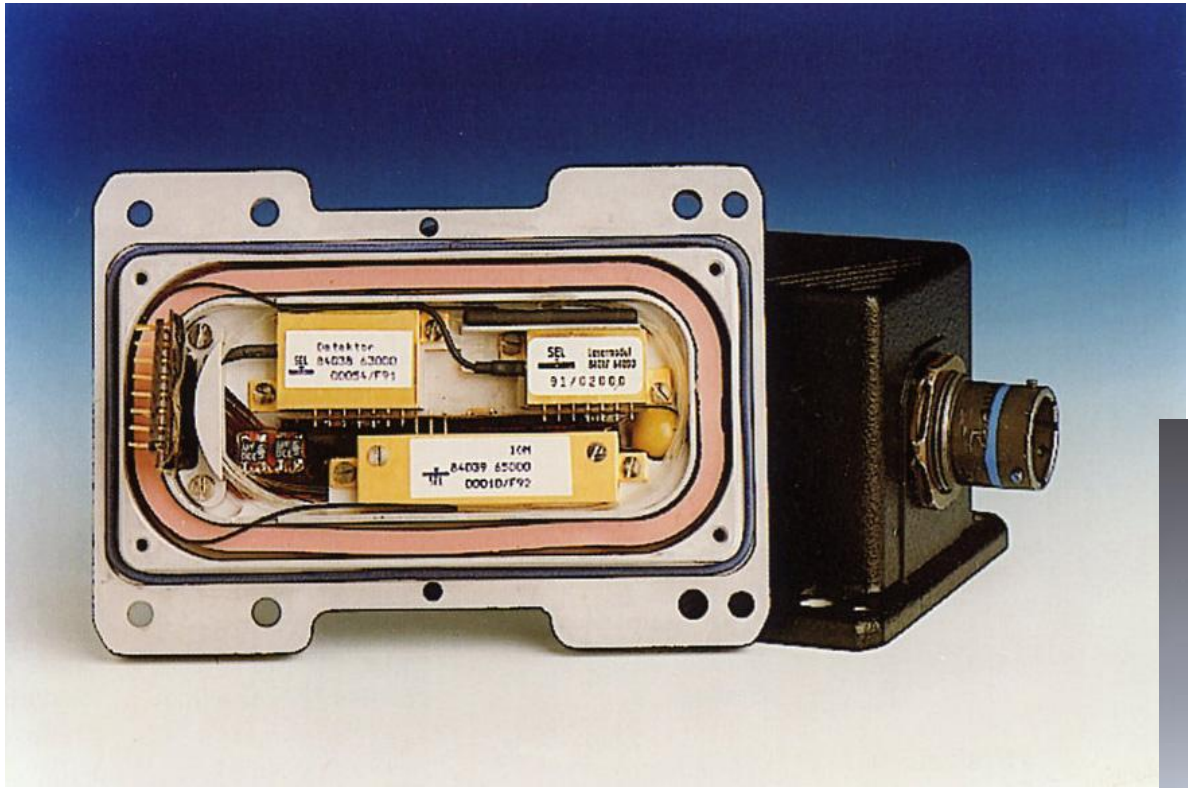
4.8. Typical Environmental Requirements

- **Temperature,**
  - **Storage, power-up, thermal cycling: -45...+85°C,**
  - **Full operation: -40...70°C,**
- **Vibration: 20...2,000Hz, 15g rms,**
- **Shock: 50g, 6ms, half sinus, 500g, 0.5ms,**
- **Acceleration: >100g,**
- **Reliability: MTTF >50,000h,**
- **Life time: up to 25a**
- **...**

4.9. FOG Based Products (1#4)

4 **FOG-P1-X Family**

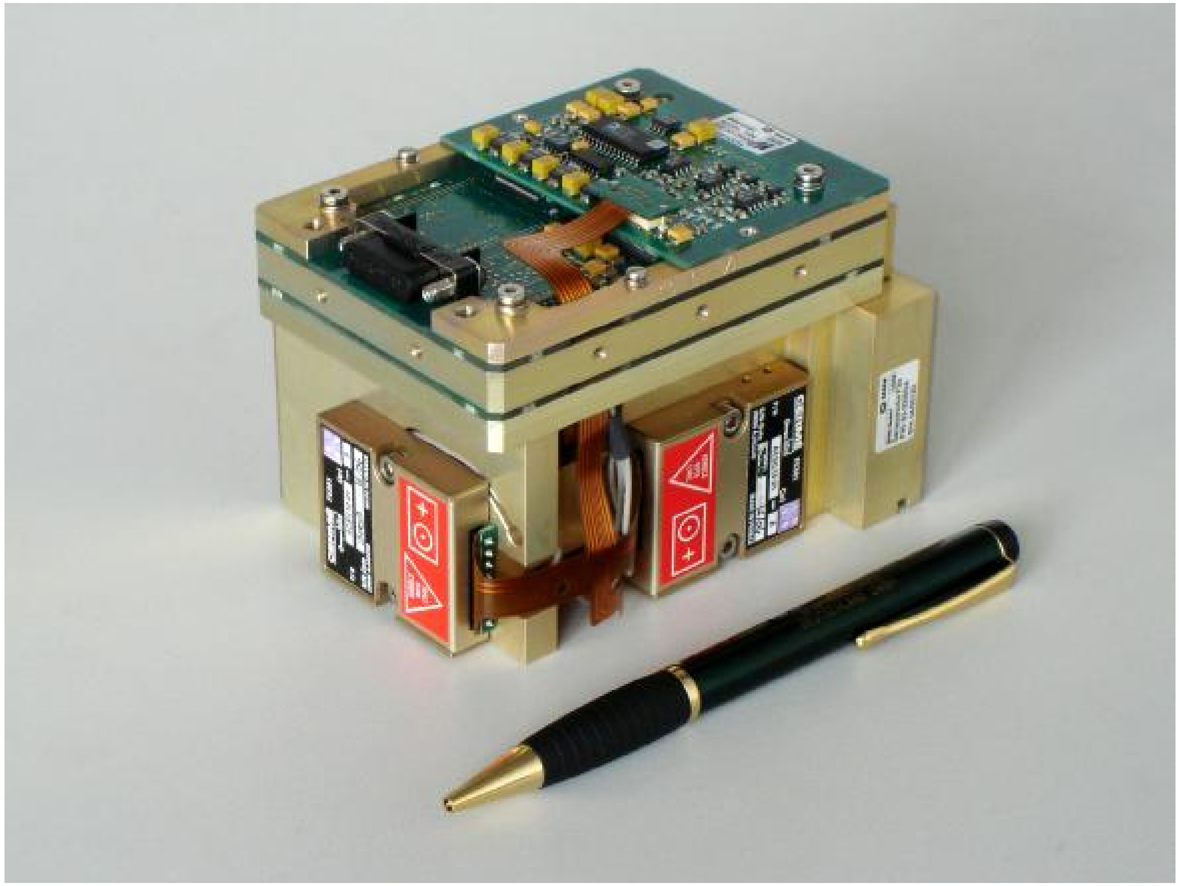


4.9. FOG Based Products (2#4)

- Rate Sensor for Backup Control Module (BCM)
- Large Environment Accelerometer Unit (LEAU)
- Rate Gyro Unit (RGU)

4.9. FOG Based Products (3#4)

- **FMU-3N: Inertial Measurement Unit**



4.9. FOG Based Products (4#4)

4 **EC135 3-axis Stability Augmentation System (SAS) Installation**

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5. Summary

6. Abbreviations

- BIT: Built-In Test
- ccw: counter clockwise
- cl: closed loop
- cw: clockwise
- DM: Detector Module
- FOG: Fiber Optic Gyroscope
- IMU: Inertial Measurement Unit
- IOM: Integrated Optics Module
- MM(F): Multi-Mode (Fiber)
- MTTF: Mean Time To Failure
- NEP: Noise Equivalent Power
- PM(F): Polarization Maintaining (Fiber)
- SLD: Super Luminescent Diode
- SM: Source Module
- SM(F): Single Mode (Fiber)

7. References

- [1] Lefèvre, H.: “The Fiber-Optic Gyroscope”, Artech House (1993)
- [2] Burns, W. K.: “Optical Fiber Rotation Sensing” Academic Press (1993)
- [3] Ghatak, A., Thyagarajan, K.: “Introduction to Fiber Optics” (1998)
- [4] Hunsperger, R.: “Integrated Optics - Theory and Technology” Springer, Berlin (1995)
- [5] Titterton, D. H.; Weston, J. L.: “Strapdown Inertial Navigation Technology” Peregrinus (1997)
- [6] Kayton, M.; Fried, W.: Avionics Navigation Systems, Wiley, (1997)