A Fiber Optic Gyroscope Prototype with High Bias Stability for Rotational Seismology Phenomena Measurement

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Outline

• Rotational Seismometer
• High Performance Gyroscope Principle
  • Optic system with large fiber coil
  • Depolarizer optimization for PN error reduction
  • Frequency modulation for $1/f$ noise reduction
• Indoor Testing
• Future Work
Rotational Seismology

- Rotation seismology phenomena have been observed for centuries
  - Rotation of a tomb, India, 1899
- Seismic motion is composed of translation and rotational motion (6 DOF)
- Rotational motion is significant for seismology but lack of study before RLG development

Seismology Rotational Motion

• Wide amplitude range
  • A few rad/s near seismic source (Nigbor 1994)
  • $10^{-11}\text{rad/s}$ at tele-seismic distances (Igel et al. 2005; Schreiber et al. 2005, 2006)

Contrast
High accuracy navigation-grade gyroscope (e.g. navigation for spacecraft)
Bias stability: around $10^{-8}\text{rad/s}$

Rotational Seismometer Requirements

- High sensitivity and high bias stability
- Wide amplitude range and frequency range
  - $10^{-11} \sim 10^0 \text{ rad/s}$
  - $10^{-3} \sim 10^2 \text{ Hz}$
- Scale factor linearity
- Immunity to environmental influences
- Low cost (for widely usage)
- Portable (for outdoor usage)

How?
Potential Solutions

- Mechanical
- Fiber Optic
- Ring Laser
- MEMS
- ......

Fiber Optic Gyroscope may be one of the most suitable solution

Sagnac Effect and Large Length FOG

To increase R·L to improve sensitivity and stability

Two FOGs were demonstrated:
- A 15km-long SMF coil of 0.3m in diameter
- A 10km-long SMF coil of 0.2m in diameter

But, noise also increased e.g. SNR drops due to loss increasing (L. R. Jaroszewicz, et al., 2008)

Sagnac phase shift

\[ \Delta \phi_{\text{sagnac}} = \frac{4\pi R \cdot L}{\lambda c} \cdot \bar{n} \cdot \bar{\Omega} \]

\( \lambda \): wavelength of light source
\( R, L \): radius and length of fiber coil

Design Principles

• High sensitivity
  • Upgrade the products of R and L to increase sensitivity
  • SMF fiber with longer length preferable

• Main noise increases with large length
  • Polarization non-reciprocity error
  • $1/f$ fractal noise
  • Shupe effect
  • SNR drops due to loss increasing
  • ......
Optical System Design

- Open-loop depolarized system under minimum polarization reciprocal configure
- Broadband ASE light source with bandwidth 40nm to overcome Rayleigh scattering
- MIOC with PMF pig tail for polarizing, modulating and coupling light into fiber coil
- SMF coil with 10km or 15km, for high sensitivity and low cost

For polarization non-reciprocity error
Use two depolarizers to ensure reciprocity
DOP < 0.5%
High Order Eigen Frequency Modulation for 1/f Noise Reduction

• The gyroscope needs a eigen frequency modulation to reduce Rayleigh backscattering error

• The backscattering beams should not be modulated

\[
\sin(2\pi f t) = -\sin \left[2\pi f \left(t + \frac{c}{L_e}\right)\right]
\]

\[
f_e = (2n + 1) \frac{c}{2L_e} \quad n = 0,1,2,\ldots
\]

1st order eigen frequency: \( f_e = \frac{c}{2L_e} \)

• High order eigen frequency can reduce \( \frac{1}{f} \) noise

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The performance of different order eigen frequency modulation

Bias stability of 10km prototype using different order of modulation frequency

Prototype 1
L = 10km
D = 0.2m

![Graph showing bias stability as a function of order of modulation frequency with a line graph and a fractal noise diagram.]

- $1/f$ fractal noise
- $f_e$, $f$, $9f_e$
The performance of different order eigen frequency modulation

Self-noise at 1Hz, in rad/s/√Hz: $1.1 \times 10^{-9} (f_e)$ Vs. $0.7 \times 10^{-9} (9f_e)$
Seismometer Prototype

Detecting Earth rotation as static testing

Earth rotation in Beijing (N39.99°, 4.70·10⁻⁹ rad/s)
Indoor Test Outcome

15km prototype
Output at 10Hz

The Allan variance
$< 8 \times 10^{-10} \text{ rad/s}$
Future work

• Calibration
• Observing seismology rotational motions
• Engineering development
• 6 DOF seismometer development
Conclusions

• The prototype demonstrated can be a suitable choice:
  • High bias stability to detect tiny rotational motion
  • Enough frequency bandpass for seismic application
  • Relatively small size and low cost

• Necessary verification:
  • Fully test and field observation for seismology rotational motion

• Portable development is in progress
Thank you!