Development of High-Radiation-Tolerant Fiber-Optic Sensors for SNS Mercury Target Strain Measurement

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7th High Power Targetry Workshop
June 4-8, 2018
Outline

• Background and motivation

• Sensor Instrumentation
  – Sensor type
  – Fiber type
  – Phase interrogation setup
  – Data acquisition

• Strain Measurement Performance
  – Laboratory test of static and dynamic strains
  – Strain measurement in the SNS target module
  – Issues and mitigation methods

• Conclusion and future work
Challenges of strain measurement in pulsed targets: Findings from the SNS mercury target vessel

- Fiber-optic strain sensors have been used to measure the dynamic strain waveforms on the mercury target vessel
  - Commercial sensors only lasted a few tens of pulses
  - Even high-OH fiber sensors have limited lifetime

- Challenges
  - High radiation - > 10^9 Gy radiation level due to protons, neutrons, and high energy photons
  - High bandwidth – high intensity particle beam induces fast dynamic strain pulses which require mega-hertz measurement bandwidth

Goal - Development of high-radiation-tolerance, high-bandwidth, high-reliability fiber-optic sensors through optimization of sensor configuration, fiber, and processor.
Fiber-Optic Strain Sensor

**Fiber Bragg grating (FBG) based sensors**
- Well developed fabrication technology
- Fiber sensitive
- Radiation induced attenuation/grating bleach
- Measurement bandwidth

**Interferometer based sensors**
- High flexibility (any type of fiber)
- Interrogation setup easy to customize
- Radiation induced attenuation
- Measurement bandwidth
### Optical Fiber Selection

<table>
<thead>
<tr>
<th>Fiber Type</th>
<th>Advantages</th>
<th>Disadvantages</th>
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<tbody>
<tr>
<td>Pure silica fiber</td>
<td>Low cost, easy to handle</td>
<td>High radiation</td>
</tr>
<tr>
<td>Ge-doped fiber</td>
<td>Low cost, easy to handle</td>
<td>Very high RIA (&lt;span class=&quot;annotation&quot; style=&quot;color:red;&quot;&gt;induced radiation (RIA)&lt;/span&gt;)</td>
</tr>
<tr>
<td>High OH fiber</td>
<td>Higher radiation resistance</td>
<td>&lt;span class=&quot;annotation&quot; style=&quot;color:red;&quot;&gt;OH concentration induces loss&lt;/span&gt; in long wavelength</td>
</tr>
<tr>
<td>Hollow-core fiber</td>
<td>Excellent radiation resistance</td>
<td>Difficult to fabricate sensor, different core size from normal fibers</td>
</tr>
<tr>
<td>Fluorine-doped fiber</td>
<td>Excellent radiation resistance</td>
<td>Similar property to all single-mode fibers</td>
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</tbody>
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Our experiment verified that Fujikura (RRSMFB) fluorine-doped single-mode fiber shows extraordinary radiation resistance at 1300 nm.
Phase Interrogation – Low-Coherence Interferometry

Low-coherence light source

SLD

Fiber circulator

Sensing interferometer

Δλ ≈ 38 nm

l_c ≈ 31 μm

τ_c ≈ 0.11 ps

Low-coherence light source

PD1

PD2

Local interferometer

Phase Interrogation System

PD1

PD2

Optical Setup

PD1

PD2

Beam splitter

Fiber collimator

Piezo actuator

Gap tuning knob

Fizeau interferometer

Optical Setup

Image of optical setup with labels for PD1, PD2, Beam splitter, Fiber collimator, Piezo actuator, Gap tuning knob, and Fizeau interferometer.
Data Acquisition and Software Platform

Strain Measurement

Phase Calibration

Sampling rate: 10 ~ 250 MHz
Measurement bandwidth: > 300 kHz
Measurement Performance – Laboratory Test

- Strain test plate
- Vibration test setup
- Optical fiber
- PZT buzzer
- Linear stage

Data plots showing:
- Measured strain vs. applied strain
- PD output signal
- Vibration displacement over time
Measured Strain Waveforms
Strain Measurement Results

![Graph showing strain measurement results with time in ms and strain in με.]
Radiation Induced Attenuation (RIA) and Sensor Lifetime
Radiation Induced Attenuation (RIA) and Sensor Lifetime

RIA measurement results: $\sim 5.5 \times 10^{-8}$ dB/Gy/m

<table>
<thead>
<tr>
<th>Location</th>
<th>Beam Energy (MWHr)</th>
<th>Peak Radiation Dose (Gy)</th>
</tr>
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<tbody>
<tr>
<td>Front</td>
<td>77</td>
<td>$1.3 \times 10^9$</td>
</tr>
<tr>
<td></td>
<td>7.1</td>
<td>$10^8$</td>
</tr>
<tr>
<td>Middle</td>
<td>$&gt;1,670$</td>
<td>$&gt; 7 \times 10^8$</td>
</tr>
<tr>
<td></td>
<td>80</td>
<td>$5 \times 10^7$</td>
</tr>
</tbody>
</table>

SNS customized sensors
Commercial sensors

Possible Mitigation Approaches

Sensor Failure Scenarios
• Sensor gap extension induced by radiation
• Epoxy failure/effects of epoxy hardening
• Sensing interferometer broken
• Lost of light reflection

Mitigations
• Gap compensation in optical interrogation setup
• Improvement of sensor mounting methods (ultrasonic welding)
• Modification of sensor design (shorten sensor length), sensor mounting method
• Fiber material optimization?
Conclusion and Future Work

- We have developed fiber-optic strain sensors using Fluorine doped single-mode fiber, low-coherence optical interferometry technique, and digital signal processing scheme.
- The sensors have been applied to a number recent SNS mercury targets and the measurement performance demonstrated higher radiation tolerance and bandwidth than commercial products.
- Future work
  - Improvement of sensor performance using all-fiber interrogation scheme
  - Investigation of radiation effects
  - Looking into ultrasonic soldering technology
  - Collaboration
Colleagues involved in this work

- W. Blokland, C. Long (RAD/Beam Science and Technology group)
- D. Winder, B. Riemer, M. Wendal (NTD/Source Development and Engineering group)
- B. Qi (CSED/Quantum Optics group)
- R. Strum (MSU), D. Stiles (ERAU)