RADIATION HARD POLYIMIDE-COATED FBG OPTICAL SENSORS FOR RELATIVE HUMIDITY MONITORING IN THE CMS EXPERIMENT AT CERN

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Motivation, needs and requirements

Silicon tracker detectors are exposed to high radiation at the LHC which demand their operation at temperatures below 0°C [1] and consequently in a dry atmosphere to avoid condensation. For this reason, a constant and effective thermal and hygrometric control of the air is mandatory.

HUMIDITY SENSORS ISSUES IN HEP TRACKERS

✓ Low mass and Small dimensions
✓ Insensitivity to magnetic field
✓ Operation at temperature down to -40 °C and response to the full range
✓ [0, 100] % RH
✓ Reduced number of wires
✓ High long term stability
✓ Radiation resistance to dose up to 1 MGy

NOWADAYS THERE IS NO MINIATURIZED HUMIDITY SENSOR ON THE MARKET WELL SUITED FOR HEP DETECTOR APPLICATIONS

We focus our attention on the investigation of fiber optic humidity sensors based on polyimide-coated Fiber Bragg Gratings (FBG), which seem to satisfy all the needs [1].
FBG Features, Sensing Principle and Proposed Method

When a broad-spectrum of light beam is emitted to an FBG, reflections of each segment of alternating refractive index interfere constructively only with a specific wavelength of light, called the Bragg wavelength ($\lambda_B$).

$$\lambda_B = 2n_{\text{eff}} \Lambda.$$  

Changes in strain and temperature affect both the effective refractive index ($n_{\text{eff}}$) and grating period (\(\Lambda\)) of an FBG, which result in a shift in the reflected wavelength.

While successful use of FBG sensor arrays for temperature and strain monitoring in CMS has been already previously reported [2], the possibility of using FBG in connection with moisture sensitive polymer coating as a mean of relative humidity (RH) detection has been also recently demonstrated [3] [4].

$$\Delta\lambda_B = S_{RH} \Delta RH + S_T \Delta T,$$

where $S_{RH}$ and $S_T$ are the sensitivities of the sensor for RH and T, respectively.

Special care has to be devoted to find the best method to decouple the cross-sensitivity of each sensor to strain and temperature and, thus, to extract humidity measurements from the global sensor readings.
PH-DT Test facility and Experimental set-up

Experimental Set-up for RH measurements

Climatic chamber in aluminum:

- Provided with a thermo-regulation circuit for temperature control and stabilization which enables the creation of controlled levels of ambient humidity in the temperature range [-20 – 30] °C

- Precise relative humidity control based on a system of valves.
Temperature FOS Sensors

Tests performed in laboratory of CERN, in the T range [-20, 20] °C.

\[ T = a (\lambda + \lambda_{os})^3 + b (\lambda + \lambda_{os})^2 + c (\lambda + \lambda_{os}) + d \]

The selected commercial FOS Temperature Sensors (Micron Optics OS-4300) provide:

- Very stable and repeatable temperature measurements
- An accuracy of ± 0.25 °C (± 0.15 °C in steady states)

EXAMPLE OF RECONSTRUCTION from Array MO1-T-1-8
Temperature FOS Sensors

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- An accuracy of ± 0.25 °C (± 0.15 °C in steady states)

Reconstruction of 8 sensors at 21.25 °C
Reconstruction of 8 sensors at -20 °C
Relative Humidity FOS Sensors

Relative Humidity FOS Sensors have been specially produced under specification with a Polyimide coating of 10 microns (+/- 2 μm)

Applied models in order to take into account the double dependency of the sensor itself to the two parameters - the swelling of the material in presence of water molecules and the sensitive of grating to temperature variations:

Traditional approach:

- described in literature and based on the application of the formula
  \[ \Delta \lambda_B = f(\Delta T, \text{RH}) = S_{RH}(T) \Delta RH + S_{T}(\text{RH}) \Delta T \]
- based on the mathematical model describing the absorption or desorption phenomena of water molecules into the coating of the grating in linear assumption

The model is too simplified, cross-sensitivities to Temperature and Relative Humidity are observed:

\[ S_{RH}(T) \sim 0 \cdot 1 \cdot S_{T}(\text{RH}) \]

- Tests performed at 4 different temperature values: 20 °C, 10 °C, 0 °C and -5°C
- Relative Humidity changes in the range [0,50] %
- Usage of Linear Fitting in order to evaluate \( S_{RH} \) and \( S_{T} \)
Relative Humidity FOS Sensors

Surface Model:

- applies a more complicated formula to translate the lambda Bragg variations in humidity

\[
RH(\lambda, T) = p_{00} + p_{10}\lambda + p_{01}T + p_{20}\lambda^2 + p_{11}T + p_{02}T^2
\]

- the parameters of the formula determined using a fitting procedure
- term \( \lambda T \) introduced in order to point out the correlation between the wavelength and temperature

- Tests performed at 4 different temperature values: 20 °C, 10 °C, 0 °C and -5°C
- Relative Humidity changes in the range [0,50] %
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THERMO-HYGROMETERS Performances

Relative Humidity

- RH ref
- F6-H-1
- F6-H-2
- F6-H-3
- F6-H-4

RH VARIATIONS IN THE RANGE [5-40]%

DewPoint

Array F6- H-1-4
from 14-062-13 to 19-06-2013

DP VARIATIONS IN THE RANGE [-35 - 0]°C

RESIDUALS

- RH Residuals
- DP Residuals

Very good shape reconstruction from FOS sensors, in respect to the references in the whole RH and T ranges of test!!!
Radiation Hardness Behaviour of the FOS T Sensors

Progressive irradiations (up to 210 kGy) performed using $\gamma$ photons in order to:

1. Determine if the radiation-induced shift saturates [5, 6]
2. Investigate the sensing characteristics of the sensors after irradiation

Radiation-induced lambda shifts after each irradiation steps

Sensitivity independence
Radiation Hardness Behaviour of the FOS T Sensors

In total 4 sensors (of 2 different batches) are tested:

- The observed radiation-induced lambda shift decreases with the total adsorbed dose and arrives to an almost linear behaviour
- The sensitivities to Temperature \(S_T\) of the sensors are unchanged after the full irradiation series

\[
\Delta \lambda_{ri} = a D + \frac{(b D)}{(1 + c D)} + d
\]

Radiation induced lambda shifts as a function of total adsorbed dose

Sensitivity to further irradiation is very low after an absorbed dose 150 kGy

Radiation induced lambda shifts after each irradiation steps

\[
Y = 0.110770021x - (0.30036x^2)/ (1-0.030027x) - 0.126241
\]

\[
R^2 = 0.999378
\]
Radiation Hardness Behaviour of the FOS T Sensors

2 POSSIBLE SCENARIOS

**CASE1** : Luminosity = 100 fb-1 AFTER 2 YEARS
- Radial Distance (R) = 65 cm
- Distance Along Beam Axis (Z) = 300 cm
- Estimated Absorbed dose in 2 years: 8.0 kGy

**CASE2** : Luminosity = 150 fb-1 AFTER 3 YEARS
- Radial Distance (R) = 40 cm
- Distance Along Beam Axis (Z) = 300 cm
- Estimated Absorbed dose in 3 years: 12 kGy

Example: MicronOptics_MO1 (ST=9.1 pm/C)
- In case of Pre-Irradiation at 150 kGy

**Case 1**: After 2 years
\[ \Delta \lambda_{\text{radiation}} = 1.6 \text{ pm} \Rightarrow \text{error in } T \text{ reading} = 0.1 \text{ C} \]
Error in RH reading due to wrong T reading = 1 or 1.5\%RH

**Case 2**: After 3 years
\[ \Delta \lambda_{\text{radiation}} = 2.4 \text{ pm} \Rightarrow \text{error in } T \text{ reading} = 0.26 \text{ C} \]
Error in RH reading due to wrong T reading = 2 or 2.5\%RH
Radiation Hardness Behaviour of the FOS T Sensors

2 POSSIBLE SCENARIOS

**CASE 1**: Luminosity = 100 fb⁻¹ AFTER 2 YEARS
Radial Distance (R) = 120 cm
Distance Along Beam Axis (Z) = 300 cm
Estimated Absorbed dose in 2 years: **1.27 kGy**

**CASE 2**: Luminosity = 150 fb⁻¹ AFTER 3 YEARS
Radial Distance (R) = 120 cm
Distance Along Beam Axis (Z) = 300 cm
Estimated Absorbed dose in 3 years: **1.91 kGy**

Example: MicronOptics_MO1 (ST=9.1 pm/C)
• In case of Pre-Irradiation at 150 kGy

![Derivative Shift vs Irradiation](image)

**Case 1**: After 2 years
\[ \Delta \lambda_{\text{radiation}} = 1.6 \text{ pm} \]
Error in RH reading due to wrong T reading = **less than 1 %RH**

**Case 2**: After 3 years
\[ \Delta \lambda_{\text{radiation}} = 2.4 \text{ pm} \]
Error in RH reading due to wrong T reading = **less than 1 %RH**
Progressive irradiation up to 150 kGy shows that also on RH sensitivity the effect of ionizing radiations is negligible (below the measurement error).

Results on 4 samples of FOS RH Sensors:

- Sensitivities to Relative Humidity of the FOS RH sensors are not affected by $\gamma$ irradiations
- Radiation-induced lambda shift is observed, progressive irradiation campaigns are on-going to define the saturation properties
Summary

• Optical thermo-hygrometer proposed to CMS, based on a Temperature and another Relative Humidity FBG sensor, in order to monitor the relative humidity in the Tracker detector and in the surrounding volume.

• Temperature sensors:
  • Calibrations provide very stable and repeatable temperature measurements with an accuracy of ± 0.15 C in steady states.
  • Results of the irradiation campaigns up to 210 kGy show that the sensitivity of the sensors to temperature is not effected by gamma radiation. The observed wavelength shift become very small above 150 kGy with linear behaviour.

• Relative humidity sensors:
  • Calibrations provide very good shape reconstruction, in respect to the references with an accuracy of ±3 % relative humidity.
  • Results on 4 samples of FOS-RH sensors after irradiation campaigns up to 150 kGy show that the variations of RH sensitivities after each irradiation campaign are negligible.
  • Progressive irradiation campaigns are on-going to define the saturation properties of the radiation-induced wavelength shift.

References


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