Fibre Optic Sensors for environmental measurements: status of the R&D at CERN EP-DT

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Paolo Petagna

N. Beni, Gaia Maria Berruti, Anna Borriello, Marco Consales, Andrea Cusano, Alajos Makovec, Tiago Pimentel Das Neves, Zoltan Szilasi, Lorenzo Scherino, Luc Thévenaz, Simona Zuppolini
Is there any commercial humidity sensor suitable for high-radiation environments?

1. Industrial high-precision dew point meters (E.g. Vaisala)
   - Remote measurements on air samples transferred over long distance
   ✓ High performance, very good accuracy, even below 5% RH
   ✓ If instrumentation placed in no-radiation area, not influenced by radiations
   ✓ Not miniaturized at all
   ✓ No distributed sensing
   ✓ Not instantaneous measurement

2. Standard capacitive relative humidity sensors
   ✓ Miniaturized
   ✓ Not designed with radiation resistance characteristic

E.g. SHT25 from Sensirion: benchmark in the market of miniaturized capacity humidity sensors

- Recommended operating range not covering the whole RH range at each T
- Accuracy of ± 2% at 25 °C (up to ± 3% below 15 °C in [0-5] %RH
- Accuracy not specified below 0 °C
- Accuracy values not including hysteresis (±1 %RH)
- Not surviving to radiation exposure (tests performed at CERN)

NO commercial humidity sensing solution well suited for HEP detector applications
Three generations of fibre-optics based environmental sensors (thermo-hygrometric FOS)

**Fiber Optic Sensors**

- **Immunity to electromagnetic interference**
- **Possibility to work in harsh environments**
- **Radiation resistance**
- **Absence of electronic circuitry** in the measurement area

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**Research and Development projects at CERN LAUNCHED in EP-DT-FS section:**

- **1st generation** based on *Fiber Bragg Grating (FBG) technology*:
  - Investigations from 2011
  - R&D completed

- **2nd generation** based on *Long Period Grating (LPG) technology*:
  - Investigations from late 2013
  - R&D still on-going (completion target 2021-22)
  - Prototype installation in ATLAS ID in March 2019
  - Target complete installation in ATLAS ITk in 2024

- **3rd generation** based on distributed sensing:
  - Investigations from 2017
  - R&D on-going

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FIRST INSTALLATION OF A NETWORK OF SENSORS IN CMS IN 2014

PROTOTYPE INSTALLATION OF SEVERAL SENSORS IN ATLAS IN 2019

PRELIMINARY RESULTS BEING PRODUCED NOW
Generations 1 & 2: FBG & LPG sensors

FBG

FBG is a permanent periodic modulation of the refraction index in the fiber core

\[ \lambda_B = 2 \cdot n_{\text{eff}} \cdot \Lambda \]

- \( n_{\text{eff}} \) is the fiber effective refractive index (\( n_{\text{eff}} \approx 1.455 \) in silica)
- \( \Lambda \) is the grating pitch (typically \( \approx 500 \) nm)
- \( \lambda_B \) is the reflected Bragg’s wavelength

LPG

Long period gratings are photonic devices obtained by inducing a periodic modulation of the refractive index of the core of a single mode fiber coupling the fundamental core mode and the cladding modes

- “Long” period of the grating (from 100 \( \mu \)m to 1 mm)

\[ \Lambda = \text{grating pitch} \approx 10^2 \mu \text{m} \]

\[ L = \text{length of the grating} \approx 2-4 \text{ cm} \]

against a few mm of FBGs
Generations 1 & 2: FBG & LPG sensors

Bare sensors: sensitive to STRAIN and TEMPERATURE (different mechanism)

FBG: RH functionalization

LPG: RH functionalization

Water molecules selected as coating material for RH sensing

Coating expansion ("Swelling effect")

Strain induced on the FBG

Bragg wavelength shift ($\Delta\lambda_B$)

Moisture absorption/desorption by the coating

Modification of coating RI

Spectral variation of attenuation bands

Optical fiber

Hygroscopic coating

Typical FBG performance (~10 μm thick PI coating)

**Relative Humidity Sensitivity**

\[ S_{RH} = 2.1 \pm 0.2 \text{ pm/RH in [-15, 20]°C} \]

**Temperature Sensitivity**

\[ S_T = 10.1 \pm 0.6 \text{ pm/C in [0, 100] %RH} \]

**Response Time**

\[ t_{response} \text{ of a few seconds, comparable to commercial miniaturized sensor} \]

**Hysteresis**

\[ \sim 1.6 \%RH, \text{ comparable to commercial miniaturized sensor} \]

**NOTE:** wavelength resolution of the best available optical interrogator = 1 pm
Pre-irradiation of FBGs is suggested to bring them in the “Safety zone” before installation in high irradiation environments.

- 10 kGy is the expected absorbed dose in 2 years of LHC activity considering:
  - Luminosity of 100 fb⁻¹
  - Sensors 40 cm distant from the beam pipe (worst case)

- Expected radiation induced shift less than 0.5 pm (corresponding to ~ 0.15C or ~ 1%RH)
  - Commercial capacity RH sensors permanently damaged before the 10 kGy dose
Pure Silica FBG: “insensitive” to radiation?

- Commercial FBGs (1st generation developed) with VERY low radiation sensitivity
  - fabricated through femtosecond laser
  - tested in the proton IRRAD facility at CERN up to 2.5 MGy & $\sim 5 \times 10^{15} \text{1MeV}_{\text{eq}}/\text{cm}^2$

Ex. Sample FBG: FEMTO- Irradiation in IRRAD (July 2018)

$\Delta \lambda$ saturated after the exposure to 0.7 MGy!

More systematic investigations needed
Network of 72 “T+RH” FBG’s active in CMS since 2014

E.g. Two years monitoring of temperature and dew point temperature in the Outside Tracker Bulkhead

**Temperature monitoring**

Dew Point temperature monitoring

One sniffing point available here (pos. 2)

The fiber optic-based thermo-hygrometers measurements in agreement with the reading of the sniffer (black) down to $T_{DP} = -30^\circ C$

**Packaging: strain free**

FBG-RH sensor

FBG-T sensor

**Packaging**

- strain free

**FBG-based thermo-hygrometers:**
- radiation resistant
- no drift in time
- providing T and RH reasonable measurements during RUN2

E.g. 4 months of T and RH monitoring in 2018 in the CMS Outside Tracker Bulkhead

(4 years after installation)

One year of FBG-based thermo-hygrometers in operation in the CMS experiment at CERN

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Typical LPG performance (~100 nm thick TiO$_2$ coating)

- **8 layers of TiO$_2$ deposited onto the grating**

- Still highly RH sensitive
  - Step from 0.5 %RH to 5.5 %RH
  - $\Delta \lambda = 0.8$ nm
  - With 3 RH steps in the range [0, 13]% RH, we use 1.3 nm of bandwidth of the optical interrogator

**Temperature sensitivity**

- Precise T - compensation required only if very precise RH measurement is needed

If no compensation is applied, a T reading error of $\pm 1 \, ^\circ$C corresponds to:
  - 7-10 %RH error for coated FBG based RH sensors (1st generation)
  - 0.5±1 %RH error for coated LPG based RH sensors

Temperature sensitivity:

$S_{T,mean} = 0.250 \pm 0.015$ nm/°C in [0-100] %RH

NOTE: maximum bandwidth of the best interrogator available = 160 nm

High sensitivity in the range of low humidity
Appealing for high precision measurements
LPG behaviour under irradiation

- 2 uncoated and 2 coated LPGs (8-10 TiO$_2$ dips) fabricated by University of Sannio (Benevento - IT)
- Several irradiation campaigns in IRRAD performed at high radiation doses (Nov 2017, July 2018, running Nov2018)

Uncoated sensors:
- High repeatability
- Steep response in [0-30] kGy
- Lower response (almost linear) to higher doses
- No saturation reached

Coated sensors:
- Lower sensitivity to irradiation compared to the uncoated LPGs
- The TiO$_2$ layer acts as a “shield” for the particles (8 dips-coated LPG more sensitive than the 10 dips-coated LPG)
- Signs of saturation

Pure Silica LPG: “insensitive” to radiation?

- **2 uncoated LPGs fabricated by University of Parthenope** (Naples-IT) delivered at CERN at the beginning of November
- Installed in IRRAD for the first proton irradiation campaign on in November 2018
- Irradiation ended. Cool down phase running (sensors still in acquisition)

- Promising results in terms of radiation sensitivity
- Coating deposition procedure only recently tested for the first time on theses samples

Extra investigations needed!!

Preliminary results
March 2019: test installation of RH+T LPG’s in ATLAS

Packaging: pre-starined
Towards a LPG-based dosimeter...

The LPG platform as basis for a novel class of dosimeters for ultra-high dose high energy physics environments.

- Variation of the LPG resonance wavelength with time and dose during the irradiation
- Coating as a tuning parameter according to the range of dose of interest

Full-range Fiber Optics Sensors for Radiation and environment monitor (FFOSRad)
- Submitted on October 30th, 2018
- UNFORTUNATELY NOT SELECTED: EP-DT & Colleagues organizing to carry on the study...

Submitted to

Analysis of uncoated LPGs written in B-Ge-doped fiber under proton irradiation for sensing applications at CERN

Gale Marie Berruezo¹,²,³, Petreto Valero¹, Giuseppe Quaresia, Diego Filleum Pimentel Dos Reis², Alessandra Boniello², Marco Consales², Paolo Petagna¹, Andrea Casana³

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FBG’s or LPG’s? Complementary performances

FBG
“Engineered” product
Some additional R&D on pure silica fibres
+ Sensors are commercially produced
+ Simple (engineered) packaging
+ Many (10 – 100) sensors on a single fibre
+ Linear sensitivity to T and RH (first order approximation)
+ Radiation-induced effects understood
- Accuracy in line with standard capacitive sensors
- Dew Point performance limited to -40 °C
- PI coating might experience aging issues

LPG
Product still in prototype phase (2 years needed)
R&D on pure silica fibres just starting
+ Extremely high RH accuracy between 0 and 10% RH
+ Extremely high T accuracy (few mK level)
+ Dew Point performance good to -70 °C (or dryer)
+ Oxide coating expected to be stable in time
- Bespoke sensors from specialized R&D institutes
- Complex packaging must be optimized
- Few (3 – 4) sensors on a single fibre
- Linear sensitivity in T but highly non-linear in RH
- Radiation-induced effects under study
The 3rd generation: “distributed” (continuous) sensing

- Measurements over the **entire length of the fiber cable, no gaps**
- **Continuous real-time** monitoring
- Up to **several kilometers**
  - *The cost is lower* compared to thousands of point sensors
- Non-electrical
  - *Immunity* to radio frequency interference and electromagnetic interference
- **Harsh environments** resistance

- Only **1 fiber and 1 optical system**
  - 0 metallic wires
  - 0 electronic boards in the sensing points
- Possibility to **detect the precise position of a temperature/strain change** in real time
  - Possibility to rebuild the fiber in the broken point in minutes

**1st Developed Prototype**
- **1 OTDR system + 1km** of humidity sensitive fiber
- Spatial Resolution **20 centimeters**
- Up to **5k measurable points**
- Measurements at each **3 minutes**
- Temperature compensation
Experimental setup

Phase-sensitive OTDR

Data Acquisition

Climatic Chamber

PT100 + HIH4000

Fiber | Length
--- | ---
RSF − 1 Layer Polymide | 100 m
RSF − 2 Layer Polymide | 100 m
RSF − 3 Layer Polymide | 100 m
RSF − 4 Layer Polymide | 100 m
NLFERNS Commercial Polymide | 100 m
FIBERCORE Commercial Polymide | 10 m
FIBERCORE Commercial Polymide | 10 m
DATWATER Acrylic Commercial | 8 m
DATWATER Bare | 8 m
DATWATER 1 Layer Polyimide | 20 m
DATWATER Acrylic Commercial | 8 m
CABIOPTIC Acrylic Commercial | 8 m

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Preliminary results (to be presented at EWOFS 2019)

Temperature reference

\(\phi\)-sensitive OTDR trace at different RH levels at 26.9°C

RH variation during test

Time response of PI-coated fibres

Time response of AC-coated fibres

Calibration fitting for all fibres

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Examples of performance

Rise Fibres PI-coated (3 layers)

Datwyler Fibres AC-coated (standard)

Resolution ~0.07%RH

Resolution ~0.14%RH
More complex interrogation system (Non-standard devices)
   OTDR system based on bulk laboratory devices
     Laser, modulators, photodetectors, etc.

More complex methods for calibration and temperature compensation
   Use a bare fiber as reference – Fragile and not suitable for harsh environments
     Use two fibres with the same $S_T$ and different $S_{RH}$
     Use the dual system used to decouple $T$ and $\varepsilon$ to decouple $T$ and RH (under study).

The whole fibre must be mounted strain-free

Cost is higher compared with few tens of point sensors
CONCLUSIONS

• Eight year of activity on Optical Fibre-based environmental sensors
• Mainly focused on thermohygrometers (combined measure of T+RH)
• Three generations of sensors in different (progressive) life phases
• Sensors respond to a lack of viable alternatives for multi-point sensing in detectors
• Complementary performance to satisfy different needs
• Two-three years to bring to maturity all technologies
• Extremely interesting perspectives for RADIATION MONITORING in sight