Outline

- Short presentation of BAM, motivation for fibre sensor activities
- What does fibre Fabry-Pérot sensor (FFPI) mean (basics)?
- Types (modifications) of FFPI sensors and typical features
- Application examples
  - Static measurements
  - Dynamic measurements
- Scientific questions (selection) - reliability aspects
- Summary
Federal Institute for Materials Research and Testing
Guideline: Safety and Reliability in Chemical and Materials Technologies

Interacting Fields

- Safety
- Materials
- Chemistry
- Environment

Main Areas of Activity

- Chemical-Technological Tasks
- Material-Technological Tasks
The Federal Institute for Materials Research and Testing (BAM) is a senior technical and scientific Federal Institute with responsibility to the Federal Ministry of Economics and Labour.

BAM is responsible for

- The technical safety in the technical domain including development legal regulations and reference methods for chemical analysis and materials testing
- Assistance in developing standards and technical rules for the evaluation of materials, structures and processes
- The advancement of safety and reliability in chemical and materials technologies
- Special tasks according to the Explosives Act, the Weapon Act and the Act for the Transport of Dangerous Goods
# The Departments of BAM

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Division S.1:
Measurement and Testing Technology; Sensors

Laboratory S.11: Reliability of Testing and Measurement Systems

Laboratory S.12: Sensors and Measurement Systems; Experimental Stress Analysis

Laboratory S.13: Optical Measurement and Testing Methods; Optical Reference Materials

Projects Group S.1901: Fiber Optic Sensors
Characteristics of fibre optic sensors

- **Small dimensions** (Diameter < 0.5 mm), that means: excellent capability of integration into components

- **no electric or electronic components on-site, chemically inert, low energy demands, thermally stable**
  - in electromagnetic fields, in areas of high lightning activities
  - in high-voltage and nuclear power plants,
  - in explosive and aggressive environments,
  - under high temperatures (> 1000 °C).

- **high static and dynamic strain resolution**
  (in some cases < 0.1 µm/m, t. m. better than 10⁻⁵ %) and up to few MHz

- **Sensor fiber can be divided into several measuring sections**
  (on-line) evaluation of deformation profiles

- **Design of distributed fiber sensor networks**

- **Compatibility with advanced data transmission systems**
Motivation for fibre optic sensor activities

Ground instabilities - threatening slope failure

Monitoring of fixed unstable Kammereck rock above the railway track near St. Goar
Motivation for fibre optic sensor activities

Damage due to wrong materials use

Deutsche Bahn befürchtete Risse an "Fester Fahrbahn" aus Beton

Haigertalbrücke - Demolition because of bad quality of concrete
Motivation for fibre optic sensor activities

Evaluation of integrity of construction
Types of fiber optic sensors

Long-gage length sensors

Optical fiber is fixed:

* between two points

\[ \varepsilon = \frac{\Delta L}{L} \]

Integral strain measurement

* at several points

\[ \varepsilon_1, \varepsilon_2, \varepsilon_3 \]

Strain profile measurement

* along the whole fiber.

Selective strain measurement ("distributed" measurement)
Types of fibre optic sensors

Short-gage length sensors

Sensitive element is positioned:

within the fiber (intrinsic sensor)

between two fiber end faces (extrinsic sensor)

Local BRAGG grating sensor

Local fiber Fabry-Pérot interferometric sensor
An interferometer converts a phase change to an intensity change

What does fibre Fabry-Pérot sensor (FFPI) mean?

1. Multiple beam interferometer

![Diagram of multiple beam interferometer showing phase relations and amplitudes.]

In contrast to dual beam interferometer

Interference of a number of waves  Sharp fringes
2. One-arm interferometer

Intrinsic type

Extrinsic type
Area of multiple reflections

Varying the distance between the fibre endfaces (gap),
What does fibre Fabry-Pérot sensor (FFPI) mean?

3. Periodic (ambiguous) signals

\[ \frac{I_R}{I_0} = 2R \left[ I + \cos \left( \frac{4\pi S}{\lambda_0} \right) \right] \]
What does fibre Fabry-Pérot sensor (FFPI) mean?

4. Periodically high sensitivity

High resolution of gap changes, but ambiguity
Measures to overcome the ambiguity:

- **Using several wavelengths** (provided by two laser diodes) and photodiodes

- **Using a white-light source, a second interferometer** (which reproduces the gap variations) and a **CCD array**

- **Use of a special sensor design**
  (twin-fibre structure or mechanical design)
Two-wavelength scanning of strain changes

Original interferometric signals

Calculated metric deformation signal
What does fibre Fabry-Pérot sensor (FFPI) mean?

5. Limited increase of the gap

\[ \Delta s = 117.65 \, \mu m \]
### Summarizing the characteristic features

**Characteristic data:**

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<th>Feature</th>
<th>Description</th>
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<td><strong>Gauge length:</strong></td>
<td>5 mm to 20 mm (extension to 70 mm possible)</td>
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<td><strong>Measurement range:</strong></td>
<td>-20,000 µstrain to +25,000 µstrain (-2 % contraction; 2.5 % strain)</td>
</tr>
<tr>
<td><strong>Resolution:</strong></td>
<td>0.1 µstrain ((10^{-7})) and better</td>
</tr>
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<td><strong>Dynamic resolution:</strong></td>
<td>up to MHz (depending on the device)</td>
</tr>
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<td><strong>Long-term reproducibility:</strong></td>
<td>defined by kind of application</td>
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<td></td>
<td>(reference to zero-measurement is lost after switching off the power)</td>
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<tr>
<td><strong>Temperature sensitivity:</strong></td>
<td>- 0.036 % / K</td>
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<tr>
<td><strong>Sensitivity to transverse strain:</strong></td>
<td>almost insensitive</td>
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Fibre Fabry-Pérot interferometer sensor

**Structural design**

- **Fibre is fixed at the capillary**
- **Coherent light**
- **Capillary Ø < 1 mm**
- **Diffusely reflecting end face**
- **Gap 10 ... 100 µm**
- **4 ... 30 mm**

**Principle of a stiff fibre Fabry-Pérot Interferometer sensor**

Very important: Definition of the gauge length!
Fibre Fabry-Pérot interferometer sensor

**Structural design**

- Coherent light
- Capillary Ø < 1 mm
- Diffusely reflecting end face
- Gap 10 ... 100 µm
- 4 ... 30 mm
- Leading fibre is sliding in the capillary
- Fixing point = gauge length

**Principle of a flexible fibre Fabry-Pérot Interferometer sensor**

**Force threshold:** 150 µN to 250 µN
Leading fibre is sliding in the capillary

Flexible fibre Fabry-Pérot interferometer sensor

Design: D. Hofmann, BAM-S.1901

Gap variations (increase or decrease) lead to periodic signal changes:

Interferometric signal

Data processing

Result
(Strain, pressure, vibration ...)

Interferometric signal
Measurement Scheme

Source → Coupler → Sensor → Detector
Commercially available systems

e. g. from FISO, Canada (www.fiso.com)

- Strain gauges
- Pressure sensors
- Displacement transducers
- Temperature probes

- One-channel portable field instrument
- Multichannel instrument with multiplexing capability
Commercially available systems

**APPLICATIONS**

The Fiber-Optic Extensometer, model no. FOE, from Fiso Technologies is designed for long term and accurate monitoring of displacements and axial deformations between two points inside or at the surface of man-made or built-in structures such as dams, bridges, buildings, etc. The base length of the extensometer is variable and is generally from 100 to 3000 mm.

To monitor very large spread deformations or movements, several FOE are assembled together in series. The in-line assembly allows the deformation gradient to be measured over the whole length of the profile.

**DESCRIPTION**

The Fiber-Optic Extensometer is comprised of (see drawing on next page):

- an outer protective telescopic housing fitted with two end flanges (other type of anchors are available)
- an inner co-axial stainless steel rod. The rod is fixed at one extremity to an end flange (other type of anchor) and has a fiber-optic linear position & displacement transducer FDQ transducer fastened to its other extremity
- a robust Kevlar reinforced fiber-optic cable linking the transducer to the fiber-optic signal condition

The heart of the FOE is composed of the fiber-optic linear position & displacement transducer FDQ which provides high precision measurement of positions and displacements. (For more information on the FDQ, see Fiso Technologies’ Fiber-Optic Product Guide). The FDQ can be seen as the fiber-optic version of the popular Linear Variable Differential Transformer (LVDT) but unlike the LVDT, the FDQ does not require any energizing AC voltage or driving signal with the associated noisy wiring. The FDQ is completely immune to EMI and RFI, and is not affected by lightning, humidity and corrosive environment. The FDQ carries no risk of current leakage and no risk of ignition. It can be safely used in hazardous environments such as those containing explosive materials. Its very low temperature dependence ensures virtually no thermal shift of the sensitivity and the zero, either on short term and long term measurements. Moreover, the FOE can be designed to produce thermal compensation for the structures to be measured. The rod and telescopic housing can be provided with PVC casing for more protection.

The signal conditioner can be configured to give an output either in absolute displacement (mm or inch) or in relative displacement such as % or microinches. The latter being the absolute displacement divided by the base length of the transducer (X Journal). The transducer signal can be transmitted through the fiber-optic cable over a distance of 1 km (and up to 5 km on special request) to the conditioner without the need of line amplifiers.

The above characteristics make the Fiber-Optic Extensometer well suited for long term and accurate monitoring of axial deformations over long base lengths.

**FEATURES:**

- **LONG TERM AND ACCURATE MEASUREMENT OF DISPLACEMENTS AND AXIAL DEFORMATIONS OVER LONG BASE LENGTHS**
- **MEASURING FIBER-OPTIC PRINCIPLE PROVIDES VIRTUALLY NO THERMAL SHIFT OF THE SENSITIVITY AND THE ZERO**
- **POSSIBILITY TO PROVIDE THERMAL COMPENSATION FOR THE STRUCTURES TO BE MEASURED**
- **RUGGED DESIGN OF THE TRANSDUCER AND THE FIBER-OPTIC CABLE**
- **SIGNAL FROM THE TRANSDUCER CAN BE TRANSMITTED OVER LONG DISTANCE TO THE CONDITIONER WITHOUT THE NEED OF LINE AMPLIFIERS**
- **EASY INSTALLATION AND MAINTENANCE WITH NO ENERGIZING AC VOLTAGE OR DRIVING SIGNAL REQUIRED**

**PRODUCT Datasheet**

**UMI Signal Conditioner**

The UMI is a tabletop, universal fiber-optic signal conditioner ideally suited to performing multi-point temperature, pressure, strain, and displacement measurements in applications that are hostile to non-fiber-optic transducers.

FISO's fiber-optic temperature, pressure, strain and displacement transducers feature complete immunity to microwave and RF radiation with high temperature operating capability, intrinsic safety, and non-invasive use. The UMI conditioner is designed to perform accurate multi-channel measurements. The system can scan through all the channels in use with a switching time of 0.15 s, or sample one specific channel at a rate of 20 Hz. All operational parameters are easily programmable using the front panel interface or through RS-232 remote control. A 7-digit gage factor affixed on the connector of each transducer allows the UMI conditioner to easily recognize the transducer type and calibration.

Through the use of a white light cross-correlator (U.S. Patents 5,392,117 and 5,292,939), the UMI conditioner is capable of measuring the absolute cavity length of FISO Technologies' Fabry-Perot fiber-optic transducers with astonishing accuracy, providing highly accurate and reliable measurements. The UMI has a 0.01% FS resolution (without averaging) and 0.025% FS precision.

The UMI conditioner has a non-volatile memory buffer that can store up to 50,000 data samples. Data logging sequences, duration and other operational parameters are easily programmable using the front panel interface or through RS-232 remote control. Each channel has a dedicated 8-bit A/D converter and the use of a Flash EEPROM allows the customer to easily upgrade the firmware.
1. Optimization of the shrinkage behaviour of cementitious materials at very early ages
   (Measurement of autogenous deformations at very ages)

Research project in cooperation with TU of Berlin, Civil Engg.

Objectives:

- Minimising cement paste shrinkage to avoid micro crack initiation

- Measurement of deformations of different hydrating cementitious materials already at the beginning of settlement process
  (in fluid cement suspension)

- Optimising the behaviour of grout deformation and self-compacting concrete mixtures

Solution:

Using movable FFPI
Preparation of the test specimen

$r = 1\ \text{mm}$

$r = 2.5\ \text{mm}$

S1 S2 S3 S4
Use of fibre Fabry-Pérot interferometer sensors to optimise the swelling behaviour of grouts
Use of fibre Fabry-Pérot interferometer sensors to optimise the swelling behaviour of grouts

2. Investigation of textile-reinforced concrete components

Research cooperation with TU of Aachen, Civil Engg.
Application Examples

Objectives:

- Investigation of the bonding behaviour of textiles in concrete

- Measurement of deformation strands embedded in the concrete matrix when concrete member is deformed

- Evaluation of the strain distribution between outer (sleeve) and inner (core) filaments in the concrete matrix

- Estimation of load-bearing capacity of newly developed textile-reinforced components

Solution:
Using movable FFPI
Embedment of flexible (movable) micro strain sensors into the textile reinforcement

Benefit of movable Fabry-Pérot sensors?

Movable sensors do not hinder the measuring object

Tiny sensor dimension enable application onto the filaments
Tests

Test specimen

Tensile test

Data recording
**Test results**

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**Graph Description:***

- **Y-axis:** Force [N]
- **X-axis:** Strain [µm/m]

- **Lines:**
  - Triangle: Matrix e = 3 mm
  - Square: Matrix e = 5 mm
  - Diamond: Roving

- **Annotations:**
  - Left and Right labels

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**Source:** Proc. of the SPIE vol. 4694(2002), 253-258.
Interpretation of the test results

- Measured values
- Load step 150 N
- Load step 200 N
- Development length 8 mm
- Change to friction bond
- Adhesive bond
- Roving
- Matrix e=3 mm
- Matrix e=5 mm
Application Examples

3. Investigation of the stability of a newly developed precast concrete track for high speed railway traffic

Research project in cooperation with Deutsche Bahn AG

- Precast plate
- Bitumen-cement layer
- Asphalt concrete
- Upper sensor frame
- Bottom sensor frame
- Sensors
Sensor Frame (inner view)

Details
Application of the Bragg grating sensors on tiny clips

Application of the EFPI sensors
Installation of the Sensor Frame

Position and casting of bottom sensor frame monitored by a camera
Installation of the Sensor Frame
Measurements at the IC-rail (Husum-Niebüll)

- Positioning of the sensor frame
- Fibre cable to PC in the trackwalker cabin
- Feste Fahrbahn (System Bögl)
Measurements at the IC-rail (Husum-Niebüll)

Positioning of the sensor frame

Cable to PC in the walker cabin
Measurements at the IC-rail (Husum-Niebüll)

Loading: IC train with two engines and nine wagons (service load: 80 t, axle load 20.3 t)
Train velocity: approx. 115 km/h

Temporary measurement facility in trackwalker cabin
Source: Proc. of the 3rd World Conf. on Structural Control in Como/Italy 2002.
Case 1: Engines did not reach meas. position

Case 2: 1. Rail couple of the 1. leading bogie (LB) is above the measurement position (MP)
4. Evaluation of strain distribution in the inner part of complex elastomeric components

Research project in cooperation with Bauhaus-Universität Weimar

Objectives:

- Improvement of theoretical models by experimental investigations
- Improvement of design rules for elastomeric components for use in Civil Engineering

Solution:
Using movable FFPI
Investigation of elastomeric materials

Sensor

and steps to instrument the elastomeric body
5. Fibre optic diaphragm gauge for pressure heads

In cooperation with Glötzl GmbH, Rheinstetten/Germany

Objectives:

- Lightning-safe scanning of the deflection of a circular diaphragm inside a pressure head used for stress transducers in geotechnics
Objectives:

- Lightning-safe scanning of the deflection of a circular diaphragm inside a pressure head used for stress transducers
- No stress-induced reaction to the diaphragm
- Long-term reliable and precise measurement (> 25 a)
- Ability to calibrate the sensor after years
- Exclusively fibre optic data transmission from sensor to control station

Solution:

Development of a highly resolvable scanning head with the possibility of pneumatic calibration
Requirements

- High resolution of diaphragm deflection (≤ 1 µm)

- Reproducibility of measurement values better than 2 %

- Ability to calibrate the sensor after installation and after years of service

- Referencing the measurement data to initial data
  (to avoid a lost of zero-point reference, that means: mastery of drift, hysteresis, ageing, …)
Measuring head with zero-point detection

- Trigger interferometer
- Diaphragm
- Springing element
- Meas. interferometer
- Launching fibre
- Connection to auxiliary Energy (presurred air)
- Spring cylinder
- Second fibre
Calibration cycles

Kalibriertest III (19.01.04)

Bearbeiter: J. Schneider-Glötzl
Umgebungstemperatur: 18,5°C
Luftdruck: 1009 mbar

Messwert [µm] m

2' versetzte Messung (Belastungsast)
2' versetzte Messung (Entlastungsast)
Long-term stability test under maximum pressure (1.000 bar)

Drifterscheinungen im Dauerbelastungstest

Durchführung: 19.01.04 12:00 bis 22.01.04 9:50
Bearbeiter: Rainer Glötzl
Umgebungstemperatur: 18,8°C - 20,8°C
Luftdruck: 1009 - 1017 mbar

6. Acoustic emission measurement on concrete tubes constructed from single segments

Research project in cooperation with TU of Berlin, Civil Engg., supported by DFG

Objectives:
Detection of damage on the back of concrete elements

Solution:
Development of a highly sensitive acoustic detector (stethoscope) based on a Fabry-Pérot cavity
Subterranean concrete tube for high voltage power cables

Vacuum-fixed sensor
7. Acoustic emission measurement on concrete piles

Research project in cooperation with TU of Braunschweig, Soil Mechanics

Damage while pile is constructed
German research project (8 partners)

Einleitend reflektiertes Signal

Charakteristische Linien

Zeit \( t \)

Reflexion am Pfahlfuß

\[ V(t) \]

\[ X \]

\[ \frac{dx}{dt} \]

Stoßwelle

freies Ende

PIT-Collector

\[ \rho \]

\[ \frac{c_D}{\rho} \]

\[ L_{\text{vorhanden}} = c_D \cdot \text{geschätzt} \cdot \frac{t_{\text{gemessen}}}{2} \]

\[ c_D = \sqrt{\frac{E}{\rho}} \]

\[ t_{\text{gemessen}} = 2 \cdot L_{\text{vorhanden}} / c_D \cdot \text{geschätzt} \]
Reliability aspects

Facility for calibration of fiber optic strain gauges

Facility for calibration of fiber optic strain gauges
Facility for calibration of strain gauges and deformation meters
Summary

- FFPI sensors have excellent potential static and dynamic strain resolution

- Apparent strain induced by thermal influences is small; FFPI sensors can be designed as temperature compensated ones (similar to resistive strain gauges)

- FFPI sensors can be designed as movable micro strain sensors (reaction-free measurement in materials with low Young’s moduli and in boundary zones)

- FFPI sensors are local sensors

- FFPI sensors are not intrinsically absolute sensors