Sensor Networks based on Optical Waveguide Sensors

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Introduction

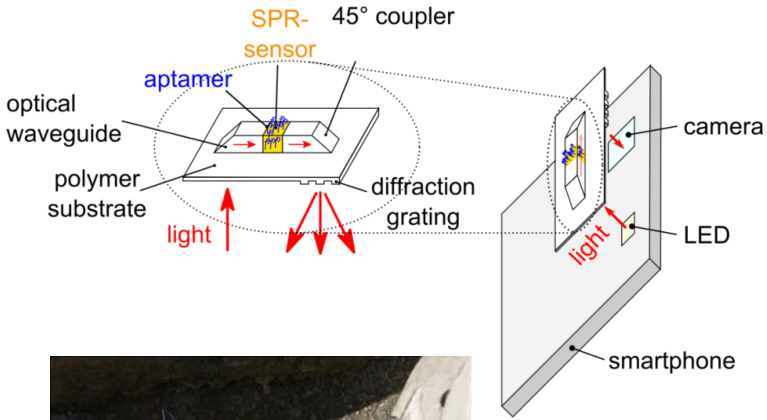
Components of an optical waveguide sensor:

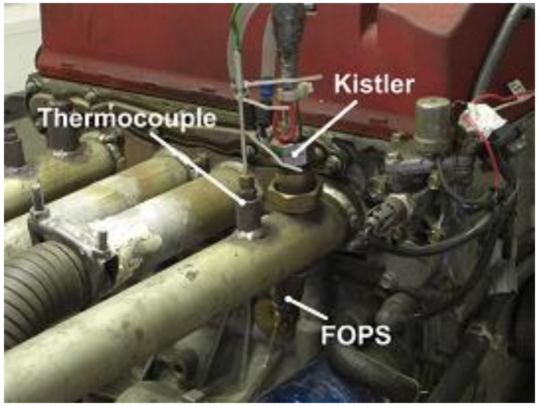
- Optical waveguide
- Light source & light detector
- Optical sensor element

Introduction

Applications:

- Structural Health Monitoring (SHM)
  - Civil engineering structures
  - Geothermal wells
  - Power transmission lines
  - Railways
- Point-of-Care Testing (POCT)
  - Biomarker detection
- Analytic
  - Environmental
  - Food chemistry





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Content

- Optical waveguides
- Sensor concepts
- Multiplexing approaches
- Summary

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Optical waveguide

Principle of Operation

- Total internal reflection (TIR)
- Photonic Crystal
- Plasmonics
- Metamaterial

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Optical waveguide

Background

- Total internal reflection (TIR)
- Requirement: $n_{clad} < n_{core}$
- Numerical aperture specifies angle of incident

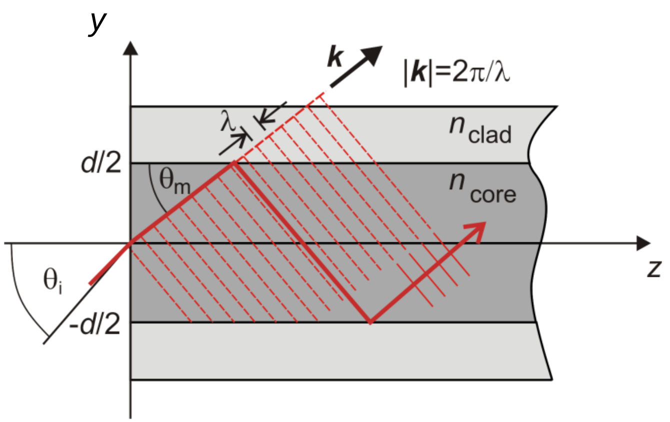
$$\mathrm{NA} = \sqrt{n_{\mathrm{core}}^2 - n_{\mathrm{clad}}^2} = \sin(\theta_i)\,.$$

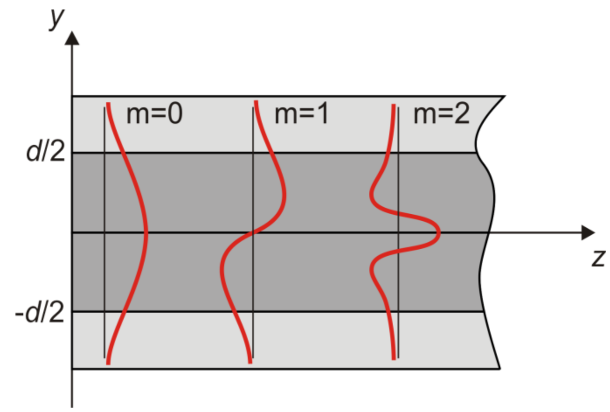
- Discrete angles of propagation = modes

$$\beta_m = n_1 k_0 \cos\theta_m$$

- Number of waveguide modes

$$M = \lceil 2d\frac{\sin\theta_c}{\lambda}\rceil = \lceil 2\frac{d}{\lambda}\mathrm{NA}\,\rceil$$





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Optical waveguide

Background

- Attenuation
  - Impurities
  - Absorption
  - Rayleigh scattering

- Dispersion
  - Material dispersion
  - Chromatic dispersion
  - Polarization dispersion
  - Mode dispersion

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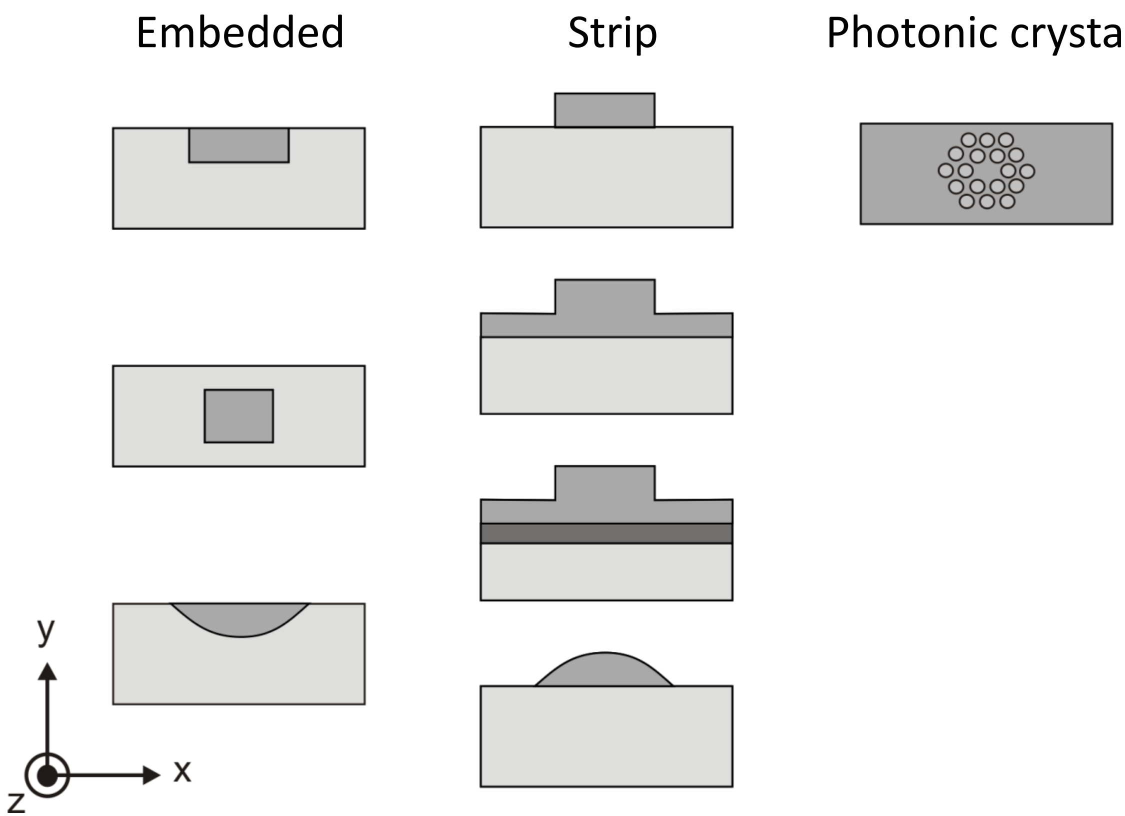
Optical waveguide

Different waveguide cross-sections/geometries (exemplary)



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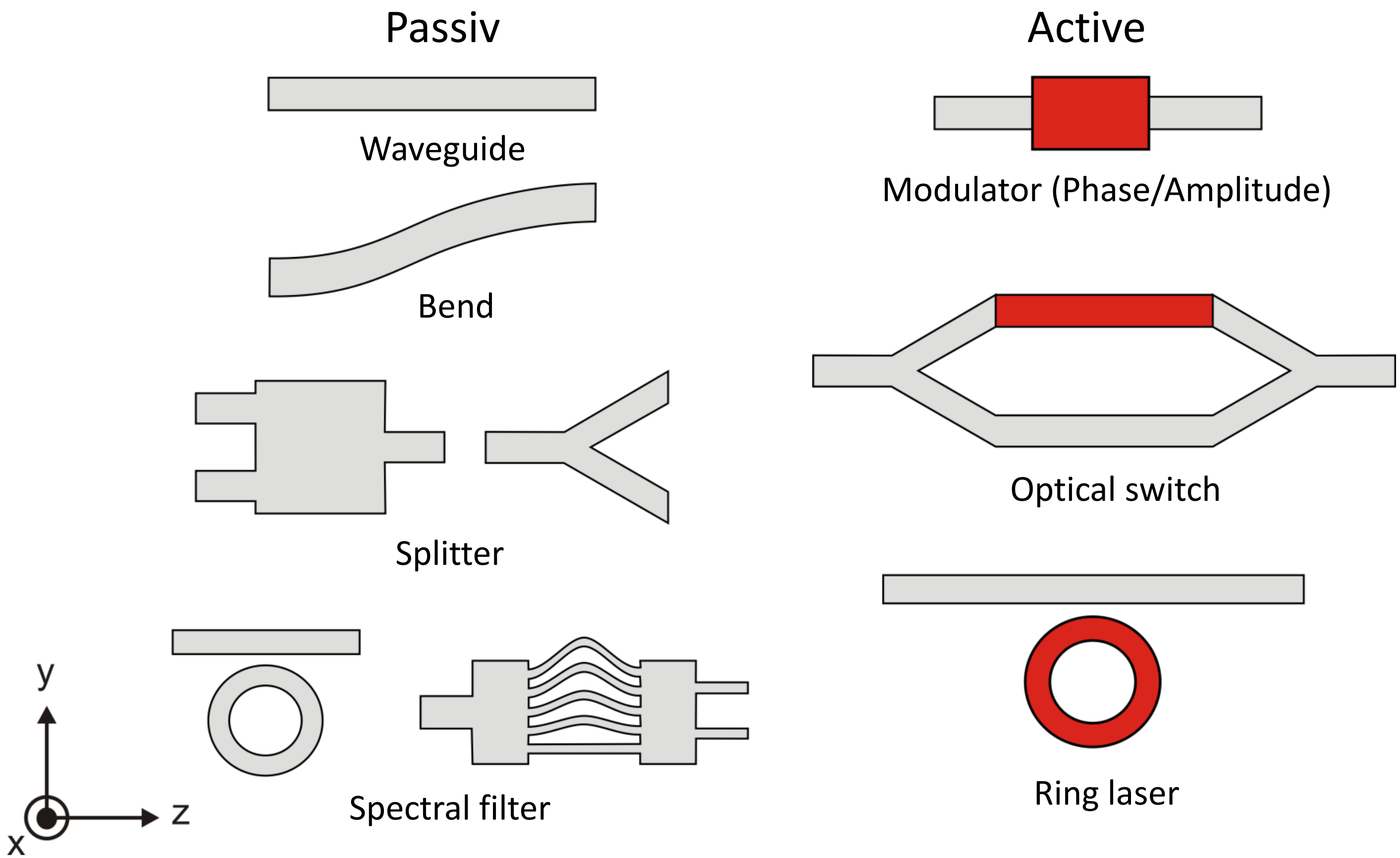
Optical waveguide

Photonic components (exemplary)



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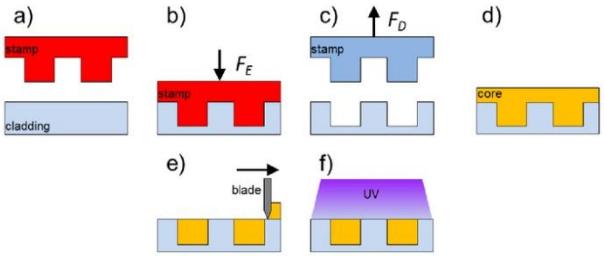
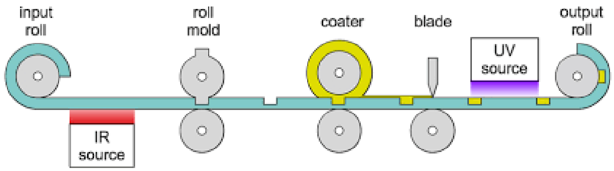
Optical waveguide

Fabrication methods

- Optical fibers
  - Draw tower (Glass and polymer fibers)
  - Extruder (Polymer fibers)



- Integrated waveguides
  - Micro/Nanoreplication
  - Photolithography
  - Laser inscription
  - Printing



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Sensors

Sensor concepts

- Intensity
- Polarisation
- Phase (Interferometric)
- Spectral
- Resonant
- Scattering

Application

- Physical quantities
  - Strain
  - Pressure
  - Shape
  - Temperature
- Chemical quantities
  - Absorption
  - Fluorescents
  - Refractive index (RI)

Sensor concepts – Intensity based

Intensity modulated sensors

- External perturbations modulate light intensity inside optical waveguide

- Displacement sensing:
  - Two optical waveguides in close proximity

  ⇒ Amount of light captured by the second fiber depends on the NA and distance d

- Pressure sensing:
  - Bending optical fiber by diaphragm
  - Optical fiber between two corrugated plates

  ⇒ Bending/Microbending introduces light losses

Sensor concepts – Intensity based

Intensity modulated sensors

- Light intensity of optical waveguide interacts with surrounding (absorption spectroscopy)

- Cavity based sensor:
  - Two optical waveguides separated by cavity
  - ⇒ Light inside the cavity is absorbed by the surrounding medium

- Evanescent field:
  - Evanescent field of light inside the optical waveguide interacts with surrounding
  - ⇒ Evanescent light is absorbed by the surrounding medium

Sensor concepts – Polarisation based

Polarization modulated sensors

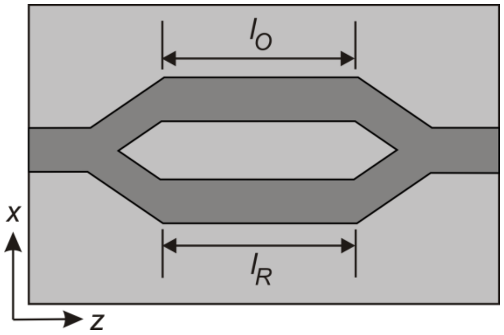
- External perturbations induce birefringence
  - Change of the refractive index due to elasto-optic effect
  - ⇒ Change of the light polarization state

- Magnetic field sensor (Faraday-effect)
  - Faraday-rotation of light is proportional to line integral of the magnetic field
  - ⇒ Plane of polarization changes with applied current

Sensors concepts – Interferometry based

Mach-Zehnder interferometer (MZI)

- Splitting an optical waveguide into an object and reference arm



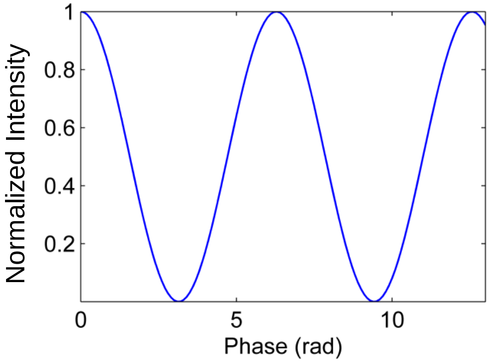
- Creating light interference by recombining both waveguide arms

  ⇒ Phase difference

$$\Delta\varphi = k \cdot \Delta n \cdot l_O$$

  ⇒ Light intensity modulation

$$I_{out} = I_R^2 + I_O^2 + 2\sqrt{I_R I_O} \cdot \cos(\Delta\varphi)$$



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Sensor concepts – Interferometry based

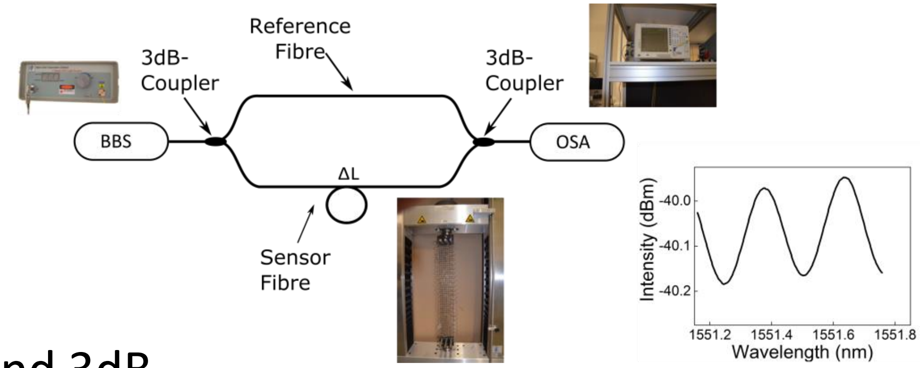
Fiber optic MZI sensor

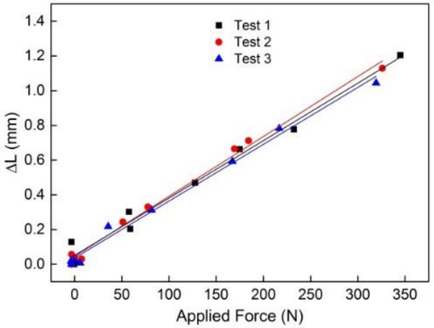
- Application:
  Strain/Force sensing

- Optical waveguide:
  Single-mode fibers

- Fabrication:
  Fusion splicing of optical fibers and 3dB-couplers

- Sensitivity:
  0.0033 mm/N (± 1.4 %)





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Sensor concepts – Interferometry based

Asymmetric optical waveguide MZI

- Application:
  Displacement sensing
  N. Zhao, Opt. Engineering 56(2), 027109 (2017)

- Optical waveguide:
  Single-mode strip waveguide

- Fabrication:
  Photolithography & Spin coating
  - Cladding: NOA61 (n = 1.54)
  - Core: SU-8 (n = 1.57)

- Sensitivity: 0.105 rad/µm

Sensor concepts – Interferometry based

Bimodal optical waveguide interferometer

- Applications:
  Point-of-care diagnostics
  Gavela *et al.*, Sensors 16, 285 (2016)

- Optical waveguide:
  Single-mode rib waveguide

- Fabrication:
  Photolithography
  - Layer 1: Silicon oxide (cladding)
  - Layer 2: Silicon nitride (core)
  - Layer 3: Silicon oxide (cladding)

- Sensitivity: $3.3 \cdot 10^{-7}$ RIU

Sensor concepts – Interferometry based

Fabry-Perot Interferometer (FPI)

- Two mirrors of reflectance R_1 and R_2 are separated by a cavity of length L

- Light interference due to optical path difference

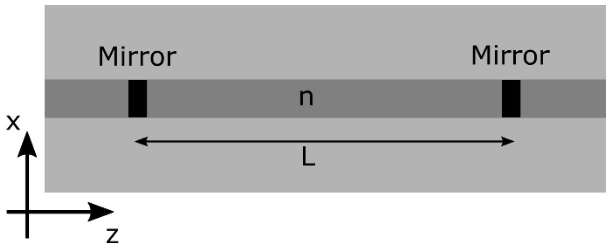
  ⇒ Phase difference

$$\Delta\varphi = 2 \cdot k \cdot n \cdot L$$

  ⇒ Light intensity modulation

$$\frac{I_R}{I_0} = \frac{R_1 + R_2 + 2\sqrt{R_1 R_2}\cos(\Delta\varphi)}{1 + R_1 R_2 + 2\sqrt{R_1 R_2}\cos(\Delta\varphi)}$$

$$\frac{I_T}{I_0} = \frac{T_1 T_2}{1 + R_1 R_2 + 2\sqrt{R_1 R_2}\cos(\Delta\varphi)}$$



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Sensor concepts – Interferometry based

Example: Fiber optic FPI sensor

- Application:
  Pressure sensing
  Hill *et al.*, Sens. Actuators, A 138, 52 (2007)

- Optical Waveguide:
  Single-mode optical fiber

- Fabrication:
  Photolithography & Spin Coating

- Sensitivity:
  1-2 mmHg (= approx. 1,3 mbar)
  (Linear range: 0 – 125 mmHg)

Sensor concepts – Spectral based

Optical waveguides with gratings

- Periodic refractive index modulation of optical waveguide core

i. Counter-propagating coupling (Bragg wavelength)

$$\lambda_B = 2\, n_{eff}\, \Lambda$$

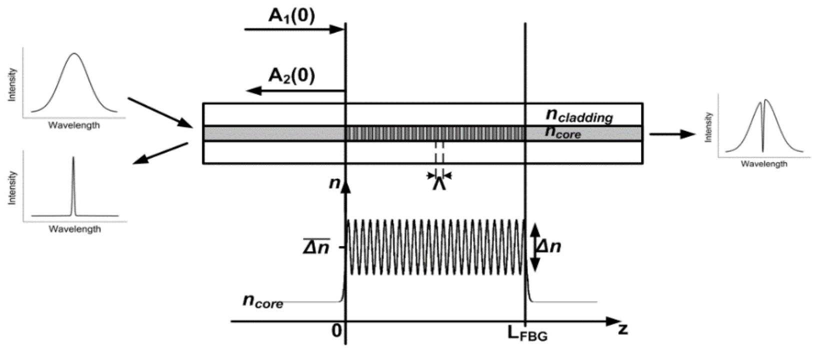
ii. Co-propagating coupling

$$\lambda_R = (n_{eff,Core} - n_{eff,Cladding})\Lambda$$

- Λ and n_{eff} are sensitive to external influences (strain, temperature and RI)

$\Rightarrow$ Shifting coupling wavelength

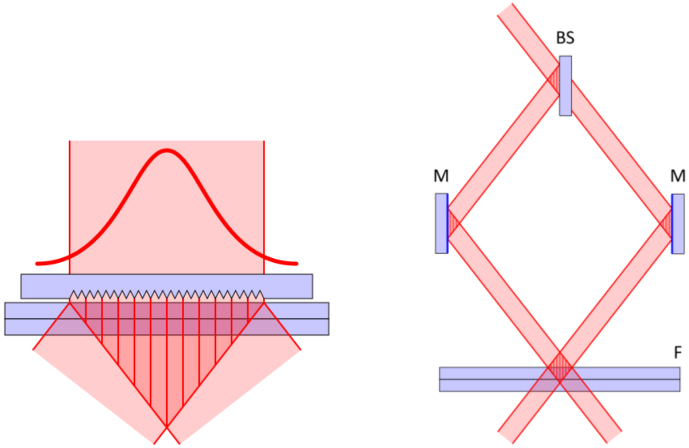
Counter-propagating



Sensor concepts – Spectral based

Fiber Bragg Grating (FBG)

- Application:
  Strain and temperature sensing
- Optical waveguide:
  Single mode optical fibers
- Fabrication techniques:
  - Point-by-point (fs-laser)
  - Phase mask (e.g. KrF excimer laser)
  - Mach-Zehnder Interferometer
- Sensitivity:
  (example Micron Optics os4100 and os3100)
  - 28.9 pm/˚C (os4100)
  - 1.4 pm/µε (os3100)



Phasemask   Mach-Zehnder

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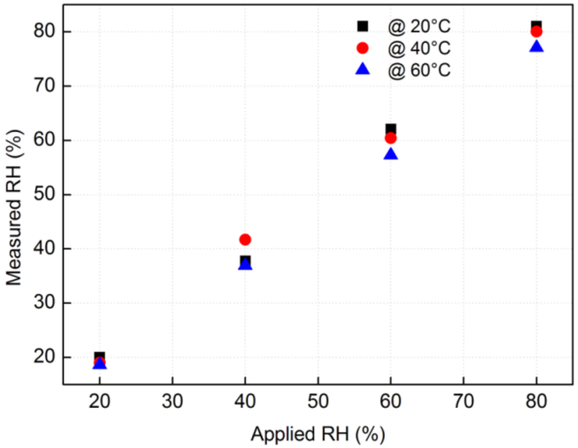
Sensor concepts – Spectral based

Fiber Bragg Grating (FBG)

- Application:
  Relative humidity (RH) sensing
- Optical waveguide:
  Single mode optical fiber
- Fabrication:
  - FBG:
    Phase mask and KrF excimer laser
  - Polyimide (PI) coating:
    Dip coating
- Sensitivity:
  0.01 nm/%RH



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Sensor concepts – Spectral based

Long period grating (LPG)

- Application:
  Refractive index (RI) sensing
- Optical waveguide:
  Single mode optical fiber
- Fabrication:
  - Amplitude mask (e.g. KrF excimer laser)
  - Point-by-point
    (fs-Laser, CO_2-Laser, splicer, etc.)
  - Microbender

Sensor concepts – Resonance based

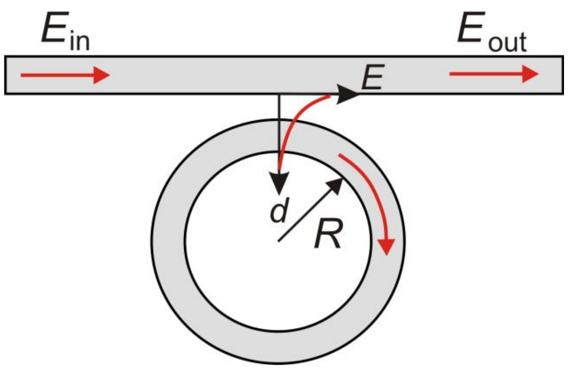
Ring Resonator

- Evanescent light coupling between waveguide and ring structure
- Circumference of ring must be an integer multiple of the light wavelength (constructive interference)
- Sensing of refractive index of the surrounding
- Characteristic parameters
  - Free spectral range

$$\Delta\nu = \frac{c}{2\pi R}$$

  - Quality factor

$$Q = \frac{\Delta\nu}{\delta\nu}$$



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Sensor concepts – Resonance based

Surface Plasmon Resonance (SPR)

- Resonant oscillation of electrons at metal/dielectric interface stimulated by incident light

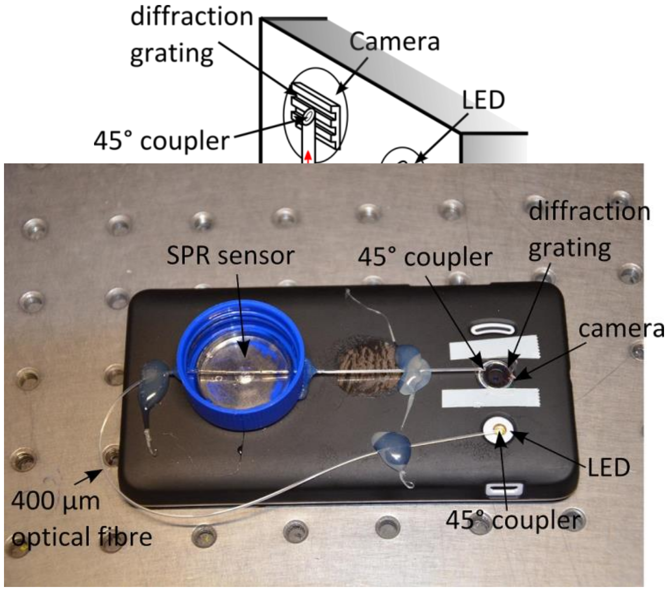
- Advantage:
  - Surface wave
  - ⇒ Strong interaction with surrounding medium

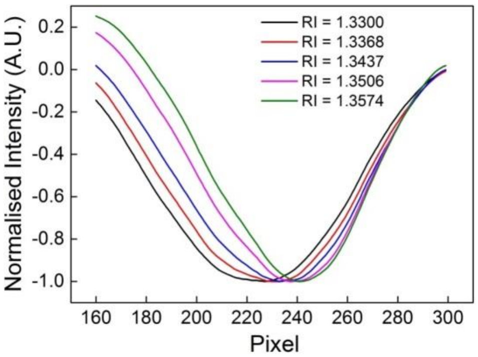
- Investigation of biomolecule interaction
  - Label free
  - Real time
  - Quantitative

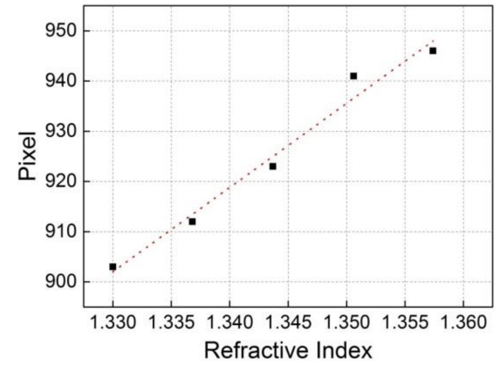
Sensor concepts – Resonance based

Fibre optic SPR sensor for Smartphones

- Application:
  Refractive index sensing
- Optical waveguide:
  Plastic cladded silica (PCS) multi-mode fiber
- Fabrication:
  - Silver coating of fiber core
  - 45˚ polishing fiber end-faces
- Sensitivity:
  $5.96 \cdot 10^{-4}$ RIU/pixel







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Sensor concepts – Scattering based

Silica optical glass fibers

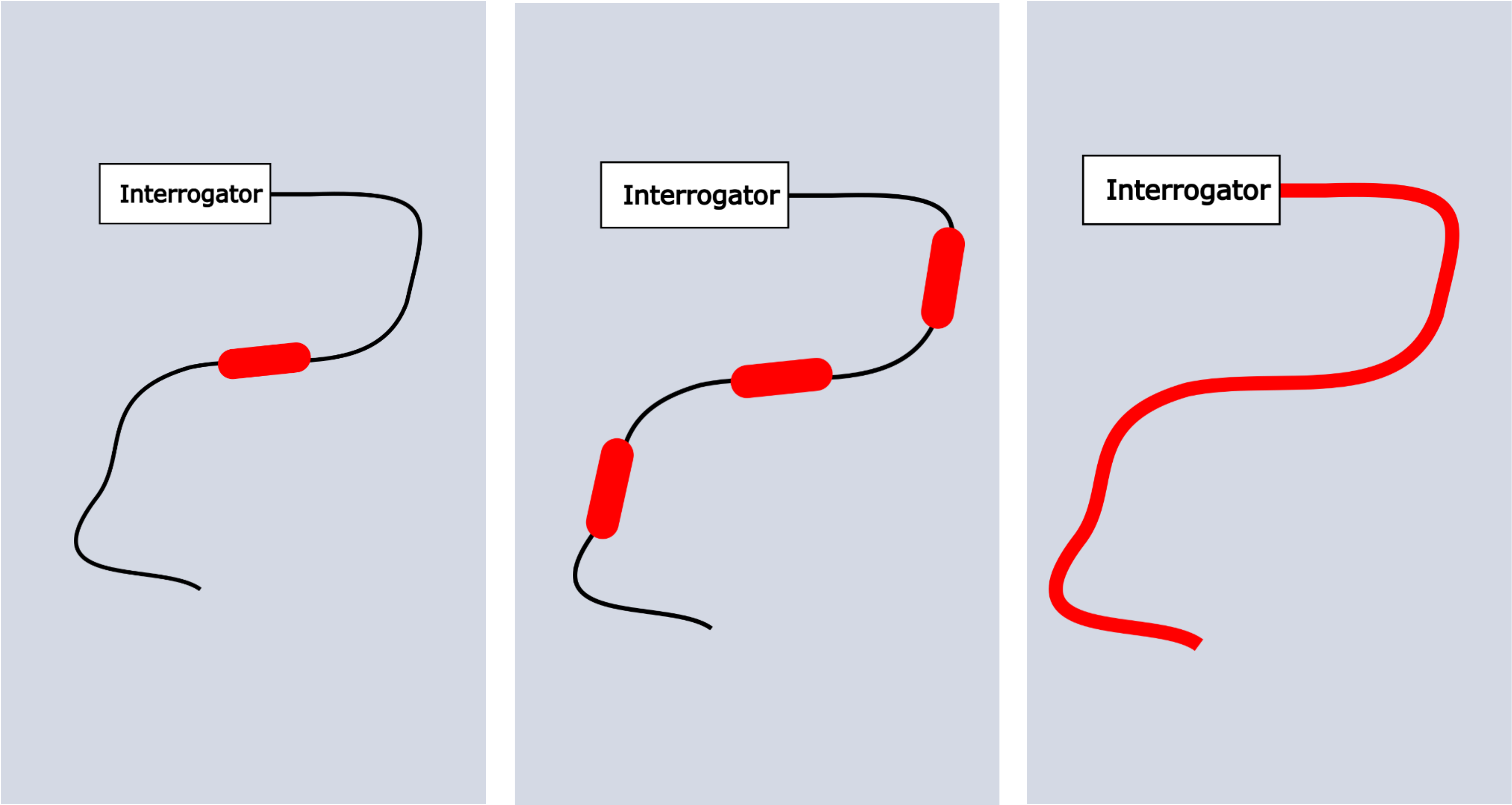
- Rayleigh scattering
  - Scattering due to density and composition fluctuations in the glass fiber
  - Elastic scattering
- Raman scattering
  - Molecular vibration of glass causes light to be scattered
  - Inelastic scattering
- Brillouin scattering
  - Light scattering from the collective acoustic oscillations of the glass
  - Inelastic scattering

Content

- Optical waveguides
- Sensor concepts
- Multiplexing approaches
- Summary

Multiplexing optical waveguide sensors

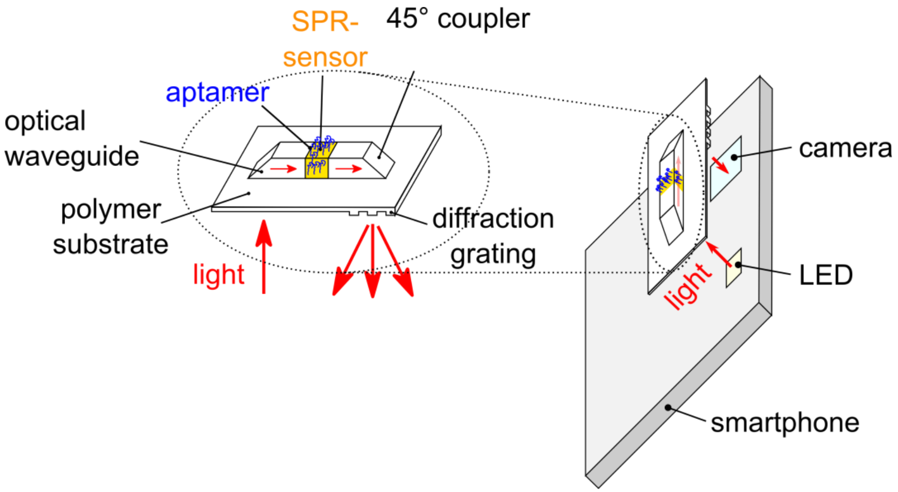
Single-Point | **Quasi-distributed** | **Distributed**



Multiplexing – Single-Point

Sensor multiplexing

- One light source and light detector per optical waveguide sensor
- Optical waveguide:
  Only acting as sensor element
- Multiplexing approaches
  - Optical:
    Space Division Multiplexing (SDM)
    Time Division Multiplexing (TDM)
    Wavelength Division Multiplexing (WDM)
  - Electrical:
    Wireless sensor networks, etc.



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Multiplexing – Single-Point

Example ring resonator based sensor network

- Space and time division multiplexing
  Iqbal *et al.*, IEEE J. Sel. Topics Quantum Electron. 16(3), 654 (2010)

- Several ring resonators are spatially separated (SDM)
- Interrogating ring resonators successively using on interrogator (TDM)
- Application:
  - Point-of-Care (POC) Diagnostic

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Multiplexing – Single-Point

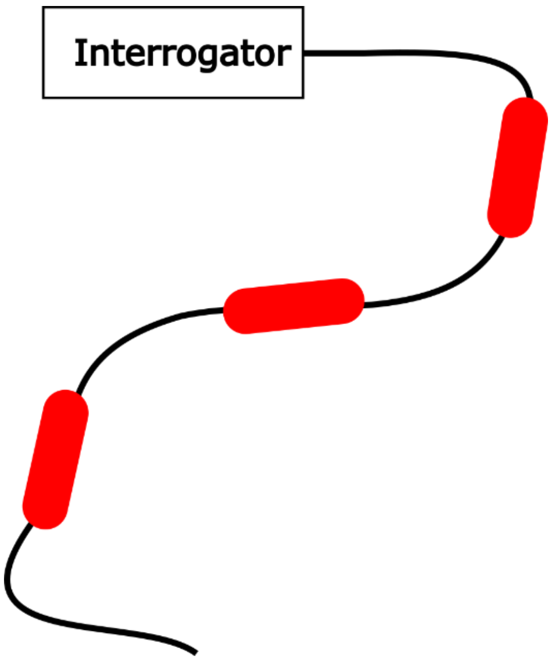
Radio-over-Fiber (RoF) based multiplexing

- RoF: Electrical carrier signal is transmitted over optical fiber
  Neumann *et al.*, Proc. of SPIE Vol. 927, 927402-2 (2014)
- Optical fiber transmission link contains optical fiber sensor element
- Quantities measured are transmitted and evaluated off-site
- Application:
  - Structural Health Monitoring:
    Strain, temperature, humidity, etc.
  - Process control:
    Refractive index, etc.

Multiplexing – Quasi-Distributed

Sensor multiplexing

- Several optical waveguide sensors per light source and light detector
- Optical waveguide:
  Optical transmission link and hosting discrete optical sensor element
- Multiplexing approaches:
  - Optical
    TDM, WDM, SDM
  - Electrical
    Wireless sensor networks



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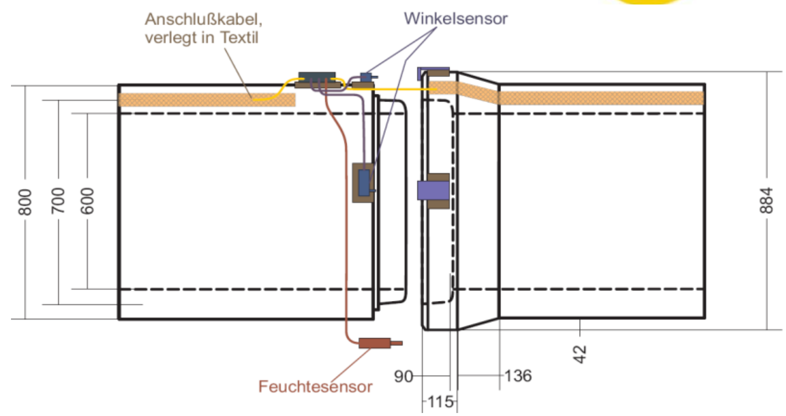
ZIM Zentrales Innovationsprogramm Mittelstand

Multiplexing – Quasi-Distributed

Example FBG based sensor network

- Wavelength Division Multiplexing (WDM) and Time Division Multiplexing (TDM)
- Multiplexing of FBG by applying different Bragg wavelength (WDM)
- Pulsed laser and fiber loop (time delay) between FBG sensors with equal Bragg wavelength (TDM)
- Application:
  - Structural Health Monitoring (SHM) of sewerage tunnels (Humidity and tilt)



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Multiplexing – Quasi-Distributed

Example FBG based sensor network

- Wavelength Division Multiplexing (WDM) and Spatial Division Multiplexing (SDM)

- Applying multi-core optical fiber for spatial separation (SDM)

- Multiplexing of FBG by applying different Bragg wavelength (WDM)

- Application:
  - Shape sensing

Multiplexing – Quasi-Distributed

Example: Fiber optic FPI sensor

- Application:
  Pressure and refractive index sensing
  Pevec *et al.*, Optics Letters 39(21), 2014

- Optical Waveguide:
  Single-mode optical fiber

- Fabrication:
  Splicing, polishing and etching

- Sensitivity:
  0.2 mbar and $2 \cdot 10^{-5}$ RIU

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Multiplexing – Quasi-Distributed

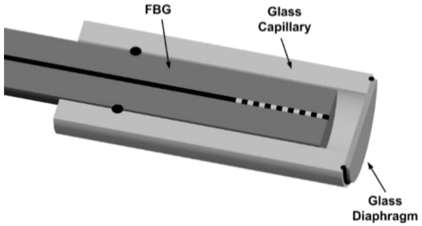
Fiber optic FPI and FBG sensor

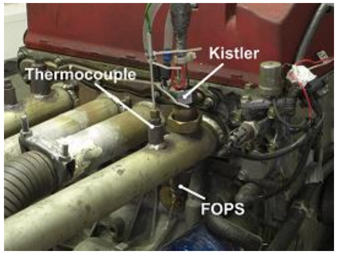
- Application:
  Pressure and temperature sensing

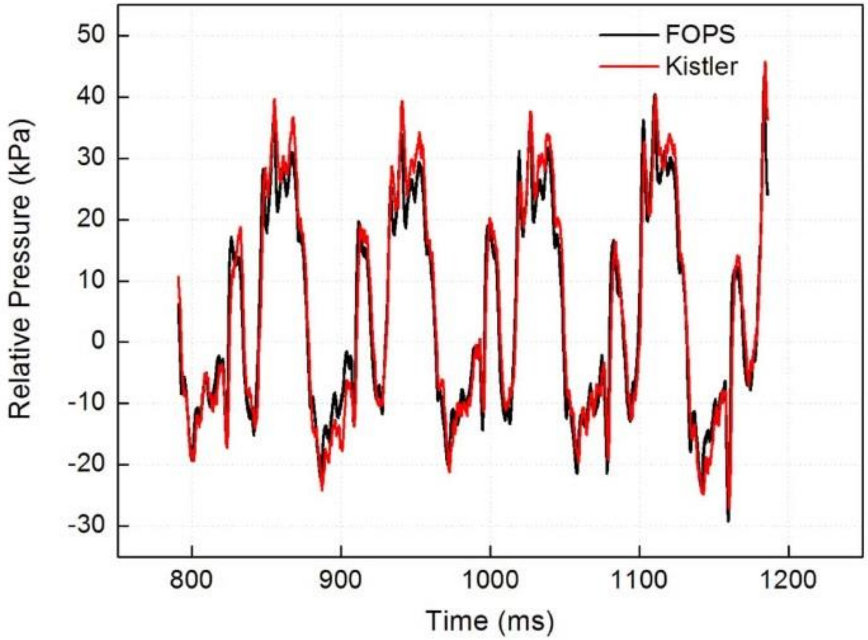
- Optical waveguide:
  Single-mode fiber with FBG

- Fabrication:
  Splicing, polishing and etching

- Sensitivity:
  4.4 nm/kPa
  (temperature ≤ 400 ° C)







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Multiplexing – Distributed

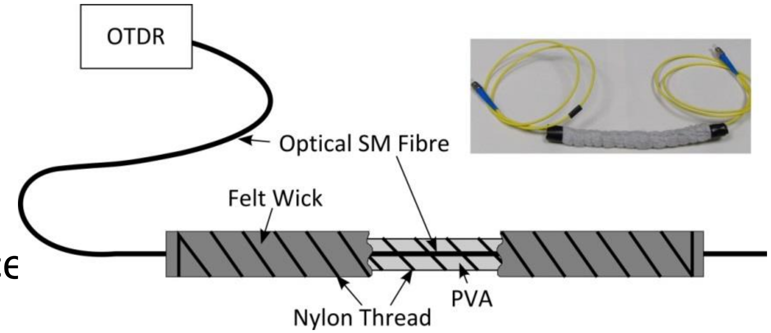
Rayleigh scattering

- Elastic scattering of light by particles much smaller than the wavelength
- In silica fibers microscopic variations of density and refractive index cause Rayleigh scattering
- Energy losses ~ λ^{-4}
- Distributed sensing approaches:
  - Optical Time Domain Reflectometry (OTDR)
  - Optical Frequency Domain Reflectometry (OFDR)

Multiplexing – Distributed

Optical Time Domain Reflectometry (OTDR)

- Principle of operation
  - Coupling light pulse into optical fiber
  - Detecting reflected light due to Rayleigh scattering or e.g. interconnection and splice
  - Strength of returned light is measured as a function of time
  - ⇒ Calculating the spatial attenuation profile
- Application examples:
  - Distributed acoustic sensing
  - Distributed crack detection of building structures
  - Distributed leakage detection



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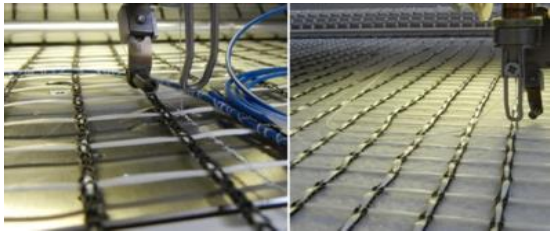

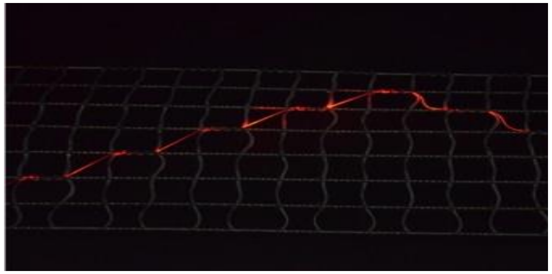

STFI

Multiplexing – Distributed

Optical Frequency Domain Reflectometry (OFDR)

- Principle of operation
  Soller *et al.*, Optics Epxress 13, 666 (2005)
  - Coupling light of a tunable laser into optical fiber
  - Detector contains interferometer
  - Detecting interference fringes
  - Calculating spatial "density" profile of fiber under test
- Applications examples:
  - Distributed strain and temperature sensing
  - Luna ODiSI-B:
    Sensor length: 10 m; Spatial resolution: 2.6 mm

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Multiplexing – Distributed

Raman Scattering

- Inelastic scattering of light
- Molecular vibration causes incident light to be scattered
- Producing stokes and anti-stroke emissions about the exciting wavelength
- Determining temperature by comparing the amplitudes of the Stokes and Anti-Stroke emissions

⇒ Distributed temperature sensing

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Multiplexing – Distributed

Raman Scattering

- Distributed temperature sensing

- Typical specifications:
  - Distance 30 km
  - Spatial resolution 5 cm to 4 m
  - Temperature sensitivity ± 0.1 K to 2 K

- Application examples:
  - Structural Health Monitoring (SHM)
  - Power transmission lines
  - Fire alarm system
  - Geothermal energy
  - Enhanced oil recovery

Multiplexing – Distributed

Brillouin Scattering

- Inelastic scattering of light
- Light scattering from the collective acoustic oscillations (acoustic phonons) of glass
- Maximum reflection when scattered light is in phase
- Temperature and strain modify the mean density and thus the velocity of sound

⇒ Distributed strain and temperature sensing

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Multiplexing – Distributed

Brillouin Scattering

- Distributed strain and temperature sensing

- Specifications (fibrisTerre fTB 2505):
  - Distance 25 km
  - Spatial resolution 0.5 m
  - Strain and temperature resolution 2με and 0.1 K

- Application examples:
  - Structural Health Monitoring (SHM)
    - Railways
    - Dikes
    - ...

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Summary

Optical waveguide sensors

+ Immune to EMI
+ Robust
+ Small in size
+ Remote operation

Applications

- Structural Health Monitoring (SHM)
- Analytic
- Point-of-Care

Sensor concepts

- Classification
  - Amplitude
  - Polarization
  - Phase
  - Spectral
  - Resonant
  - Scattering
- Multiplexing
  - Single-Point
  - Quasi-distributed
  - Distributed

Many thanks

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