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
Content

- Optical waveguides
- Sensor concepts
- Multiplexing approaches
- Summary
Content

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Optical waveguide

Principle of Operation

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

Background

- Total internal reflection (TIR)
- Requirement: \( n_{\text{clad}} < n_{\text{core}} \)
- Numerical aperture specifies angle of incident
  \[
  \text{NA} = \sqrt{n_{\text{core}}^2 - n_{\text{clad}}^2} = \sin(\theta_i) .
  \]
- Discrete angles of propagation = modes
  \[
  \beta_m = n_1 k_0 \cos \theta_m
  \]
- Number of waveguide modes
  \[
  M = \left\lceil 2d \frac{\sin \theta_c}{\lambda} \right\rceil = \left\lceil 2 \frac{d}{\lambda} \text{NA} \right\rceil
  \]

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Optical waveguide

Background

- Attenuation
  - Impurities
  - Absorption
  - Rayleigh scattering

- Dispersion
  - Material dispersion
  - Chromatic dispersion
  - Polarization dispersion
  - Mode dispersion
Optical waveguide

Different waveguide cross-sections/geometries (exemplary)

Embedded

Strip

Photonic crystal

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Optical waveguide

Photonic components (exemplary)

Passiv
- Waveguide
- Bend
- Splitter
- Spectral filter

Active
- Modulator (Phase/Amplitude)
- Optical switch
- Ring laser

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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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Content

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- Sensor concepts
- Multiplexing approaches
- Summary
## 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 %)
Sensor concepts – Interferometry based

Asymmetric optical waveguide MZI

- Application:
  Displacement sensing

- 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

- 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
  \[ \Rightarrow \text{Phase difference} \]
  \[ \Delta \varphi = 2 \cdot k \cdot n \cdot L \]
  \[ \Rightarrow \text{Light intensity modulation} \]

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

\[
\frac{I_T}{I_0} = \frac{T_1 T_2}{1 + R_1 R_2 + 2 \sqrt{R_1 R_2} \cos(\Delta \varphi)}
\]
Sensor concepts – Interferometry based

**Example: Fiber optic FPI sensor**

- **Application:**
  - Pressure sensing

- **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)
    \[ \lambda_B = 2 \ n_{\text{eff}} \ \Lambda \]
  - ii. Co-propagating coupling
    \[ \lambda_R = (n_{\text{eff,Core}} - n_{\text{eff,Cladding}}) \ \Lambda \]

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

  \( \Rightarrow \) Shifting coupling wavelength
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)
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
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
    \[ Q = \frac{\Delta \nu}{\delta \nu} \]
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:
  \(5.96 \cdot 10^{-4} \text{ RIU/pixel}\)
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
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Multiplexing optical waveguide sensors

Single-Point

Quasi-distributed

Distributed

Interrogator

Interrogator

Interrogator
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.
Multiplexing – Single-Point

Example ring resonator based sensor network

- Space and time division multiplexing

- Several ring resonators are spatially separated (SDM)

- Interrogating ring resonators successively using on interrogator (TDM)

- Application:
  - Point-of-Care (POC) Diagnostic
Multiplexing – Single-Point

Radio-over-Fiber (RoF) based multiplexing

- RoF: Electrical carrier signal is transmitted over optical fiber
- 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
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 2·10^{-5} RIU
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)
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 $\sim \lambda^{-4}$
- 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
Multiplexing – Distributed

Optical Frequency Domain Reflectometry (OFDR)

- Principle of operation
  Soller *et al.*, Optics Express 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
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
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
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

### Sensor concepts

- **Classification**
  - Amplitude
  - Polarization
  - Phase
  - Spectral
  - Resonant
  - Scattering

- **Multiplexing**
  - Single-Point
  - Quasi-distributed
  - Distributed

### Applications

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

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