Fiberoptic and Waveguide Sensors

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Optical sensors

- Advantages:

  -immune from electromagnetic field interference (EMI)

  - extreme high bandwidth capability

  - high sensitivity and high dynamic range

  - remote sensing

  - ability to be embedded under hostile environments

  - distributed and array sensors covering extensive structures and geographical locations

Fiber Optic Sensor Classification

A. Based on modulation and demodulation process of Sensor
   - intensity, phase, frequency, polarization etc.
B. Based on their applications.
   - physical, chemical, bio-medical, etc.
C. Extrinsic (sensing take place outside of fiber where, fiber only serve as conduit to transmit light to and from the sensing region) or intrinsic sensors (physical properties of the fiber undergo a change as mentioned in A above)

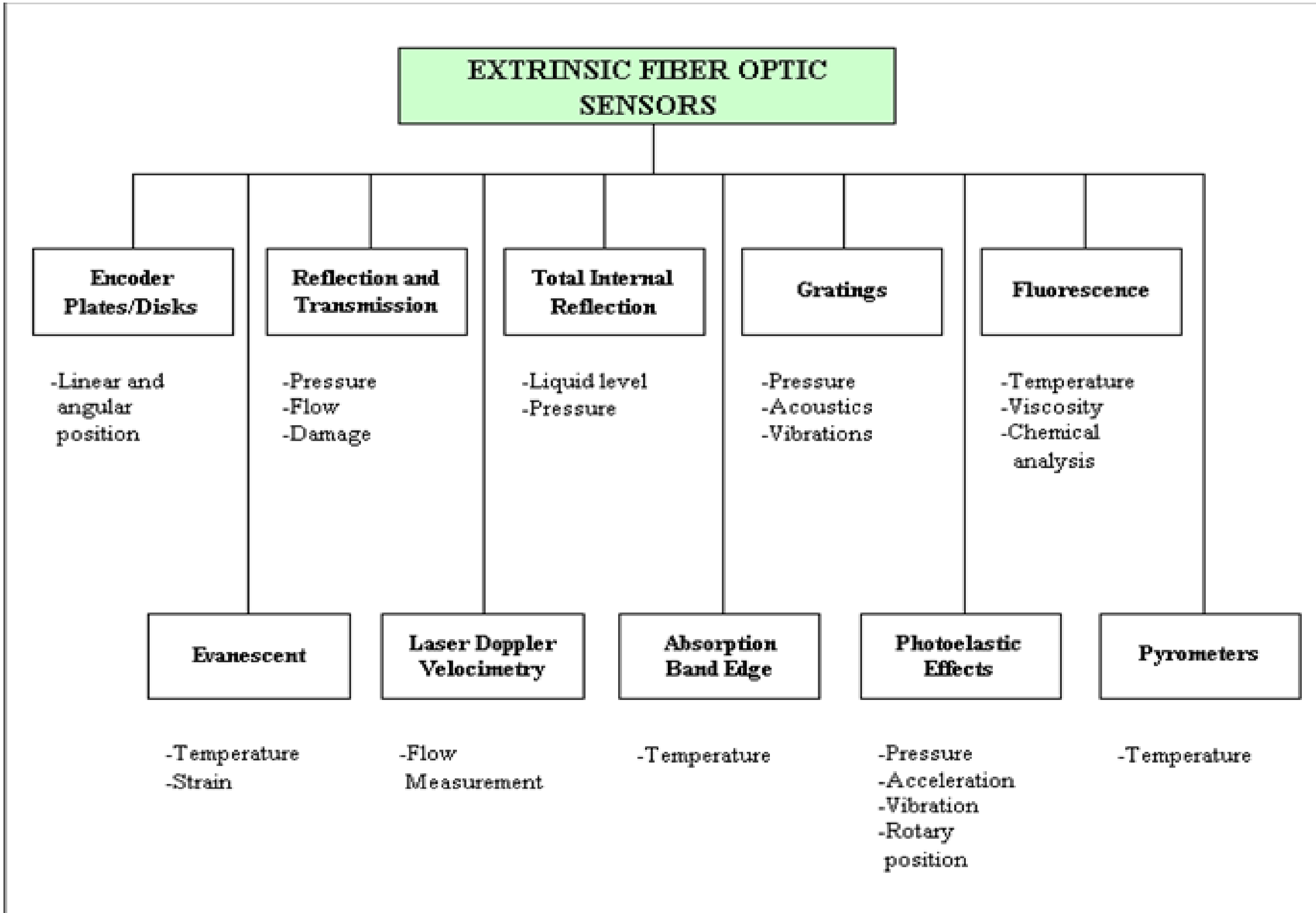
Industrial application

- Pressure
- Flow and viscosity
- Vibration
- Current-voltage
- Chemical
- Smart structure
- Accelerometer, gyroscope
- Acosutic- Microphone hydrophone
- Image acquisition

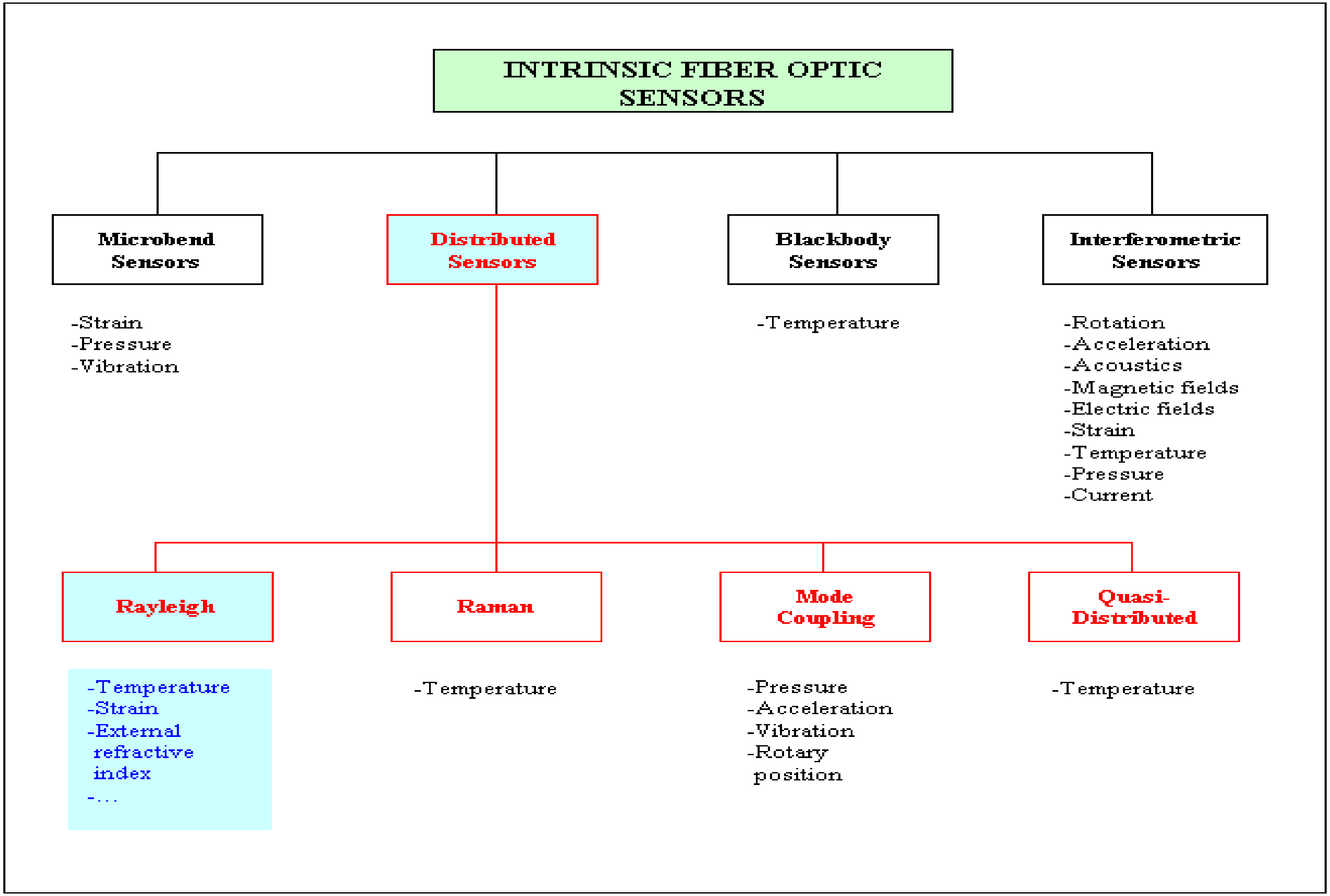
Other applications

1. Physical sensors for medical applications
   - endoscopes scanner and display
   - pressure sensor (cantilever, diaphragm)
   - blood velocity and flow
   - temperature sensor (non contact)
   - acoustic sensor
   - accelerometer (mechanical inertia, photoelastic, reflection-cantilever)
   - viscosity sensor
   - liquid level sensor
2. Chemical or biochemical sensors
   - glucose detector (viscosity)
   - gas or liquid concentration sensor (mass or viscosity)
   - surface reaction mass loading sensor (mass, viscosity or stiffness change)
   - humidity sensor (detect geometry change due to adsorption)

Extrinsic Optical Sensors



Intrinsic Fiber Optic Sensors



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Intrinsic distributed sensors are particularly attractive for use in applications where monitoring of a single measurand is required at a large number of points or continuously over the path of fiber. Examples of application areas include for example

- •Stress monitoring of a large structures such as buildings, bridges, storage tanks, and the like, and ships, oil platforms, aircraft spacecraft and so on
- •Temperature profiling in electrical power transformers, generators, reactor systems, furnaces, press control systems, and simple fire detection systems
- •Leakage detection systems in pipelines, fault diagnostics and detection of magnetic/electrical field anomalies in power distribution systems, and intrusion alarm systems
- •Embedded sensors in composite materials for use in the real-time evaluation of stress, vibration, and temperature in structures and shells, especially in aerospace industry

Techniques for Intrinsic Sensors

Phase modulation: interferometer, grating,
two mode, polarization

Intensity modulation: bend loss, discontinuity,
evanescent

Phase modulation

- Mach-Zehnder
- Michelson
- Fabry-Perot
- Sagnac

Other phase modulating sensors

- Dual mode fiber sensor
- Polarimetric
- Grating

Intensity Modulation Sensors

Macro Bend

Micro Bend

Evanescent

OTDR (impedance change)

Extrinsic Sensors

Discontinuity

Transmission and Reflection

Absorption

Scattering

Free from dispersion, beam alignment, beam divergence

Intensity (Amplitude) Sensors

In this case, the signal to be measured (the measurand), intensity (amplitude) modulates the light carried by an optical fiber. For this class of sensors a normalized modulation index (m) can be defined as

$$m = \Delta I / (I_0 P)$$

where, ΔI = change in optical power as a result of modulation by the measurand; I_0 = *optical power reaching the detector when there is no modulation; and P = perturbation (measurand).*

Intensity Sensors

The sensor response expressed as a differential voltage per unit change in measurand is given by

$$S = q I_0 R m$$

Where q = detector responsivity (A/W);
R = *load resistance.*
m= normalized modulation index

Limits on Performance

1. Signal voltage ~ noise voltage

The minimum measurable quantity in the shot noise limit is given by,

$i_d^2 = 2eBI_d$ "white noise"

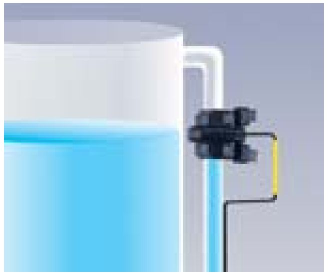
With light: $i_d^2 = 2eBI_p$

where e = electronic charge and B=detection bandwidth.

Proximity Sensor (extrinsic)

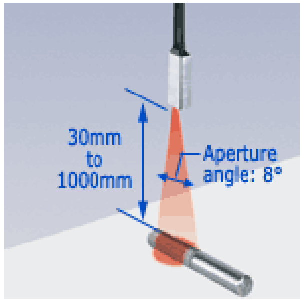
Liquid Level Sensors

Distance Detection

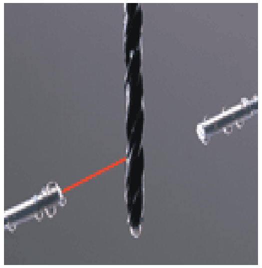


tube-mountable liquid level detection

immersion type liquid level detection



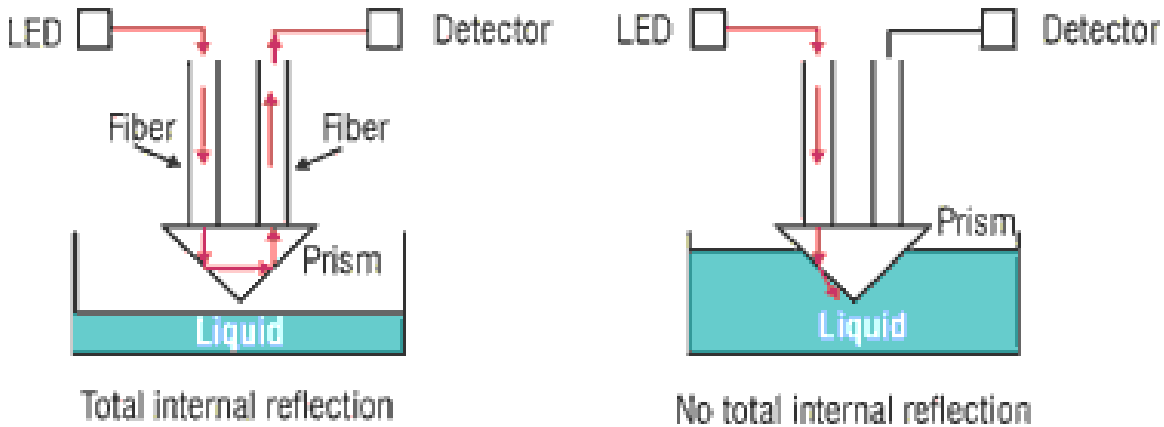
Reflective type



Transmissive type

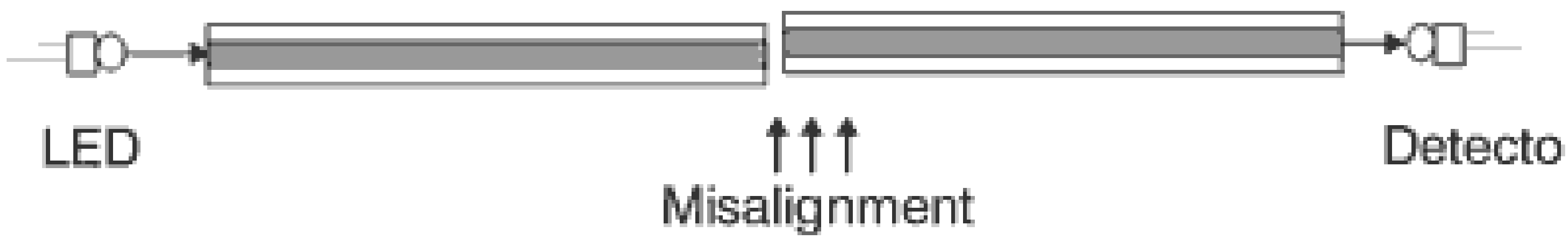
By KEYENCE CORPORATION OF AMERICA

Liquid level sensor (extrinsic)



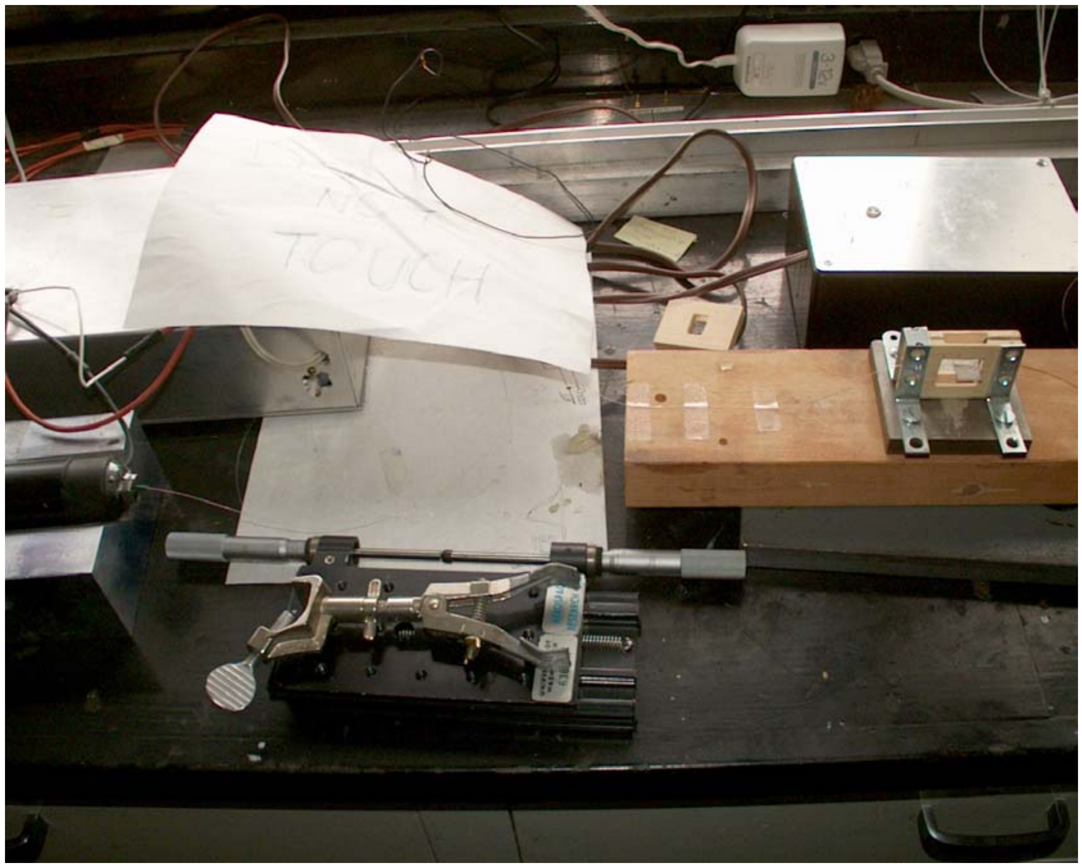
A liquid-level sensor based on changes in the critical angle due to liquid level moving up to contact the sides of the prism (using total internal reflection in air).

Displacement Sensor (extrinsic)



A change in the transverse alignment between two fibers changes the coupling and hence the power falling on the detector.

Accelerometer or Pressure Sensor (extrinsic)



Intensity modulation sensor (extrinsic)

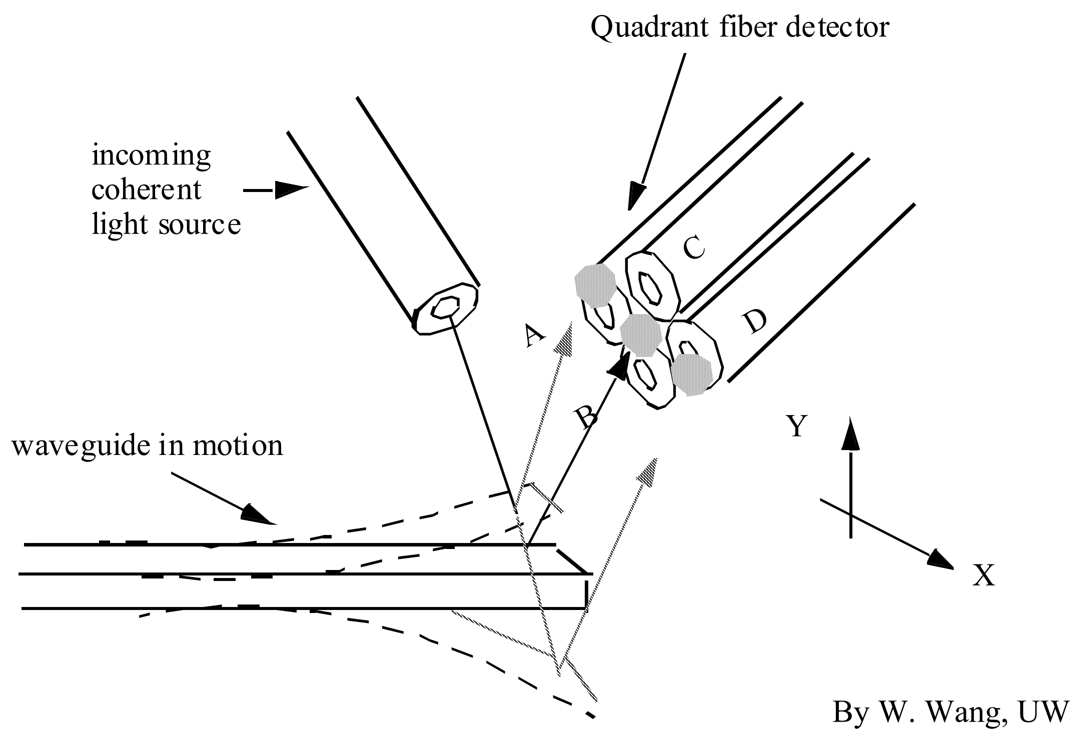


Figure 10. Quad cell photodiode position detector

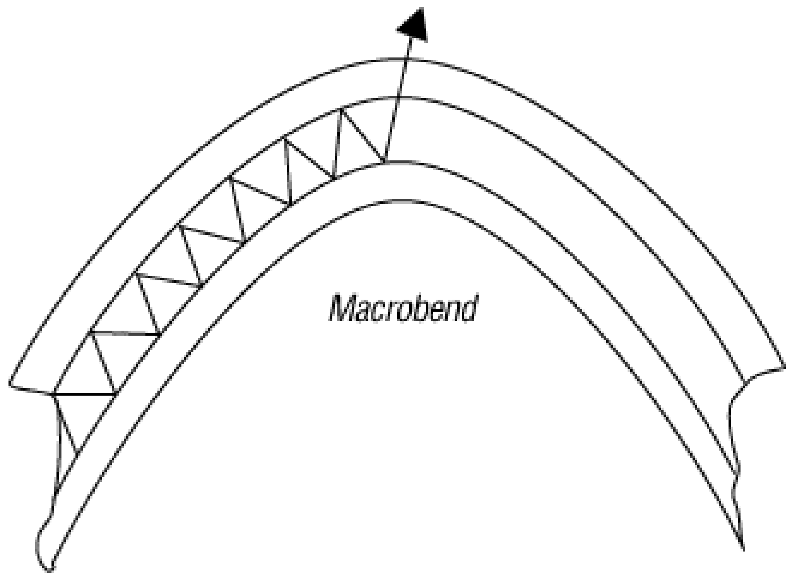
Detector Scheme

$$X = ((I_A+I_B)-(I_C+I_D))/((I_A+I_B)+(I_C+I_D))$$

$$Y= ((I_A+I_C)-(I_B+I_D))/((I_A+I_B)+(I_C+I_D))$$

I_A, I_B, I_C, I_D are Intensity from fiber A, B, C and D.

Macrobend (intrinsic)



A large-scale bend that is visible; for example, a fiber wrapped around a person's finger. To prevent macrobends, all optical fiber (and optical fiber cable) has a minimum bend radius specification that should not be exceeded.

Macrobend (intrinsic)

Macro-bend losses are losses observed when a fiber is bent to a radius of several centimeters. Large bending loss occurs at a critical bending radius of

$$R_c = \frac{3n_1^2\lambda}{4\pi\left(n_1^2 - n_2^2\right)^{3/2}}$$

where n_1 and n_2 are the indexes of refraction of core and cladding and λ is the operating wavelength. The optimum conditions for a large bending radius occur when refractive index difference between core and cladding is small or operating at a long wavelength.

Macrobend

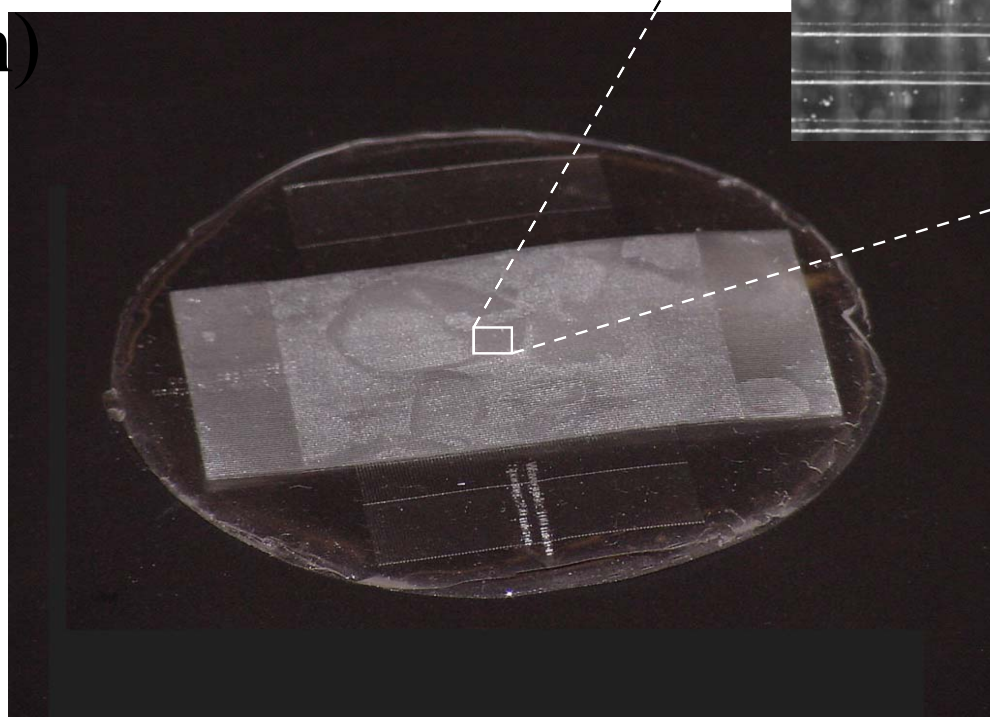
. Under the condition which $\alpha/R\Delta$ is to remain small, the light intensity attenuation is equal to

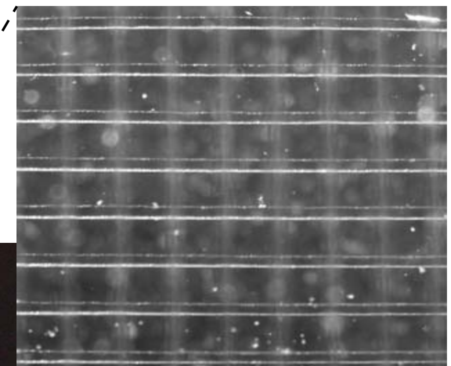
$$\gamma_B = 10(\log R)\left[\frac{\alpha+2}{2\alpha}\frac{r}{R\Delta}\right]$$

where r is the core radius, and α specifies the shape of index of refraction (for a parabolic profile, $\alpha = 2$ and for a step profile $\alpha = \infty$,) R is radius of curvature of the bend, Δ is the relative refractive index difference between core and cladding. Based on the above equation, it is apparent that the bend loss can be enhanced with a smaller refractive index difference between core and cladding or by using a larger core radius of the guide.

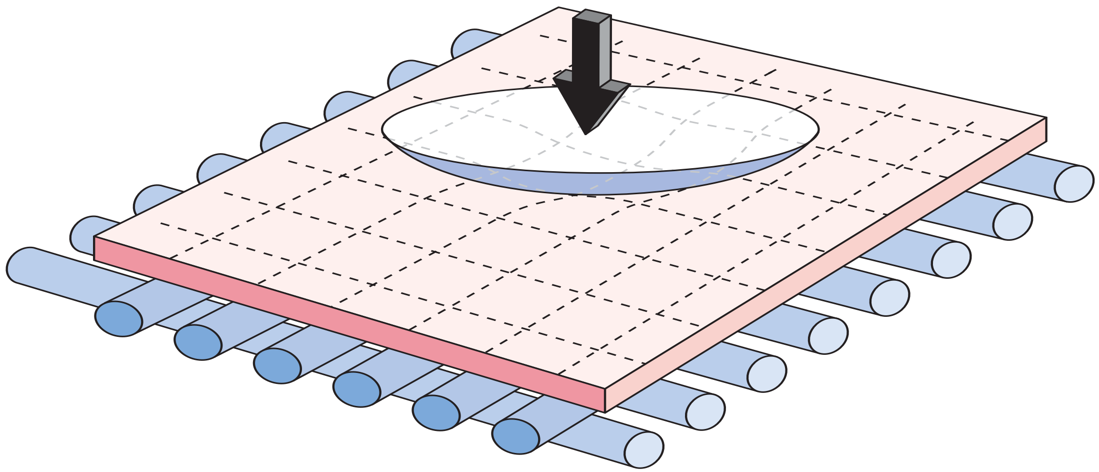
Waveguide Sensor Array

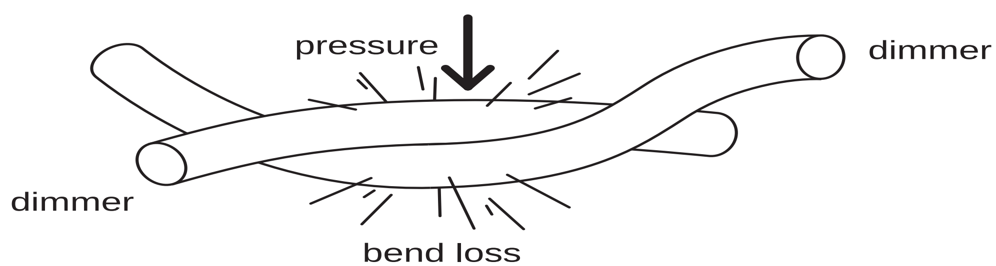
- Higher spatial resolution (250μm x 250μm)





Basic Pressure Sensor Design





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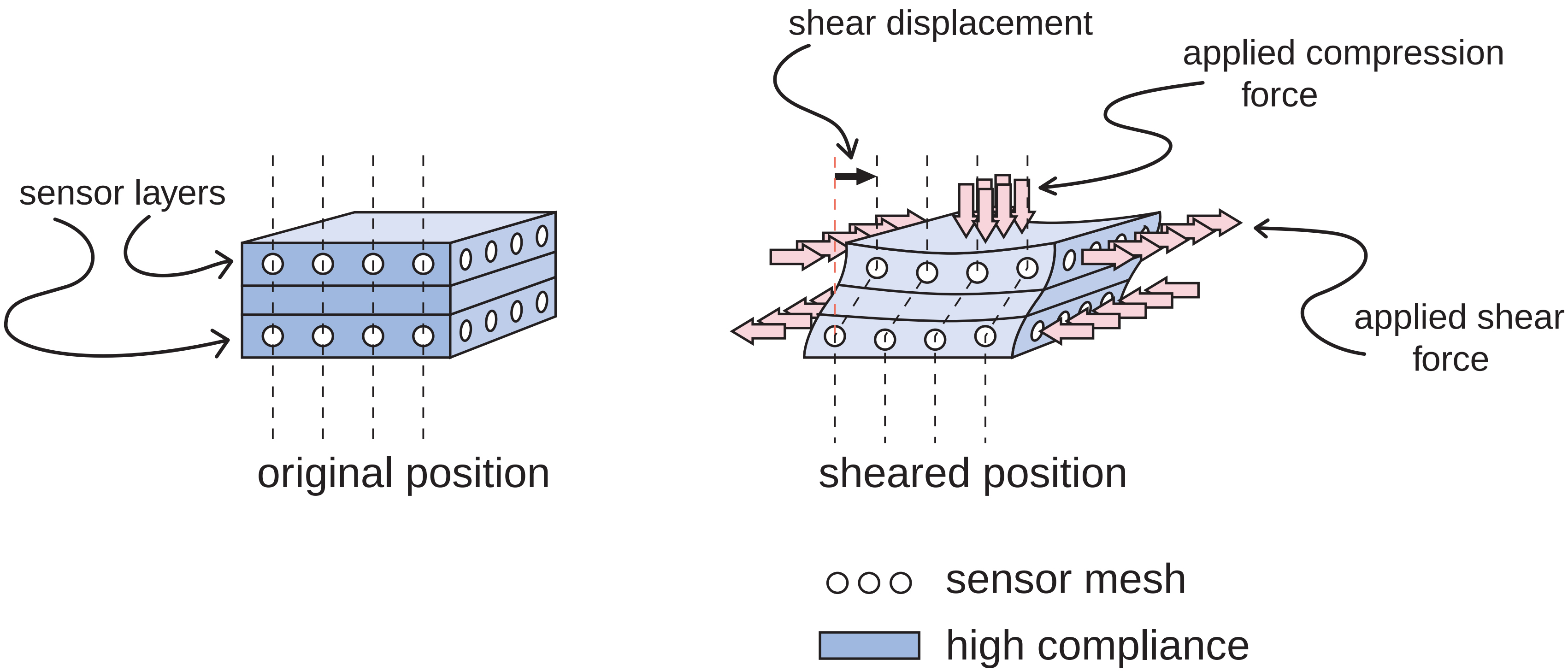
Basic Shear Sensor Design



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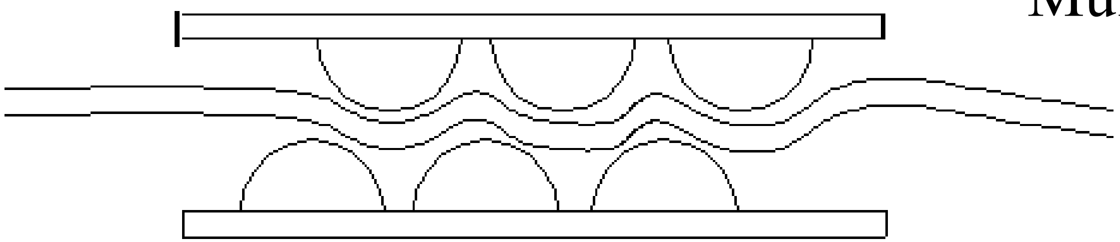
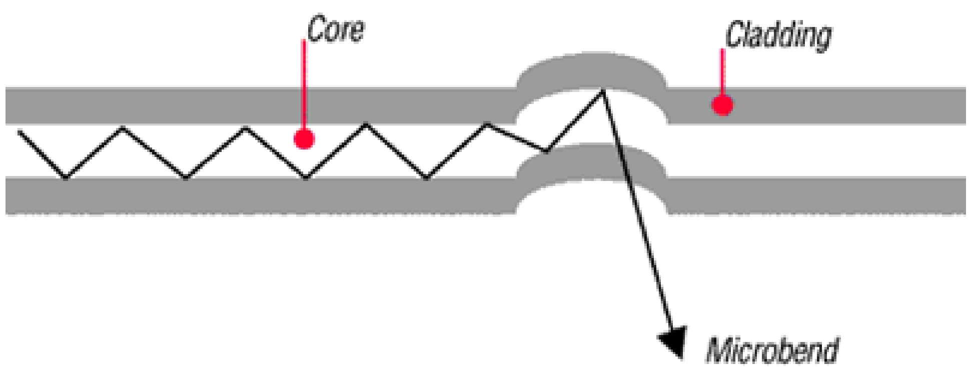
Microbend loss sensor (intrinsic)

In an optical waveguide, a sharp curvatures involving local axial displacements of a few micrometers and spatial wavelengths of a few millimeters. microbending can cause significant radiative loss and mode coupling.

Microbend Sensor (intrinsic)



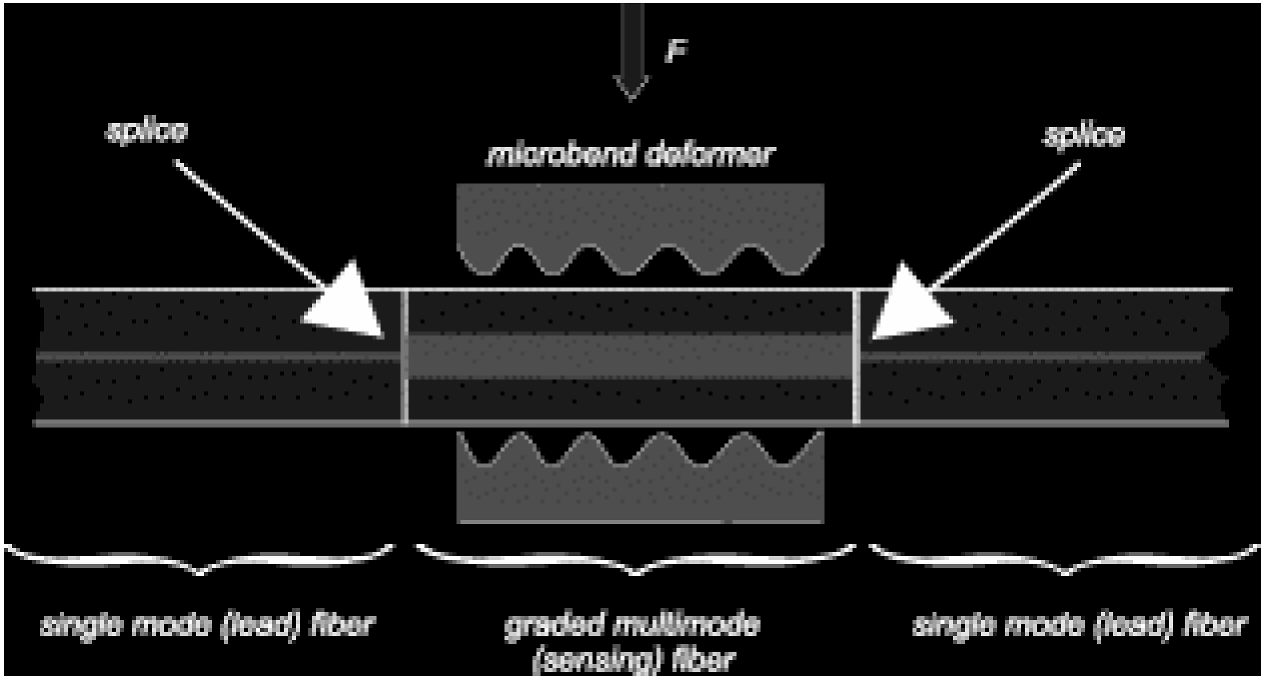
Multimode fiber



* fiber experiences multiple bends

* lower order guided modes are converted to higher order modes and are eventually lost by radiation

SMS Fiber Optics Sensor



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The structure is composed of single mode leads and graded multimode sensor fiber.

SMS Fiber Optics Sensor

Advantages

- higher sensitivity than classical microbend structures
- use of shorter deformers
- single mode leads, which eliminate intermodal interference problems
- sensitivity of 120%/N by use of low-sensitivity standard multimode fiber
- high insensitivity to macrobends

SMS Fiber Optics Sensor

Source	Sensing fiber	Lead Fiber	Measured Total Loss (dB)
He-Ne laser, 632,8 nm	Fotona G1E025EB, 50/125, N.A.=0,2	Fibercore SM600, λc=570 nm, N.A.=0,1	3,3
Laser diode, 780 nm	Fotona G1E025EB, 50/125, N.A.=0,2	Fibercore SM750, λc=680 nm, N.A.=0,1	1,5
LED, 860 nm	Fotona G1E025EB, 50/125, N.A.=0,2	Fibercore SM750, λc=680 nm, N.A.=0,1	2

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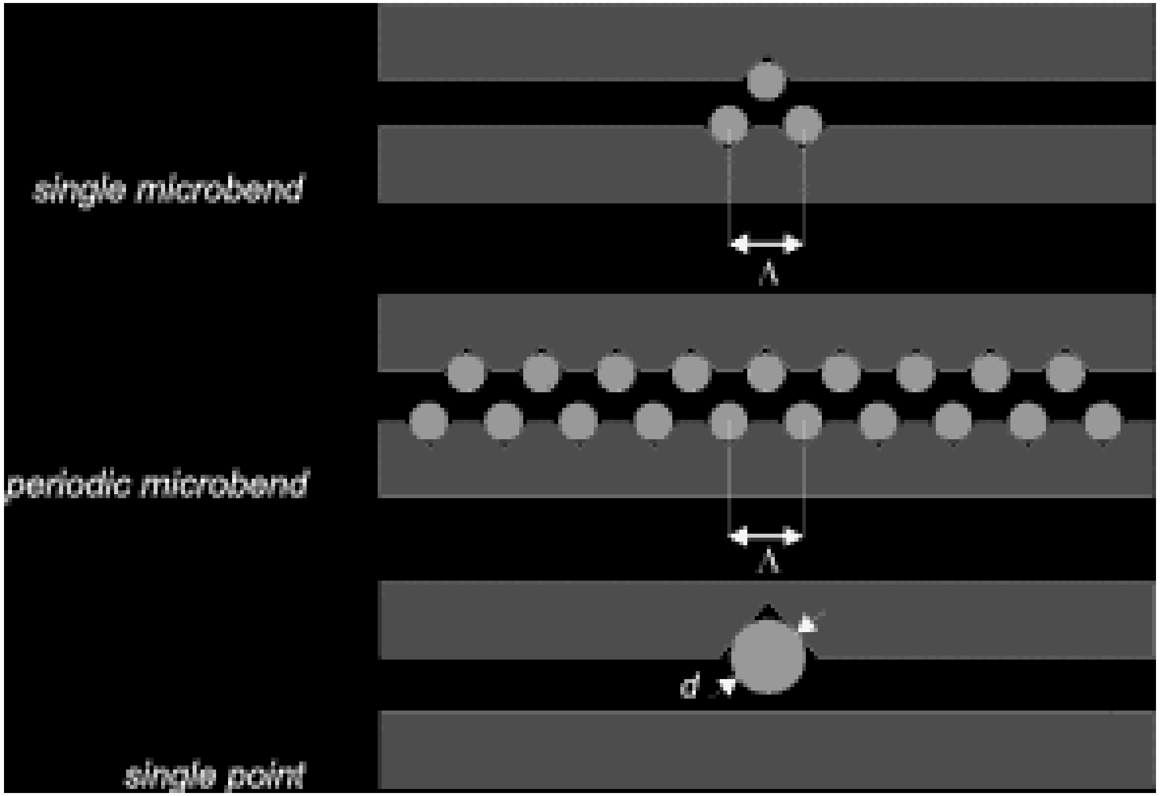
SMS Fiber Optics Sensor



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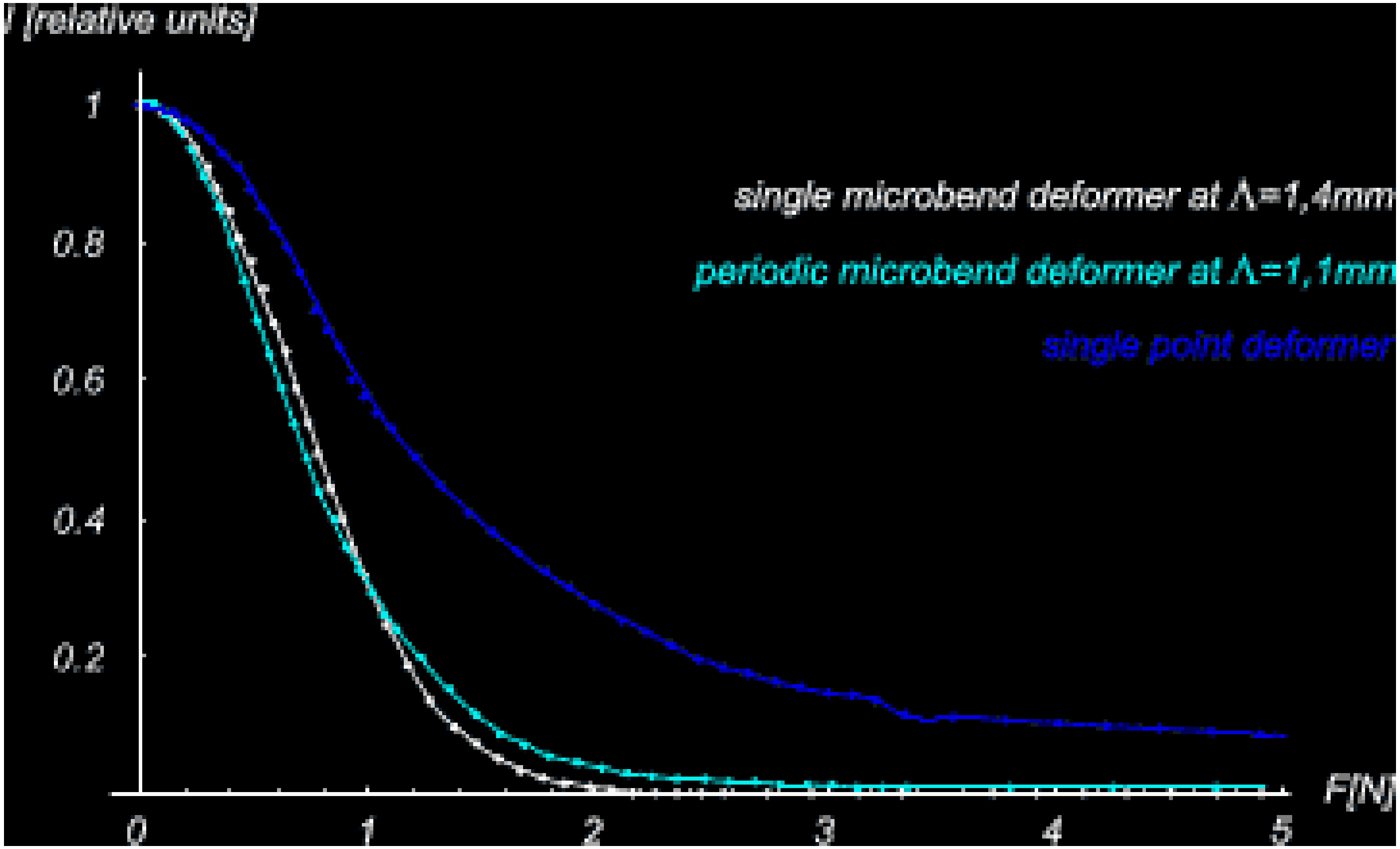

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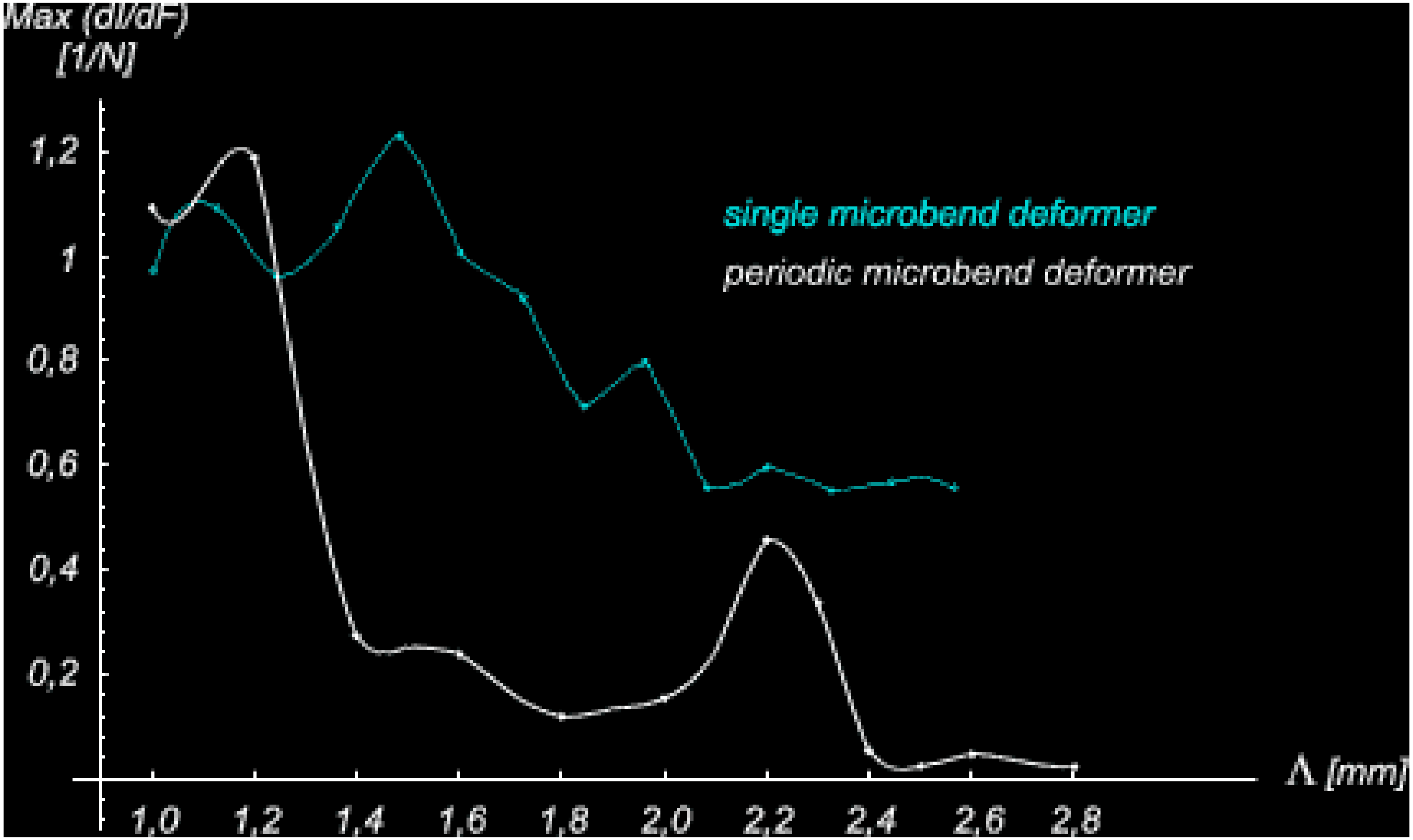

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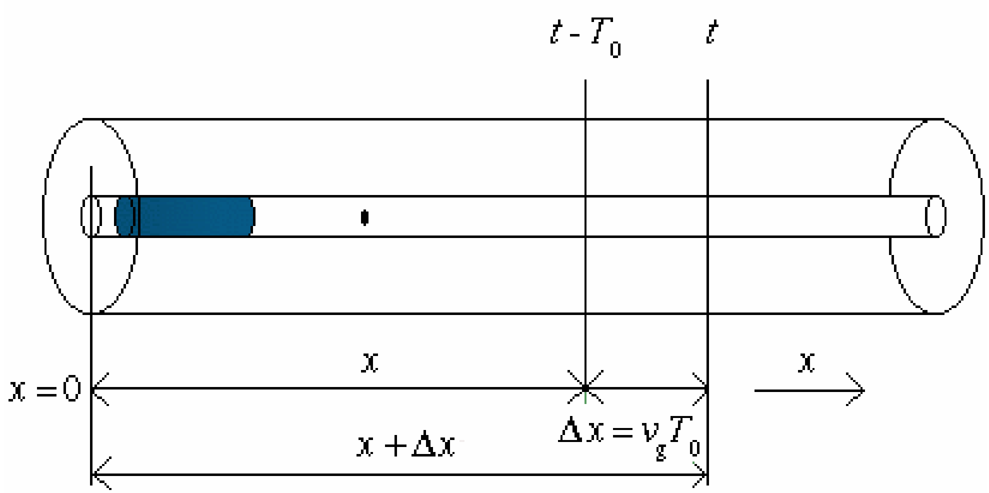
OTDR

Optical Time Domain Reflectometer (OTDR)

Intrinsic distributed sensors based on Rayleigh backscatter utilize either the measurand-dependent loss coefficient $\alpha(z)$ or backscattering coefficient $r(z)$ mechanism in a single length of optical fiber which forms an extended sensor.

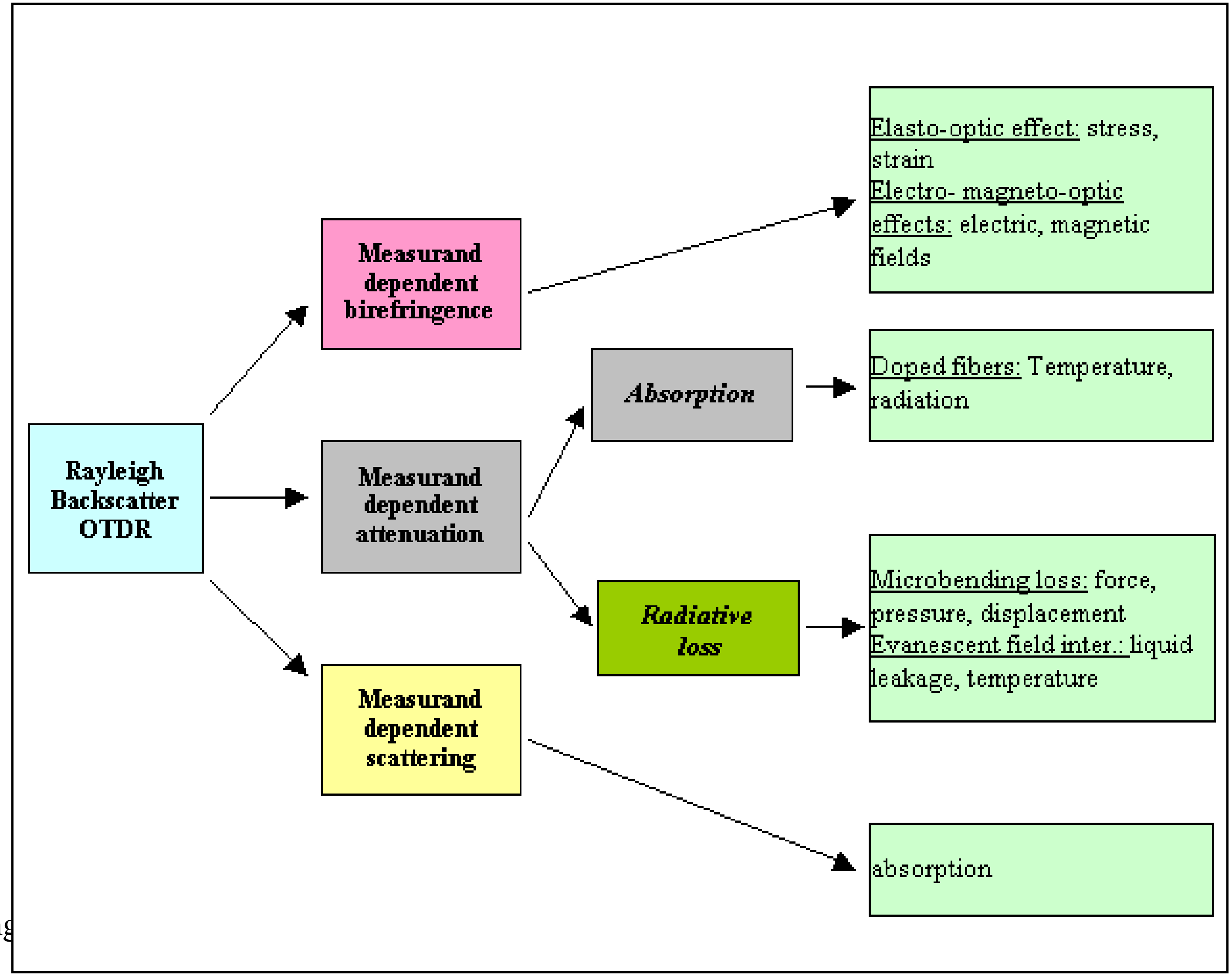
The backscattering method was invented by M. Barnoskim and M. Jensen in 1976

OTDR



Position of the optical impulse in the fiber core at time *t*

Basic Mechanisms of OTDR



OTDR

- Coherent OTDR (CO-OTDR) - The week returned backscattered signal is mixed with a strong coherent local oscillator optical signal to provide coherent amplification
- Correlation OTDR (COR-OTDR)
  - COR-OTDR based on pseudorandom signal
  - COR-OTDR based on Golay code signal
- Low correlation OTDR (LC-OTDR)
- Photon-Counting OTDR (PC-OTDR)
- Optical Frequency-Domain Reflectometry (OFDR)
  - OFDR with the frequency scanning (OFDR-FS)
  - OFDR with the synthesized coherence function (OFDR-SCF)
- Polarization OTDR (PO-OTDR)