Intensity Sensors

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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

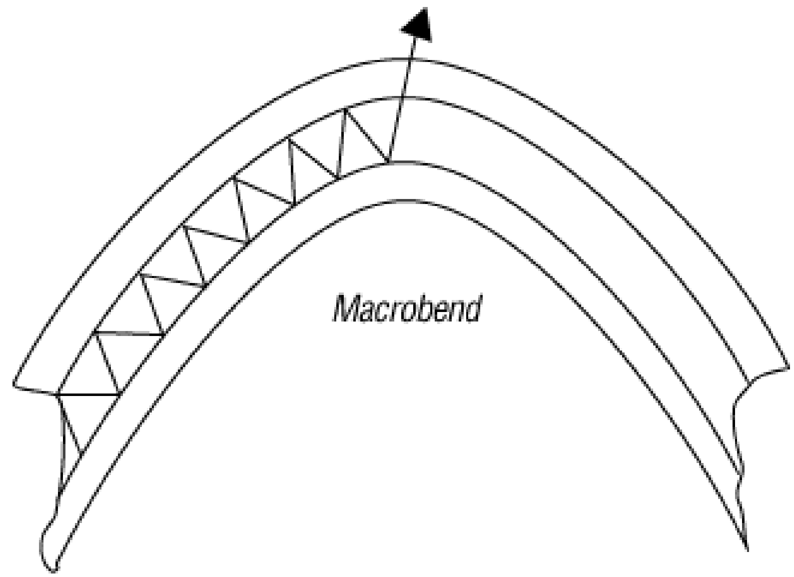
The minimum measurable quantity in the shot noise limit is given by,

$$i_d^2 = 2eBI_d \qquad \text{„white noise"}$$

With light: $i_d^2 = 2eBI_p$

where e = electronic charge and B=detection bandwidth.

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

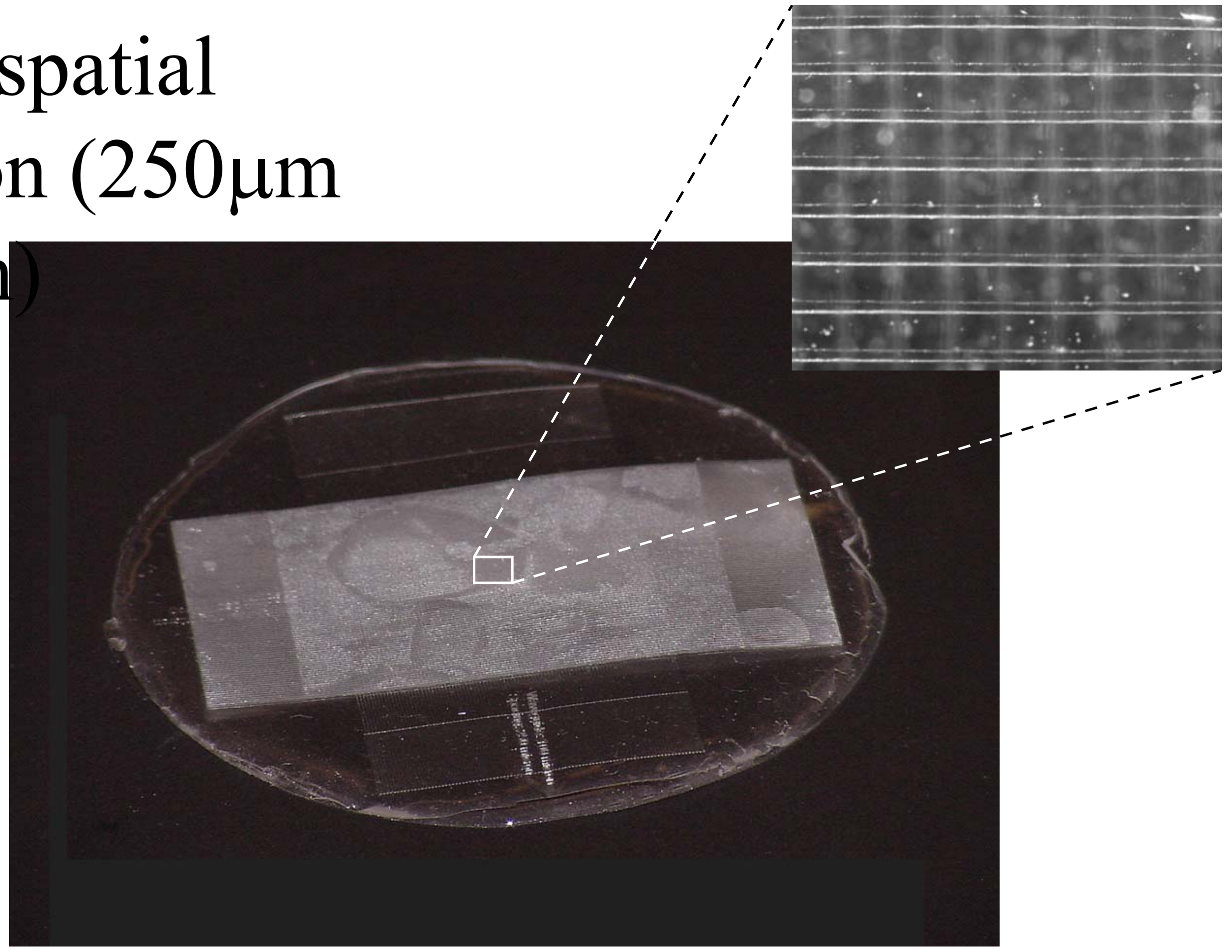
. Under the condition which $\alpha / R\Delta$ is to remain small, the light intensity attenuation is equal to

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

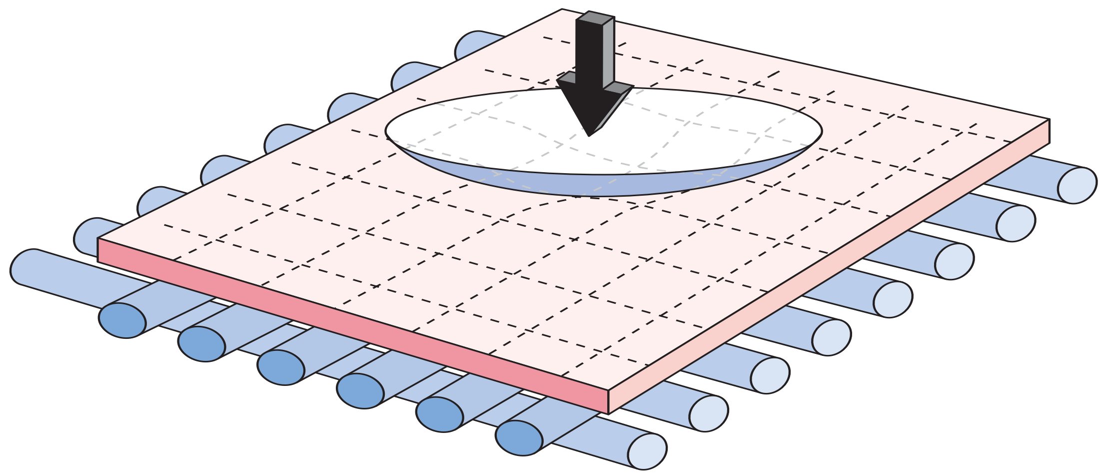
where r is the core radius, and α specifies the shape of index of refraction (for a parabolic profile, $\alpha = 2$ and for a step profile $\alpha = \infty$,) R is radius of curvature of the bend, Δ is the relative refractive index difference between core and cladding. Based on the above equation, it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

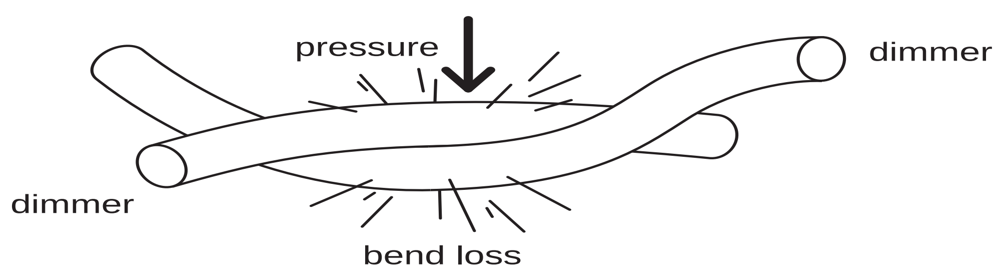
Waveguide Sensor Array

- Higher spatial resolution (250μm x 250μm)

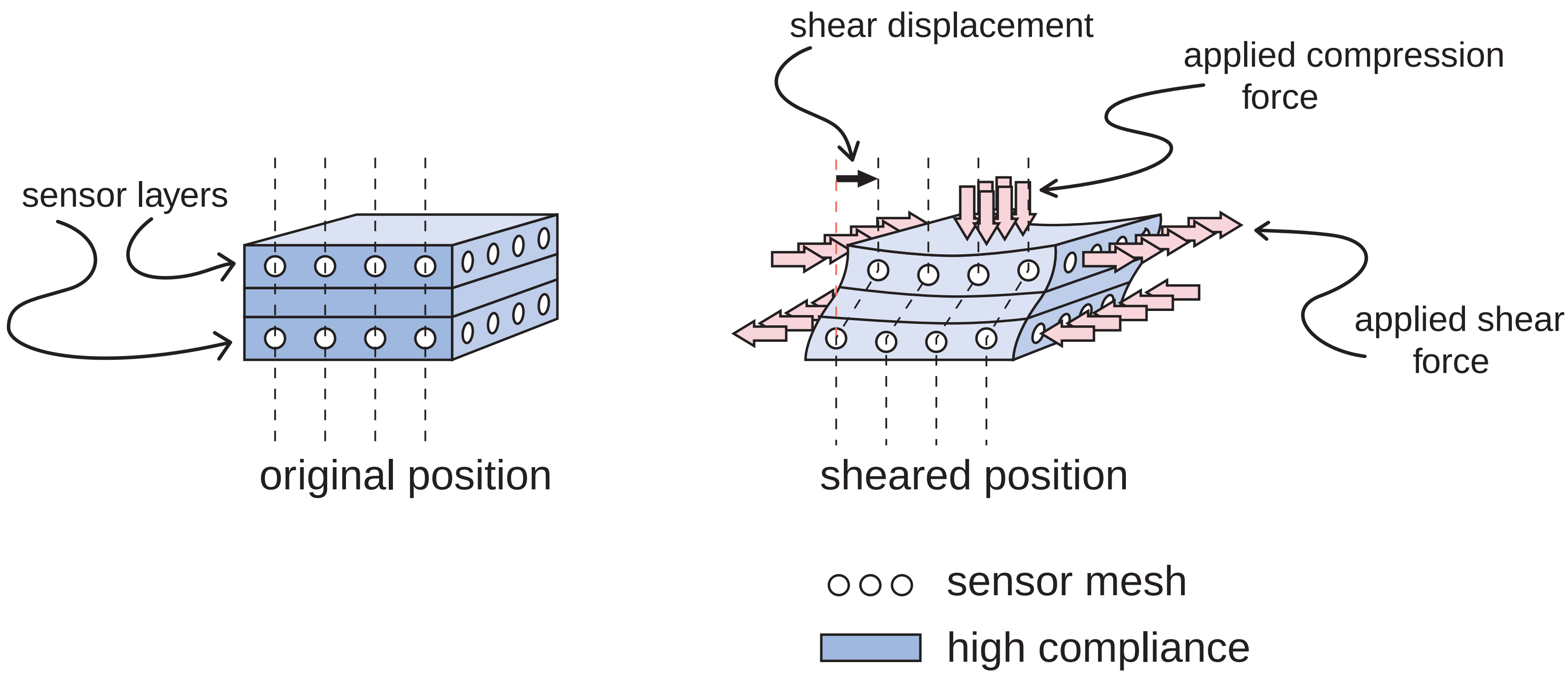


Basic Pressure Sensor Design





Basic Shear Sensor Design

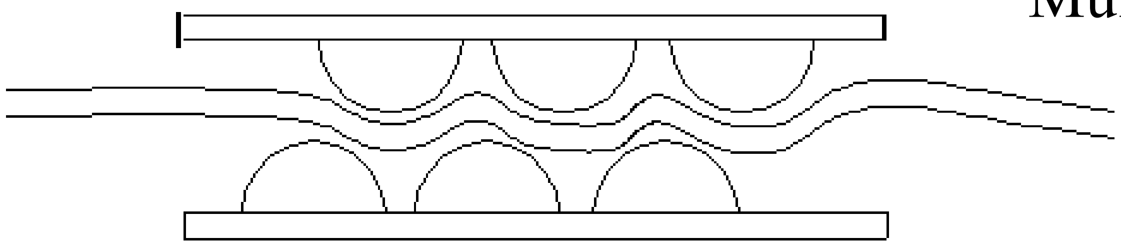


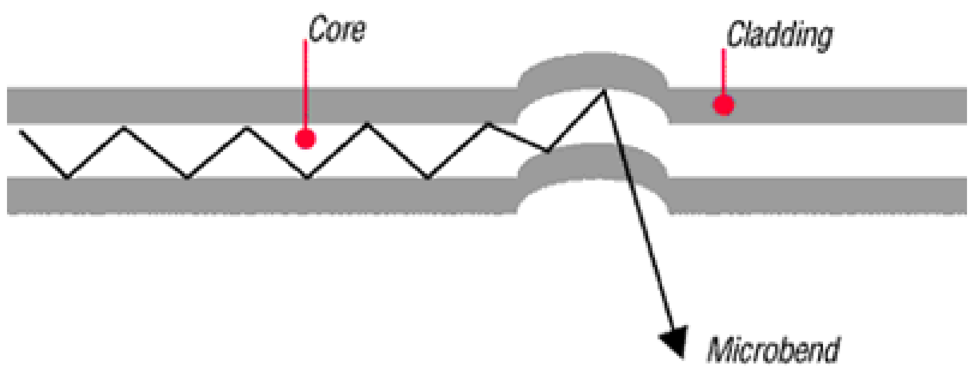
Microbend loss sensor (intrinsic)

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

Microbend Theory

For pressure sensor, the transmission coefficient for light propagating through the bend fiber changed by the amount of applied pressure is equal to [1]

$$\Delta T = \frac{\Delta T}{\Delta x} A_p (k_f + \frac{E_s A_s}{l_s})^{-1} \Delta P \cong \frac{\Delta T}{\Delta x} A_p k_f^{-1} \Delta P \qquad (1)$$

Where A_p is area under the load, k_f is the bent fiber force constant and A_s, E_s, l_s are cross sectional area, Young's modulus and length of the mechanical deformer. The approximation is assume the deformer's $A_s E_s / l_s$ is much smaller than the fiber's k_f.

For the optical portion of the modulation index $\Delta T/\Delta x$, the loss occurs when wave number of the spatial distortion is equal to the difference in wave number between the modes. The period microbending induced along the fiber axis couples power between modes with longitudinal propagation constant is [1]

$$\beta_m - \beta_n = \frac{2\pi}{\Lambda} \qquad (2)$$

where each mode has propagation constant $\beta_m = n_1 k \cos(\theta_m)$, with θ_m representing the angle which the mode's equivalent rat makes with the fiber axis, n_1 core refractive index, and k is free space propagation constant, Λ is the mechanical distortion wavelength. Based on WKB approximation, the distance in β space between adjacent guide modes in a fiber is given by [2]

$$\delta\beta = \beta_{m+1} - \beta_m = \left(\frac{\alpha}{\alpha+2}\right)^{1/2} \frac{2\sqrt{\Delta}}{r} \left(\frac{m}{M}\right)^{\frac{\alpha-2}{\alpha+2}} \qquad (3)$$

where m is the order of modal group and M is total number of modes, α is a constant ($\alpha = 2$ for parabolic index fiber, $\alpha = \infty$ for step index fiber), r is the core radius and Δ is the fractional difference in refractive index between core and cladding [2]:

$$\Delta = \frac{n_1^2 - n_2^2}{2n_1^2} \cong \frac{n_1 - n_2}{n_1} \qquad for \qquad \Delta \langle\langle 1$$

where n_1 and n_2 are refractive indices for core and cladding.

In the case of parabolic index fiber, the equation (3) becomes,

$$\delta\beta = \frac{\sqrt{2\Delta}}{r} \qquad (4)$$

It shows that $\delta\beta$ is independent of order of mode since all modes are equally spacing in k space (to within WKB approximation). This means that an efficient coupling between modes can be achieved with just one single spatial period. Since numerical aperture is defined as

$$NA = n_o \sin\theta_o = (n_1^2 - n_2^2)^{0.5} \cong n_1 (2\Delta)^{0.5} \qquad (5)$$

the spatial period based on the above NA and Δ is [2]

$$\Lambda = \pi r \sqrt{\frac{2}{\Delta}} = \frac{2\pi r n_1}{NA} \qquad (6)$$

In the case of step index, modes are not equally spaced and

$$\delta\beta = \frac{2\sqrt{\Delta}}{r}\left(\frac{m}{M}\right) \qquad (7)$$

The separation of modes in k space for step index is therefore depends on the order of the mode, m. Based on equation (2) and (7), we see larger the m, the smaller Λ and while lower order mode require larger period. The spatial period for highest order core modes coupled to radiated modes (assume m = M) is given by

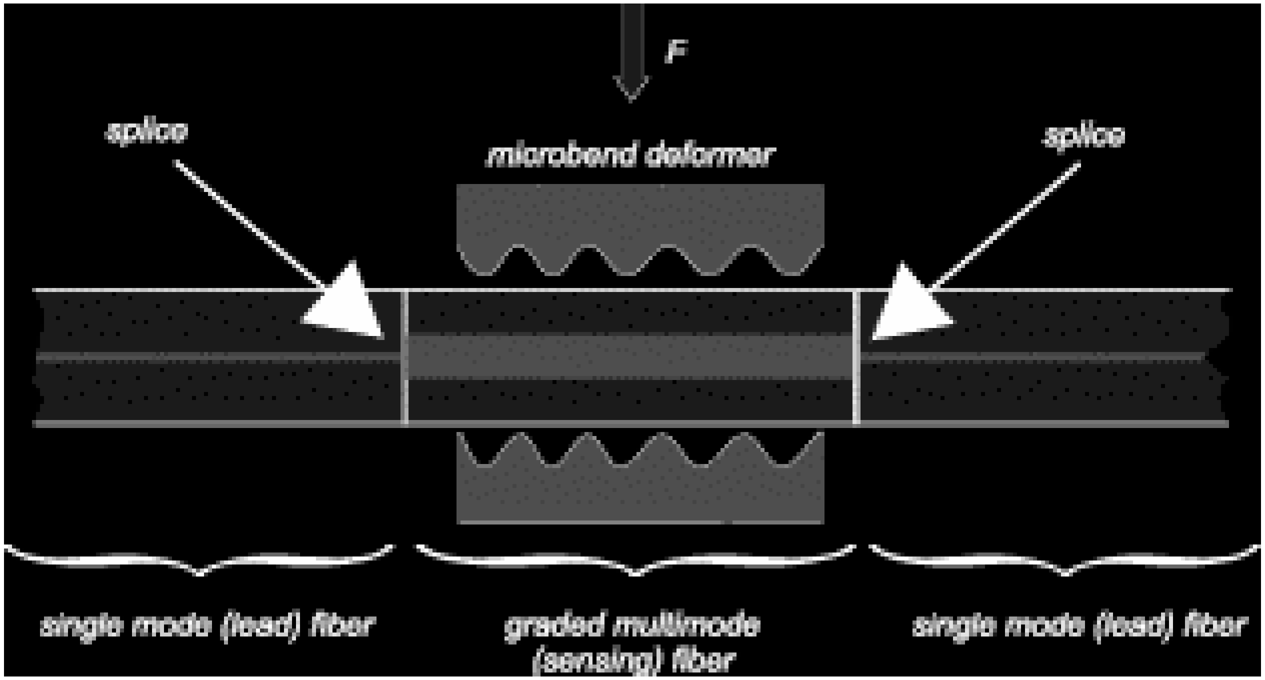
$$\Lambda = \frac{\pi r}{\sqrt{\Delta}} \cong \frac{\sqrt{2}\pi r n_1}{NA} \qquad (8)$$

The mechanical parameter also affects the outcome of the sensitivity of the sensor. The applied force and the resulted displacement Δx are related by simple $\Delta F = k_f \Delta x$. Considering the bent fiber or waveguide as a bar loaded at the center and clamped at its ends [4]

$$k_f = \frac{3\pi E_s d^4 \eta}{\Lambda^3} \tag{9}$$

Where d is diameter of the fiber and η is the number of bent intervals.

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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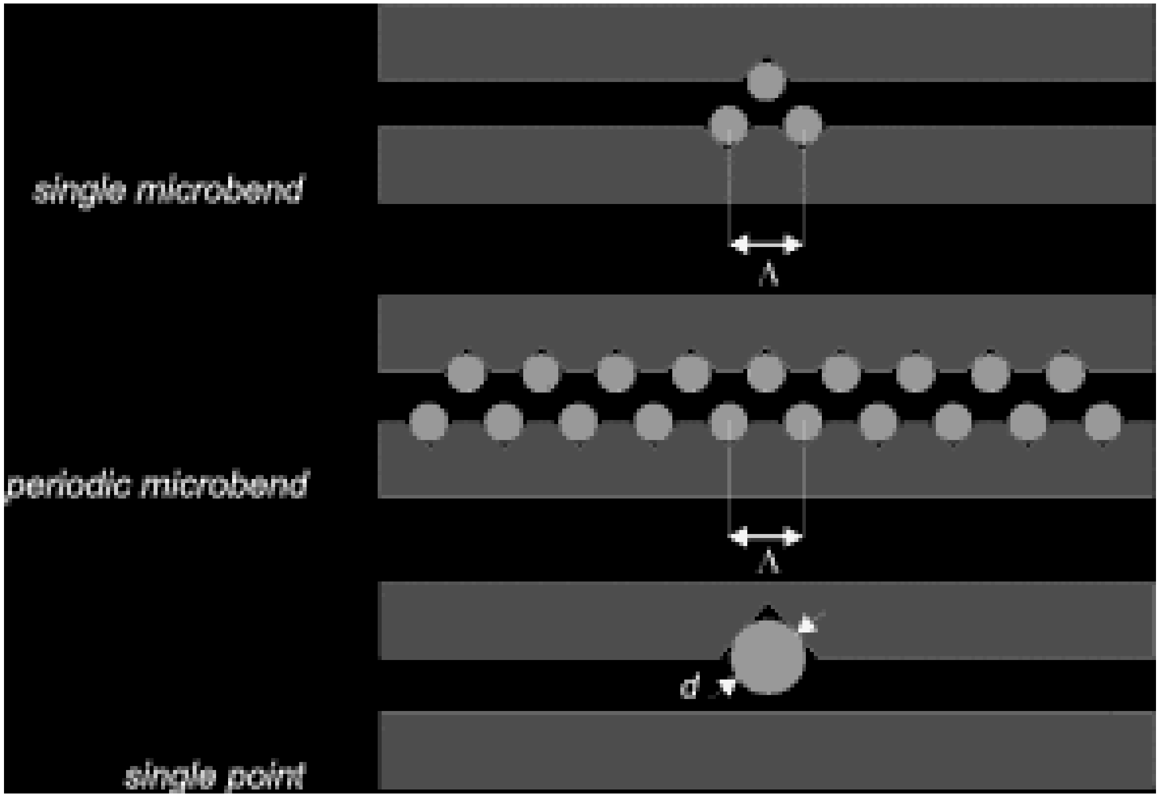
SMS Fiber Optics Sensor



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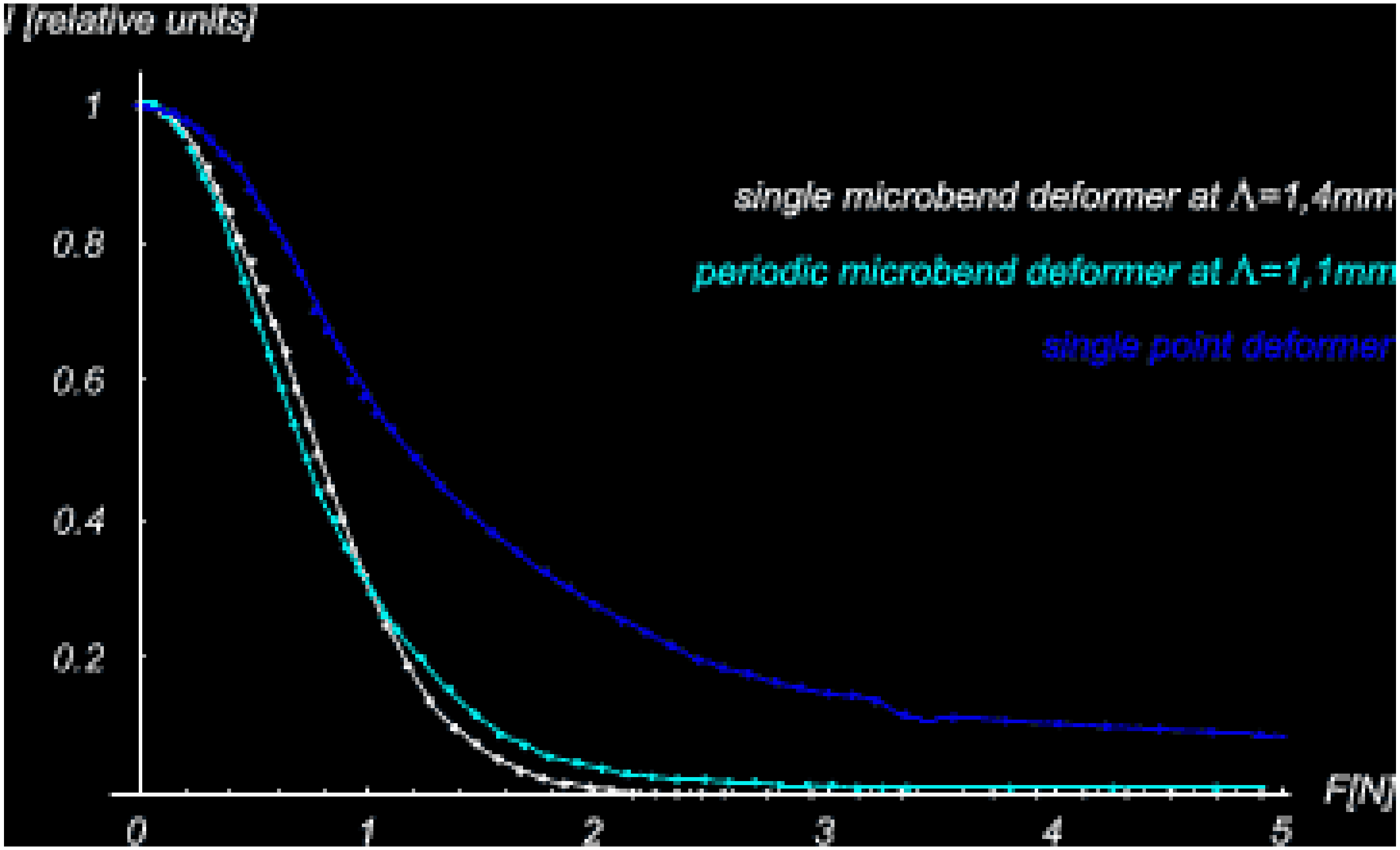

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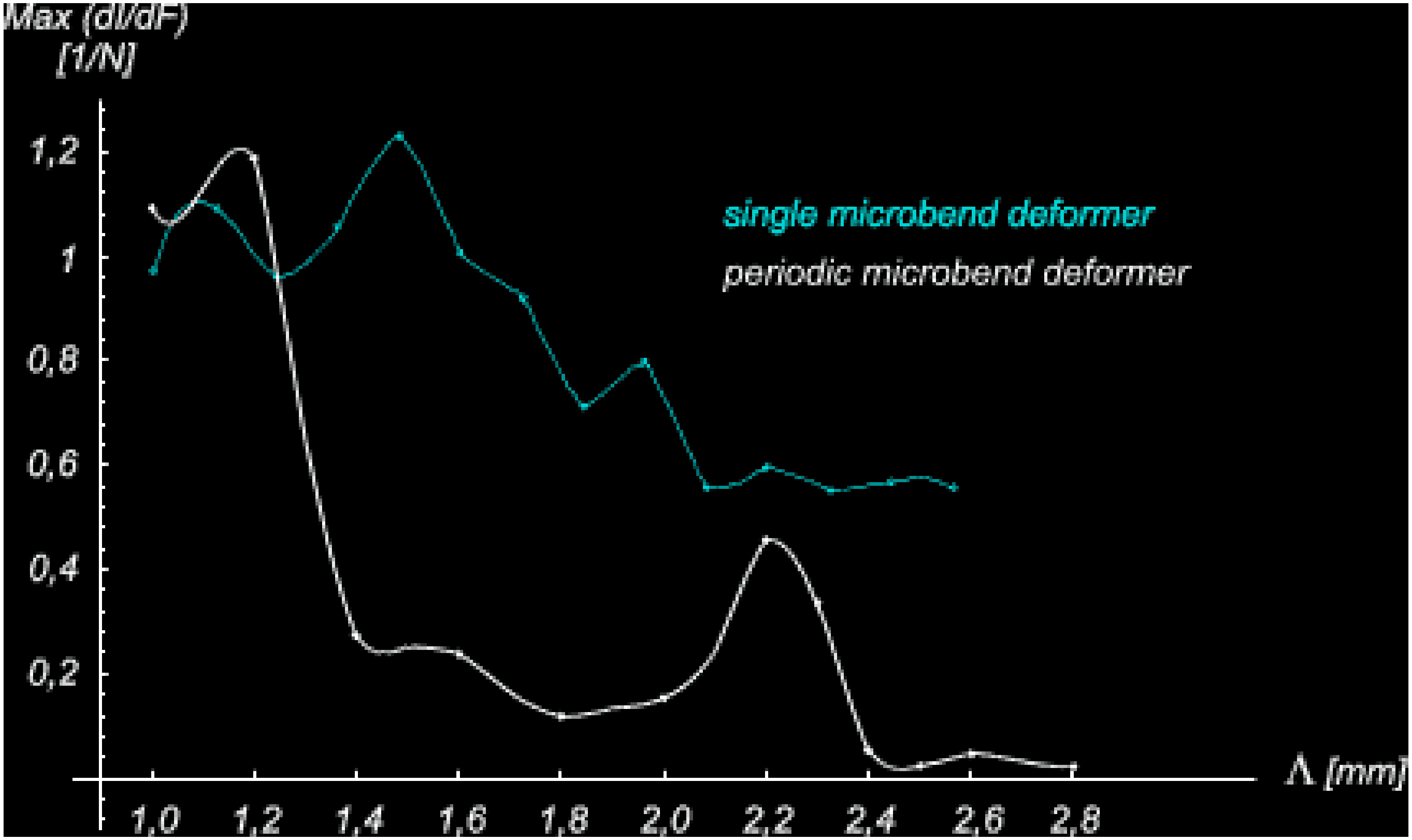

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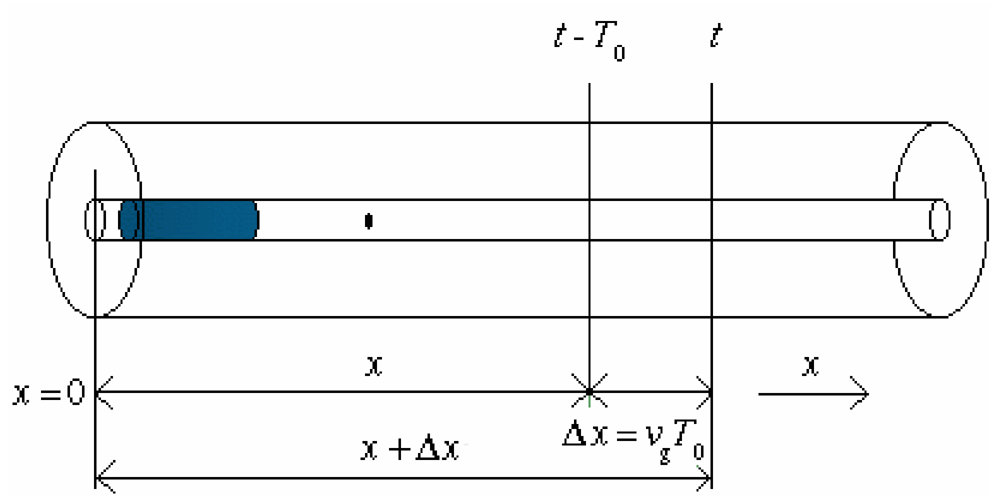
OTDR

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.

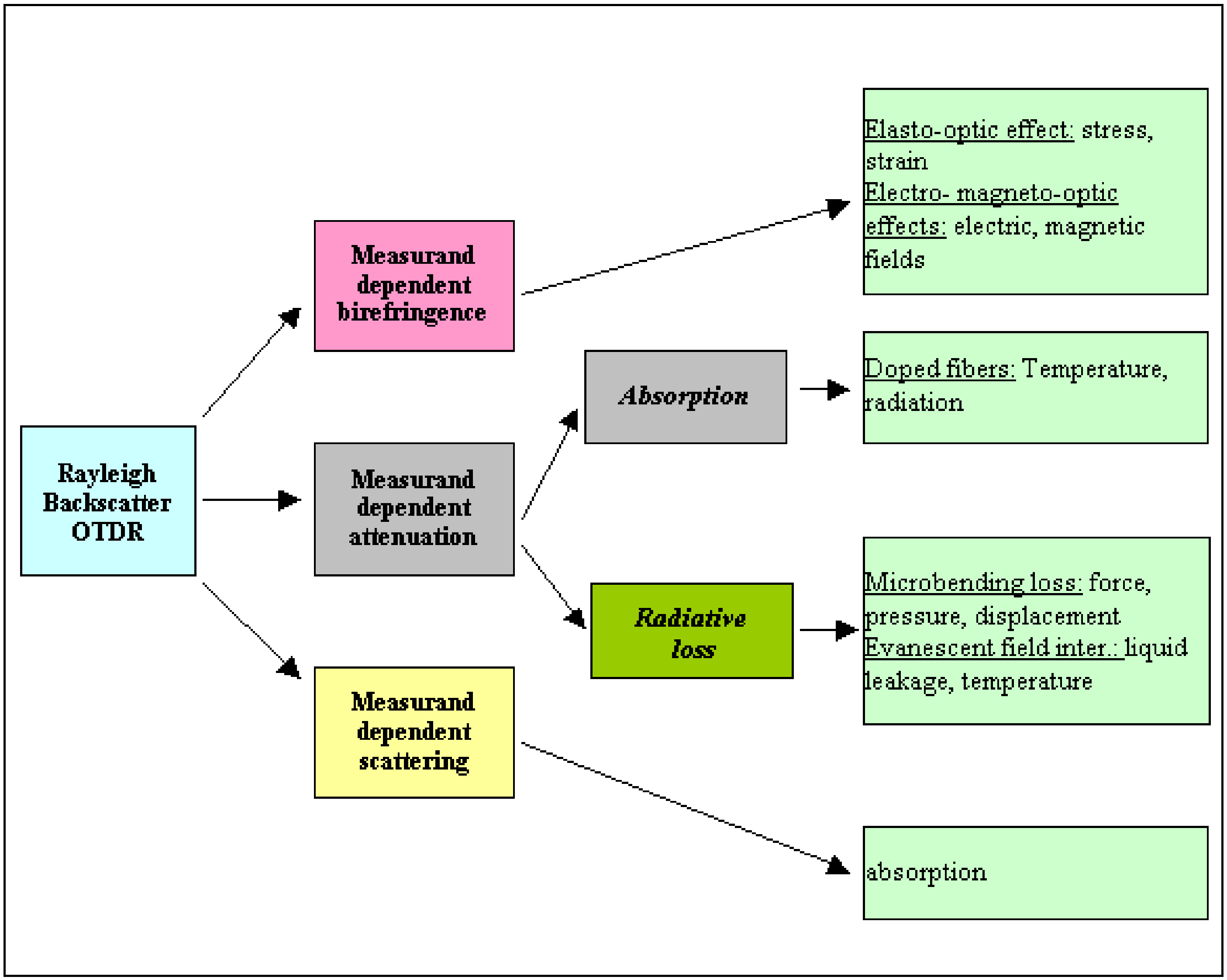
The backscattering method was invented by M. Barnoskim and M. Jensen in 1976

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)

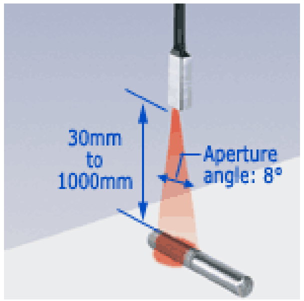
Proximity Sensor (extrinsic)

Liquid Level Sensors

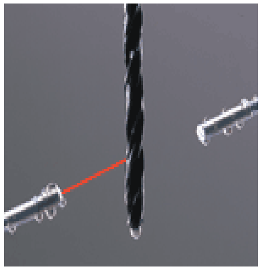
Distance Detection

tube-mountable liquid level detection

immersion type liquid level detection



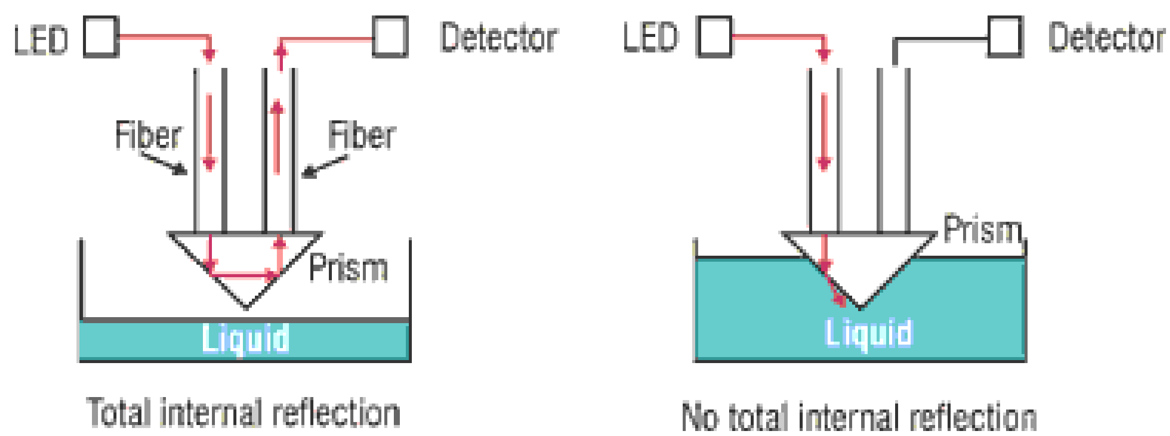
Reflective type



Transmissive type

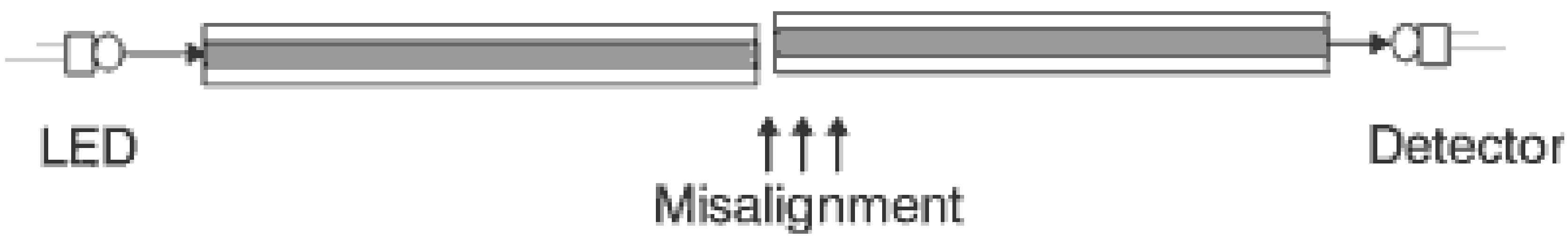
By KEYENCE CORPORATION OF AMERICA

Liquid level sensor (extrinsic)



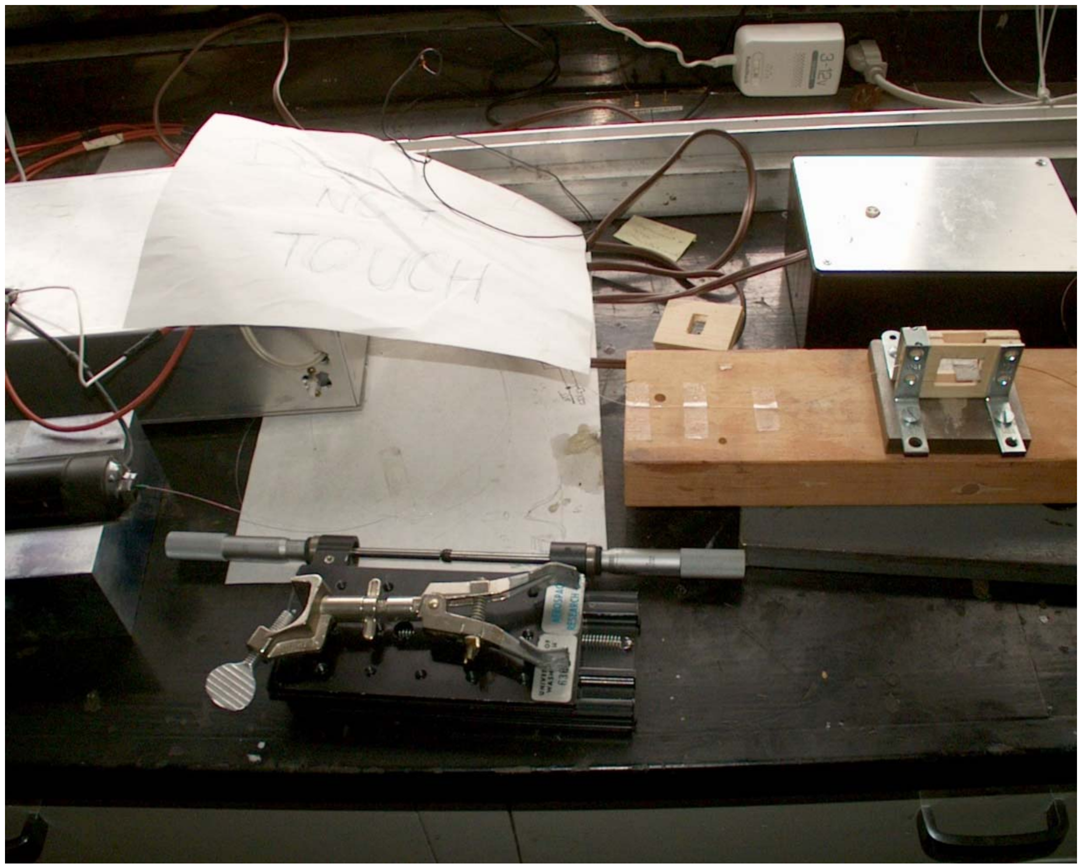
A liquid-level sensor based on changes in the critical angle due to liquid level moving up to contact the sides of the prism (using total internal reflection in air).

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)



By W. Wang, UW

Intensity modulation sensor (extrinsic)

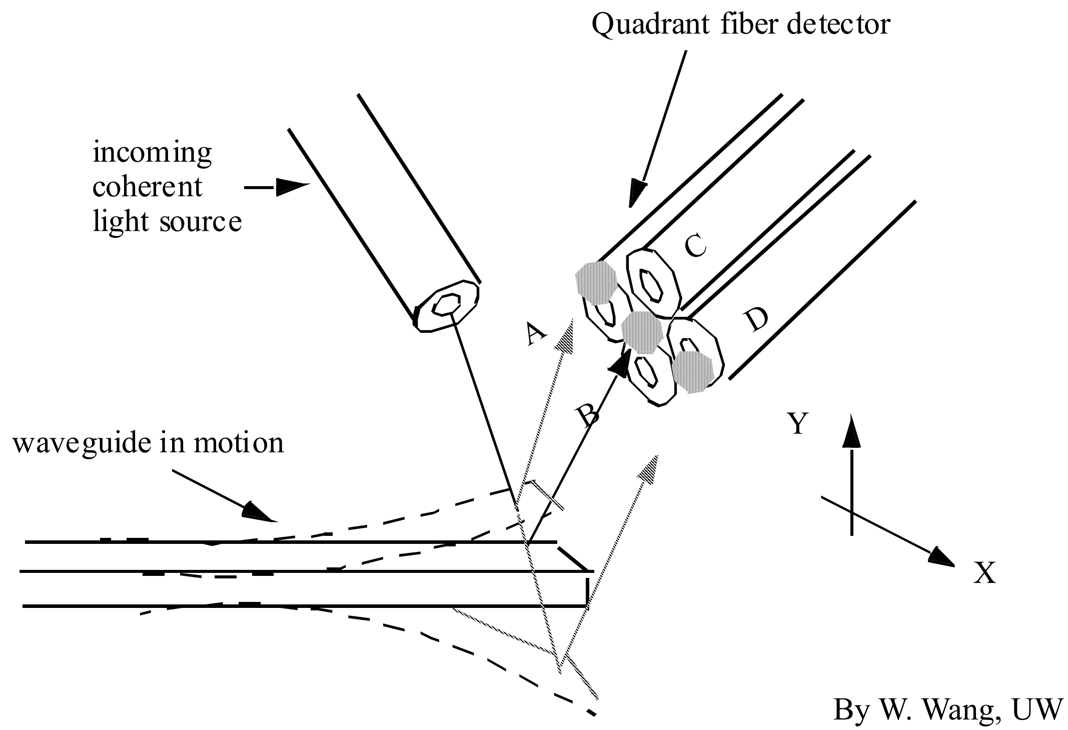


Figure 10. Quad cell photodiode position detector

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.

Assignment

- Come up with an intensity based sensor design. Please include actual design, model, calculation of the measurant of your design.