Introduction to Optical Sensors

The main goal of this course is to introduce the characteristics of light that can be used to accomplish a variety of engineering tasks especially in mechanical analysis. To develop student understanding of Fundamental of optical sensing: Intensity modulation, Phase modulation thin lens matrix method, Light sources and photodetectors.

Sensor Definition, A device that responds to a physical stimulus, as thermal energy, electromagnetic energy, acoustic energy, pressure, magnetism, or motion, by producing a signal, usually electrical.

Method for sensing:-

• Optical

• Piezoelectric

• Thermal

• Chemical

• Electric

• Magnetic

Optical Sensor:-

• Light is a form of energy which allow a physical entity to see and feel

• Optical sensor provides quantitative miscreant using optical energy.

Why optical technique?

- Sensitivity

- Free of EMI and RFI

- Compact

- Broadband

- Wide range spectrum provides unique applications

Optical path length

We define a ray as the path along which light energy is transmitted from one point to another in an optical system. The basic laws of geometrical optics are the law of reflection and the law of refraction.

Law of reflection: $|\theta r| = |\theta i|$

Snell's law, or the law of refraction: $n i \sin\theta i = n t \sin\theta t$.

If not being reflected or refracted, a light ray travels in a straight line.

The optical path length of a ray traveling from point A to point B is defined as c times the time it takes the ray to travel from A to B.

Assume a ray travels a distance d1 in a medium with index of refraction n1 and a distance d2 in a medium with index of refraction n2.

The speed of light in a medium with index of refraction n is c/n. The travel time from A to B therefore is

$t = n1 d1/c + n2 d2/c$.

The optical path length is $OPL = n1 d1 + n2 d2$.
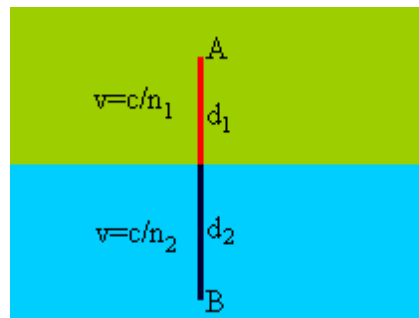
Fermat's Principle:

An alternate approach to geometric optics is Fermat's principle. The path of a ray of light between two points is the path that minimizes the travel time. In Fermat's Principle the optical path length between points A and B can be calculated in either direction, A to B or B to A, the result is the same. This leads to the principle of geometrical reversibility.

Geometrical optics:-

Most of what we need to know about **geometrical optics** can be summarized in two rules:

1) The laws of reflection: - wave vector and wave front of a wave being reflected from a plane mirror.

2) The law of refraction: - refraction of a wave from an interface between two dielectric media.
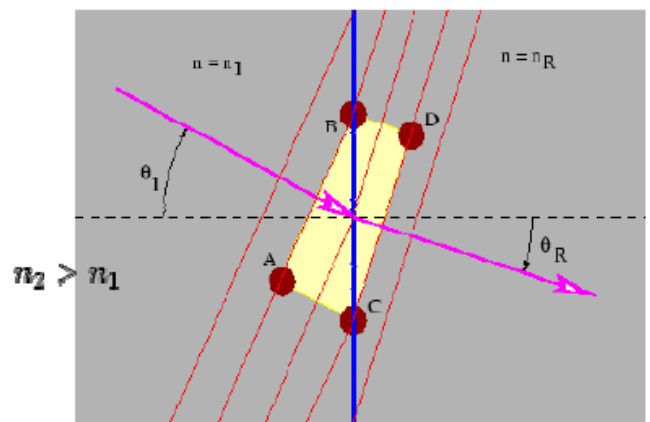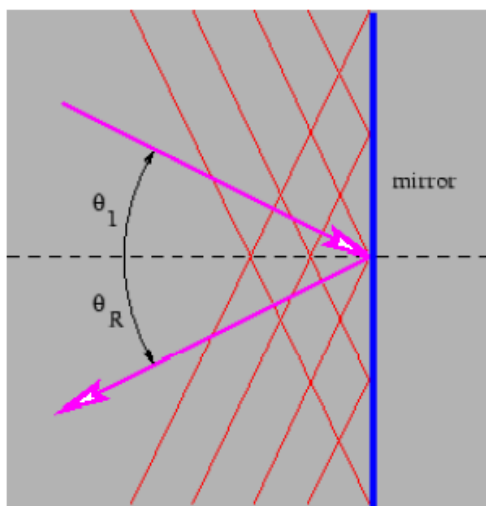
Index of Refraction In a material medium the effective speed of light is slower and is usually stated in terms of the index of refraction of the medium. The index of refraction is defined as the speed of light in vacuum divided by the speed of light in the medium.

$$n = \frac{C_o}{C}$$

The values given are approximate and do not account for the small variation of index with light wavelength which is called dispersion (n = function of wavelength).
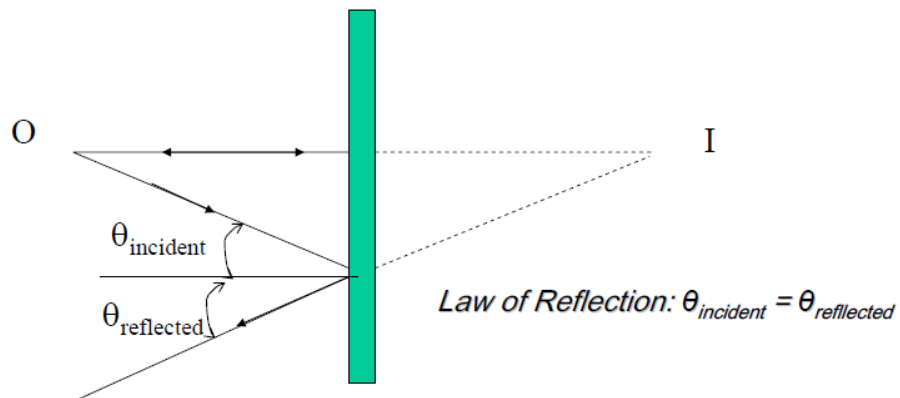
Law of Refraction


Snell's Law: no sin α = n sin β
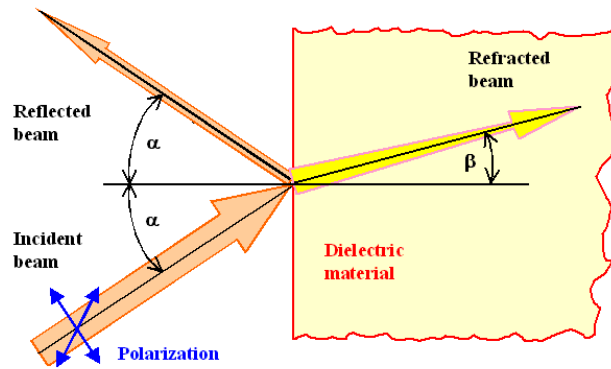
Reflection:-

The angles of incidence and reflection are defined to be the angles between the incoming and outgoing wave vectors respectively and the line normal to the mirror.

Law of Reflection: $\theta_{incident} = \theta_{reflected}$

Matrix Optics:-

Matrix optics is a technique for tracing paraxial rays. The rays are assumed to travel only within a single plane (as shown in yz plane)
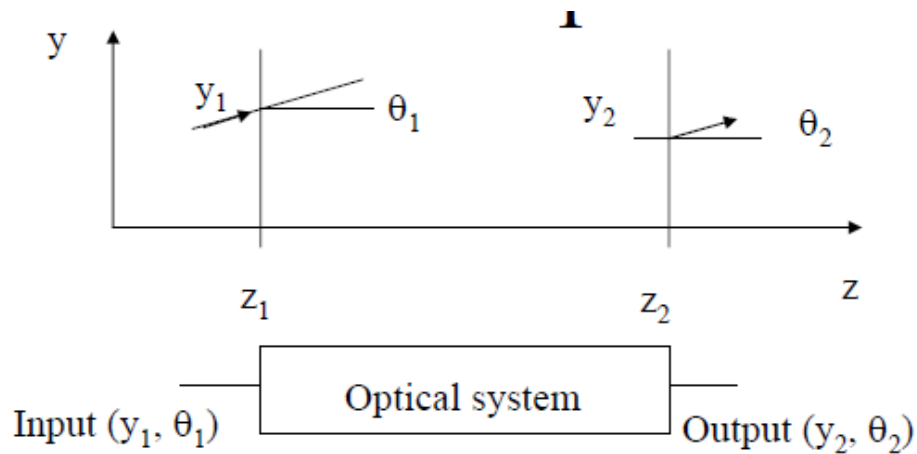
-A ray is described by its position y and its angle θ with respect to the optical axis. These variables are altered as the ray travels through the optical system, where the system can be represent by a transfer function like matrix to represent the relation between (y2, θ 2) and (y1, θ 1) as,

$$\begin{bmatrix} y_2 \\ \theta_2 \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} y_1 \\ \theta_1 \end{bmatrix}$$

Home project

• Design a mirror system to focus, diverge or collimate an incident beam or create some interesting magic tricks or illusion or something you can think of that using ray tracing technique.

Ref. Wei-Chih Wang, University of Washington, Department of Mechanical Engineering

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)

Intrinsic Fiber Optic Sensors

Intrinsic distributed sensors are particularly attractive for use inapplications 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 structure 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.

Intensity Modulation and Phase modulation sensors

Intensity Modulation Sensors:-

• Macro Bend

• Micro Bend

• Evanescent

• OTDR (impedance change)

Phase modulation Sensors:-

• Mach-Zehnder

• Michelson

• Fabry-Perot

• Sagnac

•Grating

Intensity (Amplitude) Sensors

Why Intensity Modulation

• Simple optical setup

• Broadband or mono-chromatic light source

• Less sensitive but cheaper to make

In this case, the signal to be measured (the measurand), intensity (amplitude) modulates the light carried by an optical fiber or waveguide. 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; $I0$ = optical power reaching the detector when there is no modulation; and P = perturbation (measurand).

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

$$S = q\, I_o\, R\, m$$

Where q = detector responsivity (A/W);

R = load resistance.

m= normalized modulation index

Four noise sources often encountered in connection with optical detectors.

•Johnson noise

•Shot noise

•1/f noise

•Photon noise

Johnson (thermal) noise

1. All resistive materials

2. Depends only on temp. and bandwidth of measuring system

The Johnson noise contribution is provided by the shunt resistance of the device, series resistance and the load resistance.

Johnson noise is generated by thermal fluctuations in conducting materials. It is sometimes called thermal noise. It results from the random motion of electrons in a conductor. The electrons are in constant motion, colliding with each other and with the atoms of the material. Each motion of an electron collisions represents a tiny current. The sum of all these currents taken over a long period of time is zero, but their random fluctuations over short intervals constitute Johnson noise. To reduce the magnitude of Johnson noise, one may cool the system, especially the load

resistor. One should reduce the value of the load resistance, although this is done at the price of reducing the available signal. One should keep the bandwidth of the amplification small; one Hz is a commonly employed value.

Shot noise

• Seen in photodiodes under reverse bias (dark current noise) with no photon input, the term shot noise is derived from fluctuations in the stream of electrons in a vacuum tube. These variations create noise because of the random fluctuations in the arrival of electrons at the anode. The shot noise name arises from the similarity to the noise of a hail of shots striking a target. In semiconductors, the major source of shot noise is random variations in the rate at which charge carriers are generated and recombine. This noise, called generation-recombination or gr noise is the semiconductor manifestation of shot noise. Shot noise may be minimized by keeping any DC component to the current small, especially the dark current, and by keeping the bandwidth of the amplification system small.

1/f noise

Larger noise powers at lower frequencies.

No theory: not well understood. Seems to be related to contacts, surfaces, other potential barriers, usually much smaller than shot noise except at very low frequency. The term 1/f noise (pronounced one over f) is used to describe a number of types of noise that are present when the modulation frequency f is low. This type of noise is also called excess noise because it exceeds shot noise at frequencies below a few hundred Hertz. The mechanisms that produce 1/f noise are poorly understood. The noise power is inversely proportional to f, the modulation frequency. This dependence of the noise power on modulation frequency leads to the name for this type of noise.

To reduce 1/f noise, an optical detector should be operated at a reasonably high frequency, often as high as 1000 Hz. This is a high enough value to reduce the contribution of 1/f noise to a small amount.

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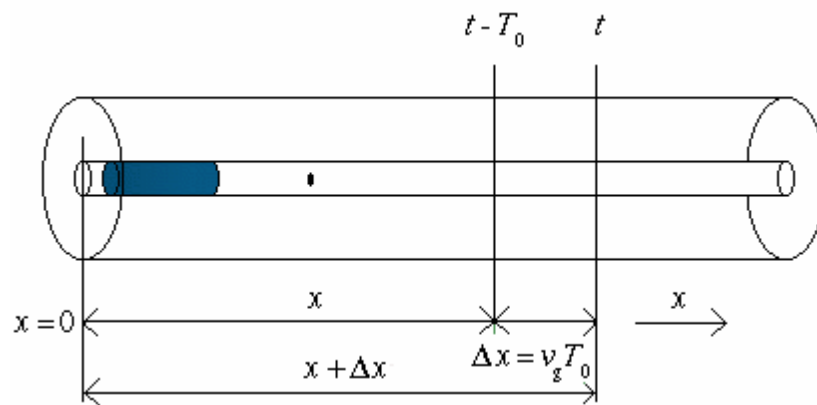
Position of the optical impulse in the fiber core at time t

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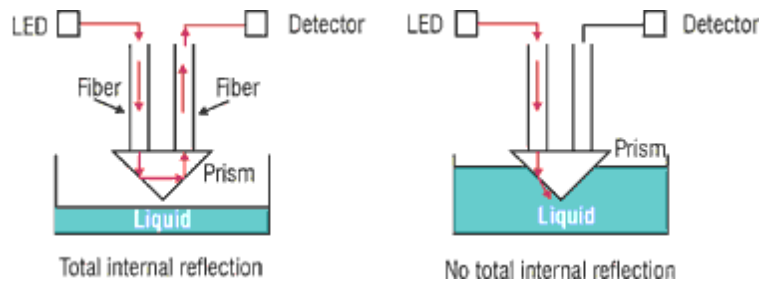
A liquid-level sensor based on changes in the critical angle due to liquid level moving up to contact the sides of the prism (using total internal reflection in air).

Phase Modulation

Why Phase modulation

• High Sensitivity (i.e. 0.1nm resolution)

• Relatively simple optical setup

• Independent of baseline intensity.

Interferometers

•Mach-Zehnder

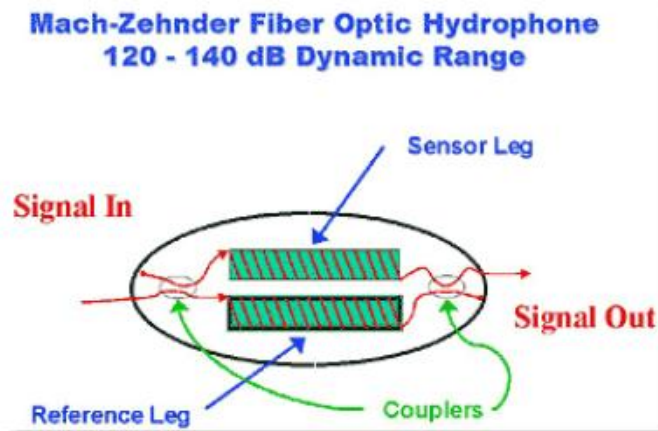•Michelson

•Sagnac Interferometer

•Fabry-Perot Interferometer

Interferometers is an optical instrument that splits a wave into two waves using a beam splitter and delays them by unequal distances, redirect them using mirrors, recombine them using another beam splitter and detect the intensity of their superposition.

Mach-Zehnder Interferometer
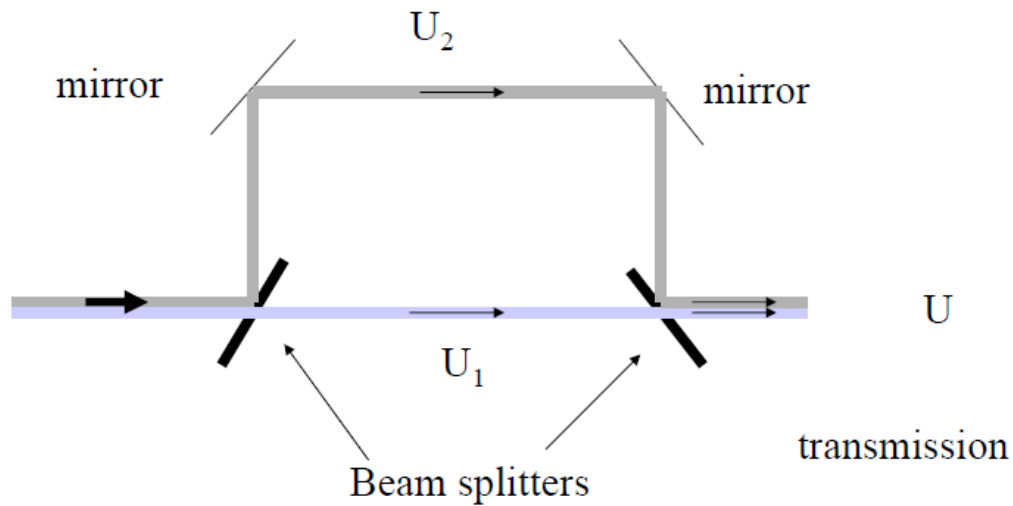
Fiber-optic hydrophone

(Mach-Zehnder Interferometer)
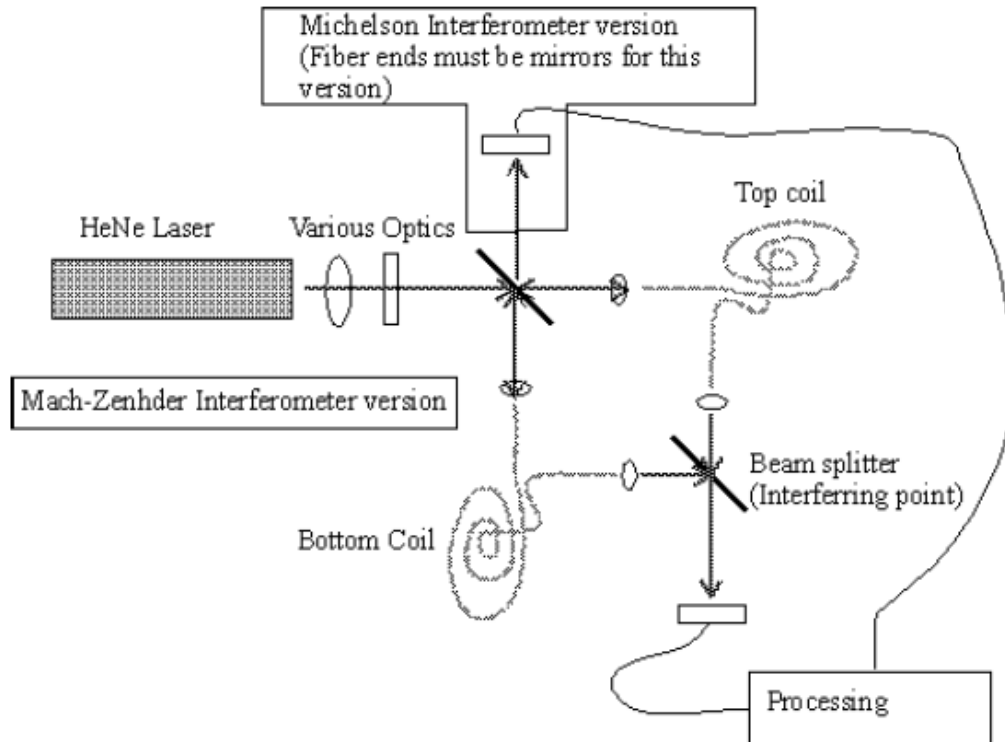
Michelson Interferometer
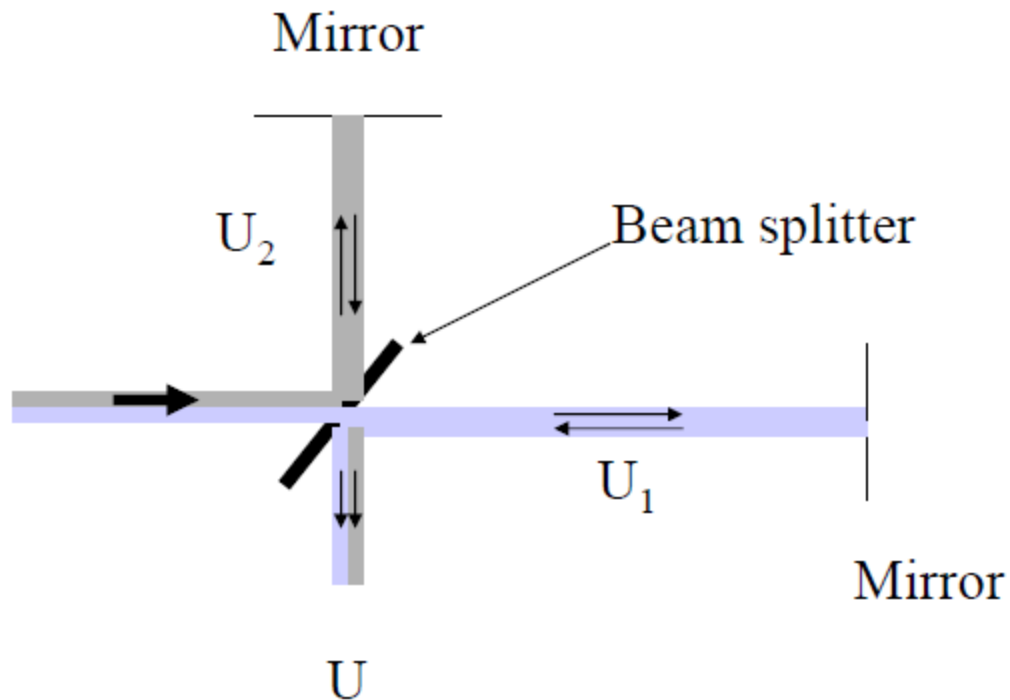
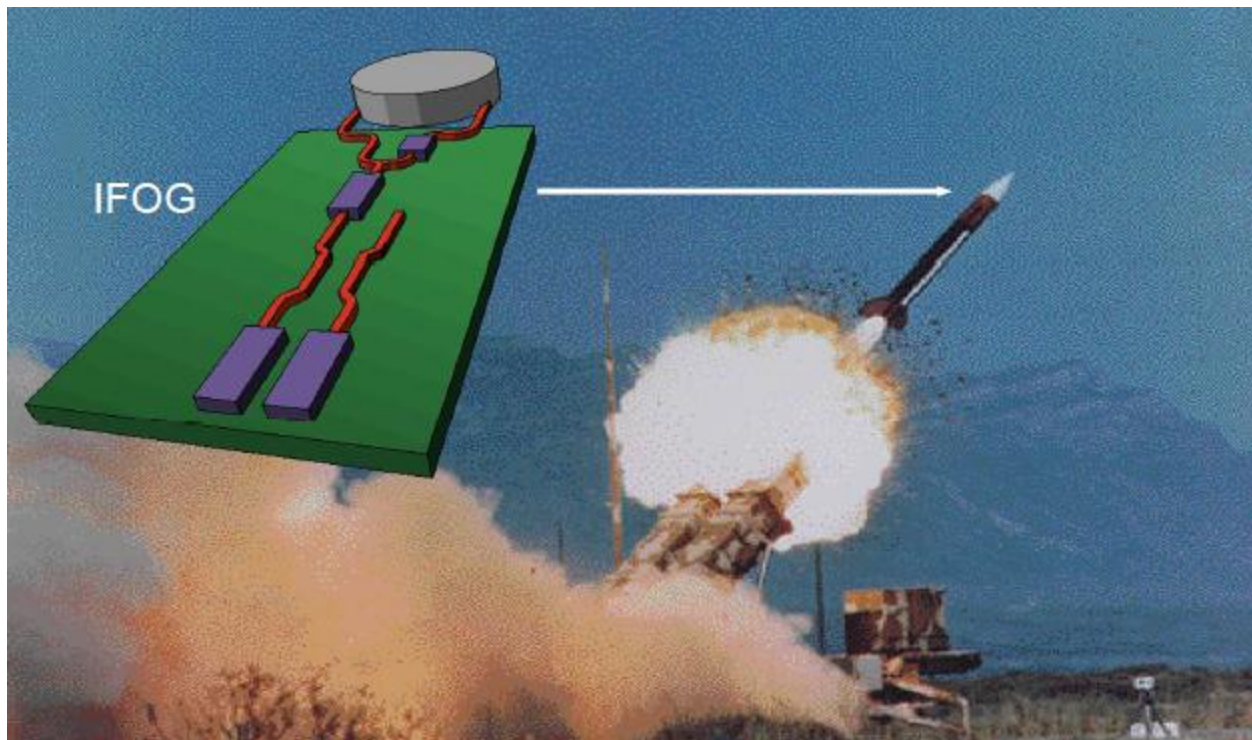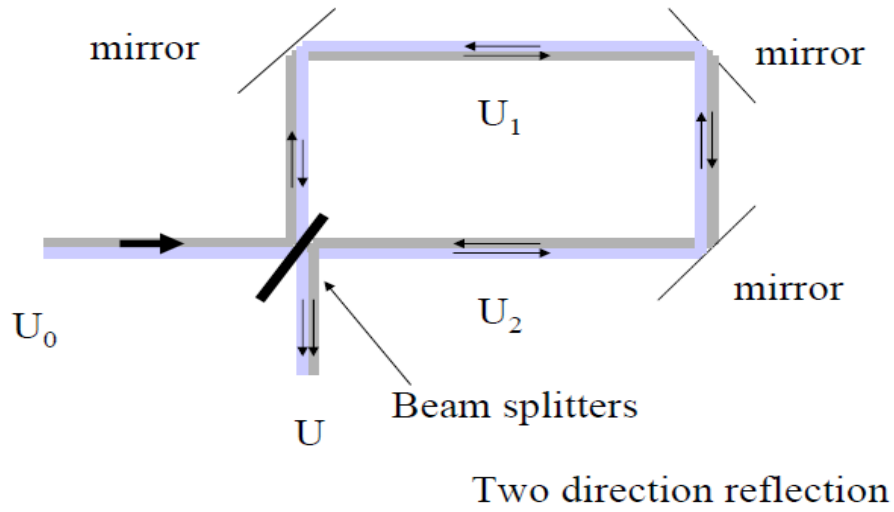Differences between Michelson and Mach-Zehnder Interferometer:

1. Single fiber coupler.

2. Pass through reference and signal fibers twice, phase shift per unit length doubled.

3. Interrogated with only single fiber between source/detector and sensor.

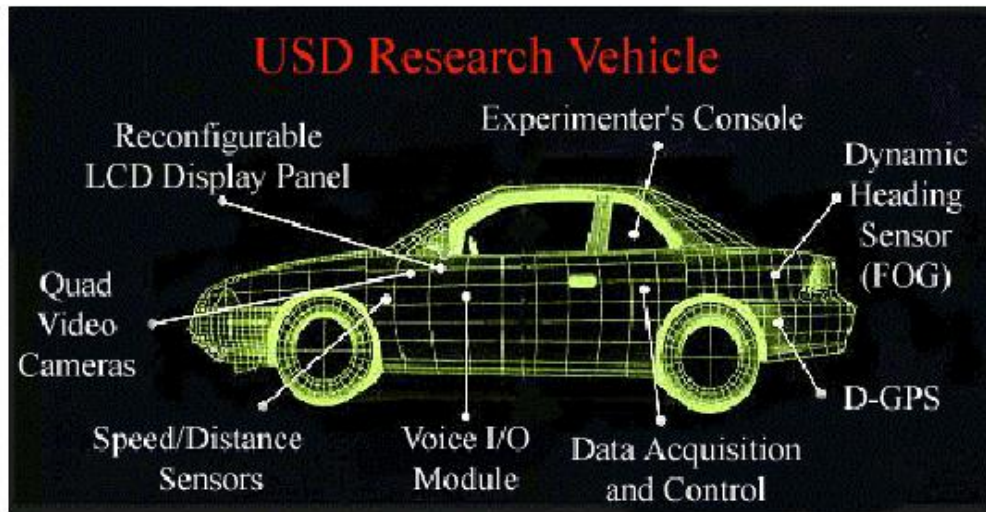# Fiber-optic hydrophone

(Michelson Interferometer)

Sagnac Interferometer

Two direction reflection
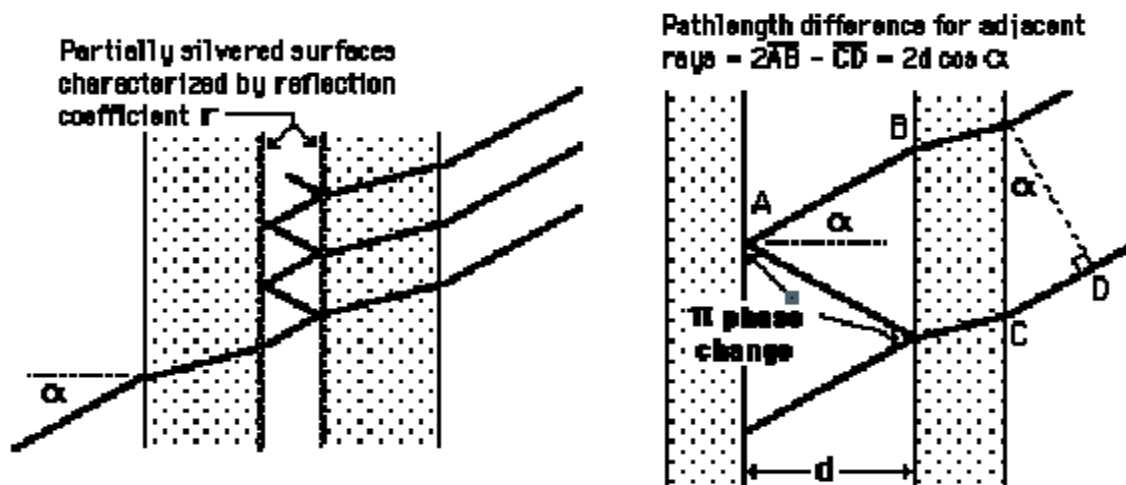

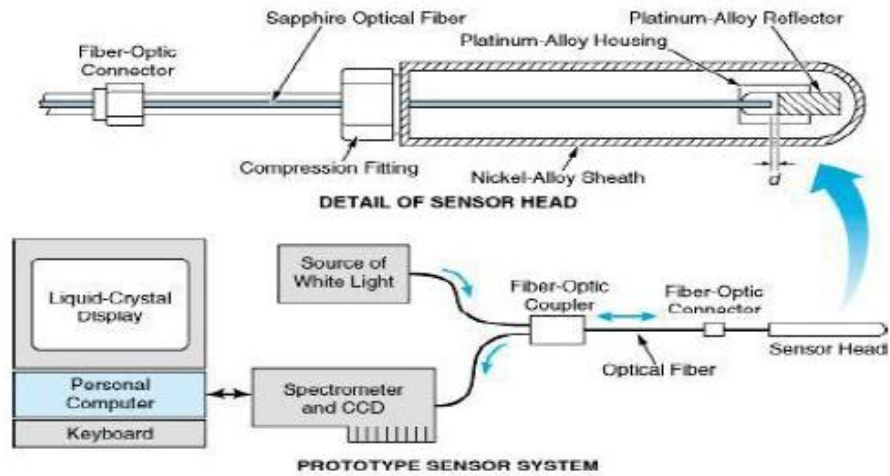**Sagnac Interferometric Fiber-Optic Gyroscope.**

Test Platform

Automobile Yaw Rate Sensor for Assessing the Intrusiveness of Secondary Tasks
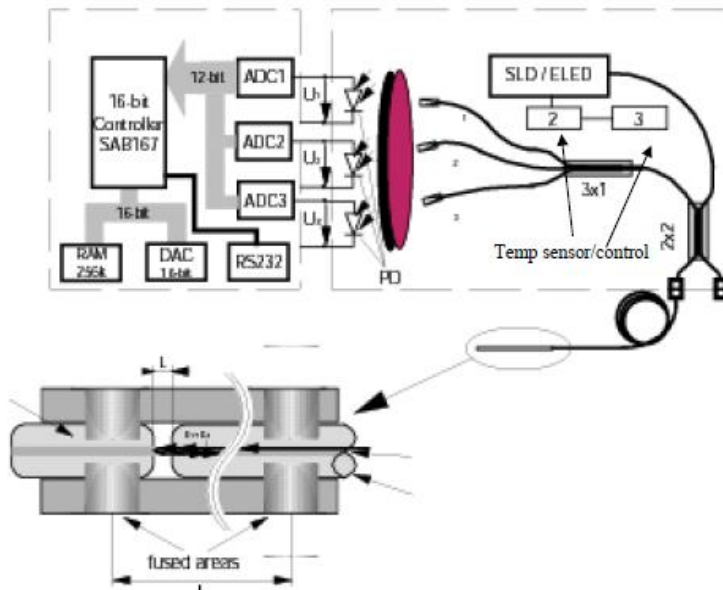
Fabry-Perot Interferometer

Interference of an infinite number of waves progressively smaller amplitude and equal phase difference.

Fabry-Perot Fiber-Optic Temperature Sensor

Extrinsic Fabry-Perot Interferometer Strain Sensor

3-λ demodulation EEPI