Topic 10

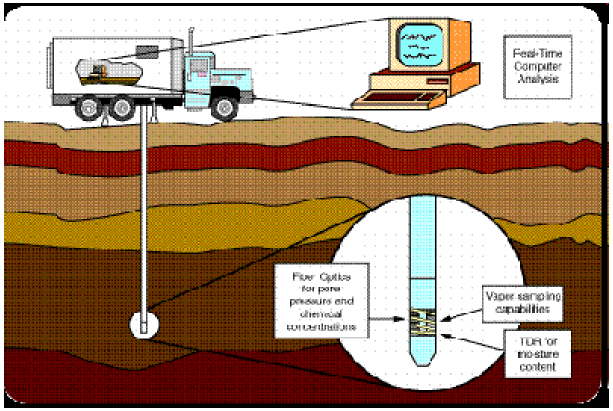
10. Fibre Optic Sensors
    - 10.1 Introduction
    - 10.2 Classification of Fibre Optic Sensors
    - 10.3 Basic structure
    - 10.4 Operation mechanisms
        - 10.4.1 Intensity Modulation
        - 10.4.2 Phase Modulation
            1. Michelson Interferometer
            2. Mach Zehnder Interferometer
            3. Sagnac Interferometer
            4. Fabry-Perot Interferometer

Introduction (1)

- **Major Applications:**

  Monitor or measure any **mechanical change** as a result of external loads, force, pressure, strain/stress, displacement, temperature, acceleration, vibration in a system.
  For example, (1) Reaction of the structure to external loads; (ii) detect variations in crack formation, strain, temperature and corrosion.



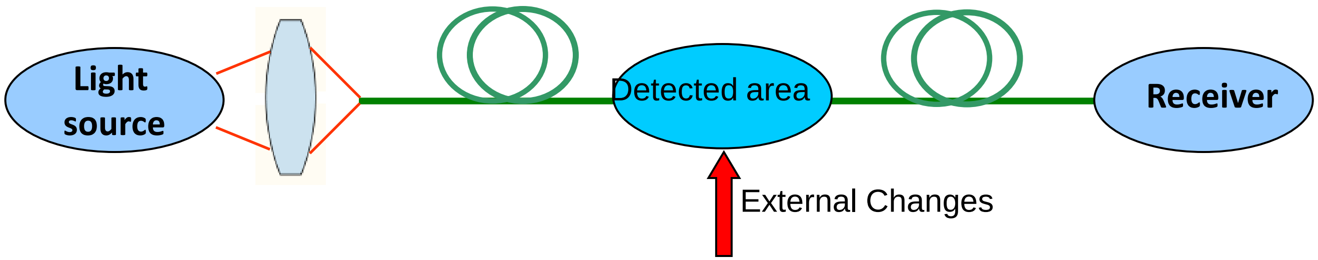


- **Major advantages**

  (1) Multiplex many sensors in a single optical fibre to form a distributed sensor system; (2) Compact size; (3) No electrical power is needed at the remote location; (4) In harsh environment; (5) High sensitivity; (6) Long range operation

Classification of Fibre Optic Sensors

• **Basic FOS system**



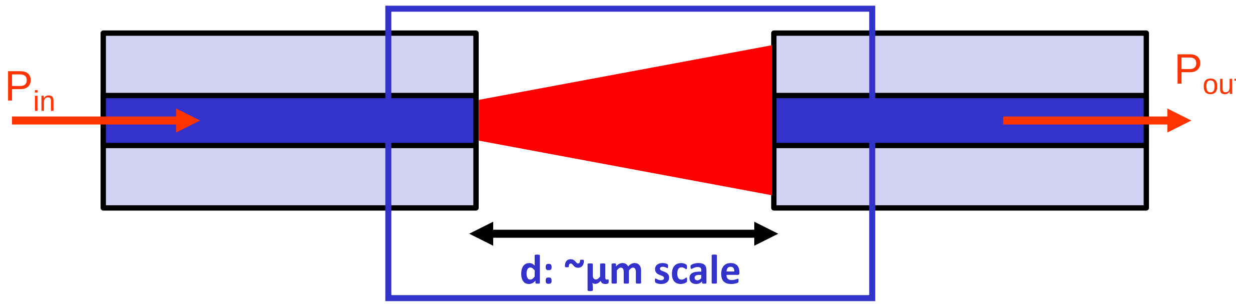
Intrinsic: The optical signal remains in the optical fibre in the detected area, and will not leave the fibre.

Extrinsic: The optical signal has to leave the fibre, and then reaches the sensing region outside and then comes back to the fibre.

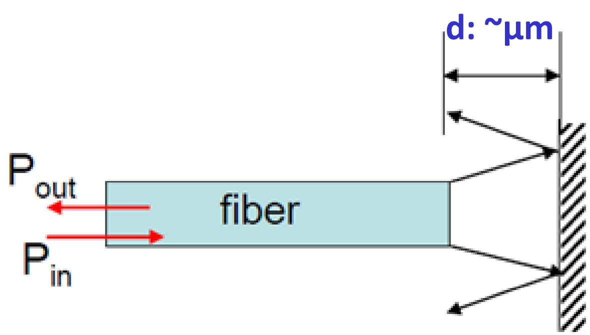
• **Optical modulation mechanisms**

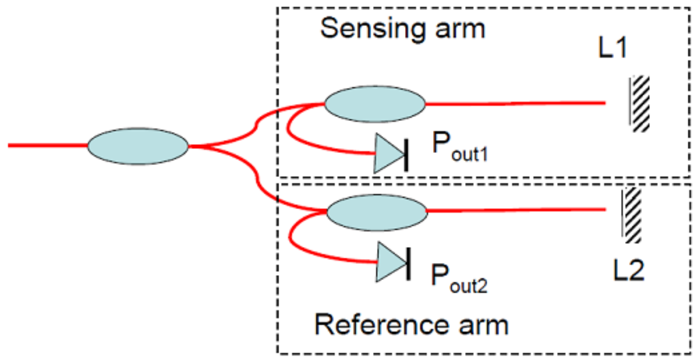
Intensity modulation
Phase modulation
Wavelength modulation
Polarization modulation

Intensity Modulation (1)



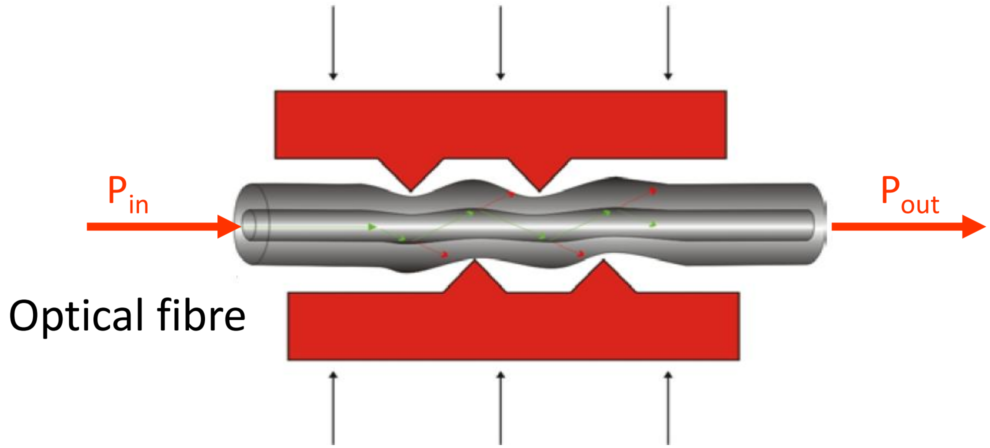
Transmission type: P_{out} depends on displacement, used as a distance or pressure sensor; Disadvantage: there is no reference signal used, and thus it suffers from light source intensity fluctuation and change in fiber loss

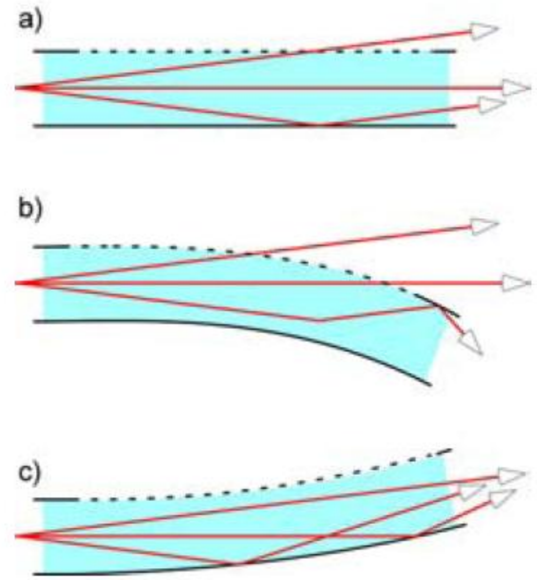




Reflection type: P_{out}-P_{in} depends on displacement, used as a distance sensor
In order to minimise the power fluctuation issue: use differential intensity signal from sensing arm and reference arm, $P_{out1} - P_{out2} \propto L_1 - L_2$

Intensity Modulation (2)

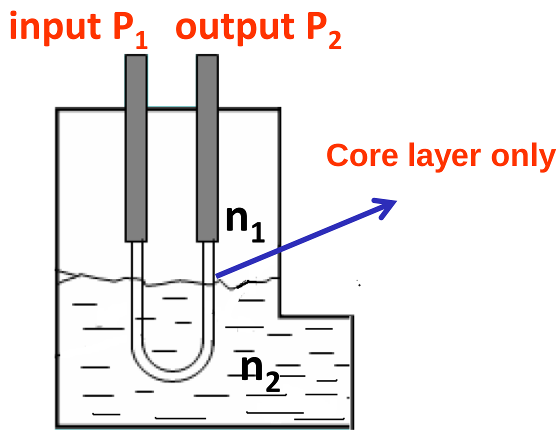




Micro-bending (~µm scale) due to pressure, deformation, stress, can be measured: P_{out}/P_{in} depending on a change in these parameters, used as a **microbending sensor**

Similar to microbending
Used as a **curvature measurement**

Intensity Modulation (3)



The output power also depends on the contrast of refractive index between core layer and cladding layer. If an optical fibre without a cladding layer is put into a solution, the output power will be changed with the level of the solution

Strong points:

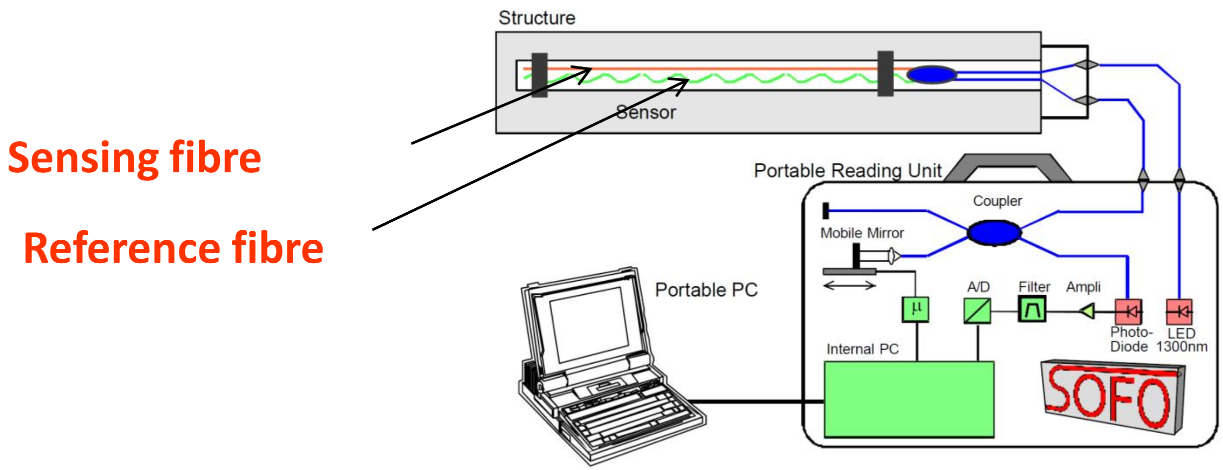
- Used for many aspects
- Both design and signal analysis are easy

Weak points:

- Suffering from intensity fluctuations
- Low sensitivity

Phase Modulation (1)

- **Phase** of can be changed by the external perturbations (distance, refractive index) so that the fibre optic sensor can also be built based on the light phase changes.



- The phase difference is **detected interferometerically**, by comparing to that in a reference fibre.

- The phase-modulation FOS is **more sensitive** than Intensity modulation FOS

- Major approaches for obtaining phase modulation

  (1) Michelson interferometer ; (2)Mach-Zehnder interferometer; (3) Sagnac interferometer; (4) Fabry-Perot interferometer; (5) Grating interferometers

Phase Modulation (2)

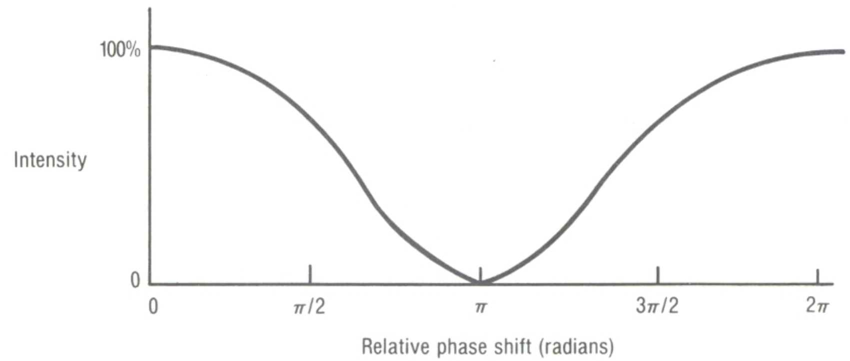
• For a lightwave of wavelength, λ, travelling in a fibre of length L, **Phase angle, ϕ**, can be calculated:

$$\phi = 2\pi n_1 L/\lambda_0$$

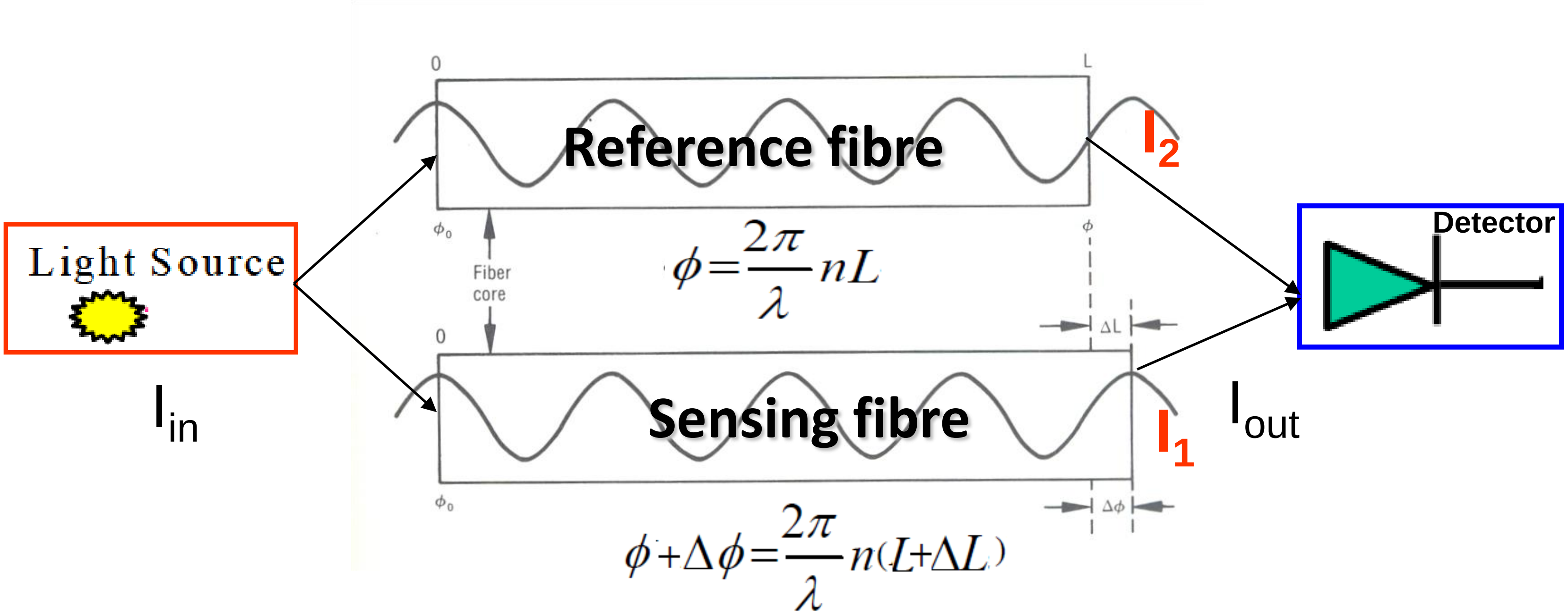
Where n_1: the refractive index; λ_0 is the wavelength in vacuum, ϕ is in radians

• Phase difference (**$\Delta\phi$**) due to a change in length (**ΔL**) and/or refractive index (**Δn_1**)

$$\phi + \Delta\phi = 2\pi[n_1 L + n_1 \Delta L + \Delta n_1 L]/\lambda_0$$



Phase Modulation (3)



Wave :

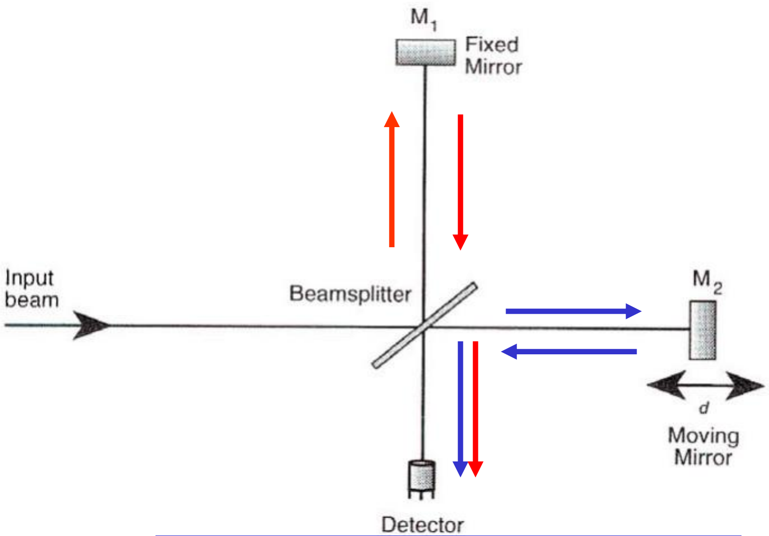
$E_1 = E_0 \cos(\omega t + \boldsymbol{\phi})$; $E_2 = E_0 \mathrm{cost}(\omega t + \boldsymbol{\phi + \Delta\phi})$

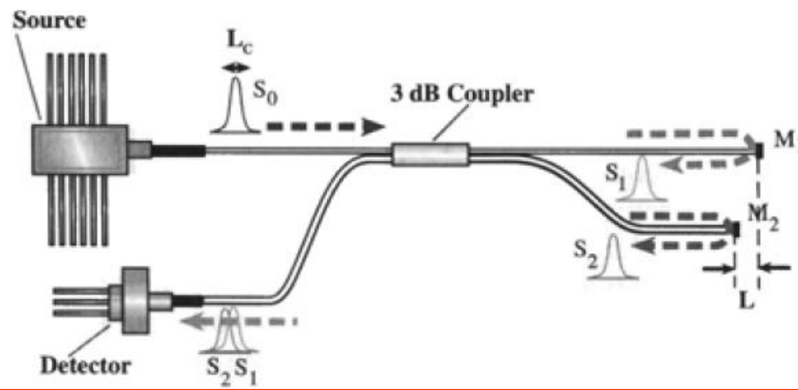
$E_{total} = E_1 + E_2$

$\mathbf{I} \propto E_{total}^2$

$$I = I_1 + I_2 + 2I_1 I_2 \cos(\Delta\Phi) = I_1 + I_2 + 2I_1 I_2 \cos(\tfrac{2\pi}{\lambda} n\Delta L)$$

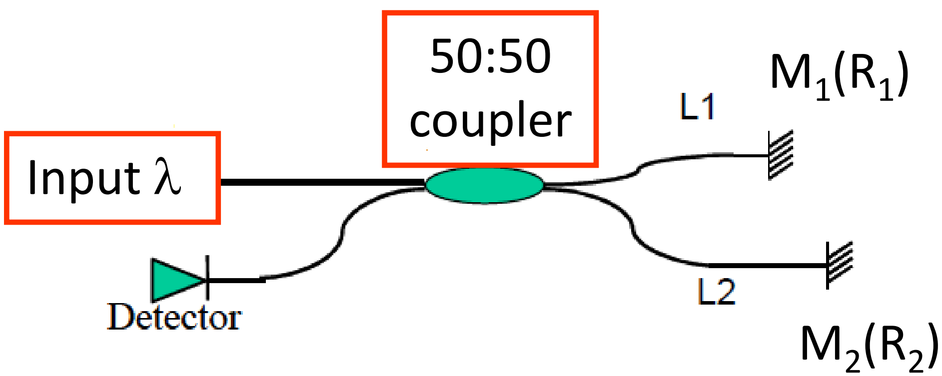
Michelson Interferometer

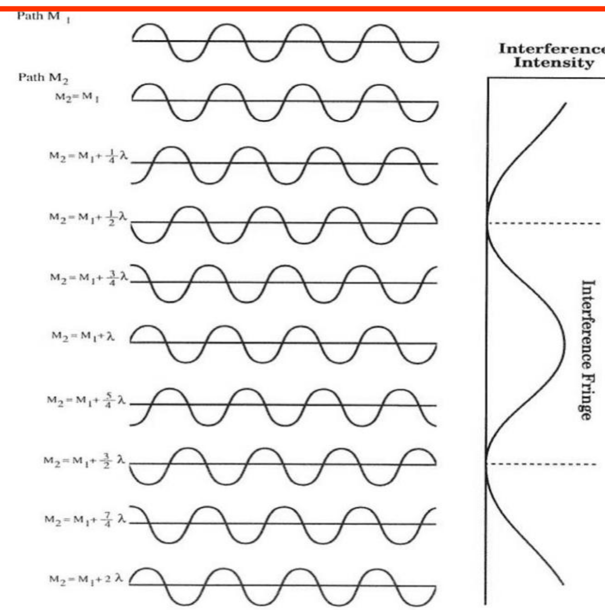




light interference

$$I = \frac{I_0}{4}(R_1 + R_2)[1 + 2\frac{\sqrt{R_1 R_2}}{R_1 + R_2}\cos[2k(L_1 - L_2)]]$$

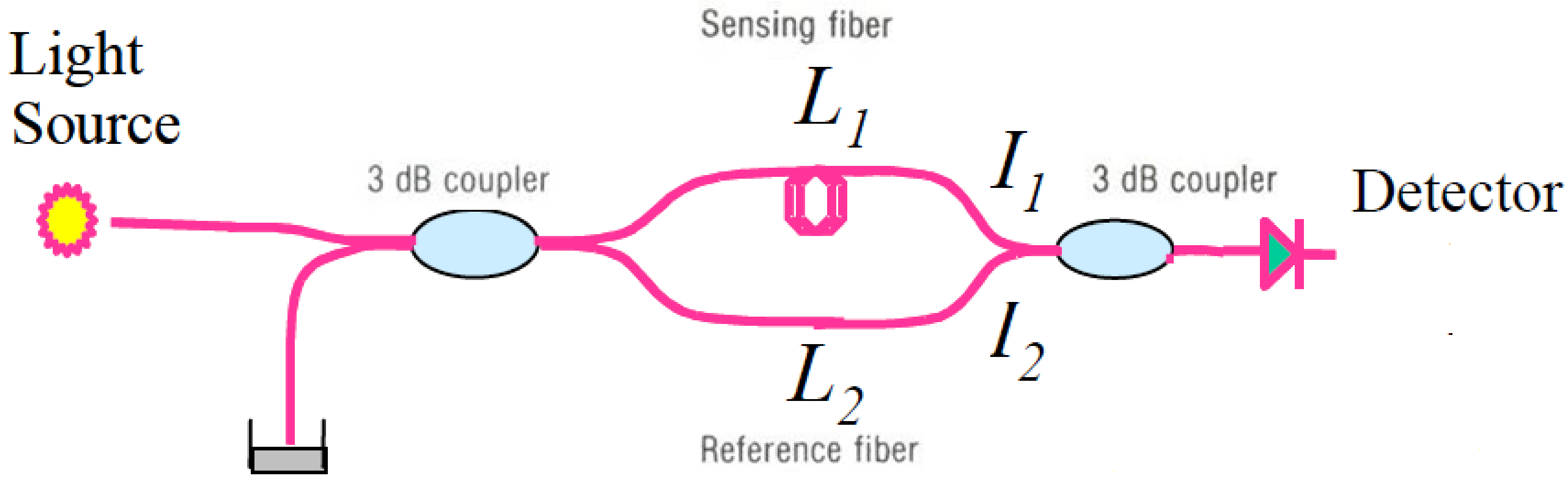




Michelson Interferometer

Optical intensity received

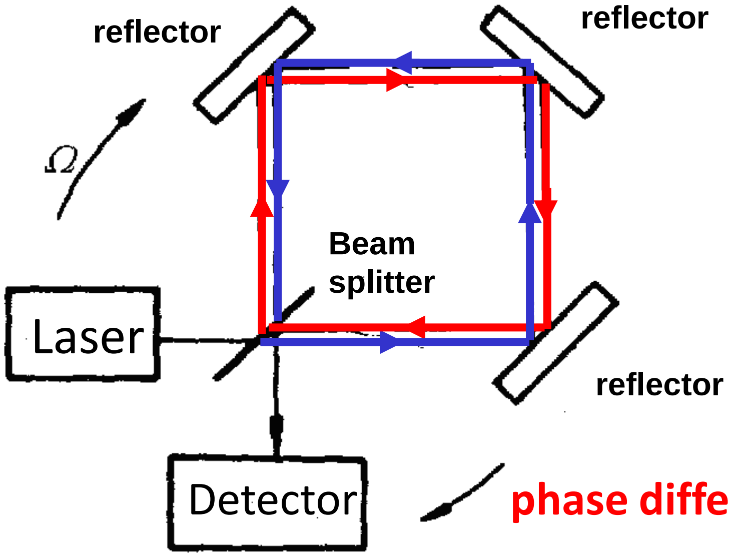
Mach-Zehnder Interferometer

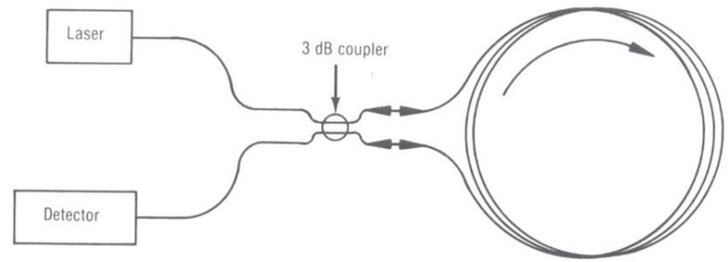


Advantages:

There is no reflected optical signal involved (reflected laser light leads to undesired feedback), and thus undesired feedback effect is reduced

Sagnac Interferometer





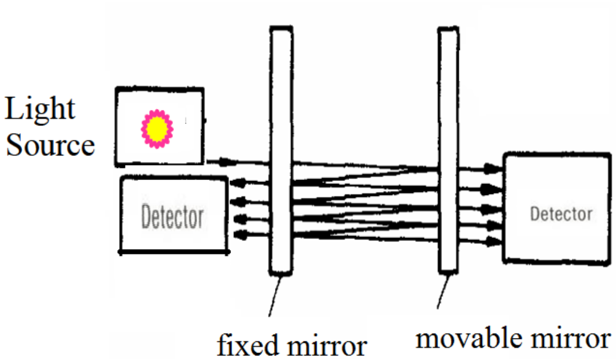
phase difference: $\boxed{2\varphi = \frac{8\pi A}{\lambda_0 C}\Omega}$ A: is coil area o

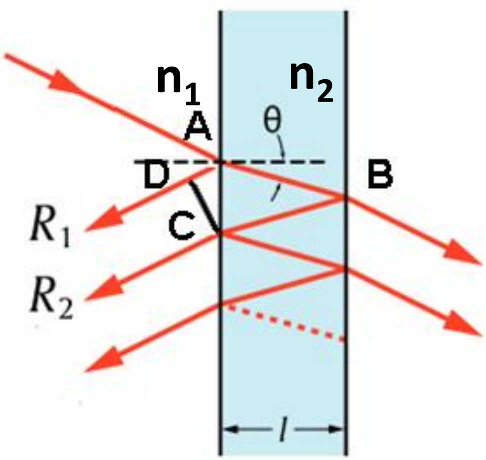
When coil is stationary – no phase difference, as the optical distance in clockwise (red) and anticlockwise (blue) direction is identical

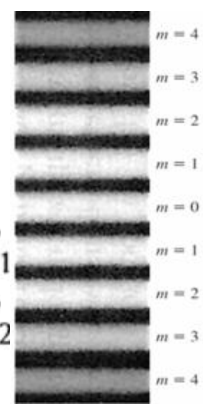
Rotation of the coil causes light propagation time to be different and so a phase difference is generated. For a clockwise rotation, the optical distance in a clockwise direction is longer (same as the rotation direction, "chase") than that in a anticlockwise direction (opposite to rotation direction, "meet")

It is a very sensitive rotation sensor – fibre Optic Gyroscopes – military / satellite / aviation applications.

Fabry-Perot Interferometer (1)







$$\delta = \frac{2\pi}{\lambda}\left[\ (n_2 AB + n_2 BC) - n_1 AD\ \right]$$
$$= \left(\frac{2\pi}{\lambda}\right) 2 n_2 l \cos\theta$$

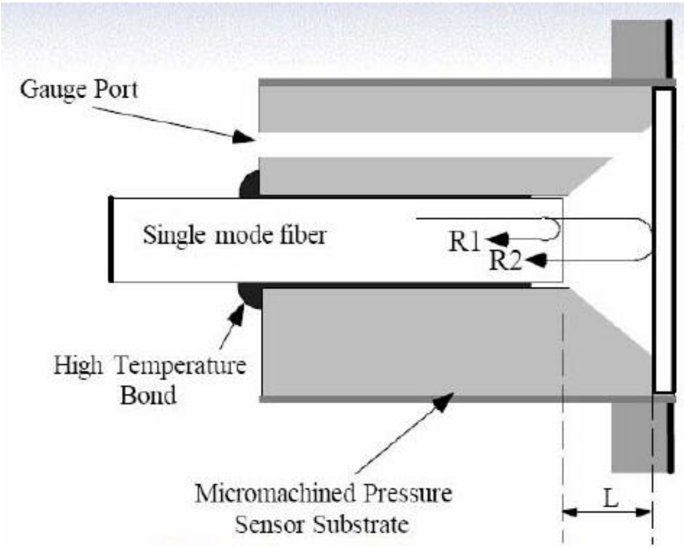
- Instrument which uses multiple beam interference between two partially reflecting plates

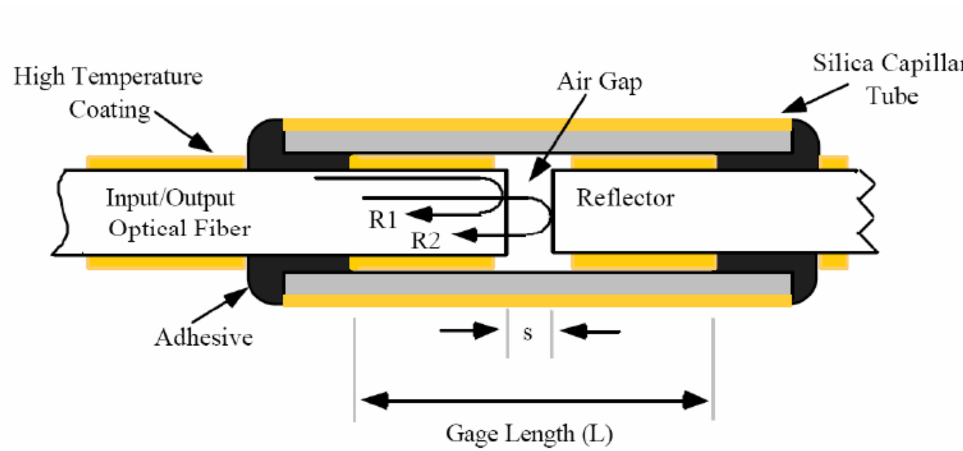
When the optical path difference of beams is integer wavelength, constructive interference gives the strongest optical intensity

When the optical path difference of beams is out of phase, destructive interference quenches the optical intensity

- The intensity of the received signal depends on the thickness (for practical applications, θ=0)

Fabry-Perot Interferometer (2)





Two reflectors: deposited on the sides of two optical fibres (The reflectivity of the reflector determine the sensitivity)

Gauge length: the distance between the spots where the optical fibres are welded

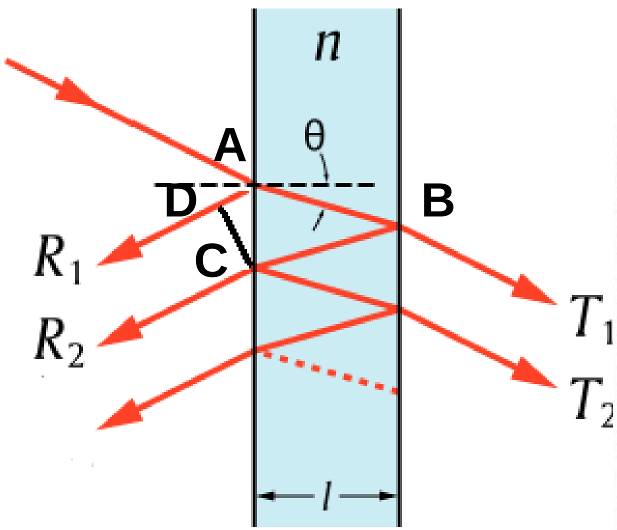
Fabry-Perot Interferometer (3)

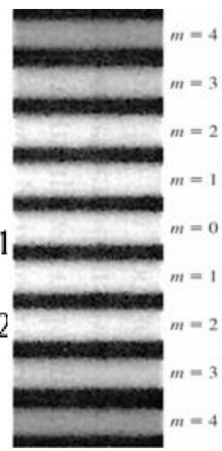
Transmission function of filter is given by
(take a look at the proofs yourself)

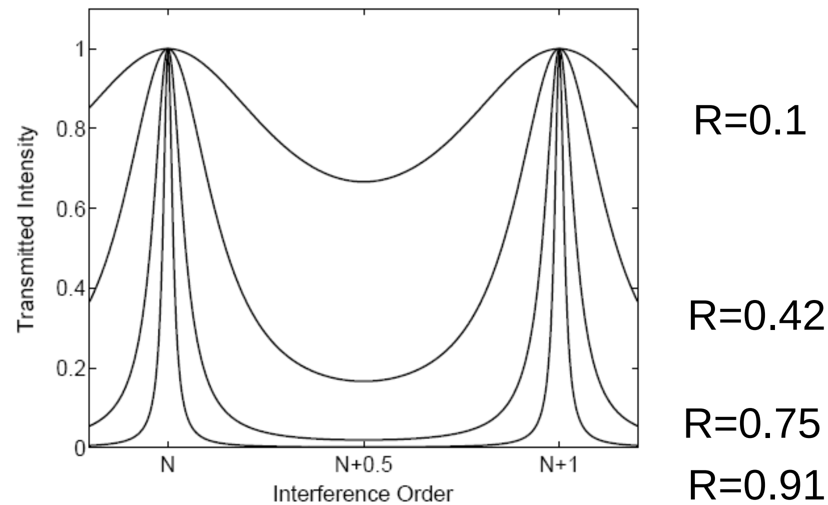
when $R_a = R_b = R$

$$T_e = \frac{(1-R)^2}{1+R^2-2R\cos(\delta)} = \frac{1}{1+F\sin^2\left(\frac{\delta}{2}\right)}$$

Finesse: $F = \dfrac{4R}{(1-R)^2}$







- Even higher sensitivity sensors – temperature, stress, strain, displacement. Practical implementation – separation of mirrors in FP filter is changed by displacement, pressure, temperature, etc.
- Reflectivity (Finesse) determines sensitivity.

Summary

- Fibre Optic Sensors can be applied in many aspects to in-situ monitor any change due to external perturbation

- For high precision measurement of displacement, interference properties of light may be exploited to give high sensitivity measurements.