Sensors and Actuators
(เซนเซอร์และตัวขับเร้า)

Chapter 1: Introduction of Sensors and Actuators, Types of Sensors

By

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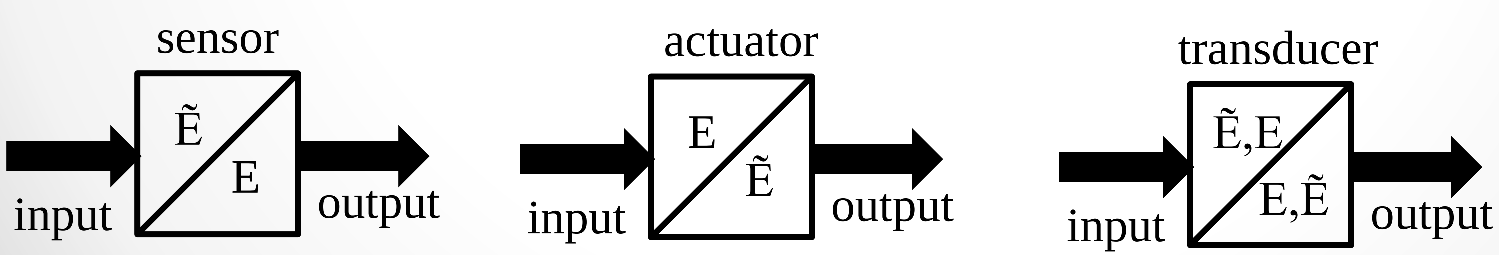
Jan 2023

Introduction of Sensors&Actuators

- A sensor is a device that converts a nonelectrical quantity Ẽ into an electrical output signal E
- An actuator is a device that converts an electrical signal E into a nonelectrical quantity Ẽ
- A transducer is a device that can be either a sensor or an actuator.
- There are 6 primary energy domains and the associated symbols are as follows:
  - ✓ Electrical (ไฟฟ้า) : E
  - ✓ Thermal (อุณหภูมิ) : T
  - ✓ Radiation (การแผ่รังสี) : R
  - ✓ Mechanical (เชิงกล) : Me
  - ✓ Magnetic (แม่เหล็ก) : M
  - ✓ Bio(chemical) (ชีวเคมี) : C



Basic input-output representation

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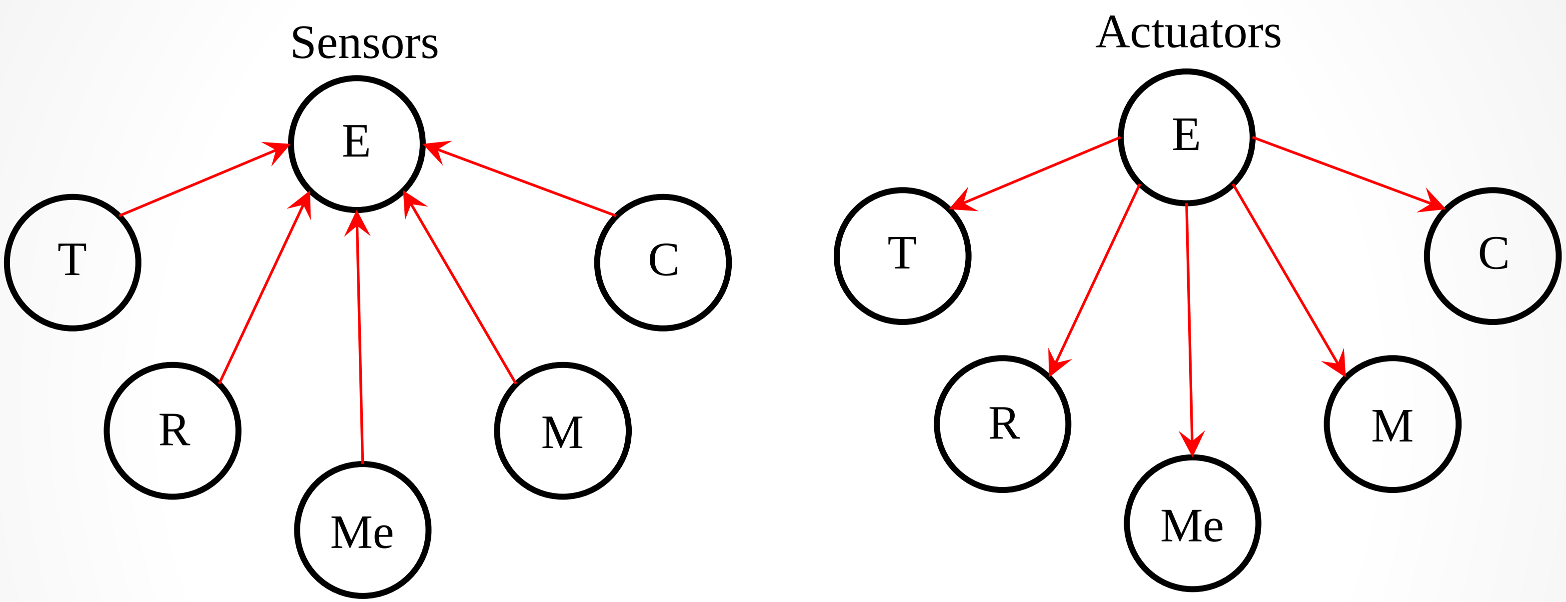

Vectorial representation of sensors and actuators.

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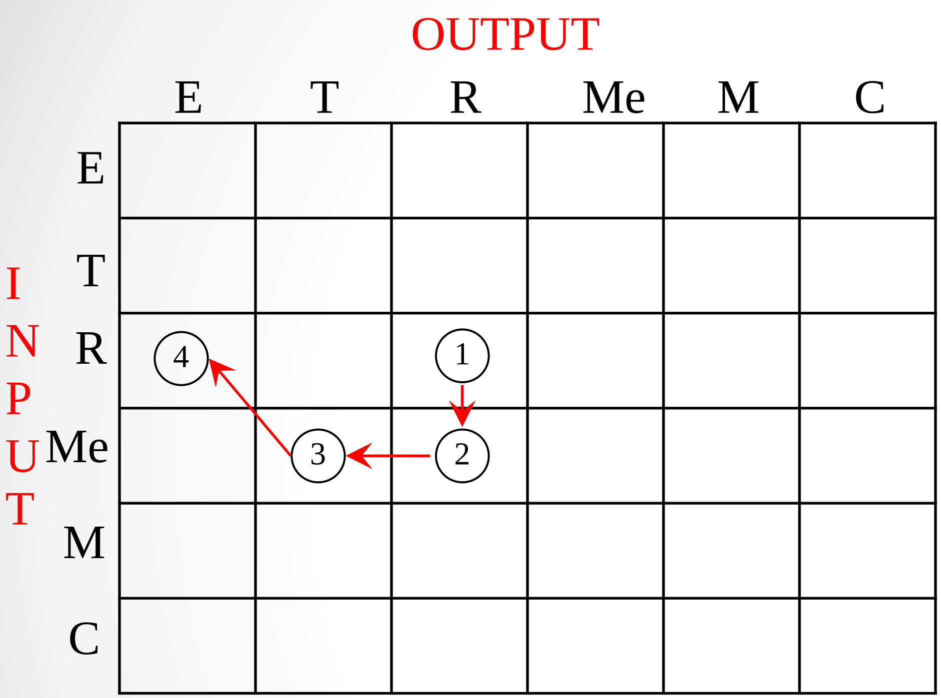
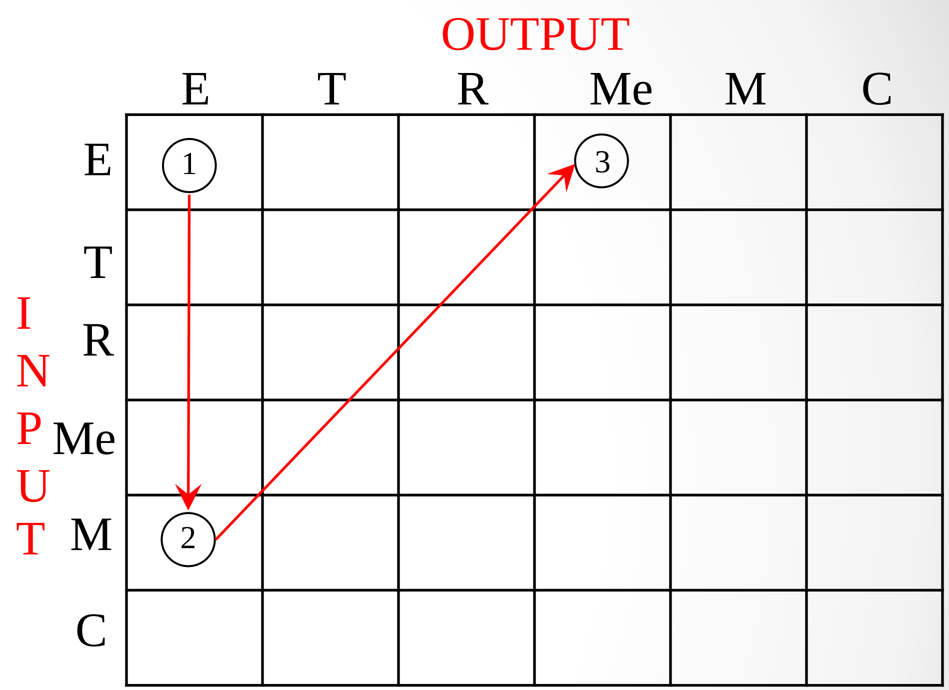


Four-stage radiation sensor



Three-stage magnetic actuator

Vectorial representation of a multi-stage transducer

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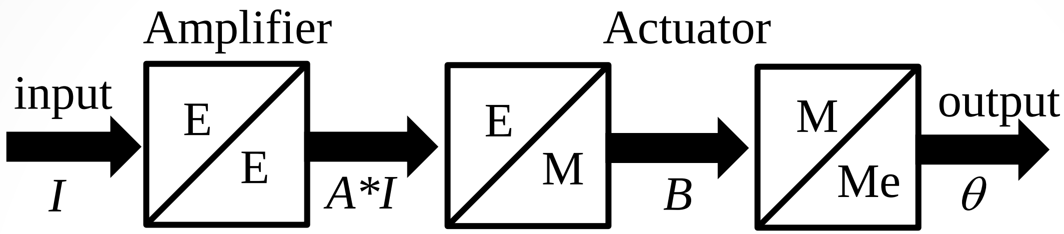
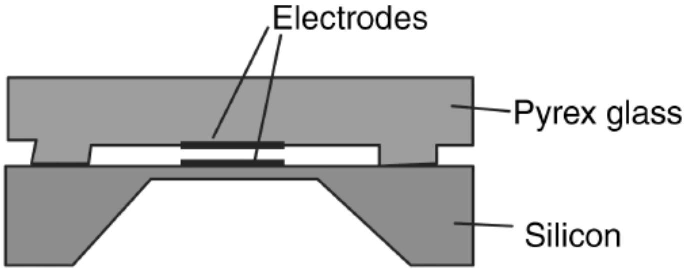


- Block-diagram representation of the transduction processes within a magnetic actuator (i.e. electromagnetic motor).

- Actuator system together with a power amplifier (A) on the front end to enhance the small electrical actuating input current signal I. In this case, the current through a coil induces a magnetic field B, which induces a torque on the rotor and hence outputs a rotational motion θ.

Capacitive Sensors

➢ Capacitive sensors consist of a pair of electrodes arranged in such a way that one of the electrodes moves when the input variable (pressure, acceleration or rate) is applied.



➢ In a parallel plate capacitor, the ***capacitance*** C is given by: $C = \frac{\varepsilon A}{d}$

➢ For a circular diaphragm sensor, the capacitance under deflection is as follows:

$$C = \iint \frac{\varepsilon}{d - w(r)} r\,dr\,d\theta$$

$$w(r) = \frac{Pa^4}{64D}\left[1 - \left(\frac{r}{a}\right)^2\right]^2$$

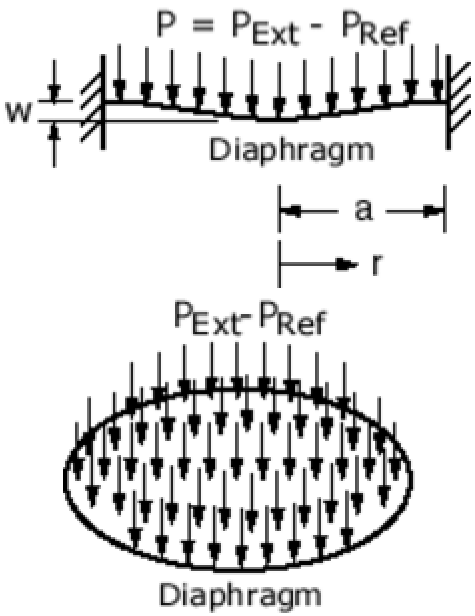
where *w(r)* is the deflection of the diaphragm, *r* is the radial distance from the center of the diaphragm, *a* is the diaphragm radius and *P* is the applied pressure.

CAPACITIVE SENSORS

$$D = \frac{Eh^3}{12(1-\nu^2)}$$

The flexural rigidity, D , where E, h and ν are the Young's modulus, thickness and Poisson's ratio of the diaphragm, respectively

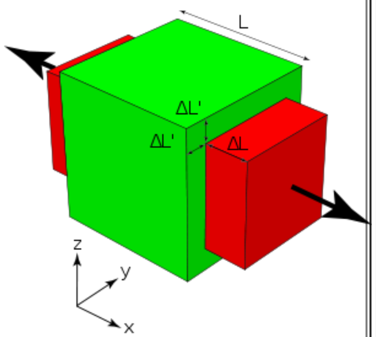
Clamped circular plate with uniformly distributed load



$$w(r) = \frac{Pa^4}{64D}\left[1-\left(\frac{r}{a}\right)^2\right]^2$$

$$w_{max} = w(0) = \frac{Pa^4}{64D}\left[1-\left(\frac{r}{a}\right)^2\right]^2$$

$$\Rightarrow P = \frac{64D}{a^4\left[1-\left(\frac{r}{a}\right)^2\right]^2} w_{max}$$

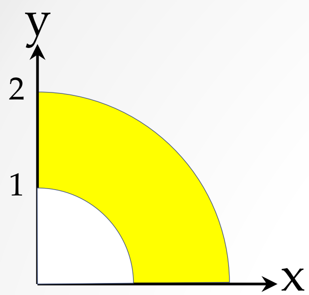


where $D = \frac{Eh^3}{12(1-\nu^2)}$ is the bending rigidity of the plate, and h and ν are the thickness and Poisson's ratio of the plate material, respectively.

$$\text{Poisson's ratio}(\nu) = \frac{\text{Lateral Strain}}{\text{Axial Strain}}$$

- Capacitive sensing utilizes the ***capacitance change*** induced by the deformation of the diaphragm to convert the sensory information (pressure, force, etc.) into electrical signals (such as changes in oscillation frequency, time, charge and voltage).

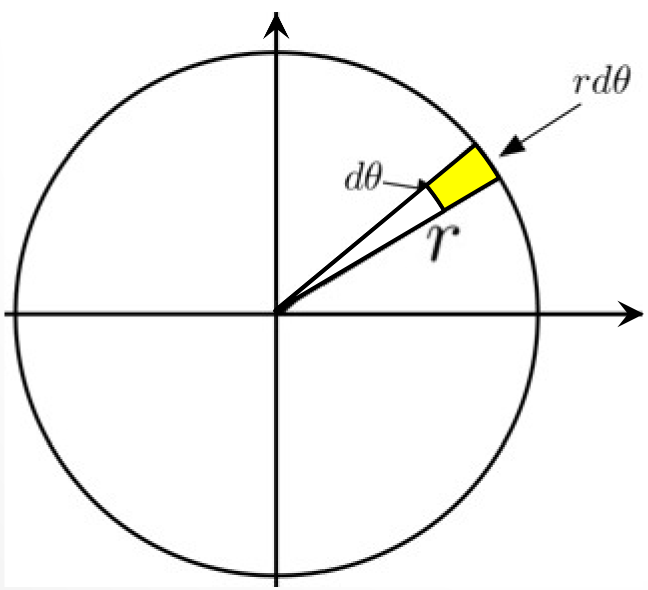
Double Integrals in Polar Coordinates



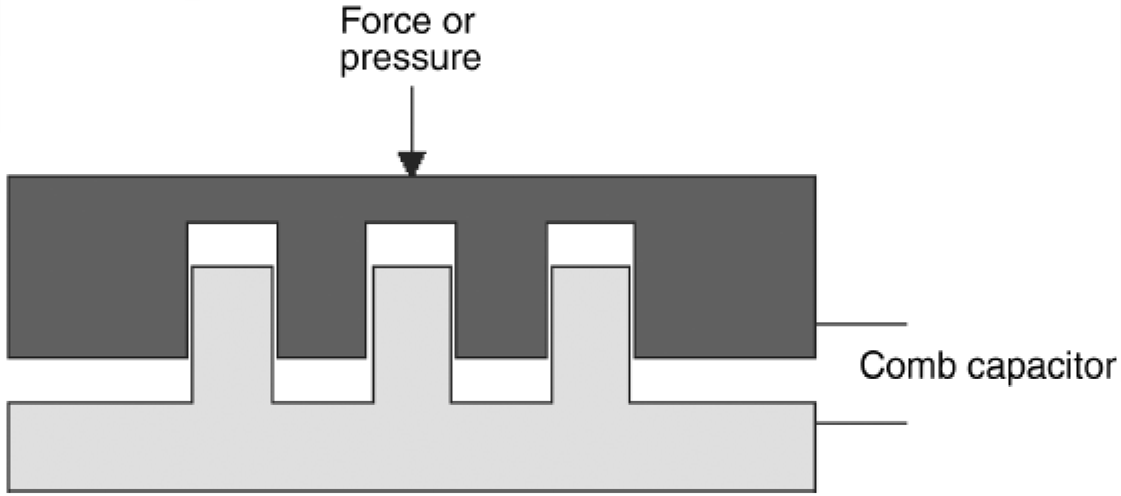
$$\int_0^{\frac{\pi}{2}}\int_1^2 dA = \int_0^{\frac{\pi}{2}}\int_1^2 r\,dr\,d\theta$$

$$\int_0^{\frac{\pi}{2}}\int_1^2 r\,dr\,d\theta = \int_0^{\frac{\pi}{2}}\left[\frac{r^2}{2}\right]_1^2 d\theta = \frac{3}{2}[\theta]_0^{\frac{\pi}{2}} = \frac{3\pi}{4}$$

$$\frac{circle\ radius\ of\ 2}{4} - \frac{circle\ radius\ of\ 1}{4} = \frac{\pi(2^2)}{4} - \frac{\pi(1^2)}{4} = \frac{3\pi}{4}$$



Capacitive Sensors



➢ Comb-type electrostatic sensing is made possible by micromachining technologies. In this case, the area between the plates is made to vary as the overlap between the 'fingers' change. Hence, this type of sensor has a much broader linear range than the parallel-plate type.

➢ Capacitive microsensors can be used for measuring pressure, force, acceleration, flow rate, displacement, position, orientation measurement, etc.

Piezoelectric Sensors

- The word ***piezoelectricity*** means electricity resulting from pressure.

- These sensors are based on the **piezoelectric effect** observed in some materials. In this, an electrical charge change is generated when a mechanical stress is applied across the face of a piezoelectric film.

- Examples of such materials include lead zirconate titanate (PZT) ($\mathbf{Pb[Zr_xTi_{1-x}]O_3}$), lead metaniobate ($\mathbf{PbNb_2O_6}$), lead titanate ($\mathbf{PbTiO_3}$) , quartz ($\mathbf{SiO_2}$) , Rochelle salt, Barium titanate, lithium niobate ($\mathbf{LiNbO_3}$), and **PVDF** (polymer polyvinyl difluoride) and their modifications.

$$V = gtT$$

A typical structure for a piezoelectric sensing device.

Piezoelectric Sensors

➢ For a piezoelectric disk of thickness t, the voltage (V) generated across the electrode disk, when subjected to a stress (T), where g is the piezoelectric voltage coefficient, defined as the ratio of the field developed to the applied mechanical stress.

$$V = gtT \quad , g = \frac{\text{open cct electric field}}{\text{applied mechanical stress}}$$

➢ The relationship between the dipole moment and the mechanical deformation is expressed by the following constitutive relationships: $D=\varepsilon_o E+eS$,and $T=cS-eE$ where T is the mechanical stress (N/m^2), S is the strain (Unit less), E is the electric field (V/m), D is the flux density (Coulomb/m^2), c is the elastic constant (N/m^2) : Young's modulas , e is the piezoelectric constant and ε_0 is the permittivity of free space (F/m).

➢ It may be noticed that in the absence of piezoelectricity these relationships reduce to Hooke's law and the constitutive relationship for dielectric materials, respectively.

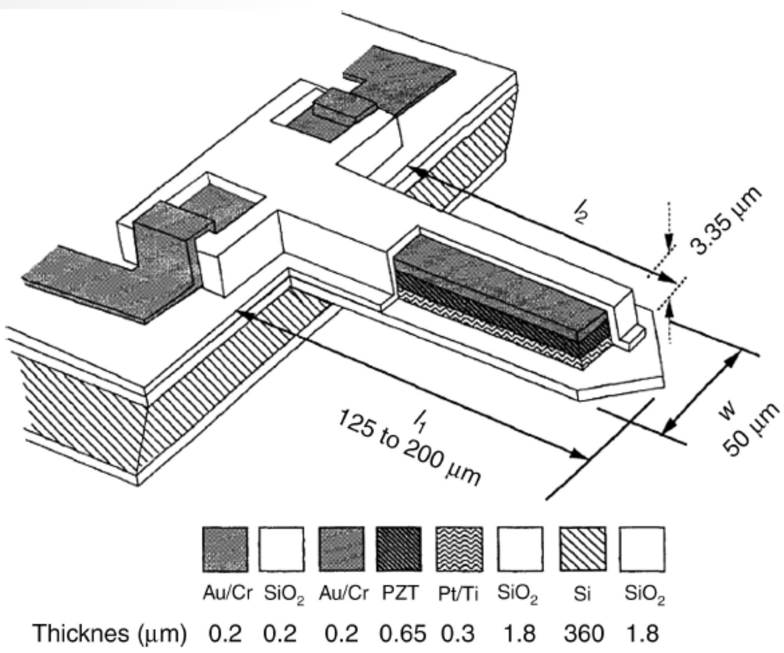
➢ The effectiveness of a piezoelectric material is best expressed in terms of its electromechanical coupling coefficient, K^2. By definition, this is related to other material parameters used in the above constitutive equations by the following:

$$K^2 = \frac{e^2}{c\varepsilon} \, , K = \sqrt{\frac{\text{mechanical energy}}{\text{electrical energy}}}$$

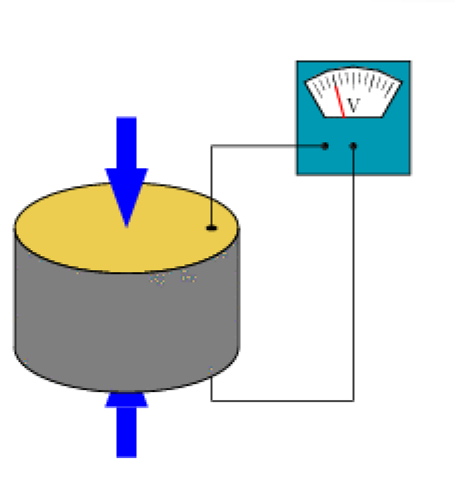
Piezoelectric Sensors

- Piezoelectric sensing is widely used in pressure and force sensors, accelerometers, hydrophones, microphones, etc.

- When Piezoelectric sensor is stressed mechanically by a force, it generates an electric charge.

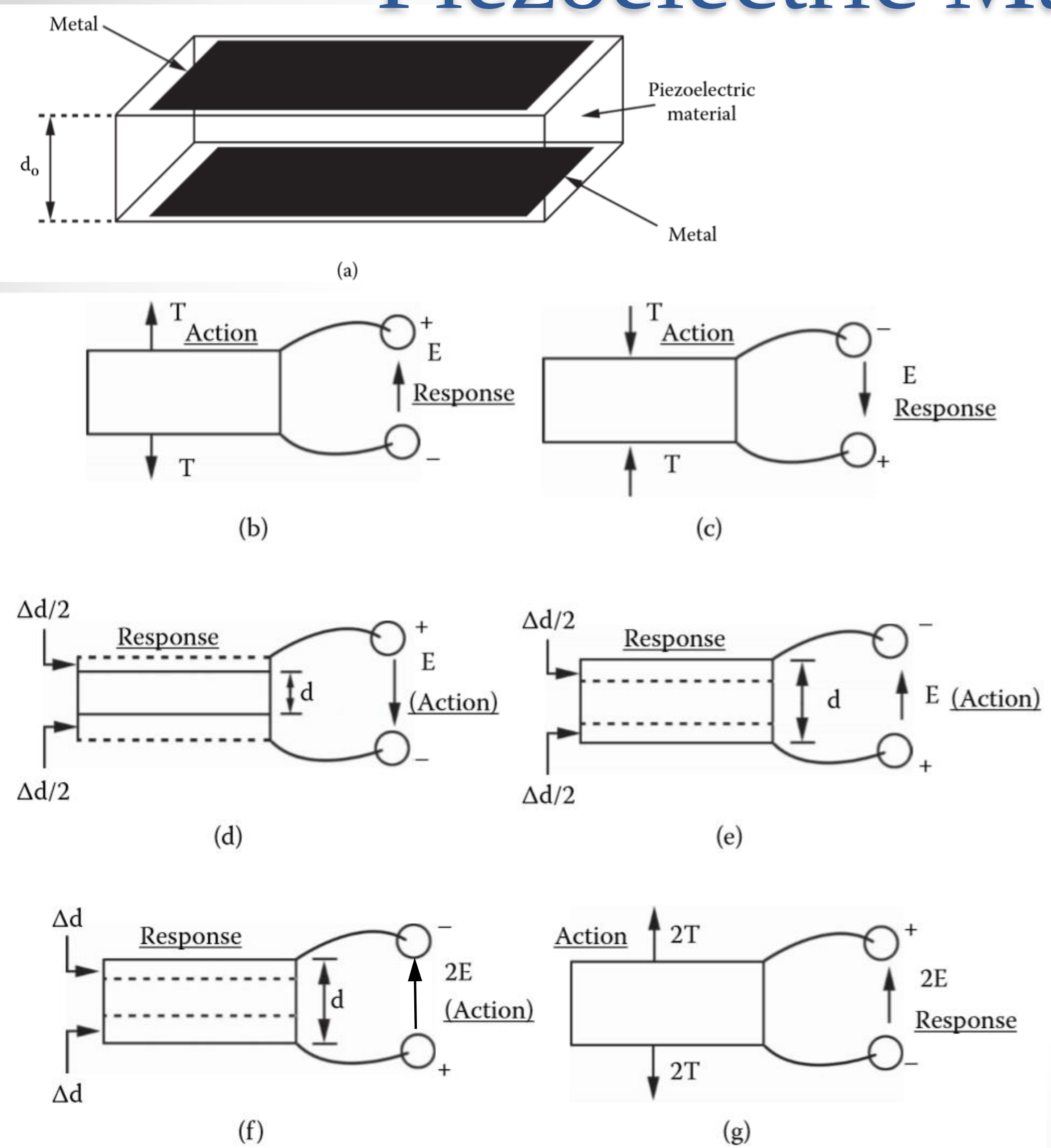


Schematic of a micromachined piezoelectric force sensor.



A piezoelectric disk generates a voltage when deformed

Piezoelectric Materials



direct piezoelectric effect

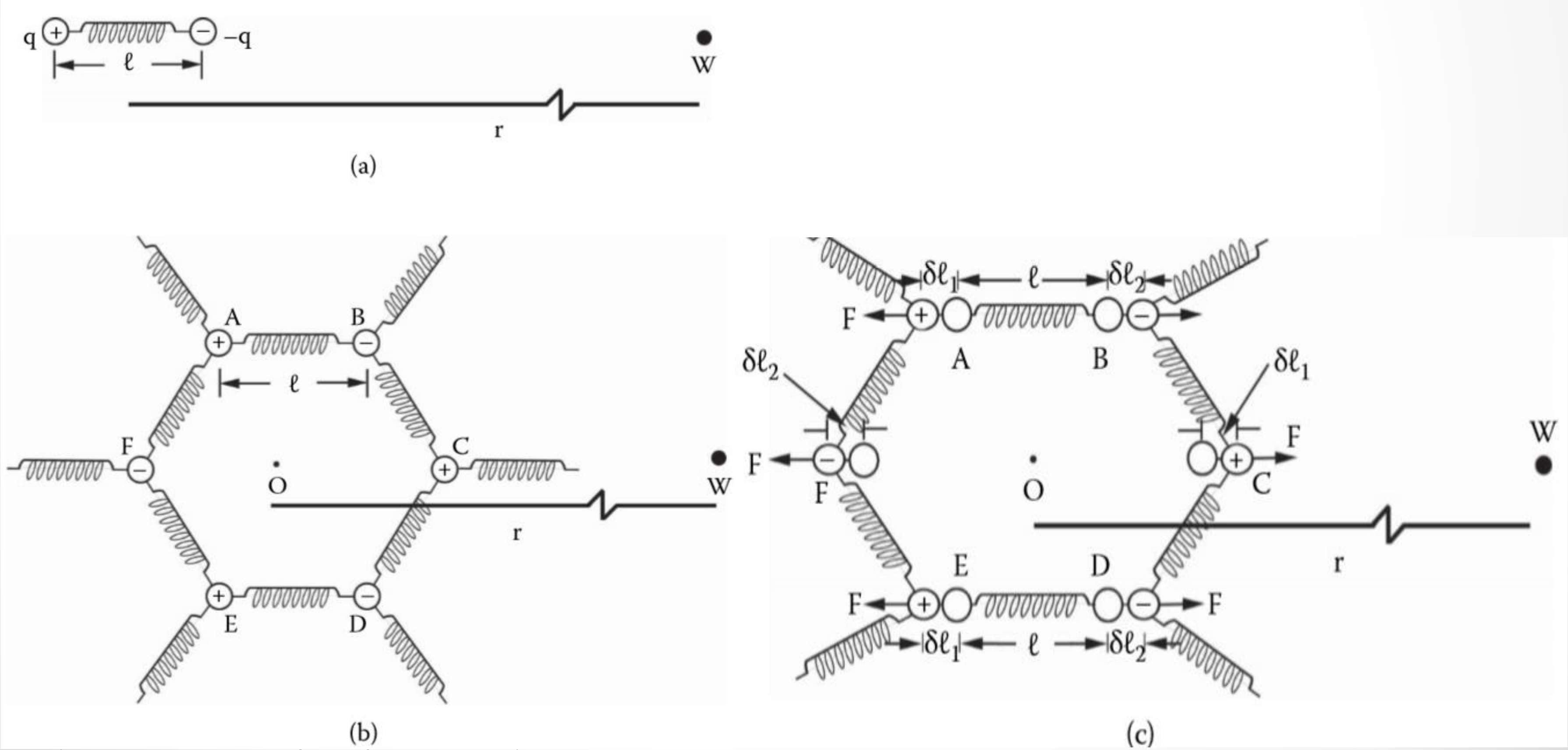
converse piezoelectric effect

f) Influence of the magnitude of the applied electric field on the magnitude of the deformation

g) Influence of the magnitude of the stress on the magnitude of the electric field

Piezoelectric Effect

- ➢ To explain piezoelectricity, a 2D hexagonal lattice consisting of oppositely charged atoms of identical charge is used as an example.
- ➢The basic element of the hexagonal cell is the dipole shown in Figure (a).
- ➢The atoms are held together by interatomic forces, which to a first approximation are represented as springs in Figure.



Vetelino, J., Reghu, A. (2011). Introduction to Sensors. Boca Raton: CRC Press

Piezoelectric Effect

- Electric field, E, from the dipole at a point W where $r >> \ell$, is given by $E = \frac{p}{2\pi\varepsilon_0 r^3}$
- Electric dipole moment $p = q\ell$, dielectric constant of vacuum ε_0
- Under the equilibrium conditions in Figure (b). The electric field at point W is the sum of the contributions of the individual fields from the dipoles AB, FC, and ED as

$$E = \frac{\left((q\ell)_{AB} - (2q\ell)_{FC} + (q\ell)_{ED}\right)}{2\pi\varepsilon_0 r^3} = 0$$

Total electric field at W from the hexagonal lattice is zero.

Vetelino, J., Reghu, A. (2011). Introduction to Sensors. Boca Raton: CRC Press

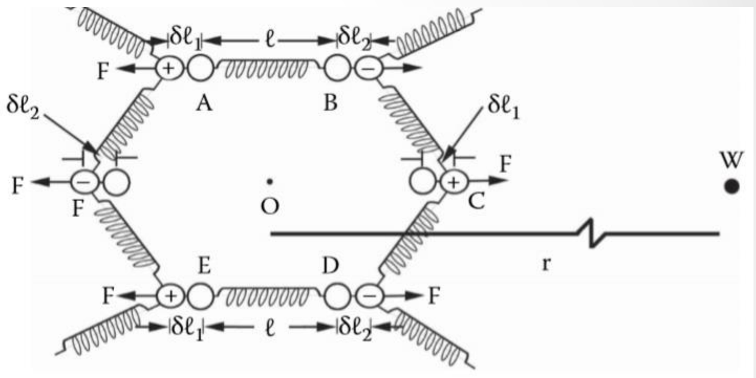
Piezoelectric Effect

- If a tensile stress, t, is applied to the lattice along the axis OW, the lattice will be deformed and each ion will be displaced, as shown in Figure (c).

- Electric field at point W becomes

$$E = \frac{p'}{2\pi\varepsilon_0 r^3}$$

- $p' = q\{(\ell + 2\delta\ell) - (2\ell + 2\delta\ell) + (\ell + 2\delta\ell)\} = 2q\delta\ell$



(c)

- The strain, s, due to the tensile stress, t, is defined as

$$s = \frac{\delta\ell}{\ell} \quad , \; p' = 2q\ell s$$

- Stress, t, is related to strain, s by Hooke's law, which is given by $s = s_c t$

s_c is the mechanical compliance

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Piezoelectric Effect

$$p' = 2q\ell s_c t$$

➢Assuming that the 2D hexagon contains N molecules per unit area, it follows that the electric polarization, P, which in this 2D case is defined as the dipole moment per unit area, is given as $P = 2Nq\ell s_c t = dt, \quad d = 2Nq\ell s_c$

➢The quantity, d, is by definition the *piezoelectric constant* or, *piezoelectric coefficient* which is the proportionality factor between the *mechanical stresses* $[t]$ and induced *electrical polarization* $[P]$.

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➢The quantity, d, is by definition the *piezoelectric constant*, which is the proportionality factor between the *mechanical stresses* and induced *electrical polarization*.

➢ Note that in an actual 3D lattice the polarization is defined as the dipole movement per unit volume.

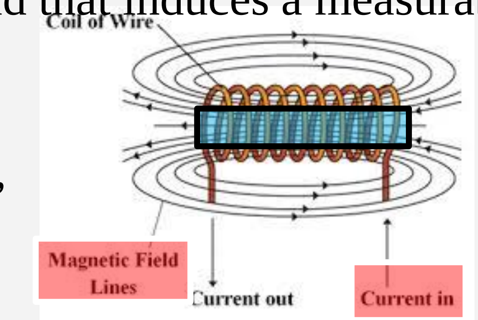
In 3D that $N = 5 \times 10^{28}/\text{m}^3$, $q = 1.6 \times 10^{-19}$ coulombs (C), $s_c = 12.7 \times 10^{-11}$ m²/N, and $\ell = 1.5 \times 10^{-10}$m, it is found that $d = 1.52 \times 10^{-12}$ C/N. It is interesting to point out that this result is comparable to an actual piezoelectric constant of quartz, $d_{11} = 2.41 \times 10^{-12}$ C/N.

Vetelino, J., Reghu, A. (2011). Introduction to Sensors. Boca Raton: CRC Press

Magnetostrictive Sensors

- ***Magnetostrictive*** materials can convert magnetic energy into kinetic energy, or the reverse, and are used to build actuators and sensors.

- By passing a current through the coil, a magnetic field is formed within in, causing the rod to extend. Alternatively, the device may operate in reverse as a sensor, where external pressures change the length of the rod, which in turn generates a magnetic field that induces a measurable current in the coil.



- Such sensors are frequently employed for non-destructive testing, such as examination of suspender cables on bridges.

- Induced voltage V at the terminals of the coil with the rate of change in displacement at the end of the bar. $g\Delta$ is the magnetostrictive strain modulus, E is the Young's modulus of the material, R_m is the total 'reluctance' of the magnetic circuit and N is the number of turns in the coil.

- Ferrites, and metallic alloys such as 'Permalloy' (45% Ni+55% Fe), 'Alfer' (13% Al+87% Fe) and 'Alcofer' (12% Al+2% Co+86% Fe)

$$V = \frac{g\Delta E N}{R_m}$$

www.linearmotiontips.com/how-do-magnetostrictive-sensors-work

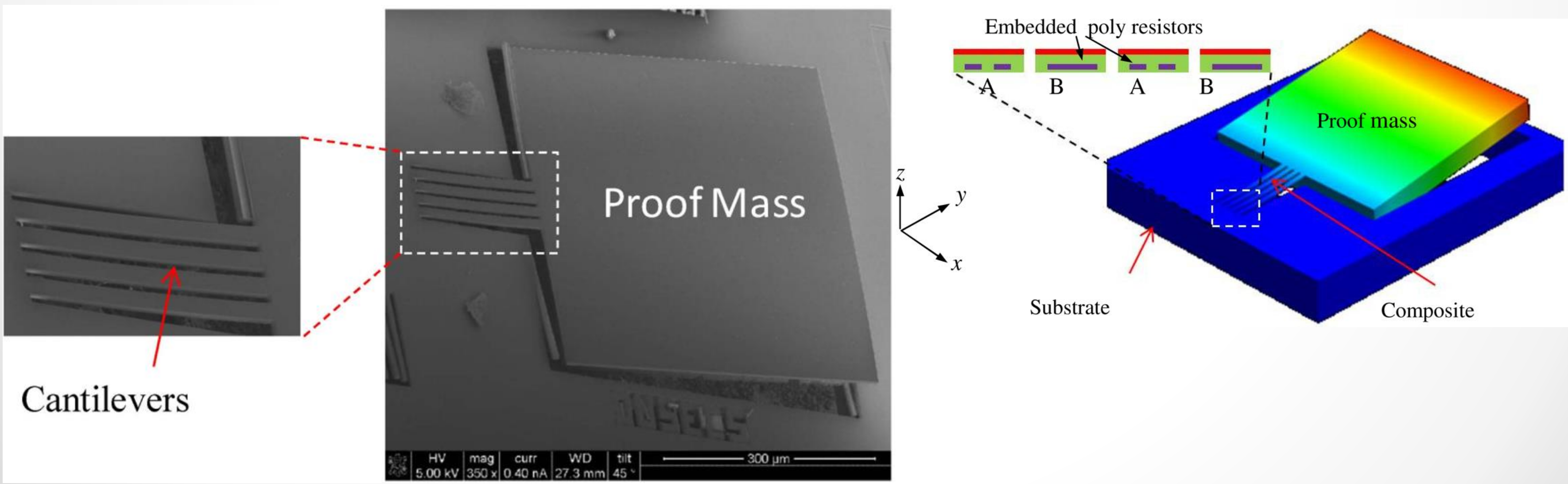
Piezoresistive Sensors

➢ The ***piezoresistive effect*** is a change in the ***electrical resistivity*** of a semiconductor or metal when mechanical strain is applied. In contrast to the piezoelectric effect, the piezoresistive effect causes a change only in electrical resistance (R), not in electric potential (Not V).

➢ In silicon, produces a larger resistance change than that under an applied stress in a typical conductor. Ex. the material is elongated 0.1% by stretching, the typical metallic resistors would change by ~0.2 %, but the resistance of silicon would change by ~10 %.

➢ Piezoresistive sensors dominate pressure, acceleration and force sensing applications.

➢ The deflection of the diaphragm leads to the dimensional change of the resistors, hence resulting in the resistance changing due to the piezoresistive effect in SiO_2/Metal.



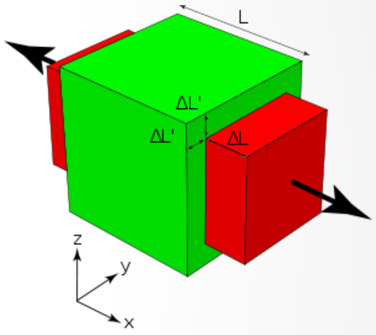
Fabricated CMOS-MEMS accelerometer with the inset showing the composite beams where piezoresistors are located.

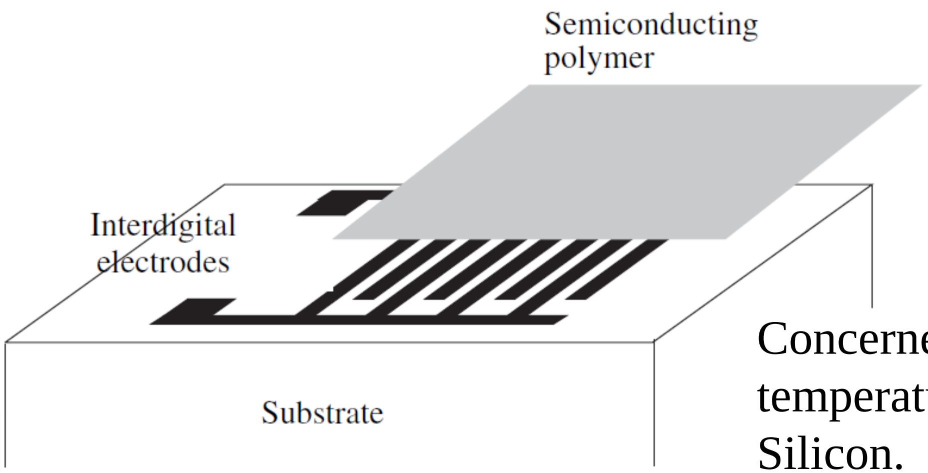
❑ *Sensors* **2011**, *11*(8), 7892-7907; doi:10.3390/s110807892

Piezoresistive Sensors

$$\frac{\Delta R}{R} = (1 + 2\nu)\frac{\Delta l}{l} + \frac{\Delta \rho}{\rho}$$

- where ΔR is the change of the resistance, R is the original resistance, ν is the Poison ratio, Δl is the length change of the resistor, l is the original length of the resistor and $\Delta\rho$ and ρ represent the resistivity change and resistivity of the resistor, respectively.





Concerned : more sensitive to temperature! If device is made from Silicon.

- If a voltage is applied to the electrodes and there is no pressure applied, the resistance is at the level of MΩ. When a force is applied, the resistance decreases due to the current that flows across the 'shunting' polymer foil [9]. Here, the sensing resistance is inversely proportional to the applied pressure.

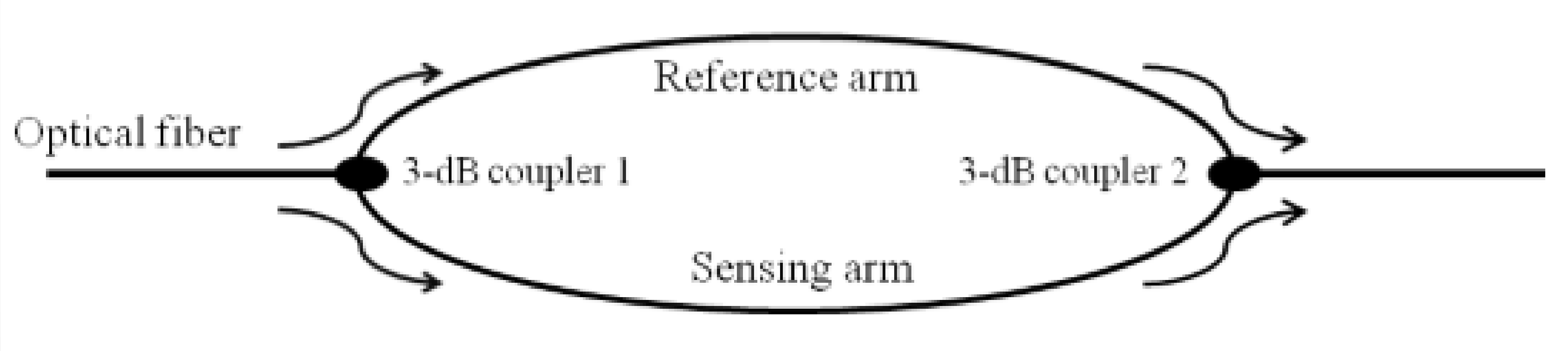
$$Sensing\ Resistance \propto \frac{1}{Applied\ Pressure}$$

Optical Sensors

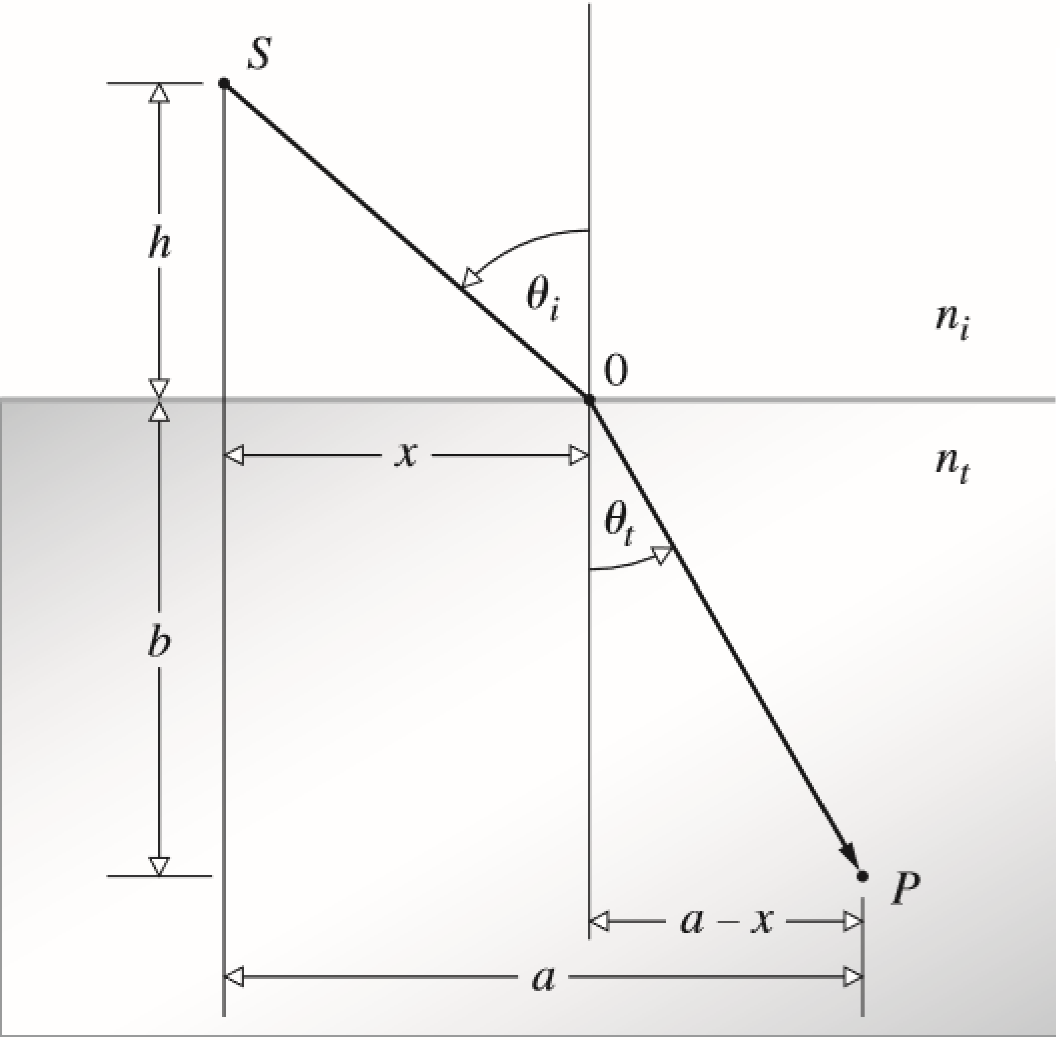
- Optical sensors are based on measuring either the intensity change in one or more light beams or phase changes in the light beams caused by their interaction or interference.

- Interferometric techniques, such as Mach–Zehnder interferometry (MZI) , Sagnac interferometry ,and Fabri-Perot interferometry

- For sensing applications, the reference arm is kept isolated from external variation and only the sensing arm is exposed to the variation. Then, the variation in the sensing arm induced by such as temperature, strain, and Refractive Index (n) changes the OPL (Optical Path Length) of the MZI, which can be easily detected by analyzing the variation in the interference signal.



Optical Path Length(OPL)



Fermat's Principle applied to refraction.

- The smallest transit time will be

$$t = \frac{\overline{SO}}{v_i} + \frac{\overline{OP}}{v_t}$$

or $$t = \frac{(h^2 + x^2)^{1/2}}{v_i} + \frac{[b^2 + (a - x)^2]^{1/2}}{v_t}$$

To minimize $t(x)$, we set $dt/dx = 0$, that is,

$$\frac{dt}{dx} = \frac{x}{v_i(h^2 + x^2)^{1/2}} + \frac{-(a - x)}{v_t[b^2 + (a - x)^2]^{1/2}} = 0$$

Using the diagram, we rewrite the expression as

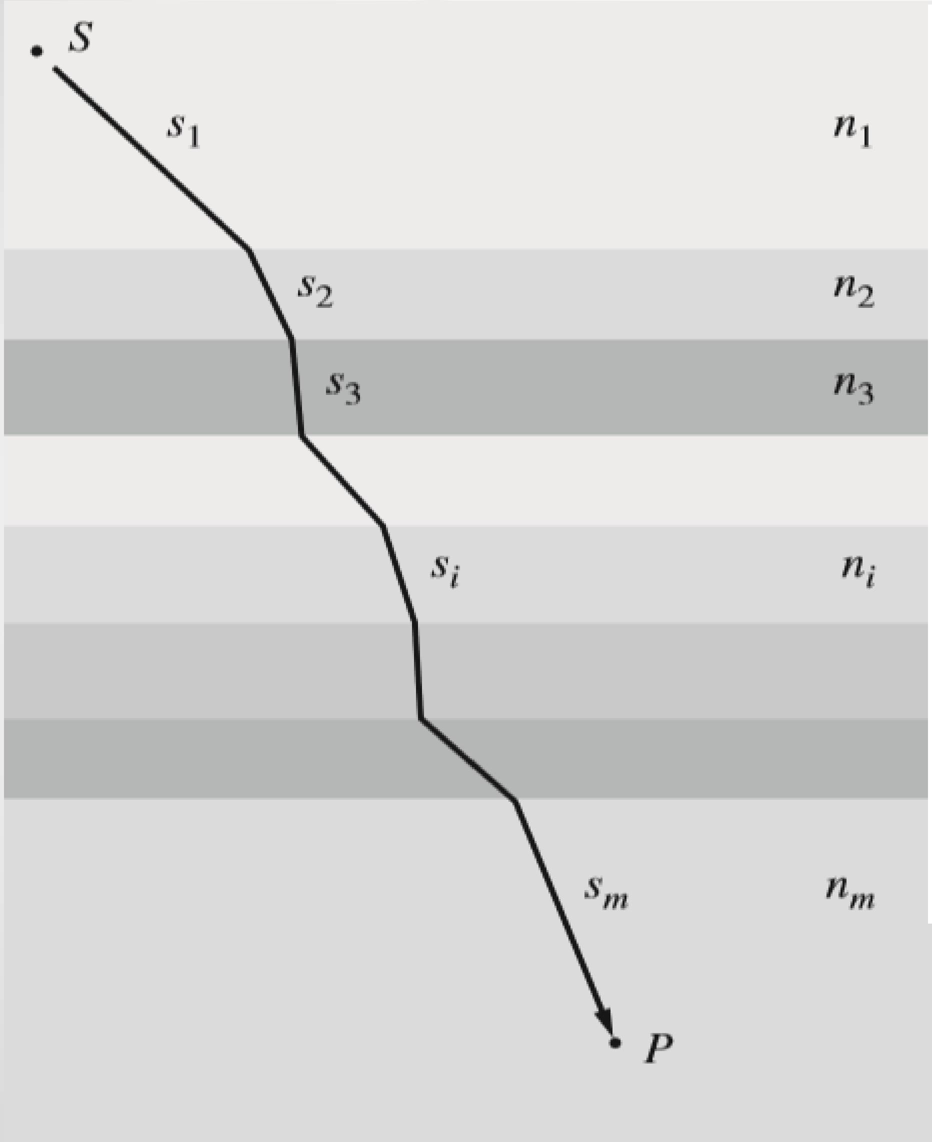
$$\frac{\sin\theta_i}{v_i} = \frac{\sin\theta_t}{v_t}$$

The transit time from S to P will then be

$$t = \frac{s_1}{v_1} + \frac{s_2}{v_2} + \cdots + \frac{s_m}{v_m}$$

or $$t = \sum_{i=1}^{m} s_i/v_i$$

Optical Path Length(OPL)



A ray propagating through a layered material.

where s_i and v_i are the path length and speed, respectively, associated with the ith contribution. Thus

$$t = \frac{1}{c}\sum_{i=1}^{m} n_i s_i \tag{4.9}$$

in which the summation is known as the **optical path length** (OPL) traversed by the ray, in contrast to the spatial path length $\sum_{i=1}^{m} s_i$. Clearly, for an inhomogeneous medium where n is a function of position, the summation must be changed to an integral:

$$OPL = \int_S^P n(s)\, ds \tag{4.10}$$

The optical path length corresponds to the distance in vacuum equivalent to the distance traversed (s) in the medium of index n. That is, the two will correspond to the same number of wavelengths, $(OPL)/\lambda_0 = s/\lambda$, and the same phase change as the light advances.

Interferometer

- The concept of interferometry is based on the phenomenon of interference, occurring when two waves with equal frequency coincide. The resulting amplitude (or intensity) varies with the phase difference between the two waves.
- At equal amplitudes of the individual waves, the total intensity doubles when the waves are in phase (constructive interference), and drops to zero when in antiphase (destructive interference).
- The wave form of monochrome light (i.e. light with just one wavelength) is described by:

$$A(x,t) = A_0 \cos(\omega t - kx)$$

where A_0 is the wave amplitude (for both the electric and the magnetic field components), $\omega=2\pi f$ is the angular frequency of the wave, $k=2\pi n/\lambda$ is the wave number and x the co-ordinate in the direction of propagation.

- When two waves with equal frequency (wavelength) travel distances x_1 and x_2, respectively, their wave forms are described as $A_1 \cos(\omega t - kx_1)$ and $A_2 \cos(\omega t - kx_2)$. Both waves fall simultaneously on the same sensor, so the wave functions are added:

- $$A_{tot} = A_1 \cos(\omega t - kx_1) + A_2 \cos(\omega t - kx_2) = A(x) \cos(\omega t - \ (x))$$

Interferometer

$$A_{tot} = A_1 \cos(\omega t - kx_1) + A_2 \cos(\omega t - kx_2) = A(x) \cos(\omega t - \quad (x))$$

Where

$$A(x) = \sqrt{A_1^2 + A_2^2 + 2A_1A_2 \cos(k(x_1 - x_2))}$$

and

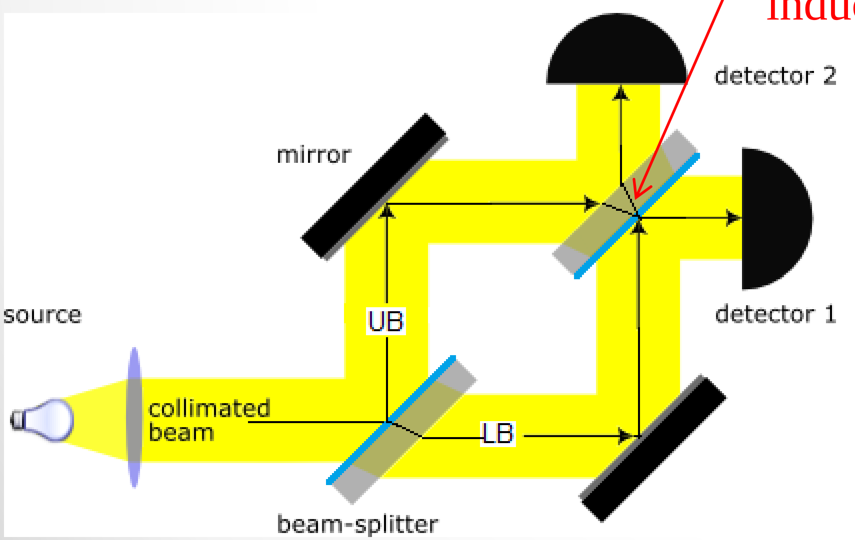
$$\tan(\phi(x)) = \frac{A_2 \sin(k(x_1 - x_2))}{A_1 + A_2 \cos(k(x_1 - x_2))}$$

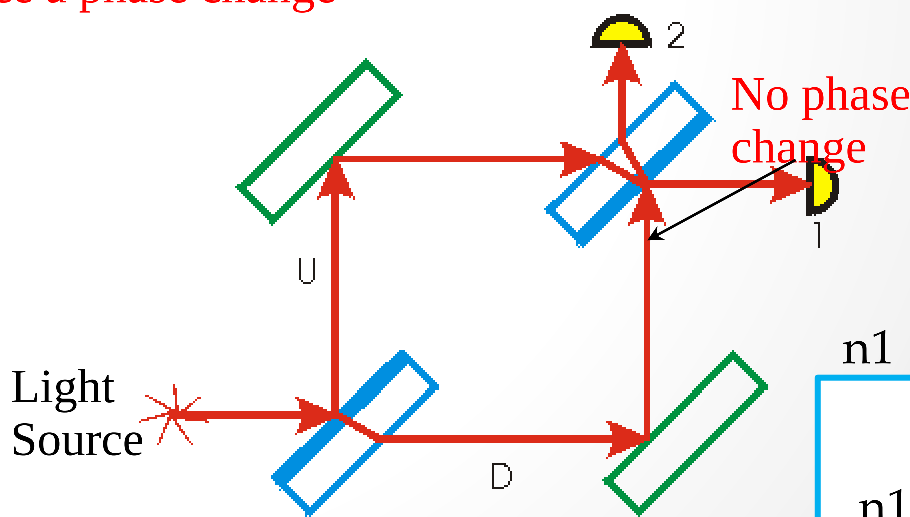
Mach–Zehnder Interferometer

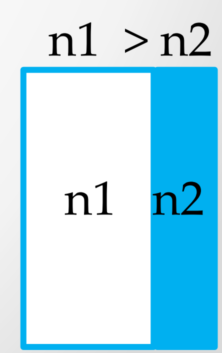
- ➢ Beamsplitter is a piece of glass with a dielectric or metal coating on the front surface. Light striking it from the front has a 50% (or any other value, depending on the coating) chance of being reflected, and a 50% chance of being transmitted.
- ➢ Phase shifts on reflection : a reflection does indeed induce a phase shift of π, whereas a transmitted light picks up no phase shift.

- ➢ There is a phase change for a reflection when light reflects off a change from low to high refractive index but not when it reflects off a change from high to low.

Here!!! reflection does not induce a phase change

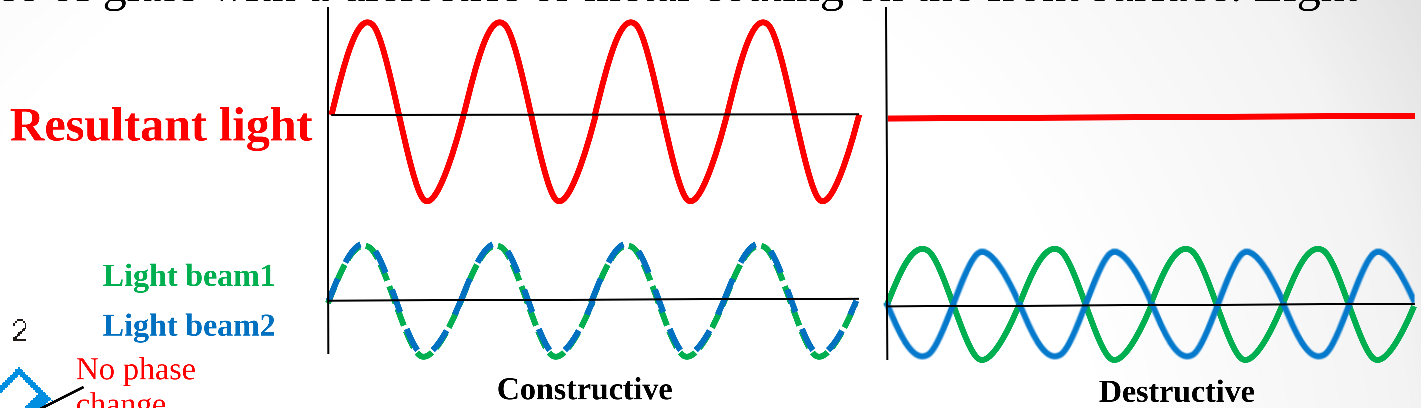


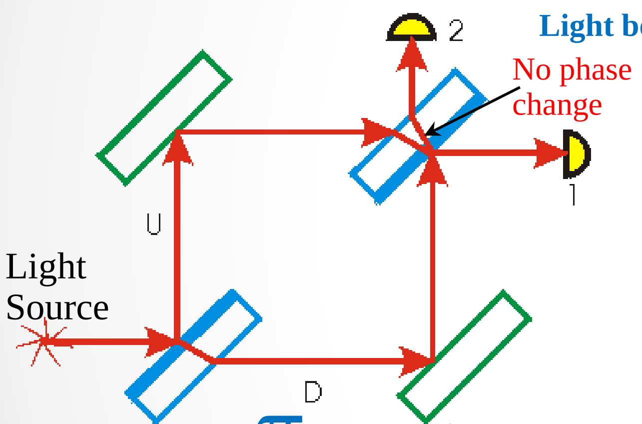


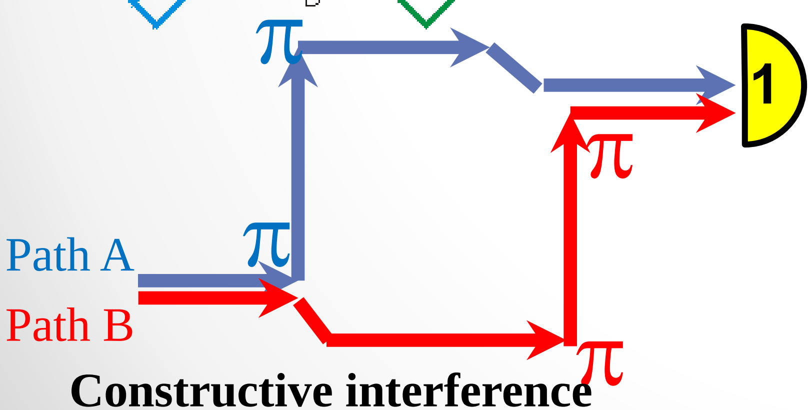


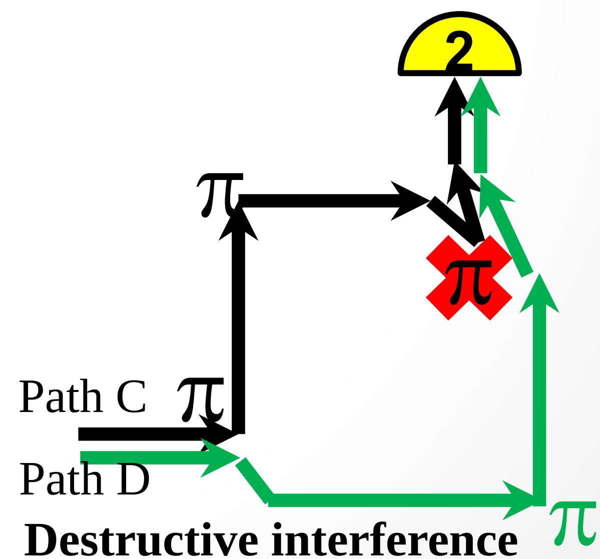
Mach–Zehnder Interferometer

- Beamsplitter is a piece of glass with a dielectric or metal coating on the front surface. Light



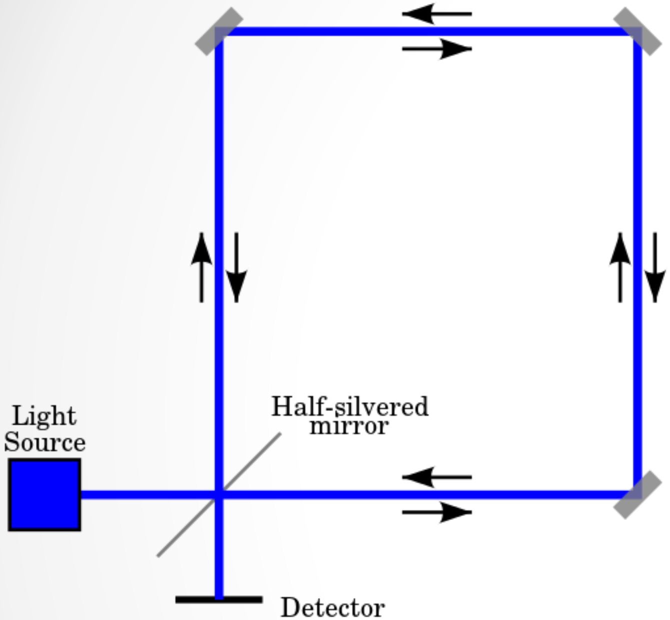




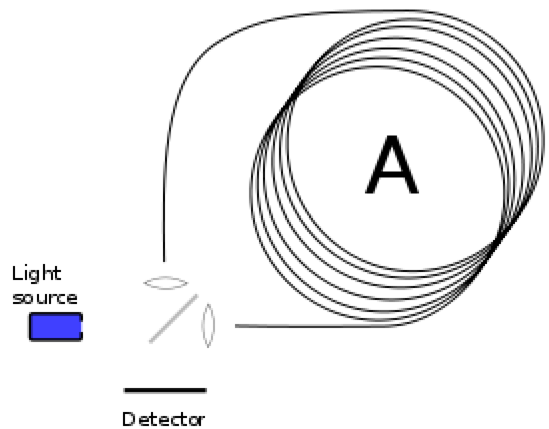


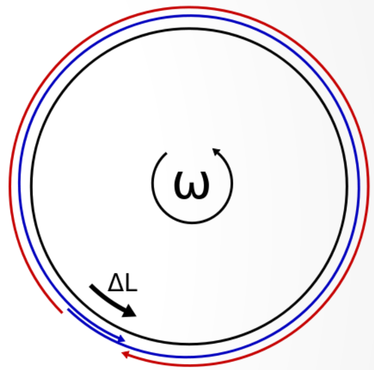
Sagnac Interferometer

➢ The Sagnac interference is a phenomenon encountered in interferometry that is elicited by rotation.



Sagnac interferometer, or
fiber optic gyroscope (FOG)





❑ https://en.wikipedia.org/wiki/Sagnac_effect

The Sagnac Effect.mp4

Sagnac Interferometer

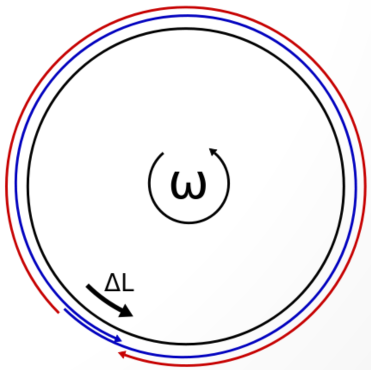
- Consequence of the different distances that light travels due to the rotation of the ring.
- The simplest derivation is for a circular ring of radius R, with a refractive index of 1, rotating at an angular velocity of ω
- Light traveling in the same direction as the rotation direction needs to travel more than one circumference before it catches up with the light source from behind (t_1).

$$t_1 = \frac{2\pi R + \Delta L}{c}$$,Where ΔL is the distance that the mirror has moved in that same time=$R\omega t_1$

$$t_1 = \frac{2\pi R}{c - R\omega}$$

- Likewise, Light traveling in the opposite direction of the rotation will travel less than one circumference before hitting the light source on the front side (t_2).

$$t_2 = \frac{2\pi R}{c + R\omega}$$



- The time difference is

$$t_1 - t_2 = \Delta t = \frac{2\pi R}{c - R\omega} - \frac{2\pi R}{c + R\omega} = \frac{4\pi\omega R^2}{c^2 - R^2\omega^2} \approx \frac{4\pi\omega R^2}{c^2} = \frac{4\omega A}{c^2}$$

- https://en.wikipedia.org/wiki/Sagnac_effect

The Sagnac Effect.mp4

Sagnac Interferometer

- Ex. Radius of fiber optic gyroscope is 5 m , an angular velocity of ω is 200 rad/sec.

$$t_1 = \frac{2\pi R}{c-R\omega} = \frac{2\pi(5)}{3*108-200*5} = 1.047201042 * 10^{-7} \text{ second}$$

$$t_2 = \frac{2\pi R}{c+R\omega} = \frac{2\pi(5)}{3*108+200*5} = 1.047194061 * 10^{-7} \text{ second}$$

$$t_1 - t_2 = 1.047201042 * 10^{-7} - 1.047194061 * 10^{-7} = 6.98 * 10^{-13} \text{second}$$

$$\Delta t = \frac{4\pi\omega R^2}{c^2} = \frac{4\pi(200)25}{9*1016} = \frac{62831.85}{9*1016} = 6.98 * 10^{-13} \text{second}$$

- https://en.wikipedia.org/wiki/Sagnac_effect

Resonant Sensors

➢ Resonant sensors are based on measuring the resonant freq. of the mechanical vibration of beams or diaphragms. The applied strain causes changes in the resonant freq. (similar to a guitar string), enabling measurement of input variables such as pressure, acceleration, rate ,and temperature.

➢In a resonant sensor, the strain caused by pressure on the diaphragm leads to variation of its natural frequency.

➢As an example, the natural resonant frequency of a flexure resonator with both ends fixed can be obtained from the following

$$f = \frac{4.73^2 h}{2\pi l^2}\left\{\frac{E}{12\rho}\left(1 + 0.2366\varepsilon\left(\frac{l}{h}\right)^2\right)^{\frac{1}{2}}\right\}$$

➢where f is the natural frequency of the fundamental oscillating mode, l the resonator length, h the resonator thickness, E the Young's modulus, ρ the density of the diaphragm material and ε the strain generated inside the resonator structure.

Resonant Sensors

- Comparing resonant sensing with piezoresistive sensing, the gauge factor of the resonant strain gauge can be determined as:

$$k_{gf} = \frac{1}{2}\left(\frac{0.2366(\frac{l}{h})^2}{1 + 0.2366\varepsilon(\frac{l}{h})^2}\right) \quad , \frac{\Delta f}{f} = k_{gf}\,\varepsilon$$

- If a strain is 100 ppm, for a 1.2-mm long, 20-micron wide and 5-micron thick resonator strain gauge, the gauge factor can be as high as 3000, whereas the piezoresistive strain gauge factor is only about 2.

Questions

1. จากบทเรียนเรื่อง Capacitive sensors จงหาว่า input&output คือสิ่งใด
   a) พื้นที่และระยะระหว่างขั้วไฟฟ้าที่เปลี่ยนแปลง
   b) พื้นที่และค่าความจุที่เปลี่ยนแปลง
   c) แรงกดและระยะระหว่างขั้วไฟฟ้าที่เปลี่ยนแปลง
   d) แรงกดและค่าความจุที่เปลี่ยนแปลง
2. จากบทเรียนเรื่อง circular diaphragm capacitive sensor เหตุใดจึงมีความซับซ้อนในการคำนวน
   a) ค่าระยะระหว่างขั้วไฟฟ้าไม่คงที่
   b) ค่าพื้นที่ไม่คงที่
   c) ค่าความจุไม่คงที่
   d) ค่า ε ของตัวกลางไม่คงที่
3. จากบทเรียนเรื่อง Comb capacitor ค่าความจุที่เปลี่ยนแปลงเป็นผลมาจากสิ่งใดเป็นสำคัญ
   a) ค่า ε ของตัวกลางเปลี่ยนแปลง
   b) ค่าระยะระหว่างขั้วไฟฟ้า
   c) ค่าพื้นที่ซ้อนกันของขั้วไฟฟ้า
   d) ค่าความนำไฟฟ้าของขั้วไฟฟ้า

Questions

4. จากบทเรียนเรื่อง piezoelectric sensors ข้อใดถูกต้อง
   a) แรงดันไฟฟ้าที่เกิดขึ้นมาจากแรงกดที่กระทำกับ **$PbTiO_3$**
   b) กระแสไฟฟ้าที่เกิดขึ้นมาจากแรงกดที่กระทำกับ piezoresistive material
   c) กระแสไฟฟ้าที่เกิดขึ้นมาจากแรงดันไฟฟ้าที่กระทำกับ **$PbTiO_3$**
   d) แรงดันไฟฟ้าที่เกิดขึ้นมาจากแรงกดที่กระทำกับ piezoresistive material
5. จากบทเรียนเรื่อง piezoelectric sensors ข้อใดไม่ถูกต้อง
   a) เกี่ยวข้องกับค่า Poisson's ratio
   b) เกี่ยวข้องกับค่า Young's modulus
   c) เกี่ยวข้องกับค่า elastic constant
   d) เกี่ยวข้องกับค่าสนามไฟฟ้า
6. จากบทเรียนเรื่อง piezoelectric sensors ข้อใดไม่เกี่ยวข้อง
   a) ถ้าไม่มีสนามไฟฟ้า piezoelectric effect จะกลายเป็นกฎของ Hooke
   b) Pressure sensor ใช้หลักการ piezoelectric effect
   c) piezoelectric sensors ถูกนำมาใช้มาใน Bio-chemical sensor
   d) hydrophones และ microphones บางประเภทคือ piezoelectric sensors

Questions

7. จากบทเรียนเรื่อง Magnetostrictive sensors ข้อใดถูกต้อง
   a) แรงกดเปลี่ยนความยาวของวัสดุทำให้เกิดสนามแม่เหล็กแล้วเหนี่ยวนำให้เกิดกระแสไฟฟ้า
   b) ความเข้มสนามแม่เหล็กเปลี่ยนความยาวของวัสดุและเหนี่ยวนำให้เกิดกระแสไฟฟ้า
   c) อุณหภูมิเปลี่ยนความยาวของวัสดุทำให้เกิดสนามแม่เหล็กแล้วเหนี่ยวนำให้เกิดกระแสไฟฟ้า
   d) แรงดันไฟฟ้าเปลี่ยนความยาวของวัสดุทำให้เกิดสนามแม่เหล็กแล้วเหนี่ยวนำให้เกิดกระแสไฟฟ้า
8. เหตุใด Piezoresistive sensor จึงนิยมทำจากสารกึ่งตัวนำมากกว่าโลหะ
   a) สารกึ่งตัวนำมีค่า Young ‘s modulus สูงกว่าโลหะ
   b) สารกึ่งตัวนำมีความต้านทานสูงกว่าโลหะ
   c) สารกึ่งตัวนำมีความต้านทานเปลี่ยนแปลงต่ำกว่าโลหะเมื่อถูกยืดออก
   d) สารกึ่งตัวนำมีความต้านทานเปลี่ยนแปลงสูงกว่าโลหะเมื่อถูกยืดออก